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PRELIMINARY DRAFT

Status of Volcanic Hazard Studies for the Yucca Mountain Site Characterization Project

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PRELIMINARY DRAFT

PREFACE

This preface is presented as a reading guide to this preliminary draft version of the Volcanism Status Report. It is undeniably a lengthy report that describes a complex topic and summarizes a wide range of work covering more than a decade of volcanism studies. The report is not designed to be read in sequence. Rather it is split into distinct topics that can be read independently. The introduction (Section I) provides an overview of the scope of the report and can be used as a guide to the content of the different sections and the major conclusions of the report. Section II describes the background geology of the record of basaltic volcanism in the Yucca Mountain region covering data for volcanic centers in order of decreasing age. A large amount of the section discusses the geology, eruptive models, and chronology of the Lathrop Wells center. Those readers interested primarily in this lively and at times controversial topic should focus on this section. It also covers the current results of the development and application of a range of geochronology methods to a topical problem of establishing, with an acceptable degree of confidence, the timing of Quaternary volcanic events. Section III is concerned primarily with the tectonic setting of the Yucca Mountain region. The spectra of tectonic models for the area, ranging from detachment, to caldera, to pull-apart basins are described. The relationship of basaltic volcanic activity to the different tectonic processes, both real and possibly non-real, are discussed. The wide range of geophysical data for the site region is summarized and examined for importance to understanding the tectonic setting of volcanism. Section IV provides an overview of basaltic volcanism in the Great Basin and Basin and Range province from a geochemical and petrologic perspective. Patterns of small volume basaltic volcanism in the interior of the province are contrasted with much larger volume and more active fields at the province boundaries. Consideration is given to the evolutionary patterns of basaltic volcanism both at the scale of a volcanic field and at individual volcanic centers. Section V reviews the dynamics of magma segregation, migration, storage, and eruption of basaltic magma. There has been much progress in quantifying processes of magmatism in the last decade and some of this progress has application to the timing, setting, and location of sites of basaltic volcanism in the Yucca Mountain region. Section VI summarizes, in chronological order, the history of volcanism studies associated with the Yucca Mountain Project. This should prove to be a useful section for readers attempting to gain an overview perspective on the scope and logic of volcanism studies. Section VII is concerned entirely with an assessment of the risk of future volcanism for the potential Yucca Mountain site. This is the suggested section to read for those who want, without wading through the accompanying details, to find out what the volcanism problem is, how it is being studied and what it means. We present the results of the most recent and comprehensive assessment of the conditional probability of magmatic disruption of the repository, the controlled area, and the Yucca Mountain region. Section VIII attempts to present in abbreviated form what future work needs to be accomplished to complete volcanism studies and why conclusions concerning the probability of magmatic disruption are unlikely to change. Finally, Section IX presents the conclusions of the report, section by section. Those readers pressed for time should read the introduction and the conclusions. Hopefully some of the information may catch your attention and lead you to read other parts of the report.

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The idea of developing an overview document of all volcanism studies was developed with David Dobson, now with Golder Associates. The volcanism studies involve a team effort that crosses a range of disciplines. While we assembled the report, it is the product of the efforts of the following people and their respective disciplines:

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This is a *preliminary report*. It has been released in draft form and has not received official technical review or been assessed for compliance with the required procedures of the Los Alamos Quality Assurance Program. Furthermore, the report has not received DOE programmatic and policy review. This preliminary form of the report is intended to provide an opportunity for overview organizations such as the Nuclear Regulatory Commission, the State of Nevada, and other interested organizations or individual reviewers to read and comment informally on the report. It is our intent to evaluate the informal comments and incorporate them, if possible, in the report when it is issued as a Los Alamos report in September of 1993.

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SECTION I: INTRODUCTION TO THE VOLCANISM ISSUE

I. ABSTRACT

The risk of future volcanic activity is being studied as one part of site characterization studies for the potential Yucca Mountain site. There are two aspects to the risk of volcanism. The first is the risk of silicic volcanism. It is judged to be negligible because of the absence of silicic volcanism in the region for the last 8.5 Ma. The second aspect is the risk of basaltic volcanism, a potentially disruptive process representing a finite risk that could potentially disqualify the site. There are several components to the risk of basaltic volcanism. These include penetration of the repository by magma accompanied by eruptions, intrusion of the repository and repository vicinity by basalt magma, and eruption and/or intrusion of basalt magma in or near the waste isolation system. Each component of volcanic risk is studied from the perspective of potential disqualification of the Yucca Mountain site as well as the contribution of future volcanic processes to the radiological releases from the waste isolation system. The timing and location of future volcanic events in the Yucca Mountain region cannot be predicted. However, the risk of future events can be defined as a tripartite conditional probability consisting of the recurrence rate of volcanic events, the probability of disruption and the probability of volcanic-driven releases exceeding regulatory requirements. Estimations of the tripartite probability are judged against the regulatory requirements for licensing of a repository for storage of high-level radioactive waste. The volcanism status report summarizes work through 1992 on assessing the risk of volcanism for the potential Yucca Mountain site. The geologic and tectonic settings of basaltic volcanism in the region and the geochemistry of basaltic magmatism in the Basin and Range province and local setting are described. The evolutionary history of basaltic magmatism is traced from generation, to ascent and storage, through eruption. The history of volcanism studies for the Yucca Mountain region, current to the preparation of this report, is summarized. Revised results of risk assessment are presented emphasizing primarily the probability of magmatic disruption of the repository. Studies required to conclude volcanism studies are summarized. The occurrence probability of direct magmatic disruption of a repository at the Yucca Mountain site by basaltic volcanism is too low to disqualify the potential site solely on the basis of the risk of volcanism. The occurrence probability of eruption through or intrusion into the controlled area or the Yucca Mountain exceed 10^{-8} yr^{-1}. The significance of these events will be determined through evaluation of the probability and consequences of radiological releases.

II. INTRODUCTION

An evaluation of the risk of future volcanic activity is an important part of studies for the Yucca Mountain Site Characterization Project (YMP). This is just one of many issues requiring resolution, either positively or negatively, for assessing the suitability of the potential Yucca Mountain site (Department of Energy (DOE) 1988). Volcanism studies are a prominent part of site suitability studies and have been ongoing for over a decade (Crowe and Carr 1980; Crowe et al. 1992). Future volcanism is a natural geologic process that could pose a risk to the integrity of a waste isolation system for a geologic repository. The duration of that risk is the regulated 10,000 year period for isolation of high-level radioactive waste. Penetration of a repository by ascending magma followed by surface eruption could, under some conditions, lead to direct releases of radionuclides to the accessible environment. Additionally, intrusion of magma through or near an underground repository could alter the integrity of the waste isolation system even if magma is not erupted at the surface. If the risk of volcanism from eruptions of magma through a repository or the effects of intrusions exceeds the regulatory requirements for licensing of a repository, the Yucca Mountain site cannot be found acceptable as a potential repository. Alternatively, if the risk of volcanism is judged to be acceptable, the potential Yucca Mountain site may not necessarily be suitable for a repository. The potential site must also meet regulatory requirements for a range of natural processes that limit the allowable release of radionuclides over the next 10,000 years.

There are two aspects to an assessment of the risk of future volcanism. The first is the risk of future silicic volcanic activity. The rocks that were uplifted by faulting in the Miocene to form Yucca Mountain were deposited as outflow facies of large volume, explosive eruptions of silicic magma. These eruptions produced hot pyroclastic flows (ignimbrites) and formed multiple, coalesced caldera complexes. The age of this silicic activity ranges from about 15 to 11 Ma. Silicic volcanism in related but spatially separated caldera centers occurred about 7.5 to 8.5 Ma (Black Mountain caldera complex). There are no Pliocene or younger silicic centers within a 50 km radius of the potential Yucca Mountain site. The nearest young silicic center is the Mt. Jackson rhyolite dome (2.9 Ma). It is located 105 km to the northwest of Yucca Mountain. Quaternary centers of silicic volcanic activity occur at the eastern and western margins of the Great Basin, more than 100 km from Yucca Mountain. The absence of post-Miocene silicic volcanism in the Yucca Mountain region supports the interpretation that the likelihood of recurrence of a large volume, explosive silicic eruption is very low, perhaps extremely low. Accordingly, it is judged not to be a significant issue for evaluation of the potential Yucca Mountain site for isolation of high-level radioactive waste (Crowe et al. 1983; National Research Council 1992).

A second, more critical issue for site suitability studies, is an evaluation of the risk of future basaltic volcanism. There are five small-volume Quaternary basalt centers within a 25 kilometer radius circle, centered at the potential Yucca Mountain site. The closest Quaternary volcanic center is the 1.1 Ma Black Cone center. It is nine km from the southwestern edge of the exploratory block. The youngest volcanic center in the region, the Lathrop Wells center, is 20 km south of the exploratory block. Other basalt sites of Pliocene or Quaternary age include two centers of the basalt of Sleeping Butte (.385 Ma) and the basalt of Buckboard Mesa (2.9 Ma). These centers are located respectively, 47 km northwest and 35 km northeast of the potential site. A north-trending alignment of eroded basalt centers (four or five centers) which are about 3.7 Ma is present in the southeast part of Crater Flat. A 4.6 Ma basalt mesa (three coalesced centers) is located south of Black Mountain. It is 35 km northwest of Yucca Mountain. A 4.4 Ma basalt center is buried beneath alluvial deposits several kilometers south of the town of Amargosa Valley, and 25 km southeast of the potential Yucca Mountain site.

Stated simply, the risk represented by the Quaternary record of volcanism is the possible recurrence of basaltic eruptive activity during the 10,000 yr isolation period of a potential repository at Yucca Mountain. The nature of the future risk of volcanism can be summarized in four questions:

1. Could a future pulse of basaltic magma penetrate the repository, erupt, and release waste radionuclides to the accessible environment (eruption scenario)?

2. Could intrusion of magma in or around the potential repository perturb the waste isolation system and cause accelerated release of waste radionuclides (subsurface scenario)?

3. Is the risk *solely from eruption or intrusion effects* sufficient to disqualify the potential Yucca Mountain site from consideration as a site for underground storage of high-level radioactive waste?

4. What is the component of radiological releases associated with future magmatic processes on the performance of a potential repository over a 10,000 yr period?

Several types of data are required to answer these questions. The recurrence rate or the frequency of occurrence of basaltic eruptions and subsurface intrusions needs to be established for the Yucca Mountain region. The possible locations of future sites of eruptions or intrusions need to be estimated or bound. An evaluation of subsurface intrusion effects requires estimating the likelihood of intrusions and their affect on both the repository and the waste isolation system encompassing the repository. Finally, the qualification or disqualification of the potential Yucca Mountain site with respect to future volcanism will be based on a comparison of data for these questions with the regulations for licensing of a repository.

Acquisition of the data needed to fulfill these requirements has been the focus of volcanism studies for the last decade. Volcanism studies are focusing on the effects of basalt intrusions (Valentine et al. 1992). The principal area of progress in volcanism studies to date has been for evaluations of the occurrence probability of magmatic disruption of a potential repository (Crowe 1986; Crowe et al. 1992). There has been sufficient progress in these studies to provide bounds on the likely results of intersection of the repository by ascending magma and eruption at the surface (eruption processes). The eruption processes have been examined in a series of reviews, both external and internal to the YMP. The reviews have concluded generally that eruption effects of volcanism do not disqualify the Yucca Mountain site. That is, the site should not be disqualified solely from the risk of future volcanic eruptions based on assessments using current site information (Crowe et al. 1983a; Crowe 1986; DOE 1986; 1988; Younker et al. 1992; National Research Council 1992).

The Nuclear Regulatory Commission (NRC) has neither refuted nor accepted conclusions about the risk of volcanism. They have provided questions and comments about the methods used for probability calculations, about the uncertainty of the probability calculations, and about the completeness of information used in risk assessment. The State of Nevada has argued in both oral and written form that volcanism is an unresolved issue with respect to the safety of the Yucca Mountain site. These arguments were based on qualitative judgments of the risk of volcanism or uncertainty in evaluations of the risk. They are not based on the regulatory requirements for a potential repository. The potential for future volcanism continues to be an issue of considerable attention and some difference of opinion.

The view that future eruption effects are not a significant issue for the potential Yucca Mountain site requires clarification. The reaction of the public to the simple perception of a risk of volcanism is often unrealistic. An erupting volcano invokes images of explosions accompanied by ejection of towering columns of ash. Surrounding areas are devastated. Forests and wildlife are destroyed. Lives are lost, and property is ruined. This imagery is reinforced by media dramatizations of volcanic eruptions. The news coverage is dominated by close-up photography of the eruptions and zones of destruction. The series of major explosive eruptions in the last twelve years (Mt. St. Helens 1980; El Chichon 1982; Mt. Pinatobu 1991-1992) perhaps have made the public more aware than usual of the potential effects of volcanoes.

However, the public is unfamiliar generally with the widely different types of volcanoes and the range in risks represented by the diversity of specific types of volcanic eruptions. Additionally, critics of the potential Yucca Mountain site often exaggerate the risks of waste isolation for issues of public sensitivity like volcanic eruptions, or earthquakes. The Pliocene and Quaternary volcanic centers (basaltic volcanoes) in the Yucca Mountain region are among the least explosive and least dangerous of the spectrum of volcanoes on the earth. They erupt small volumes of magma and are fed at depth by narrow dikes (sheet-like bodies). Basaltic magma must erupt virtually through a repository or the near-repository area to significantly perturb the waste isolation system. These volcanoes have a limited capability to disperse radioactive waste at the surface of the earth. The risk of basaltic volcanism is not zero. But the risks are small and they can be quantified and bounded.

There are often unrealistic expectations of the ability of science to provide reliable predictions of future volcanic activity. A common misconception is that comprehensive studies of the record of volcanism will lead to highly precise predictions of future volcanic eruptions. That is not true. Predictions of volcanic activity are based on the assumption that the record of volcanism provides a suitable indicator of the rates and style of future volcanic activity. This means simply, that the history of eruptive activity can be used to predict the most likely future volcanic activity. But rates and processes of volcanic activity could change. Moreover, the record of past volcanic processes may be incomplete or hard to decipher. These uncertainties markedly constrain the accuracy of future predictions. We have a limited ability to predict the location in space and time of future volcanic activity. In fact, such predictions are probably not possible for the types of volcanoes and the small number of past volcanic events in the Yucca Mountain region. Currently, volcanic eruptions can be predicted only for special conditions at historically active volcanoes (UNESCO 1971; Bolt et al. 1975; Tazieff and Sabroux 1983; Swanson et al. 1985). We lack predictive models of the triggering mechanisms of volcanic eruptions particularly for areas of intermittent volcanic activity like the southern Great Basin. Here the major concern for risk assessment is a future eruption that results in the birth of a new volcano through or near the proposed repository. This is a markedly different problem than predicting another eruption at an existing volcano.

Further, the recently evolving ideas of deterministic chaos provide a new perspective of how complex processes may evolve through time (Stewart 1989; Devaney 1990). The processes controlling the generation, ascent, and eruption of magma at the surface exhibit many properties of chaotic systems (Shaw 1987; Dubois and Cheminee 1991; Sornette et al. 1991). Studies applying these ideas suggest currently that accurate predictions of future volcanic events over an extended period may, like weather forecasts, be impossible. The record of scientists in predicting the future across a range of disciplines is marginal at best (Casti 1990). These difficulties appear, on first examination, disconcerting. But the questions posed for the volcanism studies at Yucca Mountain are *not* how well we can predict the future. The challenge for volcanism studies for the potential Yucca Mountain site is assessing risk. There is a subtle but important distinction between prediction and risk assessment for volcanism. The prediction of future volcanic eruptions requires identifying when and where an eruption might occur and forecasting the type or nature of the future eruption. The usefulness of the predictions is determined by their time and spatial accuracy and how accurately the types of eruption hazards were identified. Risk assessment in contrast requires defining primarily the existence and nature of a risk of future volcanism. The risk is bounded by defining the probability and consequences of the possible events. The important questions for forecasting volcanic risk for a 10,000 year period are how to assess the risk, and what is the uncertainty associated with the risk assessment? Ultimately, the volcanism issue will be resolved by assessing the estimation of risk, coupled with *realistic* estimations of uncertainty. These data will be compared with the regulations for licensing of a repository.

The statement that the potential Yucca Mountain site is probably not disqualified because of future volcanic risk includes several underlying implications. First, this judgment does not constitute a decision about the suitability of the potential site. The suitability of the site will be based on an assessment of the performance of the waste isolation system. The volcanism judgment states only that the site should not be disqualified because of the risk of future volcanism. Second, there never will be a complete consensus on the issue of volcanic risk. A judgment must be made about what constitutes a sufficient consensus to make a decision. Disagreement among reputable scientists is common, perhaps expected. However, the different views must be examined from a risk perspective. Often disagreements are vitally important only to the scientists holding the different views. The disagreements, when examined carefully, may have little effect on risk assessment. Third, a difficult aspect of assessing volcanic risk is judging the amount and confidence in information needed to reach resolution. What level of information is required for completeness? There will always be benefits from further studies, further testing of assumptions and conclusions, and further development of alternative models. These potential benefits must be weighed against the cost, time, and reasonableness of continued studies. Part of the process of balancing these alternatives is assessing what level of uncertainty is acceptable for licensing of a repository. Finally, there is a paradox that envelops volcanism studies. There were only a few volcanic eruptions in the Yucca Mountain region during the last 2 Ma (Crowe 1990). The small number of past events means the risk of future eruptions is low. However, because of the small number of events, the uncertainty of calculating the risk is large. If there had been more volcanic events in the Yucca Mountain area, there would be an increased opportunity to precisely define the risk of future eruptions. However, by virtue of the increased number of events, the risk of a future eruption would be *higher*. The trade off between decreased events for increased uncertainty must, of course, be viewed positively. The paradox means, however, that we cannot define risk with a high degree of accuracy. Again, the challenge is to define risk, bound the risk by *realistic* assessments of uncertainty and compare the results with the licensing requirements. This may be difficult, but it is an obtainable objective.

The purpose of this paper is to attempt to bring a sense of scientific perspective to the many questions raised in these introductory sections. The volcanism issue at Yucca Mountain will never be resolved with complete certainty. Society does not have the luxury of making risk-free decisions. As we enter an era of increasing concern over the interactions between man and the environment, we must somehow learn to make objective decisions balancing risk with potential benefits (Lewis 1990).

The approach used to assess the risk of volcanism is described in this report. It follows a threefold process that is called a tripartite probability (Crowe et al. 1992). We first identify the sequence of volcanic events and coupled effects that could affect a buried repository. Second, data are obtained to predict the controlling rates of volcanic activity, and the spatial relations of this activity with respect to a potential repository site. Third, those events are combined into a logical framework to estimate the future risk of volcanism. Such a framework has been developed for volcanism studies. It involves a probabilistic application of risk assessment where risk is a combination of the probability of a volcanic event and the consequences of that event for an underground repository (Crowe et al. 1982; Crowe 1986; Crowe et al. 1992). A probabilistic approach provides a structured framework for evaluating the volcanism problem. Initial probability calculations can be made using assumptions supported by the current data for the Yucca Mountain site. These calculations can be continually tested and refined as more data are gathered. We have made sufficient progress in volcanism studies to initiate the process of assessing the validity of probability calculations and the likelihood of new data changing those calculations. By making decisions now concerning the risk of future volcanism we can begin the intensive period of questioning those decisions and extend the important process of testing the conclusions.

The risk of volcanism is divided into four categories based on the geometry of magma intersection and the mechanism of potential dispersal of waste radionuclides. These are (Fig. 1.1)

1. Direct Intersection of the Repository by Ascending Magma Accompanied by Eruptions (upper two parts of Fig. 1.1).

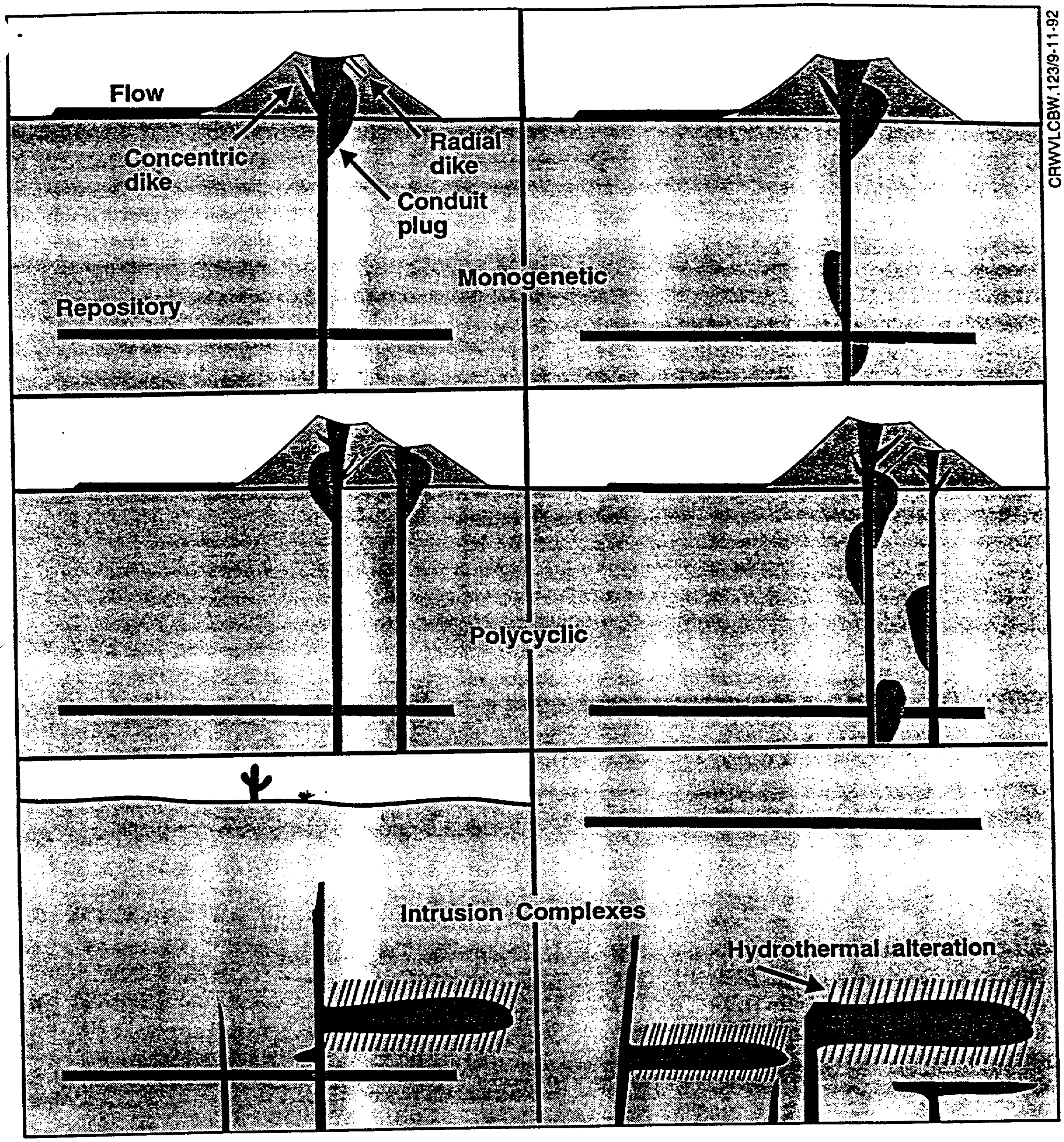

Fig. 1.1 Schematic diagrams of eruption and intrusion scenarios for potential magmatic activity in the Yucca Mountain region.

2. Direct Intersection of the Controlled Area or the Yucca Mountain Region by Ascending Magma Accompanied by Eruptions.
3. Intrusion of Magma Near the Repository (below, in, or above) Without Eruptions (bottom part of Fig. 1.1).
4. Intrusion of Magma into the Controlled Area or the Yucca Mountain Region Without Surface Eruptions.

These categories are established from the perspective of the mechanisms of dispersal of radioactive waste (Fig. 1.1). For the first two categories, the radioactive waste is dispersed by magmatic processes (eruption processes). There may be enlargement of the zone of magma-waste contact by secondary processes (thermal convection, ground-water effects) but the driving force for dispersing the waste is magmatic and the dispersal is nearly instantaneous (compared to a 10,000 year isolation time). The driving force for the dispersal of waste for the second group of categories is secondary or coupled processes. Not only the effects of volcanism on a repository must be forecast, but also how those effects might change the ability of a repository system to isolate waste.

The Volcanism Status Report provides a summary of volcanism work through 1992 and is divided into nine sections. The *first section* is this introduction. The *second section* describes the geologic setting and history of volcanism in the Yucca Mountain region. The *third section* describes the tectonic setting of the Yucca Mountain region and the relationship of sites of basaltic volcanism to that setting. *Section four* provides a brief overview of the geochemistry of basalt magmatism and magmatic models of the evolution of basalt centers in the Yucca Mountain region. The *fifth section* presents an overview of magma dynamics. The evolutionary pathways of volcanism are traced from generation of magma in the mantle, through ascent and interim storage in the mantle or crust. Literature data on pertinent parts of the problem are surveyed and mathematical and physical descriptions of magma processes are emphasized. The *sixth section* is a summary in chronological order, of the papers and conclusions developed in volcanism studies. This section provides a complete bibliography of volcanism studies and documents important conclusions developed from past work. Volcanism studies are summarized for work sponsored by the DOE, the State of Nevada, and critics of the repository program. A goal of section six is to provide a consise summary of past work. Many review questions and comments about volcanism studies neglect material already covered at length in past volcanism studies. We have attempted to make this work more assessable by summarizing the results of the past decade of volcanism studies. The *seventh section* of the paper describes the current results of an assessment of volcanic risk for the potential Yucca Mountain site. The status of data is summarized current to the writing of this report. The *eighth section* examines remaining site characterization issues. The pros and cons of different interpretations of volcanism data are examined and the impact of these different models is assessed for the probabilistically-based risk assessment. The *ninth and final section* of the paper presents conclusions concerning the status of resolution of the volcanism issue.

Each section of this report is written purposefully to stand alone. Sufficient background discussion and reference material are presented in each section so it can be read separately. To facilitate access to background material, we provide a reference list at the end of each section and compile all references at the end of the paper. This organization leads to some repetition of information. However, it allows the reader to focus on selected topics of interest without reading the entire report.

The following preliminary conclusions are presented for the risk of volcanism for the potential Yucca Mountain site. These conclusions are highlighted early to provide an introduction to the conclusions. We want to guide the reader to relevant sections of the paper for further information. A major goal of this paper is to encourage discussion, perhaps even disagreement about the completeness or validity of the conclusions. It is time to bring some volcanism issues to resolution. By doing so we hope to illuminate any differences of opinion that may exist, and identify any gaps in the logic of the arguments used to reach resolution. We are still in an early stage of site characterization studies and have many opportunities to collect focused data to attempt to resolve different views that affect risk assessment. We recognize also that no attempt to synthesize data and complex arguments will be complete and fully acceptable by all readers. By presenting conclusions, we want to identify any parts of the work that requires further study or modification.

Stated briefly, the major conclusions and perspectives of the Volcanism Status Report are:

1. The risk of future silicic volcanism is insignificant for the potential Yucca Mountain site. No additional information is needed to resolve this issue other than an evaluation of the results of drilling of exploratory holes through the identified aeromagnetic anomalies. This issue will be considered resolved if these drill holes show that none of the anomaly sites are produced by Pliocene or Quaternary silicic volcanic rocks.

2. The probability of volcanism leading to direct intersection of the repository with dispersal of the waste through surface eruptions is not sufficient by itself to disqualify the potential Yucca Mountain site. This conclusion is based on probabilistic criteria established in the regulatory requirements of 40 CFR 191 Appendix B. The most likely values of the probability of magmatic disruption of the repository are less than 1 in 10,000 in 10,000 years. The logic and supporting data for this conclusion are presented in section seven. The data supporting this conclusion appear sufficiently compelling that the conclusion is unlikely to change unless unexpected information is obtained through further site characterization studies. Pending no unexpected results, these studies can be concluded with final acquisition of qualified supporting data.

3. Additional studies are required of the effects of magmatic disruption of the repository from intrusions associated with an eruption through the repository or from surface eruptions in the controlled area or the Yucca Mountain region accompanied or not accompanied by intrusions. These studies have two areas of emphasis: 1) definition of the occurrence probabilities of eruptive and intrusive events for combination with studies of the radiological releases associated with the events, and 2) evaluations of the probability of eruptive or intrusion effects exceeding the regulatory requirements.

4. The conclusion of non-disqualification of the potential Yucca Mountain site from the risk of magmatic disruption of the repository will be tested constantly and reformed, if required, through the process of site characterization. Alternative models will be developed and tested to decide if they invalidate any conclusions or any steps leading to the conclusions.

5. The conclusions presented for parts of the volcanism issue do not imply pre-judgment of the information. The basic premise of scientific research is continuous testing of models. The best approach to establishing the validity of a conclusion is through repeated attempts to disprove. Disproof of either the conclusion or the assumptions of a conclusion, like a scientific hypothesis, are the basis for rejecting the conclusion. By stating early judgments concerning the volcanism issue, we can extend the process of attempting to disprove.

6. The conclusions of this report are presented primarily to solicit formal interactions and comments from the Nuclear Regulatory Commission. It is important to determine now, if there are disagreements with the methodology and the logic of the approaches used, if there are flaws in the assumptions, or if the conclusions are incorrect or inadequately supported. Two comments are important for this perspective. First, if the site should be disqualified because of the risk of volcanism, then it is prudent to do so immediately. There is a professional obligation of the scientists in the Yucca Mountain Site Characterization Project not only to reduce the cost of site studies, but also to protect the safety of future generations. Second, if the site is judged to be suitable with respect to volcanism, then the basis for that judgment needs to be brought forward and tested. Are the conclusions valid? Are supporting data sufficient to draw conclusions? Have data been ignored? Are alternative models omitted from the analyses? We think it is critical to start the questioning period immediately.

7. A secondary goal of this paper is to subject the volcanism studies and conclusions to the scrutiny of the scientific community through open publication.

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SECTION II: GEOLOGIC SETTING OF BASALTIC VOLCANISM IN THE YUCCA MOUNTAIN REGION

I. ABSTRACT

Yucca Mountain is a linear mountain range composed of Miocene ignimbrite erupted from the Timber Mountain-Oasis Valley caldera complex, the major silicic complex of the southwest Nevada volcanic field. Silicic volcanism in the field was succeeded by basaltic volcanic activity. This activity is divided into two episodes: basalt of the silicic episode that occurred during the waning stage of silicic volcanism and post-caldera basalt (8 Ma to Quaternary). These episodes of basaltic volcanism have been studied as part of site characterization activities for YMP. The level of detail of study varies with the age of the volcanism. The most detailed studies have been conducted for the youngest basaltic center because these are the most important events for assessing the risk of future volcanism.

The basalt of the silicic episode (BSE) occurs in three major geographic groups: 1) basalt exposed in the moat zone of the Timber Mountain caldera, 2) basalt near and flanking the Black Mountain caldera, and 3) basalt of the Yucca Mountain region. The post-caldera episode includes the older post-caldera basalt (OPB) that occurs north and northeast of Yucca Mountain and the younger post-caldera basalt (YPB) that crops out west and southwest of Yucca Mountain (except the basalt of Buckboard Mesa). The OPB consist of the 8 Ma basalt of Rocket Wash, the basalt of Pahute Mesa (8-9 Ma), the basalt of Piaute Ridge (8.5 Ma) and the basalt of Nye Canyon (6.5 Ma). Each basalt unit is a small volume basalt center formed by clusters of scoria cones with associated lava flows. The centers formed at or along basin-range faults and at the intersection of basin-range faults and ring-fracture zones of caldera complexes except for the basalt of Nye Canyon. It forms a northeast-cluster of centers that do not follow local structure. Two centers of the basalt of Nye Canyon formed partly from hydrovolcanic eruptions. The basalt of Piaute Ridge consists of dissected scoria cones and flows underlain by a complex series of sill, dikes, and lopolithic intrusions. The YPB consists of seven sites of Pliocene and Quaternary volcanism; six of the sites occur in a narrow northwest-trending zone called the Crater Flat volcanic zone (CFVZ).

The oldest and largest volume center of the YPB is the basalt of Thirsty Mesa. It consists of small dissected scoria cones surmounting a lava mesa. The age of the unit is 4.6 Ma. The basalt of Thirsty Mesa has been recognized only recently as a Pliocene center. Previous geologic studies considered the lavas of the center to underlie the Thirsty Canyon Tuff (8.5 Ma). A negative aeromagnetic anomaly was drilled by a private company and has been shown to be a buried basalt center of 4.4 Ma. The 3.7 Ma basalt of southeast Crater Flat comprises five north-trending dissected scoria cones and associated moderate-volume lava flows. The is the largest volume basalt center in the Crater Flat alluvial basin. The unit formed largely from Hawaiian fissure eruptions accompanied by outpouring of sheet-like lobes of aa lava flows. The basaltic andesite of Buckboard Mesa (2.9 Ma) crops out in the moat zone of the Timber Mountain caldera, northeast of Yucca Mountain. Nearly 1 km^3 of lava vented from a small scoria cone and an associated northwest-trending fissure located

southeast of the scoria cone. The Quaternary basalt of Crater Flat consists of an arcuate alignment of basalt centers extending along the axis of Crater Flat. Individual centers of the alignment include, from southwest to northeast, the Little Cones, the Red Cone, the Black Cone, and the Makani Cone centers. Greater than 90% of the volume of the four centers is contained in the scoria cone and lava units of the Red Cone and Black Cone centers. The Little Cones center consists of two closely spaced, small scoria cones. Lava flows were extruded from and breached the south wall of the southwest center. The Little Cones yield K-Ar age determinations that range from 1.2 to 0.7 Ma. These ages are consistent with the degree of dissection, the degree of horizon development in soils and the magnetic polarity of the center. The Red Cone and Black Cone centers are analogous volcanic landforms with similar eruptive histories. Each consists of a main scoria cone surmounted by a crater filled with agglutinated spatter, large lava blocks and scoria. The main scoria cones of both centers are flanked to the south by eroded scoria mounds that vented aa lava flows. K-Ar ages of between 0.8 and 1.5 Ma have been reported for the centers. Soil and geomorphic data are consistent with these ages, but there are differences between the degree of dissection and soil development of the Red Cone and Black Cone center suggestive of a slightly younger age of the latter center. The Makani center is a deeply dissected remnant of a scoria cone and lava flow. K-Ar age determinations for this center range from 1 to 1.7 Ma. A continuing area of controversy for the Quaternary basalt of Crater Flat is the eruptive models of individual centers and the age difference between each center. Paleomagnetic data are permissive with but do not provide conclusive proof that the centers are all close in age and formed from a single pulse of magma. Field, geomorphic, soil and petrologic data suggest some of the centers could be polycyclic and that there may be differences in the ages of individual centers.

The Sleeping Butte centers are located 45 km northwest of Yucca Mountain. They consist of two centers, the southwest Little Black Peak center and the northeast Hidden Cone center. Each consists of a small volume main scoria cone, flanked by blocky aa lava flows that vented from radial dikes at the base of the cone. The Little Black Peak center appears from field, geomorphic, petrologic and paleomagnetic data to be a simple monogenetic center with a K-Ar age of about 380 ka. The Hidden Cone center is more complex and may have formed from at least two temporally distinct eruptions. The age of the major volume of the Hidden Cone center is about 380 Ma. The age of a scoria-fall eruption that mantled the main cone of the center may be as young as late Pleistocene.

The Lathrop Wells volcanic center is the youngest and most carefully studied basaltic volcanic center of the Yucca Mountain region. The center is located at the south end of Yucca Mountain, near the intersection of northwest and northeast trending fault systems. The basalt center formed from two, possibly three, time-distinct eruptions and comprises three chronostratigraphic units. The oldest chronostratigraphic unit consists of three sets of fissure, spatter and scoria cone units and associated aa lava flows. The pyroclastic vents of these units were partially beveled by erosion prior to the formation of the middle chronstratigraphic unit. This unit consists of local scoria associated with satellite vents formed south of the main cone, pyroclastic surge deposits formed during hydrovolcanic explosions in the early phase of development of the main cone, a northwest-trending alignment of spatter cones formed at the east base of the main cone, and the main scoria cone. The main scoria cone is large, and is composed of non-agglutinated scoria emplaced during predominately Strombolian and minor hydrovolcanic eruptions. The youngest chronostratigraphic unit consists of minor scoria-fall and hydrovolcanic explosion tephra present near the south flank of the main scoria cone. These deposits contain interbedded soil with horizon development, requiring time breaks between eruptive events. The tephra units were not derived from the main cone of the Lathrop Wells center. The primary volcanic origin of these deposits is regarded as controversial by some workers.

Establishing the age of the Lathrop Wells volcanic center has been problematic. The problem has been approached by application of multiple geochronology and age-correlated methods (K-Ar, U-Th disequilibrium, cosmogenic He, thermoluminescence, geomorphic, soils, paleomagnetic, and petrologic studies). Recent results show some convergence among the different methods. The age of the oldest chronostratigraphic unit is constrained between 75 and 140 ka. The age of the chronostratigraphic unit two is less well constrained but appears to be > 40 ka. The age of the youngest tephra units, that have not been correlated with an eruptive vent, is about 10 ka.

II. INTRODUCTION

Yucca Mountain is a linear range located in southern Nevada, near the south end of the Great Basin physiographic province. The range extends from highway 95 northward to Yucca Wash (Fig. 2.1). Yucca Mountain is broken into individual blocks separated by linear valleys. These physiographic features were produced by north and northeast-trending faults that have displaced the block down to the west associated with gentle (6-7) east-directed tilting (Scott and Bonk 1984). The linear valleys mark generally the surface traces of the block-bounding faults.

Early exploration studies of the Yucca Mountain region consisted primarily of drilling of continuously cored boreholes for geologic studies and large diameter boreholes for hydrologic investigations (Department of Energy (DOE) 1986, 1988). The exploratory drilling was supplemented by surface mapping and geophysical studies. These combined studies lead to the identification of a central part of the range as the most structurally intact segment of the mountain. A 6 km^2 area was designated as the exploratory block (Fig. 2.1). An area surrounding the exploratory block (86 km^2) has been designated as the controlled area (Fig. 2.1).

The volcanic rocks that formed Yucca Mountain were emplaced during eruptive cycles of the Timber Mountain-Oasis Valley caldera complex (Christiansen and others 1977; Byers et al. 1976; Broxton et al. 1988; Byers et al. 1989). The potential Yucca Mountain site itself, including the surface rocks and the rocks extending to the depth of the potential repository horizon, comprise volcanic units of the Paintbrush Tuff. The Paintbrush Tuff is a major outflow ignimbrite of the Claim Canyon caldera segment of the Timber Mountain-Oasis Valley caldera complex (Lipman et al. 1966a).

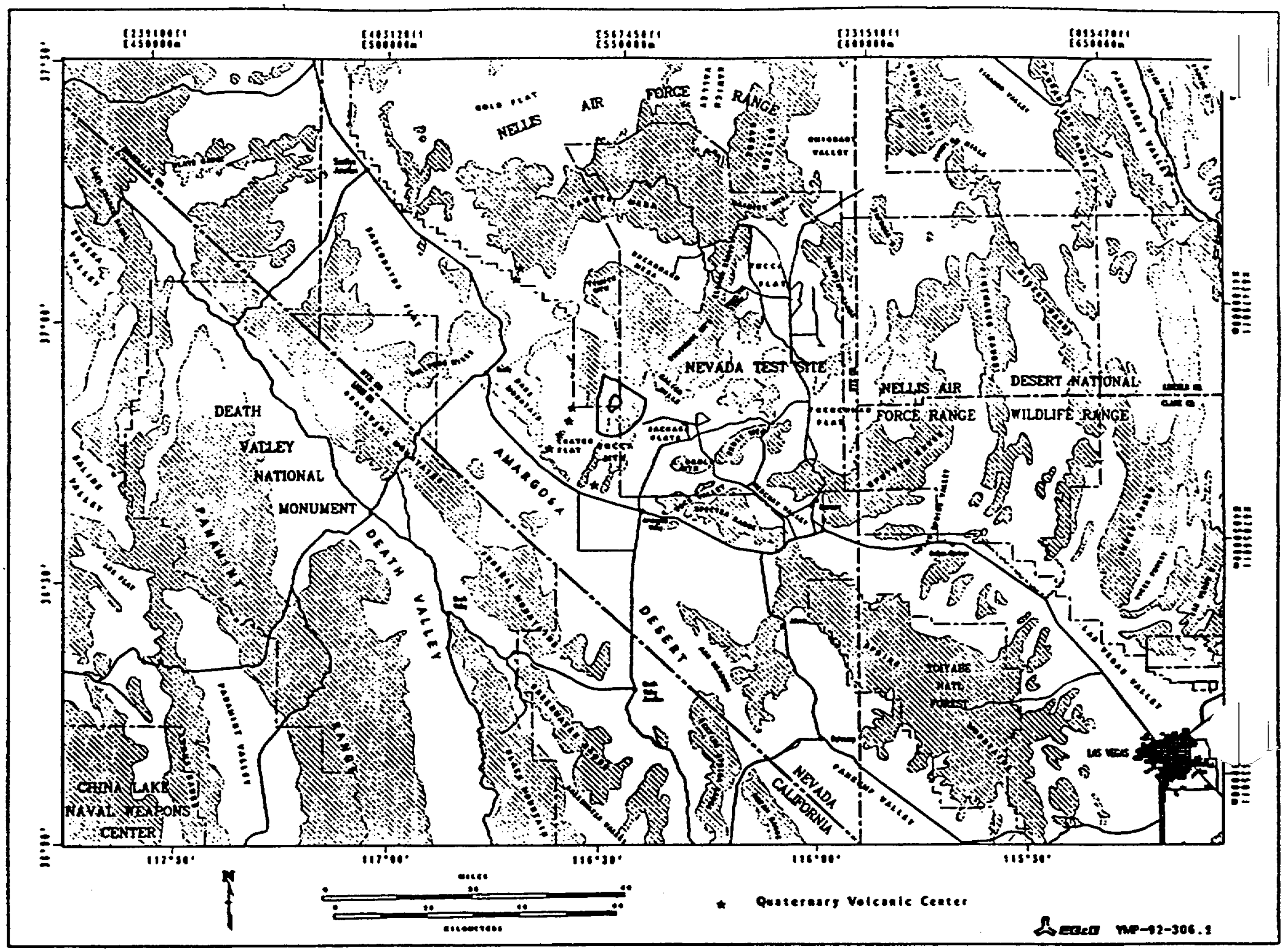


Fig. 2.1 Location of the potential Yucca Mountain site. Yucca Mountain is a linear range located on the southwest edge of the Nevada Test Site, about 160 km northwest of Las Vegas, Nevada. The mountain extends from Highway 95 on the south to Yucca Wash on the north, a distance of about 25 km. The mountain is bounded on the east by Jackass Flat (the western boundary of Jackass Flat is defined by Fortymile Wash), on the west by Crater Flat, and on the south by the Amargosa Valley. An approximately 6 km² area in the center part of Yucca Mountain has been identified as the exploratory block (DOE, 1988). It is surrounded by the controlled area, about 86 km². There are seven Quaternary basaltic volcanic centers in the Yucca Mountain area (< 1.8 Ma). These centers are noted by stars on Figure 2.1.

The voluminous record of silicic volcanism in the Yucca Mountain region is part of an extensive, time transgressive pulse of mid-Cenozoic volcanism that occurred throughout much of the southwest United States. The Yucca Mountain range is in the south central part of a major Cenozoic volcanic field that covered an area exceeding 11,000 km^2. The field has been named the Southwestern Nevada Volcanic Field (SNVF; Christiansen et al. 1977; Byers et al. 1989; Fig. 2.2).

The time-space distribution of volcanic activity in the basin-range province has been described by many authors (Armstrong et al. 1969; McKee 1971; Lipman et al. 1971; Lipman et al. 1972; Christiansen and Lipman 1972; Snyder et al. 1976; Stewart et al. 1977; Stewart and Carlson 1978; Christiansen and McKee 1978; Cross and Pilger 1978; Smith and Luedke 1984; Luedke and Smith 1984; Axen et al. 1993). During the Mesozoic, magmatism in the Cordillera was distributed in linear belts parallel to the continental margin (Armstrong and Ward 1991). In the southwest United States, these belts became locally inactive or disrupted about 80 Ma and formed the Laramide magmatic gap (Armstrong 1974). Renewed silicic magmatism following the Laramide hiatus initiated about 50 Ma in the northeast part of the Great Basin. Sites of eruptive activity migrated south and southwest progressively in time and space across an area of Nevada and adjoining parts of Utah (Stewart et al. 1977; Armstrong and Ward 1991). The loci of eruptive centers during this voluminous silicic volcanism were distributed along arcuate east-west trending volcanic fronts (Stewart et al. 1977). The leading edge of the migrating front during successive increments of time marked the area of the most intensive volcanic eruptions. There was a dramatic waning of volcanic activity in the lee or backside of the front (Stewart et al. 1977) and virtually no volcanic activity ahead of the front. The peak of silicic volcanic activity in the Yucca Mountain region (15 to 11 Ma) marks the southern limit in the spread of time-transgressive volcanic activity.

Two significant changes in the regional volcanic and tectonic patterns occurred about 13 to 10 Ma at the approximate latitude of the Yucca Mountain region. First, the progressive southern migration of volcanism halted. Silicic eruptive activity continued in diminished volumes and migrated predominantly to the southwest and southeast, following less systematic patterns than the migration of preceding volcanic activity. Post-Miocene volcanic activity approached present positions along the east and west margins of the Great Basin (Christiansen and McKee 1978; Smith and Luedke 1984). These changed patterns in migration of volcanism left a conspicuous amagmatic gap extending from the south edge of the Nevada Test Site south to the latitude of Las Vegas (Fig. 2.3). It coincides with a major increase in the regional gravity field that forms the south boundary of the gravity low of the Great Basin (Eaton 1978). This latitude (35 degrees N) also coincides with the approximate position at 10-20 Ma of the boundary between the incoherent subducted slab or "slab gap" south of the Medocino fracture zone and persisting subducted slab to the north (Severinghaus and Atwater 1990).

The second major change at about 10 Ma in the Yucca Mountain region was a transition in the composition of volcanic activity. This change is consistent with a time-transgressive switch across the southwest United States from predominantly silicic

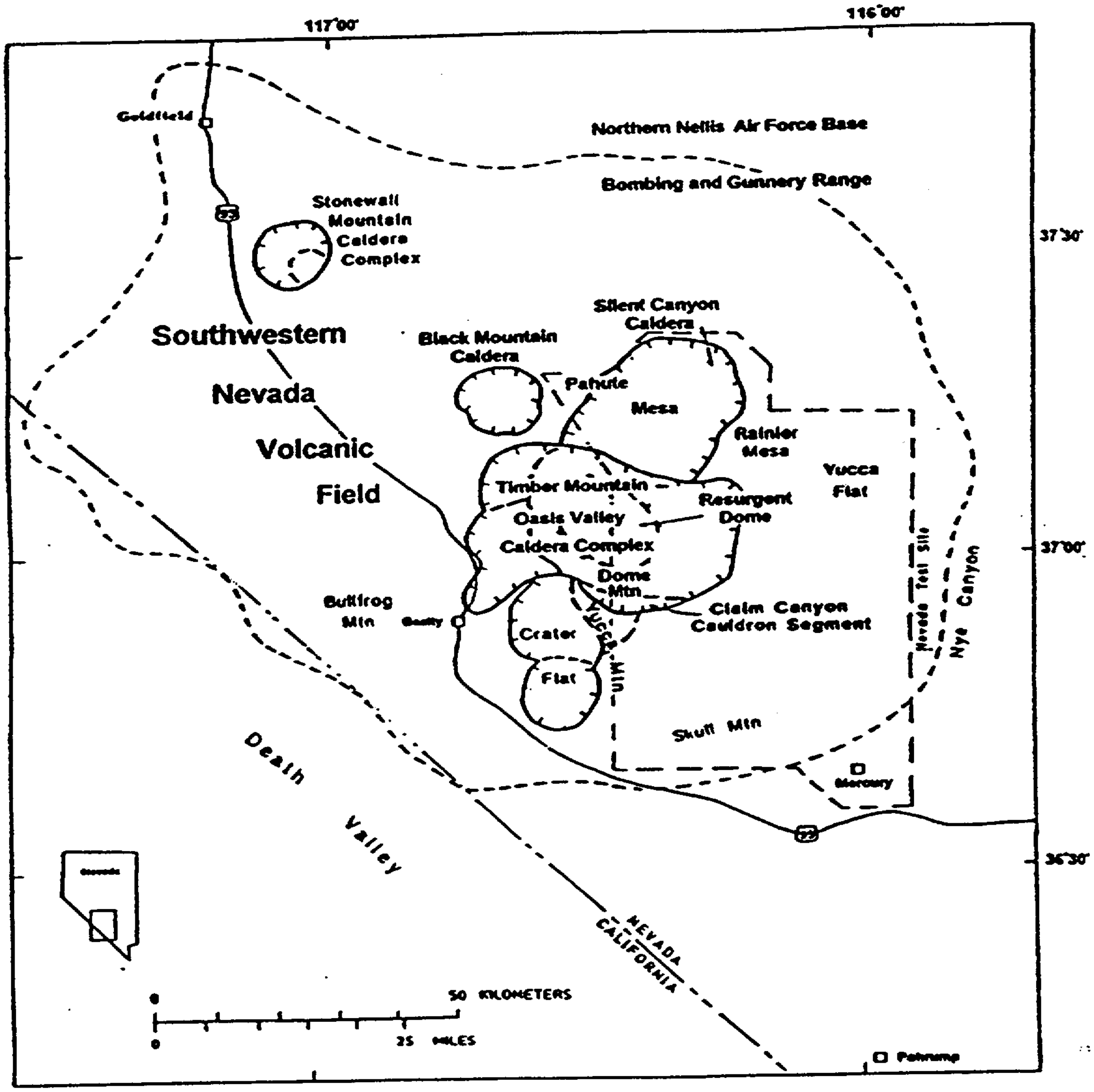


Fig. 2.2 The Southwest Nevada Volcanic Field (from Byers et al. 1989). Yucca Mountain is upheld by a thick sequence of ignimbrites derived from multiple caldera-forming, eruptive cycles of the Claim Canyon and Timber Mountain-Oasis Valley caldera complexes. The presence of caldera complexes of Crater Flat, which border Yucca Mountain to the west, is regarded as controversial by some workers.

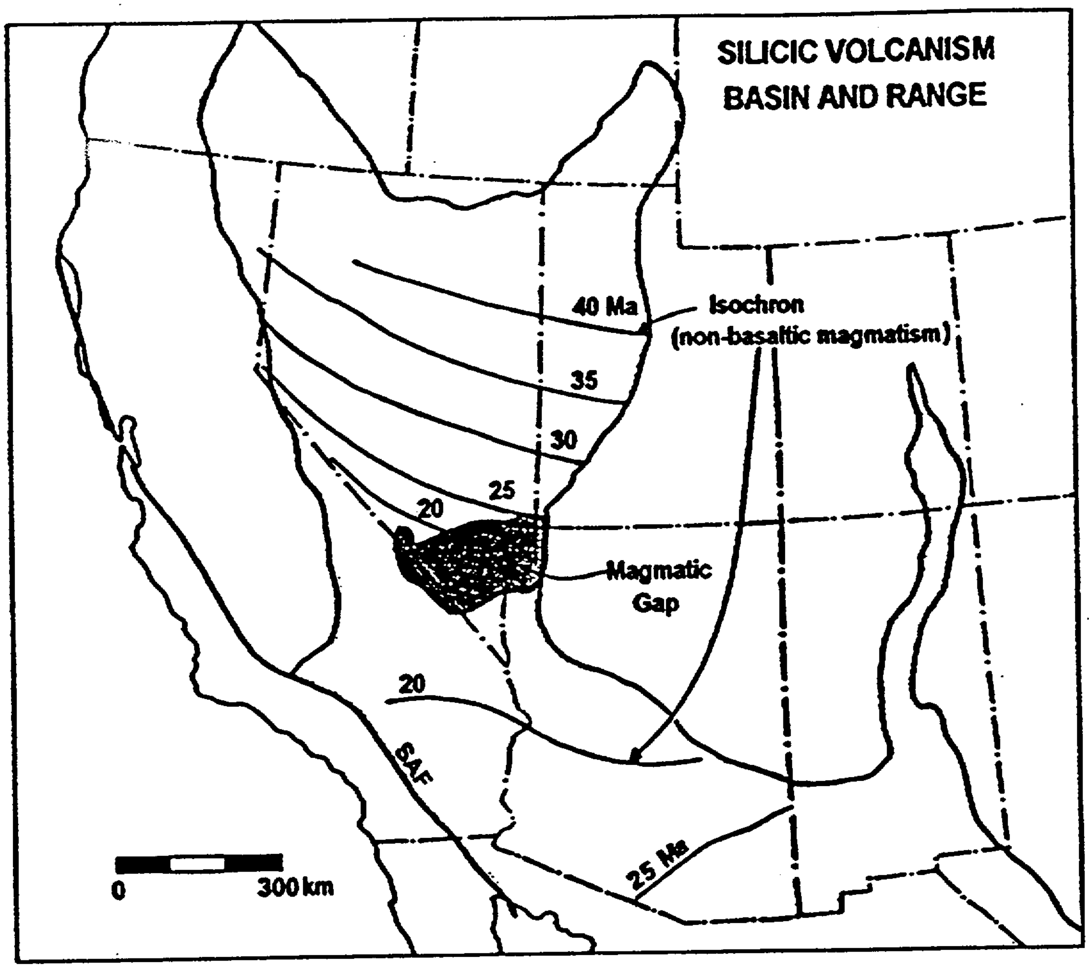


Fig. 2.3 Time transgressive, mid-Cenozoic volcanism of the basin-range province(modified from Farmer et al. 1989). Numbered contour lines locate the position of arcuate, migrating fronts of silicic volcanism during increments of Cenozoic time. Yucca Mountain is located at the southern limit of the southward migration mid-Cenozoic silicic volcanism. The Yucca Mountain area borders the north edge of a zone in southern Nevada distinguished by its absence of Mesozoic and Cenozoic volcanism and plutonism. This zone is referred to as the amagmatic gap. The amagmatic gap includes much of the central basin and range subprovince of Wernicke (1992) and Jones et al. (1992).

volcanism to bimodal basalt-rhyolite volcanism (fundamentally basaltic volcanic activity; Christiansen and Lipman 1972). The exact timing of this transition in the Yucca Mountain region is unclear. It may be marked by a transition from near homogeneous quartz latite and rhyolite ignimbrites (> 13 Ma) to eruptions of compositionally zoned ash flows units (< 12 Ma) that range from high-silica rhyolite at their base ($Si0_2$ > 75%) to quartz latitic caprocks ($Si0_2$ < 70 %). This transition in the Nevada Test Site region probably is marked by the eruption of the Paintbrush Tuff (Christiansen and Lipman 1972; Christiansen et al. 1977). Alternatively, the transition may be recorded by the widespread appearance of moderately voluminous basaltic volcanism (Crowe 1990). The age of this basaltic volcanic activity is bracketed between the eruption of the Timber Mountain Tuff (11.2 Ma) and the peralkaline ash-flow sheets of the Black Mountain caldera complex (8.5 Ma; Crowe 1990).

III. BASALTIC VOLCANISM: YUCCA MOUNTAIN REGION

Field and geochronology data for the basaltic volcanic rocks of the Yucca Mountain region define two episodes (Crowe 1990). The first episode of bimodal basalt-rhyolite volcanism is called the basalt of the silicic episode (BSE). This episode postdates most of the silicic eruptions of the TM-OV complex. For this report, we describe only the basaltic units present in and around the Timber Mountain highland and the Yucca Mountain area. Other basaltic units are present but are not described. These basalts are associated primarily with the Black Mountain-Stonewall Mountain calderas. Most of these basalt units are contemporaneous with the silicic volcanic activity of those calderas. However, there are local basalt units that predate (Crowe 1990) and some which postdate silicic eruptions (Crowe et al. 1992b) of the Black Mountain and Stonewall Mountain calderas.

The second basaltic episode includes spatially scattered, small volume centers marked by scoria cones and lava flows of alkali basalt. These rocks range in age from 8 Ma to Quaternary. They are divided into two cycles (Crowe 1990), the older postcaldera basalt (OPB) and the younger postcaldera basalt (YPB). The field relations and geochronology of the basalt cycles of the Yucca Mountain region are described in the following sections of this paper.

The level of detail of studies of basaltic units of the Yucca Mountain region varies with the age of the volcanic units. Older basalt units of the region (> 6.5 Ma) were studied primarily in reconnaissance. The outcrop relations of the units, as depicted on published quadrangle maps of the U.S. Geological Survey, were checked in the field. Samples were collected of the basalt units, examined petrographically, and analyzed geochemically (Crowe et al. 1986). The stratigraphic relations of the units were evaluated in the field and geochronology data (whole rock K-Ar age determinations) were obtained where required. The basaltic units of the YPB have been the focus of more detailed studies. All units of this cycle have been remapped at scales of 1:12000 to 1:4000. The eruptive sequences of these centers have been assessed largely through the detailed mapping. The rocks have been analyzed petrographically and geochemically. Geochronology data supplemented by age-calibrated geochronology methods for cross-checking of results have been obtained for the youngest Quaternary volcanic centers. The increase in the level of detail of studies with the decreasing age of basalt is a purposeful attempt to focus the work on assessment of the Pliocene and Quaternary volcanic history of the Yucca Mountain region. It is this part of the geologic record that provides the most important basis for forecasting the risk of future volcanic activity.

Much of the geochronology and geochemical data for the basalt of the Yucca Mountain region were collected before implementation of a fully qualified Quality Assurance program. While these data are judged to be of good scientific quality, they do not meet the quality assurance requirements of the Yucca Mountain Project as implemented by the Los Alamos program. Because of this problem, we present only brief references to the geochronology and geochemistry data with references to publications where available. This treatment of the data is not a negative reflection on the scientific quality of the geochronology or geochemical data. In fact, some of these data, if needed, will be evaluated for qualification to current programmatic requirements. Alternatively, the data will be used to focus the acquisition of new information judged to be needed for licensing.

A. Basalt of the Silicic Episode (BSE)

The BSE are identified by a suite of characteristics; none of these features are individually unique. The first is the close association, in space and time, with the eruptive activity of the calderas of the TM-OV complex. The BSE postdates closely the eruption of the Timber Mountain Tuff (11.2 Ma). Many of the basalt units of this episode underlie stratigraphically the Thirsty Canyon Tuff (8.5 Ma; Noble et al. 1992). Second, the largest volume centers of the BSE are located in the ring-fracture zone of the Timber Mountain caldera complex (Fig. 2.4). Third, all centers of the BSE were large volume (> 3 km^3 dense rock equivalent (DRE)). Their present surface outcrops form major topographic features (eroded shield volcanoes or lava mesas where basalt lavas cap modern topographic ridges). Third, the BSE exhibit a wide range in geochemical composition (basalt to basaltic andesite or latite). They exhibit a much larger range of compositional variation than the younger post caldera basalt episode (Crowe et al. 1986; Crowe 1990).

The BSE are divided into three major groups based on their geographic distribution. These are: (1) Basalt exposed in the moat zone of the Timber Mountain caldera, (2) Basalt near and flanking the Black Mountain caldera, and (3) Basalt of the Yucca Mountain region (Fig. 2.4).

1. Mafic Lavas of Dome Mountain. The most important occurrence of basaltic rocks by volume is at the southeast edge of the Timber Mountain caldera (Fig. 2.4). Here, mafic lavas are interbedded with two major successions of rhyolite lava. They overlie the rhyolite of Fortymile Wash and underlie the rhyolite of Shoshone Mountain (10.3±0.3 Ma; Noble et al. 1992). The basalt and rhyolite define a bimodal association marking the waning postresurgence stage of the Timber Mountain caldera (Christiansen et al. 1977). The largest volume of basaltic magma is the mafic lavas of Dome Mountain. These lavas have been described by Luft (1964) and Marsh and Resmini (1992). They form an assemblage of

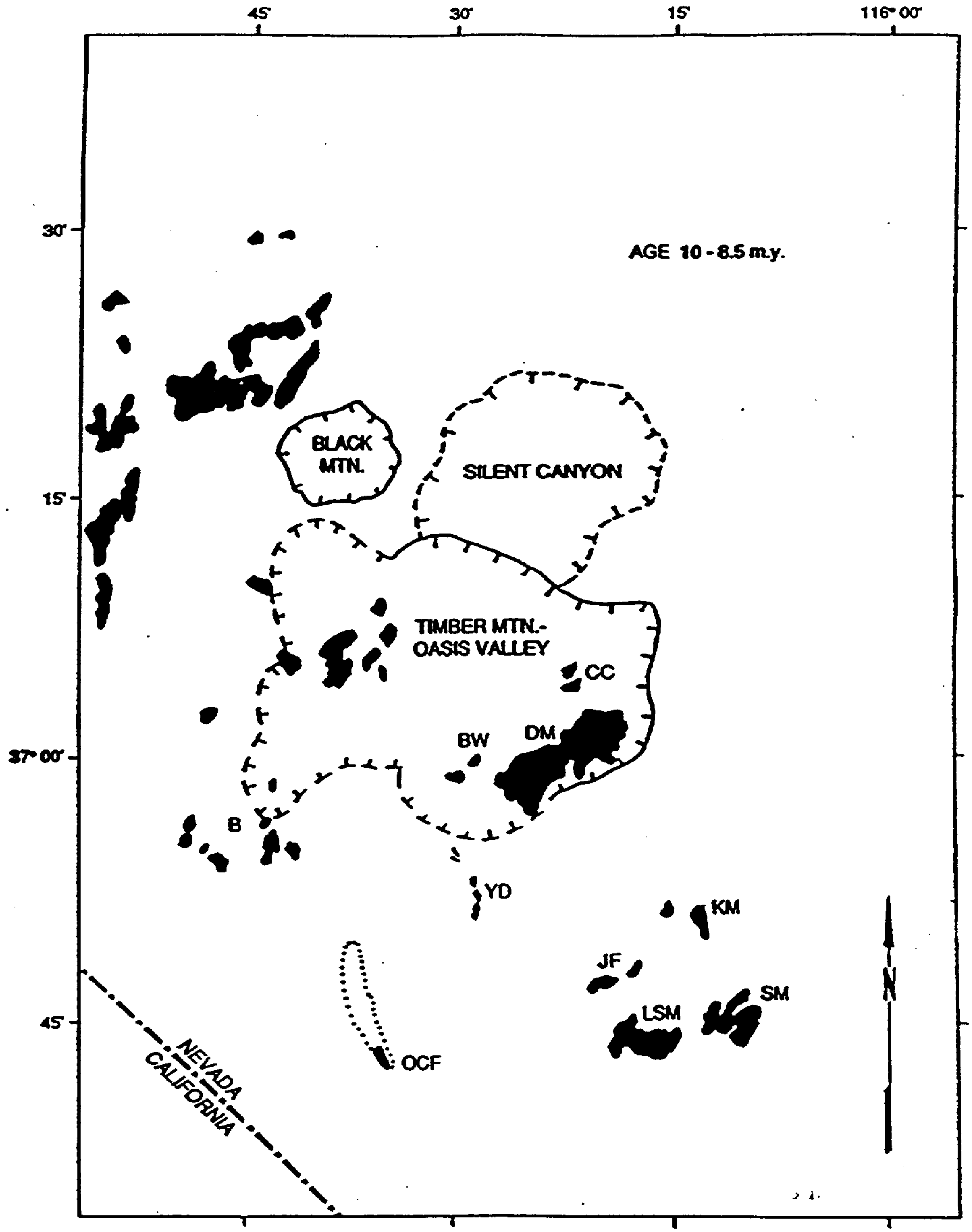


Fig. 2.4 Distribution of the Basalt of the Silicic Episode (BSE). CC: basalt of Cat Canyon, DM: basalt of Dome Mountain, BW: basalt of Beatty Wash, B: basalt of the Beatty area, SM: basaltic andesite of Skull Mountain, LSM: Little Skull Mountain, KM: mafic rocks of Kiwi Mesa, JF: basalt of Jackass Flat, YD: dike of Yucca Mountain, OCF: older basalt of Crater Flat (modified from Crowe, 1990).

basalt and basaltic andesite with a local thickness of > 300 m. They are interbedded with volcaniclastic breccia and conglomerate within the ring-fracture zone of the Timber Mountain caldera. These sedimentary units are moat breccias deposited in the down dropped interior of the Timber Mountain caldera. The outcrops of the mafic lavas of Dome Mountain form a slightly arcuate shield volcano centered at Dome Mountain proper (Fig. 2.4). The area of surface exposure of the mafic lavas of Dome Mountain is about 50 km^2. Their minimum volume is about 10 km^3 (DRE). The feeder vents for the mafic lavas of Dome Mountain, as noted by Luft (1964), are not exposed. However, a source near Dome Mountain is required by the near symmetrical centering and increased thickness of the lava shield at Dome Mountain. The likely structural control for the eruption of the mafic lavas of Dome Mountain is the ring-fracture system of the Timber Mountain caldera.

The mafic lavas of Dome Mountain can be divided into two informal units, based on their petrographic features. Porphyritic basalt (phenocrysts of olv-cpx) crop out in east Cat Canyon. The lavas are overlain locally by the Thirsty Canyon Tuff and have been dated at 10.8±0.5 Ma (Kistler 1968). These basalts were mapped as separate units from the mafic lava of Dome Mountain (Carr and Quinlivan 1966; Byers and others 1966). However, basalt lavas interbedded in the upper part of the mafic lavas of Dome Mountain in Fortymile Canyon are identical petrographically and chemically and are probably equivalents of the Cat Canyon lavas. Pilotaxitic to trachytic textured basaltic andesite form the major volume of the shield lavas of Dome Mountain. Luft (1964) describes trachyandesite to latite lavas in the upper part of the section at Dome Mountain that are similar to the basaltic andesite but with somewhat higher contents of $Si0_2$ (56-60 weight % $Si0_2$).

In the northern and western part of the outcrop area of the mafic lavas of Dome Mountain, the unit is onlapped with a slight angular discordance by thin basalt flows informally called the basalt of Beatty Wash. These lavas were mapped separately from the mafic lavas of Dome Mountain (Christiansen and Lipman 1966). They extend from Dome Mountain west along Beatty Wash (Fig. 2.4).

2. Basaltic Rocks of the Black Mountain Caldera. Basaltic volcanic rocks crop out around all but the eastern flanks of the Black Mountain caldera (Fig. 2.4). These basalt units overlap in age with the peralkaline volcanic units of the caldera. They underlie, are interbedded with and overlie ash-flow units of the Thirsty Canyon Tuff. Many of the outcrops of basalt are located in the Nellis Bombing and Gunnery Range. Because of restricted access, the basalts have been sampled only at scattered localities around Black Mountain (Crowe et al. 1986). A sequence of eroded basalt vents and lava flows are exposed south of Black Mountain. These lavas underlie the Thirsty Canyon Tuff. Basalt lava exposed north of Black Mountain underlie and locally overlie the Thirsty Canyon Tuff.

3. Basaltic Volcanic Rocks, Yucca Mountain Area. Basaltic volcanic rocks of the BSE comprise three geologic units in the eastern Yucca Mountain area, and two additional units at and southwest of Yucca Mountain. Two of the eastern units were shown on published geologic maps (Ekren and Sargent 1965; Sargent and Stewart 1971; Sargent and others 1970). These are the basaltic andesite of Skull Mountain and the basalt of Kiwi Mesa

(Fig. 2.4). A third unit, the basalt of Jackass Flats, has been separated in more recent geologic reports (Crowe et al. 1986; Frizzel and Shulters 1990).

The basalt of Kiwi Mesa crops out as a small lava mesa on the east side of Jackass Flats (Fig. 2.4). The lavas overlie the Timber Mountain Tuff and are locally overlain by the rhyolite of Shoshone Mountain. The basaltic andesite of Kiwi Mesa are chemically and petrographically identical to the mafic lavas of Dome Mountain (Crowe et al. 1986). They have been dated at about 8.5 Ma and are probably the youngest of the magmatic units associated with the sequence of lava at Dome Mountain.

The south and southeast perimeters of Jackass Flat are bounded by Skull and Little Skull Mountains. These small ranges are capped by a sequence of mesa-forming lava flows and flow breccia which locally exceed 60 m in thickness. This unit is the basaltic andesite of Skull Mountain. The lavas are distinguished in the field by the presence of abundant phenocrysts of bipymidral quartz (Crowe et al. 1986). Moreover, they are the only known lavas in the region that are subalkaline in chemical composition (Crowe et al. 1983a, 1986). These lavas overlie the lavas of the Wahmonnie-Salyer center and the Paintbrush and Timber Mountain Tuffs.

Several small outcrops of dissected lava are flanked by alluvium in the central part of Jackass Flats (Fig 2.4; Frizzel and Shulters 1990). Correlative lavas (petrographically and geochemically) are interbedded with the upper part of the basaltic andesite of Skull Mountain (Crowe et al. 1986).

The Solitario Canyon fault forms the western edge of the potential Yucca Mountain site (Scott and Bonk 1982). The north trace of the fault is intruded by a basaltic dike. The dike is exposed locally along the northwest edge of the block (Fig. 2.4) and in Trench 10. Exposures of the dike in trench 10 show that the dike both intrudes the fault plane and has been offset by subsequent episodes of movement on the Solitario Canyon fault. North of trench 10, the dike strikes northwest and crops out discontinuously, forming en echelon dikes in the Tiva Canyon member of the Paintbrush Tuff. This change in strike coincides with an abrupt topographic change from north-south to northwest trending valleys at the north end of Yucca Mountain. Scott and others (1984) suggest that the northwest-trending valleys are underlain by right-slip faults that are inferred to be part of the Walker Lane structural system. Alternatively, Carr (1984; 1988; 1990) and Carr et al. (1985; 1986) suggest that the dikes follow the outer ring fracture zone of a buried caldera. The dike has been dated at about 10 Ma (Carr and Parrish 1985).

The older basalt of Crater Flat (Crowe et al. 1986) crops out along the south slope of an arcuate ridge forming the south boundary of Crater Flat (Fig. 2.4). The outcrops consist of the remnants of oxidized vent scoria intruded by dikes and small plugs. These units are probable eroded roots of at least one, and possibly several scoria cones. Directly east of the scoria deposits, there are a sequence of thin lava flows and flow breccia that are petrographically similar to and probably derived from the plugs or cones. These lavas are overlain by slide blocks of Paleozoic carbonate. The lavas dip to the northeast and are inferred to underlie much of the south and southwest parts of Crater Flat. This is suggested by several lines of evidence (Crowe et al. 1986). First, the lavas have a reversed magnetic polarity. They coincide with and are the probably source of an arcuate negative magnetic anomaly that borders the southwest part of Crater Flat (Kane and Bracken 1983). Second, petrographically and chemically similar lavas were cored at about 360 m beneath the surface in drill hole USW VH-2 located between Red Cone and Black Cone in the central part of Crater Flat (Carr and others 1984; Crowe et al. 1986). These lavas were dated at about 11 Ma (Carr and others 1984). The lavas in the drill hole have a reversed magnetic polarity, similar to the older basalt of Crater Flat. They are the inferred source of a large circular negative aeromagnetic anomaly located in west-central Crater Flat (Kane and Bracken 1983). This aeromagnetic anomaly extends south to the described anomaly of southwest Crater Flat. The combined field, geochronology, geochemical and aeromagnetic data suggest that the west and southwest parts of Crater Flat are floored by an extensive basalt unit of 11 Ma.

B. Postcaldera Basalt of the Yucca Mountain Region

The second recognized episode of basaltic volcanism in the Yucca Mountain region is the postcaldera basalt. These basalt centers occur at sites either well removed from eruptive centers of the TM-OV complex or are younger than and cannot be related in time to the silicic magmatic activity. The basalts consist entirely of small volume (<1 km^3) centers marked by clusters of scoria cones and lava flows. They are divided into two groups, the older postcaldera basalt and the younger postcaldera basalt. This division is based on differences in their ages and geographic distribution (Fig. 2.5).

1. Older Postcaldera Basalt (OPB). The OPB occur at five localities, all north and east of Yucca Mountain (Fig. 2.5). The OPB were erupted along either north-northwest trending basin-range faults or at the intersection of basin-range faults with the ring-fracture zone of older calderas. Field evidence shows that some of the basalt units were erupted contemporaneous with movement on the extensional faults (Crowe et al. 1983b, 1986). The OPB range in age from 9 to 6.3 Ma (Fig. 2.5).

a. Basalt of Rocket Wash. A platy jointed series of thin, basalt lava flows, informally named the basalt of Rocket Wash, overlies the Thirsty Canyon Tuff in the northwest edge of the Timber Mountain caldera (Fig. 2.5). This basalt, which was mapped by Lipman and et al. (1966b) and O'Connor and others (1966), erupted along a north trending normal fault that marks the approximate edge of the ring fracture zone of the Timber Mountain caldera. The vent for the basalt lavas was located at the northern edge of the mapped outcrops. This is indicated by two features. First, the outcrops of the flow thicken consistently northward. Second, deposits of eroded cone scoria are present at the north end of the exposed outcrops where they have been preserved beneath lava flows. The basalt of Rocket Wash overlies the Trail Ridge Member of the Thirsty Canyon Tuff. The approximate volume of lavas (DRE) is about 0.2 km^3. The basalt yielded a K-Ar age of 8 Ma.

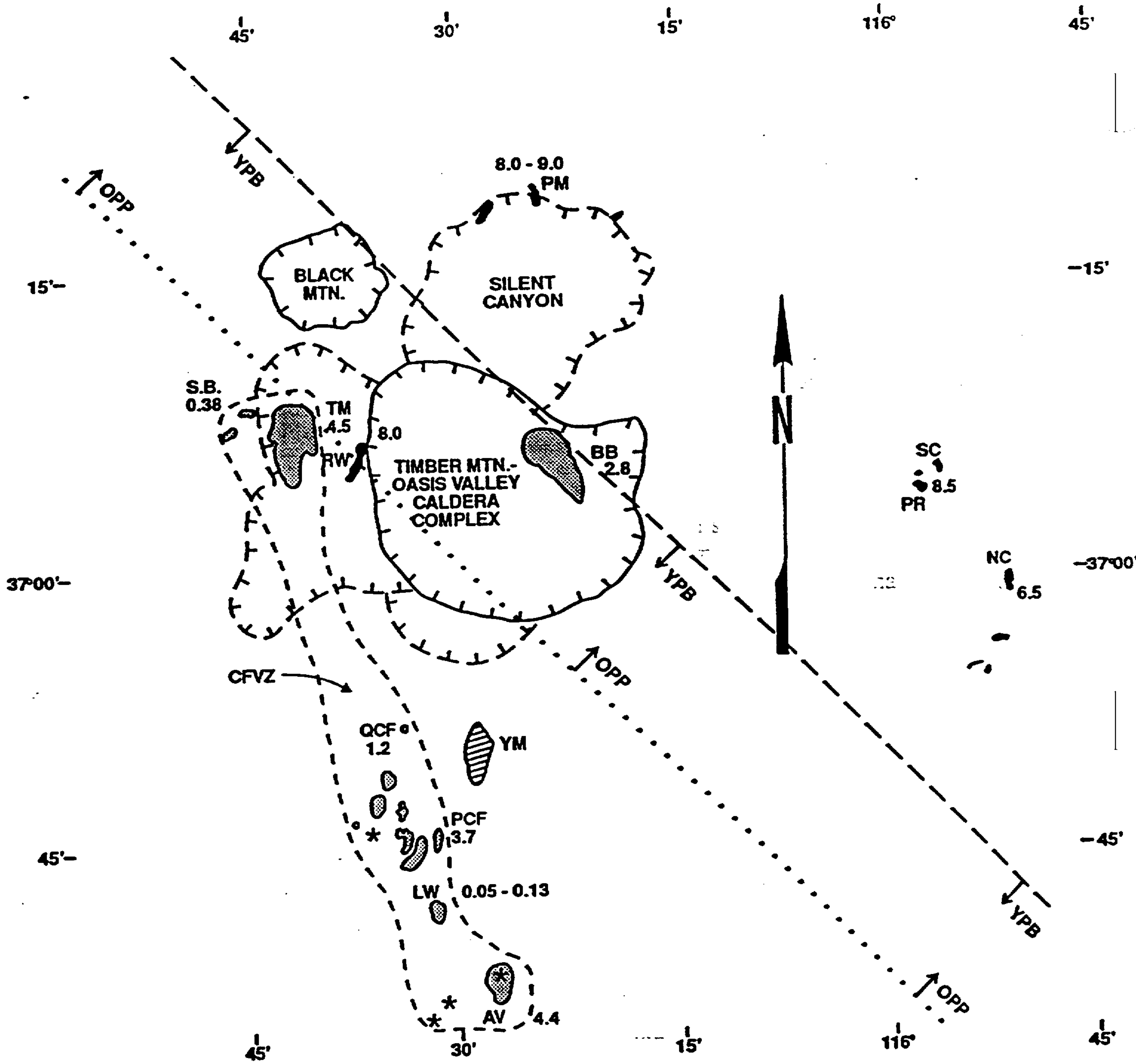


Fig. 2.5 Post-Caldera Basalt of the Yucca Mountain region. Shaded areas are the Older Post-Caldera Basalt (OPB) including: RW: basalt of Rocket Wash, PM: basalt of Pahute Mesa, SC: basalt of Scarp Canyon, NC: basalt of Nye Canyon. Stippled areas are the Younger Post-Caldera Basalt (YPB) including: TM: basalt of Thirsty Mesa, AV: basalt of Amargosa Valley, PCF: Pliocene basalt of southeast Crater Flat, BB: basalt of Buckboard Mesa, QCF: Quaternary basalt of Crater Flat, SB: basalt of Sleeping Butte, LW: basalt of Lathrop Wells. Asterisks mark aeromagnetic anomalies identified as potential buried basalt centers or intrusions (Kane and Bracken, 1983, Crowe et al. 1986). Dashed line encloses the area of the Crater Flat Volcanic Zone (CFVZ). Numbers associated with the symbols for the volcanic units of the OPB and YPB are the age of the volcanic centers in million years. Modified from Crowe and Perry (1989).

<u>b. Basalt of Pahute Mesa.</u> Three spatially separate but related basalt units of the OPB crop out in the north part of the ring-fracture zone of the Silent Canyon caldera. These basalts, which are informally named the basalt of Pahute Mesa, were localized at the intersection of north-northeast trending basin-range faults with the ring-fracture zone of the Silent Canyon caldera (Fig. 2.5). They are divided into three units, each separate geographically. These are a western basalt, a central basalt, and an eastern basalt.

The western basalt is distinctly porphyritic with large resorbed megacrysts of black clinopyroxene and plagioclase. The basalt overlies the Trailridge and Spearhead members of the Thirsty Canyon tuff. Exposed outcrops are primarily dissected cone scoria with numerous intrusive dikes. A feeder dike associated with the scoria deposits can be traced to the southwest and parallels the trend of basin-range faults. The minimum volume of the basalt center is about 0.7 km^3 DRE.

The central basalt center consists of at least three separate but subparallel dike systems associated with probable surface scoria cones. The existence of the scoria cones is inferred from the presence of eroded scoria deposits containing aerodynamically shaped bombs. The scoria deposits overlie the Trail Ridge Member of the Thirsty Canyon Tuff and feeder dikes of the center intrude the Timber Mountain Tuff and rhyolite of Quartet Dome. The lava of the middle basalt center are conspicuously less porphyritic than the western basalt; megacrysts of black clinopyroxene and plagioclase are rare. The central basalt yielded a K-Ar age of 8.8 Ma.

The eastern basalt occurs only as three small remnant outcrops of lava and dikes (Noble and others 1967). Two of the lavas crop out in alluvium, the third intrudes the Trail Ridge Member of the Thirsty Canyon Tuff. The outcrop patterns of each site are elongate parallel to north-northeast trending basin-range faults and are located on the ring-fracture zone of the Silent Canyon caldera (Orkild et al. 1972). The eastern basalt is identical petrographically to the western basalt and has not been dated.

<u>c. Basalt of Piaute Ridge.</u> The Halfpint Range, which forms the eastern margin of Yucca Flat, exposes a complex sequence of sills, dikes, and lopolithic intrusions of basaltic composition (Byers and Barnes 1967). Associated with the intrusive bodies are dissected scoria cones and lava flows indicating surface eruptions accompanied the formation of the intrusions (Crowe et al. 1983b; Valentine et al. 1992). The sills and lopolithic bodies occur in the interior of a northwest-trending graben. Subsurface magma intruded generally upward and locally eastward from dikes that are coplanar with northwest-trending basin-range faults. Eastward intruded magma formed sills by lifting the overlying sequence of tuff. At several localities, primarily in the axis of the graben, the sills sagged to form lopolithic intrusions (Byers and Barnes 1967; Crowe et al. 1983b; Valentine et al. 1992). Some of the sills differentiated in situ to form pods of syenite (Byers and Barnes 1967).

Locally, the northwest-trending dikes expand or flare upward forming vertically jointed, cylindrical bodies with associated radial dikes. These are probably roots of eroded scoria cones (Crowe et al. 1983b; Valentine et al. 1992). In the eastern and central area of the graben, irregular feeder dikes can be traced upward into surface deposits of scoria cones and lava. This complex of intrusive and extrusive basalt, which is informally called the basalt of Piaute Ridge, exposes the geometry of shallow intrusive rocks and feeder dikes. It provides an ideal locality to study the effects of shallow basalt intrusions (Valentine et al. 1992).

The surface lava from the basalt of Piaute Ridge has been dated at about 8 Ma (Crowe et al. 1983b). A separate but petrologically related basalt, the basalt of Scarp Canyon, crops out one kilometer east of the basalt of Piaute Ridge. It yielded a K-Ar age of 8.7 Ma. The geologic relations of the basalt localities record a complex history of basin-range faulting in the Half Pint range. Dikes of basalt intrude the plane of several northwest-trending faults. The faults and the graben thus predate the basalt (>8 Ma). Sills of basalt are offset by some of the faults indicating continuing movement after magma emplacement.

d. Basalt of Nye Canyon. The last major unit of the OPB is the basalt of Nye Canyon (Fig. 2.5). This unit consists of at least five centers; one is buried beneath alluvial deposits of northeast Frenchman Flat. There are three surface centers of basalt that define a northeast trending alignment of basalt centers. The basalt of Nye Canyon is the oldest basalt unit (6.5 Ma) in the Yucca Mountain region that shows a northeast structural trend. This is the predominant direction of dike elongation and alignment of clusters of centers in post-Pliocene basalt in the region (Crowe and Perry 1990; Crowe 1990).

The northeastern center of the basalt of Nye Canyon consists of a moderately dissected scoria cone surrounded on the south and southwest by a thin lava flow, mostly buried beneath alluvium deposits. The middle and southern basalt centers are eroded tuff rings (Crowe et al. 1986) formed by mixed Strombolian and hydrovolcanic activity. Both tuff rings are partly to completely infilled by scoria deposits and lava, recording episodes of mixed Strombolian and Hawaiian eruptive activity that followed the hydrovolcanic eruptions. The middle basalt center is the most primitive basalt in the region (Crowe et al. 1986; Farmer et al. 1989). It contains abundant nodules of gabbro, and less commonly, wherlite. The southern center is formed at the eastern edge of a large ring dike. The dike extends near continuously in a 320° arc from the southern center westward (Henrichs and McKay 1965). The ring dike has an approximate diameter of one kilometer. It locally widens to form cylindrical plugs that probably mark the eroded roots of former scoria cones.

A fourth basalt center was intersected in a drill hole in alluvium beneath Frenchman Flat (Carr 1984). Two small plugs of probably related basalt intrude the Paintbrush and Timber Mountain Tuffs east of the southern end of Scarp Canyon. Several dikes extend for up to five kilometers from the plugs. The strike of dikes parallels local basin-range faults.

2. Younger Postcaldera Basalt. A brief but regionally significant hiatus in volcanic activity followed eruption of the basalt of Nye Canyon. No volcanic rocks of the Yucca Mountain region, including both surface and subsurface rocks, have yielded age determinations in the range of 6.5 (basalt of Nye Canyon) and 4.5 Ma (basalt of Thirsty Mesa). The second cycle of the post caldera basalt, the younger postcaldera basalt, includes all volcanic rocks younger than the basalt of Nye Canyon. In order of decreasing age, these

basalts include the basalt of Thirsty Mesa, the basalt of Amargosa Valley, the basalt of southeast Crater Flat, the basaltic andesite of Buckboard Mesa, the Quaternary basalt of Crater Flat, the basalt of Sleeping Butte and the Lathrop Wells basalt center (Crowe 1990). These basalt centers, except the basaltic andesite of Buckboard Mesa, all occur in a narrow northwest-trending zone located west and south of the Yucca Mountain site (Fig. 2.5). This zone has been named the Crater Flat volcanic zone (CFVZ; Crowe and Perry 1989). The basalt centers of the YPB, with two exceptions, consist of clusters of probably coeval, small volume centers aligned along predominantly northeast (one north) structural trend. The exceptions are the basaltic andesite of Buckboard Mesa and the Lathrop Wells center. The basaltic andesite of Buckboard Mesa consists of a main scoria cone located on a northwest-trending fissure. The Lathrop Wells cone consists of only one center.

a. Basalt of Thirsty Mesa. The basalt of Thirsty Mesa comprises a thick accumulation of fluidal lava and local feeder vents marked by dissected scoria cones surmounting the lava mesa (Fig. 2.5). These lavas, viewed from the west, appear to form a shield volcano but the volcanic landform is actually more complex than a simple shield. The lavas were erupted onto an existing plateau formed by ignimbrite of the Thirsty Canyon Tuff. The flows form a convex upward mesa surface above the plateau.

The topographic summit of the mesa is formed by eroded deposits of scoria marking subdued mounds that probably represent the main sites of extrusion of the lavas. This interpretation is supported by the gradual increase in thickness and the symmetrical distribution of the lava flows around the scoria mounds. The mounds trend northwest, probably reflecting the structural control of the center. The basalt of Thirsty Mesa covers an area of about 22 km^2 with a maximum thickness of about 200 meters. The approximate volume of the center is 3 km^3 (DRE). The lavas are sparsely porphyritic olivine basalt with phenocrysts and microphenocrysts of olivine. Major and trace element data for the basalt show that it is an alkali basalt. All analyzed samples of basalt of Thirsty Mesa contain normative nepheline (Crowe et al. 1986).

The lava mesa shows moderate geomorphic degradation. Lava flow margins have been eroded. The lava flow surfaces have well-developed surface pavements containing soil with horizon development. There is no evidence of primary flow-top topography. The scoria vents have been dissected significantly but still maintain a rounded, mound-form and uphold the high-standing topography of the mesa. Crowe et al. (1992b) suggested, based on geomorphic data, that the center may be of Pliocene age. An $^{40}Ar/^{39}Ar$ age of 4.6 Ma has been obtained for the mesa lavas and they have reversed magnetic polarity (Champion 1992; p. 248).

The lava mesa was thought, prior to 1992, to underlie the Thirsty Canyon Tuff and therefore to be of Miocene age. It is a newly recognized Pliocene volcanic unit of the Yucca Mountain region. The basalt of Thirsty Mesa is significant for several reasons. First, the mesa is located in and provides additional evidence for the existence of the CFVZ of Crowe and Perry (1989). Second, the basalt of Thirsty Mesa is the largest volume volcanic unit of the YPB. The volume of basalt equals the volume of some of the basaltic units of the BSE.

Third, the basalt of Thirsty Mesa, is an alkali-olivine basalt, and is different chemically from the hawaiite basalt of Crater Flat (Vaniman and Crowe 1981; Vaniman et al. 1982).

b. Basalt of Amargosa Valley. A negative aeromagnetic anomaly was identified in the Amargosa Valley, several kilometers south of the town of Amargosa Valley (Kane and Bracken 1983; Crowe et al. 1986; Fig. 2.5). The anomaly was drilled in 1991 by a private company (Harris et al. 1992). Samples of cuttings of the basalt were obtained and submitted for K-Ar age determinations. A separate sample of the cuttings was collected and analyzed by Turrin (1992). He reported an $^{39}Ar/^{40}Ar$ isochron age of 4.4.07 Ma (Turrin 1992; p. 231).

The boundaries of the basalt are sharply delineated on aeromagnetic maps (Kane and Bracken 1983; Langenheim et al. 1992). The main mass of the basalt is located three kilometers south of the town of Amargosa Valley. The near-circular outline of the northern part of the anomaly suggests it may be the main conduit or vents for the center. A lobate aeromagnetic mass extends to the south of the main mass and may outline a lava flow derived from the center. The aeromagnetic anomaly is inferred to represent a former surface basalt center buried by alluvium deposits in a zone of higher sedimentation along the trace of the Fortymile Wash (Fig. 2.1; Fig. 2.5). The area of coverage of the aeromagnetic anomaly is about 20 km^2. Assuming that the basalt is a buried center and it has dimensions typical of local lava flows and scoria cones, its volume is estimated to be about 0.2 to 0.4 km^3 (DRE).

c. Basalt of Southeast Crater Flat. The basalt of southeast Crater Flat has been described by Crowe and Carr (1980), Vaniman and Crowe (1981), Vaniman et al. (1982), Crowe (1990), and Perry and Crowe (1992). The basalt unit consists of an alignment of north-trending dissected scoria cones and associated moderate-volume, lava flows (Fig. 2.5). The scoria cones extend south in an en echelon pattern from the east central part of Crater Flat. The former presence of individual centers is indicated primarily by the presence of eroded deposits of oxidized cone scoria. The scoria contains aerodynamically shaped bombs, and spatter. The large size of the bombs (> 0.5 m) and local agglutination of the spatter requires near-vent deposition. However scoria outcrops are deeply eroded, discontinuous, and retain no primary constructional topography.

The geometry of vent zones can be reconstructed by detailed mapping of three surface features. First, the north and east parts of one cone (here named Radial center) are preserved beneath a cover of thin aa flows probably derived from the center. The south side of this cone is upheld by an increased degree of induration of the scoria in proximity to a north-south trending swarm of lenticular dikes. This combination of features provides sufficient preservation of the radial dips of scoria deposits to reconstruct the location of the probable circular cone. Second, a series of elongate lava masses are exposed in the center parts of vents of the basalt of southeast Crater Flat. These masses are not lava flows. They are preserved remnants of lava ponded in the elongate vent of individual centers. This interpretation is suggested by the gentle inward dips of the lava (10-20°) around the circumference of the exposures and the presence of scoria deposits beneath and buttressed against the lava ponds. These elliptical lava ponds have long axes trending north-south suggesting the lava ponds filled elongate vents (fissures), not the craters of symmetrical scoria cones. The direction of the elongation of the lava ponds is coparallel with the trend (north-south) of linear feeder dikes. Third, lenticular dikes expanded locally forming irregular plugs with vertical cooling joints. These plugs are associated with an increased thickness of indurated deposits of scoria. The dips of the scoria deposits, recognized by the presence of aerodynamically shaped bombs, are relatively steep (15-25°) and require deposition at or near eruptive vents.

Lavas of the basalt of southeast Crater Flat are the most areally extensive of the YPB. They form sheet-like flows that flank, to the south and east, the described vent zones. In no case, however, can the lavas be traced directly to their individual feeder sources. Cross-sections of the flows show that they are relatively thin (3-5 m) aa flows with basal breccia of clinker and blocky vesicular upper surfaces. Some of the flows are offset more than a meter (west-side down) along north-south trending faults that may be related to exposed faults in the northwest part of Yucca Mountain (Crowe and Carr 1980; Smith et al. 1990). The lava flows are covered to the east by alluvium and the section is probably dropped downward by faults concealed beneath alluvium. This is suggested by several features. First, the eroded, outcrop edge of the flows trends north-south and parallels basin-range faults. This suggests the flow margin is fault controlled. Second, petrologically similar lava flows are exposed in easternmost Crater Flat where they are faulted against the bedrock tuff of Yucca Mountain or overlie an erosional surface developed on the poorly consolidated deposits of Timber Mountain Tuff. Third, aeromagnetic data show the lava flows are continuous beneath the alluvium (Kane and Bracken 1983).

The basalt of southeast Crater Flat has yielded K-Ar ages of about 3.7 Ma (Sinnock and Easterling 1983; Smith et al. 1990). Unpublished K-Ar ages of 3.7 Ma have also been obtained by the U.S. Geological Survey. All measured samples of the basalt of southeast Crater Flat have a reversed magnetic polarity, consistent with an age of about 3.7 Ma (Vaniman and Crowe 1981; Vaniman et al. 1982).

<u>d. Basaltic Andesite of Buckboard Mesa.</u> The basaltic andesite of Buckboard Mesa is the second largest basalt by volume of the post caldera basalt cycles of the region (1 km^3 DRE). It comprises aphyric lavas erupted in the northeast part of the ring fracture zone of the Timber Mountain caldera (Fig. 2.5). The lavas were erupted mainly from a scoria cone in the northwest part of the outcrop area (Scrugham Peak). Additional lava flows vented from a fissure that extends southwest for about five km from the base of Scrugham Peak. This fissure is marked both by a subdued linear ridge in the present-day topography and by the presence of scoria and agglutinated spatter exposed in craters excavated during high-explosive experiments (Lutton 1968; his Fig. 1). The basaltic andesite was erupted into and filled topographic valleys between the east and west branches of Fortymile canyon (Lutton 1968). Subsequent erosion lead to inverted topography and the flows now form a mesa top. The outcrops of the basaltic andesite of Buckboard Mesa expose a single major flow with multiple flow lobes (Lutton 1968). Lutton (1968) described core from boreholes near Scrugham Peak where two flows could be distinguished. A second, upper flow can also be discriminated in outcrops northwest of Scrugham Peak based on topography and

petrography. The younger flow contains phenocrysts of kaersutite.

The major volume of the basaltic andesite of Buckboard Mesa is an aphyric olivine basalt andesite (mean SiO_2 content of 53.5 weight percentage; Lutton 1968; Crowe et al. 1986) with abundant plagioclase microphenocrysts and microlites and minor clinopyroxene. Multiple K-Ar ages of about 2.9 Ma have been obtained for the lava flows of basaltic andesite of Buckboard Mesa. This age is consistent with the positive magnetic polarity of the lavas.

e. Quaternary Basalt of Crater Flat. A series of four Quaternary basalt centers form a north-east trending, slightly arcuate cluster of basalt centers extending along the axis of Crater Flat. From southwest to northeast, these centers consist of respectively, Little Cones, Red Cone, Black Cone, and the Makani cone (the latter cone is named informally in this report).

(1) The Little Cones. The Little Cones consist of two separate cones of small dimensions. The southwest cone is breached on the south side probably from extrusion of a lava flow that is buried beneath alluvial deposits. The dimensions of this inferred flow can be approximated from the lobate boundaries of a mass of a negatively magnetized body shown on the drape aeromagnetic data of Kane and Bracken (1983). The inferred flow extends 2 km from the south end of the southern of the Little Cones centers. A pavement surface developed above the inferred flow contains cone scoria, not lava fragments. It could be a rafted cone portion or satellite vent(s). A small satellite cone is located about 0.5 km southeast of the south cone. It is marked only by erosional rubble of cone scoria containing aerodynamically shaped bombs. A small feeder dike is exposed in the cone rubble. Most of the samples analyzed for chemistry and K-Ar age determinations have been obtained from this feeder dike.

The northeast cone is a symmetrical scoria cone and is slightly smaller than the southwest cone. There is no evidence of extrusion of lava from this cone, based either on examination of surface exposures or the aeromagnetic data of Kane and Bracken (1983).

Both of the Little Cones centers are eroded significantly. Rills are conspicuously developed on the cone slopes. The cone slope angles are less than the angle of repose and cone-slope aprons are developed at the base of the cones. Wells et al. (1990) has described preliminary soils and geomorphic data for both centers. They note that the degree of soil development and geomorphic degradation of the Little Cones are comparable to stage II soils in the Cima volcanic field. Replicate K-Ar ages of about 1.0 Ma have been obtained for samples of the Little Cones. These ages were reported in Crowe et al. (1982) and Vaniman et al. (1982). Unpublished K-Ar ages, obtained by the U.S. Geological Survey range from 1.2 to 0.7 Ma. Both of the Little Cone centers have reversed magnetic polarity consistent with the negative aeromagnetic anomaly associated with the centers (Kane and Bracken 1983). The reversed magnetic polarity and the preliminary K-Ar ages indicate the Little Cones center was probably formed in the Matayama reversed magnetic epoch.

(2) Red Cone and Black Cone Centers. The Red and Black cone centers are analogous volcanic landforms with similar eruptive histories. Each consists of a main scoria cone surmounted by a summit crater filled with agglutinated spatter, large lava blocks, and scoria (Vaniman and Crowe 1981; Smith et al. 1990; Feuerbach et al. 1990; Ho et al. 1991). The main cones are flanked by scattered scoria mounds which are erosional remnants of satellite vents. Some or perhaps all of the lavas of both centers were erupted from the satellite vents (Vaniman and Crowe 1981; Vaniman et al. 1982; Smith et al. 1990; Ho et al. 1991).

The Red Cone is significantly modified by erosion. The basal diameter of the cone is 440 meters and the height is 55 meters (measurements made using the morphometric parameters of scoria cones and colluvial aprons of Wells et al. 1990). The cone slopes have extensive development of rills, integrated channel networks, and deep gullies with inset fill. Erosional processes have produced a cone-slope apron extending as much as 400 m from the base of the cone slope (Wells et al. 1990). Two small dikes, which are probable offshoots from the main conduit, are exposed in the western wall of the cone (Vaniman and Crowe 1981). The vent or summit crater of the cone is filled by an accumulation of inward-dipping scoria and agglutinated spatter; aerodynamically shaped bombs in the crater-fill sequence exceed 2 m in length (Vaniman and Crowe 1981). A series of satellite cones or scoria mounds is exposed south of the main cone (Vaniman and Crowe 1981; Ho et al. 1991). These are clustered along northeast and northwest trends. Locally the mounds were the source vents of aa lava flows that flank the south part of the main cone and surround the scoria mounds (Smith et al. 1990). These lavas extend for as much as 1 km from the vents. The outcrop edges of the lavas have abrupt flow fronts with steep flow foliations indicating the present edges are close to the original flow margins. However, there has been sufficient removal of flow top clinker and flow margin breccia to expose the massive interior lobes of some of the aa flows.

The Black Cone center is 75 m high. The summit of Black Cone is upheld by a crater-fill sequence consisting of large blocks of strongly agglutinated spatter and small lava masses. This agglutinated sequence is much more resistant to erosion than the surrounding non-agglutinated scoria deposits and may explain partly the better geomorphic preservation of the Black Cone center. The Black cone center has generally steeper cone slopes, a higher cone-height to cone-width ratio, and smaller apron development than Red Cone (Wells et al. 1990; their Fig. 2).

There is limited evidence of preservation of original primary flow topography of the lava flows of both the Red Cone and Black Cone centers. The lava surfaces are relatively smooth because of pedogenic processes. The flow surfaces immediately north of the Black Cone center, however, retain a lobate geometry in plan view and have local irregularities in the flow-top surface that are probably remnants of primary flow topography.

Wells et al. (1990) noted that soils on the Black cone center more closely resemble phase II soils in the Cima volcanic field. In contrast, they noted that the soils on the lavas of the Red Cone center have more strongly developed K-horizons and are more analogous to Phase-III soils of McFadden et al. (1986). The degree of soil development of the Red Cone lavas is consistent with an age of > 0.70 Ma but less than Pliocene (Wells et al. 1990; p. 550). The difference in soil development, lava-flow morphology, and scoria-cone morphology of the Red and Black cone centers may indicate a slightly younger age of the Black cone center.

K-Ar ages between 0.8 and 1.5 Ma have been reported for both the Red Cone and Black Cone centers by Crowe et al. (1982), Vaniman et al. (1982), Sinnock and Easterling (1983), and Ho et al. (1991). Unpublished ages for the centers of about 1.0 Ma have been obtained by the U.S. Geological Survey. These ages are consistent with the degree of horizon development in the soils and the observed reversed magnetic polarity of the centers. The possible age difference between the Red Cone and Black Cone centers cannot be resolved by existing K-Ar age determinations. However, the combined chronology data and the reversed magnetic polarity of both centers suggest they belong to the Matuyama reversed magnetic epoch.

(3) Makani Cone. The northernmost basalt center of the Quaternary basalt of Crater Flat is herein named the Makani Cone (Hawaiian for wind) because of its proximity to Windy Wash. It is the most deeply incised of the four Quaternary basalt centers. The Makani Cone consists of an eroded aa lava flow and small remnant of cone scoria; the latter is probably part of an original scoria cone (Vaniman and Crowe 1981). The deep dissection of this center may be attributed to several causes. The center is located on a higher and steeper topographical part of the Crater Flat basin than the other centers which may have resulted in higher erosion rates. Alternatively, the center may be slightly older than the other Quaternary basalt centers of Crater Flat. K-Ar age determinations as old as 1.7 Ma have been obtained for this center. A third alternative is the Makani cone may have been a small volume center. The major volume of eruptions of the Quaternary basalt of Crater Flat are contained in the Red Cone and Black Cone centers. The volume of the Little Cones center represents only about 5% of the volume of the Black Cone and Red Cone centers.

(4) Eruptive Models for the Quaternary Basalt of Crater Flat. An area of difficulty in reconstructing the eruptive history of the Quaternary basalt of Crater Flat is in determining whether each center formed in a single eruption (monogenetic) or multiple time-separate eruptions (polycyclic). Additionally, it is difficult to establish an age of eruptive activity for each center with a reasonable degree of accuracy. Small volume basalt centers have traditionally been assumed to be monogenetic centers (Wood 1980). However, detailed studies of the Lathrop Wells and Sleeping Butte centers (Wells et al. 1990; Crowe et al. 1992a; Crowe and Perry 1991) have raised the possibility that some basalt centers may form episodically (polycyclic volcanism).

The ages of the Quaternary basalt centers of Crater Flat, based on the results of K-Ar age determinations, cluster around 1 Ma and they all give reversed polarity magnetization. This suggests the centers could be coeval. However, replicate K-Ar age determinations for the centers range from 0.7 to 1.7 Ma (Crowe et al. 1982; Vaniman et al. 1982; Sinnock and Easterling 1983).

Champion (1991) suggested the Quaternary basalt centers of Crater Flat record a single reversed polarity direction of remanent magnetization. He based these conclusions on field and paleomagnetic analyses of samples collected from 20 sites. Champion (1991) noted that the single reversed polarity direction is similar to the field directions obtained for the 3.7 Ma basalt of southeast Crater Flat, but these flows could be separated on the basis of differences in stratigraphy and K-Ar age determinations.

The paleomagnetic data (Champion 1991) permit the inference that the Quaternary basalt centers of Crater Flat formed contemporaneously (single magma pulse) with each center being of monogenetic origin (formed in one brief eruptive cycle). This interpretation requires several critical underlying assumptions. First, Champion (1991; p. 63) has argued that secular variation occurs at a rate of about 4 to 5 per century. He did not assess the variability of the geomagnetic field during the period of the eruption of the Quaternary basalt of Crater Flat. Second, the paleomagnetic data for the Quaternary centers of Crater Flat were assumed to adequately represent all volcanic events of these centers. The sample sites for collection of paleomagnetic material were not presented (Champion 1991), so this assumption cannot be tested. Third, and related to the second argument, is the reproducibility of the measurements of the field magnetic directions. Champion (1991) presented only the mean directions of remanent magnetization for the Quaternary basalt of Crater Flat. Both lava and scoria were sampled for the paleomagnetic studies (Champion 1991; p. 63). The latter may be a less reliable recorder of field magnetic directions. Without presentation of data, it is impossible to assess the variability of the field magnetization directions. The degree of measurement variability is particularly important if the secular variation is less than the assumed 4 to 5 per century. Finally, Champion (1991) did not attempt to reconcile his interpretations (single magmatic event) with either the variable K-Ar age determinations, the evidence of geochemical diversity in the lavas (Perry and Crowe 1992), or the different soil phases of the centers (Wells et al. 1990). The assumptions for the paleomagnetic data must be more carefully evaluated before accepting the conclusion that the each center is monogenetic and, especially, that all centers formed from a single magmatic event.

The recognition of time-separate events at basalt centers must be based on establishing unequivocal time gaps between eruptive events, such as the presence of soil-bounded unconformities (Crowe et al. 1992a). The best evidence of the possibility of multiple, time-separate eruptive events for these centers is the different soil descriptions of Wells et al. (1990). Additionally, but only permissively, the variable K-Ar age determinations may be suggestive of polycyclic events. Smith et al. (1990) and Ho et al. (1991) presented evidence that Red Cone and Black Cone centers could be polycyclic.

<u>f. Sleeping Butte Centers.</u> The Sleeping Butte volcanic centers are located about 20 km north of Beatty, straddling the boundary of the Nellis Air Force Range (Fig. 2.5). They are 47 km northwest of the potential Yucca Mountain site. The Sleeping Butte centers

consist of two, spatially separate, small-volume (<0.1 km^3) basaltic centers. The basalt centers comprise a main scoria cone flanked by small satellite scoria cone(s). Each center erupted multiple lobes of blocky aa lava flows that extruded from the base of their main scoria cone. The southwest center, the Little Black Peak Cone, erupted through fanglomerate deposits. The northeast center, the Hidden Cone, erupted through and draped the north-northeast facing slope of Sleeping Butte. This prominent topographic mount is upheld by resistant outcrops of moderately welded ignimbrite of Miocene age located about 1 km inward of the range front of the Pahute Mesa-Black Mountain highland. The two centers are aligned in a north-northeast direction, the preferential direction of alignment of post-Pliocene volcanic centers in the Yucca Mountain region (Crowe et al. 1983; Crowe and Perry 1989). The separation of the centers is 2.6 km, measured from crater center to crater center. These centers have been mapped at a scale of 1:5000 (Crowe and Perry 1991).

(1) The Little Black Peak Center. The oldest volcanic unit of the Little Black Peak volcanic center includes two mound-shaped accumulations of basalt scoria and volcanic bombs (Qs_2; Fig. 2.6) located at the south margin of the main cone. These mounds are similar to the scoria mounds described at the Red Cone, Black Cone (Crowe 1990), and the Lathrop Wells centers (Crowe et al. 1992a). There are no distinct vents or craters at the crest of the mounds. However, the abundance of large bombs (> 1 m in diameter) suggests the mounds were vents for basaltic eruptions. Lenticular dikes are exposed locally in the mounds. The dikes fed short, lobate lava flows exposed west of the eastern scoria mound (Crowe and Perry 1991).

The main scoria cone (Qs_1) of the Little Black Peak center has a basal diameter of 500 m and a height of 70 m (Fig. 2.6). The cone is symmetrical with a summit crater elongated slightly in a north-south direction. The upper slopes of the east side of the cone collapsed, forming an east-facing, landslide scarp extending from the east edge of the crater halfway down the eastern cone flank. Exposures of scoria deposits in the scarp show that the main cone is composed predominantly of scoria fall deposits with minor agglutinated spatter. Zones of oxidized scoria in the cone deposits were produced by oxidization of the deposits from volcanic gases emitted from the conduit or feeder dikes. The zone of oxidization is elongate in a north-northwest direction, probably reflecting the strike of the underlying feeder dike for the volcanic center. The outer slopes of the scoria cone are moderately dissected with development of radial rills. The base of the cone is encompassed by a well-developed cone-slope apron (Qs_{1a}; Fig. 2.6).

Aa lava flows were extruded from two sites on the flanks of the scoria cone. The larger, western flow, vented from the northwest base of the main scoria cone. This site is marked by a concave indentation in the profile of the cone slope, although the vent is largely covered by deposits of the cone-slope apron. The vent location is suggested also by the thickening of the flow near the vent. Additionally an asymmetrical extension of the zone of red oxidization of cone scoria extends radially from the summit crater to the flank vent. The latter evidence suggests the lava flow was fed by a radial dike extending from the main conduit (Crowe and Perry 1991). Original primary flow topography of the aa flow has been infilled by eolian material, producing a largely smooth, pavement surface. Remnants of the

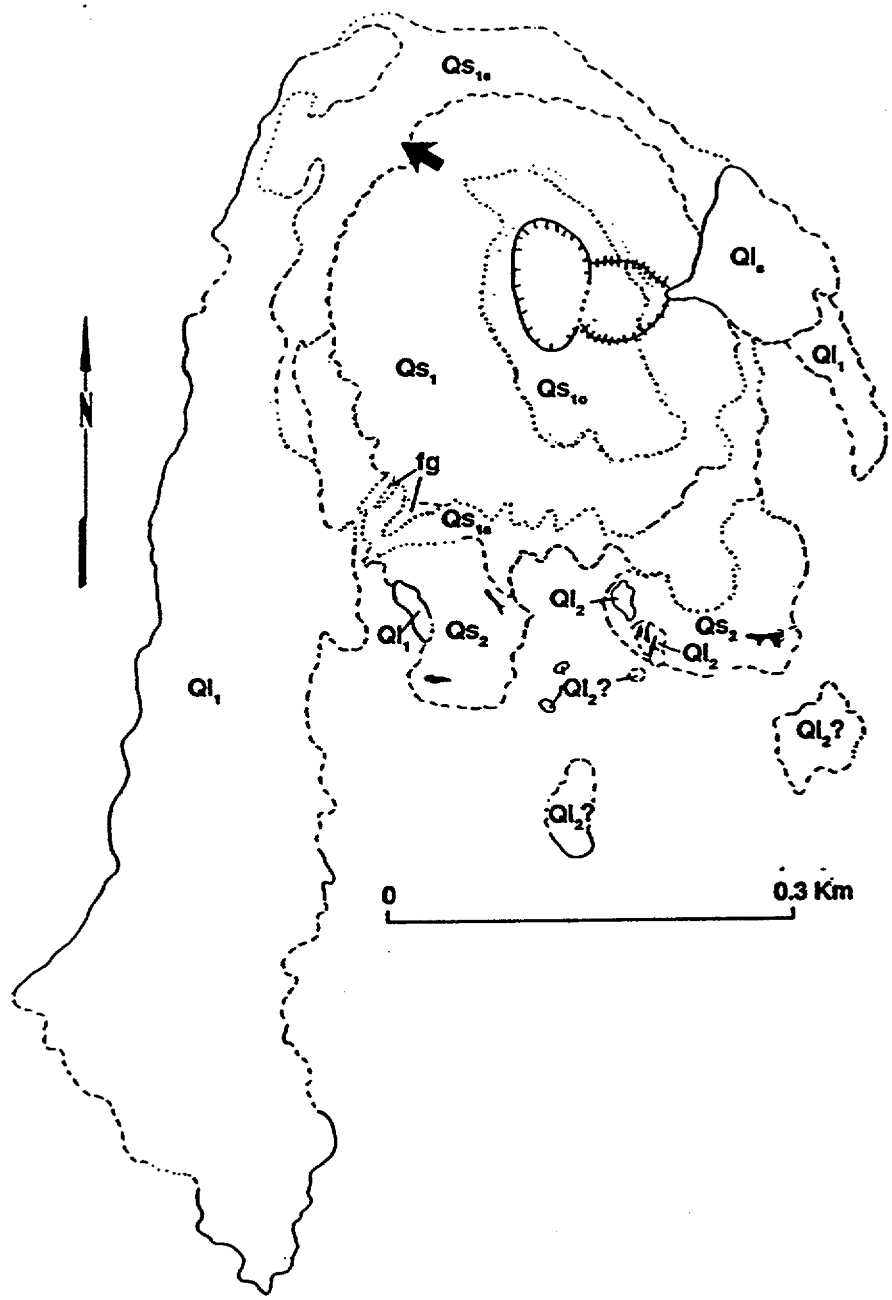


Fig. 2.6 Generalized geologic map of the Little Black Peak volcanic center of the basalt of Sleeping Butte. Map is compiled on an uncorrected aerial photograph. Lines mark contacts between geologic units. They are dashed where approximately located, and dotted where inferred or concealed. The area outlined by dots at the summit of the main cone is the vent area and underlying feeder dikes. These features are inferred from the distribution of zones of oxidization of the cone scoria. The large arrow marks the vent for the western lava lobe. Wide dark lines are feeder dikes in cone scoria. The line with inward facing dashes marks the crater rim of the summit cone. The line with cross-dashes is the slump scarp of the eastern crater wall. Line with inward facing dashes marks the crater rim of the summit cone. fg: Plio-Pleistocene fanglomerate deposits, Qs_2: scoria deposits of the south scoria mounds. Ql_2: older lava associated with the south scoria mounds; queried where identification is uncertain. Qs_1: scoria deposits of the main cone; Qs_{1a}: cone-slope apron deposits of the main cone. Qls: slide deposits. Ql_1: lava flows derived from the main cone. Figure is modified from Crowe and Perry, 1991.

primary flow topography occur only as local areas of stepped topography in the flow top. Margins of the lava flow are eroded.

A second lava flow was extruded from the east side of the cone. It is concealed partly by the landslide deposits so the actual vent site could not be confirmed. Cross-sectional exposures of the flow show that it exhibits aa morphology. This flow shows the same degree of geomorphic modification as the western flow.

(2) Hidden Cone Center. The Hidden cone center consists of a main scoria cone formed on the north-facing slope of Sleeping Butte (Fig. 2.7). The center was constructed in two stages: (1) a main scoria cone formed from central vent eruptions of mildly explosive Strombolian type, accompanied by extrusion of multiple lava flows at the northeast flank of the cone, and (2) a thin sequence of scoria-fall deposits was erupted during mildly explosive Strombolian eruptions. These deposits mantled the eroded slopes of the previously formed main scoria cone.

The first, or oldest event at the Hidden Cone center was the formation of most of the volume of the main scoria cone (Fig. 2.7). Scoria was deposited from Strombolian eruptions and built an asymmetrical cone that draped the north-facing slope of Sleeping Butte. Because of the steeply sloped topography underlying the cone, it is highest on the north side (downslope) and lowest on the south side (upslope). The basal diameter of the cone is 0.62 km. The cone height is 110 m measured from the north base of the cone and is 25 m measured from the south cone base. The scoria cone has an elliptical summit crater, elongate to the north. Oxidization of the cone scoria is centered on the crater but is skewed slightly to the west. This suggests the eruptions that formed the center were fed by magma that moved upward along a west-dipping dike. Because of the subsequent mantling of the cone slopes by younger scoria deposits, the older scoria deposits (Qs_4) are exposed only in the summit crater and the east side of the cone (Crowe and Perry 1991). A cone-slope apron containing soils with well-developed soil horizons is exposed mostly at the north and west base of the main scoria cone (Crowe and Perry 1991).

Lava vented from two radial dike sets and from a satellite cone at the northeast flank of the main scoria cone. The major feeder vent for the flows is the northern radial dike that passes upward into a thin lava flow. The lava breached the surface above the dike about 10 m upslope from the cone base. It extended eastward down the cone slope and laterally for 1.3 km. Other lavas were fed from a second set of radial dikes and a satellite cone located east of the northeast base of the main scoria cone (Crowe and Perry 1991). All lava flows of the center show an aa flow morphology.

The lava flow units of Hidden Cone show similar degrees of erosional degradation as the lava units of the Little Black Peak center. Most of the original aa flow topography has been smoothed and the flow tops are pavement surfaces. Margins of the lava flow are erosional, not flow margins.

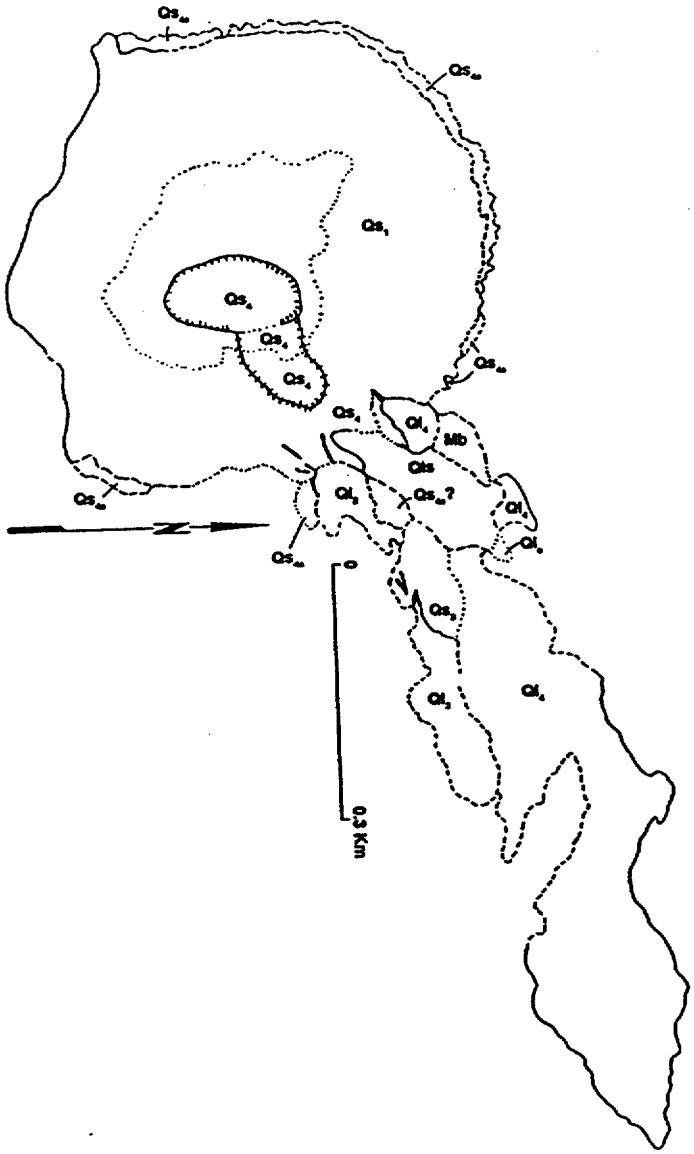


Fig. 2.7 Generalized geologic map of the Hidden Cone volcanic center of the basalt of Sleeping Butte. Map is compiled on uncorrected aerial photographs. Lines mark contacts between geologic units. They are dashed where approximately located, and dotted where inferred or concealed. The area outlined by dots at the summit of the main cone is the vent area and underlying feeder dikes. These features are inferred from the distribution of zones of oxidization of the cone scoria. The line with inward facing dashes is the summit crater; the line with cross-dashes outlines the slump scarp of the eastern crater wall. Wide dark lines are feeder dikes. Bm: Miocene basalt; Ql_4: lava flow associated with the radial feeder dike, Qs_4: older scoria deposits of the main cone, Qs_{4a}: cone-slope apron deposits of the main cone, Qls: lava flow associated with the Qs_3 scoria mound, Qs_3: flank scoria mound, Ql_2: lava flow associated wit the radial feeder dikes, Qs_1: late Pleistocene or Holocene scoria-fall deposits. Figure is modified from Crowe and Perry, 1991.

The youngest unit of the Hidden Cone center (Qs_1) comprises scoria-fall deposits that mantle the older cone except for the perimeter of the north and east base of the cone. The existence and inferred young age of this eruptive event are suggested by the following:

1. The outer slopes of the main cone show only minor degradation denoted by the formation of rills on the cone slopes.
2. There are no apron deposits associated with the Qs_1 deposits. This suggests there was an insufficient time subsequent to the youngest eruption for significant cone-slope erosion.
3. There is an erosional unconformity between the Qs_4 and the Qs_1 deposits exposed in the northeast section of the main cone.
4. There is significant horizon development in the soil on the Qs_4 deposits. There is limited horizon development in the soil on the Qs_1 deposits.
5. Fine-grained scoria-fall deposits are preserved on the modern alluvial surface about 0.5 km northeast of the main scoria cone.

Champion (1992; pp. 254-255) noted the presence of a possible second lava flow associated with the Hidden Cone center, located northwest of the north cone base. He reported a K-Ar age of about 385 ka for the flow, consistent with the age of the lava flow units of the Hidden Cone center. This western lava flow was recognized in earlier mapping of the Hidden Cone center. However, detailed field examination showed that the western lava flow could not be traced to the Hidden Cone. Instead it appears to be associated with deeply dissected scoria deposits that mark one of a series of basalt centers stratigraphically beneath the Thirsty Canyon Tuff. Additionally, the western lavas are overlain by a thick soil with dramatically greater horizon development than the Hidden Cone lava flows. The new K-Ar age determination provides evidence that the western flow could be associated with the Hidden Cone center. Additional field work will be conducted to verify the stratigraphic position of the western lava flow.

Whole rock, K-Ar age determinations have been obtained for both centers of the basalt of Sleeping Butte. These ages range from 200 to 400 ka. The analytical uncertainty of individual analyses generally exceeds 100 ka (Crowe and Perry 1991). Turrin (1992; p. 231) reported K-Ar ages of about 380 ka for lavas of both of the Sleeping Butte centers. The degree of erosional dissection of the lavas is consistent with the K-Ar age determinations. Additionally, the degrees of horizon development of soil on the lavas and cone-apron deposits are consistent with an age of several hundred thousand years (Crowe and Perry 1991).

Preliminary paleomagnetic data from a limited number of sites in the lava and scoria deposits of both basalt centers appear to give a single or closely grouped direction of remanent magnetization (Champion 1991). Champion (1991) noted these data require that both centers formed in a single eruptive event and are therefore, monogenetic volcanic centers. Such an interpretation is permissive for the Little Black Peak center (Crowe and Perry 1991) but remains to be tested by further geochronologic, geomorphic, and soil studies. However, the monogenetic classification of the Hidden Cone center may not be verifiable using paleomagnetic data. There are no deposits of agglutinated spatter associated with the youngest eruption of the Hidden Cone center that would provide reliable indicators of the field direction at the time of formation of this deposit. More geochronology work is planned to evaluate the different models of the eruptive history of the Hidden Cone center (Crowe and Perry 1991).

IV. THE LATHROP WELLS CENTER

The geology of the Lathrop Wells volcanic center was described by Vaniman and Crowe (1981), Crowe et al. (1983), Crowe (1986), Wells et al. (1990, 1991), Turrin et al. (1991, 1992), and Crowe et al. (1992a). It overlies faulted volcanic bedrock of the Paintbrush and Timber Mountain Tuffs and alluvial deposits. It is located near the intersection of several northwest-trending faults that extend from the northwest parts of Yucca Mountain and the northeast-trending Stagecoach Road fault (Fig. 2.8). The center consists of a large main scoria cone, and three sets of fissures marked by paired spatter ramparts and scoria mounds. Small volume blocky aa lava flows vented from numerous sites along two of the fissures. The main cone of the center is elongate northwest. This elongation probably was controlled in part by prevailing winds during the pyroclastic eruptions that formed the cone. Additionally, the feeder dike for the center appears to be oriented northwest, as indicated by two lines of evidence. First, there is a summit zone of red scoria centered about the crater and extending to the southeast and northwest. This cone feature was formed from oxidization of the scoria deposits by rising volcanic gases emitted from an underlying northwest-trending dike. Second, there are two sets of northwest-trending, locally paired spatter cones and scoria mounds that demarcate eruptive fissures. These are present along the east base of the main cone and at the northeast edge of the volcanic center. An alignment of east-northeast trending spatter cones and scoria mounds marking a third fissure zone is located north-northeast of the main cone.

In the early stages of work on volcanism studies, the Lathrop Wells center was assumed to be a simple monogenetic volcano with an age, based on whole rock K-Ar age determinations, of about 300 ka (Vaniman and Crowe 1981; Vaniman et al. 1982; Crowe 1986). However, two lines of evidence resulted in reevaluation of the chronology data. First, additional whole rock K-Ar age determinations were obtained (Sinnock and Easterlingly 1983). These ages ranged from -20 to > 700 ka, an unacceptably large range in age to have high confidence in the K-Ar results. Second, the soil and geomorphic features of the main cone were recognized to be inconsistent with the suggested age of 300 ka (Wells et al. 1988). In order to evaluate these anomalies, new studies were initiated at the center (Crowe et al. 1992a).

The Lathrop Wells volcanic center was remapped at a scale of 1:4000 and the volcanic rocks were divided into five lithostratigraphic units (Crowe et al. 1988). The discovery of the presence of soil with horizon development beneath the upper lithostratigraphic units provided persuasive evidence that the center is a polycyclic volcano (formed in multiple, temporally distinct eruptive events; Wells et al. 1990). Excavation of more than thirty-five

LATHROP WELLS VOLCANIC CENTER

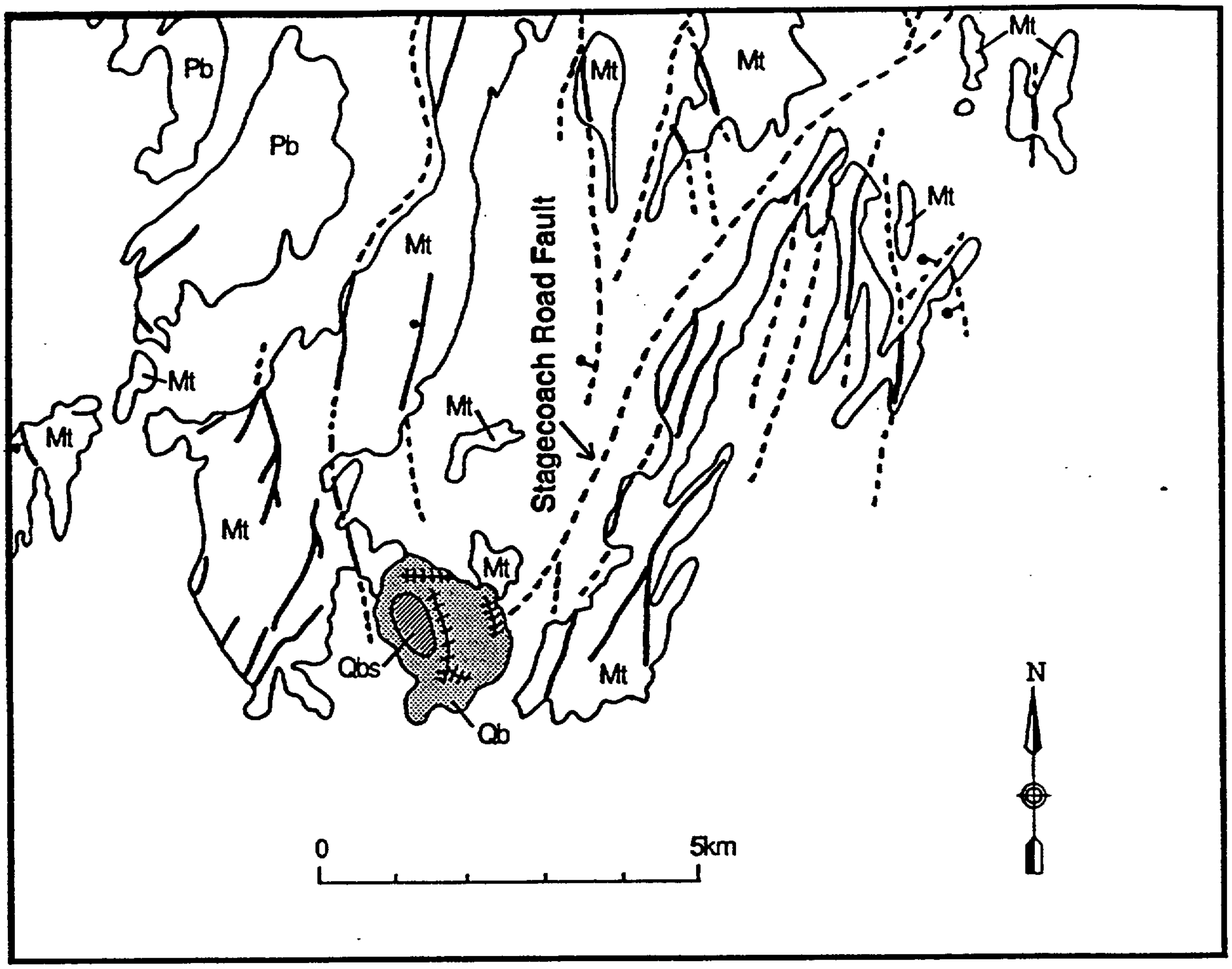


Fig. 2.8 Geologic setting of the Lathrop Wells volcanic center. The center is located at the south end of Yucca Mountain. Volcanic deposits of the center overlie Miocene tuff and alluvial deposits and are locally overlain by alluvium and aeolian deposits. Mt: Miocene tuff undivided, Pb: Pliocene basalt of Crater Flat; Qb: Quaternary lava and pyroclastic deposits of the Lathrop Wells center, Qbs: Main scoria cone of the center. Cross-hatched lines are eruptive fissures and denote structural trends of eruptive vents. Modified from Crowe et al. (1992a).

trenches for soil, stratigraphic, geochronologic, and geochemical studies (Crowe et al. 1992a) allowed detailed examination of the mapped volcanic units and description of the development of soils on the units. Based on this work, the center was divided into seven lithostratigraphic units. A buried soil was described between two lava flows inferred to be in the lower part of the volcanic sequence (Crowe et al. 1992a). The seven lithostratigraphic units were grouped into three chronostratigraphic units (temporally distinct; Crowe et al. 1992a). The available chronology data were judged to be insufficient however, to define the temporal boundaries of the chronostratigraphic units (Crowe et al. 1992a).

Additional geochronology and trenching studies were completed during the last calendar year. Heavy construction equipment was employed to expose deeply buried geologic contacts. The new work has resulted in several important modifications of the chronology and stratigraphy of the Lathrop Wells center from the most recently published studies (Crowe et al. 1992a). These changes include:

1. The soil inferred to be between the buried lava flow and the Qs_4/Ql_4 units is not between the units. Instead, it is a young soil that drapes units. The soil has locally infiltrated the fractures and penetrated into older volcanic units. Without completely exposed contacts in the deep trenches, it was impossible to determine the stratigraphic position of the soil.

2. Multiple pyroclastic surge units were identified from previous trenching studies (Crowe et al. 1992a). However, exposures in the deeper trenches show that one major pyroclastic surge unit overlies the Ql_4 lavas on the north side of the main cone but does not underlie the flow. The fine-grained, hydrovolcanic ash deposits of this unit have infiltrated fractures in the underlying units so that the proper stratigraphic relations could not be recognized in the shallow trenches. A second, unrelated tephra unit with minor pyroclastic surge deposits overlies units of chronostratigraphic unit two on the southwest flank of the cone, in an area that is heavily modified by commercial quarrying. These pyroclastic surge are separate stratigraphically from the north pyroclastic surge unit.

3. The results of new age determinations show some convergence of results for the chronology of lava flow units of the Lathrop Wells center. Newly obtained $^{40}Ar/^{39}Ar$ step-heating spectra of the Ql_3 lava yielded an isochron age of 107±33 ka (Turrin et al. 1992). This age determination could be slightly old because of the presence of excess Ar in olivine and possibly other phases (glass) in the lavas (Poths and Crowe 1992). Exposure-age measurements using the cosmogenic He method yielded ages of 65 to 70 ka for the Ql_3 lavas. These are minimum exposure ages, and may be slightly young because of coverage of the flows by aeolian sands and possibly by the pyroclastic surge deposits. Despite these potential chronology problems, both sets of data overlap in age when realistic analytical errors are assigned to the measurements. Thermoluminescence age estimates of baked sediments beneath the Ql_3 lava yielded ages of 25-30 ka. These are discordant with the other geochronology ages for this locality. We have

no explanation for the discordant ages. Additional measurements using the U-Th disequilibrium method yielded ages of 150±40 ka (Crowe et al. 1992a) and 135+35-25 ka for two separate samples of the lava sequences. These ages overlap in analytical uncertainty with the $^{40}Ar/^{39}Ar$ step-heating isochron age but not with the cosmogenic He or thermoluminescence ages.

4. Field studies show that the Qs_6/Ql_6, Qs_5/Ql_5, and Qs_4/Ql_4 scoria and lava units are significantly modified by erosion and have locally thick carbonate coatings on fracture surfaces. An erosional surface can be traced eastward from the western deposits of the Qs_4 scoria mounds. Dikes are locally exposed in the Qs_5 and Qs_4 scoria deposits. This requires removal of overlying scoria to expose the dikes. Third, the deposits at the crest of the scoria mounds expose an unusually high content of large volcanic bombs in comparison with the mound interiors (exposed by trenching). This suggests the bomb-rich, crest of the mounds is an erosional lag deposit that is a remnant from erosional removal of scoria deposits. Fourth, trenching has revealed the internal structure of several of the scoria mounds. The topography of the mounds does not correspond directly to the dip of the scoria deposits. This requires a significant degree of erosion to modify original primary topography of the mounds. This non-correspondence between topography and structure contrasts with the scoria deposits of chronostratigraphic unit two. The latter mounds show a correlation between topography and the dip of the spatter and scoria deposits. Collectively these features are consistent with ages of the lava sequences of greater than 70 ka.

The subdivisions of chronostratigraphic units for the Lathrop Wells volcanic center are described below, from oldest to youngest.

A. Chronostratigraphic Unit Three

The oldest identified chronostratigraphic unit at the Lathrop Wells center comprises all the lava flow units of the center, with local vent scoria. These lava units include, from oldest to the youngest, the Qs_6/Ql_6, Qs_5/Ql_5, Qs_4/Ql_4 and Qs_3/Ql_3 units. All of the lava units are not in stratigraphic contact. However, the sequence of the lavas can be constrained partly by stratigraphic relations. The Ql_5 and Q_{l4} lavas are overlain by the Ql_3 lavas (Crowe et al. 1988). The lava units are divided into three informal units based on their stratigraphic positions. These are the southern, the northern, and the northeastern lava units (Fig. 2.9).

1. The Southern Lava Units. The Qs_6/Ql_6 units are exposed only on the southwest side of the Lathrop Wells center (Fig. 2.9). They consist of eroded, northwest-trending mounds of scoria and agglutinated bombs. Some bombs in the scoria deposits exceed two meters in length. There is no distinct crater form to the scoria mounds. However, the abundant scoria deposits, coarse size of bombs, and local zones of agglutination require that the deposits were vented from the mounds. There has been sufficient erosional modification of the mounds to remove or obscure evidence of the vent or vents. Blocky aa lava flows were extruded from several sites along the west and northwest edges of the Qs_6 scoria

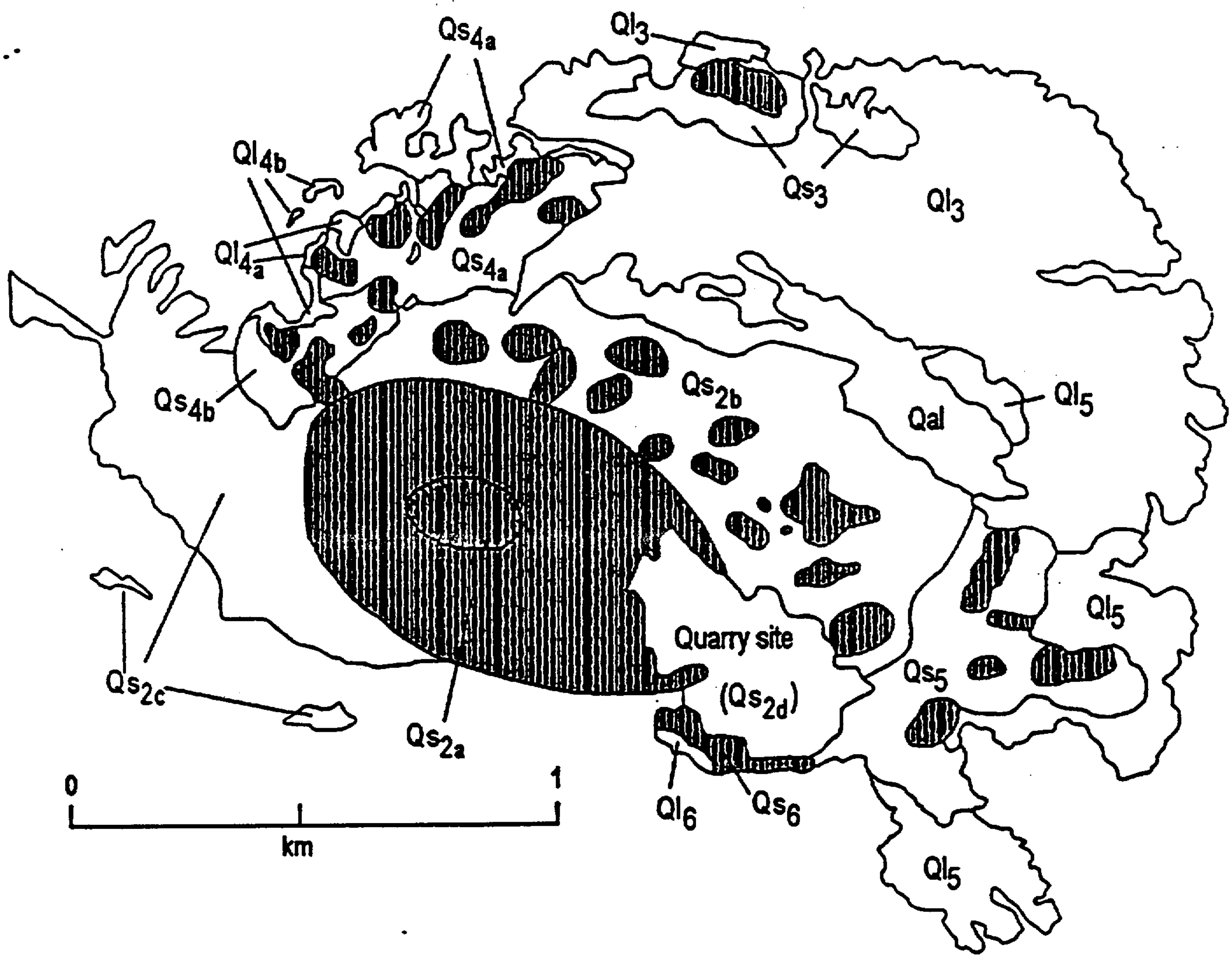


Fig. 2.9: Geologic map of the lithostratigraphic units of the Lathrop Wells volcanic center. Modified from Crowe et al. (1988; 1992a). Shaded patterns outline the scoria mounds and cones that are the primary eruptive vents for the center. Chronostratigraphic unit three includes blocky aa flow subunits (Ql_6, Ql_5, Ql_{4b}, Ql_{4a}, and vent spatter, agglutinate and scoria-fall deposits of (Qs_6, Qs_5, Qs_{4b}, Qs_{4a}). Chronostratigraphic unit two includes scoria deposits of satellite cones (Qs_{2d}), pyroclastic-surge deposits (Qs_{2c}), scoria mounds, spatter mounds and scoria fall deposits of the northwest fissure system (Qs_{2b}), and the scoria cone and scoria-fall deposits of the main cone (Qs_{2a}). Not shown on the map because of the small thickness and extent of the deposits are chronostratigraphic unit one. These are located at the site labeled QE on the figure.

mounds. These are small volume lava flows that flowed no further than several tens of meters from their vents (Fig. 2.9). The lavas were unusually viscous for basaltic magmas. They formed blocky aa flows directly at the vent and were disrupted from flowing down the slopes of the scoria mound. This disruption produced slumping and autobrecciation of the flows exposing local zones of steep and contorted flow foliation. A sample of the Ql_6 lava has been dated by the U-Th disequilibrium method at 135+35-25 ka (see chronology section).

The second lava unit of chronostratigraphic unit three is the Qs_5/Ql_5 subunit, a cluster of lavas and local eroded scoria mounds that crop out along the southern part of the Lathrop Wells center (Fig 2.9). These lavas were inferred to be derived from a fissure (Qs_5) that extends northwestward, along the east base of the main cone (Crowe et al. 1988). This interpretation was based both on the reported uniformity of the field magnetic directions for these units (Champion 1991) and the proximity of the Ql_5 outcrops to the southeast end of the fissure system. Three new observations indicate that this conclusion may be only partly correct. First, careful examination of the published sample sites of paleomagnetic studies show that the Ql_5 lavas were not sampled or analyzed (Champion 1991; Turrin et al. 1991). Thus, there is no confirmed basis for the paleomagnetic correlation between the fissure and the Ql_5 lava. Second, petrologic studies suggest that the Ql_5 lavas are distinct compositionally from most of the northwest-trending fissure (Perry and Crowe 1992). Third, the northwest-trending fissure can be separated into two parts based on geomorphic criteria. The first part includes the northwest-trending fissure exposed at the east base of the main cone. This fissure is defined by the occurrence of paired scoria or spatter mounds. Each mound along the fissure system is distinct topographically and appears relatively unmodified by erosion. In contrast, the southeast parts of the rift (as shown on earlier geologic maps of the center; Crowe et al. 1988), show considerable geomorphic modification.

The scoria deposits of Qs_5 have minimal topographic relief. They form low-standing accumulations of scoria and the boundaries between individual mounds of scoria deposits are poorly defined. Locally, there are exposures of feeder dikes in the scoria deposits suggestive of significant erosion of the unit. We have tentatively reassigned the southern parts of the main northwest-trending fissure system to the Qs_5 unit (Fig. 2.9). This assignment will be tested through a combination of continuing petrology, paleomagnetic, and chronology studies. The Ql_5 lavas have been dated at about 65 ka by the cosmogenic He method. Zreda et al. (1993) obtained an cosmogenic ^{36}Cl age if 81 ± 7.3 ka for the Ql_5 lava, in relatively close agreement with the cosmogenic He ages. An unknown factor for the ^{36}Cl age however, is the 30% correction (reduction) used in the production rate of ^{36}Cl from thermal-neutron absorption of ^{35}Cl (Zreda et al. 1993; p. 59). Their correction overestimates the exposure age. The He ages are similar to cosmogenic He ages for the overlying Ql_6 lava flows. Turrin et al. (in press) report a weighted mean of 157±98 ka for the Ql_5 lava (mean of the data set is 214±86 ka) based on conventional whole rock, K-Ar age determinations. Subsequently, Turrin et al. (1991) obtained a weighted mean of 138±54 ka and a mean of 170±114 ka for $^{40}Ar/^{39}Ar$ ages of the Ql_5 lava.

2. The Northern Lava Unit. The Qs_4/Ql_4 unit is exposed north and northeast of the main cone of the Lathrop Wells center. The unit is defined by the sequence of east-northeast-trending scoria mounds. These mounds vented small volume, blocky aa lava flows (Figs. 2.9). The sequence is tentatively divided into two subunits based on differences in erosional modification of the scoria mounds and lava flows of the two subunits.

The first subunit of the Qs_4/Ql_4 unit includes eroded scoria mounds and local lava flows exposed at the west and northwest edges of the unit (Qs_{4b}/Ql_{4b}). The scoria mounds for this unit have subdued topography and diffuse boundaries between mounds. The mounds have been significantly modified by erosion and do not form distinct topographic features. The surface formed on the Qs_{4b} scoria mounds is erosional. It contains well-developed networks of rills consistent with major erosional modification of the vents. The primary evidence that the deposits are vent zones is the abundance and size of bomb fragments in the scoria deposits.

An arcuate band of lava (Ql_{4b}) crops out north of and flanks the scoria mounds of Qs_{4b}. These lavas were probably derived from the scoria vents, and are similar to the flanking lava flows of the Qs_6/Ql_6 units. However, there has been sufficient erosion to obscure the relationship between the lavas and scoria deposits. The Ql_{4b} lavas underlie lavas of the higher-standing Ql_{4a} unit and there are local contrasts in the degree of development of carbonate coating on lava clasts with the Ql_{4b} lavas compared with the Ql_{4a} lavas. These differences could represent either different ages of the lavas or local variations in the penetration of moisture associated with pedogenesis. We have not examined the lavas systematically to attempt to discriminate causes in the variations in secondary carbonate.

There is a second site of the Qs_{4b} unit northeast of the first site (Fig. 2.9). Here lava and scoria deposits are completely buried by aeolian sands. Identification of the scoria deposits is based on exposure of the units in trenches (Fig. 2.9). No deposits of the Qs_{4b} unit at this site are exposed at the surface. However, the unit has been penetrated in numerous trenches (Crowe et al. 1992) and coincides with a topographic mound draped by aeolian sands. A lava flow unit crops out discontinuously beneath a thick cover of aeolian sand and silt north of the concealed Qs_{4b} deposits (Fig. 2.9). It has been referred to as the "buried flow" and was correlated initially with the Ql_5 lava unit (Crowe et al. 1988). However, geochemical studies have not confirmed this correlation (Perry and Crowe 1992). The contact relations of these lavas and related scoria deposits have been determined through excavation of trenches. The base of the "buried lava" is locally greater than 10 meters below the modern alluvial surface. It consists of a massive interior lobe of a single flow of blocky aa lava that rests on lava clinker and local scoria-fall deposits. The interior lobe is overlain by 7 meters of flow rubble. The flow lobe and flow rubble are overlain by colluvial rubble in turn overlapped unconformably by aeolian sands (Fig. 2.10). The "buried lava" has been traced in surface exposures to beneath the high-standing parts of the Qs_{4b}/Ql_{4b} subunit (Fig. 2.9).

Fig. 2.10 Photograph of the northwest wall of trench LW-1. The massive interior of the Ql_{4b} lava is overlain by up to 10 meters of autoclastic and epiclastic breccia composed of blocky aa flow rubble. The breccia deposits and flow lobe are overlain by a colluvial wedge of coarse lava debris that grades laterally into and is overlain by aeolian deposits.

The basis for designation of subunit Qs_{4b}/Ql_{4b} is the degree of erosional dissection of scoria deposits and deep burial of the lava and scoria deposits. These differences suggest but do not require a time difference between the subunits. Studies are in progress (paleomagnetic, geochronology and petrology) to evaluate the ages of the subunits. The only chronology data for the Qs_{4b}/Ql_{4b} subunits are the descriptions of soils on the scoria deposits (Crowe et al. 1992a).

The second subunit, Qs_{4a}/Ql_{4a} includes a sequence of higher-standing (topographically) scoria mounds that form most of the east-northeast trending fissure (Fig. 2.9). These mounds provided the source vents for local small volume lava flows. The flows were extruded from and extend mostly to the north of the fissure (Qs_{4a}/Ql_{4a}; Fig. 2.9). The scoria vents of this part of the subunit form distinct domal mounds. They can generally be separated in the field from other mounds by the geometry of their domal shapes. They are overlain by 0.5 to > 1 meter of eolian sand and silt. The aeolian deposits are capped by soil with moderate horizon development (Crowe et al. 1992a).

Lobate flows of blocky aa lavas were extruded from at least 11 distinct sites at the flanks of the north-northeast-trending fissure (Fig. 2.9). These lava flows were extended distances of only a few tens to several hundreds of meters from their sources. They erupted as unusually viscous, basaltic lavas that formed blocky aa lava flows directly upon extrusion. The lavas that spilled off the flanks of the scoria mounds were highly-disrupted by flowing down the slope of the scoria mounds. They slid, in partially solid form, down the slopes exposing steeply upturned, internal flow foliations and the massive interior lobes of the aa flows. Several of the lavas at the northeast edge of the fissure (Fig. 2.9) formed large flow masses with distinct lobate forms. These extruded down relatively low angle sand ramps exposed locally beneath the lava flows.

A lava flow lobe of the Ql_{4a} was dated by the U-Th method at 150±40 ka (Crowe et al. 1992a). Conventional K-Ar whole rock ages of the same Ql_{4a} lava lobe are 188±22 ka for the weighted mean and 139±68 ka for the mean of three replicate samples (Turrin et al., in press). $^{40}Ar/^{39}Ar$ age determinations of splits of the same sample yielded a weighted mean of 217±64 ka and mean of 153±110 ka (Turrin et al. 1991).

<u>3. The Northeast Lava Unit.</u> The youngest lava unit of the Lathrop Wells center is the Qs_3/Ql_3 unit. This sequence of lava flows and minor scoria deposits crops out along the east perimeter of the center, about 1 km from the main scoria cone (Fig. 2.9). The Ql_3 lavas were extruded from numerous sites along a northwest trending fissure (Qs_3) marked by local accumulations of scoria deposits that form sand-covered scoria mounds. The fissure is exposed only along its northwest end (Fig. 2.9). It is inferred to extend further to the southeast but has been buried beneath its own lava flows.

The Ql_3 lavas form a near-continuous lobate sheet of flows extending for a maximum length of 2.1 km and a maximum width of 0.9 km (Fig. 2.9). The flows are locally covered by a small field of active sand dunes. The Qs_3 flows buttress against topography formed by the Qs_4 scoria mounds and are presumed to postdate these deposits. The Ql_3 lavas overlie the Ql_5 lavas (Fig. 2.9). Detailed examination of the Qs_3 lavas show that they are not formed of a single lava flow. Instead, the sheet is composed of numerous partly coalesced small lobate lava flows similar in morphology to the Ql_{4b}, Ql_5 and Ql_6 lavas.

One stratigraphic discreprency remains for the Ql_3 lava unit. The base of the lava flow is exposed locally in a wash at the north end of the outcrop area of the unit. It overlies thin pyroclastic surge deposits that could be correlative with the large pyroclastic surge unit of the main cone (chronostratigraphic unit two). Alternatively, the surge unit may represent local hydrovolcanic deposits. Insufficient petrologic data have been obtained from the surge deposits to test correlations. If the former correlation is verified, the Qs_3/Ql_3 lava would be included in chronostratigraphic unit two and would postdate the oldest eruptions of the main cone. Further field work is planned to test the different stratigraphic models.

The Ql_3 lavas have been dated at about 239±189 ka by the conventional K-Ar method (mean of all age determinations reported in Turrin et al., in press). Turrin et al. (in press) reported a weighted mean of the K-Ar age determinations of 137±37 ka, but this number was obtained by discarding the results of one sample set. Turrin et al. (1991) reported an age of 183±21 ka for the Qs_3 lavas based on $^{40}Ar/^{39}Ar$ age determinations. However, this age was reported as a weighted mean of both Ql_4 and Ql_3 samples. Moreover, four samples were discarded from the data set without rejection criteria. The mean age of the $^{40}Ar/^{39}Ar$ age determinations for the Ql_3 data set using the published values of Turrin et al. (1991; their Table 1) is 277±234 ka. The mean age of the sample set becomes 182±97 ka if the four discarded samples are removed from the data set (these samples are identified as outliers using standard statistical tests). The reported age of unit Ql_3, based on an isochron age from Ar/Ar step-heating spectra is 107±33 ka (Turrin et al. 1992).

Champion (1991) and Turrin et al. (1991) described paleomagnetic data showing that the Ql_3 and Ql_4 lavas have similar field magnetic directions. Moreover, geochemical data suggest the subunits are related (Perry and Crowe 1992). These combined data provide a reasonable basis for correlating the K-Ar radiometric age determinations for the two lava subunits. The mean age of the combined subunits based on $^{40}Ar/^{39}Ar$ age determinations is 129±77 ka. Cosmogenic He ages for the Ql_3 unit are 65±7 and 73±9 ka. He ages of the Ql_{4b} lavas are 4±85 and > 49 ka. These are believed to be minimum ages because of the proximity of the dated lavas to the main cone. The lavas adjacent to the main cone may have been covered initially by pyroclastic surge deposits. A thermoluminescene age determination for sediments exposed beneath the Ql3 lava yielded ages of 25 to 30 ka (Crowe et al. 1992a). These ages appear discordant with the ages based on other methods.

B. Chronostratigraphic Unit Two

The second chronostratigraphic unit of the Lathrop Wells center comprises four subunits. These include, from probable oldest to youngest, pyroclastic surge deposits erupted from the main cone (Qs_{2c}) and exposed north and northeast of the main scoria cone, the northwest trending fissure and vent spatter at the east base of the cone (Qs_{2b}), scoria deposits marking satellite cones at the south flank of the main cone (Qs_{2d}), and the scoria deposits of the main cone (Qs_{2a}; see Fig. 2.9). There are no identified lava flow units in chronostratigraphic unit two.

Pyroclastic surge units were erupted from the main scoria cone of the Lathrop Wells center probably during the early stages of development of the cone and form subunit Qs_{2c} of chronostratigraphic unit two. They crop out extensively northwest and west of the main scoria cone (Fig. 2.9). Thick deposits of subunit Qs_{2c} are present in the subsurface beneath aeolian sands and silt north of the main cone. Detailed geologic mapping and trenching of the pyroclastic surge deposits show that they overlie Qs_4/Ql_4 lavas north and northeast of the main cone. The pyroclastic surge deposits overlie the Ql_{4b} lava in trench LW-1. Here the upper clinker surface of the lava shows development of carbonate coatings along fractures at the edges and bottoms of lava blocks. The overlying pyroclastic surge deposits contain no evidence of carbonate coating. This requires a time break between emplacement of the Ql_{4b} lava flow and subsequent deposition of the pyroclastic surge deposits.

The pyroclastic surge unit was probably derived from the main cone. This conclusion is based on two observations. First, the pyroclastic surge deposits are present in outcrops on the north and northwest circumference of the main cone. The proximity of the deposits suggest they were derived from the main cone. The thickest accumulations of the pyroclastic surge deposits occur north and northwest of the main cone. This locally reflects channeling of the pyroclastic surges in pre-eruption topographic lows but the phreatomagmatic eruptions that produced the deposits may have been deposited preferentially by north and northwest-directed blasts. Second, the volumes of the surge deposits are sufficiently large that there should have been a tuff ring formed during their eruption. The absence of such a volcanic landform is enigmatic. The preferred explanation for the absence of a tuff ring is that it was formed early in the development of the main cone and was buried by subsequent scoria-eruptions (Vaniman and Crowe 1981). The pyroclastic surge deposits have not been dated directly.

The northwest-trending fissure system forms subunit Qs_{2b}. It consists of individual and paired spatter and scoria mounds formed along the length of the fissure. The unit is exposed for a distance of 1.8 km at the east base of the main cone (Fig. 2.9). The Qs_{2b} fissure is overlain by the scoria-fall deposits of the main cone and therefore predates the final eruptions of the main scoria cone. The spatter and scoria mounds of Qs_{2b} show minimal erosional modification. There is a direct correlation between the structure of the mounds and topography. This is the primary basis for contrasting in the field, the scoria units of chronostratigraphic units two and three.

The age of the Qs_{2b} fissure deposits has not been determined with certainty. Turrin et al. (1991) lump the unit with the other deposits of chronostratigraphic unit two. They reported an age of 116±13 ka (weighted mean) for chronostratigraphic unit based on conventional K-Ar age determinations (note however, that these ages include age determinations for the Ql_5 lavas which are in chronostratigraphic unit three). The mean for the same data set of conventional K-Ar age determinations of chronstratigraphic unit two is 21±486 ka. The $^{40}Ar/^{39}Ar$ age determinations for samples that probably were collected from the Qs_{2c} fissure are 14±945 (weighted mean; Turrin et al. 1991). The mean for the same data set is 129±77 ka. No other age determinations have been obtained for this subunit.

Subunit Qs_{2d}, consists of satellite scoria deposits located south of the main cone (Fig. 2.9). These deposits have been extensively modified by quarrying activity at the volcanic center. They consisted originally of a probable cluster of small satellite scoria cones forming ashort, north-south alignment. However, the deposits associated with the vents have been removed almost entirely by commercial quarrying. The remaining deposits are resistant necks composed of agglutinated spatter. The necks are the probable conduits for the original scoria cones. The fine-grained and non-agglutinated deposits that made up the outer walls of the satellite cone have been removed by quarrying. A local prominent black tephra fall deposit with thin interbedded, pyroclastic surge units is exposed in quarry cuts on the east, and southwest side of the vent conduits of unit Qs_{2d}. These deposits cannot be traced to the vent conduits. These were probably derived from the satellite cones because they flank and obtain maximum thickness adjacent to the conduits. Because of extensive quarrying, the stratigraphic identity of these deposits cannot be established with confidence at all locations. We are attempting to develop field, petrographic and petrologic criteria for separating the units.

No age determinations have been obtained for subunit Qs_{2d}. Champion (1991) reported field magnetic directions for two Qs_{2d} vents that are reported to match the Qs_{2a} and Qs_{2b} subunits and are different from the underlying lava flow units of chronostratigraphic unit one. However, the field magnetic measurements documenting the identification and discrimination of subunit Qs_{2d} have not been published.

The scoria deposits and the scoria-fall sheet of the main cone form subunit Qs_{2a}; Fig. 2.9). These deposits form a scoria cone with several unique features. First, the cone is unusually large (Crowe et al. 1983a). Second, there were no lava flows erupted from the main cone. Third, the cone is composed of relatively fine-grained, highly vesiculated scoria with a paucity of large bombs. There is no agglutination of the scoria-fall deposits exposed through the complete section of deposits in the quarry cliffs at the south end of the cone. The cone must have been built from high energy lava fountains and Strombolian explosions that fragmented the melt and cooled the scoria clasts below magma annealing temperatures prior to accumulation around the vent.

The Qs_{2a} deposits overlie deposits of the pyroclastic surge subunit, and the northwest-trending fissure subunit. They have not been observed in contact with the scoria and tephra units of subunit Qs_{2d}. The deposits also mantle all the lava flow units of the center. Turrin and Champion (1991) show sample sites for K-Ar age determinations for the main cone (samples TSV-283 and TSV-129) but do not report results. Wells et al. (1990) have argued that the main cone may be as young as late Pleistocene or Holocene based on a comparison of geomorphic and soil data for the Lathrop Wells cone with the Black Tank cone in the Cima volcanic field. Crowe et al. (1992) reported cosmogenic He ages on three sets of bombs collected from the summit of the cone. These are respectively, 25, 25, and 45 ka.

An additional sample of a large bomb collected between 10-20 m below the crest yielded an age of about 36 ka. This bomb was aggulinated to surrounding scoria and projected several tens of cms above the modern cone surface. It appears impossible for this bomb to ever have been covered by more than a few tens of cms of scoria. This is based on the exposure geometry of the bomb, the steepness of the cone slopes (29) and the minor geomorphic modification of the cone-slope surfaces (Wells et al. 1990). We conclude, based on combined cosmogenic He ages and geomorphic constraints, that the cone age is about 40 ka.

The main cone overlies unconformably the erosional surface developed on the Qs_{4b} scoria deposits (Fig. 2.11).The contrasting degrees of erosional modification of the scoria deposits of chronostratigraphic unit three compared with the main cone suggest the main cone must be younger by at least a few tens of thousands of years.

In contrast, Champion (1991) and Turrin et al. (1991) have argued that the main cone and associated subunits of chronostratigraphic unit one are *no more than 100* years younger than the lava flow units. This conclusion is based largely on paleomagnetic studies where the authors report a 4.7 difference in the field magnetization directions for the main cone and associated subunits and the lavas of chronostratigraphic unit one. The reported differences in the magnetization directions is consistent with the contrasting degrees of erosional modification of the respective chronostratigraphic units. *(Note: The cited paleomagnetic correlations included data from scoria and lava deposits of Qs_5 with the volcanic units of the main cone. We assign, in this paper, Qs_5 and Ql_5 to the oldest chronostratigraphic unit (unit three) based on field, geomorphic, and petrologic criteria. The published form of the paleomagnetic data is inadequate to determine the stratigraphic assignment of the Qs_5/Ql_5 units).*

There are several constraints concerning both the paleomagnetic data and stratigraphic and chronological interpretations based on the paleomagnetic data. First, samples for paleomagnetic studies of chronostratigraphic unit two were collected from both agglutinated and non-agglutinated scoria deposits (Turrin et al. 1991). Some of the samples may be marginally suitable for reliable determinations of field directions (Holcomb et al. 1986). In addition, the sample sites may have markedly different measurement precision. Discrimination of the chronostratigraphic units can only be demonstrated through presentation and analysis of demagnetization data and statistical information for individual sites. Second, the cone summit is formed primarily of non-agglutinated spatter. There is only a small population of mostly non-agglutinated bombs that could record satisfactorily the field magnetization directions. The cone summit is the highest topographic point in the area. Samples collected from the summit for paleomagnetic studies are highly susceptible to modification from exposure to lightning strikes. Difficulties in measuring the field magnetizations because of high intensity lightning effects were noted for samples collected from even the low-standing lava flows (Crowe et al. 1992a). Third, the summit eruptions of the main scoria cone were formed partly by hydrovolcanic eruptions. This interpretation is based on the local presence of fine-bedded, partly palagonitized ash (Crowe et al. 1986; Wholetz 1986) and cauliflower-shaped bombs (Fisher and Schminike 1984) in the summit

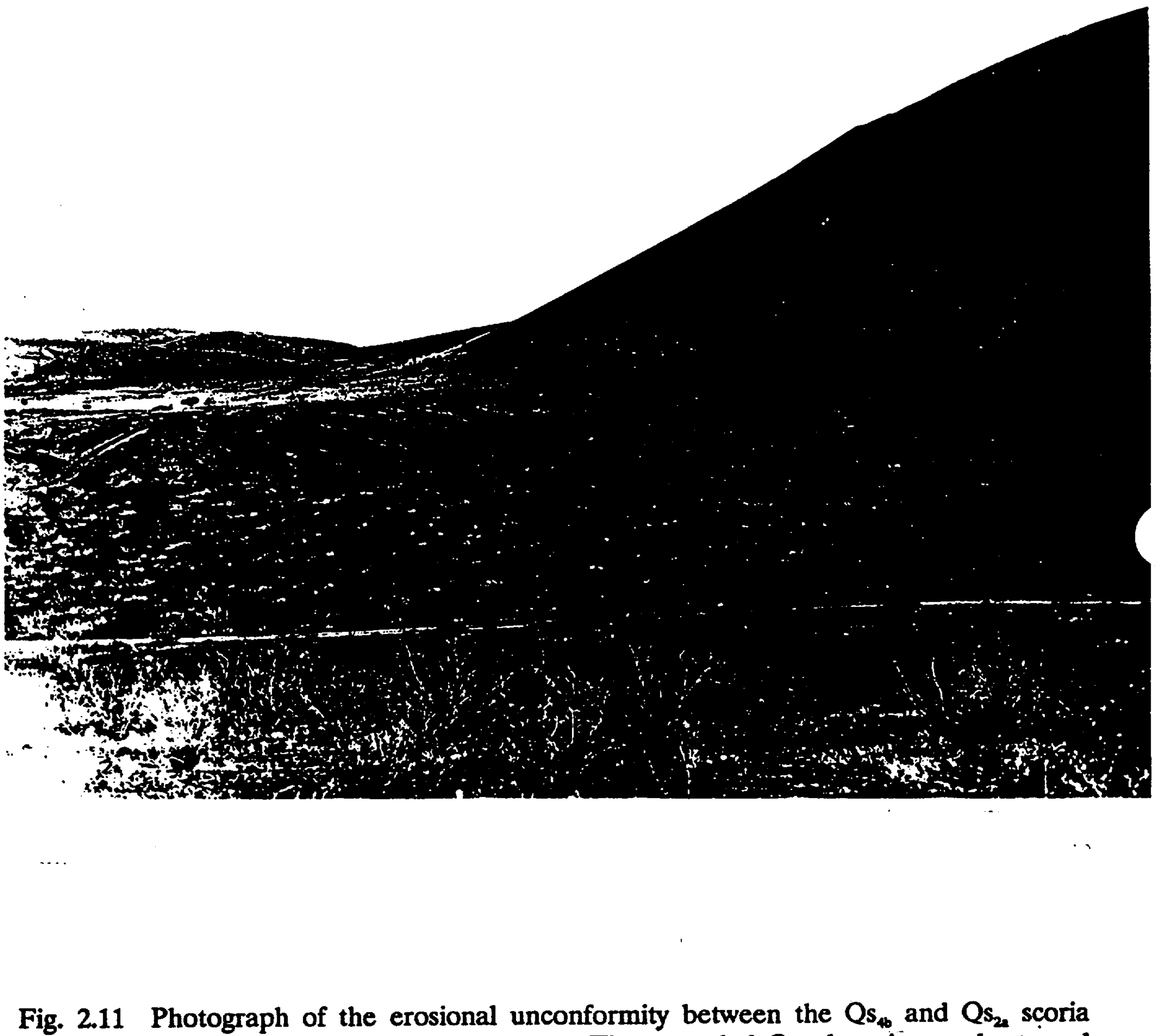


Fig. 2.11 Photograph of the erosional unconformity between the Qs_{4b} and Qs_{2a} scoria deposits on the north side of the main cone. These eroded Qs_{4b} deposits can be traced beneath the Qs_{2a} deposits which form the north flank of the main cone. The north flank of the cone is virtually unmodified by erosion necessitating a time gap between the formation of the two volcanic units.

deposits. These deposits, unless carefully screened to eliminate sampling of hydrovolcanic clasts, are probably unsuitable for paleomagnetic studies. Finally, it is difficult to use paleomagnetic data to constrain differences in the ages of volcanic units. The measured field magnetic directions of the center are close to the mean Quaternary magnetic direction (Turrin et al. 1991, 1992; Crowe et al. 1992a; Wells et al. 1992). Even if the main cone and chronostratigraphic unit three prove to be distinct, the different directions can only be used to establish a **minimum** age difference between the units (Turrin et al. 1992; Wells et al. 1992).

C. Chronostratigraphic Unit One

The youngest chronostratigraphic unit, unit one, is not shown in Figure 2.9 because its outcrop distribution limited to one outcrop. The deposits consist of thin tephra beds separated by soil with weak horizon development and occur only in a small area of quarry-cliff exposures south of the main cone (Wells et al. 1990; 1991). These tephra units were correlated initially with a distinctive sequence of plane-parallel bedded, scoria-fall and hydrovolcanic deposits identified in the south quarry wall of the main cone (Crowe et al. 1992a). However, petrologic studies have shown that the tephra units in the quarry do not match the identified scoria units from the main cone. Currently, the source of the tephra units has not been identified. They overlie the scoria-deposits of the main cone.

The presence of the soil deposits **beneath** and **between** the tephra units **at the base of the cone**, requires their separation as a distinct chronostratigraphic unit. While this separation is used herein, there is controversy concerning the origin of the tephra deposits of chronostratigraphic unit one (Whitney and Shroba 1991; Turrin et al. 1992). The basis of the controversy is whether the tephra beds are *primary* (deposited directly from fall-out from eruption columns; Wells et al. 1991) or have been *reworked* by surficial processes. If the deposits are of primary volcanic origin, they record a complex history of intermittent volcanic activity separated by periods of inactivity. The periods of inactivity must exceed several thousands of years to permit the development of horizons in the interbedded soils. Alternatively, if the deposits are reworked, they record episodes of surficial erosion and deposition and do not require multiple volcanic events.

Evidence cited in support of a reworked origin of the deposits include, the presence of aeolian sand or silt in the tephra deposits (Whitney and Shroba 1991) and granulometric data for the tephra beds that are inferred to be inconsistent with a primary origin of the deposits (Turrin et al. 1992). The authors of both papers suggest the deposits were formed from erosion of the main scoria cone of the Lathrop Wells center.

The evidence supporting a primary origin of the beds includes the planar tops and bottom contacts over an outcrop distance of several tens of meters, draping or uniformity of the thickness of the deposits over basal contact irregularities, unsupported fabric of the deposits, and reverse grading reflecting eruption column dynamics (Wells et al. 1991; p. 662).

There are several points of contradictory evidence for a reworked origin of the deposits. First, there is an absence of cross-bedding and bedding lenticularity. The tephra deposits show uniformity of bedding thickness, and no bedding lamination except poorly developed reverse grading. These deposits contrast markedly with the sequence of reworked deposits that overlie the section above the tephra beds (Wells et al. 1990). These reworked deposits are lenticular, locally cross-bedded within discrete channels, and contain supported clasts of basaltic debris with rotated long dimensions. Second, the beds are interpreted as ". . . younger cone-apron deposits formed during subsequent erosion of the cinder cone" (Turrin et al. 1992; p. 556). A key and generally undisputed observation of the characteristics of the main cone of the Lathrop Wells center is the absence of extensive cone-slope erosion and formation of a cone-slope apron (Wells et al. 1990). A further complication is the tephra deposits are located several tens of meters from the base of the main cone, **which has no cone-slope deposits.** The only way the tephra beds could represent cone-slope deposits would be if the south part of the cone (which has been removed by quarrying) was, in contrast to the rest of the cone, significantly eroded. To investigate this unlikely possibility, historic photographs of the south cone exposure have been obtained. These photographs were taken in the 1930's prior to any modification of the cone by quarrying (Fig. 2.12). There is no evidence in the photograph of extensive cone-slope erosion of the south cone wall that would be required to form **cone-slope apron deposits tens of meters from the base of the cone.** Multiple lines of evidence strongly suggest that it is physically impossible for the tephra deposits to be cone-slope deposits. Third, the presence of aeolian silt and sand in the tephra beds are not inconsistent with a primary origin of the deposits. This material was introduced as a wind-blown constituent during soil pedegenesis. It is precisely the presence and formation of soil horizons in this material that requires time intervals between the tephra-fall events. Granulometric analyses of undisputed scoria-fall deposits with soil at the Lathrop Wells center and other Quaternary basalt centers in the southwest United States overlap with the grain-size distribution curves of Turrin et al. (1992).

The lowermost soil beneath the tephra beds in the quarry deposits has been dated by the thermoluminescence method (TL) at 9.9±0.7 ka (Crowe et al. 1992a; Wells et al. 1992). The TL ages of soil beneath the reworked sequence and the uppermost tephra bed are about 3-5 ka (Crowe et al. 1992a), consistent with the stratigraphic section of the quarry exposures (Wells et al. 1990, 1991). If these age determinations correctly record the chronology of primary volcanic activity, it requires an unusually long and complicated eruptive history of the Lathrop Wells center. While this eruptive history is somewhat unexpected based on historic and geologic studies of small volume basalt centers (Wood 1980; Wood and Kienle 1990), it does appear supported by field geologic studies of the center (Crowe et al. 1992a). Additional exposures of the quarry section will be obtained by trenching and these exposures may help resolve the controversies concerning the origin of the deposits. A primary remaining concern is the source vent of the tephra units have not been obtained. However, we obtained permission to work in the quarry area only in the last six months.

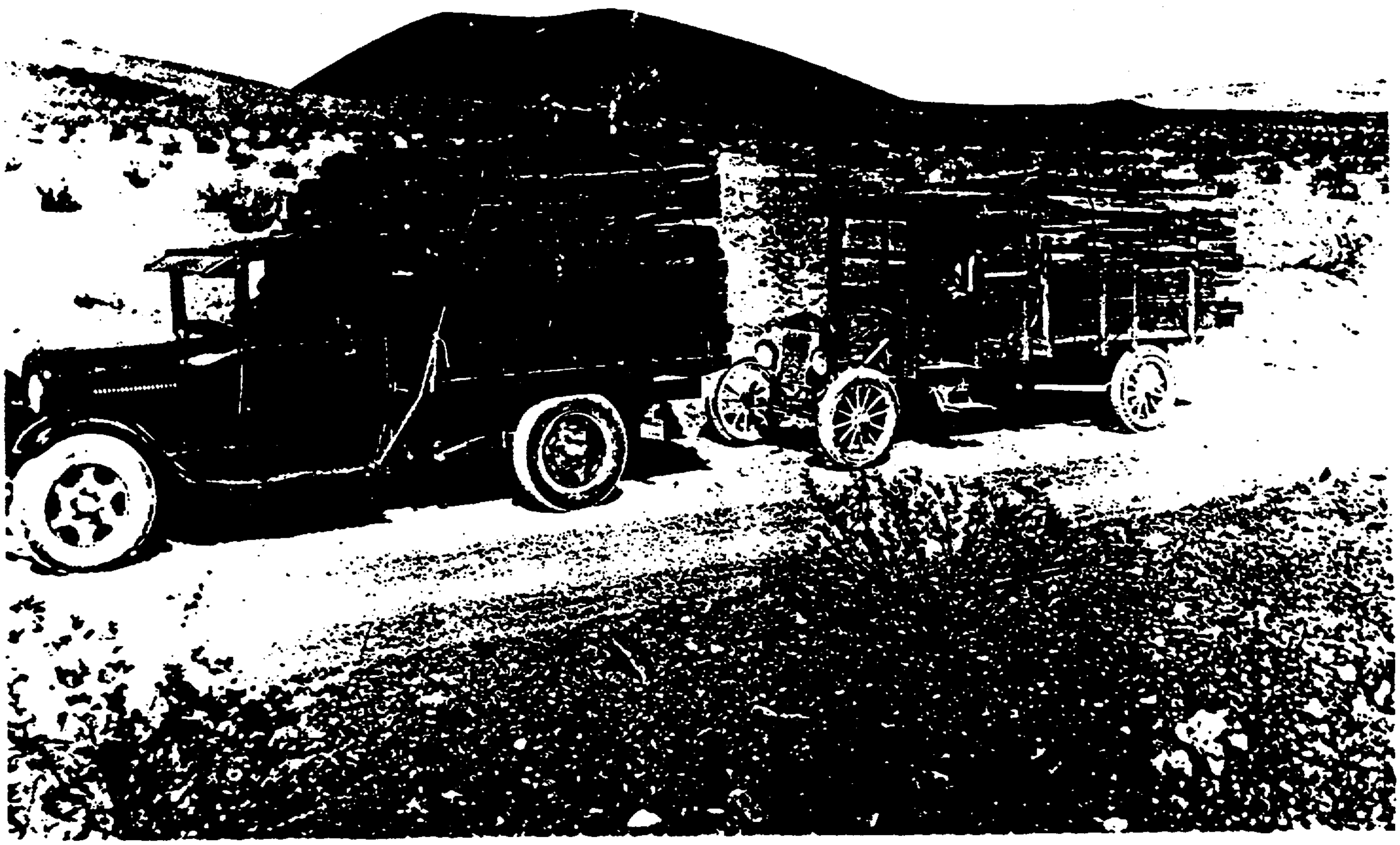


Photo courtesy of
Jack Crowell, Beatty, NV

Fig. 2.12 Historic photograph of the south flank of the Lathrop Wells volcanic center. The photograph was taken before initiation of quarrying activity at the center and shows the geomorphically unmodified south flanks of the main cone.

D. Geochronology Studies of the Lathrop Wells Center

The Lathrop Wells volcanic center has been the subject of the most comprehensive geochronology studies of all the Pliocene and Quaternary volcanic centers of the Yucca Mountain region, and perhaps of any Quaternary basaltic volcanic center. The center has proven to be the most problematic of all centers to date by conventional geochronology methods, a partial result possibly of the level of detail of study using multiple, and in some cases, developmental geochronology methods (Crowe et al. 1992a). The origins of the controversies are differences in interpretation of the age of the center (Turrin et al. 1991; 1992; Wells et al. 1992) and differences in opinions of what constitutes a conclusive data set (Crowe et al. 1992a). We have chosen, because of these problems, to apply a variety of largely independent geochronology methods. It is important to establish the age of the Lathrop Wells volcanic center with an acceptable degree of confidence in order to apply this information to volcanic risk assessment studies for the potential Yucca Mountain site. Increased confidence in the results of chronology studies will be obtained if there is convergence in the age determinations using independent chronology methods. We currently have not established the age of all units of the Lathrop Wells center. However, current data support a model of multiple, time-separate eruptions at the center (Crowe et al. 1992a). The ages of the lava units of chronostratigraphic unit three are bracketed in the interval of 70 to 140 ka. The age of the main scoria cone of the center is probably > 40 ka. The existing geochronology data do not conclusively rule out the cone being as old as the lava flows (Poths and Crowe 1992). Geomorphic and soils data suggest the cone is significantly younger than the lava flow units. We are still in the process of evaluating the significance of TL age determinations that support a late Holocene age for small volume tephra units present only on the south flank of the center.

1. K-Ar Age Determinations. A large number of conventional K-Ar age determinations of whole rock samples of basalt from the Lathrop Wells volcanic center have been obtained from multiple analytical laboratories (Sinnock and Easterling 1983; Turrin and Champion 1991; Turrin et al. 1991). These age determinations show a wide range in measured ages (negative ages to > 700 ka), generally large analytical errors for individual measurements and poor reproducibility between analytical laboratories (Crowe et al. 1992a). The most comprehensive summaries of the results of the whole rock K-Ar age determinations are by Turrin and Champion (1991), and Turrin et al. (in press). They obtained replicate K-Ar ages of whole rock samples collected at separate sites in the Ql_5, Ql_4, Ql_3, and Qs_2 units. The measured ages of their samples range from 34 to > 650 ka. Turrin and Champion (1991) reported a weighted mean of 116±13 ka for their Ql_5 unit (a combination of Ql_5, Qs_5, Qs_{2b} and Qs_{2a} units) and 133±10 ka for their Ql_3 unit (a combination Ql_3/Qs_3 and Ql_4/Qs_4 units).

There are two concerns with these reported ages. First, the combination of units does not correspond to the stratigraphic subdivisions based on the field and trenching studies. Second, the weighted mean is not an acceptable method for calculating the age of the units because the data are non-gaussian (Crowe et al. 1992; Wells et al. 1992) and there is evidence of contamination of the samples (bias toward older ages).

We have attempted to evaluate the conventional K-Ar age determinations of Turrin and Champion (1991). Their measured ages are grouped by the defined volcanic stratigraphic units used in this report. The age determinations were not collected under an approved Quality Assurance program and cannot be used for the Yucca Mountain Site Characterization Project. However, the age determinations are considered to be of high quality analytically and can be used to guide interpretations of the age of the volcanic center. Additional K-Ar age determinations are being obtained under a fully qualified Quality Assurance program and will be used to verify the non-qualified K-Ar data.

Sixteen whole rock K-Ar age determinations were obtained for chronostratigraphic unit three (3 age determinations for subunit Ql_{4}, 9 age determinations for subunit Ql_{3}, and 4 age determinations for subunit Ql_{5}; Turrin et al. in press). Descriptive statistics for the age determinations are listed in Table 2.1. The ages range from a minimum of 37±29 ka to a maximum of 571±360 ka. The mean of the data set is 214±151 ka (one σ). The sample variance is large (22719) and there are several indicators of a non-normal data distribution.

Table 2.1: Descriptive Statistics for Conventional K-Ar and $^{40}Ar/^{39}Ar$ Data Sets of Turrin et al (1991). Ages in ka.

	Conventional K-Ar	Conventional K-Ar (outliers removed)	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar$ (outliers removed)
N	16	12	32	25
Min	37	37	-20	42
Max	571	211	947	311
Range	534	174	967	269
Mean	214	134	231	161
Median	154	147	170	147
Variance	22719	2717	40082	4545
Standard Deviation	150	52	200	67
Standard Error	38	15	35	13
Skewness	1.13	-0.49	2.1	0.5

These include the mean (214 ka) is greater than the median (154 ka) and the data are positively skewed (1.13). The non-normal distribution of the data is shown on Figure 2.13, a probability plot of the data set. The plot shows a nonlinear data distribution, with significant deviation in the upper tail (older ages). The data set was evaluated using the box, and stem and leaf diagrams. These plots show the presence of outlier data points in the data set. The outliers are samples collected from a flow lobe of subunit Ql_3. This flow is notable in the field by the presence of abundant fragments of Cenozoic tuff derived from either the Timber Mountain or Paintbrush Tuffs. These samples were judged to have a high possibility of being contaminated and were removed from the data set. The revised data were rerun through successive iterations using the statistical routines. All outlier points were removed from the data set using standard statistical methods for identification of outliers. Twelve K-Ar determinations remain after this analyses. Descriptive statistics for the edited sample set are listed in Table 2.1. The minimum age of the edited sample subset is 37±29 ka (unchanged from the original data set) and the revised maximum age is 211±340 ka. The sample mean is 137±52 ka. The probability plot is near-linear (Fig. 2.14). The variance of the sample set is reduced by almost an order of magnitude from the original data set and the mean is close to but slightly smaller than the median. The data set with outliers removed shows negative skewness (-0.49). The mean of 137 (±52 one σ and 104 two σ) is an acceptable approximation for the age of chronostratigraphic unit three with one caution. The data set, even with outliers removed, shows a positive correlation between percentage radiogenic Ar and measured age of the sample (Fig. 2.15). This positive correlation along with the field evidence indicating contamination by Miocene tuff containing high K, suggests the whole rock age determinations are probably biased toward older ages. The real age of the chronostratigraphic age may be somewhat younger than the mean of 137 ka.

2. $^{40}Ar/^{39}Ar$ Age Determinations. Turrin et al. (1991) report weighted means of 183±21 ka for unit Ql_3, 138±54 ka for unit Ql_5 and 149±45 ka for unit Qs_5 for samples from the Lathrop Wells center that were analyzed using the $^{40}Ar/^{39}Ar$ method. These age determinations were not obtained under approved YMP quality assurance requirements. However, they are again judged to be good data analytically and useful for constraining the age of the Lathrop Wells center. However, the same interpretative concerns exist for these samples as for the conventional K-Ar age determinations. Specifically, the chronology data are combined for units that do not correspond to the chronostratigraphic units. Additionally, the data distribution is non-gaussian and there is evidence of contamination of some of the samples. However, in this case, Turrin et al. (1991) note that some of the samples are contaminated and exclude these age determinations from their age assignments.

The ages of chronostratigraphic unit three range from -20±263 to 947±24 ka. The mean age is 232±200 ka (Turrin et al. 1991). Descriptive statistics for the sample set are listed in Table I. The data for the sample set are, like the conventional K-Ar data, non-gaussian. The mean (232 ka) is greater than the median (170 ka). The data are strongly skewed positively (2.1) and there is large variance. The probability plot (Fig. 2.16)

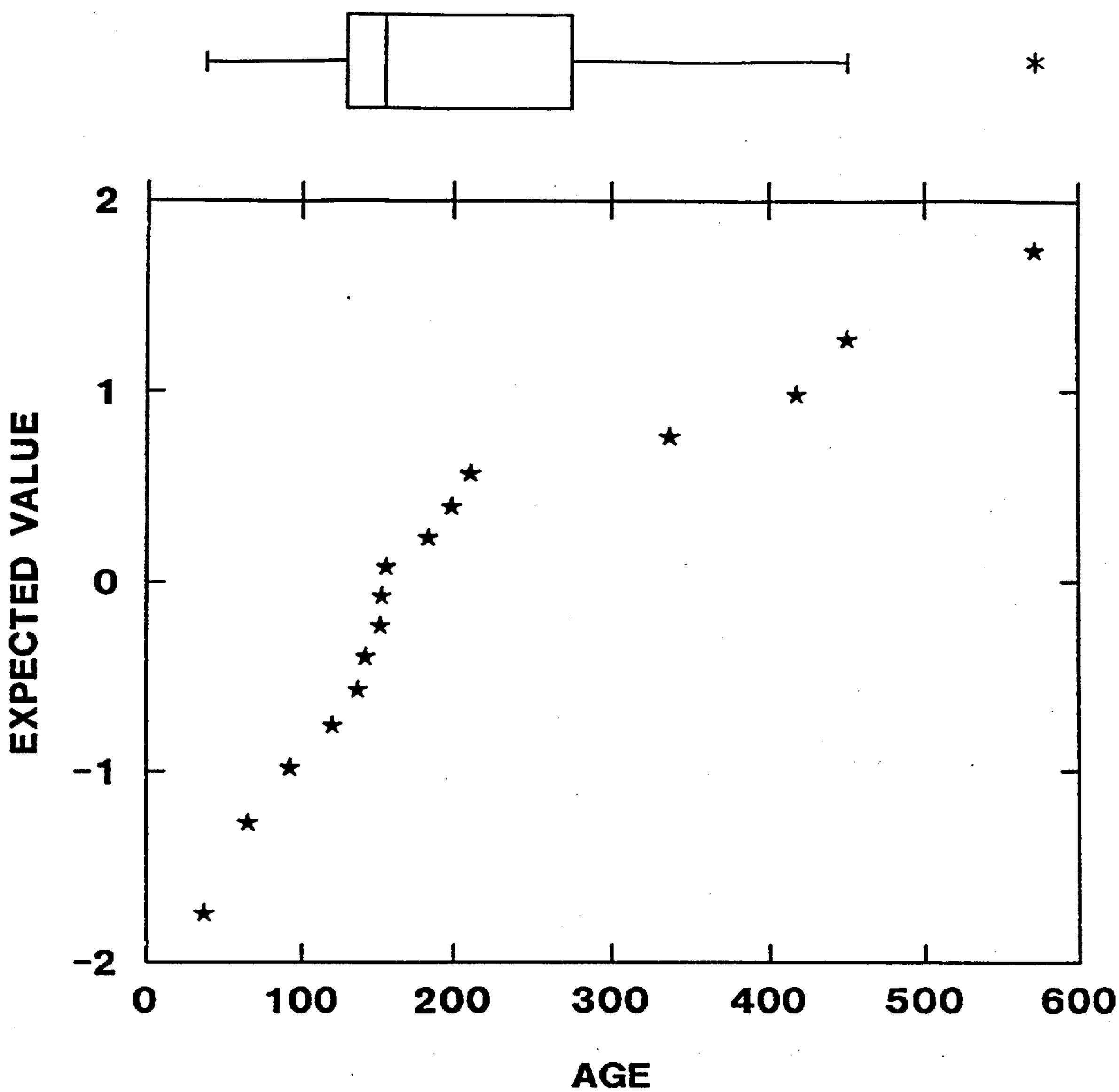


Fig. 2.13 Probability and box plots of the conventional whole rock K-Ar data of Turrin et al. (1991). The data are non-linear on the probability plot indicating a non-gaussian distribution. This is verified by the box diagram which shows non-symmetrical hinges and the presence of outliers. The median of the box diagram is marked by the center vertical line. The median splits the data in half, and the hinges split the remaining halves in half. The whiskers or end lines of the box diagram bound the range of data which fall within 1.5 Hspreads, where Hspread is the interquartile range. Values outside the whiskers are plotted with asterisks and are considered to be outliers. The scale of the box diagram is the same scale as the x-axis of the probability plot. Plots and statistical routines are from SYSTAT version 5.0 (Wilkerson 1990).

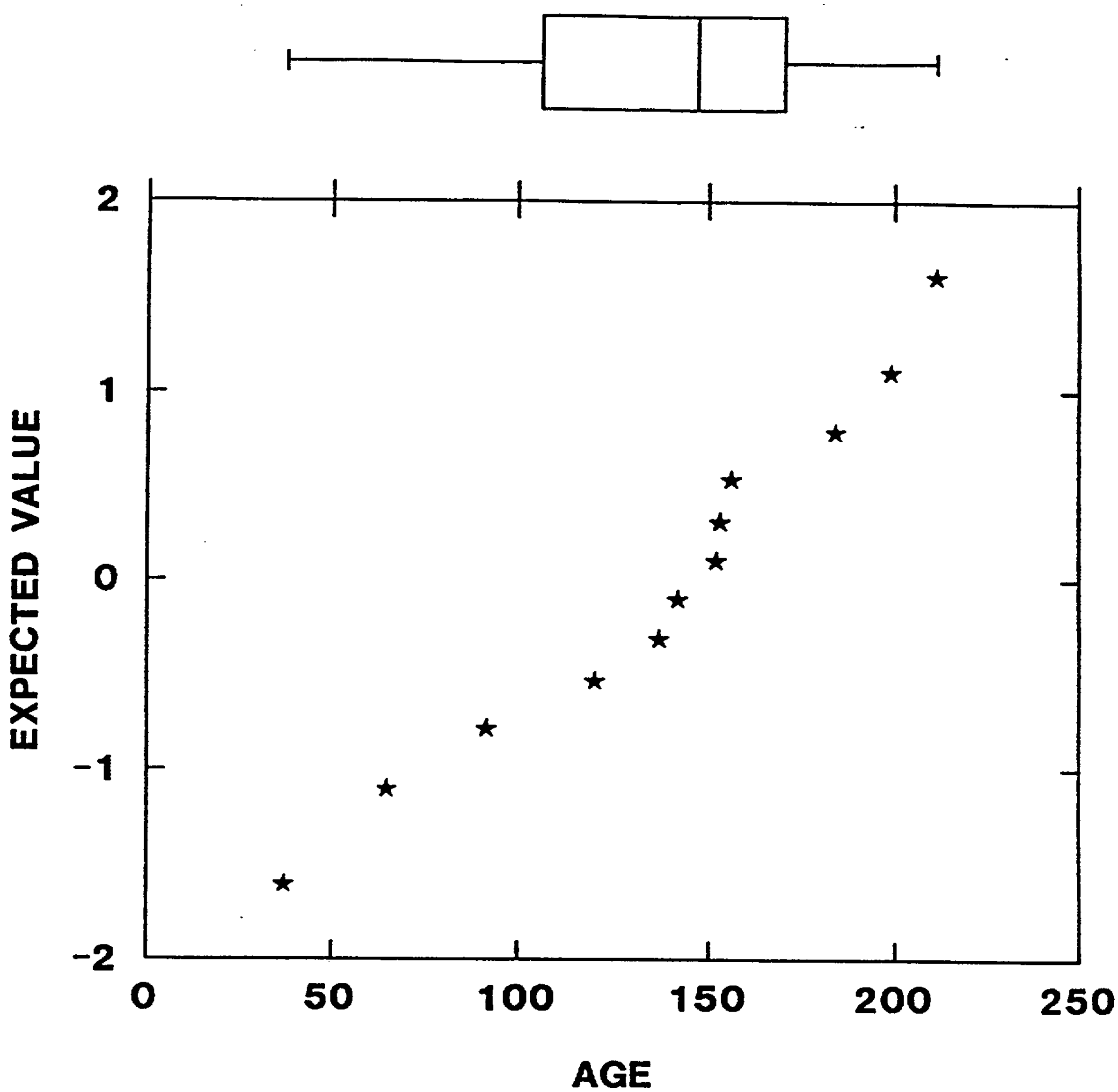


Figure 2.14 Probability and box plots of the conventional whole rock K-Ar data of Turrin et al. (1991a) with outliers removed. The data show improved linearity on the probability plot and near-symmetrical hinges on the box diagram. The features of the box diagram are the same as for Fig. 2.13. The scale of the box diagram is the same as the scale of the x-axis of the probability plot.

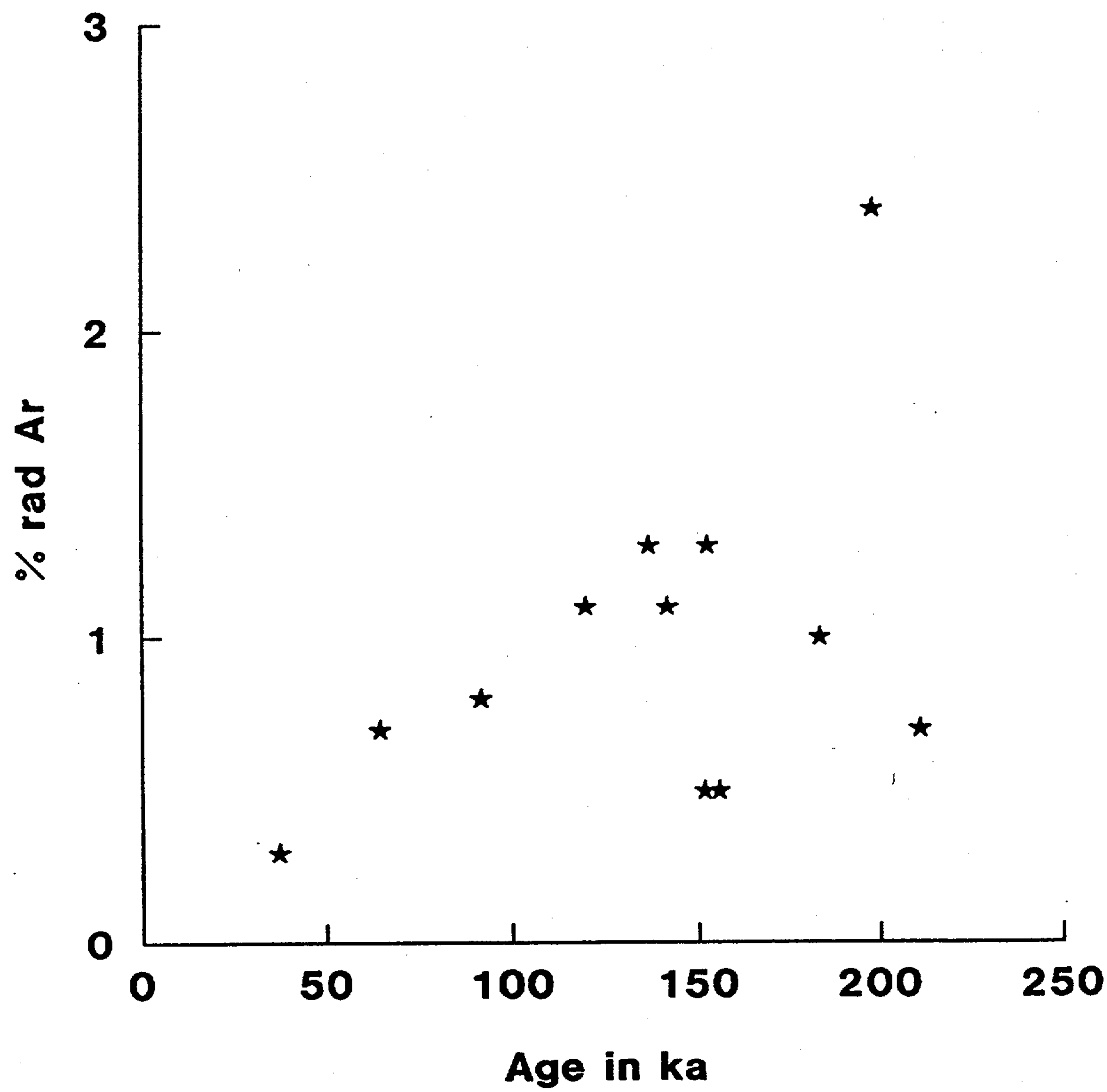


Fig. 2.15 Plot of percentage radiogenic Ar versus age of the conventional K-Ar age determinations of Turrin et al. (1991a). The data show a positive correlation between age and % radiogenic Ar suggesting the age determinations are contaminated and biased toward older ages. The plot uses the same data set as 2.14 so the effect of outliers is removed.

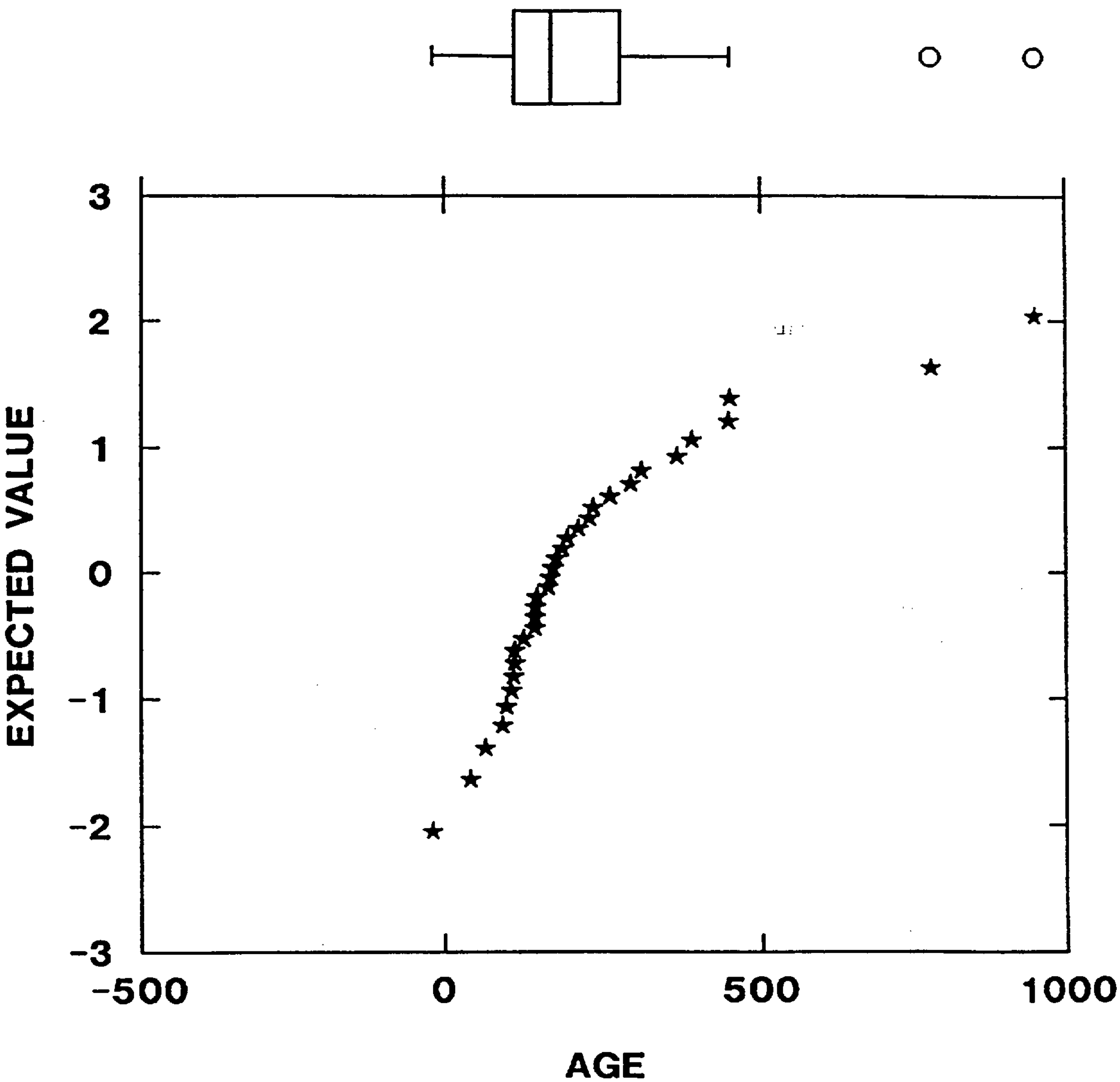


Fig. 2.16 Probability and box plots of the $^{39}Ar/^{40}Ar$ data of Turrin et al. (1991). The data show a nonlinear distribution on the probability plot indicating a non-gaussian distribution. The box diagram shows non-symmetrical hinges and the presence of far outside values or outliers. The markings of the box diagram are the same as Figure 2.12. The scale of the box diagram is the same as the scale of the x-axis of the probability plot.

shows the data are non-normal with an upper tail skewed toward older ages. The box, and stem and leaf diagrams identify through successive iterations, four samples as outliers. These are the same four samples which were noted as contaminated by Turrin et al. (1991). The samples were removed from the data set and the data set was rerun through the statistical routines until all identified outliers were removed. Descriptive statistics for the revised data set are listed in Table 2.1. The revised data show improved linearity on the probability plot (Fig. 2.17). However, the mean still exceeds the median and the data remain positively skewed (0.5). This suggests strongly that the variance in the data set cannot be entirely analytical. The best estimate of the age of the chronostratigraphic unit three from these data is 16267 (one σ) or 162±134 (two σ) ka. However, the revised data set of the $^{40}Ar/^{39}Ar$ age determinations show a positive correlation between percentage radiogenic Ar and age (Fig. 2.18). The $^{40}Ar/^{39}Ar$ data must, like the conventional K-Ar data set, be viewed as providing a maximum age for chronostratigraphic unit three.

Turrin (1992; pp. 226-235) reported preliminary results of $^{40}Ar/^{39}Ar$ step heating data for selected samples of the Lathrop Wells centers. These results show increased abundances of radiogenic Ar and thus are less subject to bias toward older ages from the presence of excess Ar or contamination. The preliminary results show considerable promise for constraining more precisely the ages of the Lathrop Wells center. The revised ages of subunit Ql_3 from the Lathrop Wells center are 104, 123, and 122 ka. Insufficient information was presented to list the analytical errors associated with these measurements. However, Turrin et al. (1992) presented an isochron age of 107±33 ka for unit Ql_3. These ages are consistently younger than the conventional K-Ar and $^{40}Ar/^{39}Ar$ data of Turrin and Champion (1991) and Turrin et al. (1991) and support the interpretation that the latter age determinations are somewhat old because of contamination.

<u>Summary.</u> Conventional and $^{40}Ar/^{39}Ar$ age determinations of chronostratigraphic unit three yield mean ages of about 137±52 (one σ) and 162±67 (one σ), respectively. Field data, the presence of data outliers, the positively skewed data distribution, and the positive correlation between percentage radiogenic Ar and age all suggest the age determinations are biased toward older ages probably from contamination. The presence of excess Ar in olivine phases (Poths and Crowe 1992) is consistent with contamination and indicates that excess Ar could be present in other phases, notably glass, which is a common groundmass constituent. The somewhat older $^{40}Ar/^{39}Ar$ age determinations than the conventional K-Ar analyses may be consistent with a higher degree of fusion of Ar-contaminated groundmass in the former analyses. A potential source of the excess Ar may be from incorporation of lithic fragments of Miocene tuff. These fragments show evidence megascopically of partial melting but the excess Ar introduced into the lava during partial melting may have had insufficient time to degas efficiently before solidification of the lavas. The range of data concerns, and particularly the correlation between radiogenic Ar and age, suggest the K-Ar age determinations may best be viewed as **maximum ages**. Collaboration of this interpretation appears to be provided by the new preliminary results of $^{40}Ar/^{39}Ar$ release spectra for a samples of the Ql_3 subunit (Turrin et al. 1992; Turrin 1992). This method gives

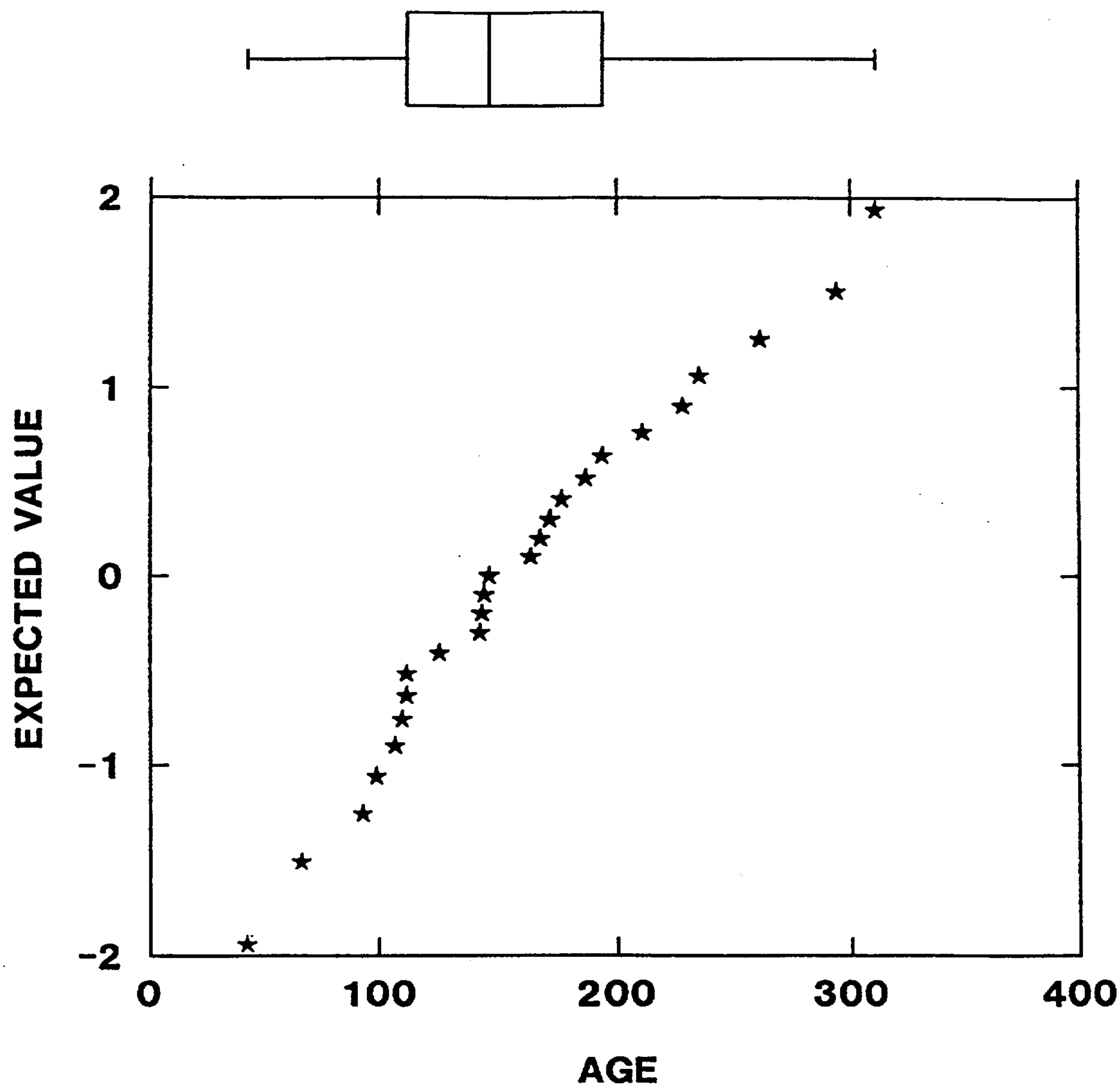


Fig. 2.17 Probability and box plots of the $^{39}Ar/^{40}Ar$ data set of Turrin et al. (1991) with outliers removed. The data show an improved distribution on both the probability and box plots but are skewed toward older ages. The features of the box diagram are the same as Figure 2.13. The scale of the box diagram is the same as the scale of the x-axis of the probability plot.

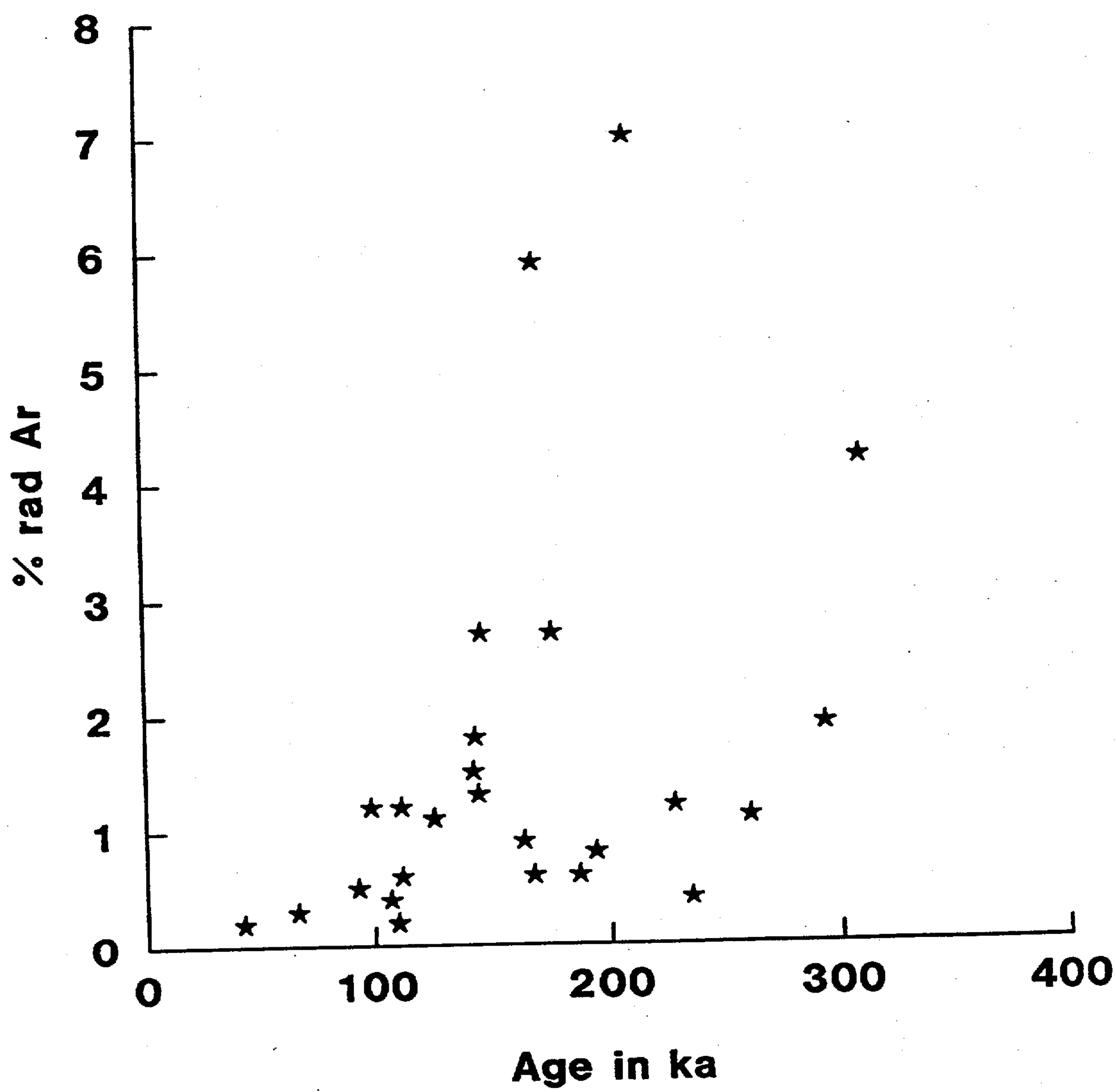


Fig. 2.18 Plot of percentage radiogenic Ar versus age for the $^{40}Ar/^{39}Ar$ age determinations of Turrin et al. (1991). These data, like the conventional K-Ar age determinations, show a positive correlation between % radiogenic Ar and age suggesting the age determinations are contaminated and biased toward older ages.

much higher yields for radiogenic Ar and ages in the range of 104-123 ka. The K-Ar results for chronostratigraphic unit three are consistent generally with stratigraphic and geomorphic data, and most other chronology measurements. There is insufficient information from the K-Ar studies to constrain the ages of chronostratigraphic units two or one.

3. U-Th Disequilibrium Age Determinations. An age of the Ql_4 lava (subunit Ql_{4a}) has been obtained using the U-Th disequilibrium method (Crowe et al. 1992a). The isochron age for this sample, measured by solid source mass spectrometry, is 140±40 ka (two sigma errors). An additional U-Th isochron age has been obtained for subunit Ql_6. This sample yielded an isochron age of 135, +35, -25 ka (two errors). Application of the U-Th method assumes closed system behavior of U and Th and a short residence time (relative to the eruption age of the rock) for the magma in both storage and ascent. Both conditions are probably met by the analyzed samples. The method requires a measurable U-Th fractionation among the minerals or phases that can be separated from the rock. The primary problems with both the Ql_{4a} and Ql_6 samples are the small grain size of the basalt (difficult separations) and the ubiquitous distribution of iron-titanium phases. We were unable, despite considerable laboratory efforts, to obtain separations with a large range of U-Th ratios. However, the reliability of the two U-Th age determinations is re-enforced by their internal consistency, their consistency with K-Ar ages and the stratigraphic constraints for the lavas of chronostratigraphic unit three. The two concerns with the U-Th isochron ages are the small degree of separation of U/Th ratios in the samples and the different disequilibrium observed for the plagioclase and olivine minerals for different grain sizes observed for the Ql_6 sample. The first concern appears unwarranted because of the agreement in the isochron ages measured in two spatially separate, but correlated lavas. The second concern may reflect alteration of the coarser-grained olivine and plagioclase grains by an uranium-rich fluid. Electron microprobe analyses will be conducted of the olivine microphenocrysts microlites to test the suitability of the mineral phases to yield reliable the U-Th disequilibrium ages.

4. Cosmogenic He Surface Exposure Ages. We have estimated the ages of chronostratigraphic units at the Lathrop Wells volcanic center by measuring the accumulation of cosmogenic ^3He in surface subunits (Crowe et al. 1992a; Poths and Crowe 1992). Samples were collected from well preserved, primary flow tops of lava flow subunits of chronostratigraphic unit three. These lavas have been covered intermittently by aeolian sand and pyroclastic surge deposits from eruptions of the main cone. This could result in minimum ages using the cosmogenic He method. To attempt to mitigate these effects, we collected samples from aa spines that projected above the height of active sand deposition. This should reduce the effects of shielding from aeolian sands, but less so for deposition of cohesive, pyroclastic surge deposits. However, the effects of cover of the lavas by the surge deposits is reduced with increasing distance from the main cone. We attempted in the field to identify and sample unmodified, primary lava flow surfaces with good geometrical exposure to the cosmic ray influx.

The measured ages of samples collected from the Ql_5 unit is 65±7 and 739 ka. Samples collected from the Ql_{4a} subunit yield ages of 4±85 and > 49 ka. These samples were collected during the first phases of study before our systematic sampling methods were developed. Additionally, the Ql_{4a} ages may be young because of the proximity of the sampled flow to the main scoria cone where it was covered by pyroclastic surge deposits. Samples collected from subunit Ql_3 yielded cosmogenic He ages of 65±7 and 73±9 ka. The lava flow samples (except the Ql_{4a} samples, as noted above), generally agree within oneσ error. This suggests the three dated lava subunits are about the same age (Poths and Crowe 1992), consistent with their assignment to chronostratigraphic unit three.

Three samples were collected from subunit Qs_{2a} at summit of the main cone. The samples yielded ages of 28±4, 23±4 and 44±5 ka (Crowe et al. 1992a). The samples selected for age determinations were large (0.3 to 0.5 m), aerodynamically shaped bombs that were judged from outcrop exposures to be in place and unlikely to have been moved by processes of erosion. The spread in ages of the bomb samples may indicate that they do not all share a similar surface exposure history. The primary process of concern is aeolian erosion of basaltic ash from the exposed rim of the crater. The Lathrop Wells center has active sand dunes and the wind is channeled and intensified at the cone summit. There is also the possibility of an inherited exposure history for the sample yielding the older He exposure age. It could have been derived (reworked) from the underlying pyroclastic units of chronostratigraphic unit three. The summit deposits were formed by combined hydrovolcanic and Strombolian eruptions. They contain clasts that were probably reworked from preexisting parts of the scoria cone or the underlying lavas. Preliminary petrologic and trace element data for the analyzed bombs suggest however, that they were derived from the same subunit (Qs_{2a}). A fourth bomb sample was collected between 10-20 meters below the cone summit. This bomb was > 1 meeter in diameter. It was agglutinated to surrounding scoria and projected several tens of cms above the cone slope. This geometry combined in the limited geomorphic degradation of the cone slopes suggest the cosmogenic He age should constrain the minimum age of the cone. The measured age is 36±4 ka. We currently argue that the main cone (Qs_{2a}) can be no younger than 40 ka. Thus the present cosmogenic He data suggest but do not require that the main cone is younger than the lava flows of chronostratigraphic unit three.

There are two concerns with the age determinations obtained by the cosmogenic ^3He method. The first is the possible varied surface exposure history of the dated material. Minimum ages will be obtained if there has been erosional removal of deposits originally covering the sampled surface. Second, the calibration of the ^3He surface production rates are still subject to debate and vary significantly with altitude and latitude. Most of the cited helium ages in the western United States are calibrated to one locality (Cerling 1990). The first concern can be constrained by replicate sampling of volcanic surfaces. If the He age determinations are strongly biased toward younger ages, we should obtain a spread of ages for samples collected from multiple sample sites. The lava flows can be no younger than the oldest age determination. Uncertainty in calibration of He ages is estimated to be about 30% (Poths and Crowe 1992).

A secondary finding from studies of the noble gas components of the lavas of the Lathrop Wells center is the presence of excess Ar in olivine (Poths and Crowe 1992).

Crushing of olivine grains released an Ar component with $^{40}Ar/^{36}Ar$ ratios of 371±8 and 328±7 for the Ql_5 and the Ql_3 lavas. These ratios are substantially above the atmospheric ratio of 295 and indicate the presence of ^{40}Ar in excess of that produced by decay of ^{40}K. The presence of excess Ar is consistent with other evidence of contamination of the lava units of chronostratigraphic unit three. Age determinations based on $^{40}K/^{40}Ar$ system require careful evaluation for the potential effects of excess Ar. This is particularly important for analytical methods based on fusion of components with small-grain sizes where groundmass components could be a large percentage of the analyses.

5. Thermoluminescence (TL) Age Determinations. Seven analyses of four different samples have been obtained using the thermoluminescence method. These results are judged to be analytically reliable and reproducible, but must be viewed as preliminary. The TL method has not been used previously in attempts to date soil units for a volcanic center. Analytical methods used for this method are described in Crowe et al. (1992a).

Three samples were collected from buried soils interbedded with tephra deposits in the south quarry wall of the main cone. These samples yielded TL ages of 8.9±0.7, 9.9±0.7 and 8.7±1.0 ka (Crowe et al. 1992a). Soil units overlying the scoria-fall deposits (Wells et al. 1990) yielded ages of 3.7±0.4, 3.7±0.4 and 4.5±0.4 ka. Important features of these TL ages are the reproducibility of the replicate analysis, and the data are in correct stratigraphic sequence. The lowest dated soil samples are interbedded with scoria-fall deposits from chronostratigraphic unit one. They provide age constraints on the youngest eruptions of the center. This presumes the tephra deposits are primary volcanic deposits. The TL ages of soil units overlying the tephra deposits constrain the age of pedogenic processes that post-date volcanic activity.

A second set of TL samples were collected from reworked, volcaniclastic deposits. These deposits were exposed several tens of centimeters from the basal contact of an overlying aa flow lobe of Ql_3. These samples yielded an age of 24.5±2.5 ka (Crowe et al. 1992a). Resampling of and analyses of a second sample yielded a preliminary age estimate of 30 ka site. Thus reproducible, TL ages of the Ql_3 lava unit are significantly younger than the results of other chronology methods. We currently have no reasonable explanation for the age discreprency.

6. Geomorphic Studies. Geomorphic features of the Lathrop Wells volcanic center were described previously by Wells et al. (1990). They equated the geomorphic and pedogenic features of the Lathrop Wells center with a 15 to 20 ka cone in the Cima volcanic field. The close comparison of the centers suggested, by inference, that the youngest eruption of the Lathrop Wells center is no older than 20 ka. These constraints are based on the assumption that the rates of operation of erosion and soil formation are approximately similar between the Cima and Crater Flat volcanic fields. New cosmogenic ^{3}He, and thermoluminescence ages for the Black Tank center in the Cima volcanic field provide increased support for the geomorphic correlation (Crowe et al. 1992). These data support an age of between 9 and 14 ka for the main cone sequences at the Black Tank center. Trenching has demonstrated that the base of the main scoria cone at Lathrop Wells

is flanked by a sand ramp which displays little evidence of mass wasting or colluviation from the cone slopes. This supports the inference that the cone slope is virtually unmodified by erosional processes (Wells et al. 1990). The systematic differences in degree of erosion of volcanic landforms between chronostratigraphic units three and two suggest there is a time difference between the units. The most compelling argument for this time difference is provided by exposures located directly north of the main cone. Here the degraded surface formed on the Qs_{4b} scoria deposits can be traced beneath the virtually unmodified cone slope of Qs_{2a}. These relations appear impossible to explain without a time gap between the two units.

7. Soil Studies. Study of soils on volcanic landforms associated with the Lathrop Wells center show that weakly developed calcic soils have formed in scoria deposits that flank the north and south side of the main cone and on the cone slope (Wells et al. 1990). The surface of the lavas flows are almost completely mantled by aeolian deposits or by pyroclastic deposits. These deposits have only incipient soil development in the upper several decimeters. The primary pedogenic features exhibited by the soils include weakly developed "vesicular A" (Avk) horizons and weakly developed B horizons in which fine sand, silt clay, calcium carbonate, and trace amounts of soluble salts have accumulated. The presence of substantial amounts of quartz and other pedogenic materials (calcium carbonate and sulfates or chloride salts) that are rare or absent in the basaltic tephra unequivocally demonstrates the aeolian origin of most of these pedogenic materials.

The most strongly developed soils have been observed on the erosional surface cut into scoria mound deposits of the Qs_{4b} located northeast of the main cone. These soils have the thickest, most well developed vesicular A horizons in soil observed to date, ranging from 5 to 8 centimeters thick and possessing strong, coarse platy structure with subordinate subangular blocky to prismatic structure. The subjacent Bwk horizons are approximately 8 to 17 centimeters thick, with subangular to blocky structure. These horizons do not, however, exhibit color hues or chromas substantially redder than those of the least altered loamy sandy parent materials or the most recently accumulated materials above the vesicular A horizon. Pedogenesis in the lowest 1 meter of the profile exposed in pits is characterized by the accumulation of moderately thick to thin, largely discontinuous coatings of carbonate, gypsum, and soluble salts. A small amount of pedogenic silica may also have accumulated. The content of these materials diminishes progressively with depth. Only the most incipient coatings can be observed at depths of 1.3 to 1.5 m in the parent scoria materials. A soil observed on the steeper part of the cone slope has a similarly thick, calcareous B horizon, but lacks the well-developed vesicular A horizon.

Soil observed in the sequence of buried scoria units exposed in the quarry on the south side of the center (Wells et al. 1990) are more weakly developed. They exhibit 2 to 4 cm thick vesicular horizons and very incipient, calcareous cambic B horizons. The scoria parent materials have carbonates, salts, and perhaps silica accumulated primarily on the bottoms of scoria fragments.

In contrast, soil formed in sand ramps that flank the cone is very weakly developed. Pedogenesis is indicated primarily by the slight increases in disseminated carbonate with depth and the accumulation of very thin, discontinuous coatings of carbonates and perhaps salts on the bottoms of many of the larger coarse fragments. Scoria fragments in such deposits commonly exhibit thicker and nearly continuous coatings of carbonate. However, the nonsystematic spatial location of the coatings on the fragments as a function of depth show that only a minor volume of material has been derived from higher positions on the cone slope by gravitational forces. Soils on the cone slope, as noted previously, have Bk horizons with carbonate coated fragments. They provide a source for most of the fragments with thick carbonate coatings observed in the sand ramp deposits and distal cone slope sediments and soils.

The medium-and fine-grained sandy deposits of aeolian origin are inferred to bury previously formed vesicular horizons of soils in the scoria deposits. These deposits range from 2 cm to over 1.3 m thick in the sand ramps. They are present below the weakly developed scoria pavement and have little or no soil development. These soil-stratigraphic relations suggest an increase in aeolian activity during the late Holocene, resulting in the deposition of locally thick accumulations of sand. Subsequent to deposition of the sand, geomorphic conditions were presumable sufficiently different to enable the development of cumulic soils. These soils incorporated much finer grained desert loess and formed accretionary cambic B and vesicular A horizons.

Soils formed in scoria deposits or in aprons that flank flows at the Cima volcanic field have also been examined (Wells et al. 1985; Renault 1989; Royek 1991). These soils are generally similar to soil on the flow surfaces. However, the soils formed in scoria deposits associated with the youngest scoria cones in the Cima volcanic field possess relatively weak development of Avk horizons. They do not have B horizons that are as red or thick as those typically observed in the phase 1 soils on associated lavas. This indicates that much of the aeolian material entrapped on surfaces associated with scoria is readily translocated through the highly permeable, open framework scoria to depths of more than a meter by infiltrating soil water. In the lower part of the soil profiles, the initially fragile, glass-coated irregularities and edges of scoria fragments are altered by infiltrating water, as shown by the presence of reddish, brown coatings on the tops of the fragments, the destruction of vesicle edges and spines and the chemical alteration of glass. Pedogenic accumulation of calcium carbonate, salts, and perhaps some amorphous silica primarily on the bottoms of the fragments is a major attribute of these soils. Soil development in cone aprons resembles that observed on flows. Equally, soil development on scoria-cone aprons of older cones is closely similar to observed phase 2 soils, demonstrating the primary role of cumulic pedogenesis on this volcanic landform.

Crowe et al. (1992a) compared the development of soils on volcanic units of the Lathrop Wells volcanic center with studied centers of the Cima volcanic field (Dohrenwend et al. 1986; Wells et al. 1990). They did not propose that pedogenic processes at the Lathrop Wells center are identical to those at the Cima volcanic field. However, there are no indications that the rates or processes of soil formation are substantially different. If aeolian influx has been higher at the Lathrop Wells center, thick deposits of desert loess would mantle stable Pleistocene and Holocene landforms and soils throughout the area. This has not been observed. Equally, aeolian activity in the Yucca Mountain region cannot be substantially lower than the Cima volcanic field because of the presence in the former, of active sand dunes on flows and the nearby dune field (Big Dune) in the Armagosa valley. Abundant sources of aeolian materials, including desert loess are provided by the adjacent basins, many of which contain large playas. Accordingly, we conclude that the weakly developed soils of the Lathrop Wells center closely resemble the Holocene soils in the Silver Lake area and the Cima volcanic field. We infer that the soils must have formed over a similar time span. The soil on the volcanic units of the Lathrop Wells center must have formed over a period spanning the late Pleistocene and Holocene.

Soil development on chronostratigraphic unit three appears initially to be inconsistent with the results of the K-Ar and U-Th age determinations that indicate ages for the lava flows of greater than 100 ka. Instead, the degree of soil development appears more consistent with the He age determinations that indicate the lava flow sequences could be < 100. However, several factors may have affected the degree of soil development on the deposits of chronostratigraphic unit three. First, studies of volcanic surfaces in the Cima volcanic field show that soil development may be retarded on rubbly aa flows compared with pahoehoe flows. The fragmental nature of the aa flow surfaces and resulting high porosity enables repeated deep flushing of aeolian materials to depths of several meters. This may prohibit development of an increasingly less permeable surface mantle in which well developed cumulic soils (and stone pavements) can form. Second, there are local indicators of greater soil development or pedogensis on some of the lavas of chronostratigraphic unit three. Trench exposures show locally the development of laminated calcite zones in buried soil, and carbonate coated fractures and joint surfaces in greater thickness and continuity than expected given the weak development of surface soils. Third, intermittent surface cover by active dunes has occurred on much of the lava and scoria surfaces of the Lathrop Wells volcanic center. Deposition of a sand mantle has profoundly influenced soil development. Where the sand deposits are deep, the development of soils has been terminated. Where sand deposits are thinner, there has been an accelerated rate of development of cumulic horizons. Fourth, the scoria mounds of chronostratigraphic three are not stable landforms where parent materials conducive to soil formation are preserved. The evidence of erosional modification of the scoria mounds (exposed feeder dikes, non-primary (volcanic) surface forms) indicates that the summits and slopes of the mounds are not stable surfaces. Finally, there has been insufficient trenching of chronostratigraphic unit three to provide thorough documentation of the *maximum* development of soils. It is premature and outside the scope of completed soil studies to conclude that soil development is inconsistent with geochronology data suggestive of ages of > 100 ka for some volcanic units. The major emphasis of work to date has been on the geomorphy and development of soils on the youngest units of the volcanic center (Wells et al. 1990; 1991).

The differences in the degree of soil development on chronostratigraphic unit two and one than chronstratigraphic unit three are consistent with a time gap between the units. However it is difficult and unwarranted to speculate on the extent of the time differences between the units. The unmodified geomorphic form and weak degree of horizon development in soil on the Qs_{2a} deposits (Wells et al. 1990) are consistent with an age of < 50 ka. Moreover, soil data appears consistent with the cosmogenic helium ages of about 25 ka. This unit has been sufficiently well studied to conclude that the limited development of horizons in soils and unmodified geomorphic form is inconsistent with an age of the cone in excess of > 100 ka (see Turrin et al. 1991).

8. Paleomagnetic Studies. Considerable paleomagnetic data have been obtained for the Lathrop Wells volcanic center in order to discriminate among different eruptive events. Turrin et al. (1991) report that the paleomagnetic data from the eruptive units fall into two statistically distinguishable populations. They correlated the populations to their revised definitions of units Qs_5 and Ql_3. Champion (1991) and Turrin et al. (1991) interpreted the angular difference between the means of the two populations to indicate an age difference between the two events of **no more** than 100 years. The geologic unit Qs_5 defined by Turrin et al. (1991) includes subunits of both chronostratigraphic units three and two as defined in this report. Specifically, subunit Qs_5 was included in the paleomagnetic used to define their map unit Qs_5. Additionally, not all volcanic subunits of the Lathrop Wells center were sampled in their paleomagnetic studies (Wells et al. 1992). The conclusions regarding the paleomagnetic data of Turrin et al. (1991) appear premature because of the combination of inconsistent stratigraphic assignment of volcanic units and the incompletely reported paleomagnetic data set.

We have attempted to augment the paleomagnetic data set for the Lathrop Wells volcanic center of Champion (1991) and Turrin et al. (1991) for two reasons. First, as noted above, not all units were sampled for paleomagnetic studies. Unsampled and unstudied units include Ql_6, Qs_6, Qs_5 and the Ql_{4b} lava flows. Second the previously conducted paleomagnetic studies of the Lathrop Wells center were not completed under an approved Quality Assurance program. While the data appear to be of good quality analytically, it cannot be used for the Yucca Mountain Site Characterization Project. We will sample and analyze new paleomagnetic sites and attempt to qualify, by comparison, much of the previously collected paleomagnetic data.

Ten paleomagnetic sites were sampled for paleomagnetic studies at the Lathrop Wells center in 1991. Each sampling site consisted of eight to twelve independently oriented samples, collected as small cylinders using a portable drilling apparatus. Individual sample sites were collected over an area of several m^3. Four sites were located in the Ql_6 lavas, four in the Ql_5 lavas, and two in the Ql_{4b} lava on the north flank of the main cone. At least one specimen per site has been subjected to progressive alternating field demagnetization, the technique most commonly used to assess the direction and relative intensity of all components of magnetization in magnetite-bearing rocks. In most cases a well-defined, univectoral decay of the magnetization to the origin of the demagnetization diagram is identified (Fig. 2.19). This magnetization is interpreted to be the primary, thermoremanent magnetization acquired in the initial cooling of each lava flow. The directions of primary magnetizations have been calculated after visual inspection of demagnetization diagrams using a form of three-dimensional least-squares fitting. The between-site dispersion of

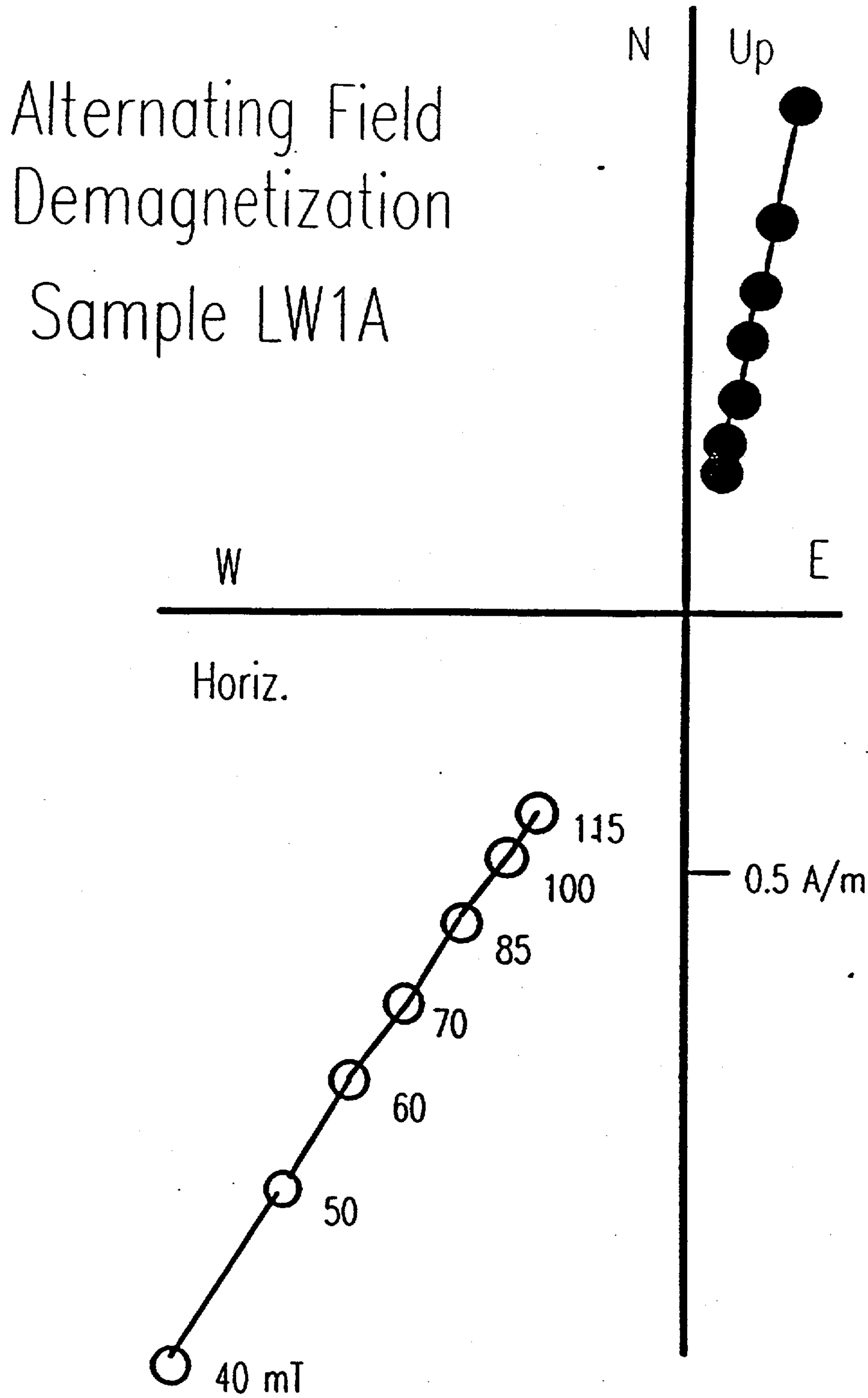


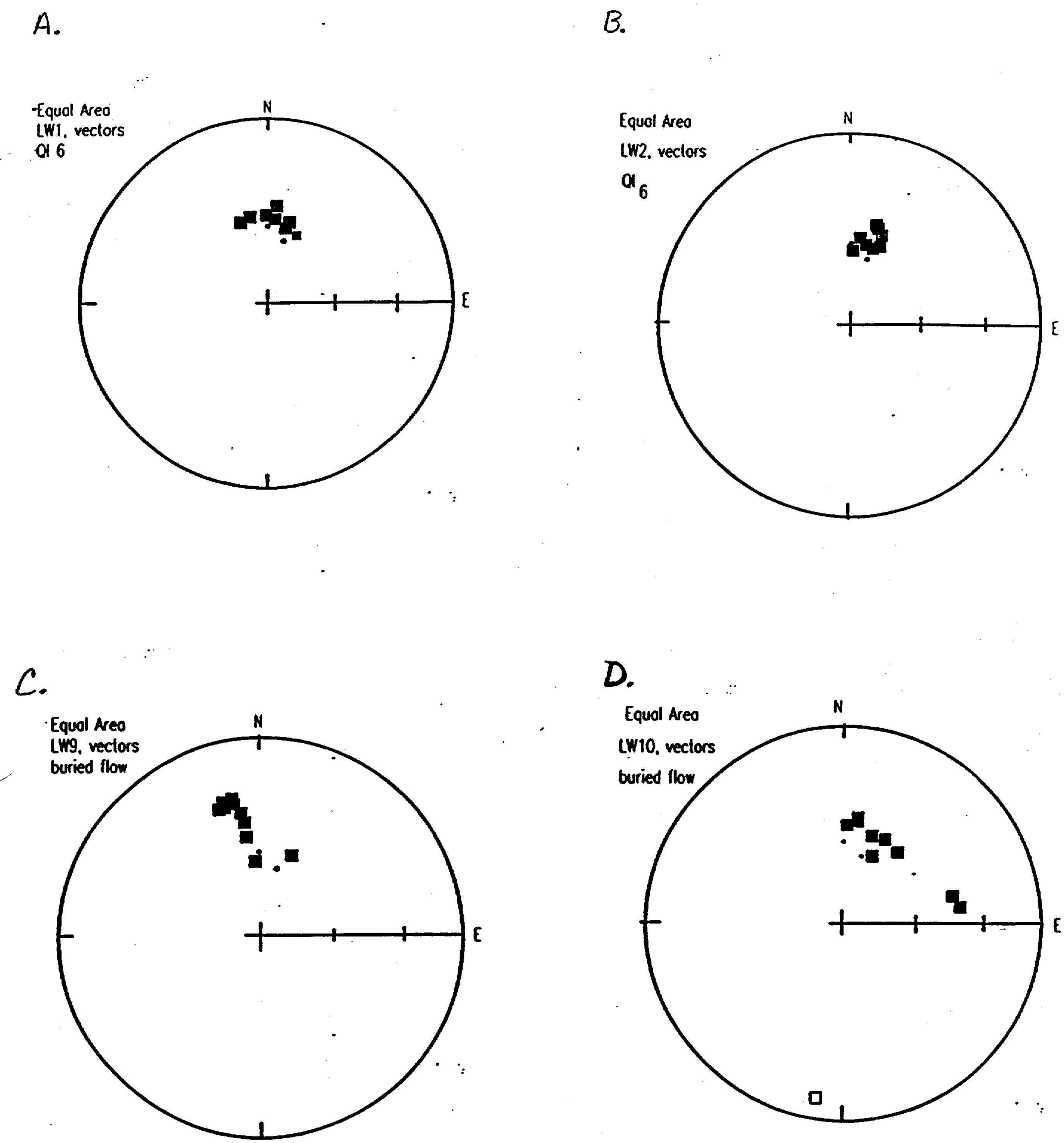
Fig. 2.19 Modified orthogonal demagnetization diagram showing the endpoint of the magnetization vector projected onto the horizontal (E-W, N-S) planed (filled circles) and the true vertical (horizontal, U-D) plane for a sample from a lava flow lobe of subunit Ql_6. The projection shows the magnetization vector measured after 40 milliTesla (mT) was well as higher peak inductions in alternating field demagnetization. This diagram displays an univectorial decay of the magnetization vector to the origin; the direction of the magnetization isolated over the interval from about 40 mT to over 100 mT is determined with a high degree of confidence.

directions of the primary magnetization differs considerably (Fig. 2.20a-d). This is interpreted to reflect one of two problems associated with sampling surface exposures of young basaltic lavas. The first is the difficulty in sampling intact material. Samples in one or a series of adjacent and out of place blocks may give directions of magnetization that are internally consistent yet discrepant in comparison to those from samples collected from the same portion of the site (Fig. 2.20). The second problem is lightning strikes. Here, an artificial, generally randomly dispersed magnetization is superimposed on a primary, well-grouped magnetization. In some cases this artificial magnetization can be fully removed in alternating field demagnetization; in others it cannot be removed.

Several sites give well-grouped, interpretable paleomagnetic data. Two sites in Ql_6, give site mean directions of magnetization (Decl.=2.7, Incl.=53.5, alph95=5.3, k=93.2, n=9; site LW1 and Decl.=13.8, Incl.=53.3, alpha95=3.5, k=210.9, n=9; site LW-2). These directions are statistically indistinguishable, at a 95 percent level of confidence, from the directions reported by Turrin et al. (1991) for their unit Ql_3. This provides consistent, but not conclusive evidence that the Ql_6 lava is correctly assigned to chronostratigraphic unit three. Two other sites in Ql_6 give dispersed paleomagnetic data (Fig. 2.20). Finding intact material in the Ql_5 subunit has proven more difficult. However, based on preliminary measurements of the directions of natural remnant magnetization, two of the sites in the subunit may give well-grouped primary magnetization. This work is in progress. Samples collected from subunit Qs_{4b} vary in dispersion. It is unlikely that a well-grouped direction of magnetization will be obtained for surface outcrops of this lava flow.

New and probably final sets of samples for paleomagnetic study were collected in the fall of 1992. These samples were chosen in an attempt to provide optimum determinations of field magnetization directions for the volcanic subunits. The buried lava flow of subunit Ql_{4b} was excavated to expose the massive interior of the blocky aa flow at two localities. Both localities were sampled for paleomagnetic studies. Scoria mounds of subunits Qs_{4a} and Qs_{2b} were dissected by backhoe. Oriented samples of scoria clasts were collected from intact sequences of vent scoria. These samples were buried beneath several meters of overlying scoria and should be effectively shielded from lightning strikes. Oriented samples of scoria clasts were collected from newly constructed road cuts in subunit Qs_6. Oriented scoria clasts were also collected from quarry exposures of the main cone (subunit Qs_{2a}). Outcrops of strongly agglutinated scoria were drilled and oriented core collected from vent zones of the Qs_5 subunit southwest of the main cone. Finally, multiple sites in the Ql_3 and Ql_4 lavas were drilled and oriented core collected for paleomagnetic studies. Studies of these samples are in progress.

The paleomagnetic data obtained from the initial phase of sampling at Lathrop Wells are not dissimilar from those reported by Turrin et al. (1991). However, an insufficient amount of information have been published to document the magnetization directions and characteristics of chronostratigraphic unit two. Champion (1991) and Turrin et al. (1991) argue that deposits of chronostratigraphic unit two give a magnetization direction that differs by 4.7 degrees from chronostratigraphic unit three. This difference, if correct,



Figs. 2.20a-d Equal area projections of sample magnetization directions determined from the results of progressive demagnetization for the following: Fig. 2.20a: sample LW-1 from the Ql_6 lava; Fig. 2.20b: sample LW-2 from the Ql_6 lava, Fig. 2.20c: sample LW-9 from the Ql_5 lava, Fig. 2.20d: sample LW-10 from the Ql_4 lava. For all projections, lower hemisphere projections are indicated in solid symbols and upper hemisphere projections in open symbols.

provides support for the subdivisions of chronostratigraphic units two and three. However, acceptance of this conclusion requires more information on the integrity and demagnetization results of individual sample data. Specific concerns include the fidelity of recording and preserving the primary magnetic signature in non-agglutinated scoria deposits that include a hydrovolcanic eruptive component. Additionally, the summit of the main scoria may be especially susceptible to lightning strikes. Finally, the paleomagnetic data obtained to date fall near the time-averaged (spin-axis) Quaternary field direction. There is no indication of the presence of a single volcanic event occurring during a period of unusual geomagnetic activity.

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SECTION III: TECTONIC SETTING OF THE YUCCA MOUNTAIN REGION: RELATIONSHIP TO EPISODES OF BASALTIC VOLCANISM

I. ABSTRACT

The potential Yucca Mountain site is located in the south part of the Great Basin physiographic province, in a complex tectonic setting. The mountain formed as a physiographic feature through a combination of eruption and deposition of large volume ignimbrites from the Timber Mountain-Claim Canyon calderas and extensional faulting. The potential site lies between the alluvial basins of Crater Flat and Jackass Flat and in a north-northeast trending structural trough. Basin-range faults that cut the rocks of Yucca Mountain trend north and north-east. The potential Yucca Mountain site is located at the north edge of a conspicuously amagmatic zone that exhibited no Cenozoic volcanism during episodes of extreme extension. The peak of a major episode of extensional faulting that controls the modern physiography of the region is dated at about 11 Ma. Earlier phases of strike-slip faulting associated with the Walker Lane structural zone may have affected the site but the effected rocks are largely concealed by the Miocene volcanic rocks. Episodes of detachment faulting may be important in understanding the structural framework of the Yucca Mountain site. However, there is a general consensus that the active faulting at Yucca Mountain, if related to detachment faulting, represents only the final stages of movement. The Crater Flat basin bounding Yucca Mountain to the west has been interpreted by some workers as a caldera complex formed by the collapse of two nested calderas associated with eruption of the Crater Flat Tuff. An alternative tectonic model for the Yucca Mountain area is that it is in a north-northeast trending, volcano-tectonic rift, the Kawich-Greenwater rift. The rift may be a pull-apart or right-stepped zone of rifting in the Walker Lane structural system. Faults that offset the Miocene ignimbrites at Yucca Mountain are inferred, by this model, to be related to rifting processes and are not detachment faults. The Amargosa Desert rift zone is a variant of the Kawich-Greenwater rift zone. It is inferred to extend from the Pahrump Valley-Death Valley basins, across the Amargosa Valley to the southern part of Yucca Mountain. The rift is marked by multiple pull-apart basins bounded by strike-slip faults. Individual basins may or may not be associated with volcanic activity. Another structural model of the Crater Flat basin is that it is the site of a major, northwest-trending strike-slip fault. This system has a proposed cumulative offset of about 26 km. Several variants of pull-apart basin origins have been proposed for the Crater Flat basin. The models assumes the basin was formed by combined east-west extension and right-slip on northwest-trending faults forming a half-rhombochasm.

Basalt of the silicic episode exhibits spatial association with Miocene caldera complexes and are distributed in a broad, northwest trending band parallel to the Walker Lane structural system. The older basalt of the post-caldera basalt episode occurs along basin-range faults and at the intersections of basin-range faults with ring-fracture zones of caldera complexes. These units all occur north and east of the potential Yucca Mountain site. The distribution centroid of the older post-caldera basalt is elongated northwest and is located in the northeast part of the Timber Mountain caldera. The younger basalt cycle of the post-caldera basalt episode occurs in a northwest-trending zone called the Crater Flat

volcanic zone (CFVZ). One site, the basalt of Buckboard Mesa, is located in the ring fracture zone of the Timber Mountain caldera, outside of the CFVZ. The distribution centroid of the younger post-caldera basalt is elongated north-northwest and coincides with the Crater Flat basin. The distribution centroids differ at the 90% confidence limit and require southwest migration of sites of volcanic activity through time. The location of the vents of basalt centers of the CFVZ show a linear fit by least squares and distance-weighted least squares regression on the basis of combinations of Quaternary and Pliocene and Quaternary basalt centers of the CFVZ. The best-fit line passes through the Lathrop Wells cone on the southeast, between Red Cone and Black Cone and between the Little Black Cone and Hidden cones on the northwest. The best-fit line coincides with the location of a three-dimensional surface fitted by distance weighted least squares regression of cone location and eruption volume. These data suggest that repeated pulses of basalt magma ascended along a northwest-trending structure and diverted at shallow levels to form northeast-trending dikes. These dikes probably followed magma-generated fractures because the trend of clustered centers is largely independent of local structure.

A wide-range of geophysical data have been obtained for the Yucca Mountain region. Seismic studies, employing a local network have been installed since 1979. Earthquakes in the region are distributed in an east-west zone and display strike-slip and dip-slip offsets consistent with a northwest-trending orientation of the least principal stress axis. Earthquake clusters are difficult to relate to surface faults. Yucca Mountain is located in an earthquake-free zone that may indicate low stress or prehistoric seismic release. There is no correlation between seismicity and the distribution of Quaternary basalts. In fact, there may be a negative correlation between basalt sites and seismicity. Strain-field modeling of fault behavior in a uniform strain field shows that off-fault locations of seismicity is expected. The seismic gap in the Yucca Mountain area is coincident with a region of modeled lowest shear strain. Gravity models of the Yucca Mountain region show a gravity high associated with Bare Mountain and a gravity low centered in Crater Flat. These data are permissive with a caldera collapse or tectonic origin of Crater Flat. Comprehensive aeromagnetic and local ground magnetic data have been obtained for the Yucca Mountain region. These data reveal the presence of multiple anomaly sites that correlate with the surface and subsurface distribution of Cenozoic basaltic volcanic rocks. Ground magnetic data show the presence of a small intrusive body associated with the Soltario fault. The close association between aeromagnetic anomalies and the location of Pliocene and Quaternary basalt centers give good confidence that all sites of basaltic magmatism have been identified. Geoelectric, seismic reflection and refraction data have been obtained for parts of Yucca Mountain. A bright spot on a seismic reflection profile in the Amargosa Valley is interpreted to represent a focusing of energy reflected from the mid-crust by low velocity basin fill lying about the bright spot. Teleseismic data reveal the presence of a large low velocity anomaly in and south of the Amargosa Valley. This has been interpreted as evidence of the present crustal magma. However, these conclusions are inconsistent with geologic, seismic, heat flow and magnetic data.

Quaternary basalt sites do not appear to be controlled by or follow prevailing structural controls. The best spatial correlations between the distribution of basalt centers and structure are with deep-seated structural features such as strike-slip faults and ring-fracture zones of caldera complexes. These structures are passive features promoting the passage of but not causing basaltic magma. Ascent of magma along these structures may permit passage of basalt upwards through the relative stable crust. There is a general tendency for basalt centers to occur in alluvial basins and not range interiors. The distribution of basalt centers can be related to caldera models, north-northeast trending rifts, pull-apart basins, the Crater Flat Volcanic Zone, local north-northeast trending structures, and alluvial basins.

II. INTRODUCTION

The purpose of this section of the Volcanism Status Report is to attempt to relate the record of Cenozoic basaltic volcanism of the Yucca Mountain region, which is described in section II of this paper, to the local tectonic setting. This is difficult for several reasons. The geologic and tectonic setting of Yucca Mountain are complex. Yucca Mountain is upheld by a thick accumulation of Cenozoic volcanic rocks overlying Paleozoic rocks. The Paleozic rocks were faulted and folded during multiple episodes of pre-Cenozoic deformation. These rocks are exposed to the northeast and west of Yucca Mountain, but not within the mountain itself. Their structural configuration beneath Yucca Mountain is not well constrained.

Yucca Mountain developed as a physiographic feature from a combination of tectonic events. There were multiple, large volume eruptions associated with the formation of the Timber Mountain-Oasis Valley caldera complex (TM-OV), the largest caldera complex of the Southwest Nevada Volcanic Field (see Section II). The closely spaced eruptions of large volumes of silicic pyroclastic rocks about 15 to 11 Ma deposited thick sheets of ignimbrites and formed plateau highlands flanking the TM-OV complex. The ignimbrite plateau south of the TM-OV was broken by extensional faulting accompanied by eastward tilting of the ash-flow units. These events caused the emergence of Yucca Mountain as an elongate range. The range was formed after deposition of the 13 Ma Paintbrush Tuff and prior to eruption of the 11 Ma Timber Mountain Tuff.

Prior to emplacement of the Paintbrush Tuff, there may have been earlier episodes of deformation in the Yucca Mountain area involving extensional, strike-slip and detachment faulting. Yucca Mountain is located in a north-northeast trending structural trough or rift zone that may extend from Death Valley, through the Amargosa basin and Yucca Mountain (Healey and Miller 1965; Wright 1989: Carr 1990; Brocher et al. 1993). The formation of the alluvial basins of Crater and Jackass Flats, bounding Yucca Mountain to the east and west occurred mostly after deposition of the Paintbrush Tuff. However, there may have been earlier episodes of basin-formation associated with formation of pull-apart basins, possibly during and postdating caldera activity. The thick volcanic cover and the complexity of the tectonic setting of Yucca Mountain make it difficult to reconstruct the detailed history of volcanic and structural events.

Basaltic volcanism accompanied but mostly post-dates the major tectonic activity that shaped the geologic setting of the Yucca Mountain area. Miocene basaltic volcanism shows strong spatial associations with pre-existing structure (basin-range faults and ring-fracture zones of caldera complexes). Many sites of basaltic volcanism formed contemporaneous with major phases of extensional faulting. In contrast, the Pliocene and Quaternary basaltic activity postdates the major tectonic events and cannot be related easily to the distribution of known surface and subsurface structural features in the area.

A second purpose of this report is to summarize current understandings of the geologic and tectonic features of the region, progressing from the scale of the broader region of the southern Great Basin region downward to the Yucca Mountain area. Such a progression places the geologic setting of Yucca Mountain into a regional tectonic perspective. This evaluation is aided necessarily by regional geophysical data that provide important views of the interrelationships between regional, local, and subsurface structures. The geophysical data can also be combined with petrologic studies of basaltic volcanism (described in Section 4) to provide constraints on the fundamental processes and causes of basaltic volcanism. This gives a perspective for evaluating not only the structural controls of volcanic activity, but also the operation of magmatic processes that produced the past record of volcanism and may control future volcanic events.

Any attempt to describe the relationship between tectonism and basaltic volcanism must be recognized as an evolutionary process tied to the state of understanding of the geological processes. Concepts concerning, for example, the origin and development of the basin and range province, have changed dramatically during the last few decades. During the 50's and 60's, the province was recognized as a site of structural extension. The mountains and valleys were viewed as rigid horsts and grabens, structurally bounded by steeply dipping, planar faults. Important advances during the latter part of the 60's and early 70's strongly reshaped thinking about the origin of the basin and range province. The unifying concepts of plate tectonics were developed. These concepts presented a largely new perspective for evaluating the driving mechanisms for development of a major extensional province in a continental setting. The basin and range province, based on plate tectonics, attracted comparison to oceanic and continental rift zones. The widespread application of radiometric dating methods to the volcanic and plutonic rocks of the province revealed the time-space variability of the igneous rock sequences. The plutonic and volcanic records of activity in the basin-range province are now recognized to be part of widespread magmatic events that occurred along the western length of the North American continent from at least the Eocene and continuing in the Quaternary. Subduction of oceanic crust associated inland by overlapping belts of continental magmatism provides a conceptual framework for explaining many, but not all, of the complex time-space associations of tectonism and volcanism.

During the 70's and 80's, perplexing sites of low angle faulting with large sections of rock displaced or missing were recognized throughout the province. The timing of movement along many of these low-angle fault systems is now sufficiently well established to relate the tectonic events to Cenozoic extension. The identification of low angle faults of Cenozoic age was paralleled by the recognition of the importance of exposures of complexes of metamorphic and igneous rocks throughout the basin-range province. The depth of formation of the these rocks, and their mid-Cenozoic uplift ages necessitated the removal of kilometers of crust by processes of uplift and erosion accompanying extension. The basin-range province is now recognized as a region of time transgressive extension accompanied by spatially varying mantle upwelling, volcanism, and lateral flow of the mantle and crust.

There undoubtedly will be continued progress in the understanding of the processes of tectonism and volcanism in a continental rift setting. Many new ideas will continue to be developed and will force rethinking or may even invalidate currently accepted concepts. Discussion of the tectonic setting of Yucca Mountain and the patterns of basaltic volcanism must be viewed only as a time-slice of the present state of knowledge.

Three perspectives overshadow the process of identifying the tectonic models for the occurrence of Pliocene and Quaternary basaltic volcanism in the Yucca Mountain region. First, it is more important to evaluate and incorporate a comprehensive set of all reasonable tectonic-volcanic models for basaltic volcanism than it is to make judgments about which set or even sets of tectonic models are more or even most correct. Second, the key product of evaluating different tectonic models is an identification of the *effects* of the different models on assessing the risk of future volcanism for the potential Yucca Mountain site. The assessments of volcanic risk far exceed in importance programmatically, scientific debates concerning the strengths and weakness of individual models. Third, while the task of developing tectonic models for volcanism is difficult, it must be placed into the perspective of the goals of isolation of high-level radioactive waste. A required 10,000 year isolation period of high-level radioactive waste is long relative to societal perspectives. It is a relatively short period compared to the millions of years required to initiate and change the fundamental tectonic processes that have shaped and will continue to shape the Yucca Mountain area. The geologic record of tectonism and volcanism provide consistent evidence that the processes of extension and volcanism peaked in the Miocene and waned in the Pliocene and Quaternary. It is very unlikely, barring unexpected discoveries in site characterization studies, that the fundamental tectonic setting of Yucca Mountain will change significantly during the next 10,000 years.

III. SOUTHERN GREAT BASIN

The potential Yucca Mountain site is located in the southern part of the Great Basin, a subpart of the basin and range physiographic province of the southwestern United States. The term "Basin and Range province" as used herein refers to the broad area of the western United States dominated by fault-bounded mountain ranges separated by alluvial valleys (Stewart 1978). The province was subdivided originally on physiographic criteria (Fenneman 1931). However, many geological and geophysical properties of the province extend beyond the strict physiographic boundaries. Eaton (1982) argued that the Basin and Range province can be defined as a tectonophysical region that includes parts of ten western states and more than 10% of the area of the United States. The generally accepted boundaries of the Basin and Range province using standard geomorphic (physiographic) criteria are shown on

Figure 3.1. A much larger area of the Basin and Range province can be demarcated simply from the distribution of late Cenozoic faults (Fig. 3.2). This area is close to the size of the basin and range province as defined by the thermophysical criteria of Eaton (1982).

There is an important distinction between the Great Basin portion of the Basin and Range Province and the southern Basin and Range (Fig. 3.3). The Great Basin has been shaped generally by the recent operation of active extensional processes. It is higher standing topographically, and contrasts geophysically from the southern Basin and Range province (Eaton 1982; Jones 1992). The boundary between these subprovinces coincides with the eastward projection between the latitudes of 36° and 37° N of the Garlock fault of California across Nevada and continuing to the Colorado Plateau in Arizona (Fig. 3.3, see also Suppe 1975; Eaton 1982). This boundary forms the north edge of an area with no Cenozoic or Mesozoic magmatism or plutonism (Farmer et al. 1989). It marks the approximate location of a gradient in the Bouguer gravity field of almost 100 mGals (increasing to the south; Eaton et al. 1978; Hildenbrand et al. 1988). This gravity step is a significant feature of the Bouguer gravity anomaly map of North America (Hanna et al. 1989). The boundary is less prominent but recognizable on the map of historical seismicity of North America (Fig. 3.4; see Hildenbrand et al. 1988, their Fig. 2.3; Engdahl and Rinehart 1988). Wernicke (1992) and Jones et al. (1992) divide the basin-range into three tectonic provinces, the northern basin and range, the southern basin and range, and the central basin and range. Their central basin and range province encompasses most of the area surrounding Yucca Mountain and the area of the amagmatic gap.

The potential Yucca Mountain site has been shaped structurally by extensional faulting and by voluminous silicic volcanism predominantly in the period of 15 to 8 Ma. Small volume basaltic volcanism postdates the silicic volcanism and has persisted in the Pliocene and Quaternary. Extensional faulting occurred along generally west-dipping faults that vary in trend from about north 30 degrees east and north 30 degrees west. Modern studies have focused increasing attention on detachment faulting as a mechanism for accommodating extension. Many workers separate episodes of faulting into an earlier period of predominantly low-angle or detachment faulting followed by a younger period of high-angle normal faulting; there is however, no consensus on the exact structural divisions and the timing of these subdivisions. The Yucca Mountain region lies in the Walker Lane structural belt, a complex zone of right-slip and subordinate left slip faults that parallels the northwestern parts of the Great Basin (Fig 3.5).

There are many published reviews of the geology and geophysical characteristics of the Basin and Range province. The following section provides an overview of the voluminous literature. Aspects of the geologic and geophysical characteristics of the Great Basin that provide an important framework for tectonic models of the Yucca Mountain region are emphasized. Noteworthy papers that describe important properties of the Basin and Range province with emphasis on the central Basin and Range subprovince include Nolan (1943), Shawe (1965), Hamilton and Myers (1966), Atwater (1970), Anderson (1971), Scholz et al.

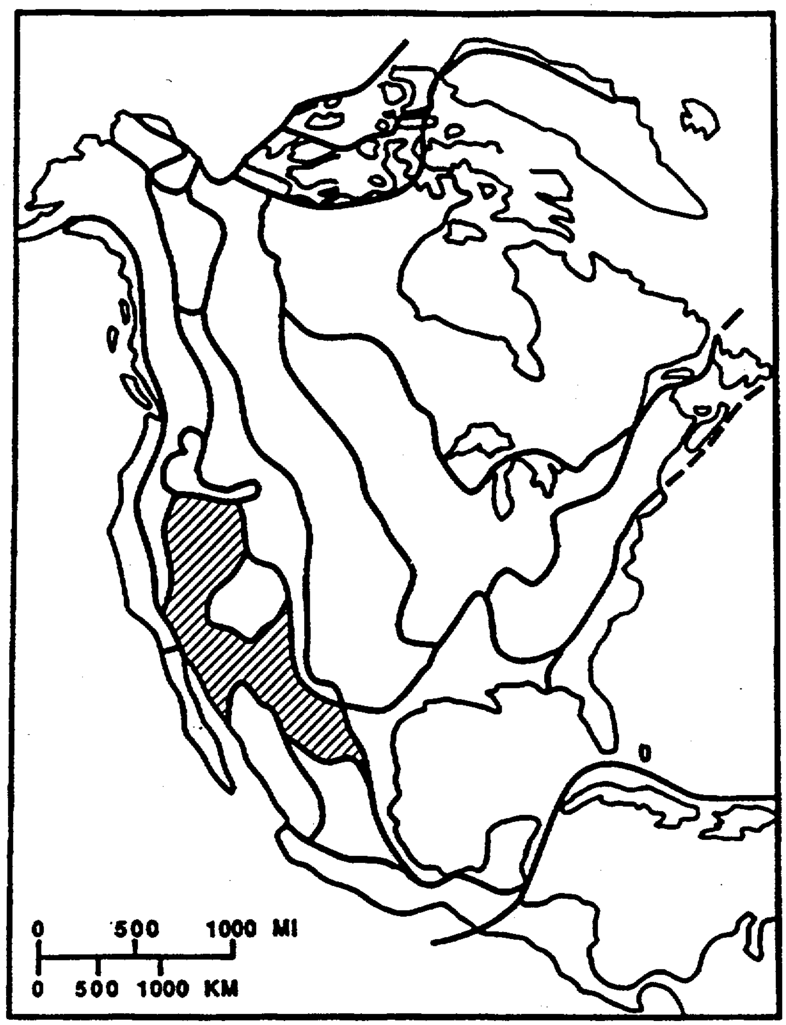

Fig. 3.1 Physiographic subdivisions of North America (modified from Bally et al 1989). The basin-range province, defined on geomorphic criteria, occupies a broad area of the west and southwest United States and adjoining areas of northern Mexico (cross-hatched area).

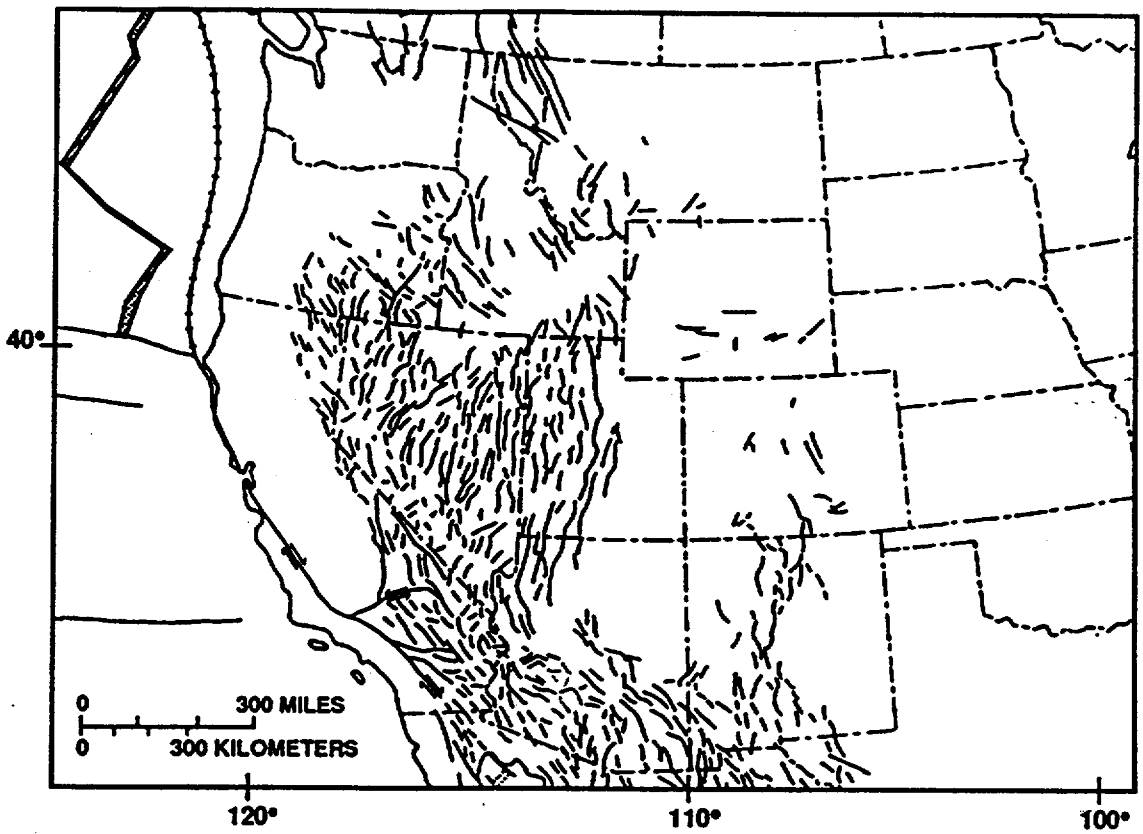

Fig. 3.2 Distribution of late Cenozoic faults in the western United States (modified from Stewart, 1978). The area outlined by faults on the Fig. 3.2 denotes the broader basin and range province as defined by the thermophysical criteria of Eaton (1982), and is equal to more than 10% of the landmass of the United States.

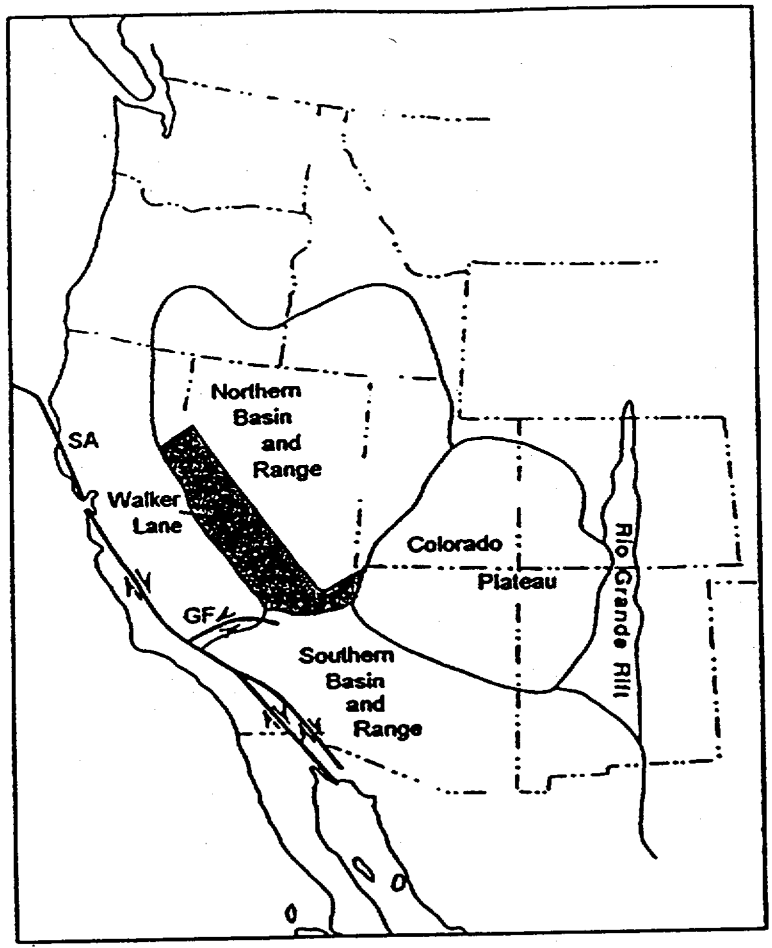

Fig. 3.3 Subdivisions of the basin and range province. The province is divided into the northern basin and range, commonly called the Great Basin when defined on physiographic criteria, and the southern basin and range commonly called the Sonoran Desert. The Yucca Mountain region is located near the southern end of the Great Basin north of a transition zone between the provinces that coincides with the approximate extension eastward of the Garlock fault to the Colorado Plateau. This transition zone has been called the central basin and range (Wernicke, 1992; Jones et al 1992). The cross-hatured area of the southwest Great Basin outlines the boundary of the Walker Lane structural zone. SA: San Andreas fault; GF: Garlock fault; CBR: Central Basin and Range; WL: Walker Lane structural zone.

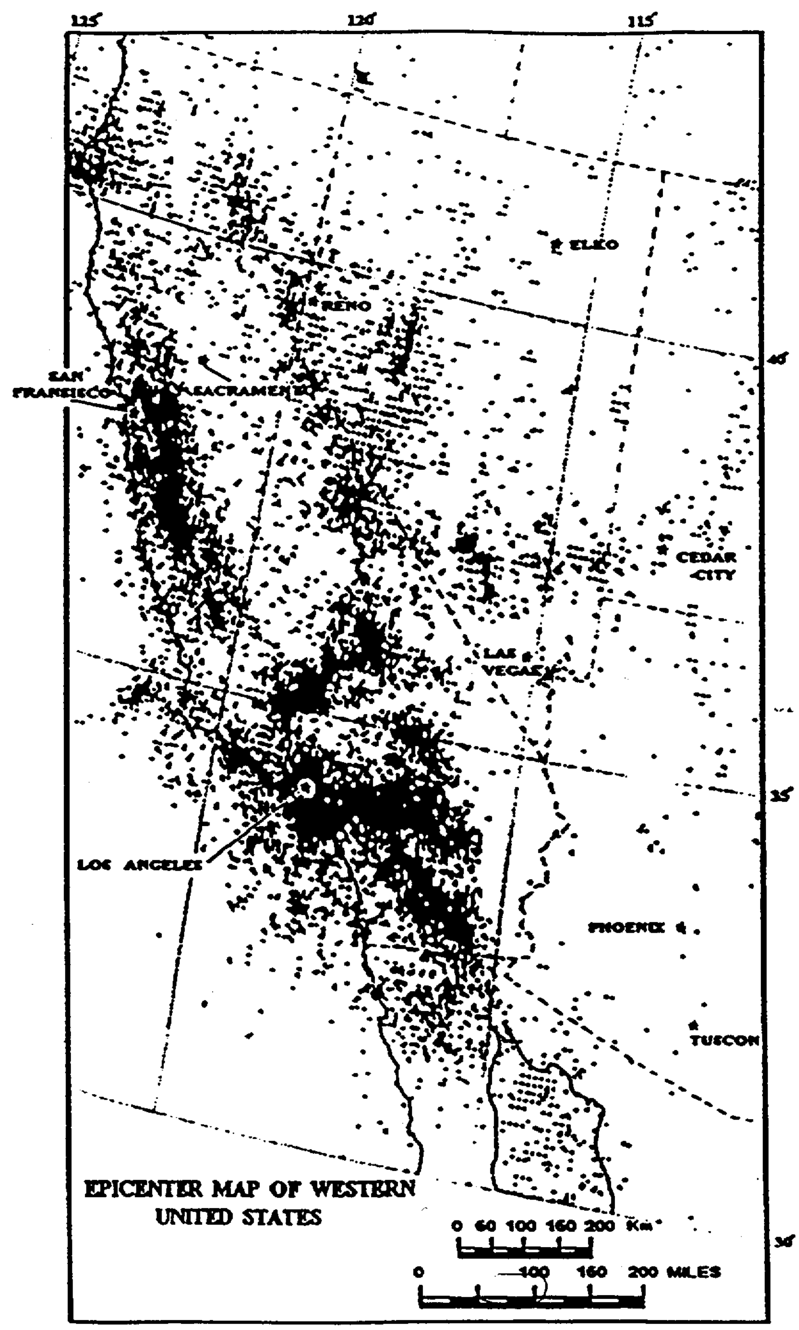

Fig. 3.4 Seismicity map of the western United States after Smith (1978).

Fig. 3.5 TM Satellite Photograph for the Yucca Mountain region showing the major caldera complexes and alluvial basins of the region.

(1971), Stewart (1971), Lipman et al. (1972), Christiansen and Lipman (1972), Noble (1972), Kistler and Peterman, (1973), Best and Brimhall (1974), Thompson (1974), Smith and Sbar (1974), Wright et al. (1974), Suppe et al. (1975), Snyder et al. (1976), Wright (1976), Proffett (1977), Snyder et al. (1976), Stewart et al. (1977), Best and Hamblin (1978), Christiansen and McKee (1978), Eaton et al. (1978), Lachenbruch and Sass (1978), Smith (1978), Stewart (1978), Zoback and Thompson (1978), Eaton (1979), Eaton (1980), Lipman (1980), Stewart (1980), Guth (1981), Wernicke (1981), Zoback et al. (1981), Armstrong (1982), Eaton (1982), Hill (1982), Glazner and Supplee (1982), Vaniman et al. (1982), Wernicke and Burchfiel (1982), Coney and Harms (1984), Farmer and DePaolo (1983; 1984), Smith and Luedke, (1984), Hudson and Geissman (1987), Hamilton, (1988), Farmer and DePaolo (1984), Snoke and Miller (1988), Wernicke et al. (1988), Farmer et al. (1989), Gans et al. (1989), Oldow et al. (1989), Carr (1990), Hodges and Walker, (1990), McKenna and Hodges (1990), Scott (1990), Severinghaus and Atwater (1990), Walker and Colman, (1991), Jones et al. (1992), Wernicke (1992), and Axen et al. (1993).

The most striking feature of the Great Basin is the contrasting topography. The region has been broken by complex, spatially heterogeneous extensional faulting into broad basins separated by narrow, high-standing ranges (Stewart and Carlson 1974; Eaton 1982; Hildenbrande et al. 1988; Wernicke et al. 1988; Jones et al. 1992). This extension occurred primarily in the Cenozoic but the detailed timing and spatial variability of the faulting remains controversial. Many workers restrict the development of the so called classical Basin and Range tectonism to episodes of extensional faulting that are younger than 17 Ma (post-middle Miocene; Stewart 1978; Christiansen and McKee 1978). There is evidence of early Cenozoic faulting that proceeded and was synchronous with subduction and arc magmatism (Axen et al. 1993). However, this faulting may not be related directly to the later faulting that shaped much of the modern topography (Coney 1978; 1989; Mayer 1986; Okaya and Thompson 1986; Best and Christiansen 1991). Other workers have emphasized the time-transgressive nature and spatial complexity of extensional faulting. The onset of the extensional deformation is emphasized rather than the age of continued faulting. In many areas of the Basin and Range province, extensional faulting may have begun in the Oligocene (Proffett 1977; Crowe 1978; Crowe et al. 1979; Rehig 1986; Snoke and Miller 1988; Gans and others 1989; Axen et al. 1993).

Some workers have suggested that extensional faulting locally may be associated with the development of metamorphic core complexes (Crittendon et al. 1980). However, it has proven difficult to directly link extension with the development of the metamorphic complexes (Oldow et al. 1989). An alternative interpretation is the metamorphic complexes were reactivated during the period of subduction of the Farllon plate (40 to 20 Ma; Coney 1978) and uplifted and exposed by later high-angle faulting. Many authors link the time-transgressive magmatism of the Basin and Range province with tectonism suggesting the tectonic activity, by inference, was time-transgressive (see references of Section II, this paper). The time transgressive nature of basin-range tectonism appears supported by the modern distribution of faulting and volcanic activity. The most active areas of volcanism and tectonism in the Great Basin are along its western and eastern margins. The present eastern margin of the Great Basin, for example, appears to be expanding outward into largely unextended terrain of the Colorado Plateau (Suppe et al. 1976; Best and Hamblin 1978; Tanaka et al. 1986).

Coney (1978) divided tectonic and magmatic activity in the Basin and Range province into a period of vast ignimbrite eruptions (ignimbrite flare-up of the late Eocene to early Miocene) which was followed by a period of widespread basalt eruptions, block faulting and collapse of the Basin and Range province (post-20 Ma). He suggested the first period was controlled by subduction of the Farallon plate and the latter period by cessation of subduction and growth of the San Andreas transform system. Severinghaus and Atwater (1990) provided a refined plate tectonic perspective for the controls of basin-range faulting and volcanism. They examined the geometry and thermal state of subducting slabs beneath North America through time based on reconstruction of the magnetic patterns of the ocean floor. They suggested subducting slabs became aseismic through time and ceased to strongly affect continental tectonism. The period required for reduction of the tectonic activity associated with subduction is dependent not only on the age of termination of subduction but also on the age of the subducted oceanic crust. The latter factor became important in the Miocene as segments of the oceanic rise approached the Americas plate (Severinghaus and Atwater 1990) resulting in subduction of young, buoyant oceanic crust.

The tectonic evolution of western North America can be constrained by the timing of formation and expansion of an aseismic slab gap associated with the termination of subduction. A slab gap developed as early as 35 Ma in southeast Arizona and southwestern New Mexico, and extended generally northwest in time across the Basin and Range province, paralleling the development of the San Andreas transform system (Severinghaus and Atwater 1990; their figures 8-14). While the correlations between plate locations and continental tectonic events have spatial uncertainty, they provide a mechanism from plate-tectonic interactions to explain the time-transgressive magmatic and tectonic patterns of the southern Basin and Range province. There are three important constraints for the Yucca Mountain area provided by the plate tectonic reconstructions of Severinghaus and Atwater (1990). First, subduction continued in the Great Basin after development of an aseismic gap in the southern Basin and Range. This is consistent with the evidence of younger extension in the Great Basin. Second, the development of a slab-free zone inland of the Medicino and Pioneer fracture zones formed beneath the Yucca Mountain area at about the time of cessation of silicic volcanism and during a major and possibly peak phase of extensionsional faulting (11 Ma). Third, the timing of the termination of the south spread of volcanism, the development of the amagmatic gap and the east-west trending boundary between the Great Basin and southern Basin and Range can be explained by the plate-tectonic reconstructions of Severinghaus and Atwater (1990).

Late Cenozoic basin-range faults in the eastern Great Basin trend predominantly north and northeast. The consistencies of fault trends are interrupted on the southwest side of the Great Basin. Here, there may be multiple sets of normal faults with variable strikes. The range trends are more diverse typical of the Walker Lane structural zone. Evidence of the Walker Lane structural zone in the southwest Great Basin include northwest alignment of silicic volcanic centers (Carr 1974; 1990; Carr et al. 1984), northwest alignment of large volume basalt centers (Crowe 1990), zones of oroclinal bending of mountain ranges (Shawe 1965; Guth 1981; Scott 1990), segmented and largely inactive zones of northwest-trending probable right slip faults (Guth 1981; Scott et al. 1984; Carr 1974, 1990), and northeast-trending left slip faults (Carr 1984). Blakely (1988) noted that magnetic anomalies in the Walker Lane structural zone of Nevada have arcuate, northwest trends but the width of the zone of aeromagnetic anomalies is wider than the boundaries of the Walker Lane. He suggests the magnetic anomalies may be shaped by an underlying tectonic fabric that predates the modern topography -- perhaps related to the Precambrian breakup of North America.

Blackwell (1978) and Lachenbruch and Sass (1978) described high values of observed and reduced heat flow in the Great Basin. This evidence is consistent with the distribution of Quaternary volcanic rocks and the abundance of thermal springs in the region. Lachenbruch and Sass (1978) suggested that much of the anomalous heat is transferred from the asthenosphere by convection accommodated by pervasive flow of the crust and/or intrusion of magma. They developed thermomechanical models of these processes and demonstrated a relationship between heat flow, asthenosphere flux, lithosphere thickness, extension rate and the rate of production of basalt magma in the mantle. Extension, based on their heat flow models, was facilitated through brittle fracturing and penetration of the crust by basalt dikes or by warming and thinning of the crust through underplating by basalt. The Yucca Mountain region is located in a region of lower heat flow called the Eureka Low. The lower heat flow of this zone may, however, be an effect of reduction of the background heat flow by ground water flow (Sass et al. 1987). Suppe et al. (1975), Eaton et al. (1978) and Eaton (1982) noted the high average elevation of the Great Basin (> 1.4 km) and the general coincidence of this area of high topography with areas of high heat flow. Eaton (1982) concluded that the high topography of the region is best explained by vertical expansion of the lithosphere as of result of heating from below.

An additional major feature of the Great Basin is its position in a regional gravity low (Eaton et al. 1978; Eaton 1980, 1982; Hildenbrand et al. 1988; Hanna et al. 1989). Eaton et al. (1978) described the collection of associated features that provide constraints on the gravity field and tectonic setting of the Great Basin. These features are the low Bouguer gravity field with a bilateral distribution of long wavelength anomalies, the thin crust, the high heat flow, the past record of widespread magmatic activity, the concentration of Quaternary volcanic rocks at the east and west margins, and widespread extensional faults.

Jones et al. (1992) examined the geological, geochemical, and geophysical data for the central part of the basin-range province. They note that there is significant heterogeneity in the record of the response of the mantle and crust to Cenozoic extension. Jones et al. (1992) suggest that limited topographic differences between strongly extended and largely extended regions of the central basin and range requires lateral flow of crustal material into the extended areas. They summarized geochemical data supporting movement of crustal material. Specifically, isotopic data for basaltic rocks show that ancient lithospheric mantle is preserved beneath the central basin and range (Vaniman et al. 1982; Farmer et al. 1989; Jones et al. 1992) while to the north and west, asthenospheric mantle lies beneath the crust.

The most buoyant and by inference warmest mantle lies under the Sierra Nevada range, and not under the strongly thinned crustal sections of Death Valley and Lake Mead (Jones et al. 1992).

Aeromagnetic data for the state of Nevada and the southern Great Basin were compiled by Hildenbrand and Kucks (1988) and Hildenbrand et al. (1988). Blakely (1988) used a two step process to calculate apparent magnetization contrasts for these data. He analyzed the distribution of the Curie temperature isotherm and the tectonic implications of regional features from an analysis of the aeromagnetic data. One of the most prominent features of the region is the presence of a magnetic "quiet zone"--a zone on the aeromagnetic map of Nevada showing a lack of magnetization contrasts. This feature has commonly been interpreted as the product of a relatively shallow depth to the Curie temperature isotherm (Zeitz et al. 1970; Christiansen and McKee 1978). However, Blakely (1988) showed that the absence of short-wavelength anomalies in the quiet zone cannot be explained by a shallowing of the Curie temperature isotherm. He noted that deep magnetic sources influence the long-wavelength anomalies not the short-wavelength attributes. Blakely (1988) examined alternative causes and suggested the quiet zone may be caused by intense hydrothermal alteration that could diminish the magnetic properties of the magnetic rocks (see Eaton et al. 1978).

Blakley (1988) described the northern Nevada rift, a north-northwest trending zone of aeromagnetic anomalies that is best developed in north central Nevada. This rift zone is inferred to be underlain by mafic extrusive and intrusive rocks that formed in response to mid-Miocene extension (Zoback and Thompson 1978). The rift zone ends in central Nevada but gravity data indicate the rift could extend further south (Blakley 1988). The gravity anomalies to the south are probably produced by upper crustal sources (Simpson et al. 1986) and may coincide with thick low density fill of caldera complexes (Carr 1990).

Blakley (1988) applied a Fourier domain technique, noting carefully the assumptions and cautions of this method, to the Nevada aeromagnetic data to estimate basal depths of magnetic sources. Two regional features persist in the analysis that correlate with recognized heat flow anomalies. These are the Battle Mountain high and the Eureka low. The Battle Mountain high is an area of shallow depth to the Curie temperature isotherm and coincides with an area of exceptionally high heat flow (Lachenbrach and Sass 1978). The Eureka low has an unusually deep basal depth to the Curie temperature isotherm (> 25 km; Blakley 1988). This correlation is not expected if the Eureka low is caused by a near-surface hydrologic phenomena (contrast with Sass et al. 1987). It must be associated with more deep seated features. Especially notable, again, are the coincidence of this area with the amagmatic gap and an area of probable preservation of lithospheric mantle (Farmer et al. 1989; Jones et al. 1992).

Patterns of historic seismicity broadly outline the borders of the Great Basin with diffuse but significant seismicity in the interior parts (Smith and Sbar 1974; Smith 1978; Engdahl and Rinehart 1988; Hildenbrand et al. 1988; see Fig. 3.4 this paper). Distinct zones of seismicity extend along the western margin of the province (east edge of the Sierra-

Nevada range, Owens valley-Long Valley region). A secondary belt of seismicity extends from this zone into central Nevada. The eastern margin of the Great Basin is defined by the southern intermountain seismic belt (Smith 1978). A somewhat diffuse zone of east-west seismicity extends across the southern Great Basin through the Yucca Mountain region (Smith and Sbar 1974). The record of seismicity in the latter area has been complicated, however, by underground explosions from testing of nuclear weapons in the Nevada Test site. A somewhat diffuse but distinctive zone of seismicity extends around the borders of the Colorado Plateau (Smith 1978; Engdahl and Rinehart 1988). There is an approximate although imperfect correlation between zones of seismicity in the Great Basin and Quaternary faulting (Naturka et al. 1982; Hill 1982; Carr et al. 1988). However diffuse seismicity commonly does not coincide with surface faults, and seismic slip at depth may be discordant with fault patterns (Arabasz and Julander 1986, Gomberg 1991a,b). Focal depths tend to be shallow and rarely exceed 20 km (Smith 1978; Eaton 1982).

The Great Basin is characterized, from seismic studies, by a relatively thin crust (< 30 to 35 km; Mooney and Braile 1989; Benz et al. 1990; Jones et al. 1992). Mooney and Braile (1989) noted slightly lower crustal seismic velocities of the basin and range province (6.2 km sec^{-1}) and the local presence of a high-velocity basal crustal layer (7.3 to 7.5 km sec^{-1}). The latter may be consistent with intrusion of mantle melts into the lower crust (Lachenbrach and Sass 1978; Okaya and Thompson 1986). An important feature of this region is the anomalously low-velocity, low-density upper mantle (Priestley et al. 1982; Benz et al. 1990; Holbrook 1990; P wave velocities 7.6 and 7.9 km sec^{-1}). Jones et al. (1992) emphasized that there is not a close correlation between buoyancy of the crustal column and degree of crustal extension. They suggest that the style of lithospheric extension must vary both along and across the strike of the Great Basin.

IV. TECTONIC SETTING: YUCCA MOUNTAIN REGION

We examine, in this section, the Yucca Mountain region, focusing on the structure of Yucca Mountain and the adjacent Crater Flat basin. The Crater Flat basin contains most of the sites of the Pliocene and Quaternary basaltic volcanism. The most recent descriptions of the tectonic setting of the area (Hamilton 1988; Carr and Monsen 1988; Wright 1989; Scott 1990; Carr 1990; Fridrich and Price 1992) are emphasized because these discussions reflect the recent addition of data acquired through the site characterization studies for the potential Yucca Mountain site.

Yucca Mountain, as noted in the Section II of this paper, forms part of the south flank of the Timber Mountain-Oasis Valley caldera complex (TM-OV; Byers et al. 1976; 1989; Christiansen et al. 1977; Noble et al. 1992). This caldera complex, a Miocene volcanic feature, is still relatively well expressed physiographically (Fig. 3.5). Many of the constructional features formed during volcanic eruptions (caldera depression, resurgent dome) are only partly modified by erosion. The caldera depression is outlined by a circular valley. The modern valley has expanded from the size of the original collapse feature by outward erosion of the caldera walls. The resurgent dome of the caldera, Timber Mountain, is a topographic high. It trends northwest, parallel to the Walker Lane structural zone. The

Timber Mountain-Oasis Valley caldera complex is flanked on the north, northwest and south by plateau highlands constructed and upheld by voluminous ignimbrites subsequently offset by normal faults. The TM-OV caldera complex is bordered to the east by high topography upheld by a north-northwest trending zone of structurally high standing, Paleozoic rocks (predominantly carbonate and argillite lithologies). Further east, Yucca Flat is a deep, down-faulted, north-trending basin. A younger sequence of ignimbrites, the Thirsty Canyon Tuff, was erupted from the Black Mountain caldera located northwest of the TM-OV complex (Noble and Christiansen 1974; Noble et al. 1984; 1992). Ash-flow sheets of these units overlie outflow facies of the Timber Mountain Tuff and extend into the caldera depression of the TM-OV complex. The west side of the TM-OV includes the Sleeping Butte and Oasis Valley caldera segments.

Ekren et al. (1968) documented two sets of basin-range faults in the Nevada Test Site and Nellis Air Force Range. They noted that basin-range faults trend northwest and northeast. These faults locally predate The Belted Range Tuff (14 Ma) and may have formed as early as about 26 Ma (Ekren et al. 1968). A second set of north trending faults is constrained by stratigraphic relations to be younger than about 18 Ma. These faults had well developed, probable fault-controlled topography prior to the eruption of the Thirsty Canyon Tuff (Ekren et al. 1968). Extensional faulting in the Yucca Mountain vicinity is largely contemporaneous with early volcanic activity about 14-16 Ma (Christiansen et al. 1977; DOE 1988). However, Byers et al. (1976) showed that this faulting did not strongly effect the distribution of the Paintbrush Tuff (12.8 Ma) particularly across the southeast, south and southern parts of the Nevada Test Site region. There are suggestions of a poorly documented phase of tectonism, possibly basin and range tectonism, that predates the Paintbrush Tuff (Snyder and Carr 1984; Fox and Spengler 1989; Wright 1989; Carr 1990). Snyder and Carr (1984) presented evidence of possible pre-Paintbrush normal faulting including a greater degree of displacement of Paleozoic rocks compared to the overlying section of ignimbrites, and evidence of a possible fault controlled Paleozoic surface extending beneath Yucca Mountain near Busted Butte. Evidence is persuasive that a younger episode of range-bounding faulting postdates eruption of the Paintbrush Tuff (12.8 Ma) and partly predates but locally involves the Timber Mountain Tuff (11.4 Ma; see Scott 1990; Carr 1990).

Considerable work for the site characterization studies is continuing as a part of assessing the risk of future seismic activity for the potential Yucca Mountain site. A key concern is defining the state of recent tectonic activity. A number of authors have presented arguments (see W. Carr 1984; M. Carr et al. 1988; Scott 1990) that strain rates have decreased markedly from a maximum in the Miocene but continue to show a low degree of activity in the Quaternary. The youngest tectonic activity may reflect a renewed episode of faulting and volcanism starting in the Pliocene and continuing in the Quaternary (Fox and Carr 1989). However a major difficulty in documenting this conclusion is the time gap in the geologic record between the eruption of the Timber Mountain Tuff (11.4 Ma) and the oldest basin-fill deposits of the alluvial valleys. Very limited geologic data are available to constrain rates of tectonism during this gap in the geologic record.

Scott (1990) provided the most complete description of the shallow structure of Yucca Mountain, based on detailed geologic mapping at a scale of 1:12,000 (Scott and Bonk 1984). He argued that Yucca Mountain has been modified by structures associated with extended terranes of the basin and range province and sites of oroclinal bending typical of the Walker Lane structural system. Scott (1990) described the mountain as a series of east-tilted, fault-controlled ridges that bifurcate southward. The southern part of the mountain shows an increase in the number of faults, an increase in the offset along the faults, a decrease or shallowing of the west dip of the faults, and an increase in the amount of east-tilt of the volcanic section. Paleomagnetic data from the Tiva Canyon member of the Paintbrush Tuff suggest progressive north-to-south (25 km) clockwise rotation of the range about a vertical axis (Scott 1990; Rosenbaum et al. 1991).

Scott (1990) summarized three types of evidence that the major normal faults of Yucca Mountain are listric (flattening downward). First, he cited a 12° decrease in the dip of a fault cutting the west slope of Busted Butte. Second, he noted, based on drilling data, a decrease in dip of about 21° km^{-1} for the Ghost Dance fault. The third line of evidence is an increase in stratal dips on the east side of tilted fault blocks (compared with the west side). Scott (1990) inferred the presence of a low-angle normal fault as an accommodation structure beneath Yucca Mountain. Such an interpretation requires the faults of Yucca Mountain to form a low angle stack of normal faults above a basal detachment fault. The east bounding break-away zone for a detachment system could be the Paintbrush Canyon fault (Fox and Carr 1989) or a structural zone bounding the east side of Yucca Mountain (Brocher et al. 1993).

Hamilton (1988) described detachment faulting in the Death Valley region of California and Nevada. He suggested that detachment faults exposed in Bare Mountain, the Bullfrog Hills, and the Funeral Mountains may be domiform exposures of a single west-northwest dipping fault surface that was eroded as the upper plate of the Grapevine Mountains slid westward. Key points of the Hamilton model (1988) are twofold. First, the detachment faults may be major, initially west-dipping faults that were raised and rotated as they were unroofed progressively by tectonic denudation. Second, the detachment systems decrease in age to the west with the youngest activity in the Death Valley region. Hamilton (1988) agrees with the model of Scott (1990) that the middle Miocene faulting of Yucca Mountain represents a headwall complex that allowed slip on the Bare Mountain detachment fault to reach the surface. However, Hamilton (1988) argues that the displacement of these faults only applies to the final "gasps" of detachment slip. Thus most of the detachment deformation predated the episodes of extensional faulting that displaced the ignimbrite sheets of Yucca Mountain.

Another perspective for the regional models of detachment systems is provided by M. Carr and Monsen (1988). They accept the continuous detachment model of Hamilton (1988) but argue that the faults of Yucca Mountain have a different movement history than the extensional terrain of Bare Mountain and the Bullfrog Hills. Fox and Carr (1989) endorse the detachment models but argue that the listric nature of normal faults at Yucca Mountain can be neither confirmed nor refuted based on current data.

Nearly all proponents of the presence of regional detachment systems relate the extensional faulting of the Yucca Mountain region to either late stage episodes of regional detachment faulting or to subsequent and possibly unrelated uplift. These differences have important implications on the timing of past faulting, the degree of modern tectonic activity and the seismic risk for Yucca Mountain. However the important perspective for understanding the distribution of basaltic volcanism is the possible role of detachment faults in providing crustal pathways for ascent of basalt magma. The differences between the detachment models are less important than the issue of whether detachment system(s) are present in the Yucca Mountain region and could, in the modern tectonic setting, provide ascent pathways for basaltic magma.

A largely different tectonic model for the Yucca Mountain setting has been proposed by W. J. Carr and associated co-authors (W. Carr 1984; Snyder and Carr 1984; Carr and Parrish 1985; Carr et al. 1986; W. Carr 1988). They suggest Yucca Mountain is bordered to the east by a caldera complex, the Crater Flat-Prospector Pass Caldera. The collapse of two proposed, nested calderas was followed by infilling of the caldera depression by ignimbrites of the Paintbrush and Timber Mountain Tuffs and alluvial sediments (Fig. 3.6). These volcanic and sedimentation events are inferred to have formed the Crater Flat basin. Carr et al. (1986) and W. Carr (1988) suggested the caldera is divided into two parts. The northern part of the caldera, the Prospector Pass caldera segment, is believed to be the source of the Tram Member of the Crater Flat Tuff. The larger Crater Flat-Prospector Pass caldera complex is believed to be the source of the Bullfrog and Prow Pass members of the Crater Flat Tuff. Evidence for the caldera complex includes: 1) the circular or similar circular shape of the southern part of Crater Flat; 2) the large compound gravity low of Crater Flat (nearly 50 mGal) which is inferred to be produced by an infilled compound caldera depression; 3) the distribution and thickness of the individual members of the Crater Flat Tuff; 4) local arcuate dike systems are present in Bare and Yucca Mountains and may represent ring-dikes of the caldera complex; 5) the presence of a thick local wedge of monolithologic breccia, resembling collapse breccia, in the upper part of the Bullfrog Member near the south edge of Crater Flat; and 6) the truncation in Crater Flat of a persistent east-west aeromagnetic anomaly.

M. Carr and Monsen (1988), Hamilton (1988), Scott (1990), and Fridrich and Price (1992) summarized arguments against the Crater Flat depression being a caldera complex. The primary arguments are several. First, the facies variations of the Crater Flat Tuff do not appear consistent with a caldera source in Crater Flat. Second, the stratigraphic sequence noted in VH-1 and VH-2, particularly the absence of a break between the Prow and Bullfrog members of the Crater Flat Tuff, are inconsistent with the presence of a caldera in southern Crater Flat. Third, the gravity data indicate the Crater Flat basin extends in the subsurface southward beyond the south Crater Flat physiographic margin and thus is not uniquely associated with the proposed caldera structure. Fourth, intrusive dikes inferred to follow the ring-fracture zone and mark the margin of the calderas may simply follow local basin-range structure.

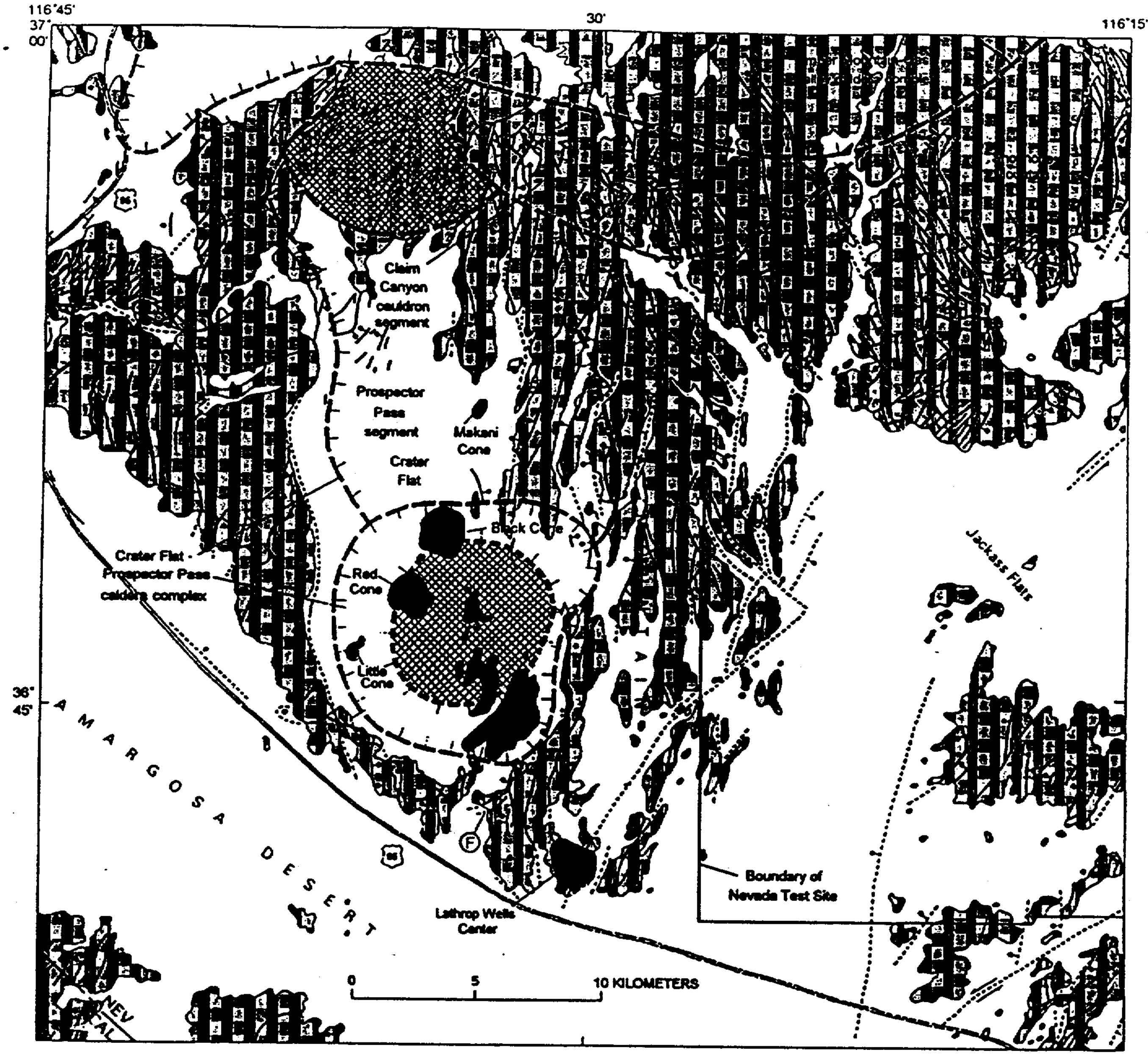

Fig. 3.6 Proposed caldera complexes and Pliocene and Quaternary basaltic volcanic rocks of the Crater Flat area (modified from Carr, 1988). Snyder and Carr (1984), Carr and Parrish (1985), Carr et al (1986) and Carr (1982; 1984; 1988; 1990) propose that the southern part of Crater Flat is underlain by the Crater Flat caldera, and the northern half of the Crater Flat basin is a segment of the larger Prospector Pass caldera. The Pliocene and Quaternary volcanic rocks of Crater Flat occur in the moat zone and across the resurgent dome of the proposed Crater Flat caldera and one center is located in the Prospector Pass caldera segment. The Quaternary basalt centers of the Crater Flat area are located and labeled on the figure.

W. J. Carr extended his concepts of the tectonic setting of the Yucca Mountain region and attempted to accommodate his caldera models with models of detachment faulting (Carr 1990). He suggested the Yucca Mountain region is split by a north-trending volcano-tectonic rift that encompasses several coalesced caldera complexes. The proposed rift represents a pull-apart or a right-stepped zone of rifting in the larger Walker Lane structural system. Carr (1990) suggests the rift became a breakaway zone for detachment faulting to the west. To the east, the normal faults are probably not associated with a recognized major detachment system. The importance of this proposed rift, the Kawich-Greenwater rift (Carr 1990), is its structural trend. The rift, or structural trough trends north-south from the Greenwater Range, on the east flank of southern Death Valley, through the Yucca Mountain area to Kawich valley (Carr 1990; Fig. 3.7, this paper). This proposed rift zone obliquely spans part of the Walker Lane structural zone in the southern Great Basin and encompasses the potential Yucca Mountain site. The rift could provide a controlling structure for the location of the past and possibly future occurrences of basaltic volcanic rocks in the Yucca Mountain region.

Characteristics of the Kawich-Greenwater rift include (all from Carr 1990):

1. It is identified structurally on the north and south by aligned caldera complexes and by closely spaced sets of north-to-northeast-trending faults that offset the ignimbrite outflow sheets. These fault systems may be distinguished by their close surface spacing and the geometry and distribution of offset of the Timber Mountain Tuff. Part of the fault system is exposed in a northeast zone extending across Pahute Mesa. An inferred related fault zone extends through Yucca Mountain (Carr 1990; his figure 6).

2. The west side of the rift is structurally more abrupt than the east forming an asymmetrical graben structure.

3. The axis of the rift, particularly on the south side, may be marked by a diffuse gravity low in the regional Bouguer gravity map.

4. Volcanism occurred along the length of the rift, primarily during the Miocene. Large volume eruptions associated with caldera centers in the Yucca Mountain region concluded with the eruption of the Timber Mountain tuff and associated units about 11.5 Ma. Tectonic activity in the area diminished markedly since the termination of silicic eruptions. The southern part of the rift was active about the same time as the northern rift, but silicic eruptions continued in the latter until about 5 Ma.

5. The Kawich-Greenwater Rift lies near and parallel to a regional volcano-tectonic feature called the Death Valley-Pancake Range basalt belt (Carr 1984), a zone marked by basaltic volcanism of primarily Pliocene and Quaternary age.

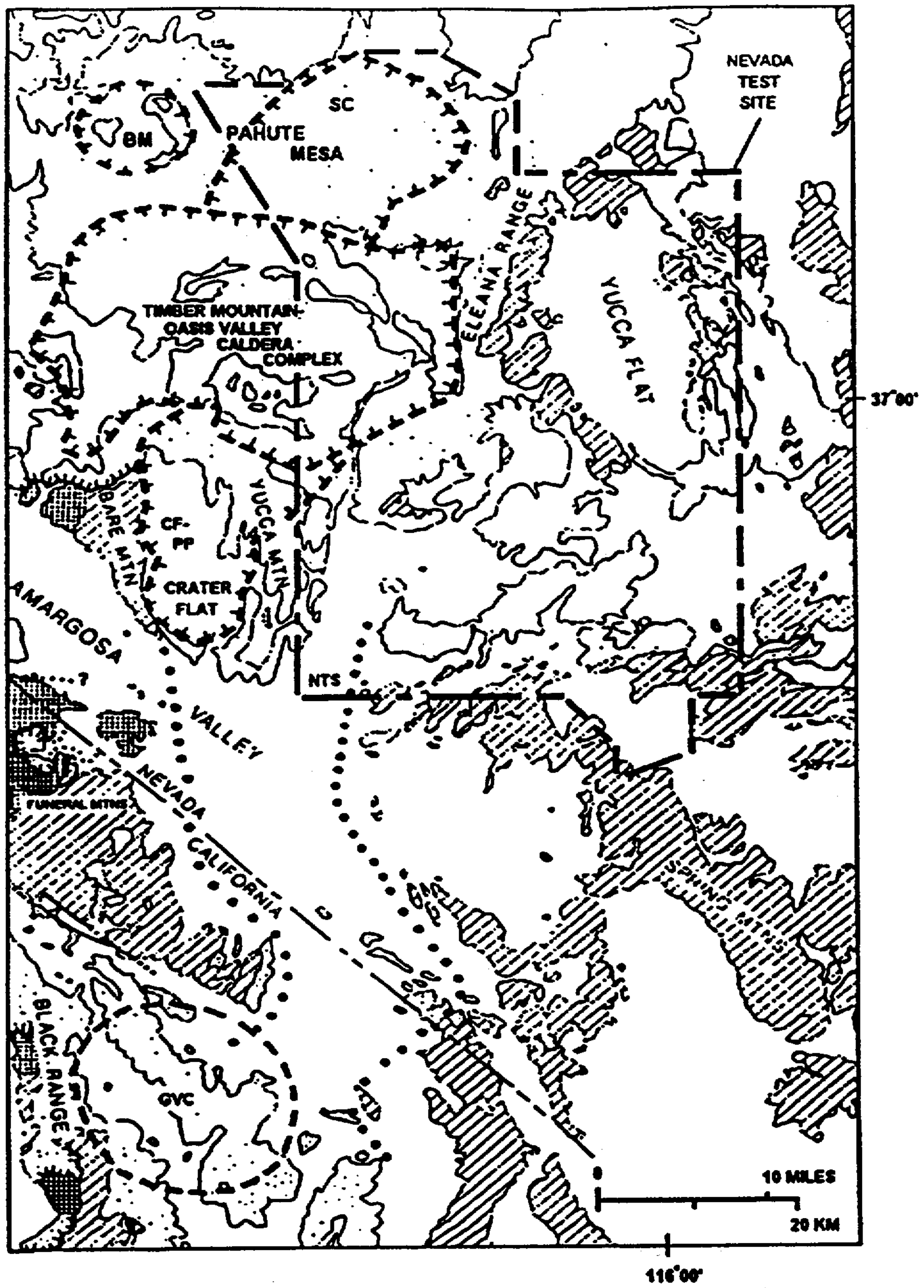

Fig. 3.7 Kawich-Greenwater rift zone after Carr (1990). The zone is marked by an alignment of coalesced caldera complexes of the Timber Mountain-Oasis Valley caldera complex. It extends south across the Amargosa Valley into the Death Valley area of California.

6. Faults of the Yucca Mountain area are inferred not to be detachment faults but are related instead to gravity sliding into a topographic low formed by a graben structure in Crater Flat.

7. The presence of Pliocene and Quaternary basalt in the Crater Flat area indicates the "... process of rifting may be continuing but at a very much reduced rate and probably under a different stress regime than in the Miocene" (Carr 1990, p. 290). These basalts are inferred to have followed ring-fracture zones of calderas at depth and diverted to northeast-striking tension fractures as they neared the surface.

An additional and alternative model of the tectonic setting of Yucca Mountain involves episodes of older strike-slip faulting. Wright (1989) argues that detachment systems typical of the Death Valley area are not regional features. He suggests instead that they are unconnected systems that were bounded originally by strike-slip faults. The timing and style of development of low angle detachment faults by this model are dependent on the history of faulting of individual basins; the detachments are not of regional extent.

Wright (1989) infers that the Crater Flat basin may be the north part of a zone of pull-apart basins called the Amargosa Desert Rift Zone (ADRZ). This structure encompasses a series of structural blocks bounded by segments of strike-slip faults connected by en echelon, obliquely oriented normal faults (Fig. 3.8). The primary evidence in support of this rift is threefold. First, a series of gravity lows is inferred to define pull-apart basins extending to the south and southeast of Crater Flat (Wright 1989). Second, pull-apart basins associated with extensional and strike-slip faulting have been documented in other adjoining areas of the Basin and Range (Death Valley, Emigrant Valley). Third, northwest trending faults of the Pahrump Valley area may be still active strands of basin bounding, strike-slip faults.

Pull-apart activity based on the Wright model (1989) may have began in the Yucca Mountain region as early as 14 to 16 Ma. This activity was replaced in time by predominantly normal faulting. The Crater Flat basin, with associated sites of volcanic activity could represent a northern segment of the ADRZ. A strike-slip component of the late Miocene (< 12.4 Ma) basin development is suggested by the rotation of the Tiva Canyon Member as inferred from paleomagnetic data (Rosebaum et al. 1991).

The Wright (1989) model shares many common features with the Kawich-Greenwater rift model of Carr (1990). A key difference is that the Wright model attributes basin formation primarily to tectonic processes; volcanic activity may be only subsidiary to tectonic activity. The Carr model, relates development of the northern part of the Kawich-Greenwater rift zone to volcanic process with tectonic activity secondary. The models overlap and are in agreement largely for the south part of the proposed rifts. Both models emphasize development of tectonic rifts or pull-apart zones south of Crater Flat extending to Death Valley (Wright 1989; Carr 1990). Wright (1989) suggests that the ADRZ may not connect with the southern Death Valley volcanic field, but instead with a pull-apart basin formed in Pahrump Valley. Carr (1990) extends the Kawich-Greenwater rift into the

Fig. 3.8 Amargosa Desert Rift zone superimposed on the Bouguer gravity map (modified from Wright, 1988). The rift zone extends from Crater Flat on the north, south-southwest across the Amargosa Valley and bifurcates into the Stewart Valley (SV) and Pahrump Valley (PV) basins, and the central Death Valley plutonic-volcanic field (DV).

volcanic and pull-apart basins of the southern Death Valley. The most marked differences in the rift models are for the origin of the Crater Flat basin. Carr (1990) maintains that the creation of the Crater Flat depression is from caldera collapse associated with cycles of ash-flow eruption. He notes, however, that the caldera collapse may have been contemporaneous with or modified by rifting and graben formation.

The absence of distinctive magnetic anomalies in or beneath the alluvial fill of the Amargosa Valley suggests the proposed pull-apart basins of the valley were not accompanied by eruption of voluminous volcanic rocks (Kane and Bracken 1983; Wright 1989). Wright suggests the timing of development of the basins of the Amargosa Valley is pre-Paintbrush (>13 Ma). His arguments are based on the geologic relations of the Crater Flat-Prospector Pass caldera and a K-Ar age of 13.2 Ma for an ash found in sedimentary fill near Ash Meadows.

A related but slightly different origin for the Crater Flat basin was inferred by Schweickert (1989). He proposed the presence of a buried right-slip fault that transects the southern Amargosa Valley and Crater Flat basin. A cumulative offset of about 26 km was inferred along the fault zone based on offset of a distinctive overturned fold-thrust system of Mesozoic age. The lack of surface expression of this fault lead Schweickert (1989) to suggest that activity on the fault predates the Paintbrush Tuff. He argues however, that the clockwise rotation of the Tiva Canyon member may indicate continued shear strain along the fault. Schweickert (1989) notes further that the strong northwest-trending alignment of the Quaternary volcanic centers (CFVZ) may mark the fault trace. This model is largely compatible with a pull-apart origin of Crater Flat. However, the strike-slip model of Schweickert (1989) requires only a single strike-slip fault. The rift model of Wright (1989) requires that the basins of the rifts formed by movement on a combination of en echelon northwest-trending faults. The latter interpretation is more consistent with the gravity data of southern Crater Flat and the Amargosa Valley. Both areas show distinct zones of northwest-trending gravity lows outlining en echelon basins (Wright 1989).

A modification of the pull-apart models was presented by Fox and Carr (1989). They suggested that the resumption of basaltic magma in Crater Flat about 3.7 Ma marked a renewed episode of extensional tectonism in the Yucca Mountain area. The eruption sites of the basalts were inferred to coincide with an axis of extension and crustal pull-apart between east-dipping faults of Bare Mountain and west-dipping faults of Yucca Mountain. O'Neil et al. (1991) described evidence of strike-slip faulting and oroclinal bending of Yucca Mountain. They suggested, based on fault geometry, fault offsets, and paleomagnetic data that formation of strike-slip, pull-apart basins on scales of meters to kilometers may be an ongoing process. Both the Fox and Carr (1989) and the O'Neil et al. (1991) require extension and pull-apart formation to be an active process, albeit much reduced from an earlier episode of Miocene extension. Fridrich and Price (1992) provided expanded data on the origin of Crater Flat based on new surface mapping. They note that the basin is bounded on the south by a northwest-trending, right-slip fault, and possibly to the northeast by an inferred right-slip fault beneath Yucca Wash. Fridrich and Price (1992) note increased faulting and tilting of the volcanic sections bordering Crater Flat with age suggesting the basin formed from intermittent tectonism from about 15 to < 11 Ma. They suggest the Crater Flat basin formed by synchronous east-west extension and north-west right-slip forming a half-rhombochasm.

V. TECTONIC SETTING: TIME-SPACE PATTERNS OF THE DISTRIBUTION OF BASALTIC VOLCANISM

This section examines the distribution of basaltic volcanic rocks in the region by the defined basaltic episodes (Crowe 1990; see also Section II, this paper) and attempts to relate the time-space patterns of volcanism to the tectonic models of the Yucca Mountain region.

A. Silicic Episode

The distribution of the oldest sites of basaltic volcanism, the basalt of the silicic episode (BSE) is shown on Fig. 3.9. Two major patterns are exhibited by this basalt episode: 1) Spatial relationships to caldera complexes, and 2) Distribution parallel to the Walker Lane structural zone.

Many of the basalt units occur in or along the flanks of the large caldera complexes of the TM-OV caldera complexes (Fig. 3.9). The basalt of Dome Mountain was erupted in the moat zone of the Timber Mountain caldera (see Section II). Basaltic volcanic rocks are present on both the north and south flank of the Black Mountain caldera. These rocks underlie and overlie the Thirsty Canyon Tuff. An extensive sequence of basaltic volcanic rocks is present in the subsurface along the west, south, and southeast margins of Crater Flat (Kane and Bracken 1983; Crowe et al. 1986). These basaltic rocks were penetrated in VH-2 (Carr and Parrish 1985). The basalt lavas may have erupted along the ring fracture zone of the proposed Crater Flat-Prospector Pass caldera. Alternatively the basaltic rocks may have erupted at the margin of a strike-slip bounded, pull-apart basin. The presence of the basaltic volcanic rocks is permissive with either model. However, the age difference between the Crater Flat Tuff (14 Ma) and the basalt units (11 to 11.5 Ma) is more consistent with pull-apart models of the basin than the caldera model. North-south trending basalt dikes dated at 10 Ma (Scott 1990; Carr 1990) are exposed along the Solitario Canyon fault at the northwest edge of the potential Yucca Mountain site (Fig. 3.10). The dikes are interpreted by Carr (1984) to follow the eastern edge of the Crater Flat-Prospector Pass caldera. Alternatively, as noted by Scott (1990), the dikes may follow basin-range faults.

The basaltic volcanic rocks of Little Skull and Skull Mountains (10 Ma; Crowe et al. 1983) exhibit no obvious relationships to caldera complexes. They occur on the south and southwest flanks of the 15 Ma Wamonie-Salyer volcanic center. However, the age difference between the volcanic groups (10 Ma versus 14 Ma) suggests they are unrelated. Scattered volcanic rocks thought to correlate with the basalt of the silicic episode have been reported in drill holes in the Amargosa Valley (Brocher et al. 1993). The relatively subdued aeromagnetic signature of the Amargosa Valley suggests these basaltic rocks are not associated with major accumulations of volcanic rocks.

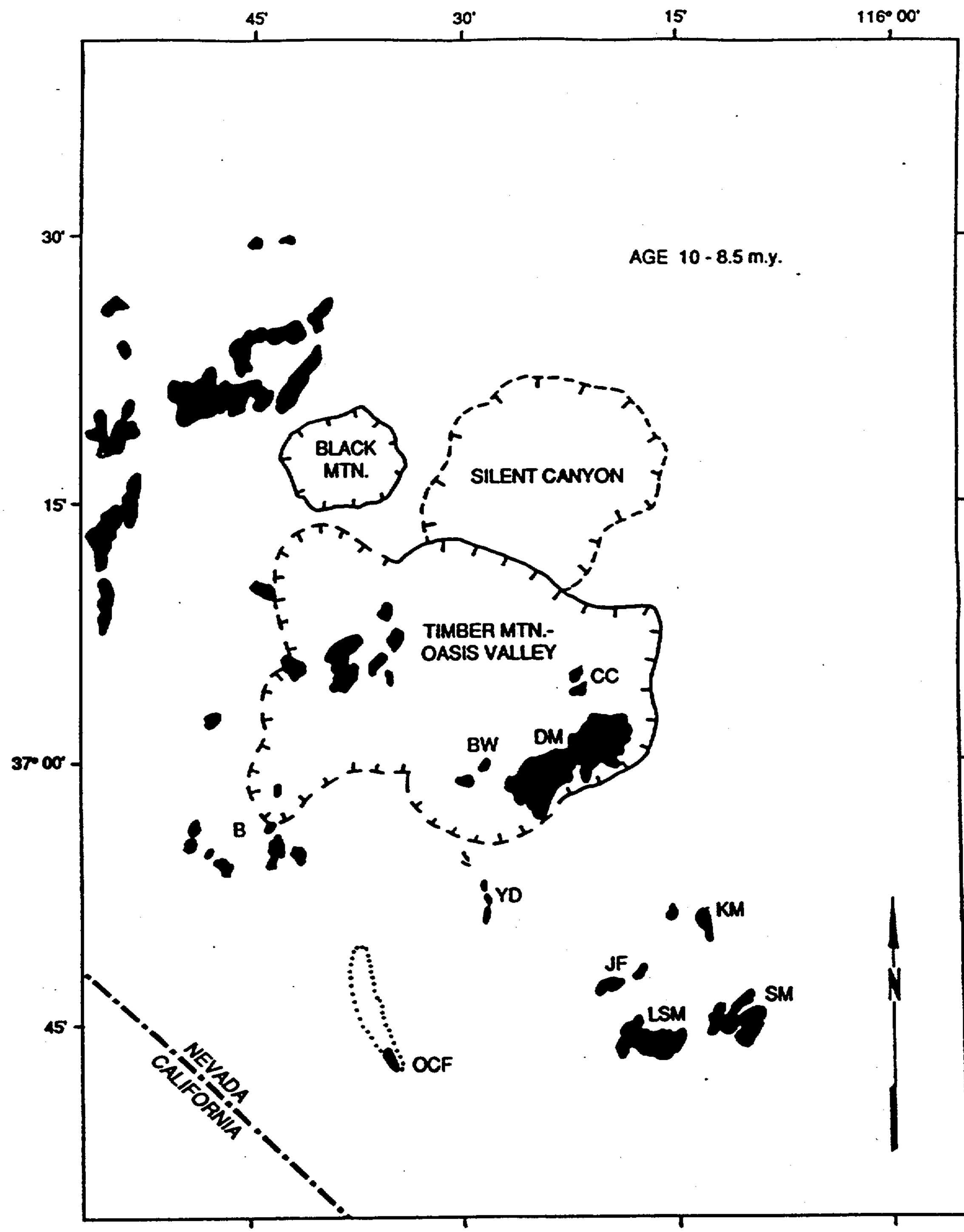

Fig. 3.9 Distribution of the Basalt of the Silicic Episode (BSE). CC: basalt of Cat Canyon, DM: basalt of Dome Mountain, BW: basalt of Beatty Wash, B: basalt of the Beatty area, SM: basaltic andesite of Skull Mountain, LSM: Little Skull Mountain, KM: mafic rocks of Kiwi Mesa, JF: basalt of Jackass Flat, YD: dike of Yucca Mountain, OCF: older basalt of Crater Flat (modified from Crowe, 1990).

The basalt of the silicic episode is inferred to represent the ending phase of the major pulse of silicic volcanism associated with the TM-OV. The close association in space and time between silicic and basaltic magmatism strongly suggests the magmatic events are related. Incursion of basaltic magma into the interior parts of the TM-OV suggests the underlying silicic magma was sufficiently crystallization to permit the upward propagation of basalt magma. A closing phase of basaltic volcanism is recognized at the end or waning stage of volcanism at many silicic centers in the southwest United States.

B. Post-caldera Basalt

An evaluation of the post-caldera basalt episodes shows several distinct patterns. The basalt cycles of the post-caldera basalt (PCB) are spatially restricted compared to the distribution of the basalt of the silicic episode. The latter basalt units (BSE) occur in a broadly distributed, northwest-trending band extending across a large part of the Yucca Mountain region (Fig. 3.9). In contrast, the PCB occur in two, relatively small northwest-trending bands (Fig. 3.10). The contrasting distribution of the basalt episodes is consistent with the close association in time between the basalt of the silicic episode and the waning stage of silicic volcanism. Basalt magma of moderate volume were erupted around the flanks of and locally in the caldera complexes in response to the waning thermal pulse that produced the large volume silicic volcanism. In contrast basalt units of the PCB are markedly smaller in volume and more restricted spatially. The volume decrease and lack of temporal or spatial association with the caldera complexes are consistent with the PCB representing a phase of basaltic volcanic activity that is unrelated to Miocene volcanism of the SNVF.

Volcanic rocks of the older post-caldera basalt (OPB) occur north and northeast of the potential Yucca Mountain site (Fig. 3.10). In contrast, all basalt centers of the younger post-caldera basalt (YPB), except one unit, the basalt of Buckboard Mesa, occur west and southwest of Yucca Mountain (Fig. 3.10). The boundary between the distribution of the two basalt episodes is shown on Fig. 3.11. This line, drawn by visual inspection, trends generally east-west and separates geographically the post-caldera basalt cycles. A second approach can be used to discriminate the basalt cycles geographically. Northwest-trending boundaries between the basalt cycles are drawn on Fig. 3.10 assuming the distribution of the units has been controlled by structural features of the Walker Lane zone (Crowe and Perry 1989). The boundaries between the cycles, so drawn, delineate northeast and southwest zones that overlap only in the area of the Timber Mountain caldera (Fig. 3.13). These spatially separate zones are consistent with a southwest migration or more correctly, a southwestward stepping, through time of the areas of basaltic activity (late Miocene to Quaternary; Crowe and Perry 1989; Crowe 1990). Note that the northwest trending boundaries are not drawn solely from the distribution of basaltic volcanic rocks. Instead the *orientation* of the lines is based on the distribution and structural features of Cenozoic volcanic rocks (Carr 1984; Crowe 1990) and the *location* of the lines is established from the distribution of the volcanic units of the PCB.

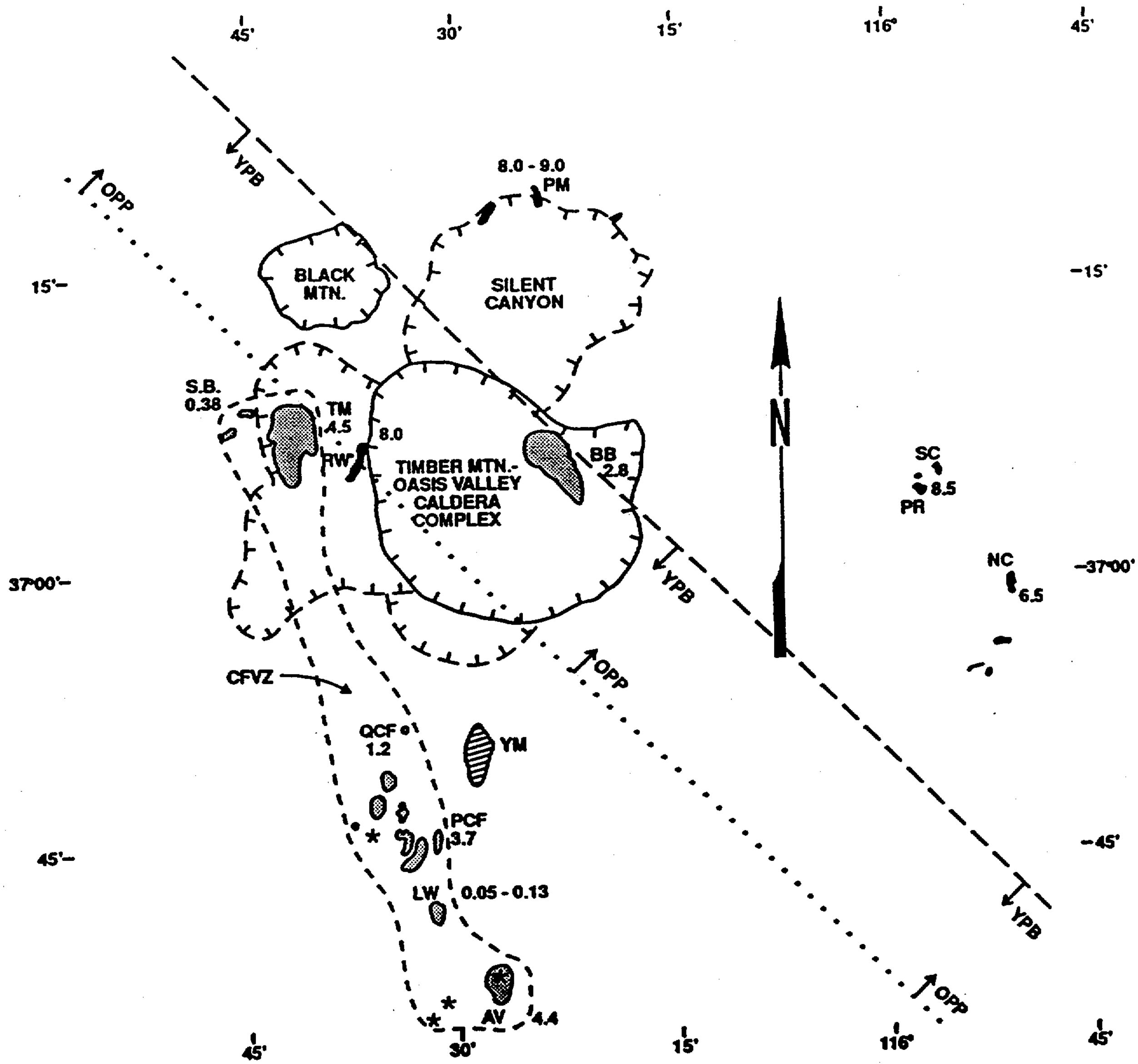

Fig. 3.10 Post-Caldera Basalt of the Yucca Mountain region. Shaded areas are the Older Post-Caldera Basalt (OPB) including: RW: basalt of Rocket Wash, PM: basalt of Pahute Mesa, SC: basalt of Scarp Canyon, NC: basalt of Nye Canyon. Stippled areas are the Younger Post-Caldera Basalt (YPB) including: TM: basalt of Thirsty Mesa, AV: basalt of Amargosa Valley, PCF: Pliocene basalt of southeast Crater Flat, BB: basalt of Buckboard Mesa, QCF: Quaternary basalt of Crater Flat,) SB: basalt of Sleeping Butte, LW: basalt of Lathrop Wells. Asterisks mark aeromagnetic anomalies identified as potential buried basalt centers or intrusions (Kane and Bracken, 1983, Crowe et al. 1986). Dashed line encloses the area of the Crater Flat Volcanic Zone (CFVZ). Numbers associated with the symbols for the OPB and YPB are the age of the volcanic centers in million years. The northwest-trending lines subdivide the OPB and the YBP into southwest and northeast fields with the boundaries following structural features of the Walker Lane structural system. Modified from Crowe and Perry (1989).

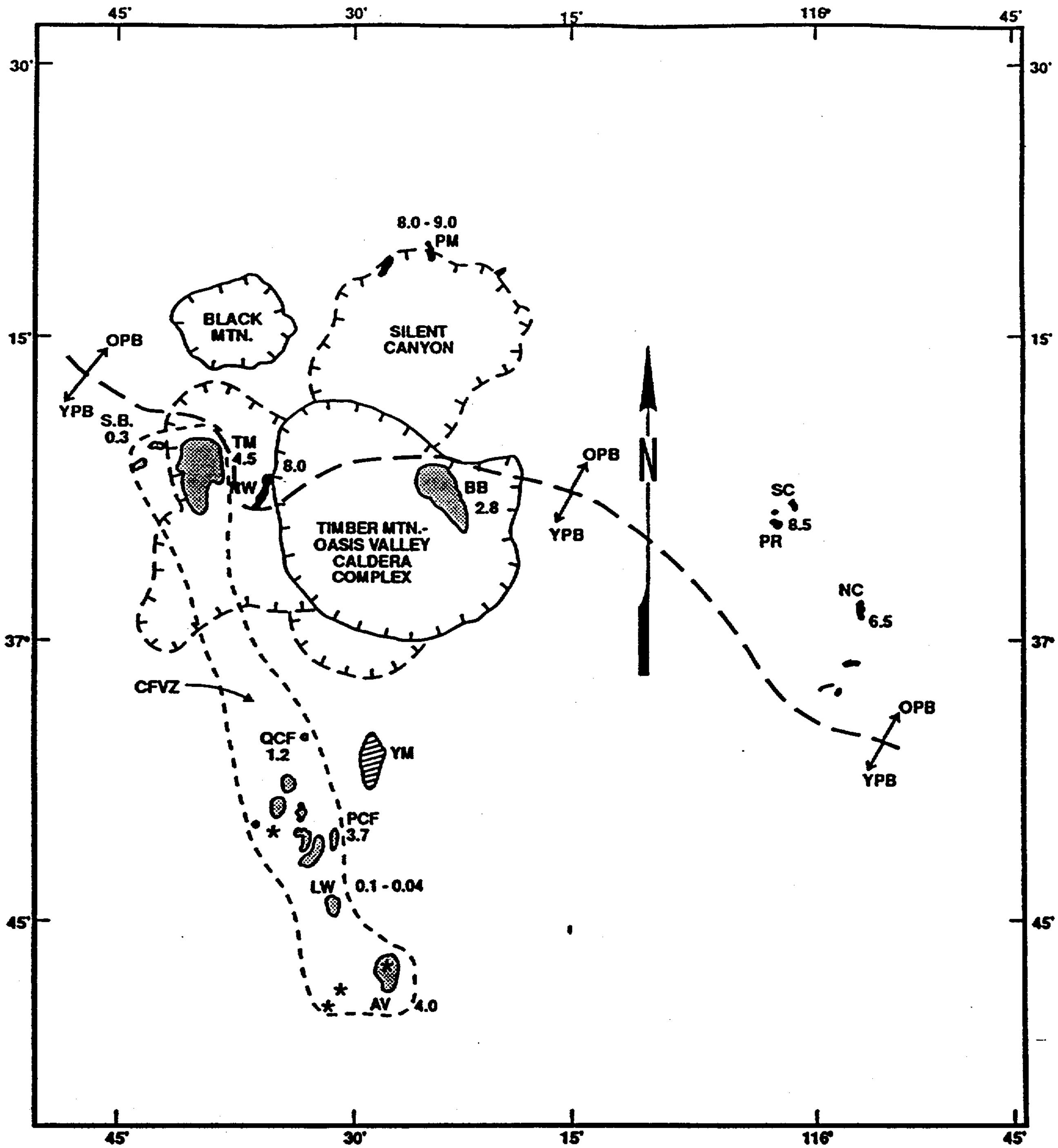

Fig. 3.11 Alternative geographic subdivisions of the Post-Caldera Basalt (PCB) episode of the Yucca Mountain region. Symbols and numbers are the same as Fig. 3.10. The thick dashed line is a line drawn visually that separates the Older Post-Caldera Basalt (OPB) and the Younger Post-Caldera Basalt (YPB). The OPB occur entirely north and east of the potential Yucca Mountain site. The YPB, except for the basalt of Buckboard Mesa (BB), are located south, west and northwest of the potential Yucca Mountain site.

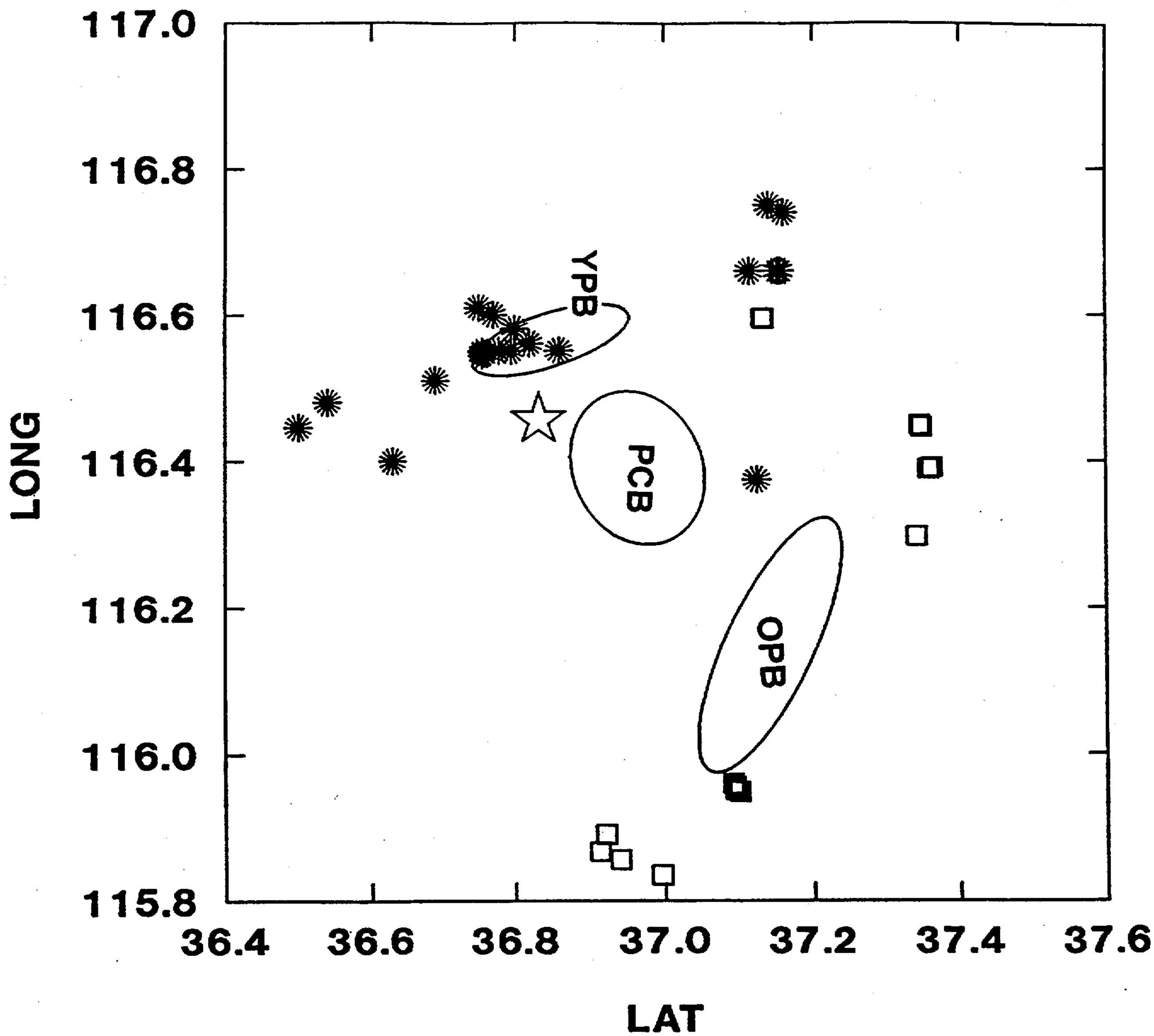

Fig. 3.12 Location of the distribution centroid by basalt cycle for the PCB. The centroid for each basalt cycle was calculated using the bivariate ellipse module of SYSTAT (Wilkerson, 1990). The centroid labeled OPB identifies the distribution of the OPB and trends northwest paralleling the approximate distribution of the basalt units of the OPB. The centroid labeled YBP identifies the distribution of the YPB. It is centered in Crater Flat and is elongate parallel to the Crater Flat volcanic zone. The centroid labeled PCB is the composite of the two basalt cycles. It is a meaningless calculation because of the different spatial distributions of the basalt cycles. Square symbols are the locations of vents of the OPB; asterisks mark the vents of the YPB. The large star is the location of the potential Yucca Mountain site.

An approach independent of tectonic models can be used to test different models of the time-space distribution of basaltic volcanic centers of the PCB. The time-space distribution of volcanism can be evaluated using unbiased statistical descriptors of the distribution of the basalt vents. If there has been no temporal migration, the statistical descriptors of the distribution of the units of the PCB should overlap and therefore be non-discriminatory. If there has been migration, the distributions should be spatially separate. Figure 3.12 is plot of the locations by latitude and longitude of the eruptive vents of the PCB, separated by basalt cycles. The centroid of the cycle distributions is calculated at the 90% confidence limit using a gaussian ellipsoid approximation of the vent distributions. This plot shows clearly that the distribution centroids of the basalt cycles are distinct spatially. A west-northwest trending ellipse is calculated for the centroid of the OPB. It is located in the northeast edge of the Timber Mountain caldera (Fig. 3.12) and parallels the distribution of the basalt units of the OPB. A spatially separate centroid is drawn at the 90% confidence limit for the basalt units of the YPB (Fig. 3.12). This ellipse is centered in Crater Flat and trends north-northwest parallel to the CFVZ (Crowe and Perry 1989). For comparison, the calculated centroid of all basalt vents of the PCB is also drawn on Fig. 3.12. This centroid is located in the southcentral part of the Timber Mountain caldera. It is meaningless because it bears no spatial relationship to the distribution of the basalt centers. The location of the centroids of the basalt distributions are based on the variance in the X and Y coordinates of the vents assuming a gaussian spatial distribution. This distribution assumption is probably not correct but the uncertainty introduced by the assumption is too small to reject the conclusion that the distributions of vents of basalt cycles of the PCB are distinctively different. These data are consistent with the proposed southwest stepping of volcanism through time in the Yucca Mountain area (Crowe and Perry 1989). Moreover, the variation in elongation of the centroids from west-northwest (OPB) to north-northwest (YPB) is consistent with a proposed clockwise rotation of the stress field through time (Zoback and Thompson 1978; Zoback et al. 1981; Zoback 1989).

C. Older Post-caldera Basalt

Basalt centers of the OPB show close spatial and temporal associations with sites of extensional faulting. The vents for the basalt of Rocket Wash are located on a north-south trending basin range fault that follows the approximate location of the ring-fracture zone of the Timber Mountain caldera (Lipman and others 1966; O'Connor and others, 1966). The three spatially separate eruptive centers of the basalt of Silent Canyon all occur on the Silent Canyon ring-fracture zone where it is intersected by northeast-trending basin-range faults (Orkild et al. 1969). Erosion has cut into these centers exposing feeder dikes. These dikes all trend northeast, paralleling the basin-range faults. These field relations are consistent with the shallow rise of magma along the planes of the basin and range faults (Orkild et al. 1969).

The basalt of Piaute Ridge occurs as a complex of basalt dikes, sills, and discordant intrusions with local preservation of surface lava flows and scoria cones (Byers and Barnes 1967; Crowe et al. 1983a; Valentine et al. 1992). Several sets of dikes that locally fed sills, intrude and follow northwest-trending basin-range faults. At several localities, the dikes are offset by northwest trending faults. These relations require that the basaltic magmatism closely accompanied extensional faulting (Crowe et al. 1983a). The basalt of Nye Canyon does not appear to follow existing bedrock structure. It forms an aligned set of four northeast trending, basalt centers. These centers are aligned parallel to the maximum compressive stress direction, the most likely direction of dike propagation in the modern stress field (Crowe et al. 1983a, Zoback 1989). This pattern of orientation of northeast trending basalt centers or clusters is repeated in the YPB. The basalt of Nye Canyon is significant for two reasons. First, it is the oldest basalt cluster that shows a northeast trend. Second, it is the only basalt unit of the OPB that exhibit orientations that cross-cut and are independent of prevailing bedrock structures.

D. Younger Post-caldera Basalt

Crowe and Perry (1989) described the distribution of the YPB. All centers, except for the basalt of Buckboard Mesa, occur in a narrow northwest-trending zone named the Crater Flat volcanic zone (CFVZ). Figure 3.13 shows a calculated best-fit line using least-squares linear regression of the locations of scoria cones of the Quaternary basalt centers of the YPB. The vents are plotted by their latitude and longitude coordinates. The distribution of basalt centers of the YPB (excluding the basalt of Buckboard Mesa) fit closely a linear model. The linear regression line passes through the Lathrop Wells center. It bisects the cluster length of the Quaternary basalt of Crater Flat, passing between Red Cone and Black Cone centers and it passes between the Little Black Peak and Hidden Cone centers (Fig. 3.13). The hyperbolic bands around the regression fit line are the confidence intervals for the linear model. They show the intervals at a 90% confidence that bound the location of the regression line. Shown also on Fig. 3.13 as a dashed curve, is the distance weighted least squares fit of the data set. The curve was fitted to the data using a weighted quadratric multiple regression method on all data points. It provides an independent test of the suitability of a linear model. Note that the distance weighted least squares deviates only slightly from the linear regression fit (Fig. 3.13). Figure 3.14 is a linear regression fit of the locations of all Pliocene and Quaternary basalt centers of the CFVZ, including the aeromagnetic anomaly south of the town of Amargosa Valley, but not the undrilled aeromagnetic anomalies located in the central Amargosa Valley. The linear regression fit line is similar to the line of Fig. 3.13, except the northwest part of the line is offset to the northeast from the addition of the data points for the basalt of Thirsty Mesa. The hyperbolic bands are the 90% confidence bands for the location of the linear regression fit. The bands are tighter then and show a better linear fit than the regression calculation using only the Quaternary centers. The dashed curve of Fig. 3.14 is the distance-weighted least squares regression fit of the data set. The curve is nonlinear on the southeast end where its geometry is affected by the buried basalt center located south of the town of Amargosa Valley.

An additional striking feature of the CFVZ is noted by combining magma volume (DRE) as a third variable with the location coordinates of the Quaternary and Pliocene basaltic centers. Figure 3.15 is a three dimensional plot of these attributes for the Quaternary basalt centers of the CFVZ. The linear regression line of Fig. 3.13 coincides

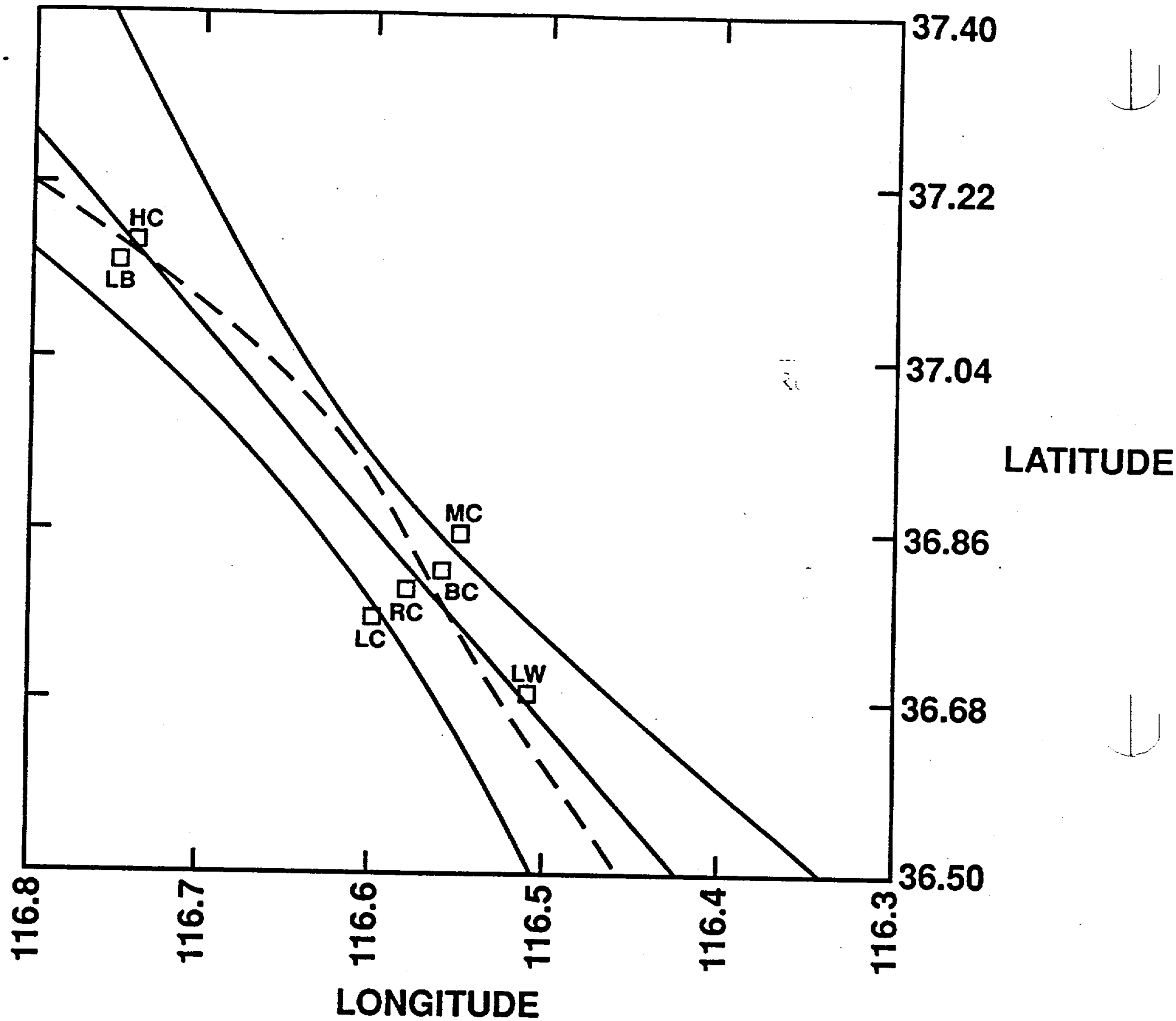

Fig. 3.13 Least squares, linear regression fit of the distribution of Quaternary basalt vents of the Crater Flat volcanic zone. The straight line is the best fit regression line; the parabolic curves flanking the regression line are the 90% confidence intervals for the regression line. The dashed line is a distance weighted least squares line. This line is allowed to flex locally to fit individual data points and provides an independent test of the suitability of a linear fit to the data distribution. LW: Lathrop Wells center; LC: Little Cones center; RC: Red Cone center; BC: Black Cone center; MC: Makani Cone center; LP: Little Black Peak center; HC: Hidden Cone center. The linear regression line passes through the Lathrop Wells center, bisects symmetrically the Quaternary basalt centers and passes between the two centers of Crater Flat. While there are only a limited number of Quaternary basalt centers, they closely fit a linear spatial distribution.

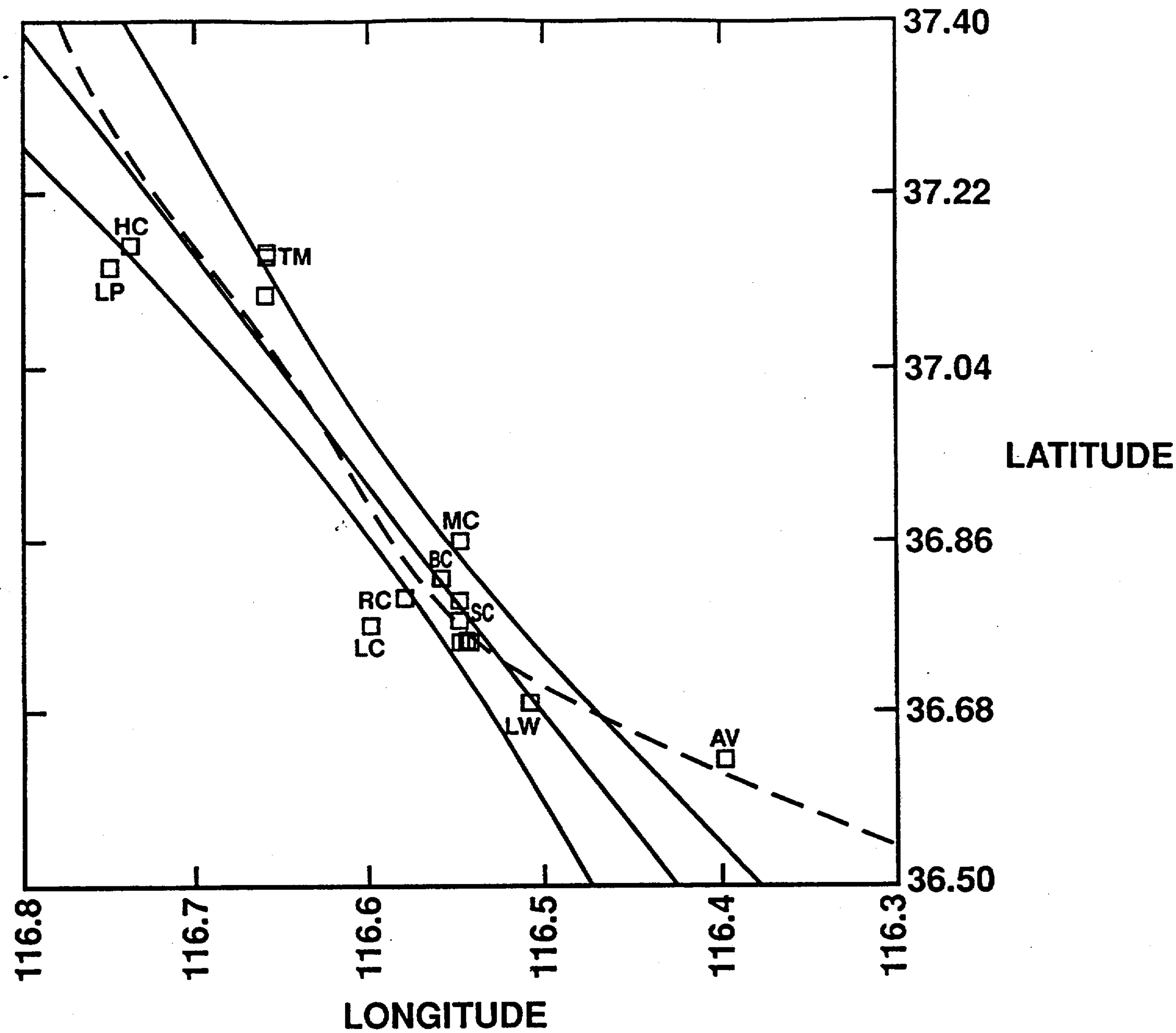

Fig. 3.14 Least squares, linear regression fit of the distribution of Pliocene and Quaternary basalt centers of the Crater Flat volcanic zone. Lines and symbols are the same as Fig. 3.13 with several additions including: AV: aeromagnetic anomaly south of the town of Amargosa Valley; SE: 3.7 Ma basalt of southeast Crater Flat; TM: Pliocene basalt of Thirsty Mesa. The distribution of the Pliocene and Quaternary basalt centers of the Crater Flat volcanic zone closely fit a linear model and have tighter 90% confidence bands than the Quaternary basalt centers (Fig. 3.13). The dashed distance weighted linear regression curve except on the southeast end where it bends to fit the location of the aeromagnetic anomaly of the Amargosa Valley.

spatially with a northwest-trending zone marking the location of the largest volume volcanic centers. Stated differently, the volcanic centers with the largest eruptive volumes occur on or adjacent to the regression line; volcanic centers located away from the regression line have decreased eruptive volumes. This observation strongly supports the inference that the location of basalt centers is controlled by a northwest-trending structure. The observed volume-location relationship of the volcanic centers remains consistent even with the addition of Pliocene volcanic centers to the data set of Fig. 3.15. Figure 3.16 is a three-dimensional plot of the volume and location coordinates of the Quaternary and Pliocene basalt centers of the CFVZ. There are two differences between this plot and Fig. 3.15. First, the volume of basalt centers shows a lognornal distribution; the data are best displayed by plotting the log of the magma volume. Second, closely spaced basalt centers are plotted as single data points because it is impossible to identify the magma volume components of individual vents. This applies to the basalt of Thirsty Mesa and the 3.7 Ma basalt of southeast Crater Flat. The volume-space relationship of Figure 3.16 can be viewed more readily by plotting the data as a surface. Figure 3.17 is the fit of a surface to the volume-location data using distance weighted least squares where the stiffness parameter for the fit is the inverse of the number of cases (1/*n*). The surface defines a northwest-trending ridge that coincides closely with the location of the linear regression and distance weighted least squares fits of the location data. These data support that inference that the subsurface rise of magma was guided by an existing northwest-trending structural feature.

A second feature of the distribution of individual centers of volcanic units of the YPB is the tendency for clusters of centers to be elongate in a north-northeast-trending direction, paralleling the maximum compressive stress direction or the most likely direction of dike propagation. This is illustrated by basalt clusters of the 3.7, Quaternary and Sleeping Butte volcanic centers (Fig. 3.10). We interpret this relationship much like Carr (1990). The magmas that fed the basalt centers probably followed a northwest-trending structure at depth and formed separate pathways as the magmas neared the surface. These pathways were probably controlled by the shallow stress field of the region. It is likely that the basalt dikes created their own fracture pathways to the surface because the location of basalt centers are largely independent of surface structures.

An important implication of these speculations is that magma rising as dikes may reorient at shallow depths below Crater Flat. The northwest elongation of the CFVZ (Crowe and Perry 1989) suggests that rising magma probably followed northwest-trending faults. However, at shallow depths the dikes must have diverged from the faults and followed the maximum compressive stress direction. This is required by the secondary north-northeast elongation of basalt cluster. This is a 90° reorientation (northwest to northeast) of the feeder dikes at depth. The most logical site for this structural reorientation is probably at the density interface beneath Crater Flat between the Paleozoic rocks and the Cenozoic volcanic rocks and/or alluvial fill of the basin.

The final important structural property of the basalt centers of the YPB is their relationship to shallow faults in the Yucca Mountain area. The 3.7 Ma basalt centers of Crater Flat are aligned north-south parallel to the trend of faults cutting bedrock in Yucca

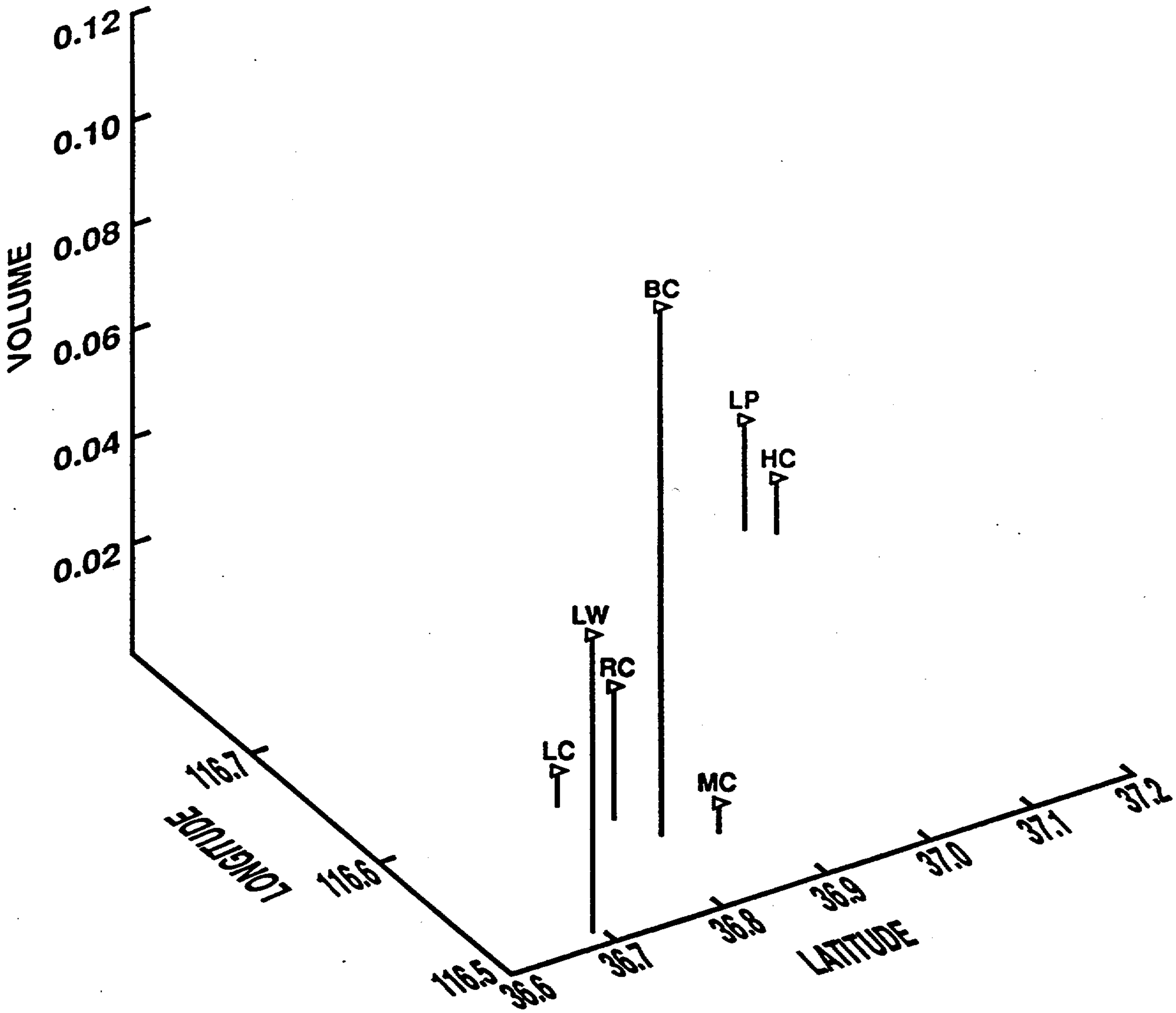

Fig. 3.15 Three dimensional plot of magma volume versus location of the Quaternary basalt centers of the Crater Flat volcanic zone. Symbols are the same as Fig. 3.13. The triangles denote the volume of the vent locations and the spikes connect the data points to the latitude-longitude plane. Fig. 3.15 shows that the maximum erupted volume of the Quaternary basalt center coincides with the location of the linear regression fit line for the distribution of the centers. This provides increased support for the interpretation that the centers were erupted along a concealed, northwest-trending structural feature consistent with the recognition of the Crater Flat volcanic zone (Crowe and Perry, 1989).

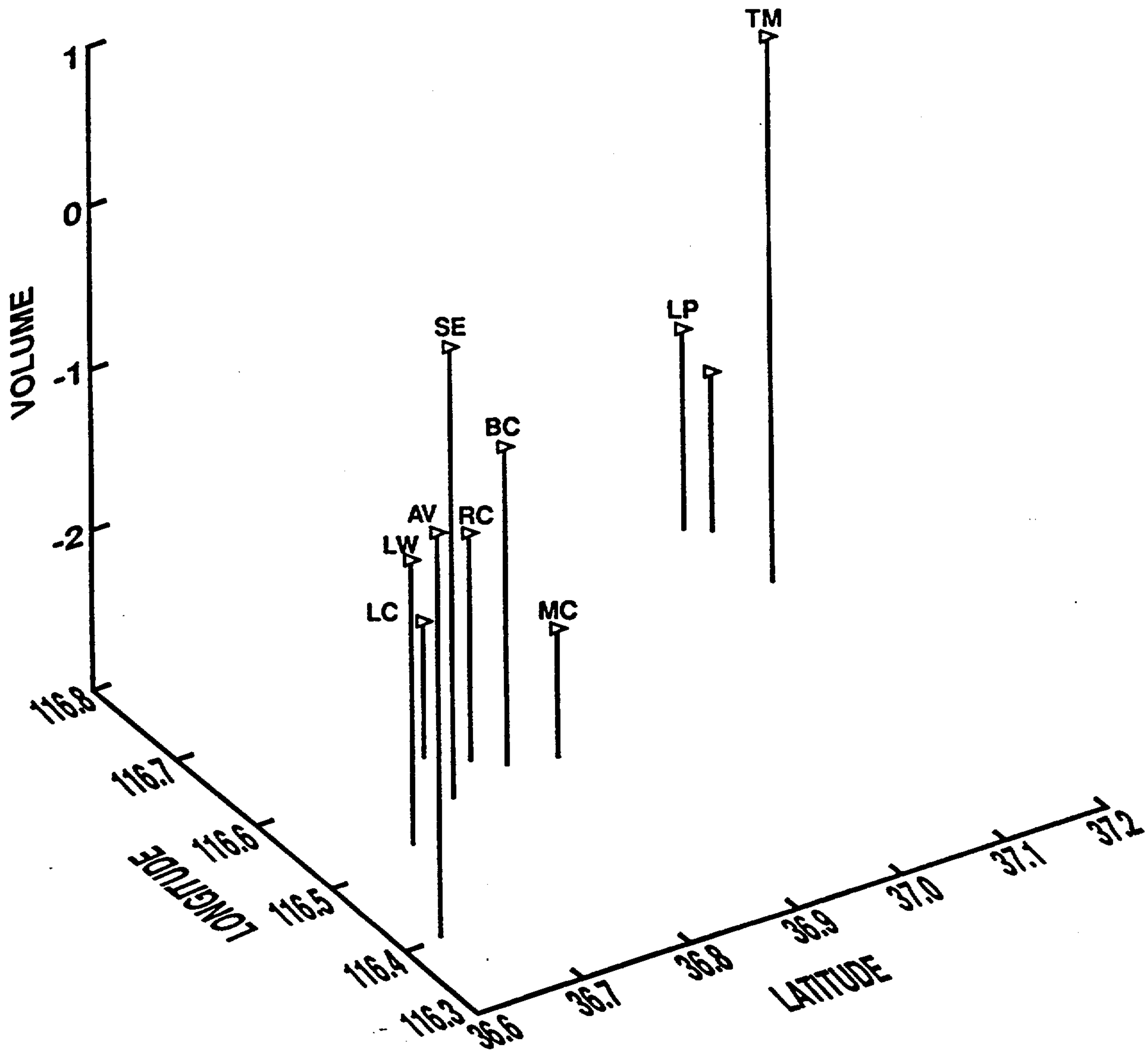

Fig. 3.16 Three dimensional plot of the log of the magma volume versus the location of Pliocene and Quaternary basalt centers of the Crater Flat volcanic zone. Symbols are the same as Fig. 3.14; plot construction is the same as Fig. 3.16. Additional of the location and magma volumes of the Pliocene volcanic centers maintains the same volume-distribution relationship noted on Fig. 3.15.

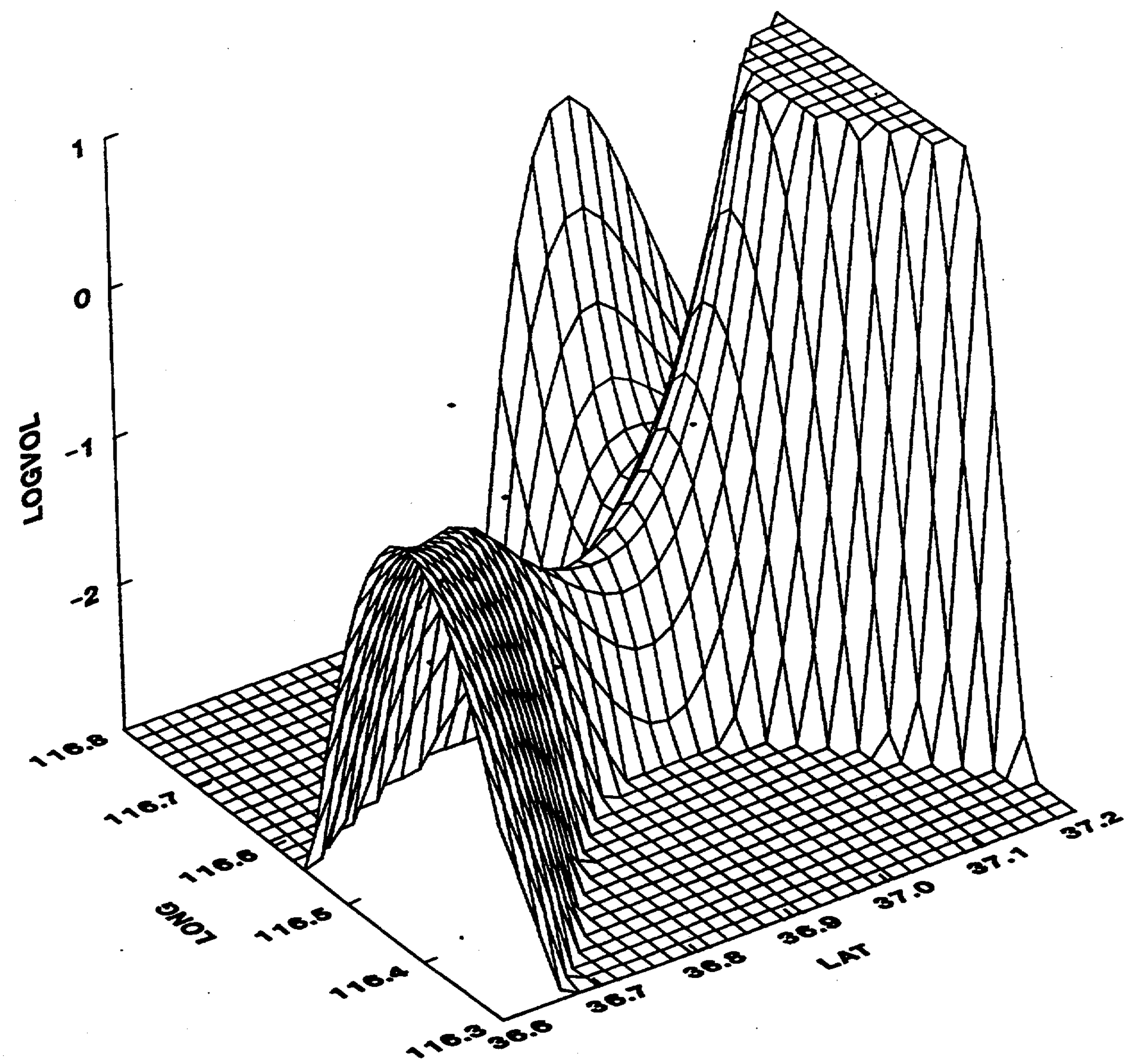

Fig. 3.17 Distance weighted least squares surface fit of the volume-location data of the Pliocene and Quaternary basalt centers of the Crater Flat volcanic zone. This plot provides a more easily visible illustration of the northwest trend of the volume-location surface for the basalt centers. This surface parallels the trend of the linear regression fit for the location of the basalt centers. This surface bifurcates at its northwest end because of the spatial separation of the Sleeping Butte and Thirsty Mesa basalt centers. The flex of the surface is controlled by a tension parameter of $1/n$ where n is the number of volcanic centers. The surface was constructed with the hide option of the surface fitting routine and conceals parts of the surfaces which should not be visible.

Mountain west of the potential exploratory block (Crowe and Carr 1980). The eruptive fissure and scoria cone of the basalt of Buckboard Mesa are oriented northwest. The fissure system may parallel approximately the ring-fracture zone of Timber Mountain, or it may follow unexposed structures of the Walker Lane structural zone (Crowe 1990).

By contrast, the Quaternary basalt centers show no clear relationship to bedrock faults. The Quaternary basalt cluster of Crater Flat trends northeast across the basin. Smith et al. (1990) argue that these trends follow bedrock faults of Yucca Mountain. There is a surprising lack of a spatial association between the Quaternary basalt clusters of Crater Flat and the Bare Mountain fault, one of the major faults in the region. The basalt of Sleeping Butte forms a northeast trending alignment that does not follow any obvious structural control (Crowe and Perry 1989). The Lathrop Wells volcanic center occurs at the approximate intersection of the northeast-trending Stagecoach Road fault, and northwest trending faults that may correlate with the Windy Wash fault (Crowe et al. 1992). These trends are paralleled by the trend of fissure vents in the center.

VI. GEOPHYSICAL STUDIES: YUCCA MOUNTAIN REGION

A wide range of geophysical data have been obtained for the Yucca Mountain region; more studies are in progress (Oliver et al. 1992). In the next section we discuss aspects of the geophysical data and the constraints these data place on models of the distribution of basaltic volcanism in the Yucca Mountain region. The geophysical data for the Yucca Mountain region compliment the abundant regional geophysical data for the Great Basin subprovince of the Basin and Range province.

A. Seismic Studies

Seismic studies have constituted a major part of the site characterization studies since the earliest stages of investigations. A 47-station vertical-component seismic network was installed within a 160 km radius of Yucca Mountain in 1979 (Rogers et al. 1987). A six station supplemental mini-net was deployed on Yucca Mountain in 1981. This net lowered the detection threshold and improved the accuracy of location of earthquakes near the potential Yucca Mountain site (Rogers et al. 1987). Horizontal component instruments were deployed at selected stations in 1984. This network called the southern Great Basin seismograph network (SGBSN; Rogers and others 1981; 1983; Rogers et al. 1987; Mermonte and Rogers 1987; Gomberg 1991a; 1991b; Harmsen and Bufe 1992) was designed to locate and study properties of earthquakes for a region containing tectonic features of possible significance to seismic risk assessment for the Yucca Mountain region. Tectonic features of regional interest (not all of which are significant for seismic risk assessment for Yucca Mountain) were reviewed by Carr (1984). They include the Death Valley-Furnace Creek fault zone and extension along the Fish Lake Valley fault zone, the east-west seismic zone (Smith and Sbar 1974; Smith 1978), the Nevada-California seismic zone and the Nevada Test Site Paleoseismic belt that now would be called the Kawich-Greenwater rift (Carr 1990).

Rogers et al. (1987) summarized earthquake hypocenters, selected focal mechanisms, and other inferred seismicity characteristics through 1987. Conclusions from this report are:

1. Earthquakes are distributed in an east-west zone generally coincident with the east-west seismic zone.
2. Earthquakes display strike-slip and normal-slip over a depth range from near-surface to 10-15 km consistent with seismic patterns of much of the Great Basin. There is an apparent preference for right-slip on north-trending faults. Left-slip is also observed on north-northeast striking faults.
3. Earthquakes are consistent with a northwest-trending orientation of the least principal stress axis, which is rotated clockwise relative to surrounding regions (Carr 1974; Zoback 1989).
4. Earthquake clusters are difficult commonly to associate with specific faults although epicenter alignments and earthquake nodal planes are frequently subparallel to fault trends (Hildenbrand et al. 1988; their Fig. 2.3).
5. A seismicity minimum may be observed between depths of 3.5 to 4.0 kilometers.
6. Earthquake release energy per unit area is lower in the immediate Yucca Mountain area compared to regional levels. This may be attributed to low stress from tectonic uncoupling or significant prehistoric seismic energy release. Alternatively, the area could be a seismic gap with high stresses and locked faults. Rogers et al. (1987) summarized several lines of evidence supporting seismic uncoupling but noted that other interpretations are possible.

There is no evidence of a positive correlation between recorded seismicity and the distribution of Quaternary basaltic centers in the Yucca Mountain area. In fact, there may be evidence of a negative correlation of seismicity with sites of Quaternary volcanism in Crater Flat (see discussion below). Increased seismicity has occurred in the Pahranagat Shear Zone (Rogers et al. 1987) near an area of basaltic volcanism (Ekren et al. 1985). However these lavas are of Miocene age and the correlation is not significant for volcanic risk for the potential Yucca Mountain site. Two cautions must accompany any discussion of historic seismicity and the spatial distribution of basaltic volcanism. First, the period of recording of earthquake locations is very short relative to the recurrence rate of basaltic volcanic events. The latter is on the order of several hundred thousands of years (Crowe et al. 1992a). Second, patterns of historic seismicity may not be good predictors or indicators of future sites of Quaternary basaltic volcanism. Basalt magma probably ascends rapidly through the crust (about 10 cm sec^{-1}) and while the ascent may be facilitated or guided by fractured rock, these pathways need not necessarily be correlated with areas of historic seismicity.

Gomberg (1991a) reviewed the seismicity patterns and the detection and location threshold of the SGBSN. She derived a spatially varying model of the detection/location capabilities of the network based on empirical relations and statistics. She used several validation tests for the model and showed that the threshold map accurately predicts the observed distribution of epicenters for all magnitude bins. This approach permits use of most of the earthquake catalog and allows evaluation of the completeness level of each subroutine. Gomberg (1991a) used the threshold model to develop a series of magnitude independent masks that were overlaid on patterns of seismicity, and Quaternary faults. She identified several areas as active because they exhibit the greatest number of events at all magnitudes. These are the north end of the Furnace Creek fault, the Paranagat Shear Zone, and the north and southeast parts of the Nevada Test Site. Gomberg noted that there is an absence of seismicity at Yucca Mountain. She discussed the same causes of low seismicity as Rogers et al. (1987), but noted that seismic models predict a minimum in shear strain at Yucca Mountain. Additionally, she drew attention to relatively low levels of seismicity west of the Death Valley-Furnace Creek faults despite an abundance of young fault scarps indicative of recent tectonic activity.

In a companion paper, Gomberg (1991b) evaluated seismicity and shear strain in the southern Great Basin focusing on identifying information that can be obtained from the distribution of earthquakes in an area with long intervals between large earthquakes. She developed strain field models assuming long term behavior of faults perturbs an otherwise uniform strain field. An important conclusion developed from the models is that a complex distribution of seismicity with off-fault locations is expected. These traits match the seismicity recorded by the SGBSN (Rogers et al. 1987; Gomberg 1991a). Gomberg (1991b) developed a boundary element representation of faults with historic or Holocene displacement that she used as input to the shear strain field. Modeled faults in the Yucca Mountain area were the Bare Mountain fault, the Rock Valley fault system and the Yucca fault. She assumed a maximum extension direction of N52°W and regional displacement vector orientation of N34°W. Results show that the highest shear strain areas, south and east of Yucca Mountain, are regions of observed high seismicity. The model showed a lack of shear strain in the north part of the Nevada Test Site. The high seismicity of this area may be induced by underground explosions from testing of nuclear weapons (Gomberg 1991b, pp. 16, 392). The seismic gap in the Yucca Mountain area is coincident with a region of modeled lowest shear strain. The aseismic nature of the Yucca Mountain area was also noted by (Brune 1991). Parsons and Thompson (1991) suggested this feature could result from volume release associated with active magmatism (see models of Shaw 1980). Gomberg (1991b) suggest that the best explanation of the low seismicity in the Yucca Mountain is that it is not an area of significant seismic hazard. The simple shear model also showed a rotational component of the regional deformation field, possibly compatible with paleomagnetic studies (Hudson and Geissman 1991; Rosenbaum et al. 1991). Additional iterations of the shear model were used with slip distributions assigned to fault systems (Gomberg 1991b; see her Figure 11). Results were not dissimilar to the simple shear model.

The most recent update to the SGBSN studies were by Hansen and Bufe (1992), who summarized seismic data through 1989. They noted the development of a concentration of earthquakes in the Reveille Range. They also discussed the difficulties of obtaining accurate data for earthquake hypocenters and the ambiguity this creates for focal mechanism solutions.

To summarize, seismicity studies of the Yucca Mountain region offer limited potential for evaluating patterns of future basaltic volcanic activity, an unsuprising result given the long recurrence time of basaltic volcanic events. One interpretation of the seismic gap noted for the Yucca Mountain area is stress release associated with Quaternary basaltic volcanism (Parsons and Thompson 1991). Alternatively, the shear models of Gomberg (1991b) suggest the gap may simply represent an area of low shear strain accumulation.

B. Gravity Investigations

Gravity investigations were begun in the Yucca Mountain area as early as 1978. About 33,000 gravity measurements have been made. All have been adjusted to a common gravity datum and recompiled (Oliver et al. 1992). Complete Bouguer gravity maps have been published of the Nevada Test Site (Healey et al. 1987), the Death Valley (Healey et al. 1980a), Goldfield (Healey et al. 1980b), Caliente (Healey et al. 1981) and Las Vegas (Kane 1979) sheets. A residual gravity map of Yucca Mountain and vicinity has been produced by Snyder and Carr (1982). The free-air, Bouguer, regional, residual and isostatic residual gravity maps have been compiled for the Yucca Mountain region (Hilldenbrand et al. 1988).

Snyder and Carr (1982; 1984) summarized the volcano-tectonic setting of the Yucca Mountain region based largely on gravity data. They summarized interpretations of more than 2500 gravity measurements on an approximate 2 km, irregular grid. In their original work (Snyder and Carr 1982), analyzed the complete Bouguer gravity anomalies using a crustal density of 2.67 gcm^{-3}. They reduced the data a second time at a density of 2.0 gcm^{-3} to compensate for gravity stations within lower density volcanic terrain. They applied an isostatic correction assuming Airy-type isotasy to remove effects of density variations deeper than 5 km. Density control was provided by density measurements of core samples and surface samples. These data were augmented by gamma-gamma and borehole gravity measurements in several drill holes (Snyder and Carr 1984). Further, they used a two-dimensional modeled, east-west cross section, and a three-dimensional multiple-polygon gravity model.

The most distinctive feature of the regional gravity field is a gravity high associated with Bare Mountain that is connected with a larger gravity high over the Funeral Mountains. This high probably delineates the Funeral Mountain-Bullfrog Hills-Bare Mountain detachment complex (Hamilton 1988; M. Carr and Monsen 1988). It is interrupted only by a gravity saddle across the area of the Amargosa River, a probably result of thick accumulation of clastic rocks of the Amargosa Valley (Snyder and Carr 1984). A second gravity high, the Calico Hills gravity anomaly coincides with the area of the Calico Hills and probably extends to the southwest beneath Busted Butte. Snyder and Carr (1984) interpret this gravity high as produced by Paleozoic rocks, possibly augmented by a fault zone of pre-Paintbrush age near Busted Butte.

An additional major feature is a large gravity low, defined by the 8-mGal residual gravity contour (Snyder and Carr; their Fig. 4c). This low is centered in Crater Flat but also extends east partly under Yucca Mountain and south into the Amargosa Valley. Snyder and Carr (1984) interpret this low as a combination of sector grabens and caldera collapse associated with the eruption of the Crater Flat Tuff. A permissive alternative explanation of these data is that the gravity low is the result of a thick accumulation of clastic alluvial fill deposits in a series of pull-apart basins marking Crater Flat and extending to the south. Neither model can be discriminated solely on the basis of the gravity data. Moreover it is possible the Crater Flat basin could be a composite volcano-tectonic depression. The base of the caldera or alluvial section in Crater Flat is estimated to be about 4±2 km from gravity modeling or between 2 and 4 km based on seismic refraction (Snyder and Carr 1984; pp. 10, 204).

A narrow band of gravity highs separates the negative gravity anomalies of Crater Flat and the Claim Canyon and Timber Mountain caldera segments to the north (Snyder and Carr 1984). These highs are bounded to the north by a large gravity low associated with the Timber Mountain and Silent Canyon calderas (Snyder and Carr 1984).

To summarize, gravity models confirm that Crater Flat is a large topographic and structural basin. It is bounded on the west by the fault-controlled, steep escarpment of Bare Mountain and on the east extends under at least part of Yucca Mountain. The combination of the depth of the structural basin and the small volume of Pliocene and Quaternary basaltic rock, makes gravity models of limited use in delineating the structural controls of the basalt units. However, the prominent gravity low of Crater Flat suggests the basaltic rocks may have followed or been influenced by structures associated with the basin. If Crater Flat is a caldera complex, it is somewhat surprising that the basaltic rocks erupted across the caldera floor. By comparison, the basalt centers of Silent Canyon and the basalt of Buckboard Mesa occur on the ring fracture zone of respectively, the Silent Canyon and Timber Mountain caldera complexes. An important corollary of the caldera hypothesis is that basalt centers might be expected to follow the ring-fracture zone of the suspected calderas. That multiple episodes of Pliocene and Quaternary basaltic volcanic activity do not occur on the inferred ring-fracture zones is a departure from the expected patterns if calderas are present in Crater Flat.

C. Magnetic Investigations

A wide variety of aeromagnetic and ground magnetic data have been obtained for the Yucca Mountain region (Oliver et al. 1992). Draped aeromagnetic profiles were flown with spacing of 0.4 and 0.8 km for a large area surrounding Yucca Mountain extending from Pahute Mesa, south to southern Death Valley, west to west of Bare Mountain and east into Frenchman and Yucca Flat (Oliver et al. 1992; Fig. 2.2-1). This area covers most of the terrain of interest for tectonic and volcanic studies in the Yucca Mountain region. Compiled maps of these areas were presented by Hildenbrand et al. (1988). Kane and Bracken (1983) described aeromagnetic anomalies in the Yucca Mountain area and surrounding region. Surface basaltic volcanic rocks have strong magnetic contrasts with surrounding rocks, particularly the alluvial fill of the valley basins. They can be correlated with a high degree of confidence with positive or negative anomalies on the aeromagnetic map, dependent on the polarity of the surface rocks (Kane and Bracken 1982).

Crowe et al. (1986) described aeromagnetic anomalies in Crater Flat and the

Amargosa Valley that may represent buried volcanic centers or intrusive rocks. Exploratory drilling at two sites has penetrated buried basalt lavas which correlate with recognized surface anomalies (Crowe et al. 1986; Crowe et al. 1992b). On the basis of examination of aeromagnetic maps and drilling of identified aeromagnetic anomalies, we have a relatively high degree of confidence that all significant sites of possible buried basalt have been identified in the Yucca Mountain area. Two of five identified anomalies remain to be drilled as part of the site characterization program.

Magnetic anomalies near the potential repository site have been described by Bath and Jahren (1984). These investigations were conducted primarily to evaluate buried geologic units or structures beneath the potential site area. A tabular mass of sedimentary rock was noted beneath thick deposits of the volcanic units. Major faults of the site were outlined from their displacement of the magnetized volcanic rock. The Topopah Springs member of the Paintbrush Tuff was identified as the primary source of anomalies from faulted sequences of volcanic rock. An east-west pattern of anomalies was identified. However, the amplitudes of these anomalies were reduced significantly when effects of the deeply buried argillite unit were removed. More detailed drape aeromagnetic data were obtained for parts of the potential Yucca Mountain site (Bath and Jahen 1985). These detected a prominent magnetic anomaly of 290 nT (nanotesla) located about 1 km northwest of USW H-3. Ground magnetic traverses were run to delineate the anomaly. Three contributing sources were identified (Bath and Jahren 1985). First, elevated topography gives a terrain effect. Second, ground anomalies south of the drape air anomaly indicate either an increase in magnetization or the presence of a small intrusive body. Third, there is an increase in magnetic influence from the adjacent Solitario Canyon fault. One possible interpretation of this anomaly is that it may be related to a 10 Ma basalt dike that intrudes the Solitario Canyon fault (Crowe et al. 1983; Scott 1990; Carr 1990). In fact, the anomaly may represent a small intrusive body of basalt composition (dike or sill) emplaced off the main trace of the fault (Bath and Jahren 1985; p. 15). This body will be investigated as part of the site characterization studies.

There is a sufficient amount of magnetic data to place a relatively high degree of confidence in the judgment that all sites of Quaternary volcanic activity have been identified in the Yucca Mountain region. All known Quaternary volcanic centers in the Yucca Mountain region are exposed conspiciously at the surface. They are not subtle features. Thus it is unlikely that other Quaternary basalt centers are present in the region. Two aeromagnetic anomalies remain to be drilled. One is located in southern Crater Flat, the second is located in the Amargosa Valley. Because basalt scoria cones and lava flows as old as 3.7 Ma are prominently exposed at the surface in Crater Flat, it is unlikely that the remaining anomalies are buried parts of former surface basalt centers of Quaternary age.

D. Geoelectric Surveys

Geoelectric surveys have been used at the potential Yucca Mountain site. Much of the work was completed in the early stages of site characterization. The locations of these surveys are discussed by Oliver et al. (1992). Over 130 Schlumberger soundings have been obtained in an area labeled F on Figure 2.3-1 in Oliver et al. (1992). This area covers the south part of Crater Flat and parts of the Amargosa Valley. These data may prove useful for delineating the structure of Crater Flat and provide independent tests for evidence of subsurface magma. Deep MT (magnetotelluric) data show a regional crustal anistoropy aligned with trends of the Walker Lane structural system as well as an apparent mid-crustal conductor at approximately 20 km or less (Oliver et al. 1992). This zone could represent pore fluids, elevated temperatures and/or the transition to crustal ductility below the seismogenic zone (Oliver et al. 1992). Additional work will be required to assess the potential application of geoelectric surveys to understanding the structure of Crater Flat and to test for the presence of subsurface magma.

E. Seismic Investigations

Seismic investigations have included both seismic refraction and seismic reflection surveys (Oliver et al. 1992). The most useful application from these investigations is for investigations of upper crustal structure and investigations of the middle, lower crust and upper mantle.

1. Seismic Refraction Surveys. Relevant seismic refrection surveys have included studies utilizing high-explosive (HE) and underground nuclear explosions (UNE) as sources (Hoffman and Mooney 1983). Additionally, high resolution upper-crustal profiles have been conducted in the Yucca Mountain area (Ackermann et al. 1988). Locations of the profiles are shown on 2.4-2 of Oliver et al. (1992).

The refraction studies using UNE and HE sources deployed up to 100 portable seismographs arrayed along lines across Yucca Mountain and Jackass Flats, the Amargosa Desert through Crater Flat, and from Yucca Mountain south to southern Death Valley (Hoffman and Mooney 1983). The upper crustal structure in the Yucca Mountain area was inferred from both the seismic P-wave delays and an unreversed refraction profile. Interpretations relied heavily on existing site models, particularly the gravity models of Snyder and Carr (1982). Major points of the seismic refraction surveys are that observed delay times clearly confirm a greater depth to the pre-volcanic rocks beneath Crater Flat and Yucca Mountain. Discrepancies were noted between observed and calculated delay times for Crater Flat where the observed delays exceed predicted delays. Hoffman and Mooney (1983) attribute this discrepancy to local thickness variations in the low velocity tuff rather than a deepening of the pre-volcanic layer. The velocity models show a distinct 2.5 km-wide bench, probably representing a down-dropped block, at a depth of 1.6 km, east of Bare Mountain. Depth to basement was estimated to about 3.2 km below Crater Flat and 1.1 km below Jackass Flat. Shot point 3 recorded a crust-mantle and two intra-crustal reflections (Hoffman and Mooney 1983). These correlate with a reflection from velocity boundaries at 24 km and 30 km depth. The crust-mantle depth was fit with a reflection from 35 km depth. Significantly, no evidence was noted of reflections from an inferred magma below the Amargosa Desert (Evans and Smith 1992).

Three additional profiles were acquired in 1985. These include an east-west profile from the northern Amargosa Valley across Yucca Mountain to Jackass Flat, a north-south profile along Fortymile Wash and an east-west profile across the Amargosa Valley south of Yucca Mountain (Oliver et al. 1992). Summaries of these surveys and data are presented in Sutton (1984, 1985). Final interpretations of the lines have not been completed. The Amargosa line crosses part of the teleseismic anomaly of Evans and Smith (1992) and extends to depths of about 30 km.

2. Seismic Reflection. Seismic reflections studies have been used primarily to examine shallow structure in the Yucca Mountain area. Recently acquired test lines that provide data on the deeper structure (up to 15 sec) have been run in the Amargosa Valley (Oliver et al. 1992). Brocher et al. (1990; 1993) described the results of a 27 km seismic reflection profile across the Amargosa Valley. The line crossed three Cenozoic alluvial basins. Interpretations of the line were concerned primarily with extensional structures. A laterally continuous near flat lying reflector at 100 to 200 m was interpreted as a basalt flow, a flow that probably is part of the BSE. Brocher et al. (1993) reported a large amplitude reflection or mid-crustal bright spot on the seismic reflection profile. While the reflection could be interpreted as a mid-crustal magma body, Brocher et al. (1993) argue that the Amargosa Valley and a similar anomaly in Death Valley are caused by focusing of energy reflected from the mid-crust by low velocity basin fill lying above the bright spot (see also Hamilton 1988).

F. Teleseismic Studies

Teleseismic topography has been used to explore the three dimensional seismic properties of the Yucca Mountain region (Iyer 1988; Montfort and Evans 1982). The recent report by Evans and Smith (1992) has the most application to evaluations of volcanic risk for the potential Yucca Mountain site. While the results of teleseismic tomography can be ambiguous, the method has been the most successful of geophysical techniques for delineating magma in the crust or mantle (Iyer 1988).

Evans and Smith (1992) described the results of analyzing analog teleseismic data from 1979-1980 and digital data collected in 1982. They noted two large velocity anomalies. The first is centered beneath the Silent Canyon caldera and the northern part of the Timber Mountain caldera. The body is present near the depth of the Moho downward to about 200 km. This high-velocity body has been noted in many previous studies (Spence 1974; Montfort and Evans 1982; Taylor 1983). It has been interpreted as the crystallized roots beneath silicic calderas and the depleted "paleo-magma pathway" of the lower crust and mantle below the coalesced calderas. The second anomaly is a velocity low. It is centered south and southeast of Yucca Mountain and Crater Flat (Evans and Smith 1992; their fig. 3). Evans and Smith (1992) suggest this body trends east-west to northeast-southwest. They argue the body may extend to an area of Pliocene and Quaternary basaltic volcanism near St. George, Utah (Dueker and Humphreys 1990). However the connection with that area is not obvious from the data of Evans and Smith (1992; see their fig. 3).

A third significant observation based on the teleseismic tomography is the presence of low-velocity material beneath and east of the Solitario Canyon area (Evans and Smith 1992) probably at mid-crustal depths. They argue that this feature is most likely related to an inferred caldera or volcano-tectonic depression in Crater Flat following the model of Carr (1988).

Evans and Smith (1992) suggest the large low velocity anomaly may be partial melt and represent the source of the basaltic magma that formed the volcanic centers in Crater Flat. They suggest further, that the location of the Crater Flat field is controlled by the intersection of the Walker Lane structural zone and the Spotted Range-Mine Mountain subzone. They suggest, again because of the correlation with the data of Dueker and Humphreys (1990) that the low velocity anomaly forms a track subparallel to the hot-spot vector of the North America plate with volcanic activity at both ends. They acknowledge however, that other interpretations are possible.

The interpretations of Evans and Smith (1992) are important to an assessment of volcanic risk for the potential Yucca Mountain site. First, the low velocity anomaly, if produced by magma, is very large -- on a scale approaching the size of continental or oceantic hotspots. It could represent a large heat source possibly capable of generating significant future volumes of presumably basaltic magma. The east-west to north-northeast trend of the proposed anomaly is parallel to volcanic features of the southwest United States that have been interpreted to track motion of the North American plate (Smith and Luedke 1984; Spence and Gross 1990). The presence of sites of Quaternary basaltic activity at the ends of the anomaly are analogous to the patterns of magmatism in the Great Basin, which are concentrated at the east and west margins (Best and Brimhall 1974). The tectonic setting of Crater Flat, near the intersection of possible buried northwest-trending strike-slip faults and the zone of northeast-trending left slip faults may be conducive to the transmittal of magma through the upper crust.

However, when examined in detail, the proposed low velocity anomaly has inconsistencies with the geologic and geophysical record of the region. Not all of the inconsistencies were considered by Evans and Smith (1992). Multiple lines of evidence are *inconsistent* with a long-lived magma body. The center of the anomaly is south of the Nevada Test Site region where there is no Pliocene or Quaternary basaltic volcanism. This location coincides with the area of the amagmatic gap of the southern Great Basin, an anomalous area that exhibited no Cenozoic volcanism during intense episodes of extension (Guth 1981; Wernicke et al. 1988). Much of the anomaly is located beneath the Las Vegas shear zone, a structure proposed by Evans and Smith (1992) to have influenced the shallow rise of basaltic magma. Yet no past history of basaltic magma is present along the complete length of the Las Vegas shear zone. The proposed anomaly overlaps in location with the major step in the regional gravity field, the trend of which partly parallels the low velocity anomaly. Further this area was probably positioned above a zone of incoherent slab or a slab gap during the period of extension and silicic volcanism to the north (Severinghaus and Atwater 1990). Both the steep gradient in the gravity field and the anomalous subduction history need to be considered in any interpretation of the low velocity anomaly.

Continuing, the shape of the anomaly and its extension to the east and northeast do not appear obvious from the data of Evans and Smith (1992; their fig. 3). The low velocity zone appears to extend more definitively into adjoing areas of Death Valley and southern and southeast Nevada then east into Utah. These former areas, except for southern Death Valley, lack Quaternary volcanism. The volume of surface volcanism associated with the low velocity anomaly is extremely small. In fact the total volume of basalt magma erupted in Crater Flat is about 1 km^3 (Crowe et al. 1983b). This is about equal in volume to the basaltic andesite of Buckboard Mesa, a 2.9 Ma center formed near the interior of the high velocity anomaly inferred to be the cooled residuum from caldera eruptions. These volumes of magma are trivial to virtually insignificant compared to the volcanic record of other hotspot traces. Detailed time-volume and petrologic studies of the basalt cycles of Crater Flat suggest a history of waning volcanism that appears inconsistent with a large body of partial melt in the lower crust and upper mantle.

There is no recognized surface expression of the low velocity zone either in the topography or structure of rocks of southern Nevada. If there is truly a large mass of partially molten rock in southern Nevada comparable to a hotspot trace, it could have only formed recently and not yet modified the shallow crust. There is no modern recognized plate tectonic process inferred to be affecting the southern Great Basin that would logically lead to formation of such a body. It would have to be formed by a secondary upwelling of mantle material long post-dating the time of most intense volcanic and tectonic activity. Isotopic data for the southern Great Basin show it to be an area of preserved lithospheric mantle, with no evidence of a significant asthenoshperic component (Farmer et al. 1988; Jones et al. 1992).

It is unclear what the effects of the shallow crustal structure of the region have on interpretations of the teleseismic data. The position of the anomaly is within the lower crust and mantle. However, the low velocity fill beneath Crater Flat and Yucca Mountain must affect the teleseismic data particularly because the method has limited resolution at shallow depths. An unexplained inconsistency in the teleseismic data is the absence of a high velocity zone beneath Crater Flat if the area is underlain by a caldera complex.

Seismic refraction and reflection lines in the Amargosa Valley overlap the north part of the teleseismic low velocity anomaly. No evidence from these seismic profiles (Brocher et al. 1993) imaged the inferred magma body of Evans and Smith (1992). Finally, perhaps the most compelling argument against the magmatic model of Evans and Smith (1992) is the unusually depth to the basal horizon of magnetic sources calculated by Blakley (1988). This regional anomaly contrasts markedly with the Battle Mountain high, an area of high heat flow, young volcanism, recent faulting, and shallow basal depth of magnetic sources.

VII. TECTONIC MODELS OF BASALTIC VOLCANISM IN THE YUCCA MOUNTAIN REGION

This part of section III, examines and identifies tectonic models of the distribution of basaltic volcanism in the Yucca Mountain region that could be used in assessment of volcanic risk. The models are selected using the background information presented on the tectonic setting of basaltic volcanism in the Yucca Mountain region. We emphasize the evaluation and consideration of multiple alternative models, and do not focus on a single or even a set of preferred models. Tectonic models that can credibly be used to describe the distribution of basaltic volcanism in the Yucca Mountain region are compiled and described briefly. Application of the models to volcanic risk assessment is described in Section VII of this report.

Crowe and Carr (1980) summarized the probable structural controls of sites of basaltic volcanism in the southern Great Basin. They noted the tendency for sites of past basaltic volcanic activity to occur along three features. These are:

1. Basin and Range faults
2. Intersection of Basin and Range faults with ring fracture zones of caldera complexes
3. Areas of intersection of northwest-trending, right-slip faults and northeast-trending, left-slip faults.

Crowe et al. (1983a) compiled a table of the structural setting of all known sites of Pliocene and Quaternary basalt centers in the southern Great Basin. They described the same patterns of structural controls of basalt centers summarized earlier by Crowe and Carr (1980). Crowe et al. (1983a) suggested there is no consistent and predictable relationship between sites of basaltic volcanic activity and structural or tectonic features. Rather they suggest the structural and tectonic features provide the structural pathways for the ascent of basalt magma from depth.

Several points require emphasis before summarizing the volcanic-tectonic models of the region. The basin-range province has unquestionably been a site of significant extensional faulting and associated volcanism during Cenozoic time. The province constitutes a major active tectonic province of the North American continent. However, tectonic activity has not continued at uniform levels in all parts of the province. Cenozoic extensional faulting and volcanism of the basin-range province exhibit time-transgressive patterns of activity. There is agreement that the major tectonic activity in the Yucca Mountain region occurred in the Miocene and peaked about 11-to-12 Ma. This latter interval coincides with the time of maximum basaltic volcanic activity. The volume of basaltic magma erupted in the Yucca Mountain region during the Miocene exceeded 10 km^3. The volume of basaltic magma erupted during the Pliocene is 4.2 km^3. The volume of erupted basaltic magma during the Quaternary in the Yucca Mountain region is < 0.5 km^3. The volume of Pliocene and Quaternary basaltic magma erupted in the Yucca Mountain region is extremely small compared with the volume of basalt magma erupted in the active eastern and western boundaries of the Great Basin. Thus while the tectonic evolution of Yucca Mountain is important, the peak of tectonic activity that shaped the region has long passed.

What is important to determine for volcanic risk assessment is the controls of the location of sites of volcanism during the waning phases of basaltic volcanism and tectonism. There is widespread evidence of a low velocity upper mantle underlying most of the Basin and Range province. The most compelling explanation for the low seismic velocities is the presence of a small component of interstitial partial melt. Thus much if not all of the area of the Basin and Range province appears to have the potential for producing basaltic magma. The abundance of Quaternary basalt and rhyolite volcanic centers in the active margins of the province strongly suggests that active tectonism plays a key role in promoting ascent of magma through the crust. Likewise the minor eruptive volumes but ubiquitous distribution of basalt centers in the less active interiors of the Basin and Range province suggest that cooled and largely inactive crust prohibits the rise of magma. We suggest accordingly that the controls of the occurrence of basalt in the Yucca Mountain region are probably provided by the distribution of structures that promote ascent of magma.

Two major generalizations can be made about the distribution of Quaternary volcanism in the Yucca Mountain region. First, Quaternary basalt sites, in marked contrast to basalt of Pliocene and Miocene age do not appear to be controlled by or follow prevailing surface structural features. Second, structures that penetrate the deepest into the crust appear to show the strongest correlations with sites of Pliocene and Quaternary basalt volcanic centers. These structures are strike-slip faults (both northwest-trending right-slip faults and northeast-trending left-slip faults) and ring-fracture zones of caldera complexes. Additionally, pull-apart basins, particularly active basins associated with strike-slip faults may be important structural elements promoting ascent of basalt magma. Third, there is not a direct relationship between structural features and sites of basaltic volcanic activity. Some structures may be preferential sites for ascent of basalt magma but there is not a causative relationship between structure and volcanism. That is, the structural features of the Yucca Mountain region which are associated with basalt sites, appear simply to be passive features promoting the passage of but not causing basaltic magmatism. In fact, the presence of favorable structures may be required to promote ascent of basalt through the relative inactive crust of the region. Basalt magma in the tectonic setting of the Yucca Mountain region may be incapable of ascending through the crust unless it encounters favorable crustal structures for ascent. Finally, there is a common but not universal restriction of sites of Quaternary basaltic volcanic centers to alluvial basins of the basin-range province. This relationship seems best established for the less tectonically active interior parts of the province than the active exteriors. All Quaternary basalt centers of the southern Great Basin, except the Hidden Cone center, occur within or at the margins of alluvial basins. The Lunar Crater volcanic field and the basalt center of Buckboard Mesa have been cited in the geologic literature as Quaternary basalt centers or fields developed inside of ranges (for example, Smith et al. 1990). However this is simply a difference of opinion concerning the definition of basins. Both examples include basalt centers developed in the basin interior of caldera complexes. Two causative processes may control the tendency for basalt centers to form in or at the margins of basins. The alluvial basins may simply be the shortest pathways to the surface for ascending magma. The likely control in this case is lithostatic load. Alternatively, the alluvial basins may be the remaining sites of active tectonism in an overall pattern of waning tectonic activity.

A. Detachment Systems

A wealth of geologic information suggests detachment systems are present in the Yucca Mountain region. Debate will undoubtedly continue concerning the location, age, geometry and regional relationships of these detachment systems. The existence of at least local detachment systems seems well established. An important remaining debate is whether the Quaternary faulting at Yucca Mountain is related to waning activity on a detachment system (Scott; 1990) or is a phase of extensional faulting that is unrelated to older detachment faulting (M. Carr and Monsen 1988).

The potential role of low angle or detachment fault systems as pathways for magma for the upward movement of basalt major is a much debated question. Several authors (deVoogd et al. 1986; Serpa et al. 1988) suggest a mid-crustal bright spot below southern Death Valley is associated with the Split Cone, a Quaternary basalt center formed along and offset by the southern Death Valley fault. They suggest low angle faults provided migration pathways for the basalt magma. However, theoretical studies of the dynamics of ascent of basaltic magma (see section 5) suggest basalt magma ascends by a mechanism of self-generated hydraulic fractures forming predominately vertical fractures. Low angle faults probably do not represent a potential or favorable pathway for basalt magma. By inference, high angle faults above detachment systems may have no deep links to magma pathways through the crust. This may explain the absence of any notable spatial relationship between detachment structures and sites of Pliocene or Quaternary basaltic magma. Detachment systems, while potentially important aspects of tectonic, faulting or seismic studies, are not judged to be important elements for understanding the structural controls of basaltic volcanism in the Yucca Mountain area.

B. Caldera Models

Ring-fracture zones of caldera complexes appear to represent potential structural pathways for basalt magma. This has long been recognized in geologic studies of the region (Crowe and Carr 1980; Carr 1984). Debate continues concerning the presence or absence of caldera complexes in Crater Flat and beneath the western edge of Yucca Mountain. The presence of Pliocene and Quaternary basalt centers in the interior of Crater Flat appears inconsistent with caldera models. However, present stratigraphic, structural and geophysical data do not prove or disprove the existence of caldera complexes. Caldera models, pending acquisition of new drill hole and geophysical data that may provide definitive tests of the caldera interpretations, must be considered in tectonic studies of the structural controls of basaltic volcanic activity.

C. North-Northeast-Trending Rifts

The Kawich-Greenwater rift of Carr (1990) is a north-northeast trending structural zone that extends through Yucca Mountain. The rift itself is not closely associated with Pliocene or Quaternary sites of basaltic volcanism. Some sites of basaltic volcanism occur within the rift, others occur outside of the rift. The rift model forms a subset of the northeast trending, Death Valley-Pancake Range volcanic zone (Crowe et al. 1986; Carr 1990). The structural model of Smith et al. (1990) can be viewed as a subset of the Kawich-Greenwater rift and the Death Valley-Pancake Range zone. None of these models provide explanations for the occurrence or location of individual sites of basaltic volcanism. They appear instead to be broad zones marked by a suite of structural features within which there are preferential occurrences of Pliocene and Quaternary basaltic volcanic centers compared to areas outside the zones. Tectonic models of northeast-trending rifts or zones extending through the Yucca Mountain region are of limited use for understanding the tectonic controls of basaltic volcanism. However, these models will be used in assessing regional structural controls of basaltic volcanism.

D. Pull-Apart Basins

Increased attention has been given in the recent geologic literature to structural models involving strike-slip bounded, pull-apart genesis of basins in the southern Great Basin (Wright 1989; O'Neil et al. 1991; Fridrich and Price (1992). Sites of basaltic volcanism may show strong spatial associations with the pull-apart basins. Basaltic volcanism may be associated with individual basins (Fridrich and Price 1992) or with aligned basins forming tectonic zones (Wright 1989). Basaltic volcanism in southern Crater Flat may be associated spatially with a half-rhombocasm (Fridrich and Price 1992). Tectonic models relating sites of basaltic volcanism to post-middle Miocene basin formation in strike-slip bounded, pull-apart basins will be used for the Yucca Mountain region.

E. Crater Flat Volcanic Zone

Basaltic volcanism in the Yucca Mountain region occurs in a narrow, northwest-trending zone located west and southwest of Yucca Mountain. This zone has been named the Crater Flat volcanic zone (Crowe and Perry 1989). The delineation of the zone is based on the distribution of Pliocene and Quaternary volcanic centers, providing a direct link to basaltic volcanism. There are a variety of permissive explanations of the zone, a direct outgrowth of the fact that the zone does not follow a continuous surface structure. The zone may represent a buried structural feature of the Walker Lane structural zone. Schweickert (1989) suggested the basalt centers may mark the traced of a concealed, northwest-trending strike-slip fault exhibiting tens of kilometers of offset of Paleozoic rocks. The zone may be associated with a strike-slip bounded basin in Crater Flat (O'Neil et al. 1991; Fridrich and Price 1992) or it may cross multiple pull-apart basins. The Crater Flat volcanic zone does not intersect the potential repository site at Yucca Mountain. Nonetheless, structural models have been developed for relating the volcanic zone to risk assessment (Crowe et al. 1988; DOE 1991). The Crater Flat volcanic zone will be used in the application of tectonic models to determinations of the structural controls of basaltic volcanism in the Yucca Mountain region.

F. North-Northeast Trending Structures

A sub-model of the Crater Flat volcanic zone is the presence of north-northeast elongated clusters of basalt centers, secondary to the northwest-trending volcanic zone. These northeast-trending zones probably represent control by the shallow stress field of the direction of injection of basalt dikes. These dikes may be offshoots of basin-bounding strike-slip faults (DOE 1990; Fridrich and Price 1992), concealed strike-slip faults (Schweickert 1989) or concealed structural features of the Walker Lane structural zone (Crowe and Perry 1989; Crowe 1990). Smith et al. (1990) has suggested the northeast-trending clusters are following normal faults exposed in the bed-rock west of the potential Yucca Mountain site. Tectonic models incorporating possible structural controls of north-northeast trending structures will be used in assessment of volcanic risk for the Yucca Mountain site.

G. Alluvial Basins

Structural models associating sites of basaltic volcanism with alluvial basins will be used in assessing tectonic models for the potential Yucca Mountain site.

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SECTION IV: BASALTIC VOLCANISM IN THE GREAT BASIN

I. ABSTRACT

Basaltic volcanism has been the predominant form of volcanism in the Great Basin over the last 5-10 Ma. Great Basin basalts are primarily alkalic in composition indicating small degrees of partial melting of relatively deep mantle sources. The compositions of basalt have become more undersaturated with time, both in the Basin and Range province as a whole, and within individual volcanic fields, suggesting that the intensity of melting in the mantle has declined with time on a regional scale. The volume of basalt flux into the crust has also declined in a broad sense throughout the middle and late Cenozoic, considering that the enormous volumes of ash-flow tuff erupted in the mid-Cenozoic were fueled by a comparable volume of basaltic magma. The transition from the eruption of evolved magmas to basalt in the late Cenozoic can be attributed to changes in plate tectonic processes and crustal properties with time. Isotopic and trace-element studies of basalt have documented the role of both asthenospheric mantle and lithospheric mantle in the generation of basaltic magma in the western United States. The regional distribution of these sources correlates with tectonic setting and history, and may control the volume and compositional distribution of basalt relative to major physiographic boundaries.

Basalt eruptions at Crater Flat follow many of the same patterns seen in other basalt fields of the western United States. Eruptive volumes and the depth of magma chambers both decrease with time, suggesting an overall decrease in basalt flux from the mantle with time. An unusual aspect of the Crater Flat basalt centers is that they may have erupted multiple times over many thousands of years (polycyclic volcanism). Petrologic and geochemical data indicate that multiple magma batches erupted to form these centers with no evidence for mixing or homogenization of magmas, suggesting long time periods between eruptions.

II. INTRODUCTION

The Great Basin (encompassing most of the northern Basin and Range province; see section III of this report) is a region that was affected during the middle and late Cenozoic by extensional tectonism and magmatism. As a result, it is characterized by thinned lithosphere, high heat flow, active faulting, high seismicity, abundant thermal springs, and the widespread distribution of Tertiary volcanic rocks (for example, Eaton 1982; see section III of this report). Small-volume basaltic volcanism has been the characteristic form of volcanism in the Great Basin for the last 5-10 Ma.

Basaltic magma is generated in the upper part of the earth's mantle by partial melting of mantle peridotite. Differences in the pressure and chemistry of the source region, and in the proportion of source rock melted, create a continuous spectrum of basaltic compositions that erupt at the surface. In a simple way, basalt can be divided into two compositional categories, alkalic and tholeiitic. Alkalic basalts have high total alkalis

(Na_2O+K_2O), and are generated at greater depths (45-65 km) by small degrees of partial melting. Tholeiitic basalts have lower total alkalis and are generated at shallower depths (35-45 km) by relatively larger degrees of partial melting (Jaques and Green 1980). Nearly all of the basalts erupted within the Great Basin since the late Miocene are alkalic (Leeman and Rogers 1970; Best and Brimhall 1974; Farmer et al. 1989; Fitton et al. 1991). Experimental data (Takahashi 1980; Takahashi and Kushiro 1983) indicate that alkalic basalts compositionally similar to those of the basin and range province equilibrated at pressures of 14-20 kilobars, equivalent to a depth of 45-65 km.

Cenozoic intermediate to silicic calc-alkaline volcanism began in the northern Great Basin during the late Eocene, and gradually swept south, ending in southern Nevada by the late Miocene (see section II of this report). This southward sweep is thought to be related to declining plate convergence rates and steepening of the dip of the subducted slab, resulting in activation of the asthenospheric mantle wedge and generation of basaltic magma to fuel crustal magmatic systems (Cross and Pilger 1978; Lipman 1980; Best and Christiansen 1991). Eruption of calk-alkaline ash-flow tuffs reached a peak in the Great Basin during the period of 30-20 Ma years ago (the "ignimbrite flare-up") when >50,000 km^3 of tuff was erupted (Best and Christiansen 1991). Isotopic studies of zoned ignimbrite systems suggest that an equal or greater volume of basaltic magma was required to generate these ash-flow tuffs (Johnson 1991). Large-magnitude extension also migrated southward during the Cenozoic (see section III of this report), although less systematically than silicic volcanism. The timing of extension and volcanism may not be well correlated in any particular area; extension locally predates, is contemporaneous with and post-dates silicic volcanism (Axen et al. 1993).

The initiation of true basaltic volcanism in the Great Basin began in the early to middle Miocene (<17 Ma ago) and generally post-dates major silicic volcanism and some of the major phases of extension in any particular region. For example, silicic volcanism of the Timber Mountain complex and peak extension rates in the southern Great Basin occurred simultaneously 15-10 Ma ago (Wernicke and others 1988; Scott 1990; Carr 1990). The commencement of basaltic volcanism occurred during the latter part of this period, and small volume basaltic volcanism has continued into the Quaternary (see section II of this report). Citing several similar examples, Glazner and Ussler (1989) argued that the transition to eruption of basalt in the western United States was not due to increased rates of extension, since basaltic volcanism in any region usually begins *after* extension rates have declined. They proposed instead that the transition was due to increases in mean crustal density resulting from extensional thinning of low density upper crust and intrusion of mafic magma into the lower crust. Denser crust would enhance buoyant ascent and eruption of basaltic magma (see section V of this report). This mechanism would however be limited to areas that had undergone high-magnitude extension or focused mafic intrusion.

The "ignimbrite flare-up" was fueled by a large flux of basaltic magma into the crust (Johnson 1991; Best and Christiansen 1991), probably as a result of reactivation of the mantle wedge above a steepening subducted slab following the slowing of subduction rates after the Laramide (Coney and Reynolds 1977; Cross and Pilger 1978; Lipman 1980).

Basaltic intrusion, convection in the underlying mantle wedge, and thick crust inherited from the Laramide created an unusually hot crust by the end of the Oligocene. Thermally weakened crust may have been a prerequisite for large-magnitude "ductile" extension in the Basin and Range province in the late Oligocene to early Miocene (Morgan et al. 1986). The extensional collapse of over-thickened and thermally weakened crust followed the slowing of subduction and easing of compressional forces at the continental margin (Coney 1987). Coupled with decreased basalt flux into the crust, conductive cooling of the thinned crust would be favored.

Overall cooling of the Cordilleran crust in the late Cenozoic is consistent with changes in extensional style and the transition to the eruption of basalt. Two overlapping phases of extensional deformation are recognized during the Cenozoic: (1) an early, mid-Tertiary phase characterized by high strain rates, a shallow brittle-ductile transition, shallow fault penetration, and eruption of voluminous intermediate to silicic volcanic rocks, and (2) a late, Miocene-Pleistocene phase ("basin and range event") characterized by lower strain rates, deeply penetrating faults, the establishment of modern Basin and Range topography, and bimodal eruptions of basalt and high-silica rhyolite (Christiansen and Lipman 1972; Zoback et al. 1981; Eaton 1982; Morgan et al. 1986; Coney 1987; Keller et al. 1990; Armstrong and Ward 1991). The high strain rates characteristic of Oligocene extension probably in part required a hot and thermally weakened crust, while lower strain rates associated with deep, high angle faulting are consistent with a cooler, more brittle, and mechanically stronger crust (Morgan and others 1986). Cooling of the crust may have favored the eruption of basalt because (1) cooling of the crust increases crustal density on a regional scale (enhancing buoyant ascent of basaltic magma), (2) contamination or mixing with more silicic crustal magmas would be inhibited, and (3) basaltic magmas intruded into brittle crust would have access to deeper crustal fractures that would favor rapid ascent without differentiation (Perry et al. in press).

III. TIME-SPACE TRENDS IN THE LOCATION, COMPOSITION AND VOLUME OF BASALTIC VOLCANISM

Basaltic volcanism in the Great Basin and adjoining regions has exhibited systematic trends in location, composition, and eruption volume through time. These trends can be related to both tectonic processes in the crust and melt generation processes in the underlying mantle.

Figure 4.1 summarizes the distribution of basaltic rocks in the western United States (excluding the Columbia Plateau) during two time periods: (1) 16-5 Ma, from near the inception of basaltic volcanism to the end of the Miocene, and (2) 5-0 Ma, from the end of the Miocene to the present. First, basaltic volcanism was concentrated increasingly along major physiographic margins with time, in particular along the margins of the Great Basin and the Colorado Plateau. Post-Miocene eruption of basalt within the Great Basin interior has been sparse, with the notable exception of a band of post-Miocene basalt that extend from Death Valley to Lunar Crater in central Nevada, including the basalt of Crater Flat (Crowe et al 1983). The migration of basaltic volcanism to the margins of the Great Basin

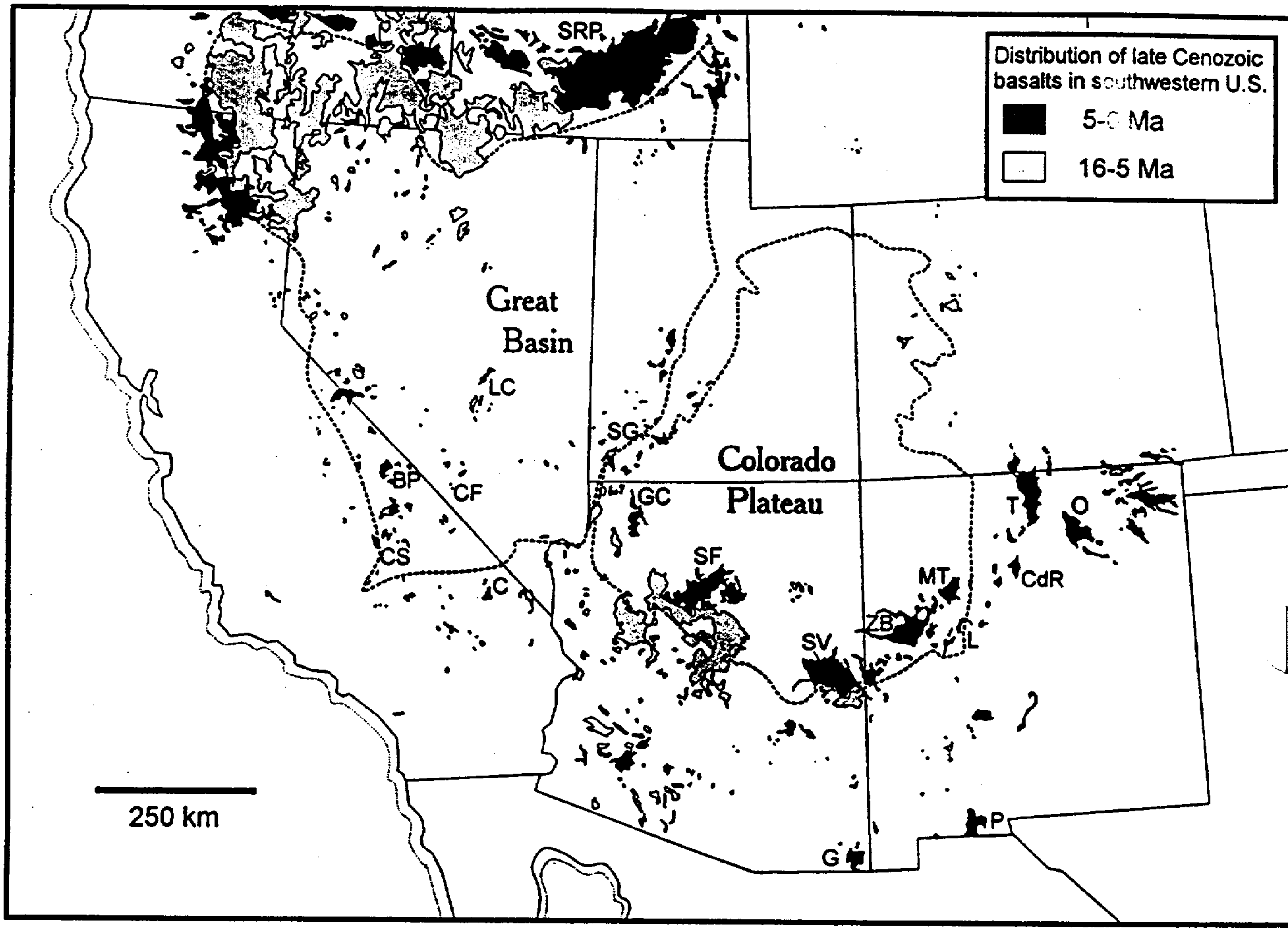

Fig. 4.1 Map of the western United States showing the distribution of basalt erupted during the past 16-5 and 5-0 Ma (after Fitton et al. 1991). Labeled volcanic fields are: BP, Big Pine; C, Cima; CdR, Cerros del Rio; CF, Crater Flat; CS, Coso; G, Geronimo; GC, Grand Canyon; L, Lucero; LC, Lunar Crater; MT, Mount Taylor; O, Ocate; P, Potrillo; SF, San Francisco; SG, St. George; SRP, Snake River Plain; SV, Springerville; T, Taos; ZB, Zuni-Bandera.

correlates with increased extension and seismicity in these areas, indicating that the stress regime exerts a broad control on the location of basaltic eruptions. (Christiansen and McKee 1978).

In the southwestern United States, basaltic volcanic fields that erupted the largest volumes and had the highest eruption rates are associated with the Colorado Plateua margin (Fig. 4.2). Many of these basalt fields erupted tholeiitic basalt in addition to alkalic basalt, indicating higher degrees of partial melting at shallower mantle depths compared to the Great Basin/Basin and Range interior. Basalt fields in the interior of the Basin and Range have volumes that seldom exceed a few tens of cubic kilometers, while several fields along the Colorado Plateau boundary have volumes of 100-300 km^3 (San Francisco, Springerville, Zuni-Bandera, Taos). Long-term eruption rates for several volcanic fields on the Colorado Plateau margin exceed 50 km^3/Ma, while rates within the Basin and Range are < 20 km^3/Ma (Fig. 4.2). The volume and eruption rates of basalt fields of the Colorado Plateau margin suggest higher production rates of basaltic magma in the mantle beneath these areas, compared with mantle beneath the Basin and Range interior.

The composition of basalt erupted within the Great Basin/Basin and Range has also changed systematically through time (Fitton et al. 1991). Basalt erupted since 5 Ma ago are as a group more silica-undersaturated (more nepheline normative) than basalt erupted before 5 Ma ago, and also have a higher average MgO content, indicating less fractionation in route to the surface (Fig. 4.3). These data suggest that the younger group of basalt represent smaller degrees of partial melting at greater depths in the mantle (e.g., Jaques and Green 1980). Similar changes in composition through time are seen in a number of individual volcanic fields within the Basin and Range, as discussed in a later section. The more primitive nature of the younger basalt indicates rapid ascent from the mantle with minimal crustal residence time, possibly because of higher volatile concentrations resulting from smaller degrees of partial melting (Fitton et al. 1991). A trend to smaller degrees of partial melting through time in the Basin and Range is consistent with a decrease in volume erupted through time for a number of individual fields in the Basin and Range. The more volatile-enriched nature of these basalts, however, may result in more frequent eruptions (cf. Smith and Luedke 1984) since these magmas are more likely to ascend rapidly through the crust without stalling (Spera 1984).

IV. THE ROLE OF THE MANTLE IN BASALTIC VOLCANISM

Numerous isotopic and trace-element studies of basalt have demonstrated that basalt in the western United States are derived from either asthenospheric mantle (equivalent to oceanic mantle), or ancient lithospheric mantle that has been isolated from asthenospheric convection for periods of greater than a billion years (Menzies et al. 1983; Hart 1985; Perry et al. 1987; 1988; Farmer et al. 1989; Lum et al. 1989; Menzies 1989; Cooper and Hart 1990; Kempton et al. 1991; Fitton et al. 1991; Daley and DePaolo 1992). Perry et al. (1987, 1988) proposed that the source of basalt in the western United States depends on the timing and intensity of lithospheric extension relative to the timing of basalt eruption. In regions that

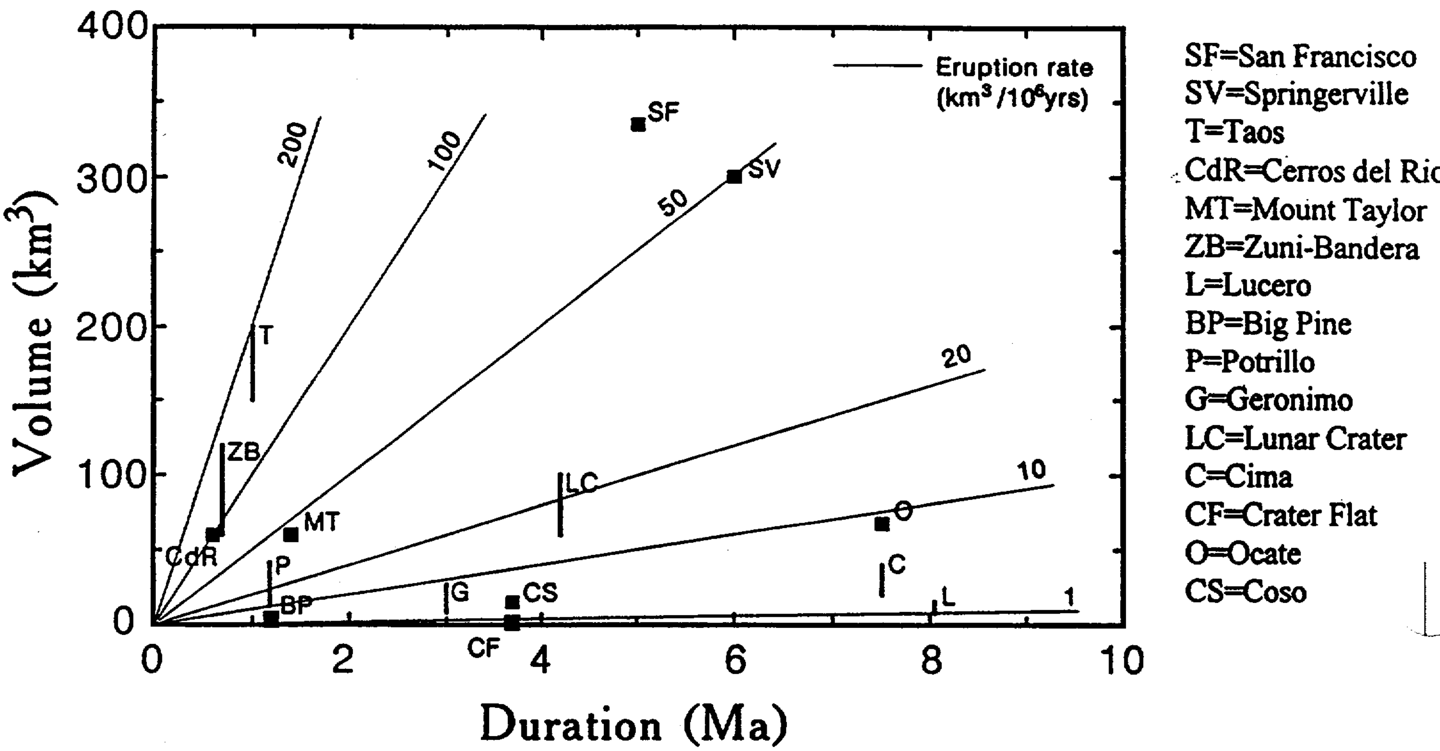

Fig. 4.2 Approximate volume versus eruption duration for late Cenozoic basaltic volcanic fields for which reasonable data is available.

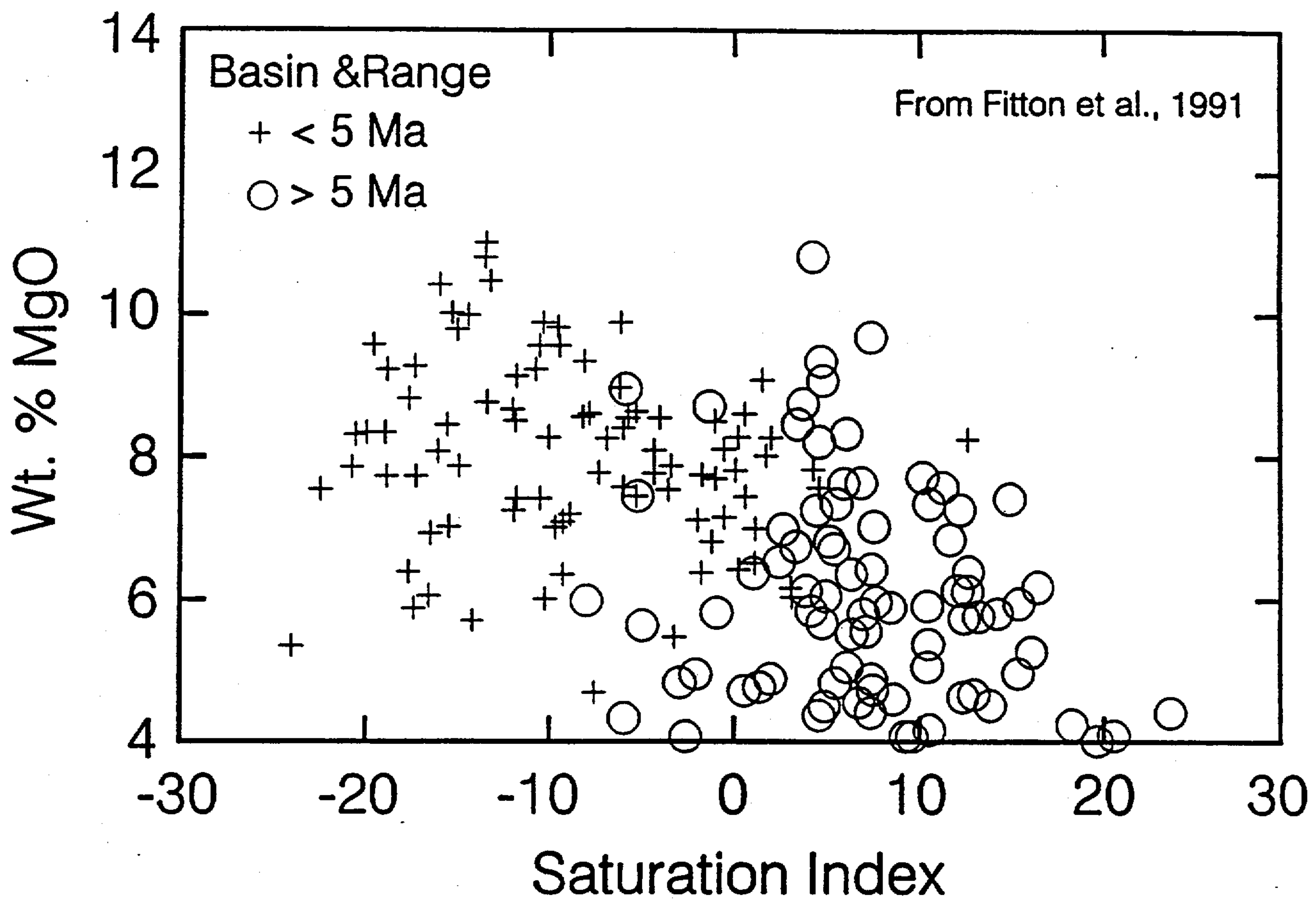

Fig. 4.3 MgO versus saturation index for basalts of the Basin and Range province, after Fitton et al. 1991. Basalts with saturation index < 0 are nepheline normative, basalts with saturation index > 0 are hypersthene normative.

have undergone little or only recent lithospheric extension, basalts are derived from lithospheric mantle, because asthenospheric upwelling has been limited and has not replaced the preexisting lithospheric mantle. In regions of more pronounced or prolonged extension, asthenospheric mantle eventually replaces lithospheric mantle and becomes the source for basalt. Isotopic evidence indicates that asthenospheric sources are present beneath the southern Basin and Range of New Mexico, Arizona, and southeastern California, as well as the central Great Basin of Nevada. These areas generally underwent the earliest and most intense extension within the Basin and Range province. Lithospheric mantle is still preserved beneath the stable regions of the Colorado Plateau, Rocky Mountains, and Great Plains. Mixed asthenosphere/lithosphere sources are present beneath most of the Colorado Plateau/Basin and Range transition zone, suggesting that these transitional areas are undergoing active conversion of lithospheric sources to asthenospheric sources (Perry et al. 1987).

Farmer et al. (1989) presented isotopic and trace-element data which suggest that basalt of the southern Great Basin have been derived from lithospheric mantle over the last 10 Ma, despite erupting in a region that has undergone active extension for the past 15-10 Ma. This region coincides with the amagmatic gap of Eaton (1982), and was the last portion of the Basin and Range province to begin extending (15-10 Ma ago). The relative lack of magmatism in this region may have left the lithosphere "cold" and difficult to extend (Wernicke et al. 1987). Both the thermal state and the late initiation of extension of this lithosphere may have combined to preserve lithospheric mantle beneath this region (Farmer et al. 1989).

The presence of lithospheric mantle beneath the southern Great Basin is not wholly compatible with the generation of basaltic magma beneath this region, since lithospheric mantle is generally considered too cold to partially melt. Daley (1992) proposed that if lithospheric mantle beneath the southern Great Basin is hydrous, it can generate basaltic magma at small rates of lithospheric extension, since a small amount of water in the mantle will substantially depress the peridotite solidus. A hydrous mantle source for the basalt of Crater Flat is consistent with their low Rb contents relative to other incompatible trace elements, which suggests that phlogopite may have played a role in the partial melting process (Vaniman et al. 1982). Daley (1992) calculates that for a 100 km thick lithosphere and no extension, 1-2 km^3 of basalt could be erupted per 100 km^2 of surface, assuming that 10% of the mantle lithosphere is hydrous, 90% of the melt generated separates from the residue, and 10% of that melt is erupted.

Melting of hydrous lithospheric mantle may also have played a role in the concentration and volume of basaltic volcanism along the Colorado Plateau margin. Best and Brimhall (1974) and Tanaka et al. (1986) suggest that volcanism within the Colorado Plateau transition zone may be caused by viscous heating as asthenospheric flow encountered the thicker lithospheric "edge" beneath the Colorado Plateau. Secondary convection in the asthenosphere, caused by lateral temperature variations (juxtaposition of hot asthenosphere and colder Colorado Plateau mantle lithosphere) may have locally enhanced asthenospheric flow, facilitating heat transport into the adjacent lithosphere (Perry et al. 1987). The combination of hydrous lithospheric mantle and enhanced heat transport from the asthenosphere may have favored the generation and eruption of voluminous alkalic and, in some cases, tholeiitic basalt. In the Great Basin/Basin and Range interior, hydrous lithospheric mantle may have been substantially removed by lithospheric extension and asthenospheric upwelling by the end of the Miocene. The absence of easily fusible lithospheric mantle, and of lateral mantle discontinuities found at physiographic margins, may combine to restrict melting to relatively small amounts at greater depths within dry and relatively less fusible asthenosphere.

Low mantle P_n velocities beneath much of the Basin and Range province suggest that the upper mantle contains a small percentage of partial melt at all times. Ascent of this melt through the crust to produce basaltic volcanism may depend partly on where local stress regimes are conducive to magma ascent (Smith and Luedke 1984). Against the general background of small melt fractions in the Basin and Range mantle, three northeast trending zones of enhanced partial melting have been proposed based on identification of low-velocity mantle anomalies (Spence and Gross 1990; Dueker and Humphreys 1990; Humphreys et al. 1992). The northernmost and southernmost of these zones correspond to zones of pronounced magmatism: the Snake River Plain-Yellowstone zone and the Jemez zone of the southeastern Colorado Plateau margin (Fig. 4.1). The middle zone extends from central Utah to southern Nevada and corresponds with surface volcanism at the St. George area of Utah (Dueker and Humphreys 1990) and the Crater Flat area of southern Nevada (Evans and Smith 1992). The volume of basaltic volcanism associated with the St. George zone is far less than the zones to the north and south. At Crater Flat, in particular, 4 Ma of basaltic volcanism has produced only about 1 km^3 of basalt. If the low-velocity anomaly beneath Crater Flat does represent an unusual degree of partial melting relative to the rest of the Basin and Range, it suggests that the local stress regime does not strongly favor magma ascent and eruption.

V. EVOLUTION OF BASALTIC VOLCANIC FIELDS

Many long-lived (>2-3 Ma) basaltic volcanic fields in the southwestern United States display a characteristic evolution in terms of eruption volume and chemistry that can be related to changes in the intensity and depth of partial melting in the mantle. Perhaps the best documented example of systematic volume and chemical relationships through time is the Springerville volcanic field on the southern Colorado Plateau margin of Arizona (Condit et al. 1989). At Springerville, the earliest and most voluminous basalt is tholeiitic (large degree of partial melting), which erupted between 6.5 and 1.75 Ma (Condit et al. 1989, Cooper et al. 1990). After 2 Ma, volcanism shifted to less voluminous eruptions of alkalic basalt, representing smaller degrees of partial melting at greater depth in the mantle. A similar relationship is seen in the Zuni-Bandera volcanic field on the Colorado Plateau margin of western New Mexico (Laughlin et al. submitted). Tholeiite was erupted exclusively in the earliest two episodes (700-600 ka and 200-100 ka), while the youngest episode (<100 ka) erupted both tholeiitic and alkalic basalts. The relationships at Springerville and Zuni-Bandera are consistent with gradual waning of the intensity of mantle melting through time and the eventual extinction of the volcanic field.

Less voluminous basalt fields in the Basin and Range interior show similar patterns of evolution, although the intensity of mantle melting associated with these volcanic fields was apparently never great enough to produce tholeiitic basalt. Examples are the Cima volcanic field of southeastern California and the Lunar Crater volcanic field of central Nevada (Crowe et al. 1986; Wilshire et al 1991; Foland and Bergman 1992). In these volcanic fields, Pliocene eruptions of alkali basalt form relatively voluminous, sheet-like flows, while Quaternary eruptions were less voluminous and compositionally more undersaturated, again indicating a progression to less intense and deeper mantle melting.

Basaltic volcanism at Crater Flat occurred in three episodes at approximately 3.7, 1, and <0.2 Ma. All of the basalt erupted at Crater Flat are alkalic (Vaniman et al. 1982), indicating relative small degrees of partial melting in the mantle throughout the lifetime of the field. The volume of alkali basalt erupted through time has decreased, from a minimum of 0.65 km^3 in the oldest cycle, to 0.06 km^3 at the youngest center (Lathrop Wells), producing a total volume of about 1 km^3. The relatively long lifetime of the Crater Flat field, combined with the small volume of erupted material, results in one of the lowest eruptive rates of any basaltic volcanic field in the southwestern United States (Fig. 4.2).

Although declining volumes through time indicate a waning magmatic system, the normative compositions of basalt from different episodes (Vaniman et al. 1982) do not clearly indicate a shift to more undersaturated compositions (and hence, smaller degrees of partial melting) through time. Differences in normative composition appear to be related more to fractionation history (e.g., amphibole removal) than differences in degree of partial melting (Vaniman et al. 1982).

Another factor bearing on the evolution of the Crater Flat field is changes in the fractionation depth of magmas through time which is probably related to changes in magma chamber depth (Perry and Crowe 1992). Lavas of the oldest episode contain plagioclase, olivine, and clinopyroxene phenocrysts, while lavas of the younger episodes contain only olivine. Experimental studies of alkali basalt (Knutson and Green 1975; Mahood and Baker 1986) indicate that clinopyroxene will crystallize early in the crystallization sequence relative to plagioclase at pressures exceeding 8 kb. The lack of plagioclase in lavas of the younger episodes indicates fractionation at high pressure, within the lower crust or upper mantle. The high Sr (which partitions into plagioclase) of the younger episodes also indicate that plagioclase was not an important fractionating phase in the younger episodes. Sc (which partitions into clinopyroxene) is lower in the youngest episodes relative to the oldest episode, indicating fractionation of clinopyroxene at high pressure. In contrast, lava of the oldest episode contains plagioclase phenocrysts, relatively low Sr , and relatively high Sc (Vaniman et al. 1982), indicating fractionation at low pressure where plagioclase and olivine dominate fractionation. These relationships indicate that magma chambers were relatively shallow (middle to upper crust) at 3.7 Ma, but were deep (lower crust or upper mantle) during the younger two episodes (Perry and Crowe 1992).

Frey et al. (1990) suggest that the depth at which magma chambers were established at Mauna Kea is controlled by magma flux into the crust, with older, higher level chambers being sustained by higher magma flux, and younger, lower crustal chambers being established after magma flux declines. Younger lavas at Mauna Kea are more differentiated, suggesting that lavas derived from lower crustal chambers ascend only after magma density is lowered by fractionation of olivine+clinopyroxene. The changes in phenocryst assemblage, trace-element content, and degree of evolution of lavas erupted during the waning of Mauna Kea volcanism almost exactly mirror the changes seen at Crater Flat, suggesting that the evolution to deeper magma chambers at Crater Flat may also reflect a waning magma flux. The Mauna Kea model must be applied cautiously to Crater Flat because (1) the eruption rate at Mauna Kea is orders of magnitude higher, raising questions about whether vastly different magma fluxes can lead to similar ascent dynamics, and (2) Mauna Kea is a single volcano, with an integrated plumbing system, whereas eruptive activity at Crater Flat is spread over several distinct eruptive centers with separate plumbing systems.

VI. POLYCYCLIC VOLCANISM IN THE CRATER FLAT VOLCANIC FIELD

One of the controversies regarding the Lathrop Wells volcanic center, the youngest center in the Crater Flat volcanic field, is whether it monogenetic, erupted during a short period of time, or polycyclic, erupting over a period of several thousands of years (Wells et al. 1990; Turrin et al. 1991; Wells et al. 1992; Turrin et al. 1992).

A monogenetic volcano is formed by the ascent and eruption of a single batch of magma, generally within a period of months to years (Wood 1980). A small-volume polycyclic volcano, if formed over a period of thousands to tens of thousands of years, would necessarily involve the eruption of multiple magma batches, since small-volumes of magma have limited lifetimes within the lithosphere. Geochemical data can distinguish whether lavas erupted from a volcanic center are derived from single or multiple magma batches. Over 100 geochemistry samples have been collected from the Lathrop Wells center to constrain models for the formation of the center. Sampling has been based on eruptive units defined by geologic mapping (Crowe et al. 1988).

Perry and Crowe (1992) presented trace-element and isotopic data which showed that chemical variations among different eruptive units at the Lathrop Wells center are inconsistent with derivation from a single magma batch. This conclusion was based on the premise that compositional variations produced by fractionation of a single magma batch are predictable and depend on the behavior of each element during fractionation (i.e., whether the element is incorporated or excluded from fractionating minerals). As discussed by Perry and Crowe (1992), the behavior of La, Sm, Sc, and Sr can be predicated during fractionation of olivine, plagioclase, and clinopyroxene, the major minerals that fractionate during the evolution of a basaltic magma (Fig. 4.4). For instance, La/Sm ratios do not change substantially during fractionation of basalt, and any changes are accompanied by an increase in the absolute concentrations of La and Sm. The different La/Sm ratios of eruptive units (Ql_6 and Qs_{2d} or quarry units) at the same La content preclude derivation from fractionation of the same magma batch. Eruptive units also occupy different relative positions on trace-element variation plots, again ruling out derivation of all units from the same magma. Unit Ql_6 is the *least* evolved eruptive unit in terms of its La and Sm composition, but the

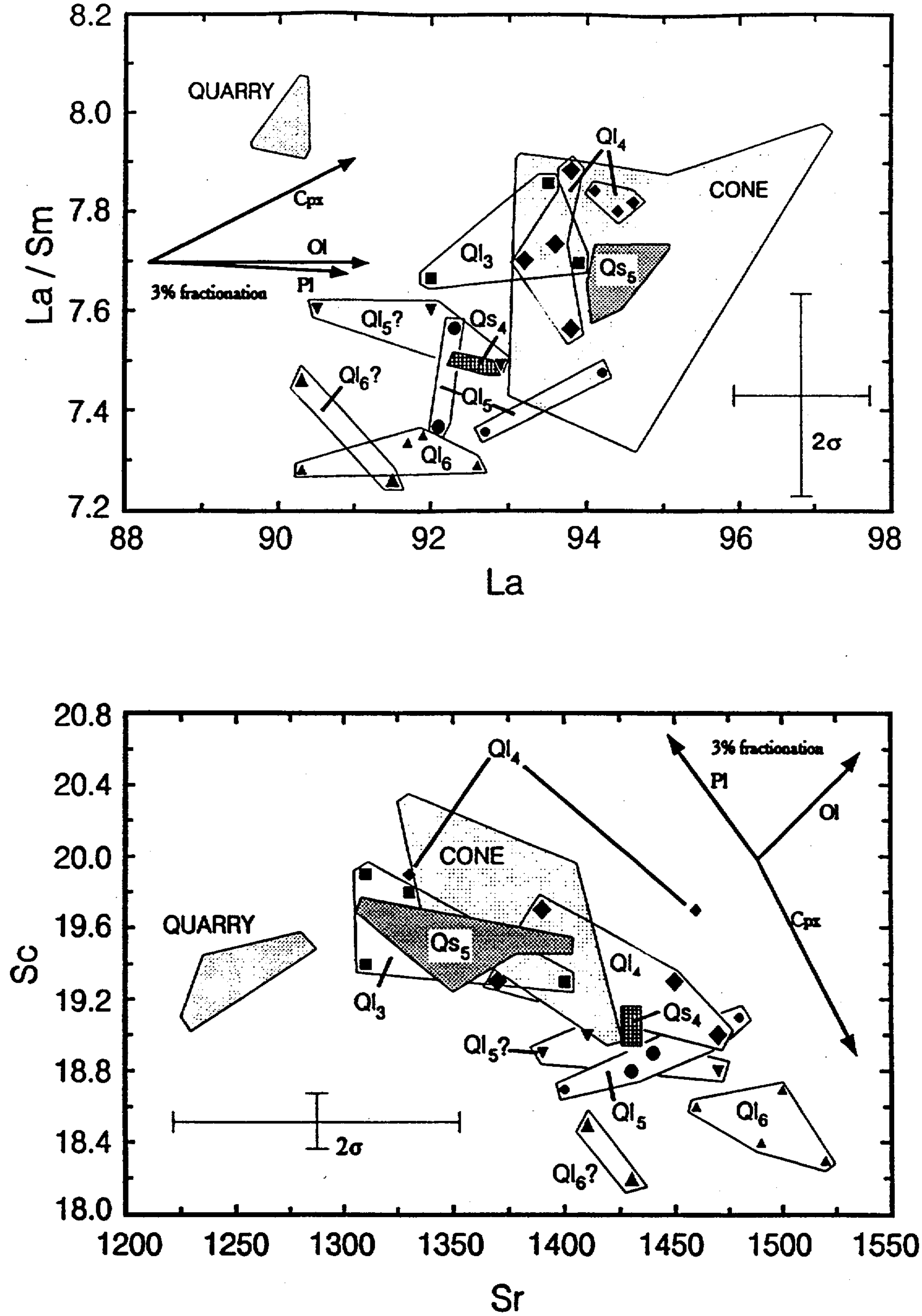

Fig. 4.4 La versus La/Sm and Sr versus Sc for basalts of the Lathrop Wells volcanic center. Shaded areas represent fields for scoria and bomb samples. Vectors represent 3% fractional crystallization of plagioclase (Pl), olivine (Ol), and clinopyroxene (Cpx).

most evolved in terms of Sc composition (Fig. 4.4). These relationships are again inconsistent with the chemical variations being due to the evolution of one magma batch. Variations of La/Sm with La are, however, consistent with a series of magma batches being produced by slightly different degrees of partial melting in the mantle (Allegre and Minster 1978). In this case, the younger eruptive units at Lathrop Wells would represent smaller degrees of partial melting than older units, suggesting that activity at Lathrop Wells may be waning. This cannot be considered a firm conclusion until further stratigraphic and geochemical studies are completed.

Trace-element data can also be used to constrain the origin of tephra exposed within the Lathrop Wells quarry. A plot of Rb versus Th (Fig. 4.5) shows that tephra of the main scoria cone (chronostratigraphic unit 2) is geochemically distinct from overlying tephra of chronostratigraphic unit 1. The different Rb/Th ratios of these two tephra indicate that they are not related by fractional crystallization but instead represent distinct magma batches. These data also preclude derivation of chronostratigraphic unit 1 tephra from the main cone by erosional processes (Turrin et al. 1992).

Nd and Sr isotopic data (Fig. 4.6) show that eruptive units at Lathrop Wells have small, but systematic, isotopic differences, further evidence that eruptive units at Lathrop Wells represent separate magmas that followed unique, but similar, evolutionary paths. Major-element analyses of the Lathrop Wells eruptive units are needed to fully test conclusions based on trace-element and isotopic data.

Additional evidence for multiple magma batches at Lathrop Wells is the presence of different phenocryst assemblages in different eruptive units. Except for unit Ql_6 (which field and geomorphic evidence indicate is probably the oldest eruptive unit), all of the eruptive units contain olivine as the only phenocryst phase. Unit Ql_6 also contains plagioclase as a phenocryst phase. Changes in phenocryst assemblage among rocks representing the same differentiation series are common, but these changes invariably are mirrored by significant changes in geochemistry (Walker and Carr 1986). There is no mechanism recognized that can lead to changes in phenocryst assemblages without significantly changing the chemical composition of the magma. Differences in the chemical composition of unit Ql_6 and units without plagioclase phenocrysts are small and inconsistent with phenocryst sorting involving a single batch of magma.

In addition to the petrologic and geochemical differences for separate magma at Lathrop Wells, trace-element data from lava flows at Black Cone, in Crater Flat, also indicate that different eruptive units represent distinct and unrelated magma batches. For example, a plot of Rb versus Ce from two lava flows at Black Cone defines a negative slope relating the two flows (Fig. 4.7). However, since both of these elements are incompatible during fractionation of a basaltic phenocryst assemblage, fractional crystallization will result in a positive slope (increase in both Rb and Th) between related parent and daughter magmas. The geochemical relationships at Black Cone again indicate that the center was formed by the eruption of multiple magma batches.

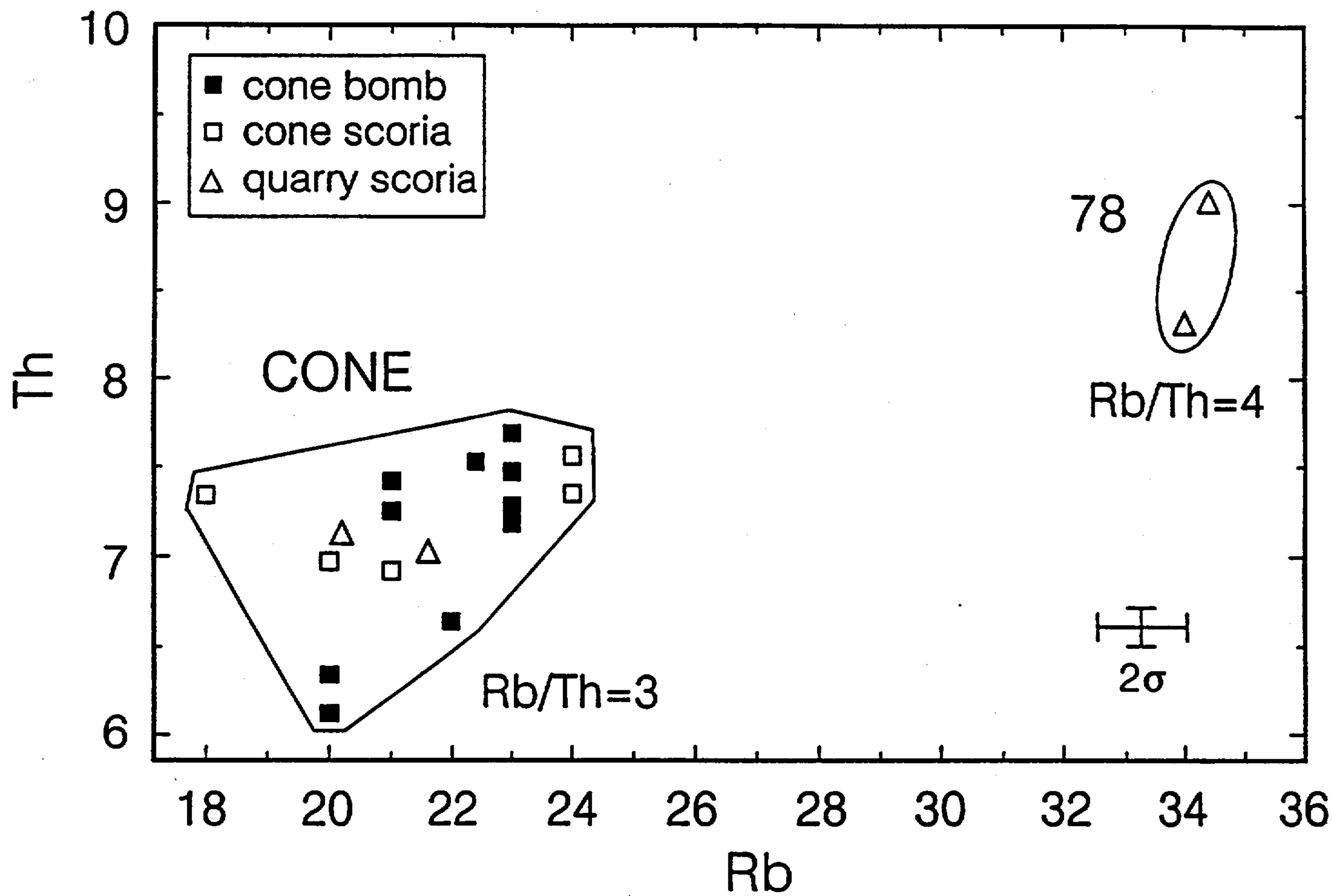

Figure 4.5 Rb versus Th for samples of the main cinder cone and tephra units exposed in the quarry of the Lathrop Wells volcanic center.

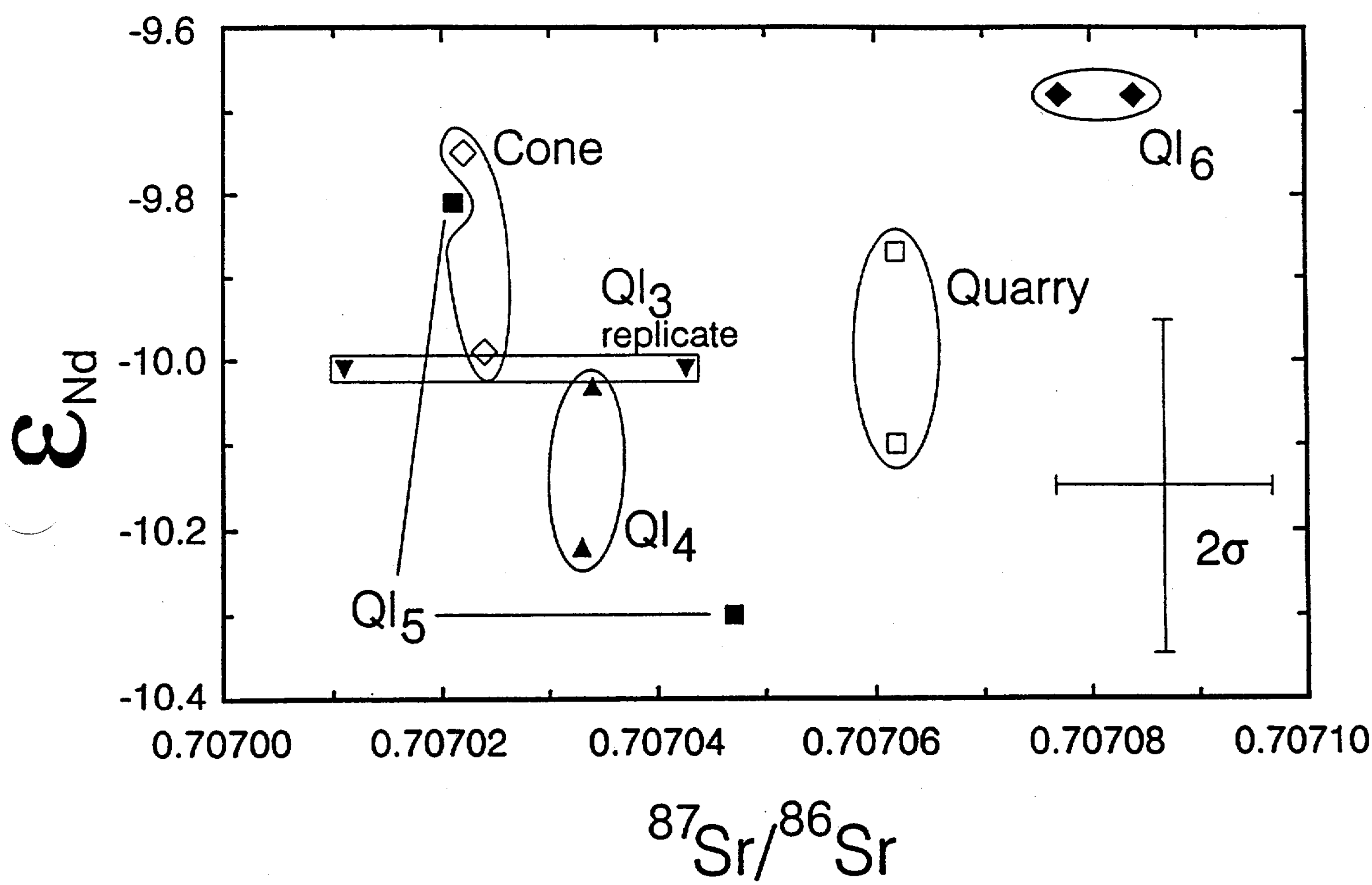

Fig. 4.6 $^{87}Sr/^{86}Sr$ versus e_{Nd} for basalts of the Lathrop Wells volcanic center.

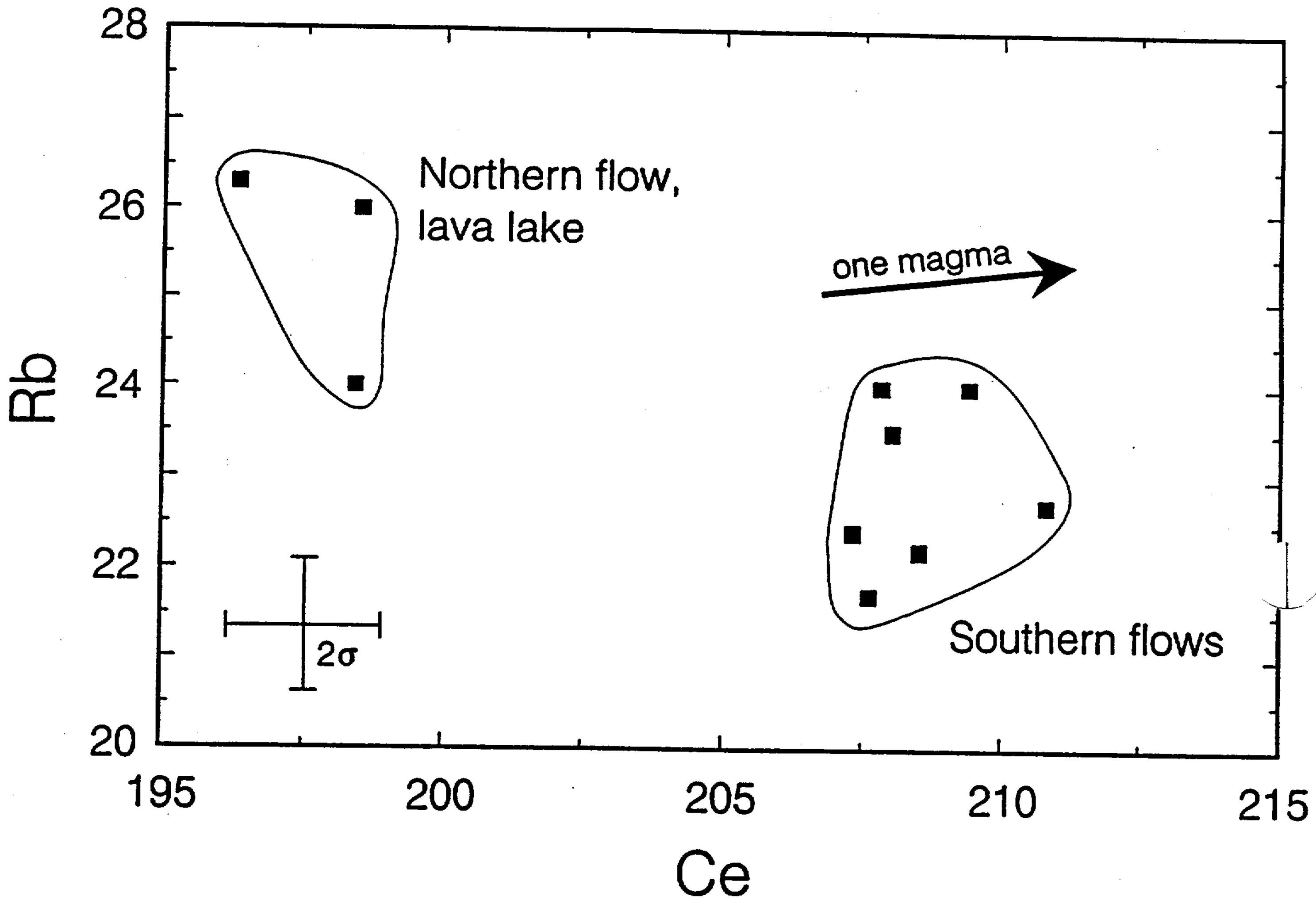

Fig. 4.7 Ce versus Rb for basalts of the Black Cone volcanic center. Vector represents the shift in Rb and Ce concentrations expected for a magma undergoing fractional crystallization.

The eruption of multiple magma batches at individual eruptive centers in the Crater Flat volcanic field is compatible with the concept of polycyclic volcanism, which was first proposed based on field, geomorphic, and soils data (Wells et al. 1990). It is unlikely that separate magma batches could form and ascend at or near the same time without mixing or homogenization of the magmas in some part of the magmatic plumbing system. Yet, eruptive units at both Lathrop Wells and Black Cone retain unique geochemical signatures and contain no physical or geochemical evidence of magma mixing. It is therefore more plausible that eruptions of separate magma batches at Lathrop Wells and Black Cone were separated by periods of at least several thousands years.

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SECTION V: SEGREGATION, TRANSPORT, AND LOCAL STORAGE OF BASALTIC MAGMA

I. ABSTRACT

Basaltic magma of the Yucca Mountain region originates in the upper mantle probably by processes of decompression melting. Once a melt is formed, it segregates from its solid mantle residue through a process of two-phase flow involving buoyant rise of the melt accompanied by deformation and compaction of the matrix. The mechanics of melt segregation are controlled by the equations of conservation of mass and momentum. The form of melt-matrix equations have been determined in general but not for all assumptions of boundary conditions. A controversial aspect of computer modeling of the melt segregation equations is the existence of solitons. Some workers argue that the formation of solitons may lead to spatial and temporal episodicity of melt segregation. Alternatively the features may be short-lived and incapable of effecting surface volcanic patterns. There is near complete agreement that basalt magma ascends via fluid-assisted fracture propagation as dikes. The formation and form of magma transport in dikes has been described by many authors using different assumptions dependent on whether the shapes of magma-formed fractures are controlled by the rock properties or the dynamics of flowing magma. The latter view requires assessment of elastic deformation of the country rock and fracture, flow and gas-properties at the dike tip. Field evidence shows that dikes can be modeled as planar cracks formed in brittle solids by pressurization and dilation associated with magma injection. Magma in the form of dikes will rise until it erupts, solidifies or reaches the level of neutral buoyancy (LNB). The position of the LNB in the Yucca Mountain area may be influenced by the density interface between low density basin fill and the Paleozoic rocks. Other processes such as crack-rate propagation, wall-rock permeability, magma-gas content or mechanisms of volatile concentration in a dike tip could negate the controls of the LNB. One additional issue is the control of dike orientations by pre-existing fractures. Field observations show that dikes can both fill fractures or fault planes, or propagate by magma-induced fracture in directions controlled by the stress field. The structural controls of basaltic centers in the Yucca Mountain region suggest that feeder dikes may follow northwest-trending structure at depth but divert at shallow levels to north-northeast strikes following the maximum compressive stress direction.

II. INTRODUCTION

This section provides a brief overview of the processes of accumulation and ascent of basalt magma in a continental extensional setting and emphasizes the mechanisms of melt segregation, and transport of magma via magma-driven fracture through the mantle and crust. Consideration is given as well to storage of basalt in the mantle and crust and at its level of neutral buoyancy (LNB), where magma may propagate laterally. There has been substantial progress particularly in the 1980s in mathematically describing the processes of segregation, migration and eruption of magma. We review the relevant aspects of these processes focusing primarily on the constraints which can be developed for the physical dimensions of magma systems, the mechanical interactions of magma and country rock, and the rates of operation of magmatic processes. These constraints are applied where possible in attempting to understand the time-space patterns of basaltic volcanism in the Yucca Mountain region.

III. MELT GENERATION AND SEGREGATION

We assume first, that partial melt of basaltic composition originates in the upper mantle at depths of 45 to 60 km. There is a wealth of petrologic information on the geochemical processes of melt formation constrained mostly by the major, trace element and isotopic composition of erupted basalt (see Section IV). The processes controlling the formation of the magma are perhaps best known for the generation of mid-ocean ridge basalt (MORB). Melting of oceanic mantle almost certainly occurs as a result of adiabatic upwelling beneath mid-ocean ridge spreading centers. Here oceanic lithosphere is upheld on a reservoir of convecting asthenospheric mantle of probable relatively uniform composition. Recent reviews of processes controlling melting in the upper mantle were provided by Kinzler and Grove (1992), and Eggins (1992). They note that decompression melting results when mantle rises faster than it can exchange heat with the surrounding rocks (adiabatically). Excess heat is lost through melt production and that loss is controlled by the latent heat of fusion of mantle periodotite, the heat capacity, the ambient mantle temperature, and the pressure and compositional fields of the mantle solidus (Kinzler and Grove 1992). The degree of melting generally increases with continuing decompression. Melting continues until either conductive cooling from above lowers the temperature below the solidus or a basaltic component is extracted. The extracted melt may migrate through the matrix or move preferentially in channels. Percolation allows the melt to maintain equilibrium with the matrix; channel segregation isolates the melt from the matrix (Eggins 1992). The two processes have different effects on the resulting melt geochemistry.

Melt production in the mantle below the Yucca Mountain region is constrained by the somewhat unique upper mantle of the southern Great Basin. First, the area is located on the north edge of the amagmatic gap (see Section III, Farmer et al. 1989; Jones et al. 1992). The region south of Yucca Mountain exhibited no magmatism during the Mesozoic and Cenozoic despite major plutonic episodes in the late Mesozoic (Farmer and DePaolo 1983) and profound mid-Cenozoic extension (Jones et al. 1992). Second, the isotopic composition of Sr and Nd in basalt in the Yucca Mountain region shows that it is underlain by preserved lithospheric mantle (Farmer et al. 1989). The isotopic characteristics of basalts generated in the lithospheric mantle have remained uniform for basalt melts from about 10 Ma to the age of the youngest center in the region, the Lathrop Wells center (Farmer et al. 1989). The presence of thick and cold lithospheric mantle reduces significantly the ability of athenospheric upwelling to penetrate the crust and generate magma that feeds surface volcanism (Nicolas 1990). Finally, while initiation of a melting anomaly probably occurs in the athenospheric mantle, the isotopic composition of the basalt of the Yucca Mountain region requires that most of the erupted melt component was derived from or equilibrated with the lithospheric mantle (Farmer et al. 1989).

Once a melt is formed by decompression melting, it must be segregated from its solid residue and ascend before solidification in order to erupt eventually at the surface. Sleep (1974) noted that melt can move as a two-phase flow involving the solid rock and the melt which exists in the matrix at grain intersections. These melt-filled grain intersections form a porus three-dimensional network in the rock. The basic dynamic process is that when melt is formed, it will tend to rise and segregate driven by buoyancy. A relatively new aspect of understanding of buoyant magma transport is that movement of melt in a porous rock matrix needs to account for the effects of compaction of the solid matrix. The equations for a two-phase flow system rising through buoyancy of the melt phase accompanied by deformation and compaction of the matrix have been described by a number of workers (Scott and Stevenson 1984; McKenzie 1984; Fowler 1984; Scott and Stevenson 1986; 1989).

Ribe (1987), Scott and Stevenson (1989), and Fowler (1990a) provided the most recent reviews of the basic equations of melt segregation and compaction. They noted that the mechanics of melt segregation are controlled by conservation of mass and momentum. Summarizing and using the form of the compaction-migration equations of Fowler (1990a), conservation of mass for the melt requires:

$$\chi_t+\nabla\cdot[\chi u^l]=S$$

where χ is the liquid mass fraction, u^l is the liquid velocity and S is the melting rate. Darcy's law for the melt velocity is:

$$u^l-u^s=-k\chi\nabla[p_l+\rho_l gy]$$

where u^s is the solid velocity, k is the permeability coefficient, p_l is the liquid pressure, ρ_l is the liquid density, g is gravity, and y is the vertical coordinate. The viscous compaction relation requires:

$$p_s-p_l=-\left(\frac{\eta_m}{\chi}\right)\left[\frac{\tau_m}{p_s-p_l}\right]^{n-1}\nabla\cdot u^s$$

where p_s is the solid pressure, η_m is the mantle viscosity scale, and τ_m is the mantle deviatoric stress scale. Conservation of energy requires:

$$\rho_s LS+\rho_s c_p \frac{dT}{dt}-\beta T[\frac{\rho_s}{\rho_l}\chi(\frac{\partial p_l}{\partial t}+u^l\cdot\nabla p_l)+ \quad (4)$$

$$(\frac{1-\chi}{1+r_\chi})(\frac{\partial p_s}{\partial t}+u^s\cdot\nabla p_s))=k\nabla^2 T$$

where L is the latent heat, c_p is the specific heat at constant pressure, T is the temperature, β is the thermal expansion coefficient, d/dt is the material derivative, r is the shrinkage ratio, and k is the thermal conductivity. Finally, the Clapeyron relation requires:

$$T=T_0+\Gamma p_1$$

where T_0 is a reference temperature and Γ is the slope of the Clapeyron curve.

The equations for the matrix flow include conservation of mass:

$$\nabla\cdot u^s=-\nabla\cdot[\chi(u^l-u^s)]$$

conservation of momentum:

$$-\nabla p_s+\nabla\cdot\tau+\nabla[(\rho_s/\rho_l)\chi(p_s-p_l)]+\rho g=0$$

and the stress/strain rate relation:

$$\tau_{ij}=\eta(\frac{\partial u_s^i}{\partial x_j}+\frac{\partial u_s^i}{\partial x_i})$$

Fowler (1990a) notes that there is general agreement on the form of the matrix and melt flow equations but there are widely varying assumptions concerning the boundary conditions of the modeled processes. There are two areas of concern. First, a common assumption is that all the segregated magma ascends through the lithosphere via dike propagation. An alternative view is that some component of the partial melt solidifies during segregation and ascent. Second, the dynamics of melting are often ignored by assuming the melting rate S to be zero and ignoring the energy equation. A proposed alternative (Fowler 1990a) is to establish the boundary conditions by applying mass conservation, force balance, surface energy balance and the continuity of temperature and free energy.

A number of workers (Scott and Stevenson 1984; 1986; 1989; Richter and McKenzie 1984; Scott et al. 1986; Scott 1988) have examined through computer modeling and laboratory experiments, flow through compacting media using modified forms of these equations. Their results reveal the somewhat surprising existence of solitary wave solutions which have been called solitons or magmons (Scott and Stevenson 1984; 1986). Solitons are waves which propagate through the compacting media as a porosity pulse responding to pressure gradients. Assignment of reasonable permeability and rheological properties to these features gives wavelengths of kilometers and velocities of centimeters per year. The volume of liquid within a magmon of this size is about 1 km^3 (Scott and Stevenson 1986). Most authors have been cautious about applying concepts of solitary waves to surface volcanic patterns, but this phenomenon could lead to spatial and temporal episodicity of melt segregation if the patterns are not removed or obscured by processes of crustal transport.

Fowler (1990b) examined applications of a compaction model for melt transport. He argued that solitary waves can propagate primarily under conditions of zero melting ($S = 0$). Under conditions when $S \neq 0$, solitary waves move at a non-constant speed of $2z^{1/2}/\zeta$ where z is the vertical coordinate ($z=0$ at the base of the melt zone) and ζ is the compaction height. The amplitude of the solitary waves decay according to $1/z^{1/2}$ and may exhibit nonlinearity and diffusion, leading to degrading. Fowler (1990b; his appendix B) also obtained nonlinear equations for solitary waves by adding other melting variables and argued that the waves are only short-term features. He verified the concept of compaction length but argued that other complications such as bulk viscosity, melt refreezing and fracturing need to be considered. Scott and Stevenson (1989) agree that solitary waves are probably not important under conditions of high melt production (fast-spreading). They suggest however, that solitary waves could provide a mechanism for explaining oscillating magmatic rates at slow spreading ridges. This suggests the wave phenomenon could be important for areas of low melt production such is small volume continental basaltic volcanism. The exceptionally small volume of Pliocene and Quaternary basaltic volcanism of the Yucca Mountain region may be especially appropriate. However, this requires that the episodic nature of solitary wave phenomena be preserved through the processes of ascent and eruption of magma. A interesting but highly speculative concept is that the episodic nature of polycyclic eruptive models may originate or be influenced by oscillatory solitary waves. Scott and Stevenson (1989) admit the existence of solitary waves has only been indicated from one-and two-dimensional modeling; it has not been explored yet for three dimensional modeling.

Nicolas (1986; 1990) considered constraints on the depth of melting and melt extraction of basaltic magma. While most of the considerations are for MORB, they can be applied by inference to continental settings. First, the melting process is thought to occur primarily in the athenosphere, which corresponds to the convecting mantle where heat is transferred by convective flow and the system is adiabatic (Nicolas 1990). Second, in general, a diapir initiated in the athenosphere will rise accompanied by melting until it reaches the lithosphere. Here it may keep rising but melting ceases (McKenzie 1984; Nicolas 1990). If the asthenosphere diapir has a slow ascent rate, it will barely penetrate the lithosphere. Again, we note the presence of the thick, largely unmodified and presumably cool lithospheric mantle beneath the Yucca Mountain region (Farmer et al. 1989). This cold upper mantle should inhibit the development of large zones of upwelling in the region. The diapirs under these conditions are probably less energetic with low upward velocities, low degree of extracted melt (< 7%), and limited penetration of the lithosphere (Nicolas, Lacazeau, and Bayer 1987; Nicolas 1990).

IV. MAGMA ASCENT

Once basaltic melt is segregated, it must move to the surface rapidly to avoid solidification with decreasing temperature. There is near complete agreement that transport occurs through fluid-assisted fracture propagation. This conclusion is based on the global observation of basalt dikes in a range of tectonic settings in both oceanic and continental crust. Fissure eruptions at many volcanoes demonstrate that magma is fed from linear dikes. Dikes are exposed commonly in the vent facies of dissected volcanoes. Dikes are exposed in country rock beneath and adjacent to deeply dissected volcanoes. Dike swarms are commonly observed cross-cutting cratonic and ultramafic rocks. Flow of basaltic magma through fractures provides the most compelling mechanism for transmitting magma through cool country rock without temperature loss resulting in solidification (Lister and Kerr 1991).

Extraction of magma into conduits opened by melt-fracture requires the melt pressure to exceed the yield pressure of mantle peridotite. The depth of this process can be best constrained by the depth of earthquakes and deep harmonic tremor; this information is known only for oceanic island basalt (OIB). Aki and Koyanagi (1981) examined the depth distribution of tremors below Kilauea volcano, Hawaii. They distinguished tremors from earthquakes by the duration and period of the former. The amplitude of tremor is sustained longer than earthquakes and distant stations show the same period as close stations. Deep tremor is separated from shallow tremor by a uniform distribution of amplitude over distance for the latter. Aki and Koyanagi (1981) found seismic evidence of deep tremor to a depth of about 55 km which may mark the depth of onset of magma transport by magma-fracture. They also noted that the reduced displacement of tremor (directly proportional to the rate of magma flow) is an order of magnitude smaller than estimates of magma supply for Kilauea (Swanson 1972; Shaw 1980; 1987). Aki and Koyanagi (1981) suggested, based on this discrepancy, that a significant component of magma is transported through dikes that may propagate aseismically. Ryan (1988) showed that the seismicity patterns below Kilauea volcano, reveal the presence of a primary magma conduit that is concentrically zoned to 34 km. He interprets the zonal structure to be a central region of higher permeability surrounded by a region of numerous dikes.

The formation and form of magma transport in dikes has been described by many authors. Pollard (1976; 1987), Pollard and Muller (1976) and Delaney and Pollard (1981) described theoretical studies of dikes and calculated solutions for the equilibrium shapes of magma-formed fractures largely from a prospective of rock mechanics. Lister and Kerr (1991) note that these analysis are valid only if the intrusion shapes are determined after the magma stops flowing but has not solidified. Moreover, they suggest the dynamics of magma fracture must incorporate properties of the flowing magma, including elastic deformation of the country rock and fracture at the dike tip.

Spence et al. (1987) derived equations governing the steady, vertical propagation of a two-dimensional dike driven by buoyancy from a linear source. Lister (1990) extended their analysis and showed that elastic deformation and country rock strength are important primarily at the dike tip. The most recent review of fracture propagation and magma transport in dikes is by Lister and Kerr (1991). We draw heavily from their work in the following summary.

Field observations of dikes show that country rock around intrusions moved apart; there has been little sliding or offset parallel to the dike margins (Pollard 1987, p. 14). This suggests that dike intrusions can be modeled as planar cracks formed in brittle solids by pressurization and dilation associated with injection of magma (Lister and Kerr 1991). This treatment requires consideration of elastic pressures, stresses at the fracture tip, density-driven buoyancy, viscous pressure drop associated with flowage of magma, deviatoric tectonic stress normal to the dike and the overpressure of the magma (Lister and Kerr 1991).

The response of mantle and crustal rocks to fracture is dependent on the stresses applied and the time scale of rock response. Observed and inferred propagation velocities of magma in dikes (tens of cm to m sec^{-1}) suggest a short time scale of rock response. The strain imparted to the rock by dike emplacement is measured by the ratio of dike thickness to length (Pollard 1987); it is typically < 10^{-3} to 10^{-4}. These conditions suggest rock response can be modeled as an elastic response (Lister and Kerr 1991).

Elastic response in rocks is measured by the shear modulus *u*, and the Poisson's ratio *v*; typical values are 25-35 GPa and 0.22 - 0.28 for basalt (Lister and Kerr 1991). Dike geometry can rarely be established from field relations but can be approximated as a two-dimensional, blade shaped crack, or a three-dimensional penny shaped crack (Maaloe 1987; Pollard 1987). Representative lengths of dikes are about 2 km long and a meter wide (Maaloe 1987).

Fractures propagate primarily by extension of pre-existing microcracks which are governed by the stress field and bond strength in the vicinity of the crack tip (Lister and Kerr 1991). The stress field near the tip of a crack has the form (Lister and Kerr 1991):

$$\sigma_{ij}=Kf_{ij}(\theta)/(2r)^{1/2}$$

where r and θ are plane polar coordinates centered on the crack tip, f_{ij} are a function of θ

and K is a coefficient known as the stress intensity factor. Crack propagation is governed by a critical stress intensity factor called the fracture toughness K_c (Pollard 1987).

Magma will tend to rise by buoyancy if its density is less than the density of the surrounding rock. The LNB is the level of neutral buoyancy where magma is neither positively nor negatively buoyant. The position of this zone in the crust will determine whether and at what depth magma may form lateral intrusions or magma chambers (Walker 1989). The difference in gravitation force on a magma body is equivalent to a hydrostatic pressure gradient on the magma given by (Lister and Kerr 1991):

$$\frac{dP_h}{dz} = (\rho_r - \rho_m)\, g$$

where $\rho_m(z)$ and $\rho_r(z)$ are the densities of magma and rock at a depth z below the surface. If the density difference is assigned a general value of $\Delta\rho$, during ascent of magma, then the total hydrostatic pressure is $\Delta P_h \approx \Delta\rho g h$ where h is the height of rise. Generally, magma is less dense than the mantle and the lower crust. The LNB in Hawaii is on the order of 3 to 6 km below the surface (Walker 1989).

The mean velocity of magma averaged across a dike width (w) depends on ∇p, the spatial gradient in the fluid pressure. For laminar flow the velocity u is:

$$u = -\frac{w^2}{3\eta} \nabla p$$

where η is the magma viscosity. Conservation of fluid volume shows that the thickness of a dike-induced fracture varies with (Lister and Kerr 1991):

$$\frac{\partial w}{\partial t} = \nabla \cdot (uw)$$

An approximation of the flow velocity u in a fracture is

$$u \sim \frac{1}{t}$$

where l is the length of the fracture and t is the time since initiation of the fracture. A typical pressure drop in laminar flow along a fracture of length l may be estimated from combining the proceeding two equations:

$$\Delta P_v \sim \frac{\eta l^2}{w^2 t}$$

The crust of the earth is in a complex state of stress and the regional lithospheric stress deviates from the lithostatic value dependent on location. If the tectonic stress perpendicular to a dike is σ then the shape of a dike depends on σ by an effective normal stress $\sigma - \Delta P_i$. For most cases the effective overpressure $\Delta P_o = \Delta P_i - \sigma$. Lister and Kerr (1991) argue that σ does not vary significantly with depth, therefore ΔP_o can be assumed to be constant.

Lister and Kerr (1991) evaluated the balance between ΔP_e, ΔP_f, ΔP_h, ΔP_v, and ΔP_o. They used the following equations from Weertman (1971) and Pollard and Muller (1976) assuming a constant Δp:

$$p(z) = \Delta P_o + \Delta \rho g z$$

where $p(z)$ is the magmatic pressure and

$$w(z) = \frac{h}{m}\left(\Delta P_o + \frac{1}{2}\Delta \rho g z\right)\left(1 - \frac{z^2}{h^2}\right)^{1/2}$$

where $w(z)$ is the dike width and

$$K(\pm h) = h^{1/2}\left(\Delta P_o \pm \frac{1}{2}\Delta \rho g h\right)$$

Lister and Kerr (1991) examined the relations among the last three equations to evaluate the closure of ends of dikes and the conditions of dike propagation. They note that a dike must exceed a vertical extent of 100 m and a width of 2 mm to propagate upwards by buoyancy (p. 10,055). Further as h increases ΔP_h increases and ΔP_f decreases. This requires that as h gets large $\Delta P_f << \Delta P_h$ and demonstrates that rock toughness or resistance to fracture is much less important than the hydrostatic pressures. A dike will propagate until it reaches the LNB or solidifies. The relation between ΔP_f and ΔP_h suggests there is limited advantage gained by magma ascending along pre-existing fractures (Lister and Kerr 1991), a conclusion that is not always consistent with field observations (Delaney et al. 1986; Pollard 1987). An exception to this conclusion would be if the dike tip is deflected by existing fractures or joints and therefore preferentially follows fractures. Lister and Kerr (1991) argue that the rate of propagation of magma is controlled primarily by viscous resistance of the flow of magma into the dike tip and that a dike is unable to close from the bottom upwards because it is difficult to expel viscous magma from a closing crack.

Lister and Kerr (1991) note that $\Delta P_h \approx \Delta P_e$ when:

$$\frac{h^2}{w} \sim \frac{m}{\Delta \rho g} = 7\,Mm$$

Since dikes are generally only one or two meters wide $h^2/w >> 7$ Mm, therefore $\Delta P_h >> \Delta P_e$. They conclude that the transport of magma in feeder dikes is dominated by the balance between buoyancy forces and viscous drag. They also argue that the local hydrostatic pressure gradient does not need to be positive throughout ascent. It needs to be positive only when averaged over the length of the conduit. Other considerations are that a dike is held open against elastic stresses ΔP_e by a small fluid overpressure ΔP_o. The latter is determined by the supply rate of magma from below, a variable that has not been well defined in magma transport models. The elastic pressures are large at the dike tip. Overall, propagation and transport of a feeder dike is controlled by the balance between $dP_h/dz \approx dP_v/dz$ (Lister and Kerr 1991). This allows the derivation (Lister and Kerr 1991; see also Spence and Turcotte 1990, their equation (1));

$$\frac{\partial w}{\partial t} + \frac{\partial}{\partial z}\left(\frac{\rho_r - \rho_m g w^3}{3\eta}\right) = 0$$

The preceding equation shows that (neglecting temperature effects) magma will rise through the crust to be erupted at the surface or will stagnate and be emplaced laterally at the LNB. Ryan and Blevins (1987) and Walker (1989) discussed the importance of the LNB, particularly for the Hawaiian volcanoes. Important problems related to these concepts are the degree of overshoot of rising magmas beyond the LNB and the lateral spread of magma at the LNB. Both could lead to eruption, the former if the LNB is located at a shallow level in the crust, the latter if the combination of lateral propagation of dikes and topographic irregularity lead to breaching of the surface. The controls of lateral movement of magma at the LNB forming blade-like dikes have been discussed extensively for Kilauea Volcano, Hawaii and Krafla Volcano, Iceland by Rubin and Pollard (1987).

Buoyancy driven magma ascent following the concepts of Lister and Kerr (1991) has several important applications to the Yucca Mountain region. The shallow structure of the region is characterized by low-density (basin-fill) deposits in Crater Flat and possibly beneath Yucca Mountain. The density interface between these deposits and underlying higher density deposits (Paleozoic rocks) may be about 2 to 4 km below the Yucca Mountain area based on interpretations of gravity and seismic refraction data (Snyder and Carr 1984). This density interface could control the depth of the LNB. In this case, the depth of the density interface suggests the LNB may be lie deep beneath the region, perhaps considerably below the depth of the potential repository. However, an unknown variable is the degree of magma overshoot through and above the LNB. Additionally, if the LNB was a completely effective barrier to ascent of magma, the basalt of Crater Flat would not be present. Either the LNB is not an effective barrier or other processes such as crack-propagation rate, wall rock permeability or initial gas content of magma may be more important. If the LNB is an important barrier to magma ascent, the depth of the density interface suggests that magma could not propagate to the surface by lateral spread at the LNB. This phenomenon may be important primarily in evaluating the importance of intrusions on the waste isolation system of the Yucca Mountain region.

The concept of a LNB could provide a means of explaining the length of propagation of the longest cluster of basalt centers in the Yucca Mountain region, the Quaternary basalt of central Crater Flat. The length of this aligned chain is 12 km, significantly longer than typical dike lengths (Crowe et al. 1983b; Maaloe 1987; Pollard 1987; Rubin and Pollard 1987). An alternative interpretation is that the chain represents magma that upwelled beneath the Red and Cone and Black Cone centers and propagated laterally as a bladed dike, at a relatively shallow level. Makani cone and the Little cone centers may represent eruptive centers formed at the ends of a bladed dike system. This would require a dike propagation length outward from the centers of only 6 km (1/2 the cone cluster length). Additionally, it could explain the small volume of the end centers (Little and Makani Cones) compared to the Red Cone and the Black Cone centers. This interpretation may be testable by modeling of aeromagnetic data for Crater Flat. The basalt magma of the centers is distinctly more magnetic than the alluvial fill of Crater Flat (Kane and Bracken 1983). It may be possible to model the aeromagnetic data, enhanced with ground magnetic data to test for the presence and geometry of lateral feeder systems beneath the centers.

The presence of sills and lopolithic centers at the Paiute Ridge area may suggest trapping of magma at the LNB. These intrusions form just above the interface between the Paleozoic carbonates and the primary and reworked pyroclastics of the Paintbrush Tuff (distal facies of the units exposed at Yucca Mountain), a potential density contrast and possible zone of weakness (Crowe et al. 1983b). Support for this interpretation is provided by the lopolithic structure of some of the intrusions (Byers and Barnes 1967; Crowe et al. 1983b). Sagging of the floor of some of the intrusions may have been caused by emplacement of magma with a density greater than the density of the underlying country rock. Alternative interpretations other than the LNB control of the intrusions of the Piaute Ridge area are possible. Many of the intrusions were fed by dikes that propagated to the surface. If the LNB had been an effective barrier, the magma would have not reached the surface. In some cases, the intrusions formed locally above the carbonate-pyroclastic interface not at the interface (Valentine et al. 1992). The local formation of intrusions may be controlled by asperities along fault planes that the dikes occupy. The sagging of the floor of intrusions to form lopoliths may be associated with locally intense welding of the country rock and the attendant porosity reduction, not density sagging.

An additional mechanism that may be important for the transport of magma in dikes is the possibility of exsolution of volatiles at the tips of the dikes. Lister and Kerr (1991) note that the width w of a dike approaches 0 at the crack tip. This requires the mean velocity to be very small or the pressure gradient very large. Extension of a fluid-filled crack requires low fluid pressure in the tip promoting exsolution of volatiles. Lister (1990) has, using assumptions of thermodynamic equilibrium, evaluated numerically the effects of volatiles on the dike tip. He uses the equation for the solubility of water in a basalt melt from Wilson and Head (1981) and notes that magmas are saturated in volatiles at pressures corresponding to a lithostatic overburden of at most a few km and probably not more than a few hundred meters. When p_{vol} is large under a lithostatic overburden exceeding the volatile saturation pressure, volatiles should occupy only a small region of the tip. The length of this volatile-filled region extends as the dike propagates towards the level of $p_{vol} = 0$ and the magma is saturated in volatiles (Lister and Kerr 1991). At this volatile saturation level, the rate of bubble nucleation from the magma will be too large to maintain thermodynamic equilibrium between the volatiles in the dike tip and the magma. Volatile exsolution will extend throughout the melt and the system would have to be modeled as a two-phase compressible flow. This mechanism would decrease the density and propagate dikes above the LNB of a volatile undersaturated melt (Lister and Kerr 1991; p. 10,070). Lister (1990) approximated the length of the volatile-filled region and noted that it can become surprising large below the depth of volatile saturation (Lister and Kerr 1991; their fig.18). This again, may be a critically important mechanism to promote overshoot of the LNB and eruption of magma at the surface.

The viscosity of basalt magma is strongly temperature dependent (Ryan and Blevins 1987). A small drop in temperature caused by heat loss to the country rock promotes a viscosity increase, and an increase in viscous pressure. Delaney and Pollard (1982) note that a magma traveling more than a few kilometers from an upper crustal source at typical propagation velocities will solidify in a few hours (assuming a 2 meter dike thickness). The time for compete solidification of a dike can be approximated by (Lister and Kerr 1991):

$$t_s = \frac{w^2}{\lambda k}$$

where λ is a numerical coefficient dependent on the solidification temperature and thermal properties of the magma and solidification layer and k is the thermal diffusivity of the magma. This calculation neglects the advective supply of heat caused by the flow of the magma and tends to overestimate the likelihood of dike solidification. Bruce and Huppert

(1990) emphasized the importance of latent heat of solidification and the effect of thermal advection of magma on the temperature profile of a dike. They used two-dimensional modeling to show that for dike widths of greater than about 1 m, flow blockage from solidification will be reversed by continued supply of heat through magma flow. This reversal can exceed heat loss into the country rock and result in melting and expansion of dike widths. Bruce and Huppert (1990) also suggest that preliminary three-dimensional modeling of a range of other effects, the most important being the well described localization of fissure eruptions in distinct conduits through the duration of a fissure eruption. An unconsidered implication of the Bruce-Huppert model, however, is the effect of melting on magma composition. Geochemical and isotopic studies of basalt magmas in a range of setting show that it is rare for basalt to be contaminated with country rock, particularly shallow country rock. If the advective supply of heat is significant over a depth range, country-rock contaminated basalt should be observed more commonly.

Lister and Kerr (1991) conclude that a dike cannot propagate further than a critical length which is approximated by:

$$l_s \sim Pew$$

where *Pe* is the Peclet number. They suggest that while models are not yet capable of incorporating the mechanics of dike propagation and effects of solidification, several important conclusions can be drawn. First, solidification rates are significant for narrow dikes (tens of cms) over distances of a few kilometers. Narrow dike regions have a tendency to freeze and become narrower and wide regions have a tendency to melt and become wider. Second, loss of heat from the narrow dike tip will cool the magma and increase viscosity increasing the need for source pressure to maintain flow into the dike tip. This can lead to inflation of a dike behind a blocked dike tip. It may provide a mechanism for observed large dike widths in frozen magma conduits beneath eruptive centers. Third, the earlier discussions of the relatively unimportance of elastic stresses associated with dike propagation suggest the growth of a chilled layer may be easily overcome by dike expansion.

A final problem of importance for this section is the issue of whether a dike path follows a pre-existing fracture or fracture system or the dike propagation direction is determined by the stress field. To examine this question, basic data have to be gathered on the geometry of dike systems, their relation to local fractures, and the relationship to other features such as magma reservoirs. Pollard (1987) has noted that many dikes display minor irregularities called cusps, steps, buds and segments. He notes that these irregularities have a length scale that is much less than the dike length and are not important unless they are near the dike tip. Pollard (1987; his fig. 9) showed that the principal direction of dike propagation is parallel to the long dimension of these features.

The geometry of a dike is determined at least in part by the path established by the dike tip. A long recognized feature of dikes is that they are emplaced commonly perpendicular to the least compressive stress direction (Pollard 1987). Delaney et al. (1986) described mafic dikes that intruded sedimentary rocks on the Colorado Plateau. These dikes are associated with joint sets in country rock that are closely spaced near the dikes but increase in spacing away from the dikes. They suggest that the joints are formed by fracturing of the host rock by tensile stress generated by magmatic pressure beyond the tips of propagating dikes. The joints become juxtaposed with the dike body with continued propagation. Delaney et al. (1986) contrast dikes with self-generated fractures propagated perpendicular to the least compressive stress direction with dikes that parallel regional joint sets. They suggest that magma can invade older or existing joints if the magmatic pressure exceeds the horizontal stress acting across the joint plane. This may be optimized by two situations. First, it may occur if the horizontal principal stress difference is small compared to the magmatic driving pressure. Second, it may also occur if joints are nearly perpendicular to the direction of least compressive stress.

Delaney et al. (1986; their appendix A) developed criteria for identifying dikes intruded along older joints. These include field evidence for slip that is substantial in comparison to dilation and formation of crack splays if the dike propagates beyond the ends of the joint. In the latter case, magma must create its own fracture and would turn or splay toward the direction of maximum principal stress.

Pollard (1987) recognized three fracture modes for the orientation of dikes. The first is a planer dike which follows a fracture produced by the least compressive stress acting perpendicular to the dike plan. The second is a curved dike. This is produced by a spatial rotation of the least compressive stress about an axis parallel to the dike periphery. The third is a segmented dike produced by a spatial rotation of the least compressive stress about an axis parallel to the propagation direction. Pollard (1987) presented criteria needed to verify control of dike paths by pre-existing fractures that are not parallel to the least compressive stress direction. These are that the fractures must be older than the dikes and have comparable planar dimensions. Second, shear displacements must be found along the dike indicating that dilations were accompanied by slip induced by the resolved shear stress across the dike.

Baer and Reches (1991) examined dike propagation mechanisms for a dike swarm crossing different rock units. They noted that intrusion mechanisms were somewhat different for each rock unit indicating host rock properties played a role in controlling dike propagation mechanisms, directions and detailed geometry. Dikes in a stratified sequence formed segments which were contained within distinct stratified layers. Dikes in massive sandstones formed smaller segments and had associated dike fingers with intermittent smooth portions and patches with slickensides. The dike propagation through the massive sandstones were inferred to form through alternating stages of fluidization, viscous flow and brittle deformation. These dike systems were emplaced horizontally, along dike-generated fractures. Baer (1991) suggest the dikes propagated at the LNB and were driven by the density difference between the magma and host rock.

We have limited information about the geometry and relationship of feeder dikes for Pliocene and Quaternary basalt centers in the Yucca Mountain region because of the minor degree of erosional modification of the centers. The primary exposure of dikes are in cone scoria where the dikes exhibit highly irregular geometry which is unrelated to the regional stress field (Crowe et al. 1983b).

Several inferences can be offered on the probable form of subsurface dikes in the area. First, the regional alignment of major vents for all Pliocene and Quaternary basalt centers of Crater Flat are northwest (see Section III). This alignment is inferred to be controlled by structural features at depth and may not be controlled by the shallow stress field. This inference is based on the repeated appearance of basalt centers ranging in age from 4.6 to < 0.1 Ma along a preferential northwest trend. The recurrence of temporally distinct events (contrasted with coeval cone clusters) on the same directional trends, suggests the presence of a long-lived subsurface structural control of the ascent of magma. Additionally, as shown in Section III, the direction of alignment of Pliocene and Quaternary volcanic centers coincides with the surface of maximum magma eruption volumes. The strong correlation between center alignment and eruption volumes provides significant support for the rise of magma at depth along northwest-trending structures. Second, the sub-alignment of clusters of scoria cones of probable similar age provide the best indicator of the local trend of shallow feeder dikes (Nakamura 1977). These alignments are north-south for the 3.7 Ma centers and north-northeast for the Quaternary basalt centers except for the Lathrop Wells center. These directions are perpendicular to the least compressive stress direction (Stock et al. 1985). The Lathrop Wells consists of only one center and no structural trend can be assigned to a single cone. However, fissure systems in the center trend northwest and northeast. The small difference in orientation of the 3.7 Ma centers and the Quaternary basalt centers probably reflects a late Cenozoic, clockwise rotation of the local stress field (Zoback et al. 1981; see section III). The two distinct structural settings of basalt centers in Crater Flat (northwest-trending localization of vents of different ages; northeast-trending, coeval cone clusters) requires re-orientation of dikes probably at a relatively shallow depth.

A preferred model for dike emplacement in the Yucca Mountain area is ascent of pulses of basalt magma at depth along northwest-trending structures followed by a shallow north-northeast reorientation of dikes (90 degrees) following the maximum compressive stress direction. This is consistent with the lengths of the different structures. The northwest-trending Crater Flat volcanic field (Crowe and Perry 1990), extends for over 50 kilometers. This exceeds the maximum length of known dikes except bladed dikes, propagating laterally from a shallow magma reservoir. Northeast trending cone alignments range from 2.6 to 12 km, consistent with formation from individual feeder dikes. The dike model may be testable with geophysical data, particularly aeromagnetic data. It may be possible to use geophysical methods to determine if there is a change in dike orientation from north-northwest to northwest with depth. If this reorientation is recognized, the depth of the reorientation relative to the depth of the potential repository at Yucca Mountain may provide key information on the likely depth of occurrence of basalt intrusions.

Finally, it is difficult to establish a relation between vent alignments and local structure for individual basalt centers in the Yucca Mountain region. Alignments of fissures, vents, scoria mounds and scoria cones define conjugate northwest and north-northeast trends (Crowe and Carr 1980; Vaniman and Crowe 1981; Crowe et al. 1983; Crowe 1990, Smith et al. 1990; Ho et al. 1991). These directions parallel the bimodal directions of expected dike and structural trends. Exposure of dikes in country rock associated with the Pliocene and Quaternary basalt centers are insufficient to identify structurally controlled or stress-controlled dike features using the criteria of Delaney et al. (1986) and Pollard (1987). If these features could be identified, northwest-trending dikes would be expected to be structurally controlled and north-northeast trending dikes would be stress-controlled.

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SECTION VI: HISTORY OF VOLCANISM STUDIES

I. ABSTRACT

Volcanism studies for the Yucca Mountain Site Characterization began in 1979 with an assessment of silicic volcanism. The geochemistry of the Black Mountain and Silent Canyon caldera complexes were compared and identified as separate magma systems. Evidence was summarized in support of the inference that the Black Mountain magma system is extinct. Silicic volcanism was judged not to be a significant issue for the potential Yucca Mountain site.

In 1980, the methods of risk assessment for future basaltic volcanism were formalized. Preliminary bounds on the probability of magmatic disruption and the consequences of such an event were assessed. Regional patterns of volcanism were assessed and structural controls of sites of basaltic volcanism were identified.

Geologic, petrologic and geochemical studies of basaltic volcanism in Crater Flat were presented in 1981. Major, and trace element variations of the basalt cycles and the major-element analyses of mineral phases were presented. A systematic decrease in the volume of erupted magma through time was recognized.

In 1982, the trace element enriched, hawaiite lavas of Crater Flat were described. Revised calculations of the probability of magmatic disruption of a potential repository were completed. The probability was bounded between 4.7×10^{-8} and 3.3×10^{-10} yr^{-1}. The first volcanism drillhole was completed in Crater Flat in 1982. A large positive magnetic anomaly was shown not to be associated with the Pliocene or Quaternary record of volcanism. Additionally, in 1982, the first evidence of what would be a long-lived controversy concerning the results of whole rock, K-Ar age determinations of basaltic volcanic was recognized. Replicate splits of samples of basalt lava from the Lathrop Wells volcanic center were analyzed at three independent laboratories. The resulting ages ranged from negative ages to > 700 ka.

Three major studies of basaltic volcanism were completed in 1983. First, a summary status report on all volcanism studies was published. The regional geology of basaltic volcanic fields extending from southern Death Valley to the Pancake range of central Nevada was described. The regional patterns of the petrology and geochemistry of basaltic volcanism in the southern Great Basin were described. The status of risk assessment studies for future volcanism was summarized. Second, volcanic scenario development for future volcanic events was completed. Small volume eruption of hawaiite magma was identified as the most likely volcanic event to occur in the future in the Yucca Mountain region. Magma was inferred to ascend as dike-like bodies with velocities of 1 to tens of cm sec^{-1}. The composition and petrology of hawaiite magmas were recognized to require a multi-stage ascent history. Data on the dimensions and forms of basalt feeder dikes was described. Linear dikes were recognized as the most common form of basalt feeders but sill-like

intrusions were described at one locality. The dispersal of radioactive waste in basalt eruptions was bounded by analogy to the distribution of lithic fragments in basalt magma. Hydrovolcanic explosions were judged not to be important for the setting of Yucca Mountain. Third, the first calculations of radiological releases associated with a scenario of basalt magma penetrating a repository and erupting were assessed. Radiological releases were examined for waste entrained in basalt eruption components (scoria cones, lava flows, scoria-fall sheet and regional dispersal of fine-grained ash).

In 1984, a summary paper on the structural and tectonic setting of the Yucca Mountain region was competed.

The results of completion of drilling and examination of core from the second volcanism drill hole was completed in 1985. A large negative aeromagnetic anomaly in west-central Crater Flat was shown to be produced by a sequence of buried lava flows (360 m). The lavas are reversely polarized and were dated at 11.3±0.4 Ma.

A generalized overview of volcanism studies was published as a chapter in a book in 1986. The paper summarized all aspects of volcanism studies and presented new information on the possibility of hydrovolcanic eruptions at the potential Yucca Mountain site. The second volcanism status report was also completed in 1986. The report summarized the progress for volcanism studies covering topics identified as areas of uncertainty from previous studies. Appendices were compiled with sample descriptions, and major (140 samples) and trace element (68 samples) analyses of basaltic rocks in the southern Great Basin. The environmental assessment (EA) for the potential Yucca Mountain site was completed in 1986. Volcanism was identified as a potentially adverse condition for the potential site and judged to require additional investigations.

The formal strategy of volcanism studies was described in the Site Characterization Plan published in 1988. A three part strategy for volcanism studies was formalized in three separate studies. These included: Study 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, Study 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on a Potential Repository, and Study 8.3.1.8.5.1, Characterization of Volcanic Features. The chronology of the Lathrop Wells volcanic center was reassessed in 1988 on the basis of new geomorphic and soil studies, and continuing concerns with the results of conventional whole rock, K-Ar age determinations. The center was recognized to have formed during multiple, time-separate volcanic events. The age of the youngest event at the center, the formation of the main scoria cone, was estimated to be late Pleistocene or possibly as young as Holocene. A revised geologic map (scale 1:4000) of the Lathrop Wells center was completed in 1988.

In 1989, a paper was published on the significance of new developments in the concepts of basaltic volcanism applied to volcanic risk assessment. The complex evolution of the Lathrop Wells center was described, and new K-Ar age determinations were presented for the lavas of the center. The concept of polycyclic volcanism was defined and revised assessments of volcanic risk for the potential repository were presented incorporating new information.

Attempts to bring aspects of volcanism studies to closure were initiated in 1989. A paper was published on the recurrence rate of volcanic events. The Crater Flat volcanic zone was identified and described. An alternative method of calculating λ, the recurrence rate of volcanic events, through assessing cumulative magma volume versus time was presented. A third publication in 1989 summarized studies of the isotopic composition of Sr, Nd, and Pb for basalt centers of the Yucca Mountain region.

The year of 1990 continued efforts to conclude parts of volcanism studies. An overview paper was presented on the time-space patterns of late Cenozoic basaltic volcanism in the Yucca Mountain region. Alternative chronology models were presented for the Lathrop Wells volcanic center. These models attempted to accommodate the different opinions on the age and eruptive history of the center. Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, was released in 1990. This Study Plan provided a detailed description of the activities and methods for gathering the fundamental data that would be used for volcanism studies. Five activities were described: 8.3.1.8.5.1.1, Volcanism Drill Holes, 8.3.1.8.5.1.2, Geochronology Studies, 8.3.1.8.5.1.3, Field Geologic Studies, 8.3.1.8.5.1.4, Geochemistry of Scoria Sequences, 8.3.1.8.5.1.5, Evolutionary Patterns of Basaltic Volcanic Fields. The year of 1990 saw the publication of the first technical overview studies by the State of Nevada. They described the regional patterns of basaltic volcanism and suggested that high-angle normal faults control the location of volcanic centers in the Yucca Mountain area. They defined a hazard zone assignment of sites of basaltic volcanism using chain lengths from other basaltic volcanic fields.

In 1991, several papers describing alternative views of the chronology and eruptive models of basaltic centers in the Yucca Mountain region were presented by the U.S. Geological Survey. Paleomagnetic data were inferred to show that Pliocene and Quaternary basalt centers formed as simple monogenetic eruptive events. Two eruptive events were recognized at the Lathrop Wells center. The difference in age of the events was inferred to be no more than one century. A second paper presented preliminary results of $^{40}Ar/^{39}Ar$ ages combined with conventional K-Ar age determinations for the Lathrop Wells volcanic center. The age of the center was bracketed between 119 and 141 ka. The same data were published in a third paper which concluded that the Lathrop Wells center formed in two eruptive events dated at 136±8 and 141± 9 ka. A geologic map of the Sleeping Butte centers was also completed in 1991. Both centers formed by mildly explosive Strombolian eruptions and consist of main scoria cones, flanked by satellite vents and aa lava flows. The Little Black Peak center was judged to be a monogenetic center, and the Hidden Cone center was inferred to have formed in at least two distinct volcanic events. Several papers were published by the State of Nevada on volcanic probability studies of the Yucca Mountain region in 1991. Alternative distribution models of the recurrence of basaltic events were presented. Arguments were made that the existing data base of basaltic events is inadequate to define the time recurrence of volcanic events. The paper concluded that past studies of the recurrence of volcanic events underestimated rates. Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository was completed in 1991.

This Study Plan was divided into four activities. These include: Activity 8.3.1.8.1.1, Location and Timing of Volcanic Events, 8.3.1.8.1.1.2, Evaluation of the Structural Controls of Basaltic Volcanic Activity, 8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site, and 8.3.1.8.1.1.4, Revised Probability Calculations and Assessments.

The year 1992 saw a large number of papers completed on volcanism studies related to the Yucca Mountain project. The long-awaited resumption of surface disturbing activities allowed construction of soil pits at the Lathrop Wells volcanic center. A summary paper was completed on the status of field and geochronology studies for the center. The center was divided into three chronostratigraphic units. The results of K-Ar, U-Th, cosmogenic helium, thermoluminescence, soil, geomorphic, and paleomagnetism studies of the center were described. A paper was published on recurrence models of volcanic events. Arguments were presented in favor of application of a simple or homogeneous Poisson model for calculating the recurrence of volcanic events. Summary and revised calculations of the recurrence rate were published and the rate was bounded by comparison to other large volume basaltic volcanic fields of the Basin and Range province. A separate paper described Monte Carlo techniques for estimating the disruption ratio of the conditional probability of repository disruption. Simulations were used to constraint the ratio based on the geometry and physical constraints of dike dimensions. Models of northwest and northeast trending dikes and a renewal of volcanic activity at the Lathrop Wells center were used in the simulations, a paper on interpreting teleseismic tomographic data for the Yucca Mountain region was published in 1992. A large low-velocity anomaly was described south and southeast of the potential Yucca Mountain site. This anomaly is attributed to the presence of basalt magma in a broad zone that extends northeast, parallel to the trace of hot-spot vectors of the North America plate. The patterns of temporal and geochemical variation of basaltic magma in the Crater Flat area were described in another 1992 paper. Systematic differences in mineral assemblages, and trace-element and isotopic geochemistry indicate that magma chambers of the youngest cycles of basaltic activity have deepened through time consistent with waning volcanic activity. Trace-element and isotopic data for the Lathrop Wells volcanic center show that it did not form as a simple monogenetic center. Instead, the data support formation from temporally or spatially discrete magma batches. Revised assessments of the consequences of magmatic disruption of the potential repository were described in 1992. Two processes of volcanic activity that could effect a potential repository were recognized. First, magma could ascend through a repository and erupt. Second, subsurface effects of hydrothermal processes could alter the hydrologic conditions of a waste isolation system from intrusion of basalt magma through or near a repository. Analog studies of shallow intrusions in the Paiute Ridge area were described. The results of two-dimensional modeling of emplacement of a basalt sill in country rock were evaluated. The preliminary results of two-phase flow modeling of pyroclastic eruptions were presented. A review paper of progress in volcanism studies was published in 1992. New information was presented on the structural controls of volcanic activity. A summary table of all calculated disruption ratios for the Yucca Mountain region was listed. Another review of probability studies was published by the State of Nevada. A nonhomogeneous Poisson process was used to estimate the instantaneous recurrence rate and a homogeneous Poisson process was used to estimate future events. The 90% confidence intervals were assigned to the recurrence rate to assess uncertainty. A worst case disruption ratio of volcanic events was determined by applying a variant of the volcanic chain structural model. This value combined with the confidence intervals for the recurrence rate were used to estimate a probability of magmatic disruption of 1 x 10^{-7} to 6.7 x 10^{-7} yr^{-1}. A comment and response to interpretations by the U.S. Geological Survey on the age of the Lathrop Wells center were published in 1992.

II. INTRODUCTION

The purpose of this section of the Volcanism Status Report is to trace the history of development of studies that led to the present understanding of the assessment of risk of volcanism for the potential Yucca Mountain site. We summarize the important literature on volcanic studies for the Yucca Mountain Site Characterization Project (YMP) starting from 1979. The improvements in data collection and interpretation from field and laboratory studies are highlighted for each described paper. Conclusions developed from the data are described along with their implications for an evaluation of volcanic risk. We divide this section into two parts. The first part covers information completed before the Site Characterization Plan (SCP; DOE 1988). The second part includes information obtained since publication of the SCP. Discussions are labeled by the year of the publication and descriptive titles of the described volcanism studies are provided. We have attempted to describe and preserve the original content of the publications. However, editorial comments have been added where new information has changed interpretations, where data are incorrect, or where assumptions for data that are critical to interpretations were not presented. Additionally, some editorial comments are presented to highlight information from the perspective of the present knowledge of volcanism data. The comments have been italicized to alert the reader. A primary purpose of this section is to aid the reader in acquiring an overview perspective of volcanism studies. Additional detailed information on individual topics can be found in the cited references and in other sections of this paper.

The potential risk of future volcanic activity relative to underground isolation of high-level radioactive waste was recognized as an important concern in the earliest stage of studies of the potential Yucca Mountain site. A peer review panel was convened in July of 1979 to evaluate concerns of tectonics, seismicity, and volcanism (Crowe et al. 1983a). Two statements were issued from this panel. First, the risk of future silicic volcanism was judged to be negligible. Second, the risk of basaltic volcanism was judged not to be a disqualifying issue for location of a repository for storage of high-level radioactive waste. The issue was recognized however, to require additional study.

III. PROGRESS BEFORE THE SITE CHARACTERIZATION PLAN

A. Publication in 1979

1. Silicic Volcanism. Crowe and Sargent (1979) described the geology and geochemistry of the Black Mountain and Silent Canyon volcanic centers. The volcanic rocks

of both centers comprise a subalkaline-peralkaline geochemical association. The Silent Canyon volcanic center is a buried cauldron of late Miocene age located on the north part of the Nevada Test Site (NTS). The Black Mountain volcanic center forms an elliptical cauldron complex of late Miocene age. It is the youngest silicic volcanic center in the Yucca Mountain region. Both calderas formed from the eruption of voluminous ignimbrites and lavas. The Belted Range Tuff was erupted from the Silent Canyon center, the Thirsty Canyon Tuff from the Black Mountain center. Major element geochemical data were compared with geologic data for the two centers to determine if the centers share a common magmatic origin. The resulting data show that the Black Mountain and Silent Canyon centers are distinctly separate in time, space and composition. They both exhibit peralkaline geochemical affinities but evolved from unrelated magma pulses. Volcanic activity associated with the formation of the Black Mountain center represents a separate and renewed phase of volcanism following a relatively brief magmatic hiatus. Several lines of evidence suggest the magmatic cycle of Black Mountain has ended. The youngest volcanic rocks of the center are > 8 Ma. Cooling times for large silicic bodies, even assuming heat loss solely by conduction are insufficient to maintain molten magma without replenishment by new magma injected at depth. Second, the volume of magma erupted during successive cycles of activity declined progressively during the evolution of the Black Mountain center. There remains a finite but numerically incalculable probability of recurrence of Black Mountain-type volcanism in the Yucca Mountain region. That possibility was judged not to be a significant issue for isolation of high-level radioactive waste in the Yucca Mountain region. *There have been two new developments in regional studies of silicic volcanism. First, regional studies of silicic volcanism not associated with the YMP (McKee et al. 1989) revealed the presence of a Pliocene silicic center, the Mt. Jackson dome complex located west of Stonewall Mountain. This center is 105 km northwest of Yucca Mountain. It is too distant to be significant, but it is now recognized to be the youngest silicic volcanic center in the region. Second, three sites of aeromagnetic anomalies that could represent silicic intrusive rocks have been investigated by exploratory drilling. None of the drilled anomalies are produced by silicic volcanic rocks. The judgment that the risk of future silicic volcanism is not significant for the YMP continues to be valid.*

B. Publication in 1980

1. Development of Methods of Risk Assessment for Future Basaltic Volcanism. The first published evaluation of the hazards of basaltic volcanism for the potential Yucca Mountain site was by Crowe and Carr (1980). They established a two-fold approach to volcanism hazards. The first involved characterizing the geology, chronology, occurrence, and tectonic setting of Pliocene and Quaternary volcanism in the Yucca Mountain region. The second included using the gathered data for assessment of the consequences and probability of repository disruption. The second approach used a procedure for volcanic hazard assessment developed by Crowe (1980).

Crowe and Carr (1980) described the volcanic record of Crater Flat. They divided the volcanic centers into three age groups based on geomorphology. These divisions correspond to the southeast basalt of Crater Flat, the Quaternary basalt centers of central Crater Flat, and the Lathrop Wells volcanic center. *These subdivisions continue to be used in volcanism studies.* Crowe and Carr (1980) recognized the presence of aeromagnetic anomalies near the Red, Black, and the Little Cones centers that were inferred to be buried volcanic centers. They summarized the results of preliminary K-Ar whole-rock ages for the centers and assigned the three units to magnetic epochs based on the magnetic polarity of the rock units and the results of K-Ar age determinations.

Crowe and Carr (1980) assessed the risk of volcanism as a conditional probability defined as the product of a rate of volcanism and an area ratio. Rate calculations were estimated by examining the number of events per time using different combinations of volcanic centers and time periods. They established the area ratio by noting first, that basalt centers are fed from narrow dikes with small disruption zones and second, by assuming that there are three feeder dikes for each center. Because the combined area of the multi-dike disruption zone was small (0.36 km^2) compared to the area of the repository, the area ratio was defined as the area of the repository divided by the area of a 25 km circle centered at the potential Yucca Mountain site. The sensitivities of these calculations were examined by using different combinations of centers within circles of 25 and 50 km radii. Calculated values of the conditional probability ranged from 10^{-8} to 10^{-9} yr^{-1}. *These were the first probability calculations for the potential Yucca Mountain site. The probability calculations were defined as a linear combination of attributes instead of as an exponential equation. This did not introduce significant errors in the calculations because the exponential equation is linear for the duration of the waste isolation period (length of time of the probability calculations).*

Preliminary consequence analyses were evaluated for disruption of a potential repository. Crowe and Carr (1980) listed the following constraining variables for assessing the potential for radionuclide releases from an underground repository:

1. Depth of burial of waste below the surface
2. Geometry of magma-waste interaction
3. Nature or style of volcanism
4. Lag time prior to magmatic disruption

Important constraints for these variables are that future volcanism is likely to consist of Strombolian or phreatomagmatic eruptions of basaltic magma. Deep burial of waste reduces the potential for disruption and dispersal of waste because basalt centers are fed by linear dikes. The longer the interval between emplacement of waste and potential volcanic disruption, the lesser the consequences of dispersal because of radioactive decay of radionuclides.

Crowe and Carr (1980) summarized the regional patterns of volcanism in the Great Basin. They noted past spatial migration of silicic volcanism and the restriction of basaltic activity largely to the east and west margins of the Great Basin region. They identified four areas of Quaternary volcanism in the interior of the Great Basin. These include southern Death Valley, Crater Flat, an area north of Beatty (Sleeping Butte centers), and the Lunar Crater field. Crowe and Carr (1980) suggested that there are three typical tectonic settings for Pliocene and Quaternary basalt in the southern Great Basin. These include:

1. Small northeast-trending rift zones or areas of relatively young extension
2. Caldera ring fracture zones
3. Right-stepped offsets in northwest-trending, right slip shear zones, or intersections of northeast-trending, left-slip faults with these zones

C. Publications in 1981

1. Geology, Petrology, and Geochemical Studies of Basaltic Volcanism in Crater Flat. The field geology, petrology, and geochemistry of the basalt of Crater Flat were described by Vaniman and Crowe (1981). They subdivided the basaltic rocks of Crater Flat into three distinct cycles (3.7, 1.1, and 0.3 Ma) based on geologic mapping, K-Ar age determinations, and measurements of the magnetic polarity of the rocks. These subdivisions followed the three basalt cycles established by Crowe and Carr (1980). Each cycle of basaltic volcanic activity consists of multiple scoria or spatter cones and associated lava flows. The volcanic landforms are progressively more eroded and modified with increased age. Preliminary geologic maps (scale 1:12000) were compiled for parts or all of the units of each volcanic cycle. The petrography, major and trace element whole rock geochemistry, and mineral chemistry of the basalt units was described. The rocks are sparsely porphyritic with phenocrysts of olivine, minor plagioclase, and rare amphibole. Geochemically, they are mildly nepheline to hypersthene normative and are classified as hawaiite in composition. Seven K-Ar whole rock age determinations for the basalt cycles were published. Crowe and Vaniman (1981) provided the first estimates of magma volumes of the associated centers. They were the first to recognize a systematic decrease in the volume of erupted magma and a possible increase in eruptive frequency through time. They suggested the systematic decreases in magma volume provided possible evidence of waning of magmatic activity during the last 4 Ma. *The volume decrease in erupted basalt of Crater Flat remains a valid observation, even with refined volume calculations using more recent large scale geologic mapping.*

D. Publications in 1982

1. Origin of Trace Element Enriched, Hawaiite Lavas of Crater Flat. Vaniman et al. (1982) described further the petrology and geochemistry of the three cycles of hawaiite lava of the Crater Flat area. They noted that the cycles considered together, form a straddle-type association defined by Miyashiro (1978). Less evolved basalt plot near the normative olivine-diopside divide on the basalt tetrahedron and the more evolved basalt project into the hypersthene or nepheline fields. They modeled possible fractionation trends for the rocks, noting that removal of olivine, clinopyroxene, and amphibole could produce the lavas of more evolved composition. Varied parentage is more evident between cycles although the cycles are consistently of hawaiite composition. Basalt of the youngest two cycles are enriched in incompatible trace elements, but depleted in Rb. The Rb/Sr ratios of the rock are far too low to generate the $^{87}Sr/^{86}Sr$ ratios typical of basalt of the southern Great Basin. The low Rb/Sr ratios limit processes that could produce the trace-element enrichment.

Possible processes of magma formation and evolution include cyclic recharge of an evolving magma chamber, or decreased degrees of partial melting with residual phlogopite of a metasomatically enriched mantle source.

2. Revised Probability Calculations; Probability Bounds. Crowe et al. (1982) refined the volcanic risk assessment for the Yucca Mountain site. They developed a mathematical model for the volcanic disruption probability assuming that eruptive events occur independently, they are exponentially distributed, and the number of events in time intervals of length t is Poisson distributed with mean λt where λ is the recurrence rate. They estimated recurrence rates by counting volcanic events per time and by evaluating the cumulative volume of erupted magma versus time. Crowe et al. (1982) developed a refined method for calculating the disruption ratio (area ratio of Crowe and Carr 1980). They recognized that disruption ratios based on circles of different radii are arbitrary and do not assess spatial trends in the distribution of volcanic centers. Crowe et al. (1982) developed a computer program to find the minimum area circle containing the volcanic centers of interest and the potential repository site. They included all combinations of recognized volcanic centers in the region in systematic calculations of the disruption ratio.

Crowe et al. (1982) assembled all probability calculations into tables, emphasizing the importance of the range of values not individual calculations. They established a lower or minimum annual probability bound of repository disruption from a future volcanic event of 3.3×10^{-10} yr^{-1} from the probability tables. This was based on a Quaternary rate of magma production and a disruption ratio established by the minimum area ellipse for all volcanic centers of Quaternary age in the Yucca Mountain region. The upper or maximum probability bound of 4.7×10^{-8} yr^{-1} was established by including all volcanic centers of the Pancake Range-Death Valley volcanic zone (see section three, this paper) and the minimum area ellipse for that zone. These values have been used subsequently in many reports assessing the suitability of the Yucca Mountain site with respect to the risk of volcanism. *There have been no valid published estimations of the probability of magmatic disruption of the potential Yucca Mountain site that fall outside these calculations, despite being completed over ten years ago.*

3. Results of the First Volcanism Drillhole. The exploratory hole USW-VH-1 was drilled in central Crater Flat in December of 1980 (Carr 1982). The hole was sited to explore a positive aeromagnetic anomaly in south-central Crater Flat to determine if it was produced by late Cenozoic volcanic rocks. Additionally, the anomaly was drilled to investigate a possible source of a silicic pumice dated at 6.3±0.8 by the fission-track method on zircon. The source of the pumice was not located in VH-1, nor were new basalt units noted in the section penetrated by the drill hole (Carr 1982). The source of the positive aeromagnetic anomaly was inferred to be a thickened section of the Bullfrog member of the Crater Flat Tuff.

4. K-Ar Age Determinations: The First Glimpse of a Long-Lived Controversy. Sinnock and Easterling (1982) analyzed the reproducibility of the K-Ar dating method for young basalt. They submitted controlled samples of basalt from the Lathrop Wells center,

the Red Cone center and the 3.7 Ma centers to three separate analytical laboratories. None of the laboratories were informed of the identity of the samples. Variance in the analytical results increased with decreasing age of the basalt units. There was good agreement in K-Ar ages for the 3.7 Ma basalt, moderate agreement for the Red Cone center, and poor agreement for the Lathrop Wells center. The K-Ar ages for the Lathrop Wells samples ranged from negative ages to > 800 ka. Mean ages were 80 to >700 ka (Sinnock and Easterling 1982). *This paper provided the first indication of potential problems with whole rock K-Ar age determinations of young (< 500 ka) basalt, a problem that continues for modern studies.*

E. Publications in 1983

1. Volcanism Status Report, Death Valley-Pancake Range Volcanic Zone, Basaltic Volcanic Fields of the southern Great Basin, Tectonic Setting, Uncertainty of Volcanism Risk Assessment. Crowe et al. (1983a) summarized the status of volcanism studies for the Yucca Mountain region. They described the geology of basalt fields extending from southern Death Valley, California through the Pancake Range of central Nevada. The regional distribution of Pliocene and Quaternary basaltic volcanic rocks was established to place the volcanic patterns of the Yucca Mountain area in a regional perspective. Crowe et al. (1983a) noted that there are two types of volcanic fields in the region. These are major fields (Type I) with large magma volumes and a high cone density (number of cones per km^2; examples include the Lunar Crater, Reveille and Greenwater fields), and small fields (Type II) with low magma volumes and a low cone density (examples include Crater Flat, and the Quaternary record of the southern Death Valley field). The potential Yucca Mountain site is adjacent to a Type II volcanic field. Crowe et al. (1983a) defined the Death Valley-Pancake Range volcanic zone (DV-PR Crowe et al. 1983a, Plate I; see also Carr 1984) and summarized the geologic, petrologic features and tectonic setting of volcanic fields in this zone (Crowe et al. 1983a, Table I). Crowe et al. (1983a) calculated basalt volumes for basalt centers of the Yucca Mountain region. The petrology and geochemistry of basaltic volcanism in the southern Great Basin were summarized with emphasis on trends through time. The status of volcanic risk assessment for the Yucca Mountain region was summarized. They presented and discussed three major questions important to an understanding of volcanic risk assessment. These are (Crowe et al. 1983; p. 36):

1. Can the processes of basaltic volcanism be understood with a sufficient degree of confidence to define the potential hazards of future volcanism?
2. What are the areas of uncertainty in volcanic hazard assessment?
3. What are the procedures to resolve the issue of potential volcanic hazards for geologic disposal of radioactive waste within the NTS area?

Crowe et al. (1983a) discussed each of the three questions. They noted that there are uncertainties in understanding processes of basaltic volcanism used to assess volcanic risk The uncertainties are dominated by the reliability of predictions based on the past geologic record, which is controlled by how well the geologic record is interpreted and magmatic processes can be quantified for predicting (estimating) future volcanic events. These uncertainties will remain, but they can be accommodated by **bounding** the risk of volcanism using multiple approaches. Crowe et al. (1983a) summarized evidence why the risk of volcanism for potential disposal of high-level radioactive waste in the Yucca Mountain area is very low. The primary evidence is the low rates of volcanic activity in the region since the Pliocene, the low probability of future volcanism disrupting an underground repository and the limited consequences of repository disruption by magmatic activity. They listed studies in progress that may provide further information to assess volcanic risk. The studies are the mechanism and frequency of formation of shallow intrusions, the compositional changes in volcanic fields through time, the possibility of future bimodal volcanism (contemporaneous basalt-rhyolite eruptions) and the origin of incompatible-element enriched Pliocene and Quaternary basalt. Crowe et al. (1983a) identified predictive geology as nothing more elaborate than **estimations** of future events. They noted that there is time-uncertainty in probability calculations and additional uncertainty in assumptions required for consequence analysis. Finally, Crowe et al. (1983a) recognized the need for presenting information on volcanic risk for a potential repository at Yucca Mountain in scientific and public forums and attempting to establish acceptability levels of risk from scientific and public perspectives. *An uncertainty that continues in assessments of volcanic risk is the absence of clearly defined regulatory standards of acceptable or non-acceptable risks. While the risk of volcanism for the Yucca Mountain site has been bounded through scientific studies, the interpretation of the significance of that risk continues to be interpreted subjectively.*

2. Scenario Development for Consequence Analysis. Crowe et al. (1983b) traced the processes of magma generation, ascent, eruption and dispersal of basalt magma with respect to potential magmatic disruption of a repository at Yucca Mountain. They reiterated the conclusions of Vaniman and Crowe (1981) and Vaniman et al. (1982) that the composition of Pliocene and Quaternary basalt in the region are hawaiite. They noted the basalt follows the Staddle-A classification of Miyashiro (1978). Basalt magma was assumed to ascend in narrow dikes with velocities ranging from one cm sec^{-1} to one meter sec^{-1}. The composition and mineralogy of erupted basalt were recognized to require interrupted ascent; the magmas were inferred to be stored at the crust-mantle interface where they fractionated and decreased the density of the melt, promoting continued ascent by buoyancy.

Crowe et al. (1983a) summarized data on the dimensions and forms of basalt feeder systems. The most important feeder systems were inferred to be linear dikes that were recognized at several of the dissected centers of Miocene age. However, shallow intrusions consisting of dikes and sills were recognized at one locality . Evidence was summarized suggesting linear dikes are the most common forms of feeder systems for basalt centers like the basalt of Crater Flat. The dispersal of waste material in erupting basalt magma was constrained by analogy to the distribution of country rock fragments (lithic fragments) in basalt deposits. The primary mechanism of dispersal was inferred to be by Strombolian eruptions. The exclusion of hydrovolcanic activity was based on the considerable depth of the water table beneath Yucca Mountain and the low moisture content of most rocks above the water table. Both factors suppress the likelihood of hydrovolcanic eruptions.

Size parameters of basalt centers in the Yucca Mountain region were compiled, including height, widths, cone volume, flow volume and total magmatic volume converted to dense rock equivalents. A noteworthy feature of the basalt centers of the region is a high ratio of cone volume (pyroclastic component) to flow volume (lava).

Crowe et al. (1983a) evaluated the dispersal pathways of waste radionuclides should a potential repository be disrupted by ascending magma which erupted at the surface. Waste pathways were inferred to follow primarily, the pyroclastic component of a Strombolian eruption. Major depositional sites were the scoria cone, the scoria-fall sheet and a fine-grained component carried by prevailing winds. The most important pathway of waste material by volume using this analogy is in the scoria-fall sheet.

Subsequent studies have largely verified the studies of Crowe et al. (1983a) but with two important modifications. First, the issue of the subsurface geometry of basalt feeder systems remains an area of concern. While the general model of scoria cones fed by linear feeder dikes at depth is valid, it is difficult to establish statistics on the relative abundance of simple feeder dikes versus basalt intrusions. The concept that rising magma seeks a position of neutral buoyancy at shallow crustal levels (see section three) has received increased attention in the last few years. Magma reservoirs formed at shallow crustal levels appear capable of propagating dikes horizontally for long distances (Rubin and Pollard 1987; Walker 1989; Baer and Reches 1991). Second the occurrence of future hydrovolcanic activity in the Yucca Mountain setting while unlikely based on field criteria, may not be ruled out conclusively based on theoretical models of water-magma interaction.

<u>3. Completion of Consequence Analysis for Basaltic Volcanism: The First Radiological Release Calculations for Magmatic Disruption of the Repository.</u> Link et al. (1983) used the data foundation from Crowe et al. (1983a) to calculate radiological releases from magmatic disruption of a hypothetical repository located at Yucca Mountain. These studies, which generally fall under the title of consequence analysis, involve identification of volcanic processes that could lead to failure of a waste-isolation system and calculation of the results of failure expressed as radiological levels of released waste elements. Link et al. (1983) calculated the radiological releases associated with magmatic disruption for two possible hypothetical repositories located at Yucca Mountain (unreprocessed spent fuel and reprocessed waste). The calculations assumed a repository capacity of half the estimated volume of spent fuel or reprocessed waste generated by commercial reactors through the year 2000. A range of geometric arguments was used to determine the number of canisters intersected by magma rising along a linear dike. Assuming a random orientation of the dike geometry relative to the repository tunnel complex, magma would intersect about seven canisters of spent fuel and one canister of reprocessed waste. All waste contacted by magma was assumed to be erupted preferentially with the pyroclastic component of a Strombolian eruption. Radiological releases were examined from waste entrained in the basalt eruption column and from exposure to waste-bearing scoria deposits, resuspended particles, and radionuclides entering the food chain. The worse case for an airborne dose resulted in a cumulative total of 25 health effects in 10^6 yrs. A second worse case was calculated for dose effects from scoria deposits (scoria cone, scoria fall-sheet), including effects of erosional transport during a period of 10^6 yrs. This yielded 2800 health effects. Link et al. (1983)

calculated the total activity that would be transported to the surface normalized to 10^3 MTHM. The total expected release for 10^4 yrs is 1.8 Ci or 0.038 Ci/10^3 MTHM for spent fuel and 1.3 Ci or 0/034 Ci/10^3 MTHM for reprocessed waste (Link et al. 1983; p. 163.)

Several assumptions used in this study will require modification for revised release calculations. First, more recent data on repository design, tunnel geometry and nature of the waste inventory should be used. The geometry of waste-magma intersection in a repository should be evaluated assuming the most probable direction of dike propagation. This direction is north-northeast, perpendicular to the least compressive stress direction. Additionally, the assumption that all waste encountered by a magma rising in a dike would be carried to the surface is undoubtedly too conservative. Finally, field observations show that lithic fragments are present in lava as well as the pyroclastic component of Strombolian and Hawaiian eruptions.

F. Publication in 1984

1. Structural and Tectonic Setting of the Yucca Mountain Region. Carr (1984) described the structural setting of the Yucca Mountain region. He provided expanded discussion of the DV-PR zone and suggested that some of the Pliocene-Pleistocene basalt centers of the Yucca Mountain region occur along northeast-trending, rift-like structures.

G. Publication in 1985

1. Second Volcanism Drill Hole. Drill hole USW-VH-2 was drilled and cored to a depth of over 1200 meters in 1983. The hole was located on the flanks of a negative aeromagnetic anomaly centered west of Red and Black Cones. The purposes of the drill hole were to evaluate evidence of the post-Pliocene evolution of volcanism in Crater Flat, to determine the cause of an aeromagnetic gradient between the drill hole site and drill hole USW-VH-1 (Carr 1982), to evaluate the origin of a large negative aeromagnetic anomaly in east central Crater Flat, and to evaluate the late Cenozoic structural history of Crater Flat (Carr and Parish 1985). Buried basalt was intersected in the drill hole at a depth of 360 m. It consisted of lava of reversed magnetic polarity that were dated at 11.3±0.4 Ma (Carr and Parish 1985). The basalt lava was judged to be the source of the prominent aeromagnetic low. The basalt was correlated with an exposed basalt at the south end of Crater Flat dated at 10.5±0.1 Ma (Carr and Parrish 1985).

H. Publication in 1986

1. Volcanism Summary Report in a Book Published by the National Research Council Entitled *Active Tectonics: Impact on Society.* Crowe (1986) completed a review of volcanic hazard assessment for disposal of high-level radioactive waste focusing on studies of the Yucca Mountain region through 1985. The purpose of the paper was to publish the methods of assessing volcanic risk in a forum where it could be read by a wide audience of the geologic community. Crowe (1986) summarized data presented in past publications. New information was presented on the possibility of hydrovolcanic eruptions. A relative-frequency diagram of crater depth for hydrovolcanic craters was presented. The average

depth to the potential repository horizon at Yucca Mountain is greater by more than four standard deviations than the mean depth of hydrovolcanic craters. Crowe (1986) discussed the reliability of geologic data used for risk assessment. He noted that the data must be judged against research standards established in the current geologic literature. Further, the results of risk assessment have been published in the geologic literature to provide wide exposure to the geologic community. Crowe (1986) discussed the possibility of bias in volcanic hazard studies. He suggested the best method to overcome bias was to present both positive and negative findings of scientific studies. Finally, he noted that there is an element of uncertainty in all probabilistic studies in geology. *An important assumption of the behavior of small volume basaltic volcanic centers described in this paper is that they are monogenetic (formed in short-duration eruptions (weeks, months or at most years). This assumption leads to the inference that a volcanic event represented by ascent of magma through a repository and feeding an eruption is a single transient event. Subsequent work has raised the possibility that some of the basalt centers of the Yucca Mountain region was formed by multiple, temporally distinct volcanic events. This possibility requires re-evaluation of the consequences of repository disruption by more spatially and temporally complicated volcanic events.*

2. Second Volcanism Status Report; Discussion of the Issues of the Mechanism of Emplacement of Shallow Intrusions, the Possibility of Future Bimodal Volcanism, the Origin of Trace-Element Enriched Basalt, and the Likelihood of Hydrovolcanic Activity. Crowe et al. (1986) published a second status report on volcanism for the Yucca Mountain Project. The 1986 report discussed areas of uncertainty identified in the previous volcanism status report. A series of appendices in the report compiled major element data (original analyses and normalized to 100%) for over 140 analyses, trace element data for 68 analyses, sample descriptions for all analyzed rocks and grain-size data for tephra from the Lathrop Wells volcanic center.

The first area of identified uncertainty was the mechanism of emplacement of shallow intrusions. Crowe et al. (1986) noted that the most common feeder structure exposed in dissected basalt centers is linear dikes. Exceptions were described at three areas, the Paiute Ridge area east of Yucca Flat, the Funeral Mountains west of Amargosa Valley, and the middle and southern tuff rings of Nye Canyon, northeast of Frenchman Flat. Crowe et al. (1986) summarized arguments for and against the formation of sills and irregular intrusions beneath Yucca Mountain. They concluded that shallow intrusions may be possible in the tectonic setting of Yucca Mountain. This topic represents an area of uncertainty in consequence analysis for volcanic risk assessment.

The second area of uncertainty was the time-space patterns of basaltic volcanic fields of the Great Basin. Crowe et al. (1986) discussed the possibility that the Crater Flat volcanic field might evolve in the future to form a large volume, high-cone density volcanic field. They examined the volcanic patterns of the Yucca Mountain region and contrasted them with long-lived, high-cone density volcanic fields of the Death Valley-Pancake Range volcanic zone. These fields include the Lunar Crater volcanic field, and the Death Valley volcanic field. No evidence was noted in the patterns of the three fields to support the interpretation that the Crater Flat volcanic field would evolve toward a more active field.

Crowe et al. (1986) listed two cautions with this conclusion. First, only three volcanic fields were examined for the evaluation of the volcanic patterns. These data may be too limited for confidence in predicting future volcanic patterns. Second, volcanism and tectonism are closely coupled in time and space. Volcanism models must be integrated with tectonic models of the Yucca Mountain region to assess future patterns of activity.

Crowe et al. (1986) examined the possibility of future bimodal volcanism in the Yucca Mountain region (coexisting basalt-rhyolite magmas). They noted that the subsurface feeder systems of silicic centers are much larger and there is an increased potential for regional dispersal of tephra in explosive eruptions of silicic composition. Both factors could increase the consequences of repository disruption. They summarized data concerning the identified aeromagnetic anomalies in the Yucca Mountain region and noted that the size of some of the anomalies suggests they could be produced by buried silicic centers. Crowe et al. (1986) described the results of two drill holes: VH-1 in east-central Crater Flat and VH-2 located between Red Cone and Black Cone. Neither drillhole intersected silicic intrusive rocks. A third aeromagnetic anomaly that could be a silicic center was identified in the Amargosa Valley, a few kilometers south of the town of Lathrop Wells. They suggested this anomaly must be penetrated by exploratory drilling to resolve concerns of the potential for future silicic volcanism. *The aeromagnetic anomaly in the Amargosa Valley was drilled in exploration studies by a private company. Samples of cuttings recovered from the drill hole show that the aeromagnetic anomaly is caused by a buried basalt of Pliocene age.*

The origin of trace-element enriched basalt of the Yucca Mountain region was evaluated. Crowe et al. (1986) concluded that the causative process(es) for generation of trace-element enriched basalt could not be either crustal contamination or a young (late Cenozoic) metasomatic volcanic event. They noted that the origin of trace-element enriched basalt remains a much debated topic of volcanic petrology. *More recent studies have attributed the isotopically anomalous and trace-element enriched basaltic volcanic rocks of the Yucca Mountain area to generation of the basalt magmas from ancient lithospheric mantle (Farmer et al. 1989).*

Crowe et al. (1986) gathered additional data on the possible importance of future hydrovolcanic eruptions at Yucca Mountain. They completed revised geologic mapping of the southern and middle basalt centers of Nye Canyon, noting that both are tuff rings, formed from hydrovolcanic explosions and infilled subsequently by lava lakes with interbedded scoria deposits. Tephra studies were completed for the Lathrop Wells volcanic center. These studies showed that the tephra sequences were formed by two distinct fragmentation mechanisms. These include fragmentation from both Strombolian eruptions and hydrovolcanic eruptive mechanisms. They noted that hydrovolcanic eruptions occurred both early and late in the evolution of the main cone of the Lathrop Wells center. Crowe et al. (1986) summarized experimental data from fuel-coolant interactions that could be applied to hydrovolcanic explosions. These data are consistent with a spontaneous nucleation-pressure suppression model but less so with a thermal detonation model. They concluded that theoretical models of magma-water interaction show that hydrovolcanic explosions are possible at the Yucca Mountain setting. However, geologic evidence indicates hydrovolcanic explosions are unlikely to exhume a repository. They suggested consequence studies of radioactive releases should be revised to incorporate an opening phase of hydrovolcanic activity followed by Strombolian eruptions.

Finally, Crowe et al. (1986) noted that more complete models of the tectonic framework of the Yucca Mountain region are needed. These models need to be integrated with observed patterns of past volcanic activity.

3. Environmental Assessment. The probability estimates of magmatic disruption of a repository of Crowe et al. (1982) were used in the Environment Assessment (EA) for Yucca Mountain (DOE 1986). The conditional probability of magmatic intrusion of the repository was evaluated for the favorable condition of 10 CFR Part 960.4-2-7 b. A mean value of 1.3×10^{-4} events yr^{-1} with a standard deviation (one σ) of 1.33×10^{-4} events yr^{-1} for 10,000 years was calculated for the volcanic disruption probability using the data tables of Crowe et al. (1982; Tables IV and V). The conclusion of the EA (DOE 1986; pp. 6-262) was that additional investigations were needed to more accurately constrain the probability of volcanic disruption. *The mid-range value of the probability of volcanic eruptions may not be well represented by a calculation of a conventional mean from the data tables of Crowe et al. (1982). The data tables were constructed to establish the bounds of the probability of repository disruption. No attempt was make to establish a representative probability range or examine the statistical properties of the distribution of probability values.*

I. Publication in 1988

1. Site Characterization Report. The risk of basaltic volcanism for the Yucca Mountain site was summarized in sections 1.5.1.2 and 1.5.1.3 of the Site Characterization Report (DOE 1988; SCP). The conclusion of the EA (DOE 1986) was reiterated with respect to the favorable condition of 10 CFR Part 960.4-2-7 b: additional work was recognized to be required to resolve the volcanism issue. The plans for this additional work were summarized in Chapter 8.3 of the SCP (DOE 1988). These included Study 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository, Study 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on a Potential Repository, and Study 8.3.1.8.5.1, Characterization of Volcanic Features.

A tripartite strategy was presented in the Site Characterization Plan for volcanism studies. First, the probability of magmatic disruption of a repository would be calculated to determined if the site would or would not be disqualified solely from the direct effects of volcanism. The basis for this decision would be a determination of whether the probability of magmatic disruption of the repository is less than 1 in 10,000 in 10,000 years. If the answer to that question is yes, studies of the eruptive effects of volcanism would be ended. If the answer to that question is no, the second part of the strategy would be started. Studies would evaluate the probability of magmatic disruption of a repository and eruptive releases of radionuclides to the accessible environment. This work would be based on evaluation of natural analogues (eroded volcanic centers) to quantify or bound the percentage of a repository inventory that would be released at the surface in an eruption. If the probability of releases exceeding the regulatory criteria are less than 1 in 10,000 in 10,000 years, studies of the eruptive releases of volcanism would be terminated. If the probability is less than the cut-off value, performance assessment studies would be required to assess the possibility of disqualification of the Yucca Mountain site. The third part of the study will evaluate the potential radiological releases from eruptive and intrusion (coupled) effects of magmatic disruption of the controlled area and intrusion (coupled) effects of disruption of the repository. The thrust of these studies is to provide data for evaluating the contribution of potential releases from eruptive and intrusion scenarios for the waste isolation system.

IV. PROGRESS SINCE THE SITE CHARACTERIZATION REPORT

A. Publications in 1988

1. Reassessment of the Chronology of the Lathrop Wells Volcanic Center: New Geomorphic and Soils Studies. In 1988, there was a major re-evaluation of the chronology of the Lathrop Wells volcanic center based on comparative soils and geomorphic studies of the volcanic landforms (Wells et al. 1988; 1990; Crowe et al. 1988). Geomorphic and pedologic data from selected volcanic landforms in the Cima volcanic field were compared with data from the Crater Flat volcanic field. These results coupled with newly obtained K-Ar age determinations and revised geologic mapping compelled re-evaluation of the chronology and stratigraphic data. Wells et al. (1990) concluded that the age determinations of the Lathrop Wells center could overestimate the age of the center. They suggested the youngest activity from the center could be as recent as late Pleistocene or Holocene. Further, the center could be polycyclic: formed from multiple, time-discrete eruptive events. Wells et al. (1990) compared morphometric, pedogenic and stratigraphic data for volcanic centers from the California and Nevada volcanic fields. They showed that a sequence of tephra deposits exposed near the south cone base contained interbedded soils with significant horizon development. The presence of the soils provided the primary basis for the interpretation of polycyclic volcanic activity. *The recognition of the potentially young age of the main cone of the Lathrop Wells center was significant for two reasons. First, it provides evidence that the most recent volcanic event in the region is younger than originally estimated. Second, the possibility that the center could have formed by multiple (polycyclic) events requires re-evaluation of scenarios used for determining the consequences of volcanic events. There has been continued controversy whether the main cone of the Lathrop Wells center is as young as late Pleistocene or Holocene and formed during multiple, temporally separate events. This controversy may not be resolved to the satisfaction of all research scientists. Nonetheless, the possibility and implications of polycyclic volcanic events must be assessed to insure the consequences of volcanic disruption of a potential repository are not underestimated.*

2. Revised Geologic Map of the Lathrop Wells Volcanic Center. Crowe et al. (1988) completed a revised geologic map of the Lathrop Wells volcanic center. The center was remapped at a scale of 1:4000 on color aerial photographs. The eruptive history of the center was reconstructed using a combination of field mapping, geomorphic studies, geochronology studies and preliminary results of paleomagnetic studies of volcanic units. The center was inferred to have formed from multiple volcanic events separated by intervals

of no eruptive activity (polycyclic activity). The duration between events was estimated to be several thousand to several tens of thousands of years. The age of the volcanic center was estimated to be less than 100 ka and probably less than 50 ka. *Recent studies providing compelling evidence that the lava flow sequences of the Lathrop Wells center may be > 100 ka. The age of the main cone is still not well constrained. It is probably > 45 ka.*

B. Publications in 1989

1. New Developments in Concepts of Basaltic Volcanism, Evidence of Complex Evolution of the Lathrop Wells Center, New K-Ar Age Determinations, Definition of Polycyclic Volcanism, Revised Volcanic Risk Assessment using Multiple Volcanic-Eruption Scenarios. Crowe et al. (1989) summarized new developments in volcanism studies for the Yucca Mountain Project. They noted that small volume basalt centers have traditionally been inferred to form during short duration events (months or years; Wood 1980). However, the recent studies of the Lathrop Wells center show that it may be substantially younger than the K-Ar age estimate of 270 ka. They summarized evidence that the scoria cone could be substantially younger than the K-Ar age determinations and the center may have a long and complex history of volcanism. First, new mapping showed that there were at least four major eruption events. Second, geomorphic features of the cone were inferred to be consistent with an age of late Pleistocene to Holocene. Third, stratigraphic sections exposed in quarry cliffs south of the cone revealed a sequence of buried soils, primary and reworked tephra and eolian deposits. The presence of soils between tephra units requires a hiatus between eruptive events. Different field magnetic directions were recorded from paleomagnetic studies of volcanic units.

New K-Ar age determinations were obtained from five sample sites in the lava flow units of the center. The data were judged to be of good quality analytically, but difficult to interpret. The resulting ages were clearly younger than previously reported K-Ar ages for the center. They may or may not separate into two groups. The lava flow groups were not statistically different in age (F test) unless one sample site was discarded. This sample site appeared anomalous and yielded a K-Ar age of 480 ka. It plotted as an outlier on a probability plot of percentage radiogenic Ar versus age.

Crowe et al. (1989) defined and contrasted polycyclic versus polygenetic volcanism. They noted that polygenetic volcanoes are characterized by intermittent eruptions over time spans of 10^5 to 10^6 yrs. Volume of eruptions may exceed 10 km^3. They commonly are associated with a subvolcanic reservoir. Fedotov (1971) argued that a high magma supply rate, > 10^7 m^3 yr^{-1}, is required to maintain intermittent or continuous basaltic volcanism in a continental setting. The term polycyclic volcanism is used (Crowe et al. 1989) to refer to small volume (< 1 km^3) volcanic centers that exhibit intermittent volcanic activity where the time between events exceeds the cooling time for basalt magma in the shallow crust (several tens of years).

Crowe et al. (1989) assessed the impact of the revised chronology studies and polycyclic activity on volcanic risk assessment for the Yucca Mountain site. They completed revised regression calculations with time as the independent variable and magma volume as the dependent variable. The slope of the curve, which is the magma output rate, did not change significantly from previous calculations (Crowe et al. 1982). Revised calculations of O_r, the magma output rate, declined from 130 $m^3 yr^{-1}$ to 66 $m^3 yr^{-1}$ during the approximately 4 Ma history of volcanism in the Crater Flat area.

Two scenarios were developed for future volcanic activity in the Yucca Mountain area (Crowe et al. 1989). These are the recurrence of a small volume scoria eruption at either the Lathrop Wells or the Hidden Cone centers and the formation of a new center of basaltic volcanism. The former event is judged to be insignificant because of the distance of the centers from the potential Yucca Mountain site. Identified concerns are seismic activity, which would be of small magnitude and centered more than 20 km from Yucca Mountain. This activity would be much smaller than the design earthquake for the potential repository. No mechanism could be identified for small volume eruptions at these centers that might affect the ground water system at Yucca Mountain.

The second scenario, formation of a new volcanic center has been the focus of studies for volcanic risk assessment. It is the identified volcanic event that has a finite probability of disrupting the repository. *The possible recurrence of another eruptive event at the Lathrop Wells or Hidden Cone center is not used to justify a low risk of volcanic activity for the potential Yucca Mountain site. Instead it is recognized as a low consequence event that is far less important from a risk perspective than the risk associated with the formation of a new volcanic center.*

<u>2. Recurrence Rate of Volcanic Events: Cumulative Magma Volume Versus Time, Recognition of the Crater Flat Volcanic Zone.</u> Crowe and Perry (1989) described methods for estimating volcanic recurrence rates for probability calculations. This was the first of a series of papers that attempted to bring to closure parts of the studies of volcanism risk assessment. They described the distribution of volcanic centers, emphasizing a southwest stepping of volcanism between 6.5 and 3.7 Ma. They described a recurrence pattern of basaltic events where new eruptive sites are marked by probable coeval clusters of centers. These clusters appear to be of similar age within the limits of K-Ar age determinations. Crowe and Perry (1989) noted that all basalt centers of the youngest episode of volcanism, except the basalt of Buckboard Mesa, occur in a narrow northwest trending zone. They named this zone the Crater Flat volcanic zone (CFVZ).

Crowe and Perry (1989) summarized methods to calculate λ, the recurrence rate of volcanic events. These include evaluation of intervals of volcanic activity for evidence of periodicity, event counts for set periods of geologic time (Quaternary period, 3.7 Ma basalt cycle), and calculation of magma output rates. They noted first, that the number of volcanic events is insufficient to establish recurrence intervals. Second, they discussed limitations of events counts. This method is based on an assumed poisson distribution of events in time. However, vent or cone counts record only the recognition of a volcanic event. They do not account for the magnitude of events. Additionally, vent counts are insensitive to variations in rates through time. Therefore, the λ can be biased toward higher or lower values by varying the observation period *t* of the rate estimations.

Crowe and Perry (1989) suggested a preferred alternative for calculating λ , which is used repeatedly in published studies of active volcanic fields. This alternative method is based on constructing a curve of cumulative magma volume versus time. They provided background information on the use of this plot and cited examples of this usage from the volcanological literature. The most significant feature of a plot of cumulative magma volume versus time is it provides a method of assessing the time variability of magma output rates. They suggested that the magma output rate represents a composite response to the initiation, growth, and decline of a thermal or magma-generating event in the mantle. The lithosphere in this model, acts as a moderating influence (event filter) on volcanic activity. Crowe and Perry (1989) presented a plot of cumulative magma volume versus time of the Springerville volcanic field using data from Conduit et al. (1989). This field exhibits classic stages of time-volume-evolution of a volcanic field, including a short waxing period during the birth of the field, a long interval of steady-state activity, and waning activity during the last 100 ka (Crowe and Perry 1989; their Fig. 2).

Several important assumptions are required to use a magma output rate for extrapolating future volcanic events. First, the volcanic record must reflect the operation of a coherent period of tectonic activity. They argued that the youngest episode of volcanic activity in the region (4.0 Ma and younger) provides that perspective. Second, the magma output rates are assumed to be regulated by the tectonic setting of the site. Magma is generated in the mantle. It ascends through or is trapped in the crust in response to the dynamics of the tectonic setting. Third, the record of basaltic volcanism must be considered carefully with respect to the temporal and spatially variability of volcanic events in establishing a magma output rate.

The magma output rate for the Yucca Mountain region shows a curve with negative slope (flattens with decreasing age). Magma output rates are about 30 to 40 $m^3 yr^{-1}$. If the basalt of Buckboard Mesa (2.8 Ma center in the moat zone of Timber Mountain) is added to the cumulative volume curve, the flattening of the curve through time is more pronounced.

There are several key questions or areas of uncertainty for establishing the magma output rate for the Yucca Mountain region. Are steady state rates valid for an area of intermittent volcanism over a period of the last 3.7 Ma? What is the significance of the variability in calculated magma output rates? Crowe and Perry (1989) noted in particular that a sensitive assumption for calculating the magma output rate is the inferred volume of the scoria-fall sheets of each center and particularly the Quaternary basalt of Crater Flat that includes four centers (greater uncertainty in extrapolating the volume of eroded scoria-fall sheets).

Evaluating estimates of λ obtained from magma output rates, require a careful identification of the physical meaning of the rate. It is a long-term rate associated with the intermittent formation of basalt centers. More correctly, it is a rate that applies to formation of clusters of volcanic events since each plotted point is a summation of the volumes of multiple centers. Studies are still in progress for estimating the volume of an initiating volcanic event. Crowe and Perry (1989) presented several methods. The recommended approach is to use the volume of the smallest volcanic cluster, the basalt of Sleeping Butte. *An alternative model that is being studied is to calculate the minimum volume of magma required to initiate a dike ascent event which propagates through the crust without freezing because of solidification. Spence and Turcotte (1985) estimated the minimum magma volume of a dike initiation event to be 10^8 m^3 based on assumed values of crustal thickness, dike thickness and dike cooling rates.*

3. Isotopic Composition of Sr, Nd, and Pb for Basalt of the Yucca Mountain Region, Preservation of Ancient Lithospheric Mantle. Farmer et al. (1989) presented new trace element and Nd, Sr and Pb isotopic data for late Cenozoic basalt of southern Nevada and adjacent parts of California. They noted that Nd values range from +10.1 to -10.4 and vary regularly with geographic position. The Nd values for basalt from southern Nevada are increasingly more negative for an area extending from central Nevada (+4.7 Lunar Crater volcanic field) to -10.4 (Yucca Mountain region). Farmer et al. (1989) showed that most basalt in the Yucca Mountain region has Nd values less than -7 independent of age or degree of trace-element enrichment. The $^{87}Sr/^{86}Sr$ values of the basalt of southern Nevada covary with the Nd isotopic compositions. Basalt of the Yucca Mountain region has strontium isotopic ratios of 0.7070 to 0.7075. Lead isotopic data for the basalt of the Yucca Mountain region plot within a narrow range of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ (Farmer et al. 1989). The values plot to the right of the geochron and above the northern hemisphere reference line.

Farmer et al. (1989) argue that basalt of the Yucca Mountain region comprises a spatially distinct isotopic population that can be separated isotopically from basalt inferred to be derived from upwelled asthenospheric mantle. One possible explanation for the isotopic characteristics of the basalt of the Yucca Mountain region is that they have undergone a greater degree of crustal contamination than other basalt of the Basin and Range province. However, a critical observation for the basalt of the Yucca Mountain region is the uniform Nd, Sr, and Pb isotopic compositions since about 10 Ma. This would not be expected if the basalt represented mixtures of mantle-derived magma and bulk, or selectively assimilated crust (Farmer et al. 1989). A preferred alternative is that the basalt was derived from lithospheric mantle that has been preserved beneath this region despite late Cenozoic extension, an observation consistent with the amagmatic history of this region throughout the Phanerozoic. Thus the mantle may have been relatively cold and difficult to extend. The preservation of mantle lithosphere in southern Nevada was therefore, largely controlled by the preextension thermal gradient within the lithosphere itself (Farmer et al. 1989). This is consistent with the mantle lithosphere representing ancient continental mantle formed during formation of Precambrian continental crust. The data and interpretations support the hypothesis that preextension lithospheric mantle currently exists beneath southern Nevada and eastern California. The preservation of lithospheric mantle appears to be unique relative to the other parts of the Basin and Range province (Farmer et al. 1989).

C. Publications in 1990

1. Volcanic Patterns of the Yucca Mountain Region; Time-Space Migration of Volcanism, Multiple Chronology Models for the Lathrop Wells Volcanic Center. Crowe (1990) described basaltic volcanic episodes of the Yucca Mountain region, located in the south-central part of the Southwest Nevada volcanic field. He presented evidence of two distinct episodes of basaltic volcanism in the last 10-12 Ma. These include large volume basalt associated with the waning phase of the Timber Mountain-Oasis Valley caldera complex, and small volume, postcaldera basalt. The latter was divided into two cycles. These include: 1) an older cycle of activity (9 to 6.3 Ma), all units of which occur north and east of Yucca Mountain, and 2) a younger episode of activity, the Younger Postcaldera Basalt (YPB; 3.7 Ma to late Pleistocene). All basalt of the YPB, except the basalt of Buckboard Mesa, lies within a narrow northwest-trending zone west and southwest of Yucca Mountain (CFVZ of Crowe and Perry 1989). Crowe (1990) showed that there are two distinct patterns through time for the volcanic activity of the episodes. The first is a dramatic decrease in the volume of eruptive units. Eruptive volumes of individual events of the basalt of the silicic episode exceed several cubic kilometers. Eruptive volumes of centers of the YRB are less than 1.0 km^3 and average about 0.1 km^3. *This does not include the newly recognized basalt of Thirsty Mesa.* There has been repetition of small volume basalt eruptions in the Yucca Mountain region since about 8.5 Ma. Second, the time-space patterns of volcanic activity of the YPB are consistent with a southwest stepping of volcanic activity between eruption of centers of the OPB and YPB. This pattern mimics the migration patterns of older silicic volcanic activity.

Crowe (1990) described the geology of each center of the postcaldera basalt, providing more detailed data for the Pliocene and Quaternary volcanic centers. He described the controversy concerning the age of volcanic units of the Lathrop Wells volcanic center. Because the chronology data is incomplete, he summarized three permissive models for the age and eruptive sequence of the center. Crowe (1990) repeated established predictions of the nature of future volcanic activity in the Yucca Mountain region. These are:

1. The most likely composition of future volcanism is alkali basalt (hawaiite).
2. Future eruptions will probably be Strombolian with a potential for hydrovolcanic activity at sites where the water table is shallow.
3. The highest probability of a recent event is a recurrence of a small volume eruption at either the Lathrop Wells or the Sleeping Butte volcanic centers. These eruptions would probably be analogous to the last eruptions at these centers. This prediction is based on an assumed validity of the polycyclic model of basalt eruptions, a concept still being investigated actively.
4. The primary event of concern for siting of a potential repository at Yucca Mountain is the formation of a new volcanic center or cluster of centers. This event has a finite probability of occurring at and disrupting the Yucca Mountain site. The most likely site of formation of a new volcanic center, however, is in the CFVZ.

2. Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features: Data Gathering Activities for Volcanism Studies. Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features was completed and submitted to the Nuclear Regulatory Commission in 1990. This Study Plan describes planned research for five activities that are the major data gathering activities for volcanism studies for the Yucca Mountain Site Characterization Project. The first activity is 8.3.1.8.5.1.1 Volcanism Drill Holes. The purpose of this activity is to evaluate, using exploratory drilling, the origin of aeromagnetic anomalies that could represent buried basaltic volcanic centers or shallow intrusive rocks of basaltic or silicic composition. The second activity is 8.3.1.8.5.1.2 Geochronology Studies. The purpose of this activity is to refine the geochronology data for volcanic events in the Yucca Mountain region with an emphasis on basaltic volcanic rocks of Quaternary age. Multiple age measurements using a variety of isotopic, radiometric and age-correlated methods will be used. These studies attempt to increase confidence in the accuracy of geochronology results by seeking convergence among different geochronology methods. The geochronology methods are cross-checked further by field, stratigraphic, soil, geomorphic and petrology data. The third activity is 8.3.1.8.5.1.3 Field Geologic Studies. The purpose of this activity is to collect samples and provide geologic control on the stratigraphic relations of samples used for the geochronology studies. Additionally, field studies will establish the field geologic relationships, the volume of erupted volcanic material and the eruptive history of Pliocene and Quaternary basaltic volcanic centers in the Yucca Mountain region. A third part of this activity will be an evaluation of the distribution and the significance of Pliocene and Quaternary silicic volcanic centers in the Great Basin. The fourth activity is 8.3.1.8.5.1.4 Geochemistry of Eruptive Sequences. The purpose of this activity is to sample and analyze the composition of volcanic units recognized from the field geologic studies of Quaternary basaltic volcanic centers in the Yucca Mountain region. Eruptive units established from field and geochronology studies will be analyzed for whole rock, major and selected trace elements. Mineral compositions will be determined for phenocryst, microphenocryst and groundmass phases. These data will be used to evaluate the magmatic evolution and geochemical processes of each center. Strontium and neodymium (and possibly lead and oxygen) isotopic analyses will be obtained for selected eruptive units. These data will be used to evaluate geochemical processes of magma formation, and to test plausible models that may lead for understanding the genesis of the magmas that formed the Quaternary centers. Additionally, polycyclic and monogenetic models for the centers will be tested through examination of the geochemical and isotopic data. The fifth activity is 8.3.1.8.5.1.5 Evolutionary Cycles of Basaltic Volcanic Fields. The purpose of this activity is study the evolutionary patterns (time, space, magma effusion rates, volume, geochemistry) of continental basaltic volcanic fields in the southwest United States. We will attempt to determine if there are systematic patterns to the initiation, evolution, and decline of activity in basaltic volcanic fields. Additionally, we will attempt to determine if these patterns can be used to identify the stage of activity of the basaltic volcanic field of Crater Flat, which in turn would be used to predict and constrain the nature of future volcanic activity.

3. First Publication of Technical Overview Volcanism Studies by the State of Nevada. Smith et al. (1990) described the area of most recent volcanism near Yucca Mountain and examined the implications of that information for an assessment of volcanic risk. This work

was sponsored by the State of Nevada in their role of providing technical overview of the Yucca Mountain Site Characterization Project. Smith et al. (1990) examined the spatial and temporal patterns of post-6 Ma volcanism in the southern Great Basin. They suggested that volcanism in the Yucca Mountain area should be viewed as part of the volcanic record of the southern Great Basin. They argued that local patterns of migration of volcanic activity in the Yucca Mountain area (summarized in Crowe and Perry 1989; Crowe 1990) lack regional significance. Smith et al. (1990) suggested that basalt centers occur commonly along range margins but also in range interiors. They cited supporting evidence for the latter observation based on the setting of the basalt of Buckboard Mesa and the basalt centers of western Arizona, adjacent to Lake Mead. Finally, they suggest that high-angle normal faults control the location of volcanic centers in the Yucca Mountain area.

Smith et al. (1990) defined the area of most recent volcanism (AMRV) as an area enclosing all known post-6 Ma volcanic centers in the region. *This is not a new definition of an area of volcanism for risk assessment studies. It is identical in concept and area to Case 1a of the random structural model of Crowe et al. (1982).*

Smith et al. (1990) described the geology of the Red and Black Cone centers of Crater Flat and presented a preliminary geologic map of Red Cone. They infer that the arc of Quaternary volcanic centers in Crater Flat follows the same fault set that offsets the Paintbrush Tuff west of the Yucca Mountain site. They suggest further, that the faults controlling vent locations experienced clockwise rotation similar to the rotation of Yucca Mountain (Rosenbaum et al. 1991). They suggest that the Lathrop Wells volcanic center formed along a splay of the Solitario Canyon fault.

The geology of the Fortification Hill and Reveille Range volcanic fields were described as possible analogues to the volcanic centers of the Yucca Mountain area. The Fortification Hill volcanic field is composed of alkali basalt centers and associated lava that erupted between 5.9 and 4.7 Ma (Smith et al. 1990). The Reveille Range volcanic field is located in central Nevada, 80 km east of Tonopah. Basaltic volcanism in the field ranges from 6 to 3 Ma. Dikes exposed in the Fortification Hill field have aspect ratios of 10^{-2} to 10^{-3} and widths of 0.5 to 2 m (Smith et al. 1990). *A significant difference between the basalt centers of the Fortification Hill and Reveille Range fields and the basalt of the Yucca Mountain is the volume of eruptive units. Basalt centers of the former fields exhibit volumes in excess of 1 km^3. In contrast, the basalt centers of Crater Flat have eruptive volumes of < 0.1 km^3.*

Smith et al. (1990) defined volcanic chains as aligned groups of related volcanic centers that are controlled by a single or set of related structures. They suggest the Fortification Hill-Lava Cascade Group forms a chain 25 km long with a width of 3 km or possibly 15 km. They suggest chain dimensions for the Reveille Range are comparable to those of the Fortification Hill volcanic field.

The analog data from the Fortification Hill and Reveille Range fields are used to define high-risk zones for volcanism in the AMRV (Smith et al. 1990). These risk zones are centered on the Quaternary volcanic centers of the Yucca Mountain region and have assigned dimensions from the analog studies. *This usage of risk does not follow standard definitions of risk which is a product of probability and consequences. Rather the risk zones of Smith et al. (1990) are based on the assumption that future volcanic activity will occur along the same zones is past activity. This assumption has merit and follows traditional methods used to assess volcanic hazards of active volcanic centers and fields. However, the defined zones are structural or effect zones identified from past sites of volcanic activity. The assumption is made that past sites and their associated structural zones will be sites of future volcanic activity. An observation based on examination of this approach however, is that none of the past zones overlap, even using unrealistically long chain lengths of other volcanic fields. There is a 0% success rate using older sites of volcanic activity (Pliocene) to predict the location of sites of younger volcanic centers sites (Quaternary) using the criteria of Smith et al. (1990).*

D. Publications in 1991

1. Alternative Views by the U.S. Geological Survey: Monogenetic versus Polycyclic Eruption Models. Champion (1991) summarized paleomagnetic data for the Pliocene and Quaternary basalt centers of the Yucca Mountain region. He noted that the 3.7 Ma volcanic centers of Crater Flat exhibit tightly grouped mean magnetic directions suggesting contemporaneous or near contemporaneous eruptive events. Similar conclusions were reached for the four aligned, 1.2 Ma basalt centers of Crater Flat. Champion (1991) also examined the Sleeping Butte centers northwest of Yucca Mountain. Here two directions of remanent magnetization were described for the lava flows and cone scoria of the two centers. However, the directions are separated by an angular difference of only 3 degrees. Champion (1991) suggests the cones and associated flows probably formed during an approximately 100 year interval. Finally, Champion (1991) presented results of paleomagnetic studies of the Lathrop Wells center. Two directions of remanent magnetization were obtained from the two units of the Lathrop Wells center. The angular difference between the directions is 4.7 degrees which he suggested indicates an age difference of only a century. Champion (1991) argues, based on paleomagnetic data, that all of the centers of the Yucca Mountain region are monogenetic in disagreement with polycyclic eruption models. *Three significant assumptions and limitations of the data of Champion (1991) were not discussed. First, Champion (1991) did not present demagnization or measurement data for individual sites of collected samples. The presented data are inadequate to document his conclusions. Second, he assumed secular variation during the time of eruption of the different volcanic cycles was analogous to modern secular variation. Third, paleomagnetic data cannot be used to constraint the maximum difference in the age of volcanic units, particularly for volcanic events that have magnetization directions close to the time-average (spin-axis) Quaternary magnetic direction.*

2. Alternative Views by the U.S. Geological Survey: Age of the Lathrop Wells Volcanic Center. Turrin and Champion (1991) summarized the results of $^{40}Ar/^{39}Ar$ and conventional whole rock, K-Ar ages of the Lathrop Wells volcanic center. They suggested that the age of the center is bracketed between 119 ± 11 and 141 ± 10 ka. This age estimate is based on calculation of a variance weighted mean of replicate K-Ar whole and $^{40}Ar/^{39}Ar$ laser fusion age determinations. They suggest the age determinations are consistent with age

constraints for surficial deposits in the Yucca Mountain region. Turrin and Champion (1991) combined the results of K-Ar and paleomagnetic studies and concluded that while there were two distinct volcanic events at the Lathrop Wells center, the events are closely spaced in time and should be treated as a single event for assessments of volcanic risk. *The K-Ar ages published by Turrin and Champion (1991) are accepted as potentially valid measurements of the ages of volcanic units of the Lathrop Wells center. In question however, is the use of a variance weighted mean for measurements that are non-guassian and contain possible errors that are not solely attributable to the analytical measurements. Additionally, the measured ages are for lava units of the center and may not constrain the age of the main cone.*

3. Geologic Map of the Sleeping Butte Volcanic Centers; Polycyclic Eruptions of the Hidden Cone Center. Crowe and Perry (1991) completed a preliminary geologic map and report on the basalt of Sleeping Butte. This unit includes two, spatially separate, small-volume basalt centers. The centers are estimated to be between 200 and 400 ka based on whole rock K-Ar age determinations with large analytical uncertainty. The southern center, the Little Black Peak center, consists of a main scoria cone, two small satellite scoria mounds and associated small lava flows. The northern center, Hidden Cone, formed in two eruptive episodes. The first included formation of the main scoria cone and was accompanied by intrusion of multiple lobes of aa lava erupted from radial dikes. The second episode consisted of formation of a scoria-fall event that draped the older cone and deposited thin tephra northeast of the cone. The latter event may, based on multiple lines of evidence, be of late Pleistocene or Holocene age.

4. Alternative Views by the U.S. Geological Survey; The Lathrop Wells Volcanic Center. Turrin et al. (1991) calculated the age of the Lathrop Wells volcanic center based on paleomagnetic and new $^{40}Ar/^{39}Ar$ age determinations. They argue that there have been only two eruptive events at the center and those events are indistinguishable analytically. The preferred ages of these events are, using a variance weighted mean, 136±8 and 141±9. Turrin and Champion (1991) suggest that the two identified units at the center have mean field magnetic directions that differ at the $P = 0.0002$ significance level. They note that the time interval between two directions of magnetization cannot be established from field magnetic data. However, they argue by analogy to paleomagnetic studies for Sunset Crater, Arizona, that the age difference between the two eruptive events is about 100 years. Turrin and Champion (1991) correlate primary and reworked cinders located 3 to 4 kilometers northwest of Lathrop Wells to the volcanic center. They argue that uranium trend ages on Quaternary stratigraphic units indicate the cinders were deposited between 240 and 145 ka. Finally, Turrin and Champion (1991) argue that the age constraints of Wells et al. (1990) based on geomorphic and soil criteria are miscalibrated. *The same constraints described above apply to the radiometric age determinations and the paleomagnetic data. Additionally, the stratigraphic relations and age of the Quaternary alluvial units associated with the basaltic ash have not been sufficiently well established to constrain the ages of the volcanic events of the Lathrop Wells center.*

5. Volcanism Probability Studies; State of Nevada. Ho (1990; 1991) examined the applicability of the simple Poisson model for eruption forecasting. He argued that the

Poisson model may not be applicable to all volcanoes and proposed two alternative distribution models. The first is a negative binomial distribution where the Poisson process is expanded to include a gamma-mixing distribution on λ. The second is for a nonhomogeneous Poisson process with a Weibull intensity. An advantage of this model is it can accommodate non-steady state eruptive activity. Ho examined published eruption data for a range of volcanoes using his suggested nonhomogeneous Poisson models.

Ho (1991) undertook time-trend analysis of past patterns of basaltic volcanism in the Yucca Mountain region. He argued that a simple Poisson model may not be applicable to volcanism in the region if there has been variability in activity through time (waning, or waxing). Further, he argued that a simple Poisson model is hard to justify for the limited data set (small number of Pliocene and Quaternary volcanic events) in the Yucca Mountain region.

Ho (1991) estimated the instantaneous recurrence rate of volcanic events using a nonhomogeneous Poisson process with Weibull intensity. He based the time-trend analysis on a combination of basalt episodes and age cycles. The observational intervals ranged from 12 to 1.6 Ma and he varied assumptions on the nature and chronology of volcanic events. Ho estimated midpoints of the time interval for the next eruption which ranged from 4.2 to 0.6 Ma. For all but one estimation, he noted a slight developing trend (β values of 1.09 to 2.55). Ho concluded on this basis that a simple Poisson model could underestimate the risk of volcanism for the potential Yucca Mountain site. *The midpoint intervals of Ho (1991) yielded values that are consistent or smaller (lower probability) than the recurrence rate calculations of Crowe et al. (1982). There is not a significant difference in the calculations. The β values of > 1 were obtained by assuming polycyclic volcanic activity at all the centers of Crater Flat, an unverified assumption. This usage is inconsistent with the definition of volcanic events corresponding to the formation of a new volcanic center. Polycyclic activity is based on the argument that once an event occurs at a volcanic center there is an increased probability that another event will occur at the same center. So defined, these events are no longer independent and are not modeled correctly using the distribution model of Ho (1991). An alternative and more physically meaningful way to structure the probability model is to define the formation of a volcanic center as an individual event and treat polycyclic events as a geometric complexity of a repository disrupting event.*

Ho (1991) suggested that volcanic risk for the potential Yucca Mountain site should be expressed as a percentage of the required isolation time of high level radioactive waste. On the basis of this recommendation, he estimated a risk of volcanism to be about 5% for the specified 10^4 yr isolation period. *Volcanic risk can be expressed as an annual or interval-specified value; either usage is correct and widely used in the risk assessment literature. Ho (1991) did not calculate volcanic risk. He calculated a 5% chance of a future volcanic eruption in an unspecified area of the Yucca Mountain region during the next 10,000 yrs. Stated simply, he calculated the probability of recurrence, only one parameter of the probability of disruption of the potential Yucca Mountain site. Estimating the risk of volcanism requires calculation of the recurrence probability, the probability of repository disruption and the probability of releases exceeding the regulatory requirements for disposal of high-level radioactive waste.*

Ho et al. (1991) examined the probability of disruption of the potential Yucca Mountain site by future volcanic eruptions. They noted the probability procedure outlined in Crowe et al. (1982) was a more formal approach to probability modeling than attempted previously. However, they argued that the existing data base (for the Yucca Mountain region) is inadequate to constrain the recurrence rate of volcanic events.

Ho et al. (1991) reviewed past methods used by Crowe et al. 1982) to calculate , the recurrence rate of volcanic events. They argued that none of the methods are satisfactory and proposed alternative methods to estimate . They used a method called maximum likelihood estimates, and let X denote the number of volcanic events from an assumed Poisson process. They estimated the successive number of eruptions from consecutive intervals of length constrained to the Quaternary period. The estimator became simply the total number of eruptions divided by the observation period (Ho et al. 1991). They adopted the definition of repose time used by Klein (1982) which measures events from repose time to the onset of the next eruption. Ho et al. (1991) noted that the repose time is difficult to define and redefined this variable to represent the time between the onset of eruptions for a specified observation period. Ho et al. (1991) argued that volcanic calculations are invalid because the volume of eroded volcanic deposits was not calculated. *This assumption is incorrect. The volume of eroded deposits was estimated for the volume calculations of Crowe et al. (1983a).*

Ho et al. (1991) argued that estimation of E the number of volcanic events has not been determined. *They defined E to include polycyclic events not the formation of a new volcanic center (see Crowe et al. 1992a). Their definition does not maintain the event independence required for the Poisson model. Moreover, defining as the rate of formation of volcanic events where a volcanic event is the formation of a new volcanic center makes E readily definable. It is simply the number of volcanic centers in the Yucca Mountain region.*

Ho et al. (1991) described the geology of Black Cone and argued that the complexity of the center invalidates previous models of the total number of eruptions. *The main basis of this statement is a semantics disagreement in the definition of a volcanic event. Ho et al. (1991) treated each vent in a scoria-complex as an event. This conflicts with their own definition (see Ho et al. 1991; p. 53).* Ho et al. (1991) made the valid observation that there is no method to distinguish ages of volcanic events using the K-Ar method of cones within clusters of centers. They conclude by calculating recurrence rates based on their equations (2) and (4) and suggest that Crowe et al. (1982) underestimate the risk of volcanism. *Their estimated values of the recurrence rate are bounded by the range established by Crowe et al. (1982).*

<u>6. Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository.</u> Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository was completed and submitted to the Nuclear Regulatory Commission in 1991. This Study Plan is divided into four activities. The first activity 8.3.1.8.1.1.1 is the Location and Timing of Volcanic events. This activity involves simply collating geologic maps of the location of volcanic centers, with accompanying tables listing and referencing information on the geochronology of volcanic

events, the eruptive history of the center, and the volume of major volcanic deposits. The second activity is 8.3.1.8.1.1.2, Evaluation of the Structural Controls of Basaltic Volcanic activity. This activity attempts to establish the probability that, given a future volcanic event, the event would disrupt the repository or the controlled area associated with the repository. The locations of sites of volcanic activity are controlled generally by existing structure or the local stress field. This activity seeks to identify those controls and determine how the controls would affect the disruption parameter of the probability calculation. The third activity is 8.3.1.8.1.1.3 Presence of Magma Bodies in the Vicinity of the Site. This involves an assessment of whether there is evidence of recent changes in processes controlling volcanism that could modify future patterns of volcanic activity. The major concern is with the possible existence of magma in the crust beneath the Yucca Mountain region. The final activity is 8.3.1.8.1.1.4, Revised Probability Calculations and Assessment. This activity will attempt to establish numerically the probability of future magmatic disruption of the repository and the controlled area of the repository. It is concerned primarily with the determination of whether the Yucca Mountain site could be disqualified solely on the basis of the likelihood of future magmatic activity. *The Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository is currently in revision based on review comments by the Nuclear Regulatory Commission. They correctly pointed out that the Study Plan only considers the probability of eruptive effects and should be expanded to include discussion of the probability of both the eruption and intrusion effects on a potential repository.*

E. Publications in 1992

1. Resumption of Surface Disturbing Activities for Site Characterization Studies; Status of Field and Geochronology Studies of the Lathrop Wells Volcanic Center. Crowe et al. (1992a) described the status of field and geochronology studies of the Lathrop Wells volcanic center current to December of 1991. They summarized the past controversies concerning the age and eruptive sequence of the center. They emphasized the importance of increasing the confidence in interpretations of chronology data by using combined isotopic, radiogenic, and age-correlated methods. The assumptions, strengths and weaknesses of each chronology method need to be assessed to facilitate an impartial evaluation of the results. The stratigraphy of the Lathrop Wells volcanic center was revised based on the results of exposure of stratigraphic contracts through surface trenching. This surface trenching was initialed in 1991 following several years of no surface disturbing activity because of refusal by the State of Nevada to issue required permits to the DOE.

The volcanic units of the Lathrop Wells center were divided into three chronostratigraphic units (Crowe et al. 1992a). These chronostratigraphic units are separated by soil-bounded unconformities. The degree of horizon development in the soils requires the time between eruptions to far exceed the inferred duration of basaltic eruptive events and the longevity of basalt magma in the shallow crust. This is the basis for the classification of the volcano as a polycyclic center.

The oldest unit of the Lathrop Wells center, chronostratigraphic unit three, consists of three lavas, with minor cone scoria exposed discontinuously beneath younger deposits.

These include a buried lava and scoria deposits on the north side of the cone, an elevated and dissected lava flow and cone scoria exposed on the southwest edge of the center. The third unit includes lava and minor cone scoria exposed on the southwest side of the center. Trenching of the buried lava flow revealed that it underlies primary and reworked surge and scoria-fall deposits that contain a soil with distinct horizon development. This sequence in turn underlies younger lava flows. *Subsequent trenching studies completed after publication of this paper showed that the buried flow is not separated from an overlying lava flow by a buried soil. The described soil infiltrates but does not underlie the youngest lava flow of this flow sequence.*

Chronostratigraphic unit two consists of the major volume of the deposits of the volcanic center including the main cone, a northwest-trending fissure formed at the base of the cone, two sequences of blocky aa lavas north and northeast of the main cone, and two fissure systems associated with the lava flows.

Chronostratigraphic unit one consists of tephra-fall deposits with interbedded soil with horizon development exposed in quarry walls at the south flank of the main cone. This includes the deposits described by Wells et al. (1990). *There is continuing controversy concerning the origin of the tephra-fall deposits. A number of workers maintain the tephra deposits are of reworked origin and do not record multiple volcanic events.*

A range of geochronology methods has been used to attempt to establish the age of the Lathrop Wells volcanic center (Crowe et al. 1992). The methods include the conventional K-Ar and $^{40}Ar/^{39}Ar$ methods, The U-Th disequilibrium method using solid source mass spectrometry, surface exposure dating using cosmogenic ^{3}He, and the thermoluminescence. Additional age determinations for the center have been reported by other workers using the ^{36}Cl method.

The results of K-Ar and $^{40}Ar/^{39}Ar$ methods have been described by Turrin and Champion (1991) and Turrin et al. (1991). They have been summarized previously. The strengths of these results are that they represent the most established and tested of the chronology methods used a the Lathrop Wells volcanic center. Additionally, the reported ages are consistent with the preliminary results obtained using the U-Th disequilibrium method. The weaknesses of the methods are several. First, both whole rock and laser fusion ages extract K and Ar from an assemblage of minerals. This requires the assumption that the distribution of K and Ar is uniform in the mineral and glass phases. Second, the laser fusion method can yield anomalous old ages because of recoil effects of ^{39}Ar during neutron activation (McDougall and Harrison 1988). Third the spread in reported ages is too large to be explained readily as analytical error. There are differences in the sample distributions of the K-Ar and $^{40}Ar/^{39}Ar$ data sets. Averaging of the data sets may not be appropriate. Finally, and perhaps most important, the distribution of the age determinations is non-Gaussian. The data are skewed toward older ages. Averaging of the data sets using a variance weighted method is not an accepted descriptor of the age of the volcanic units.

The results of Uranium-series dating of samples of the Lathrop Wells volcanic center were described by Crowe et al. (1992). They obtained an isochron age of 150±40 ka for a lava unit of chronostratigraphic unit two. The precision of the isochron is limited by the small degree of Th/U fractionation for the separated phases. There is no reason to discount the age, but it is regarded as preliminary and more age determinations are in progress.

The surface exposure ages of chronostratigraphic units of the Lathrop Wells center have been estimated by measuring the accumulation of cosmogenic ^{3}He (Crowe et al. 1992). Ages of 23 to 48 ka have been obtained for chronostratigraphic unit two. The variability in the ages of this unit may result from differences in the surface exposure history of the samples, particularly for samples collected from the summit of the main cone. A cosmogenic exposure age of 64±6 ka was obtained for chronostratigraphic unit three. Concerns with the cosmogenic ^{3}He method are the uncertainty of the surface exposure history of samples, and the calibration of ^{3}He production rates.

Thermoluminescence age estimates (TL) have been obtained for the chronostratigraphic units of the center (Crowe et al. 1992). Samples from soil units interbedded with tephra units of chronostratigraphic unit one yielded TL ages of about 9 ka. A sample was collected from sediments below a lava flow lobe of chronostratigraphic unit two. It yielded a TL age of 24.5±2.5 ka. *Subsequent field examination and trenching of pyroclastic surge deposits has shown that the sample dated by the TL method does not underlie the lava flow unit. The TL age therefore does not constrain the age of the lava flow. Instead it is a minimum age of the lava determined from deposits that overlie and infiltrate the lava flow.*

Soil and geomorphic studies of the Lathrop Wells center have been aided by trenching of stratigraphic and soil units. These data continue to support the age assignment of Wells et al. (1990). The weakly developed soils of the center most closely resemble late Pleistocene and Holocene soils in the Silver Lake and Cima areas of California (Crowe et al. 1992). These data suggest the presently studied soils of the volcanic units of the Lathrop Wells center probably cannot be older than 20 ka and almost certainly cannot be older than 50 ka. The uncertainty of those assignments is the possible variability in pedogenic processes at the correlated sites.

New paleomagnetic data have been obtained for previously unstudied volcanic units of the center (Crowe et al. 1992b). These data yield results that are generally consistent with the averaged field magnetic directions reported by Champion (1991) and Turrin et al. (1991). However, several cautions accompany the interpretation of the paleomagnetic data. First, the field magnetic directions coincide with the average Quaternary direction. This reduces the utility of discriminating eruptive events based on field magnetization directions. Second, the angular difference between paleomagnetic data sets can at best constrain the **minimum** age difference between the sampled rocks, not the **maximum** difference. Third, the reproducibility of field magnetic directions may be more variable than reported by Champion (1991) because of a combination of lightning-induced isothermal remanent magnetization and the quality of the preserved outcrops.

2. Recurrence Models of Volcanic Events; Definition of the Tripartite Probability, Application of a Simple Poisson Model, Revised Values of the Recurrence of Volcanic Events. Crowe et al. (1992b) defined the tripartite probability used to define the risk of volcanism and the geologic assumptions required for a probabilistic model of magmatic disruption of a potential repository at Yucca Mountain. This probability combined with the likelihood of release of radionuclides to the accessible environment during the 10,000-yr isolation period (Pr_{dr}) is modeled as:

$$Pr_{dr} = Pr(E3 \text{ given } E2,E1)Pr(E2 \text{ given } E1)Pr(E1)$$

where E1 denotes the recurrence rate of volcanic events in the Yucca Mountain region, E2 denotes the probability that a future magmatic event intersects the repository, and E3 denotes the probability that magmatic disruption of the repository leads to eruptive releases of radionuclides to the accessible environment. A volcanic event is defined as a spatially and temporally distinct episode of surface basaltic volcanism. There may be multiple sites or eruptive vents on the surface but the event is defined from the perspective of a buried repository. It represents an incursion of magma into the repository followed or not followed by surface eruption. *An item of continuing confusion in the published literature of probabilistic risk assessment for the potential Yucca Mountain site is the definition of a volcanic event. The preferred usage of a volcanic event is the formation of new volcanic center. This event has a finite probability of intersecting the potential repository site. Individual vents at a volcanic center are not recognized as separate volcanic events, nor are polycyclic events.*

The assumptions required to estimate Pr(E1) include (Crowe et al. 1992):

1. The past record of basaltic volcanic activity in the region is judged to provide the most reliable indicator of the recurrence of future volcanic events.
2. Interpretations of the geologic record are judged to be reliable in forecasting future events. If there are discrepancies or differences of opinion over the geologic record, these can be resolved by developing alternative models of the recurrence rate.
3. There have not been recent (Quaternary) changes in the rate of operation of processes which control the generation, ascent and eruption of basalt magma.

There is a clear and non-reducible element of uncertainty introduced by applying a probabilistic approach to the limited data set of past volcanic events in the Yucca Mountain region. The current level or anticipated level of knowledge of the predictability of magmatic processes precludes development of a fully deterministic approach to predicting volcanic events. In fact, the new science of chaos requires scientists to rethink fundamental ideas about the inherent predictability of physical processes. Rather than debate this issue however, Crowe et al. (1992) evaluated three questions concerning recurrence of volcanic events. What are reasonable time-distribution models? Can the models be structured to not underestimate volcanic risk? Can the uncertainty of a small data set be bounded by comparison with analog studies of other volcanic fields?

Crowe et al. (1992) reviewed time-distribution models for volcanism ranging from simple Poisson, nonhomogeneous Poisson, to deterministic chaotic. They concluded that a simple Poisson model represents the most direct approach to probabilistic assessments using a small data set. It does not introduce unsupported complexity that may be non-meaningful physically. It can be tested against physical models of volcanic processes. The types of errors associated with a poisson model can be assessed and bounded. *Ho (1991) argued that a poisson model is not appropriate for a limited data set. A corollary of that argument however, is that any distribution model is hard to justify based on a limited data set. The absence of data precludes evaluating the data set using standard tests for goodness of fit. Ho (1991) also rejected arguments by Crowe and Perry (1989) that a plot of cumulative magma volume versus time provides a method for testing time trends in volcanic activity. He argued correctly that evaluation of magma volume versus time is simply a modified form (similar to a sequenced or triggered process) of a simple Poisson process. He did not recognize, however, that an assessment of erupted volumes of magma through time provides a means of testing assumptions of steady state eruptive behavior.*

Calculations of the recurrence rate of volcanic events (E1) using a simple Poisson model were listed by Crowe et al. (1992). They summarized assumptions and listed Pliocene and Quaternary volcanic events in the Yucca Mountain region. A potentially new Pliocene event was identified based on recognition of a lava mesa east of the Sleeping Butte volcanic centers. This lava mesa was estimated to be of Pliocene age and it was included in subsets of the recurrence calculations. Recurrence rate estimations range from 10^{-5} to 10^{-7} events yr^{-1}. The geometric mean of the recurrence rates is about 4×10^{-6} events yr^{-1} or equivalent to the formation of a new volcanic center every 250 ka. Simple evaluation of the physical plausibility of recurrence rates allows rejection of unrealistic high or low rates. Accordingly, recurrence rates cluster in the range of 1 to 6×10^{-6} events yr^{-1} (Crowe et al. 1992). After over a decade of study, there have been no significant changes in the recurrence rate calculations of Crowe et al. (1982). Moreover, calculations by other workers using different approaches (Ho 1991; Ho et al. 1991) yield results that fall within this range.

The uncertainty in the recurrence models of volcanic events can be bounded by applying simple Poisson models to the Quaternary record of volcanism in the Cima and Lunar Crater volcanic fields. By analogy, a recurrence rate of 10^{-5} yr^{-1} (an event recurrence time of 100 ka) can be regarded as a very robust upper bound to rates of volcanic activity for the Yucca Mountain region.

3. Monte Carlo Technique for Estimation of the Probability of Disruption of a Repository by Propagation of Volcanic Dikes. Sheridan (1992) developed a method for determining a probability function for different spatial models of the structural controls of volcanic activity in the Yucca Mountain area. He used a Monte Carlo simulation to plot the trace of volcanic dikes. Input parameters for the simulation are the geometry of the volcanic field, and the geometry of the dikes. He developed a computer code that counts the number of intersections of the repository during simulations. The geometry of the volcanic field is constrained by alternative hypothesis of the structural controls of the volcanic field and the distribution of vents in the field. Three models were used. The first is based on the record

of basaltic volcanism in the region. The volcanic field is oriented northwest; dikes within the field are oriented northeast. The second model assumes the volcanic field and the dikes are controlled by the shallow stress field and both are oriented northeast. Model three assumes that a center of renewed volcanism will be located at Lathrop Wells,; it was modeled with a narrow aspect ratio and was oriented toward the potential Yucca Mountain site. Sheridan rated model three as the least likely, model two as less likely than model one and model one as the most likely.

Results of the simulation modeling show that the frequency of repository intersection is controlled by the field geometry and the standard deviation of the field size. The frequency increases as a generally linear function of low values of the standard deviation of the field size but reaches a peak and declines slightly. This is because the spacing between dikes increases at a faster rate than the increase in the size of the field (Sheridan 1992). The position of the slope change in the frequency varies somewhat with the different field models. Maximum probability values for the models one through three are, respectively, 6×10^{-3}, 1.4×10^{-2}, and 1.7×10^{-2}. If the distribution of volcanic centers in Crater Flat is used to define the standard deviation, the modeled frequency of intersections is 1.1×10^{-3}, 1.0×10^{-2}, and 5.3×10^{-3} for models one, two and three, respectively.

4. Teleseismic Tomography of the Yucca Mountain Region; Applications to Volcanism Studies. Evans and Smith (1992) presented the results of application of teleseismic tomographic studies of compressional phases to delineate subsurface magma chambers. They observed an upper-mantle, high-velocity anomaly beneath the Miocene Silent Canyon caldera that is inferred to represent the residuum of voluminous Miocene silicic volcanism. A second observed feature is a large low-velocity anomaly south and east of Yucca Mountain. The center of the anomaly is southeast of Yucca Mountain. Evans and Smith (1992) suggest that the low-velocity anomaly may be the source of Quaternary basalt in the Crater Flat area, and the anomaly may extend northeast to the area of St. George, Utah, parallel to the trace of hot-spot vectors of the North America plate. They infer, because of the association with young basaltic volcanism, that the anomaly is produced by partial-melt. They acknowledge however, that other interpretations are permissive. Dueker and Humphreys (1991) suggest the anomaly may record the remnants of the poorly absorbed slab of the Farallon plate. Evans and Smith (1991) suggest the partial-melt model can be tested by additional experiments using shear-wave velocity and compressional-wave attenuation teleseismic tomography. *A major inconsistency with the Evans and Smith (1991) interpretation of the teleseismic data that was not discussed is the presence of the anomaly in an area that has been amagmatic throughout the Mesozoic and Cenozoic (Farmer et al. 1989; Jones et al. 1992).*

5. Geochemical Evidence of Waning Magmatism; Polycyclic Volcanism. Perry and Crowe (1992) described the temporal and geochemical evolution of basaltic magmatism in the Crater Flat area. Additionally, they examined geochemical and isotopic variation among the basalt units of the Lathrop Wells volcanic center to test models of volcanic activity (monogenetic versus polycyclic). Systematic differences in phenocryst assemblages, trace-element concentrations and isotopic compositions of Sr and Nd, indicate that magma

chambers of the youngest two episodes of basaltic magmatism in Crater Flat were at deeper crustal levels than the oldest episode. The primary evidence for this conclusion is the absence of plagioclase as a near-liquidous phase in the younger basalt episode. This requires crystallization below 8 kb (Perry and Crowe 1992). This interpretation is consistent with the Sr and Sc contents of the basalt units, reliable indicators of the importance of fractionation of plagioclase and clinopyroxene.

The evolution of the postshield alkali basalt of Mauna Kea, Hawaii, shows striking similarities to the patterns of evolution of the basalt of Crater Flat. In both cases, declining eruptive volumes through time were accompanied by a change from more primitive porphyritic basalt to evolved, aphyric basalt (hawaiite). Again, in both cases, lower Sc contents and higher Sr contents in the younger basalt provide a distinctive signature of the progression to deeper crustal magma chambers. Frey et al. (1990) attributed the changes at Mauna Kea to a waning magma flux that could no longer maintain shallow magma chambers. Perry and Crowe (1992) apply the comparisons to the Mauna Kea system cautiously because of the vastly higher magma fluxes for the Hawaiian system. Moreover, the changes in the Crater Flat field are recorded at spatially isolated centers, not a single shield complex, as in the case of the Mauna Kea volcano.

Geochemical data for eruptive units of the Lathrop Wells volcanic center can provide important tests of the monogenetic versus polycyclic models of volcanism. A monogenetic origin of the center requires the units to be related to evolution of a single magma batch. The polycyclic model suggests the center was formed from temporally discrete magma batches.

Trace-element variations of the Lathrop Wells center show that the eruptive units identified from detailed field studies are distinct geochemically (Perry and Crowe 1992). They used process identification diagrams to test the origin of the trace-element variations. A plot of La versus La/Sm shows that eruptive units at Lathrop Wells have a range of La/Sm ratios, even at similar La contents. An increase in La/Sm with increasing La content could be produced by fractionation of clinopyroxene. This would require the unit Ql_6 to represent the least evolved magma. However, a plot of Sr versus Sc, shows that unit Ql_6 is the most evolved magma (with respect to fractionation of clinopyroxene). This inconsistency rules out derivation of the eruptive units from a single magma that fractionated at shallow levels. Sequential variation in units from the oldest to the youngest at the Lathrop Wells center in La/Sm contents is consistent with decreasing degrees of partial melting. This is consistent with a waning of processes of melt production with time through the evolution of the center.

Nd and Sr isotopic data indicate that unit Ql_6 is distinct from the rest of the analyzed eruptive units. While the isotopic variations could be produced in a single magma batch undergoing a complex evolution, the trace-element variations make it more likely that the isotopic differences record variant evolutionary paths of distinct magma batches.

More work is needed to assess the geochemical variations of the Lathrop Wells center.

Current data, however, appear to discriminate consistently against a simple monogenetic origin of the volcanic center.

6. Revised Assessments of the Consequences of Magmatic Disruption of the Potential Repository, Perspectives From Modeling of Intrusion and Eruption Processes. Valentine et al. (1992) examined the physical processes and effects of magmatism in the Yucca Mountain region. Volcanic activity can affect the isolation system of a repository by two potential processes. First, disruption of a repository could occur by ascending magma followed by surface dispersal of a portion of the radioactive inventory from subsequent eruptions. Second, subsurface effects of hydrothermal processes and altered hydrology can be induced by intrusion of magma through or near a repository. The subsurface effects do not need necessarily to be coupled with surface eruptions. Initial calculations of the volume of waste that might be erupted during a basalt eruption indicate the regulatory release limits might be exceeded. However, these calculations are based on the conservative assumption that all waste that comes into contact with magma is carried to the surface and dispersed.

Valentine et al. (1992) summarized continuing field studies of the characteristics of shallow intrusions in the Paiute Ridge area, an analog for shallow volcanic intrusions. These studies are concerned with identifying the potential for dispersal of waste by basalt intrusions and their effects on a waste isolation system. Observations at the Paiute Ridge area show that intrusive sills occurred only on the floor of a graben. Dikes only locally intrude the horst blocks. Most dikes are coplanar with normal faults. Small radial dikes are present in country rock associated with probable conduit plugs. Some dikes locally fed sills that differentiated to form concentric pods with syenite interiors.

The host rocks (primary and reworked Paintbrush Tuff) in the Paiute Ridge area were welded at the contact with the basalt intrusions (Valentine et al. 1992). Welding effects decrease to zero at a distance of 1 to 5 meters from the dike margins. Welding effects can be used to constrain modeling of the thermal and hydrothermal processes that may affect a repository intruded by basalt magma. Moreover, welding alters the hydrologic properties of rock so that ground water flow would be altered from a preintrusion state. The hydrologic properties of the dike itself may produce changes in groundwater flow, although those changes would be most pronounced in the saturated zone, not the unsaturated zone.

Valentine et al. (1992) presented preliminary results of two-dimensional modeling of emplacement of a basalt sill in country rock. The sill chamber is formed of two parts, a stable bottom half (cooler, denser on the bottom) and an unstable upper part (cooler, denser on top). The magma cools along a thermal boundary layer. As the boundary layer thickens, the roof and sidewalls become unstable and form downwelling plumes. The bottom layer grows by simple thermal diffusion. The plumes can carry cool fluid downward until they reach the lower bottom boundary layer.

Valentine et al. (1992) also carried out two-phase flow modeling of basaltic pyroclastic eruptions. They are developing quantitative methods for mapping pyroclastic facies of small basaltic centers and using this data in combination with two-phase hydrodynamic simulation to estimate eruption conditions of ancient volcanic centers.

7. Structural Controls of Volcanic Activity. Crowe et al. (1992c) reviewed progress in volcanism studies during 1990 and 1991. They summarized information presented in Crowe and Perry 1991, Crowe et al. 1992a, 1992b, Perry and Crowe (1992), and Valentine et al. (1992). New information was developed on the structural controls of volcanic activity. They noted that the major limitation of this calculation (Pr(E2)) is similar to the limitation for calculation volcanic recurrence models; there is only a small number of basalt centers formed in the region. This makes it virtually impossible to prove or disprove structural models. They emphasized an approach of attempting to define or bound the range of values for alternative approaches to estimating Pr(E2).

Crowe et al. (1992c) summarized the different models for the structural controls of volcanic activity. These include the random models of Crowe et al. (1982), the CFVZ model of Crowe and Perry (1989), the area of most recent volcanism model of Smith et al. (1990), the volcanic chain model of Smith et al. (1990), and the northeast-trending structural zone of Nauman et al. (1991). A table of estimated values of E1 was developed. The values range from 1.3×10^{-3} (dimensionless ratio) to 3.9×10^{-3} for the northeast-trending structural zone. An estimated median value for E2 based on the compiled data table is $2.8 \times 10_{-3}$.

8. Estimations of Volcanic Disruption, Continued Probability Studies by the State of Nevada. Ho (1992) published another review of probability studies for the potential Yucca Mountain site. He summarized background information on the National policy for disposal of high-level waste and the importance of estimating the potential risk of volcanism for the Yucca Mountain site. He described the volcanic history of the Yucca Mountain region, mostly referencing work by Crowe and Perry (1989), Crowe (1990) and Smith et al. (1990). Ho (1992) discussed the probability model of volcanism used by Crowe et al. (1982) and described the assumptions of the simple Poisson model. He reiterated the point made in a previous article (Ho et al. 1991) that a poisson model does not allow for waning or waxing trends in volcanism through time. He criticized the ". . . statistical work of Crowe et al. (1982), and Crowe and Perry (1989) as seriously flawed. Specifically, the probabilistic results of Crowe et al. are based on idealized model assumptions, a premature database, and inadequate estimates of the required parameters, which lead to questionable conclusions about (the) volcanic stability of the proposed Yucca Mountain repository." (p. 351).

Ho (1992) argued that a homogeneous Poisson process (HPP; or simple Poisson process) is based on the assumption that is independent in time t and the repose times between eruptions are independent exponential variables with mean $= 1/\lambda$. He proposed using a nonhomogeneous Poisson process (NHPP) where the constant λ is a function of $\lambda(t)$ called the nonhomogeneous intensity function. Ho (1992) suggests using the rate function, $\mu\ (t)$, in a form that follows a Weibull distribution *WEI(,)* where

$$\mu(t) = (t/\theta)\beta$$

The parameter μ increases as a function of t if β is > 1 and decreases with t if β is < 1. For the case of $\beta = 1$, the form of the distribution is the same as the exponential expression of the HPP. Ho (1992) recognized that volcanic eruptions may be caused by a range of physical processes resulting in random effects on the time-distribution of eruptive events. For this reason, Ho (1992) suggests estimating the instantaneous recurrence rate ((t)) at time t using a NHPP with Weibull intensity, but uses a HPP to estimate future eruptions, treating future events as a stochastic process. *This form of the probability distribution means that the approach used by Ho (1992) differs from simple Poisson model only if $\beta \neq 1$.*

Ho (1992) examined the recurrence rate for basaltic volcanic events in the Yucca Mountain region. He assigned one volcanic event to each major volcanic center and assumed for lack of contradictory data that each center is about the same age. Ho (1992) identified four volcanic events at 3.7 Ma, one at 2.8 Ma, five at 1.2 Ma, two at .28 Ma and one at 0.01 Ma. *The number of volcanic events and age assignments for the vents are in agreement generally with other probability studies with only two significant differences. Ho (1992) chose the youngest possible age for the Lathrop Wells volcanic center, an age of 10 ka (p, 348). A more realistic age assignment would be between 45 and 120 ka since only a very small volume of the center could be as young as 10 ka. Further the dates on the Sleeping Butte center are probably young by about 100 ka based on new geochronology results described in Section 3 of this report.*

Ho (1992) calculated an instantaneous recurrence rate of 5.0×10^{-6} yr^{-1} for the Pliocene and Quaternary volcanic events (6 Ma period) with $\beta = 2.29$ and an instantaneous recurrence rate of 5.5×10^{-6} yr^{-1} and $\beta = 1.09$ for Quaternary volcanism. *The calculated rates are roughly similar to rates calculated by other workers. They are equivalent, assuming an exponential distribution model, to 30 eruptive events in the Pliocene (there were 14 to 17 events) and 8.8 events in the Quaternary (there were 7 events). Why the discrepancy for the Pliocene events? The answer is in how the problem was constructed. The Pliocene calculation was for a 6 Ma period. There were no volcanic events during the first 2.3 Ma of this period. The choice of a 6 Ma period forces the majority of the volcanic events into the latter half of the period and produces a calculation of $\beta = 2.29$. A more realistic calculation would be to choose an observation period that is equal to the duration of the activity of the Younger Post-Caldera basalt. This illustrates two things. First, probability estimations must be constructed carefully to be physically meaningful, particularly if an instantaneous rate is calculated (Crowe and Perry 1989). Second, the $\beta = 1.09$ for the Quaternary period is close to an exponential fit and suggests that the simple Poisson model would provide an equally adequate fit to the data.*

Ho (1992) argues that the estimated recurrence rates are point estimates and do not assess uncertainty. He calculated 90% confidence intervals for the Quaternary calculation that give interval bounds of 1.85×10^{-6} yr^{-1} to 1.26×10^{-5} yr^{-1}. He uses these interval bounds in his calculations of the probability of volcanic disruption of the potential Yucca Mountain site.

Ho (1992) examined the probability that any single volcanic event is disruptive, or intersects the potential repository. He let p represent the probability that an eruptive event is disruptive. Assuming the event follows a HPP, the number of disruptive events $X(to)$ in

$[0,t_o]$ has a constant rate of $(t)pt_o$ (p. 356).He argued that the probability of at least one disruptive event represents "risk". *In reality Ho (1992) examined the probability of repository disruption, not risk which requires an assessment of both the probability and consequences of repository disruption. However he carefully defined his use of the term risk so there is no confusion. He calculated the probability of repository disruption.*

Ho (1992) defined risk as,

$$= 1 - \exp\{ - \lambda\ (t)\ pt_o\}$$

This is a modified form of the same equation used by Crowe et al. (1992). Ho (1992) used a Bayesian approach that allows a prior distribution of **p** and assumes the instantaneous recurrence rate is constant. His "risk" model becomes

$$\text{risk} = 1 - \int_p \exp\{ -\lambda(t)\ pto\}\pi(p)\ dp$$

Ho (1992) discussed at length the determination of the prior for **p**. He attempts to choose the prior based on the structural control of volcanic centers in the Yucca Mountain region. Ho (1992) uses the structural models of Smith et al. (1990) where the high risk zones of volcanism are identified based on assigning northeast-trending structural zones to the location of past volcanic centers. *The concerns with this structural model were described in the discussion of the work by Smith et al. (1990).* Ho (1992) uses the half length of the chain model for the Lathrop Wells center to obtain p = a/A = 8/75 = 0.11, where a is the area of the repository and A is the half-length area of the chain for the Lathrop Wells center. He chooses this value as the upper limit for **p**. He applies the 90% confidence bounds to the instantaneous rate and calculates the probability of repository disruption as 1.0×10^{-7} to $6.7 \times 10^{-7}\ yr^{-1}$.

These are the first published values for the probability of repository disruption that exceed the bounds published in Crowe et al. (1982). It is instructive to try to understand why the values differ and the physical meaning of the calculations of Ho (1992). First, a major paradox of volcanism studies is provided by the number of volcanic events. There are only a small number of volcanic events that have affected the Yucca Mountain region in the Quaternary (7-8 volcanic events dependent on whether the Little Cones center is counted as two events). The small number of events means there have been few past events and by inference are likely to be few future events. However a corollary of the inference is that while the risk (used as a relative term) is small the uncertainty of calculating the risk is relatively large (by virtue of the small sample size that prohibits statistical robustness of calculations). Reversing the logic of this argument, if there were a larger sample size (more volcanic events) the uncertainty of the calculations would decrease but the risk would increase. There are probably few people (an untested but hopefully correct assumption!) who would argue that increase risk would be preferred to increased uncertainty.

We are faced therefore with assessing the question of the risk of future volcanism knowing that the uncertainty of the answer will be by definition large. Crowe et al. (1992b) constructed *arguments based on observations of the physical processes of volcanism that there are bounds to the recurrence rate that can be assigned to volcanic events in the Yucca Mountain region. Those bounds are provided by the number or recurrence rates of volcanic events in large, very active volcanic fields of the Basin and Range province. Ho (1992), using straightforward statistical arguments, assigned upper or bounding intervals to λ, the recurrence rate, based on 90% confidence limits. Yet the values he used are equal to recurrence rates of the most active basaltic fields in the Basin and Range province.*

Second, Ho (1992) held the recurrence rate fixed and assigned it to an area of 75 km^2 to determine the probability of repository disruption. This means that the value he determined for, was estimated for an area exceeding 3000 km^2 but assigned without modification to an area of only 75 km^2. This would be realistic only if there was some reasonable geologic explanation why the next volcanic eruption will occur only within the confines of the small 75 km^2 rectangle. As noted above, the Smith et al. (1990) has a 0% success rate at predicting the sites of future eruptions based on the location of past eruptions. The significance of the calculations of Ho (1992) can be placed in perspective by comparing his calculations to recurrence rates of very active volcanic fields. Basaltic volcanic fields have vent densities (number of vents or cones per square kilometer) that range from .2 to approaching 0.4 events km^{-2} (Crowe et al. 1992b). Extrapolating the upper rate interval of Ho (1992) to the 75 km^2 area for the length of Quaternary period gives a vent density of about 0.3. Thus Ho's (1992) calculation establishes an upper bound that states that the probability of disrupting a repository at the potential Yucca Mountain site is about equivalent to placing a repository in the middle of the Lunar Crater or Cima volcanic fields. Clearly, that is not a physically realistic calculation and illustrates the pitfalls of making probability estimations without examining their physical meaning.

9. Comment and Response to the Article Published in Science on the Age of the Lathrop Wells Volcanic Center: The Continuing Controversy. Wells et al. (1992) commented on the paper by Turrin et al. (1991) on the age of Lathrop Wells volcanic center. There was a range of concerns expressed in the comment. First, the paper by Turrin et al. (1991) ignored published information on the stratigraphy and presence of soil-bounded unconformities in the volcanic units of the Lathrop Wells center. These unconformities suggest a hiatus in eruptive activity. They noted that several sources of data supporting a younger age of the center were ignored, including thermoluminescence ages of soil and cosmogenic helium ages. The K-Ar and $^{40}Ar/^{39}Ar$ age determinations were critiqued not based on the analytical results but on the method of averaging the data. Specific concerns were that the determinations have a mean larger than a median, outliers are present and unrecognized in their data set, four age determinations were discarded without criteria, there are influential cases in the regression plots, there were no discussions of possible sources of data error other than analytical, and there was no discussion of potential problems of recoil of ^{39}Ar. Wells et al. (1992) concluded that the weighted mean is unsupported at best and may be invalid if all sources of variance in the data set are not analytical. Second, they noted that paleomagnetic data can only be used at best to infer a minimum age difference between volcanic units. Moreover, they discussed inconsistencies in the presentation of the paleomagnetic data and concerns with the measurement of magnetization directions for samples collected from the summit of the main scoria cone.

Finally, Wells et al. (1992) noted that the simplified volcanic history proposed for the volcanic center by Turrin et al. (1991) was inconsistent with geochemical and isotopic data. These data support a polycyclic model for the center where it was formed from magma batches that were both physically or/or temporally distinct.

Turrin et al. (1992) rebutted the comments presented by Wells et al. (1992). They noted that the evidence of soil bounded unconformities is based on the presence of sand, silt and lapilli-size tephra in deposits near the south flank of the cone. They argue that the deposits are simply reworked parts of the cone and are irrelevant to the age of volcanic activity at the center. They presented granulometry data for the deposits they interpret as indicating the tephra deposits are not "volcanogenic" in origin and dismiss on this basis the thermoluminescence age determinations. Turrin et al. (1992) argue that cosmogenic helium ages for the Lathrop Wells center represent results of developmental methods and are minimum ages. They cite a U-Th disequilibrium age for one of the lavas that is consistent with their K-Ar and $^{40}Ar/^{39}Ar$ results. Turrin et al. (1992) argue that samples were discarded from their data set based on $^{37}Ar/^{39}Ar$ ratios, their analytically distinct ages, or both. They suggest the data set is normally distributed with the contaminated samples removed. They argue that there are not influential data points in their regression calculations and they used a regression method that does not permit influential data points. Turrin et al. (1992) argue that ^{39}Ar recoil is not a problem with the Lathrop Wells volcanic samples. They presented new $^{40}Ar/^{39}Ar$ step-heating spectra that give an isochron age of 107±33 ka. Turrin et al. (1992) agree with the comments by Wells et al. (1991) that the angular difference between two field magnetization directions by itself only suggest a minimum age difference between volcanic units. They argue however, that the paleomagnetic data used in combination with other geologic information can be used to estimate "absolute" age differences. They note that problems with the paleomagnetic data at the summit of the main cone are attributable to samples that were rotated by a slope-dependent slumping process. Finally, Turrin et al. (1992) argue that the geochemical and isotopic data for the Lathrop Wells center provide no constraints on the duration and number of events. They suggest the slight variations in the chemical data are consistent with monogenetic volcanism.

The differences in opinion concerning the age and eruptive history of the Lathrop Wells volcanic center are long-standing and probably not resolvable to the mutual satisfaction of all researchers involved in the work. The important point of the controversies is not the existence of the differences of opinion. In fact, different points of view for problems like volcanism are a clear indication that multiple opinions are being considered by the Yucca Mountain Site Characterization Project. What is important is how the different opinions affect assessment of the volcanic risk for the potential Yucca Mountain site.

The differences in opinion concerning the age of the Lathrop Wells center have narrowed to an age range that has no significance in assessment of volcanic risk for the potential Yucca Mountain site. The age of the lava-flow sequences appear well bracketed between 70 and 140 ka. Further resolution of their ages may be beyond the capability of the present geochronology methods. A remaining concern is the age of the main cone of the Lathrop Wells center. An important point of recent agreement is that the cone is probably > 45 ka. This is sufficiently *old that the event is not significant using volume-predictable probability models. Finally, the issue of the monogenetic versus polycyclic eruptive history of the Lathrop Wells center remains unresolved. It can be accommodated reasonably by using both polycyclic and monogenetic models in assessments of the consequences of potential repository disruption. This is the approach that has been used in all recent assessments of volcanic risk for the potential Yucca Mountain site.*

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SECTION VII: VOLCANIC RISK ASSESSMENT FOR THE POTENTIAL YUCCA MOUNTAIN SITE

I. ABSTRACT

The risk of future volcanism for the potential Yucca Mountain site is assessed as a tripartite conditional probability: $Pr_{dr} = Pr(E3 \text{ given } E2,E1)Pr(E2 \text{ given } E1)Pr(E1)$, where E1 denotes the recurrence rate of volcanic events (eruptive or intrusive), E2 denotes the probability of intersection of the area of interest, and E3 is the probability of exceeding regulatory releases. This is expressed mathematically as an exponential equation on the basis of several assumptions: 1) a homogeneous or modified homogeneous Poisson distribution of volcanic events in time and space, 2) forward projection of past patterns of volcanic events for estimation of future events, 3) adequate identification of past volcanic events, and 4) the reliability of interpretations of the past volcanic record. Uncertainty in the probability calculations is accommodated by using alternative interpretations of the eruption models of volcanic centers and the chronology and structural controls of volcanic events.

The strategy for resolution of the issue of volcanism is to determine if the potential Yucca Mountain site should be disqualified on the basis of volcanic risk. If the site is not disqualified, the occurrence probabilities and consequences of future volcanic scenarios are assessed. The evaluated scenarios include ascent of magma and eruption and/or intrusion through the repository, the controlled area or the waste isolation system. The potential for future igneous activity in the Yucca Mountain region is identified as an unfavorable condition. It may be assessed by proving an occurrence probability of < 1 in 10,000 in 10,000 years or proving that the direct or secondary releases associated with eruptive or intrusive activity does not violate the regulated release limits.

The most current data from site characterization studies are used in revised probability calculations. The definition of a volcanic event for the revised calculations is the formation of a new volcanic center. Volcanic centers are inferred to be fed by linear dikes with aspect ratios of 10^{-2} to 10^{-3}; dike widths are known from studies to be 1 to 5 meters. Polycyclic volcanism is evaluated through assessments of E3. These events are not included in E1. A volcanic event may involve the rapid emplacement of 1 to three dikes. The depth of enlargement of dikes into conduit plugs is an important variable in assessing the intrusive effects of basaltic volcanism. Seven volcanic centers of Quaternary age are present in the Yucca Mountain region. Four Pliocene volcanic centers have been identified from field and geophysical studies.

Published values of E1 range from 1.3×10^{-5} to 6.0×10^{-7} events yr^{-1}; the geometric mean of the calculations is 3.5×10^{-6} events yr^{-1}. This geometric mean is biased toward worse case calculations because of the use of conservative assumptions. The repose time between events ranges from 285 to 1.8 Ma with a mean of 590 ± 570 ka. The minimum

observed repose interval during the last 4.6 Ma is equivalent to a recurrence rate of 3.5×10^{-6} events yr^{-1}. Homogeneous Poisson models of event counts through time are calculated for Quaternary events and for events during the interval of the Younger Post-caldera basalt cycle (YPB; 4.6 Ma). Models used for these calculations include minimum event, most likely event, stress-field dike and maximum event. The uncertainty of these calculations cannot be determined because of the small number of events. The uncertainty can be bounded by comparison to recurrence rates of the Lunar Crater and Cima volcanic fields. Recurrence rates must be less than 1.2×10^{-5} events yr^{-1}. The most likely value for the recurrence rate is 3.3×10^{-6} events yr^{-1}. The maximum and minimum values based on event counts are 4×10^{-6} and 1.6×10^{-6} events yr^{-1}, respectively.

Values for E1 can also be calculated using volume-predictable recurrence models that are in the form of a modified homogeneous Poisson models. The magma-output rate is calculated from the variation in volume of erupted magma (dense rock equivalent) through time. This calculation is sensitive to variations rates of in volcanic activity through time. The most difficult attribute to constrain is the volume of a representative volcanic event because the volume of volcanic centers has declined almost three orders of magnitude from the Pliocene to the Quaternary. Reasonable values are obtained using the maximum stress-field dike model for the Quaternary. All other calculations give unrealistically long recurrence intervals. Worst case bounds of the volume-predictable recurrence rate are established using the magma volumes of the Sleeping Butte centers. These rates are 1.4 to 2.8×10^{-6} events yr^{-1}. The most likely value of E1 combining the results of time trend, event counts and volume-predictable models is 2.6×10^{-6} events yr^{-1}.

Calculated values of E2, the disruption ratio, using published studies range from 8×10^{-2} to 1.1×10^{-3}. The geometric mean of published values is 3.6×10^{-3}, and is judged to be skewed toward the worse case. The validity of random disruption models is dependent on whether the potential Yucca Mountain site is located in a structural zone of basaltic volcanic activity. If the site is in a structural zone, the random disruption model can underestimate E2. If it is not in a structural zone, the models overestimate E2. The geometric mean of the random model for disruption is 2.2×10^{-3} for the repository, 3.2×10^{-2} for the controlled area, and > 0.1 for the Yucca Mountain region. Structural models give a wide range of values for the disruption ratio. They are divided into forced intersection models, intersection models, and models of structural bounds. Integration of the results of all models gives a most likely value of 2.5×10^{-3} for repository disruption, 3.6×10^{-2} for intersection of the controlled area, and 0.3 for intersection of the Yucca Mountain region.

The conditional probabilities of event occurrence and intersection of the area of interest (Pr = Pr(E2 given E1)Pr(E1)) are 6.5×10^{-9} events yr^{-1} for the repository, 9.4×10^{-8} events yr^{-1} for the controlled area, and 8.8×10^{-7} events yr^{-1} for the Yucca Mountain region. These are shifted slightly toward worse case values because the recurrence rate attribute has not been modified for structural models that exclude volcanic events. The most likely value of the occurrence probability of repository disruption is less than 1 in 10,000 in 10,000 years and > 1 in 10,000 in 10,000 years for disruption of the controlled area and the Yucca Mountain region. The occurrence probability of repository disruption is low because of the combined small recurrence rates and the requirement that a future event must intersect a relatively small area.

II. INTRODUCTION

Section VII of the Volcanism Status Report presents the status of volcanic risk assessment for the potential Yucca Mountain site current to the preparation of this report. The assessment builds upon past studies (Crowe and Carr 1982; Crowe et al. 1983; Crowe 1986; Crowe et al. 1989; Crowe and Perry 1989; Smith et al. 1990; Ho et al. 1991; Crowe et al. 1992; and Ho 1992) and incorporates the most recent results of information obtained from site characterization studies. The primary emphasis of past volcanism studies was to evaluate the potential disqualification of the Yucca Mountain site because of the risk of future volcanic activity. These studies attempted to bound the risk of volcanism and focused on identifying a range of *permissive* values that could be assigned to attributes of the probabilistic assessment. If there was uncertainty involving assignment of data values, conservative values or values that would *not* underestimate risk were assigned (Crowe and Carr 1980; Crowe et al. 1982; 1992). In this report, we build on past studies by initiating the task of assessing attribute values for probabilistic risk assessment that are the most likely values based on alternative models of the geologic record of basaltic volcanism. Assignment of most likely values avoids the addition of non-systematic bias toward worse case calculations that is unavoidable when conservative attribute values are used. This bias results from the absence of a standard definition of conservative in the assignment of probability values. The choice of what constitutes "reasonable" levels of conservatism in assigning attribute values varies dramatically with the perspective of the assignee. This applies especially to an issue like assessing risk for a potential site for storage of high-level radioactive waste. The political and scientific sensitivities of the issue can lead to dramatic differences in probabilistic assessments for technical issues that could potentially disqualify the site. In contrast, assigning mean or most likely values for probability attributes is better defined.

There are two approaches that can be used to assess the hazards of volcanism for the Yucca Mountain site (Crowe 1986). The distinctions between the terms *hazard* and *risk* for volcanism studies are used following Peterson (1986). Hazard refers to the perception or recognition of a threat from volcanic activity; risk denotes the attempt to quantify or define the nature of the hazard. The traditional and most common approach for defining volcanic hazards is to study the past record of volcanism at and around the site of interest. These studies employ standard geological methods (field mapping, geochronology, petrology, geochemistry and geophysics). Information from the conventional studies is used to make subjective judgments about the hazards of future volcanism. This generally involves identifying the eruptive styles of past volcanic events, the area affected by past volcanic activity and the hazards represented by similar future events. A general but not universal assumption of these studies is that future volcanic activity will follow the same patterns as past volcanic activity. This approach has utility for historically active volcanoes where recent growth in world population has lead increasingly to occupation of zones surrounding the flanks of many active volcanoes. There is an element of predictability to these types of hazards assessment because eruptive activity from many historically active volcanic systems develops in response to the formation of a high-level magma chamber. The continued existence and the periodic replenishment of the chamber with new pulses of magma results in a high chance that future volcanic activity will follow the same vent areas and eruptive patterns of past volcanic activity. The time perspective of volcanic hazard studies is months, years to decades at most. The assessments are concerned with near-term threats to life and property and are often carried out in a crisis situation.

A conventional approach to volcanic hazard studies is not easily applied to the issue of defining risk for the long-term isolation of high-level radioactive waste. Here the task of defining the nature of a future volcanic hazard is straightforward. It is the simple recognition that future volcanic activity could disrupt a buried repository and spread radionuclides to the accessible environment. The more critical question is how can the risk of the perceived volcanic hazard be quantified? If the risk is high, the site is unsuitable for storage of high-level radioactive waste. Equally, if the risk of volcanism is low, it should not prevent the site from receiving careful consideration for storage of radioactive waste.

Past basaltic volcanic activity in the Yucca Mountain region was characterized by the intermittent formation of spatially isolated, small volume basalt centers of Pliocene and Quaternary age (Crowe 1986; Crowe and Perry 1989; Crowe 1990). The geochemistry of these lavas almost certainly is inconsistent with storage of magma in a shallow crustal magma chamber (see Section IV, this report). The basalts are aphyric and probably ascended rapidly from a depth below the plagioclase stability field (Perry and Crowe 1992). Magma formed as spatially and temporally separate pulses and followed unique pathways to the surface. The location of subsequent volcanic events bears no simple relation to the location of preceding volcanic activity. This type of volcanic activity lacks the spatial predictability of repeated volcanic eruptions of a stratavolcano that is fed from a shallow and long-lived magma chamber. The risk that must be defined for the potential Yucca Mountain site is the likelihood that a new volcanic center will erupt through or near the potential repository. The key questions are how often and where do new volcanoes form?

A preferred strategy to attempt to quantify the risk of future volcanism is to use a probabilistic approach; it has several distinct advantages over standard volcanic hazard studies. First, a probabilistic approach attempts to quantify a problem and provide a more easily defined basis for judging acceptable or unacceptable risks. Second, a probabilistic approach brings a structured formalism to the problem. This allows a complex issue like predicting the risk of future volcanism to be subdivided into logical sections. Precise answers cannot always be given for each section of a probabilistic approach, but the probabilities can generally be bounded and decisions can be made whether the bounding data are acceptable or unacceptable. Third, an often unappreciated advantage of a probabilistic approach is flexibility. The importance of alternative models or different data interpretations can be assessed by examining how they change the probability distribution. Volcanic studies for the potential Yucca Mountain site require working with a small data set. The limitations of the date set make it likely, if not expected, that there will be different views of the nature and risk of future volcanic activity. However, the different views become important from a risk perspective only if they change the probability distribution. Fourth, probabilistic studies are iterative. Once formulated, they can be refined readily with the addition of new data from site characterization studies. In fact, the test for judging the importance of new site characterization data is a determination of whether the new data change the probability distribution. Finally, the most important advantage of a probabilistic approach is it allows the data to be compared with the regulatory requirements for licensing of a repository. The resulting data need not be highly precise; it is not expected to be so because of the limited record of Quaternary volcanism in the Yucca Mountain region.

There are three parts to this section of the Volcanism Status Report. First, the probability models and the logic of how the probability models are applied to assessing the risk of volcanism for the Yucca Mountain site are described. Much of the confusion in assessing volcanic risk for the potential Yucca Mountain site results from a lack of consistency in applying a probabilistic approach and stating clearly the assumptions used for that assessment. Second, we summarize, mostly in compiled probability tables, the probability of future eruptive and intrusive magmatic events in the Yucca Mountain region. We define the data set used for the probabilistic assessment, the assumptions used in the data set and the underlying physical models of the processes of basaltic magmatism. These data are applied to estimations of revised values of the probability of magmatic disruption of a potential repository located beneath Yucca Mountain. We attempt to identify most likely, maximum, and minimum values of the distribution of probability attributes. This section of the volcanism status report constitutes the formal initiation of the systematic process of probabilistic studies described in Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository.

There is always the possibility of new discoveries that may change the results of the assessment of the risk of volcanism. Science advances through a process of discovery. The fundamental processes of developing a hypothesis and discovering new scientific insights are implemented by questioning and attempting to disprove existing data. The basic data and approach used for assessing the risk of volcanism for the potential Yucca Mountain site were described as early as 1980 (Crowe and Carr 1980) and formalized in 1982 (Crowe et al. 1982). Despite review, evaluations, and questioning of these assessments for more than a decade, the evaluations have not changed significantly. It is time to make judgments about accepting or rejecting the soundness of the logic used, the completeness of the supporting data, and the judgments made about the potential Yucca Mountain site with respect to the risk of future volcanic processes.

III. PROBABILITY MODEL

The probability of magmatic disruption of a repository and release of radionuclides to the accessible environment or waste isolation system by an eruption (Pr_{dr}) is defined as a tripartite probability:

$$Pr_{dr} = Pr(E3 \text{ given } E2,E1)Pr(E2 \text{ given } E1)Pr(E1),$$

where *E1* denotes the recurrence rate of volcanic events in the Yucca Mountain region, *E2* denotes the probability that the future magmatic event intersects an area of interest, and *E3* denotes the probability that magmatic disruption leads to rapid release of radionuclides to the accessible environment in quantities that exceed the regulatory requirements. This probability can be expressed mathematically as (Crowe et al. 1982):

$$\Pr[\text{no eruptive event before time } t] = exp^{(-\lambda pr)},$$

where λ is the recurrence rate of volcanic events, p is the probability that an event is disruptive, and r is the probability that the radionuclide releases to the accessible environment exceed the regulatory requirements for licensing a repository. The λ is defined as the rate of formation of new volcanic centers or magmatic intrusions. The p is defined as a/A where a is the area of concern (repository, controlled area or Yucca Mountain region) and A is the area of the established volcanic rate or λ.

The probability model assumes a homogeneous or modified homogeneous Poisson distribution of the volcanic events through time (Crowe et al. 1982; Crowe 1986). Crowe et al. (1992) reviewed recurrence models for volcanic events and discussed the rationale for choosing a simple Poisson model. Briefly, the model is conceptually simple, assumptions using this model are well defined and potential errors can be constrained. The Poisson model is particularly appropriate and even conservative for the case of the Yucca Mountain region where multiple lines of evidence indicate volcanism is waning (Vaniman and Crowe 1981; Crowe et al. 1982; Crowe et al. 1992a, Perry and Crowe 1992). The homogeneous Poisson model does not introduce unwarranted complexity that cannot be justified by the time-distribution properties of a small data set. Moreover, by virtue of the small data set, calculations incorporating other distribution models do not yield results that differ significantly (for example, Ho et al. 1991; Ho 1992). Finally, there is ample justification in both the seismic and volcanological literatures for application of a simple Poisson model (Crowe et al. 1992).

Several assumptions are required to apply a probabilistic approach. First, the past record of basaltic volcanic activity in the Yucca Mountain region is judged to be the most reliable indicator of the rates and nature of future volcanic events. This assumption is supported by the consistency of the record of volcanism in the region for the last 10 Ma. All post-late Miocene volcanic centers formed from the eruption of small volumes ($< 1\ km^3$) of basaltic magma (Crowe 1990). The activity formed spatially isolated centers comprising scoria and spatter cones, fissure systems, and associated aa lava flows.

Second, we assume there has been a sufficiently detailed study of the Yucca Mountain region to identify all Quaternary volcanic centers. This assumption is based on several lines of evidence. Quaternary basaltic volcanic centers are conspicuous and relatively stable geomorphic landforms in arid regions of the southwest United States. They retain parts of their primary topography that was constructed by volcanic eruptions over long periods. The centers can be identified through simple visual inspection of aerial photographs and even satellite photographs. Detailed geologic mapping has been completed of the areas near and surrounding the potential Yucca Mountain site. The presence and location of Quaternary volcanic centers in the region have long been recognized, and their identifications have remained unchanged for several decades. Third, detailed drape aeromagnetic surveys were completed for the Yucca Mountain region (Kane and Bracken 1983; Langenhelm et al. 1991). Basaltic volcanic rocks have high magnetic susceptibility and are identified easily among the Paleozoic rocks and the alluvial fill of the basins around Yucca Mountain. Surface Pliocene and Quaternary volcanic centers form prominent anomalies on aeromagnetic data (Crowe and Carr 1980; Kane and Bracken 1983; Crowe et al. 1986). Any subsurface basaltic rocks of significant volume that are present above depths of several kilometers should be identifiable from aeromagnetic data.

Finally, we assume that the observations and interpretations of the geologic record are reliable, an assumption that is difficult to quantify. Here there are two sources of uncertainty. First, the primary method for dating of Quaternary basaltic volcanic rocks is the K-Ar method. The method becomes increasing less precise with decreasing age of the rocks. However, this problem can be constrained by using multiple chronology methods (Crowe et al. 1992b). Additionally, we assign multiple models for the age of volcanic events where there is uncertainty in age determinations. The homogeneous Poisson model requires only the recognition of Quaternary volcanic centers. Second, the reliability of interpreting the record of basaltic volcanism decreases with increasing age of the volcanic centers. This is because older centers are progressively more modified and parts of the record of volcanic events are removed or covered. To reduce this uncertainty, we have attempted to reconstruct original volumes, have drilled exploratory holes, and used aeromagnetic and ground magnetic data to estimate the areal extent of buried basalt units (Crowe et al. 1983). Additionally, we accommodate this uncertainty by varying the assumptions of the eruptive models and the volume determinations for the probability calculations. The volume-predictable, modified-homogeneous Poisson model uses the age and erupted magma volumes as variables to calculate magma output rates. Because the volume of erupted magma has declined by several orders of magnitude through time in the Yucca Mountain region, the volume-predictable model is less affected by the uncertainty of the determinations in the ages or eruptive volumes of the centers. Finally, we assume that both competing eruptive models for the youngest Quaternary volcanic centers (monogenetic and polycyclic) are valid and apply to the Pliocene and Quaternary volcanic centers. The two models are not different for establishing the rate of formation of volcanic events but are different in assessing the consequences of volcanic activity. By evaluating the effects of both models, we are assured that the complete ranges of potential effects of repository disruption by magmatic activity are fully considered .

IV. STRATEGY FOR RESOLUTION OF THE VOLCANISM ISSUE

There are two fundamental questions that must be answered to determine if volcanism is a significant issue with respect to the licensing of a potential repository at Yucca Mountain. These are:

1. Should the potential Yucca Mountain site be disqualified solely on the basis of the

risk of future volcanism?

2. What are the probability and consequences of a range of future volcanic scenarios that could affect either the waste isolation system of a repository or the repository itself?

Assessment of both of these questions requires information from two classes of scenarios. The first is what is referred to as the eruption scenario. This represents a category of direct releases to the accessible environment from a volcanic eruption. Volcanism processes are an abrupt and potentially catastrophic threat to the isolation system of a repository. Should magma intersect a repository and erupt at the surface, there is the potential for immediate release of radionuclides to the accessible environment. This scenario requires virtual intersection of the potential repository because of the small geometric area of subsurface dikes that feed a surface eruption. Establishing the occurrence probability of magmatic disruption of the repository is a primary emphasis of this report.

The second category of volcanism scenarios is the disruption or modification of the repository or isolation system from the effects of intrusions accompanied by or not accompanied by an eruption. Here emplacement of magma into or through the controlled area or immediate vicinity of the repository could result in changes in the long term performance of the natural barriers of a waste system to isolate radioactive waste. This is a more complicated problem than a determination of eruptive effects. It requires identifying a range of secondary or coupled processes caused by the intrusion of magma into or near a repository and projecting the effects of those changes over the isolation period of a repository. The probability of an intrusive event is defined somewhat differently than the eruptive scenario because of a more complicated subsurface geometry and affected area of an intrusive event. The scenarios of this second category will be evaluated through a combination of estimating their occurrence probabilities and the consequences of their induced effects. This report discusses the occurrence probabilities of magmatic events.

The logic of assessing the volcanism issue is illustrated on Fig. 7.1. Volcanism studies have several decision points. These decision points determine whether the scenario categories can be eliminated on the basis of a low occurrence probability or whether the consequences or releases must be assessed to determine the suitability of the potential site with respect to volcanic processes (Fig. 7.1). The primary basis for the decision points is determined by an assessment of whether the initiating volcanic events can or cannot be shown to have a probability of occurrence of less than 1 in 10,000 in 10,000 years (10^{-8} yr^{-1}).

If the events have an occurrence probability of < 10^{-8} yr^{-1}, they will be judged not to be an issue that could lead to disqualification of the potential Yucca Mountain site *(Note: the judgment of non-disqualification does not necessarily eliminate the events from consideration for their contribution to the cumulative releases from the waste isolation system)*. If the events have an occurrence probability of > 10^{-8} yr^{-1}, a two-step logic will be used to assess the significance of the events. First, the occurrence probability will be evaluated that the event will occur and will result in immediate releases to the accessible environment which exceed regulatory requirements. If the occurrence probability of exceeding allowable releases is <

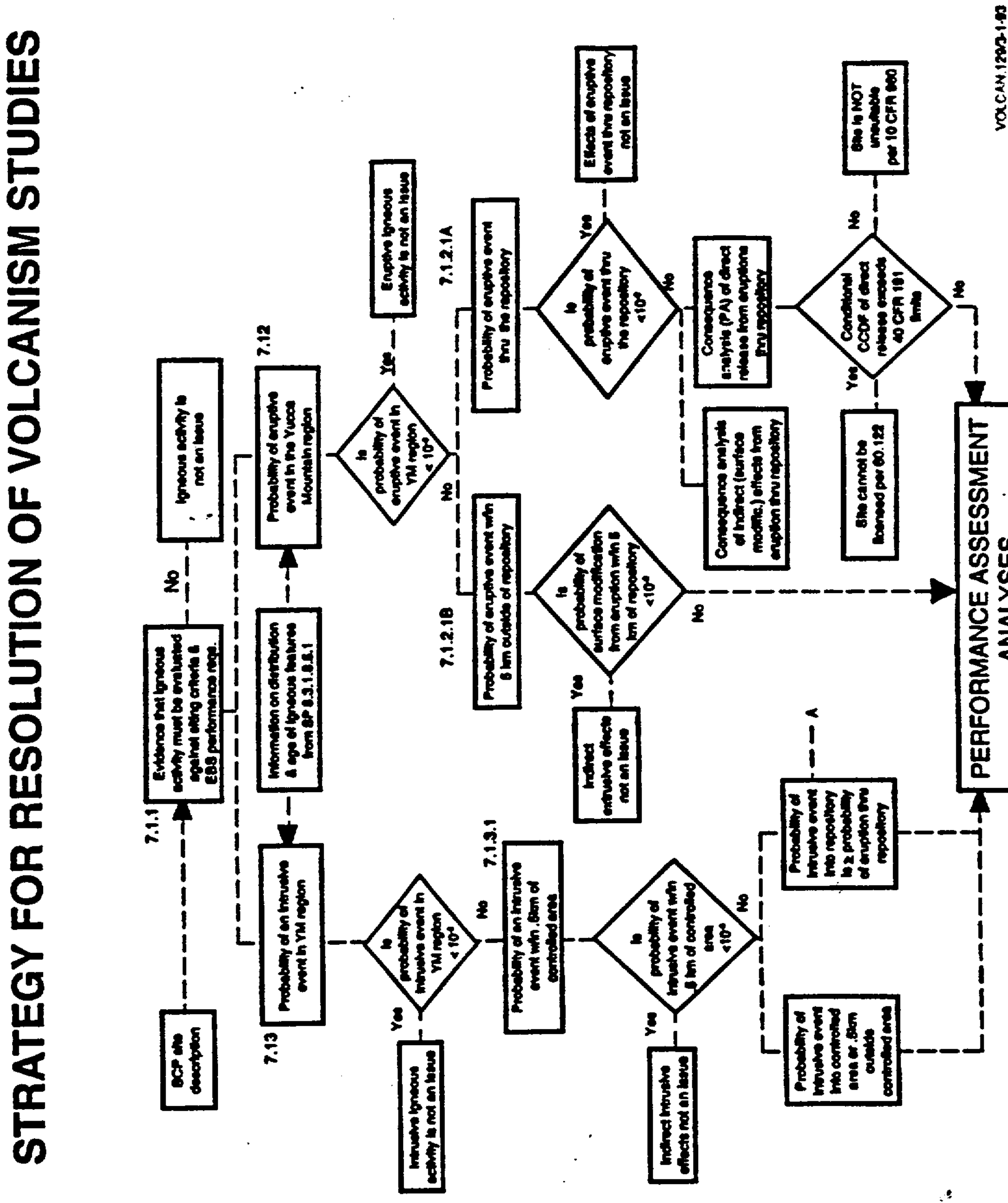


Fig. 7.1 Diagram of resolution strategy for volcanism studies for the Yucca Mountain Site Characterization Project.

10^{-8} yr^{-1}, the event will be judged **not** to be an issue that could lead to disqualification of the potential Yucca Mountain site. If the occurrence probability of exceeding allowable releases is > 10^{-8} yr^{-1}, detailed studies will be undertaken to establish the contribution of releases to the cumulative releases from the waste isolation system. This second component of studies, quantifying magmatic related radiological releases, is **not the subject of this volcanism report**. Volcanism studies for Study Plan 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on the Potential Repository provide the information needed to identify secondary effects of magmatic activity on the waste isolation system. The calculation of the radiological releases from secondary or coupled effects of magmatic activity will be undertaken as part of performance assessment studies.

There are several key questions that must be answered to assess the risk of future volcanism. The first is whether igneous activity is a concern for the potential Yucca Mountain site (7.1.1)? We have established already that the presence of five Quaternary volcanic centers in the vicinity of Yucca Mountain is a potentially adverse condition and requires assessment as a part of site characterization activities (DOE 1986; 1988). The second question is what is the probability of a future igneous event during the 10,000-yr isolation period of a repository for disposal of high-level waste? This is divided into two questions. What is the probability of a volcanic eruption (7.1.2) and what is the probability of an intrusive igneous activity (7.1.3)? These probabilities are dependent because each volcanic eruption must be accompanied by an intrusive event but all intrusive events do not have to be associated with an eruptive event. Logic requires therefore that Pr_i is greater than or equal to Pr_v, where Pr_i is the probability of an intrusive event and Pr_v is the probability of a volcanic event. Assessment of current site data has not revealed any evidence in the Yucca Mountain region that an intrusive event has occurred at or near the depths of a potential repository without an accompanying volcanic eruption. Basalt magmas are likely to be above the depth of volatile saturation at repository depths. The volume expansion from volatile release provides a strong driving force to produce an eruption. Thus understanding of magma processes and current site data suggest that $Pr_i = Pr_v$. Nonetheless, we will continue to assess data through ongoing studies (Study Plan 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository) to determine if there are any conditions where Pr_i could be > Pr_v. For either case, existing data (Crowe and Carr 1980; Crowe 1986; Crowe et al. 1982; 1988; Crowe and Perry 1989; Ho et al. 1991; Ho 1992; and Crowe et al. 1992) show that the probability of a volcanic event **in the Yucca Mountain region** is > than 10^{-8} yr^{-1}. Therefore the effects of these events must be assessed for the potential Yucca Mountain site (*Note: Because $Pr_i = Pr_v$, the remaining discussion will only mention Pr_v recognizing that the described assessments apply to both events*).

We have established and accept the probability of a future basaltic volcanic eruption somewhere in the Yucca Mountain region is > 10^{-8} yr^{-1}. The next important question is where does the event occur (7.1.3.1, 7.1.2.1a, and 7.1.2.1b)? There are three options. The volcanic or intrusive event could occur in or through: 1) the Yucca Mountain region, 2) the controlled area of a repository, and 3) the repository.

The likelihood of the first option, a future volcanic or intrusive event in the Yucca Mountain region is:

$$Pr_o = 1 - exp^{(-\lambda p)}$$

where Pr_o is the probability of intrusion or eruption outside of the repository and the controlled area. The attribute p is significant for the equation only for events close to the boundary of the controlled area. This attribute drops out of the equation as the area of the possible event gets large because $a/A \approx 1$ as a approaches A. For this case, the annual probability of a volcanic event occurring in the Yucca Mountain region approaches λ, the recurrence rate of volcanic events. We have already established that λ is $> 10^{-8}$ yr^{-1}. Therefore Pr_o is $> 10^{-8}$ yr^{-1} for many cases of this option of probability estimations. The significance of volcanic eruptions or magmatic intrusions in the Yucca Mountain region must be assessed through evaluation of secondary radiological releases. While this evaluation has not been completed, an obvious relationship is that the r_s, the probability of secondary releases exceeding the regulatory requirements associated with a volcanic event or intrusion in the Yucca Mountain region, decreases with increasing distance of the event from the repository. At some distance from the repository, the likelihood of secondary effects resulting in secondary releases that exceed the regulatory requirements becomes very small and approaches 0. For these cases, the probability of an eruptive or intrusive event occurring outside the controlled area *and* resulting in secondary releases that exceed the regulatory requirements is $<< 10^{-8}$ yr^{-1}. One of the goals of the studies of the secondary effects of magmatic processes on the waste isolation system is to identify the required distances and directions where this relationship is satisfied.

The second option is that a future volcanic event or intrusion can occur within the controlled area. Here the likelihood of the event is:

$$Pr_{Ca} = 1 - exp^{(-\lambda p)}$$

where Pr_{Ca} is the probability of intrusion or eruption through the controlled area, and p is the a/A where a is the controlled area. The controlled area is larger than the area of the repository by slightly greater than a factor of ten. Therefore, it is likely (see discussion of values of the disruption ratio in B. Revised Probability Calculations) that $Pr_{Ca} > 10^{-8}$ yr^{-1} and this case will require an evaluation of the secondary effects of magmatic activity.

The third option is that a future volcanic event penetrates the repository (7.1.3.3). The likelihood of a volcanic event penetrating the repository is:

$$Pr_d = 1 - exp^{(-\lambda p)}$$

where Pr_d is the probability of intrusion or eruption through the repository, and p is a/A where a is equal to the area of the repository and A is the area of the volcanic recurrence rate. If the risk of this event exceeds some unspecified value, the site should be disqualified because of the risk of volcanism (8.1.3.4a). We suggest a realistic value could be 10^{-6} yr^{-1}. Studies to date indicate it is physically implausible for Pr_d to be less than 10^{-6} yr^{-1} (Crowe et al. 1982; 1992b; Ho 1991; 1992; Ho et al. 1991). For this to be true would require either a major change in λ, or the discovery of some unrecognized structural control of the site of future volcanism that directly focuses future volcanic events at the potential Yucca Mountain site. Alternatively the site would be disqualified if the radiological releases associated with magmatic disruption of a repository exceed the regulatory requirements.

If Pr_d is $< 10^{-8}$ yr^{-1}, the direct effects of repository disruption and eruption are not an important issue. Volcanism studies of the disqualification of the potential Yucca Mountain site from an eruption through a repository would be ended. This is a distinct possibility based on current site data. It is a major consideration of this volcanism status report. An important question for assessing this relationship is what constitutes an acceptable value of the probability of magmatic disruption of the repository. Is it the most likely value? Is it a confidence interval about the most likely value? Is it a determined percentage on a cumulative probability distribution?

If Pr_d is $> 10^{-8}$ yr^{-1}, assessments will be conducted of the probability of direct releases of radioactive waste to the assessable environment by a volcanic eruption. This relationship is modeled as:

$$Pr_{dr} = 1 - exp^{(-\lambda pr)}$$

where Pr_{dr} is the probability of disqualification of the repository from future volcanic eruptions and r is the probability that volcanic eruptions release radionuclides to the accessible environment in quantities that exceed the regulatory requirements. This relationship does not apply to the probability of volcanic intrusion because this event does not result in direct releases of radionuclides to the accessible environment. If Pr_{dt} is $< 10^{-8}$ yr^{-1}, we will conclude studies of the eruptive scenarios for volcanism. This is considered a likely possibility for several reasons. First the probability of magmatic disruption of the repository [Pr(E2 given E1)Pr(E1)] is $< 10^{-8}$ yr-1 (see discussion below). Second, the repository will be located about 300 meters below the surface. Mildly explosive basaltic eruptions (Hawaiian and Strombolian) do not carry country rock debris from depth (> 200 m) to the surface (Crowe et al. 1983b; Valentine et al. 1992). Waste will be contained in metal cladding that does not melt at magmatic temperatures. The density of the waste and waste package exceeds the density of magma. The density of the waste package is greater than the density of basalt melt (2.8 gcm^{-3}). It would be very difficult for magma to physically lift and transport a waste package to the surface. Therefore the probability of volcanic releases exceeding regulatory limits is < 1. If it is smaller than 1 by more than an order of magnitude, then Pt_{dt} is $<< 10^{-8}$ yr^{-1}.

If $Pr_{dr} > 10^{-8}$ yr^{-1}, we will determine if the radiological releases from a volcanic event exceed the regulatory requirements. If that is the case, the recommendation will be made that the site be disqualified because of the risk of the eruption scenario for volcanism. If that is not the case, the radiological releases from a volcanic event will be included as part of assessments of the cumulative releases from the waste isolation system over a 10,000 yr period.

A. Volcanic Record: Assumptions and Physical Models

The most current data from site characterization studies are used to make revised calculations of the probability of magmatic disruption of the potential Yucca Mountain site. Data on the distribution and chronology of Pliocene and Quaternary volcanic centers are taken from Crowe (1990), Wells et al. (1990), Smith et al. (1990); Turrin et al. (1991; 1992), Crowe et al. (1992a; 1992b). Data for the volume of volcanic units is modified from Crowe et al. (1983a) using the revised geologic mapping of Crowe et al. (1988; 1992b) and Crowe and Perry (1991).

The definition of a volcanic event is repeated for emphasis. This attribute of the probability formula has been used differently by different workers and has caused considerable confusion in calculating the bounds of the recurrence of volcanic events. A volcanic event for probability assessment is defined as the formation of a new volcanic center. It is the birth of a new volcanic center that has spatial variability and therefore represents a finite probability of forming in or near a potential repository. The formation of satellite vents or polycyclic events at an existing center does not represent a risk of an eruption at a new location. Therefore, these events are considered in assessing the consequences of volcanic activity. The development of a new volcanic center is the result of the ascent, in dike form, of a pulse of basaltic magma that is erupted. That pulse must be both temporally and spatially distinct. It must be temporally distinct because of the thermal constraints on emplacement of magma in the shallow crust (Delaney and Pollard 1982; Delaney 1987; Bruce and Hubbert 1990). Loss of heat by magma to the country rock results in a rapid increase in magma viscosity, which decreases the ability of the lava to flow, promoting rapid solidification. Any number of vents can form during eruption of a single pulse of basalt magma. However, it is the upwelling and eruption of magma that represents a unique breaching event from the perspective of a buried repository (300 m below the surface).

The spatial identity of volcanic events can be bounded by the dimensions of feeder dikes. Dikes typically have aspect ratios ranging from 10^{-2} to 10^{-3} and widths of 1 to 5 meters. We consider any volcanic vent or center that is over 5 km distance from another center to require a separate feeder dike and to be a separate volcanic event. Any vents spaced closer than 5 km can represent single events unless field or geochronology data suggest the vents formed from time-separate events.

Polycyclic volcanism (Crowe et al. 1989; Wells et al. 1990; Perry and Crowe 1992) represents a special case of volcanic events. A polycyclic event is defined as an event that occurs at a preexisting volcanic center where the time between events exceeds the resident time of basaltic magma in the shallow crust. By definition, polycyclic events represent eruptions of discrete pulses of magma. Dike cooling times in the shallow crust assuming dike widths of 5 meters or less or no more than 10 years (Hubbert and Bruce 1990; Lister and Kerr 1991). Thus a polycyclic event is regarded as the recurrence of an eruptive event at an existing center where there has been no activity for a minimum of several decades. The existence and significance of polycyclic events are still under investigation and have been the subject of controversy (Crowe et al. 1989; Wells et al. 1990; Whitney and Shroba 1991; Champion 1991; Turrin et al. 1991; 1992; Crowe et al. 1992b). However, using this definition of polycyclic events (time-separation of ≥ 10 yrs), there is agreement among all workers that the Lathrop Wells volcanic center is polycyclic. Currently, the only uncertainty remaining is how common polycyclic events are at the basalt centers of the Yucca Mountain region, and the temporal spacing between polycyclic events.

The concept of polycyclic events have been mis-applied at volcanic centers of the Yucca Mountain region by Ho et al. (1991). They counted possible polycyclic events in estimation of E1 (Ho et al. 1991; p. 54). This is not consistent with the requirement of independence of the attributes of the tripartite probability and their usage results in higher values for E1. A polycyclic event viewed probabilistically means that given a previous event which forms a volcanic center, there is an increased likelihood of another event forming at the same volcanic center. The probability of a polycyclic event should be added to the λ, the recurrence rate of volcanic events, because the events are not independent. Ho (1992), in his most recent paper, distinguished correctly the difference between volcanic events and polycyclic events in calculating the probability of magmatic disruption of a repository. A determination of the importance of polycyclic events is evaluated in studies of E3, the probability of releases of radioactive waste at the surface. A polycyclic event based on this usage would increase the area of magma-waste contact and the likelihood of transporting waste to the surface.

We assume a volcanic event consists of the rapid emplacement of 1 to 3 dikes that feed surface volcanic eruptions. More than one dike is probably required because the geometry of vent zones and fissures at volcanic centers cannot easily be satisfied by a single dike. Figure 7.2 is a schematic block diagram of a typical dike-fed, eruptive event. The flow of magma moves upward initially along a near-vertical, sheetlike dike. As an eruption proceeds, magma flow is concentrated in a conduit that becomes the predominant eruptive site or vent. From the perspective of the repository, the key variables are the depth of formation of multiple dikes and the depth of channeling of flow into conduits. Events occurring above the repository have limited effect. Events occurring below the repository can increase the geometric area of waste-magma contact and the area affected by magmatic intrusion. Scenarios of magma-waste interaction are shown schematically in Fig. 7.3. An eruption may be fed from a single dike system with the main conduit formed above the repository (monogenetic eruption model). Satellite vents are probably fed from offshoots of the main dike system. Pulsating magma flow and variations in the depth of magma fragmentation can lead to enlargement and deepening of the conduit associated with the formation of radial dikes. While these events appear to occur near the surface, they may propagate under some circumstances to repository depths. Important variables in controlling the geometry of basalt feeder systems are the depths of volatile exsolution, volatile concentration and magma fragmentation. Polycyclic events require multiple penetrations of magma with separate feeder systems (Fig. 7.3). In some cases, sill-like intrusions may form as offshoots at depth from feeder dikes (Crowe et al. 1983; Valentine et al. 1992) with or without eruptions (Fig. 7.3). Studies to date have not identified an intrusive complex that did *not* erupt. However, studies of basalt intrusions are limited to sites with deep erosional

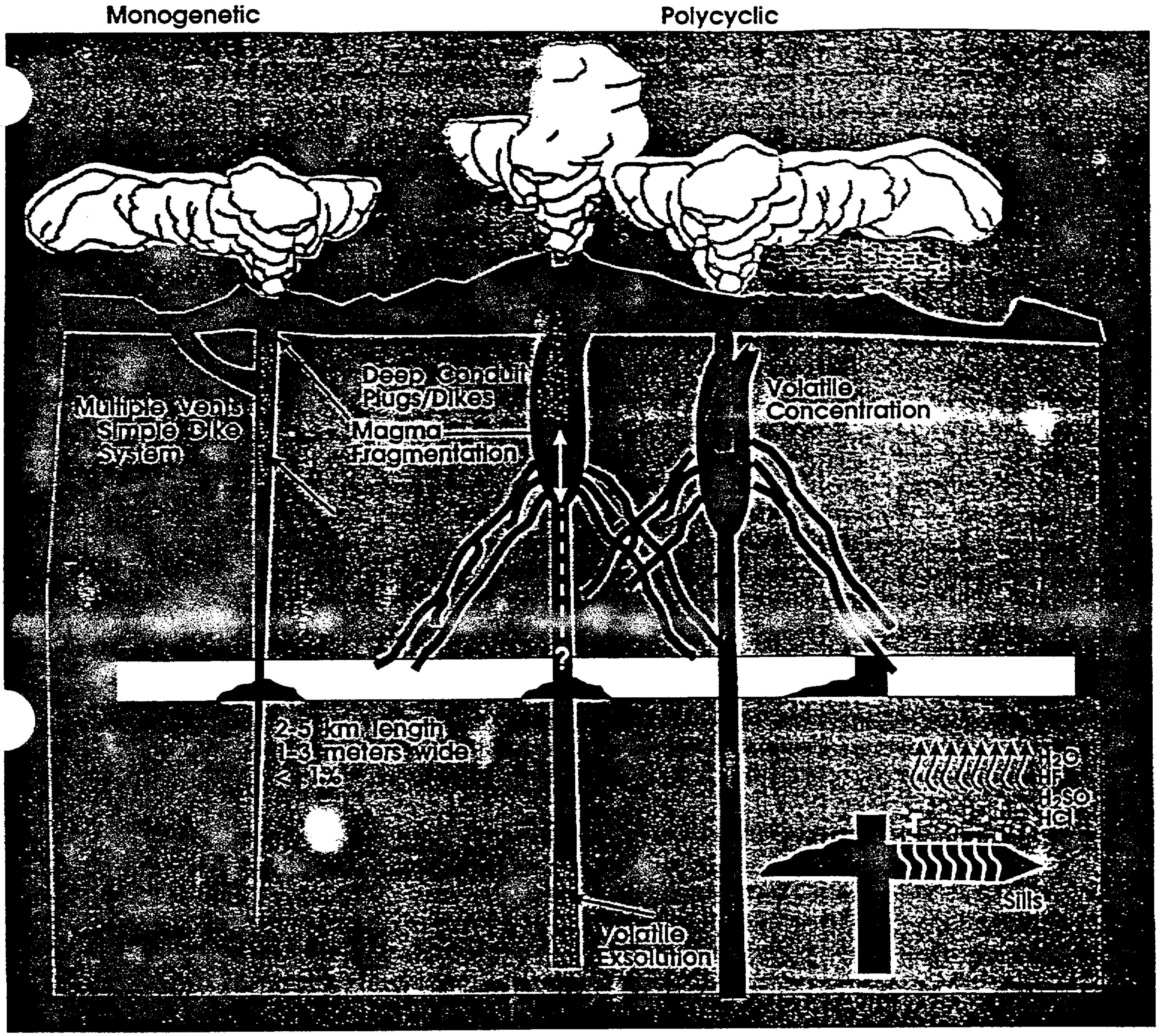


Fig. 7.3 Schematic cross-section of volcanic scenarios associated with intrusive and eruptive events. A simple monogenetic eruption is associated with penetration of the repository at the point of intersection for a feeder dike. Typical dike lengths are 2-5 km with widths of 1-3 meters. Polycylcic eruptive events are fed by multiple, time-separate eruptions and result in multiple intersection sites of the repository. Important processes for both monogenetic and polycyclic events are the depth of volatile exsolution, the depth of volatile concentration, and the depth of magma fragmentation. Intrusions may form in association with or independent of monogenetic or polycyclic eruptions. No intrusions without eruptions have been observed in the volcanic record of the Yucca Mountain region.

Basalt Feeder Dike Model

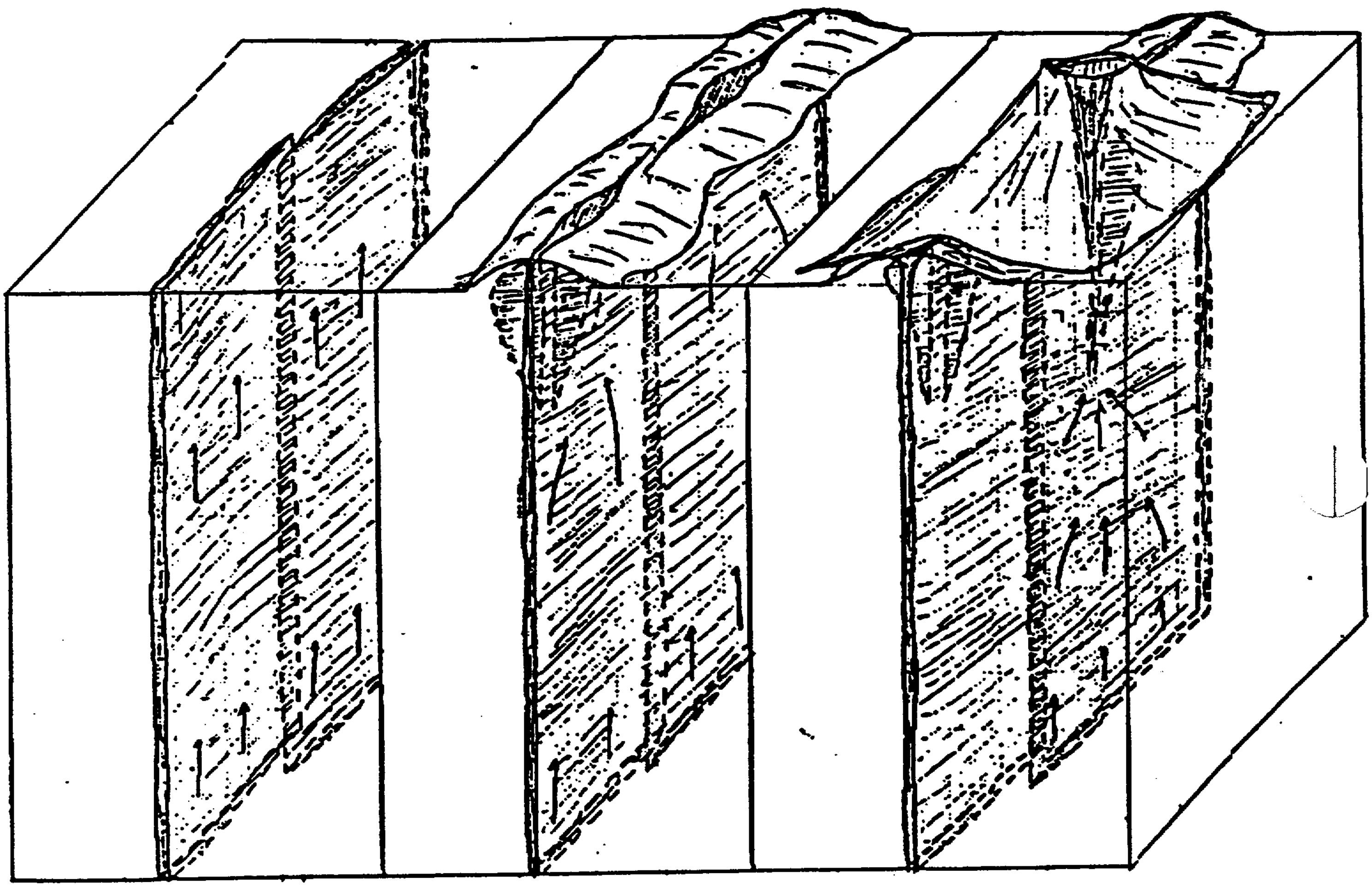


Fig. 7.2 Cross-section of the geometry of dike feeder systems during fissure-fed and Strombolian volcanic eruptions.

dissection; natural exposures may be insufficient to provide confidence in estimations of the occurrence frequency of intrusions.

We use the following data set for probability calculations. Quaternary events in the Yucca Mountain region include (oldest to youngest):

1. 1.1 Ma Centers: **Quaternary basalt of Crater Flat.** These are treated as four individual centers formed by one to four volcanic events (one model assumes five events for the Quaternary basalt of Crater Flat but this model is regarded as unsupported). The Red Cone and Black Cones centers are closely spaced and could be treated as a single event. However petrologic data suggest they are probably separate events (Vaniman and Crowe 1981; Perry and Crowe 1992). The close spacing and petrologic similarity of the Little Cone centers supports treating these cones as a single event. The age of each center of the Quaternary basalt of Crater Flat is assumed to be about 1.1 Ma.

2. 0.38 Ma Centers: **Basalt of Sleeping Butte.** These are treated as two individual centers formed either in one or two events at about 380 Ma (Crowe and Perry 1991; Champion 1991; Turrin 1992).

3. 0.1 Ma Center: **Lathrop Wells center.** This is treated as a single event center formed in two pulses of activity, one at about 100 to 140 ka the other at > 40 ka. The existence of a potential young volcanic event (10 ka) at the center remains controversial but possible. An event time of 100 ka is assumed for calculations of the repose intervals. An event time of 40 ka is used for the time since the last volcanic event, since this is the youngest large volume volcanic event.

Pliocene volcanic events in the Yucca Mountain region include (oldest to youngest):

1. 4.6 Ma Centers: **Basalt of the Thirsty Mesa.** This is a lava mesa formed from three coalesced vents. It is treated as one or three events with an age of 4.6 Ma (Champion 1992).

2. 4.4 Ma Center: **Basalt of the Amargosa Valley.** This volcanic event is represented by the aeromagnetic anomaly located a few kilometers south of the town of Amargosa Valley. The shape and size of the anomaly suggest it can be treated as one volcanic event.

3. 3.7 Ma Centers. **Basalt of southeast Crater Flat.** This Pliocene unit consists of five centers representing one to five events (Vaniman and Crowe 1981; Crowe et al. 1983b; Champion 1991). The age of the centers is assumed to be well dated at 3.7 Ma.

4. 2.9 Ma Center. **Basalt of Buckboard Mesa.** This consists of one center or event forming a lava mesa and small cone in the moat zone of the Timber Mountain caldera (Crowe 1990).

B. Revised Probability Calculations

1. Revised Calculations of E1: The Recurrence of Volcanic Events. This section of the Volcanism Status Report initiates the revised calculations of the E1, the recurrence of volcanic events. We follow the logic of Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository and systematically examine values for E1 using three methods: time-trend patterns, homogeneous Poisson models using cumulative volcanic events for specified periods of time, and modified homogeneous Poisson models using magma-output rate.

Table 7.1 is a list with the referenced publication of values of the recurrence rate (E1) for volcanic events for the Yucca Mountain region. The results are taken from publications ranging from 1980 to 1992. The calculated rates span a range from 1.3×10^{-5} to 6.0×10^{-7} events yr^{-1}. Distribution models for the calculations include homogeneous Poisson models based on event and cluster counts, modified homogeneous Poisson models using magma-output rate and Weilbull models. The observation periods for the calculation of the rates vary from 1.6 to 6 Ma. The geometric mean of all the calculated rates is 3.5×10^{-6} events yr^{-1} which is equivalent to a volcanic event every 285 ka. Most of the recurrence rates are in the range of 1 to 6×10^{-6} events yr^{-1}. Numbers in this range are not considered to be different given the underlying uncertainties of the calculations (Crowe et al. 1992a).

There are some important limitations of the data summarized in Table 7.1. First, as noted earlier, most of the calculations attempted to bound the recurrence probability to determine if the risk of volcanism could result in disqualification of the Yucca Mountain site. This perspective results in the introduction of non-systematic bias in the calculations toward higher recurrence rates because assumptions used for the calculations attempt to insure that the probability values were not underestimated. Second, no attempt was made in the different calculations to structure the results so a representative distribution of recurrence rates could be determined. Thus descriptive statistics derived from the calculations are difficult to interpret and may have limited meaning. Third, the recurrence rates were calculated with different quality of data for the ages and identification of eruptive centers. Generally, the more recent the calculations, the more complete the data sets used.

a. Time-Trend Analyses. Table 7.2 lists the age, volume, cumulative volume, the log of the volume and the repose period for the major volcanic events of the Younger Post-caldera basalt cycle. The event repose times vary from 285 ka to 1.8 Ma with a mean of 590 ± 570 ka (n=5). The number of events is too limited to be statistically significant. However, we note two potentially important observations. Three of the five repose periods are between 600 and 800 ka with the remaining two periods being approximately half and double those values (Fig. 7.4). Second, the minimum repose period between events for the duration of the YPB (4.5 Ma) is 285 ka. If the minimum recognized repose period is used

Table 7.1 Published Values of E1, the Recurrence Rate of Volcanic Events

Table I: Disruption Parameter (E2)

Publication	a (repository area) km^2	A (event area) km^2	Model	Parameter E2
Crowe and Carr, 1980	10	1963	25 Km radius circle	5.1E-3
	10	7854	50 km radius circle	1.3E-3
Crowe, Johnson, and Beckman, 1982	8	2437	Min area circle	3.3E-3
	8	4419	Min area ellipse	1.8E-3
	8	2470	Min area circle (Buckboard)	3.2E-3
	8	1953	Min are ellipse (Buckboard)	4.1E-3
Crowe, Johnson, and Beckman, 1982 (Revised repository area)	6	2437	Min area circle	2.5E-3
	6	4419	Min area ellipse	1.4E-3
	6	2470	Min area circle (Buckboard)	2.4E-3
	6	1953	Min area ellipse (Buckboard)	3.1E-3
Smith et al 1990	6*	1953	AMRV	3.1E-3 1.6E-2
	6*	375	Lathrop Wells Chain	2.2E-3+
Naumann et al 1991	6*	1530*	NE Fault Zone	3.9E-3
Crowe et al 1992	6	1670	Cluster Length (3σ) Crater Flat Volcanic Zone	3.6E-3
Sheridan 1992	6		Mono Carlo Dike Propagation**	
			Model 1	6E-3
			Model 2	1.4E-2
			Model 3	1.7E-2
			Model 1a	1.1E-3
			Model 2a	1.0E-2
			Model 3a	5.3E-3
Ho 1991	6*		ARMV/Chain	8.0E-2

* Assigned to model.
\+ Assuming the CVFZ could produce clusters that are directed toward the Yucca Mountain Site over 14% of the length of the zone.
** Maximum probability values.

Table 7.2 Magma Volumes, cumulative magma volumes, and repose intervals of Pliocene and Quaternary volcanic events in the Yucca Mountain region.

EVENT	AGE	VOLUME	CUMVOL	LOGVOL	REPOSE				
Thirsty Mesa	4.60E+06	3.00E+09	3.00E+09	9.477121255					
Amargosa Valley	4.40E+06	3.00E+08	3.30E+09	8.477121255	-2.00E+05				
CF3.7	3.70E+06	6.80E+08	3.98E+09	8.832508913	-7.00E+05				
Buckboard	2.90E+06	9.20E+08	4.90E+09	8.963787827	-8.00E+05				
CF1.2	1.10E+06	2.30E+08	5.13E+09	8.361727836	-1.80E+06				
Sleeping Butte	3.85E+05	5.90E+07	5.19E+09	7.770852012	-7.15E+05				
Lathrop Wells	1.00E+05	1.40E+08	5.33E+09	8.146128036	-2.85E+05				
Trend Forecasting									
Thirsty Mesa	Amargosa	CF3.7	BuckBoard	CF1.2	Sleeping	Lathrop	Next Eruption	Forecast Method	
Event Age									
4.60E+06	4.40E+06	3.70E+06	2.90E+06	1.10E+06	3.85E+05	4.00E+04			original data
4.60E+06	3.69E+06	2.79E+06	1.88E+06	9.79E+05	7.41E+04	-8.31E+05	-1.74E+06	linear	
4.60E+06	4.40E+06	3.70E+06	2.90E+06	1.10E+06	3.85E+05	4.00E+04	-9.63E+05	autofill	
5.05E+06	4.18E+06	3.31E+06	2.45E+06	1.58E+06	7.15E+05	-1.51E+05	-1.02E+06	Trend/Linear	
Eruption Volume									
3.00E+09	3.00E+08	6.80E+08	9.20E+08	2.30E+08	5.90E+07	1.40E+08			original data
3.00E+09	2.66E+09	2.32E+09	1.98E+09	1.64E+09	1.30E+09	9.62E+08	6.22E+08	linear	
3.00E+09	3.00E+08	6.80E+08	9.20E+08	2.30E+08	5.90E+07	1.40E+08	-5.98E+08	autofill	
1.78E+09	1.44E+09	1.10E+09	7.61E+08	4.22E+08	8.19E+07	-2.58E+08	-5.98E+08	Trend/Linear	

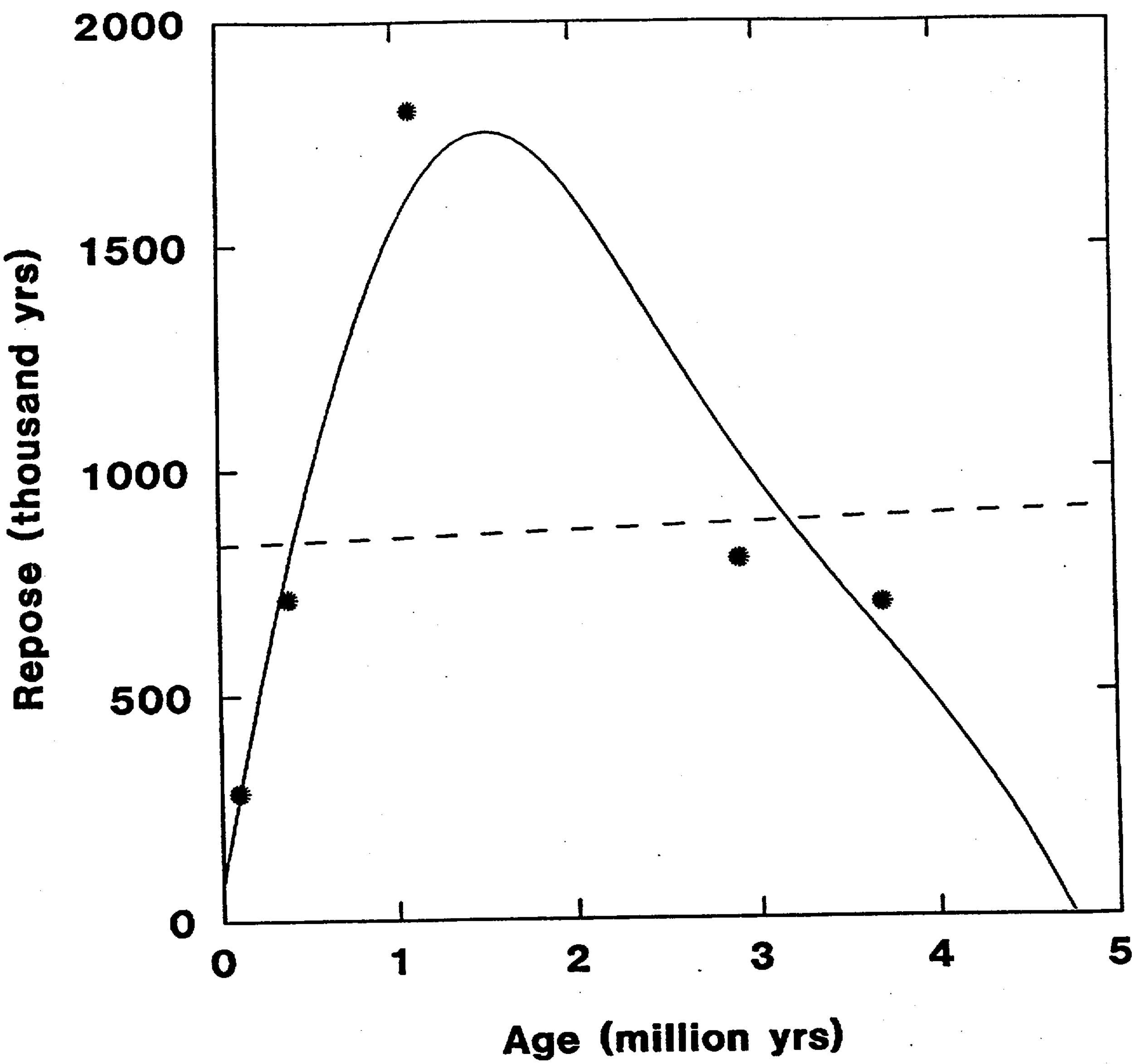


Fig. 7.4: Plot of repose time versus age of Pliocene and Quaternary volcanic centers of the Yucca Mountain region. The Thirsty Mesa and Amargosa Valley centers are grouped as one event because their ages overlap. The age of the Lathrop Wells center is used as 100 ka, the suspected age of the initiating event of chronostratigraphic unit three at the center (see Section II). The solid line is a distance weighted least squares fit of the data points; the dashed line is a linear least squares fit. There is insufficient data to draw major conclusions from the repose data.

as a worst case bound for predicting the next volcanic event (corrected for the time since the last eruption, the Lathrop Wells volcanic center; 40 ka) the predicted minimum time to the next event is 245 ka which is equivalent to a recurrence rate of 4.0×10^{-6} events yr^{-1}. The repose period data of Table 7.2 were run through time-forecasting routines. None of the calculations yielded statistically meaningful data.

b. Homogeneous Poisson Models (Event Counts). Table 7.3 is a compilation of revised calculations of the recurrence rate of volcanic events using a homogeneous Poisson model for the record of volcanic events in the Yucca Mountain region. We attempted, in this data compilation, to provide a representation of the distribution of values by identifying models that give the minimum, most likely and maximum values using geologically reasonable combinations of event counts. The emphasis of this approach is to accumulate data to aid in selection of the most likely value and the distribution about the most likely value.

The event count models of Table 7.3 are divided into two categories. The first category includes combinations of Quaternary volcanic events. The Quaternary period is used to correspond to the NRC reqirement in 10 CFR 60 of consideration of igneous events in the Quaternary. The second category includes all Pliocene and Quaternary volcanic events. This period is based on the recognition of the basalt cycle of the Younger Post-Caldera basalt (YPB; Crowe 1990). The observation period represents a volcano-tectonic event: the youngest cycle of post-caldera basaltic volcanism.

The minimum event models for both the Quaternary and YPB event counts are based on the interpretations of the paleomagnetic data of Champion (1991). He argues that all geographically adjacent centers have closely spaced field magnetization directions and therefore formed from a single magma pulse. This interpretation represents the *minimum* number of volcanic events (spatially and temporally distinctive magma pulses) that can be assigned to the volcanic centers of the Yucca Mountain region for both the Quaternary and the YPB.

The most likely volcanic model for Quaternary and YPB volcanic events is based on all existing data for the volcanic centers. Current geologic, geochronologic, petrologic and geophysical data are used to identify volcanic events. Emphasis is placed on identifying centers as individual events when either geochronologic, geochemical or spatial evidence require their separation as distinct events. In some cases, the geochronologic, petrologic and paleomagnetic data are insufficiently precise to provide convincing proof of single magmatic events. For example, the Quaternary basalt centers of Crater Flat can be divided into one to as many as four events because the cluster length (12 km) exceeds the likely lengths of individual feeder dikes. Red Cone and Black Cone could be identified as one event, but the volume of each center, and their geochemical data (Vaniman and Crowe 1981; Perry and Crowe 1992) suggest the centers may have formed from separate magma batches. Additionally, the geochronology and paleomagnetic data for the centers provides permissive but not conclusive proof that the centers formed from a single magma batch. The Little Cones center is inferred to be a single event because of the close spacing of the scoria cones,

Table 7.3 Homogeneous Poisson Event Count Models for Pliocene and Quaternary Volcanic Events in the Yucca Mountain Region

Event Count Models	Events	Cumulative Events	Duration (yrs)	Rate (events/yr)
Quaternary Minimum Model				
1.2 Crater Flat	1	1	1.80E+06	1.67E-06
Sleeping Butte	1	2		
Lathrop Wells	1	3		
Quaternary Most-likely Model				
1.2 Crater Flat	4	4	1.80E+06	3.89E-06
Sleeping Butte	2	6		
Lathrop Wells	1	7		
Quat Stress-Field Dike Model (min)				
1.2 Crater Flat	1	1	1.80E+06	1.67E-06
Sleeping Butte	1	2		
Lathrop Wells	1	3		
Quat Stress-Field Dike Model (max)				
1.2 Crater Flat	2	2	1.80E+06	2.78E-06
Sleeping Butte	2	4		
Lathrop Wells	1	5		
Quaternary Maximum Model				
1.2 Crater Flat	5	5	1.80E+06	4.44E-06
Sleeping Butte	2	7		
Lathrop Wells	1	8		
Cycle Minimum Model				
Thirsty Mesa	1	1	4.50E+06	1.56E-06
Amargosa Valley Anamoly	1	2		
3.7 Ma Crater Flat	1	3		
Buckboard Mesa	1	4		
1.2 Crater Flat	1	5		
Sleeping Butte	1	6		
Lathrop Wells	1	7		
Cycle Most Likely Model				
Thirsty Mesa	1	1	4.50E+06	2.89E-06
Amargosa Valley Anamoly	1	2		
3.7 Ma Crater Flat	3	5		
Buckboard Mesa	1	6		
1.2 Crater Flat	4	10		
Sleeping Butte	2	12		
Lathrop Wells	1	13		
Cycle Stress-Field Dike Model (min)				
Thirsty Mesa	2	2	4.50E+06	2.22E-06
Amargosa Valley Anamoly	1	3		
3.7 Ma Crater Flat	2	5		
Buckboard Mesa	1	6		
1.2 Crater Flat	2	8		
Sleeping Butte	1	9		
Lathrop Wells	1	10		
Cycle Stress-Field Dike Model (max)				
Thirsty Mesa	2	2	4.50E+06	2.67E-06
Amargosa Valley Anamoly	1	3		
3.7 Ma Crater Flat	3	6		
Buckboard Mesa	1	7		
1.2 Crater Flat	2	9		
Sleeping Butte	2	11		
Lathrop Wells	1	12		
Cycle Maximum Model				
Thirsty Mesa	3	3	4.50E+06	3.78E-06
Amargosa Valley Anamoly	1	4		
3.7 Ma Crater Flat	4	8		
Buckboard Mesa	1	9		
1.2 Crater Flat	5	14		
Sleeping Butte	2	16		
Lathrop Wells	1	17		
Univariate Statistics	All Models	Preferred Model		
Mean	2.94E-06	3.63E-06		
Geometric Mean	2.60E-06	3.35E-06		
Median	2.78E-06	3.63E-06		
Mode	1.88E-06			
Standard Deviation	1.16E-06	1.05E-06		
Variance	1.31E-12	1.10E-12		
Kurtosis	-6.21E-01			
Skewness	6.43E-01			
Range	3.44E-06	1.49E-06		
Minimum	1.56E-06	2.89E-06		
Maximum	5.00E-06	4.38E-06		
Sum	2.94E-05	7.26E-06		
Count	1.00E+01	2.00E+00		

their small volumes and their petrologic similarity (Vaniman and Crowe 1981; Crowe et al. 1986). The assignment of the Sleeping Butte centers is less clear. We have assigned the centers to two events for the most likely model because one center (Little Black Peak) is monogenetic (single event) and the second (Hidden Cone) appears to be polycyclic (multiple events; Crowe and Perry 1991). However, the close spacing of the centers (2.6 km; Crowe and Perry) and the paleomagnetic data (Champion 1991) are permissive with the centers representing a single volcanic event.

The stress-field dike model for the Quaternary and YPB categories is based on two observations described in Sections II and III. The clusters of basalt centers of the CFVZ are elongate north-northeast, parallel to the maximum compressive stress direction. This is the inferred direction of dike propagation in the shallow crust. The clustered centers may have formed by upwelling of magma along a buried northwest-trending structure. At shallow levels the magma diverted from the northwest-trending structure and was emplaced by magma-generated fracture parallel to the maximum compressive stress direction. The site of upwelling is identified by the northwest alignment of basalt centers in the CFVZ which coincides also with the location of the surface of maximum erupted magma volumes (see Fig. 3.15). Magma upwelling has an equal probability of propagating either northeast or southwest to form clustered volcanic centers. On the basis of this model, for example, the 1.1 Ma basalt centers of Crater Flat can be inferred to have formed by two distinct or related dikes propagating in opposite directions; one to the northeast forming Black Cone and Makani cone centers, and one to the southwest forming Red Cone and the Little Cone centers. An appealing aspect of this model is that it is consistent with the volume relations of the Quaternary basalt centers of Crater Flat. The smallest volume centers of the cluster are located at the opposite ends (Makani and Little Cone centers) of the northeast and southwest propagated dike(s). The stress-field dike model is divided into two cases, minimum and maximum dike models, where the minimum case is the smallest number of dikes that could form the centers and the maximum case is the largest number of dikes that could form the centers based on geometry and spacing of the eruptive vents.

The Quaternary and YPB categories correspond to the maximum number of volcanic events that can be assigned to the Quaternary centers based on a consistent definition of volcanic events (volcanic event = formation of a new volcanic center). In most cases, these assignments are similar to the most-likely models. The only differences between models are from the assignments of Ho (1992). He separates the Little Cone center into two events.

In most cases, there are sufficient data to make reasonable judgments about the event assignments for the model categories. These assignments will, of course, be tested and refined by acquisition of additional information from ongoing site characterization studies. The identification of uncertainties in data, their implications on volcanic risk assessment and the plans for obtaining data to complete volcanism studies are described in Section VIII. There are limited data for selection of volcanic event models for the basalt of Thirsty Mesa and the basalt of Amargosa Valley. The basalt of Thirsty Mesa was recognized only recently as a Pliocene center and accordingly, there are less data available on the geochronology, geochemistry and stratigraphy of this center. The basalt of Amargosa Valley has been penetrated only in a single, exploratory drill hole (Harris et al. 1992). Information on the dimensions of the center are based on interpretations of aeromagnetic data (Kane and Bracken 1983; Crowe et al. 1986; Langenheim et al. 1991).

One major question concerning the listed calculations of Table 7.3 is what is a reasonable representation of the uncertainty? There is not a simple answer to that question. One method for defining the uncertainty is to derive descriptive statistics using the data summarized in Table 7.3. Volcanic event rates using combinations of homogeneous Poisson models listed in Table 7.1 are $2.7 \times 10^{-6} \pm 1.2 \times 10^{-6}$ events yr^{-1} for all models, and $3.6 \times 10^{-6} \pm 1.0 \times 10^{-6}$ for the most likely model events yr^{-1}. This range is equal to average recurrence intervals for volcanic events spanning 625,000 to 220,000 years. These numbers equated to the number of events in the Quaternary and the interval of the YPB using the recurrence estimates are 3 to 7 events for the Quaternary and 7 to 21 events for the YPB. For comparison, the observed events using the models summarized on Table 7.3 are 3 to 8 events for the Quaternary and 7 to 17 for the YPB. There is an element of circular reasoning in making these comparisons, but the comparisons serve to illustrate that the recurrence calculations are physically reasonable.

An alternate method of calculating the uncertainty of E1 is to use the method of Ho (1992). He used a nonhomogeneous Poisson model (Weibull intensity) and provided estimations of E1 of 5.0×10^{-6} yr^{-1} (Quaternary) to 5.5×10^{-6} yr^{-1} (6 Ma). These results are slightly higher than the results from the homogeneous Poisson model (Table 7.3) because he used maximum counts cones (the values are probably best represented as a worst case). However the results do not differ significantly from maximum model categories of Table 7.3. The recurrence rates of Ho (1992) are equal to event intervals of 180,000 to 200,000 yrs and equate to event projections for the Quaternary and Pliocene of 8 to 9 and 30 to 33, respectively. These numbers compare reasonably well with observed event counts of 3 to 8 (Quaternary) but are much larger than the observed Pliocene events (7 to 17). The Pliocene numbers are larger than the observed event numbers for the Pliocene by a factor of about 2 to 4. Ho (1992) used a time interval of 6.0 Ma despite a record of basaltic volcanic events that extends only to 4.6 Ma. This arbitrary observation period forces the volcanic events into the latter part of the time distribution resulting in a β factor of greater than 1 for the Weibull distribution model. A more important comparison is how the uncertainty of the calculations was determined by Ho (1992). He calculated a 90% confidence interval for the recurrence of Weibull-distributed volcanic events. The resulting values are 1.85×10^{-6} to 1.26×10^{-5} events yr^{-1}. Ho (1992) makes a valid argument that interval estimates are more informative than point estimates. However, he calculated the confidence intervals from worst case recurrence values. The 90% recurrence intervals of Ho (1992) are equivalent to event intervals of 550,000 to 80,000 years (assuming a Poisson distribution). These interval estimates can be equated to event estimates for the Quaternary of 3 to 20 events and 11 to 76 events for the Pliocene. These are very much larger than the observed number of events for the Yucca Mountain region and equal event rates of volcanic activity in major basaltic volcanic fields (Crowe et al. 1992a).

How can apparently reasonable approaches to assessments of the event recurrence and the uncertainty of the event recurrence produce such different results? The answer is in the logic paradox of the volcanic record of the Yucca Mountain region as described earlier in this section. To repeat, the logic paradox is the following:

There are only a small number of volcanic events that have occurred in the Yucca Mountain region during the Quaternary. The small number of events means that the risk of volcanism is low, but the uncertainty of calculating the risk is large. Viewed conversely, if there were more volcanic events in the Yucca Mountain region during the Quaternary, there would be less uncertainty in calculating the risk of future events. However, the risk of future events, by virtue of the larger number of events, would be higher. The trade-off between decreased risk and increased uncertainty seems logical. Accepting the opposite view leads to two mutually illogical conclusions: 1) The best place to locate a repository would be in an active volcanic field because the risk can be calculated with an acceptable uncertainty or 2) The worst place to locate a repository would be in an area of no volcanic events because the uncertainty of calculating volcanic risk is unbounded.

The position taken in this volcanism status report is that the record of volcanic events in the Yucca Mountain region cannot be used to make robust calculations of the risk of volcanism. The risk of future volcanism is low, but the data sets are too limited to meet the statistical requirements of a robust data set. Therefore it is unrealistic to attempt to define the uncertainty of risk assessment using a conventional statistical approach. Instead the uncertainty must be bounded by comparison. Recurrence rates of volcanic activity must be lower for the Yucca Mountain data set than for more active basaltic volcanic fields. The basaltic volcanic field of Crater Flat is one of the smallest and least active basaltic volcanic fields in the southwestern United States (Settle 1980; Crowe et al. 1986; Wood and Kienle 1990; Crowe et al. 1992a; see Section IV, this report). The activity of basaltic fields is measured as number of events per time (Quaternary), and can also be expressed as the number of volcanic events per area, or erupted volume per time. Upper limits can be placed by comparison of recurrence intervals of future volcanic events in the Yucca Mountain region. *The recurrence rate of future volcanic events in the Yucca Mountain region can be no greater than and realistically must be less than recurrence rates of basaltic volcanism in much more active basaltic volcanic fields.*

The closest major basaltic volcanic fields to the Yucca Mountain region are the Lunar Crater volcanic field in central Nevada and the Cima volcanic field located in the Mojave Desert in southeastern California. The Lunar Crater volcanic field was mapped and described by Scott and Trask (1971), Bergman (1982), Crowe et al. (1986) and Folan et al. (1992). The basalt field extends north-northeast across the Pancake range and into the topographic valley marking the location of the Lunar Crater caldera. Quaternary basaltic volcanic centers in the field occur along the ring-fracture zone of the caldera and as multiple, northeast-trending fissure systems. Bergman (1982) and Smith and Luedke (1984) recognized a gradual decrease in age of basalt centers from the Reveille range northeast through the northeast end of the Lunar Carter basalt field. The older basalt centers tend to occur on the southeast part of the field and on the ring-fracture zone of the Lunar Crater caldera. The youngest vents in the field are located near the northeast end but the patterns are not completely systematic. Basalt vents in the field are marked by symmetrical to asymmetrical spatter cones, scoria cone, tuff cones and tuff rings. The Lunar Crater volcanic field differs from the CFVZ by the number of cones in the field and the much larger volume of pyroclastic deposits erupted from individual vents. The vent density of the composite field is 0.16 vents km^{-2}; the greatest area of concentration of cones has a vent density of 0.34 vents km^{-2}.

Figure 7.5 is a generalized map of the distribution of Quaternary vents in the Lunar Crater volcanic field. The identification of Quaternary centers is based on existing geochronology data and evaluations of the degree of erosional modification of the centers (Crowe et al. 1986). If there was uncertainty in the age assignments, we skewed the data toward higher vent counts to insure that recurrence rates would not be underestimated. There are 82 centers in 28 clusters of inferred Quaternary age in the Lunar Crater volcanic field (Fig. 7.5). A cluster is defined as a closely spaced group of vents that probably shared a common feeder dike system.

The Cima volcanic field is located in the northeastern Mojave Desert, California, about 120 km southwest of Las Vegas, Nevada (Katz and Boettcher 1980; Dohrenwend et al. 1984). The field consists of about 40 basaltic volcanic centers and associated lava flows. The chronology of the volcanic field, based on K-Ar age determinations supplemented by paleomagnetic data, is described by Dohrenwend et al. (1984). The geomorphology of the scoria cones in the field and an empirical model of cone degradation is described by Dohrenwend et al. (1986). The petrology of the lavas and ultramafic xenoliths was described by Wilshire (1987). The number of Quaternary volcanic centers in the Cima volcanic field was compiled from the geologic map of Dohrenwend et al. (1986). The volcanic field contains 29 basalt centers forming an inferred 22 clusters, all of Quaternary age (Fig. 7.6).

Recurrence rates of volcanic events can be estimated for the Lunar Crater and Cima volcanic fields using a homogeneous Poisson model. Recurrence rates for the Lunar Crater field are between 4.5×10^{-5} events yr^{-1} (center count) and 1.5×10^{-5} events yr^{-1} (cluster count). This is equivalent to a recurrence interval of 22,000 to 67,0000 years. Recurrence rates for the Cima volcanic field are between 1.6×10^{-5} events yr^{-1} (center count) and $1.2 \times 10^{-5} yr^{-1}$ (cluster count). These rates are equivalent to the formation of a new volcanic center or cluster every 63,000 to 83,000 years.

Several conclusions can be derived by comparison of the recurrence rates of the Yucca Mountain area, the Lunar Crater and Cima volcanic fields. First, all rates are long compared to the required isolation period of a repository (10,000 years). Stated differently, if a repository was located in the center of any of the three volcanic fields, a future volcanic event would not be expected during the isolation period of a repository because the recurrence intervals are all > 10,000 years. Second, the recurrence rates of the basaltic volcanic events in the Yucca Mountain region are significantly lower than recurrence rates of the Cima and Lunar Crater volcanic fields. The number of volcanic centers and clusters of Quaternary age in the Lunar Crater volcanic fields are larger by almost a factor of 10

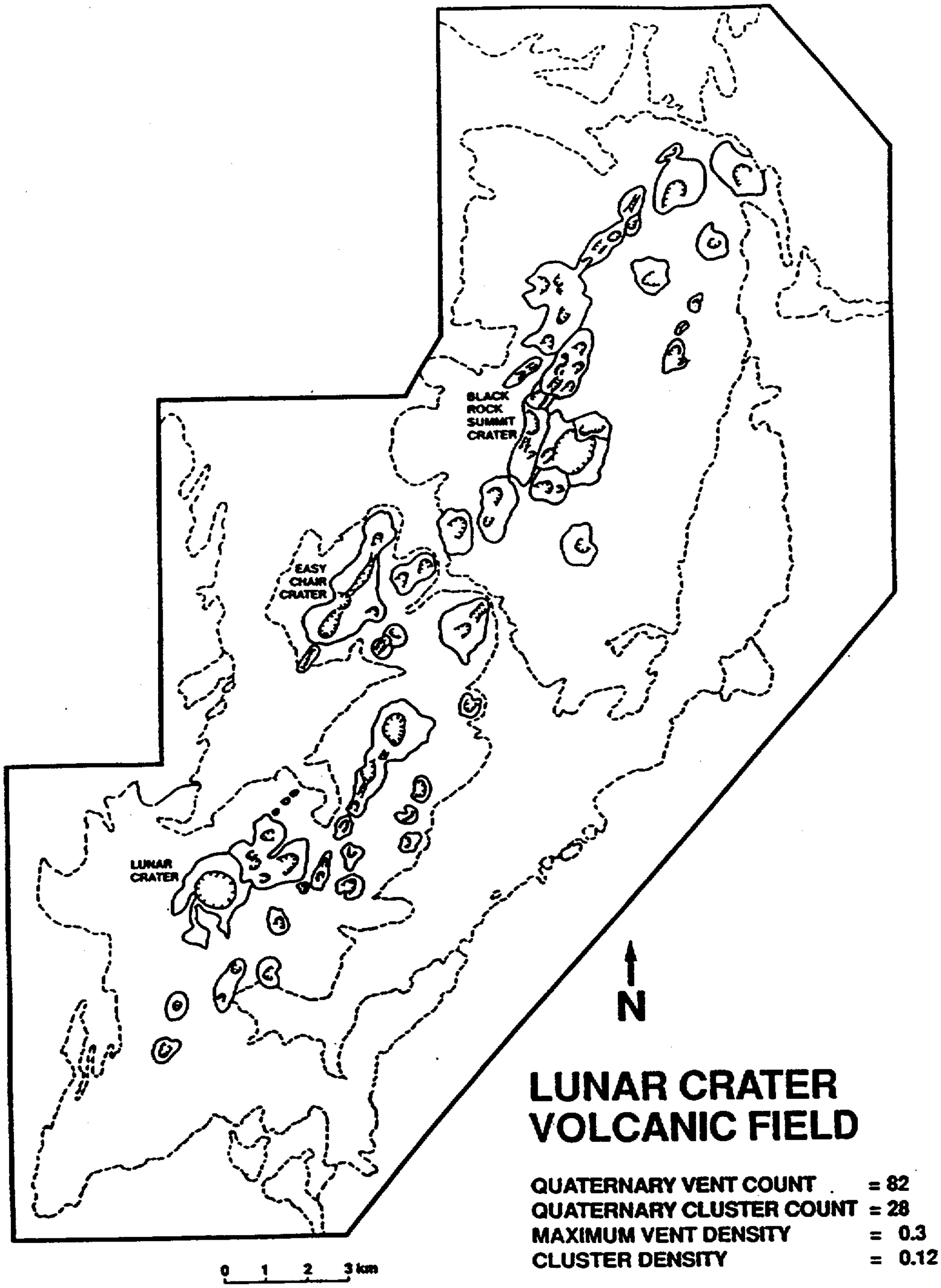


Fig. 7.5 Generalized geologic map of the distribution of Quaternary volcanic vents in the Lunar Crater volcanic field, Nevada. The map was modified from Scott and Trask (1971) and Crowe et al (1986).

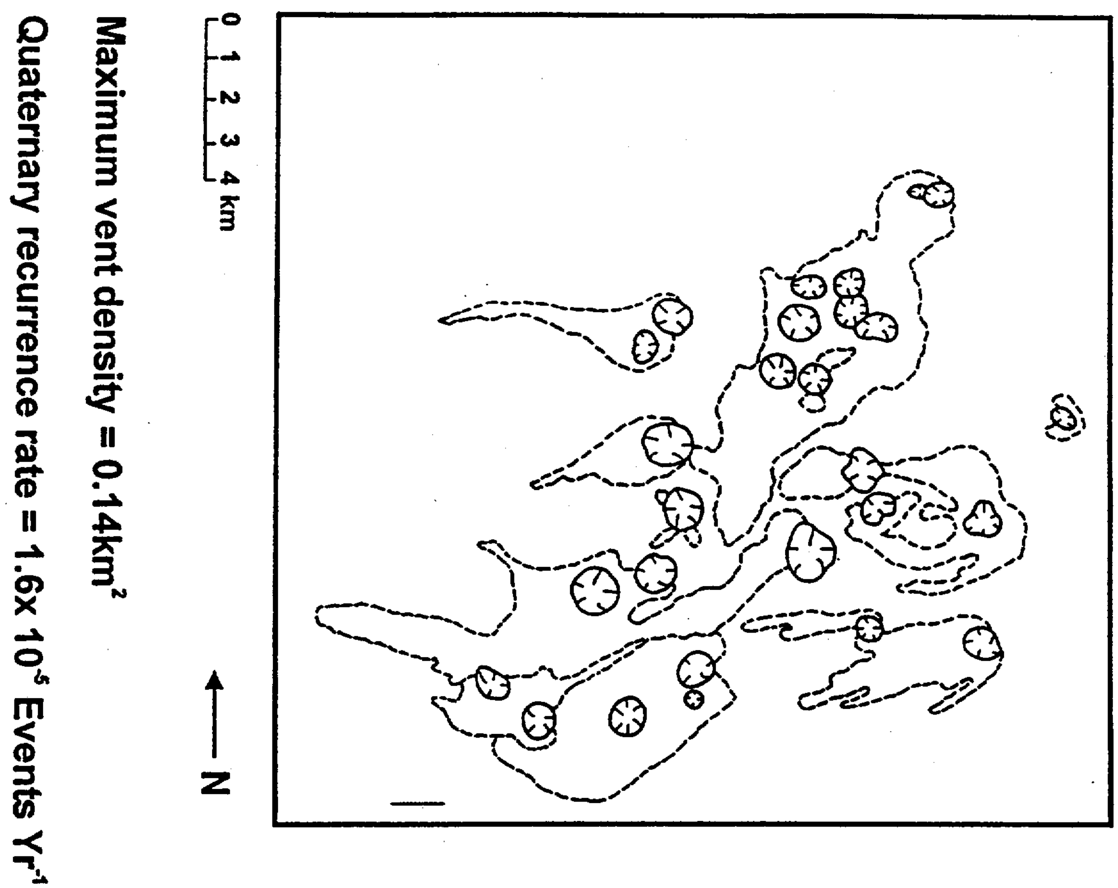


Fig. 7.6 Generalized geologic map of the distribution of Quaternary volcanic vents for the Cima volcanic field, California. The map was modified from Dohrenwend et al. (1986).

than the Yucca Mountain region. Likewise, the Quaternary event count for the Cima volcanic field is greater than the Yucca Mountain region by about a factor of 4 to 8. Third, the recurrence rate of volcanic activity in the Lunar Crater and Cima volcanic field provide bounds on the maximum rates of volcanic activity for the Yucca Mountain region. It is physically implausible to estimate values or assign uncertainty intervals to recurrence rates for the Yucca Mountain region that equal or even approach rates in the Lunar Crater or Cima volcanic fields. The only way estimated recurrence rates for the Yucca Mountain region could reasonably be inferred to approach rates for the Lunar Crater and Cima volcanic field would be if there was evidence that volcanism in the Yucca Mountain region was increasing through time. All known evidence indicates the opposite conclusion. The volume of magma erupted in the Yucca Mountain region has declined systematically since the Pliocene (Vaniman and Crowe 1981; Crowe et al. 1989; 1992. The geochemistry of basaltic magmatism is consistent with a progressive deepening of the depth of crystallization of basalt magma and a waning of magmatic processes through time (Perry and Crowe 1992; see Section IV, this report).

We conclude that the best estimate of a most likely recurrence rate of basaltic volcanic events in the Yucca Mountain region based on counts of volcanic events and using a homogeneous Poisson model is 3.3×10^{-6} events yr^{-1} (derived from the most likely values of Table 7.3). A recurrence rate of about 1.2×10^{-5} events yr^{-1}, derived from estimation of event rates during the Quaternary for the Lunar Crater and Cima volcanic fields provides a robust upper bound to maximum plausible recurrence rates for the Yucca Mountain region. The alternative models of event counts can be used to establish the shape of the distribution for estimations of the recurrence rate. Models of maximum event counts give recurrence rates of about 4×10^{-6} events yr^{-1}. The recurrence rate using minimum event counts is about 1.6×10^{-6} events yr^{-1}.

2. Volume-Predictable Recurrence Rates. Crowe et al. (1982) developed an alternative approach to estimating the recurrence rate of volcanic events. They examined magma-output rates (terminology of Kuntz et al. 1986) from a plot of the erupted volume of magma versus time for basaltic volcanic events of the Yucca Mountain region. The slope of the curve on this plot is the magma-output rate. Crowe and Perry (1989) noted that there are several limitations of a homogeneous Poisson model based on event counts that can be overcome by application of volume-predictable recurrence rates. First, vent counts record only the recognition of a volcanic event. Its magnitude, commonly expressed as the volume of the event, is not accounted for through a vent count. A large volume eruption is given an equal weight in an event count as a small volume eruption. Second, dependent on the observation period, vent counts can be insensitive to changes in recurrence rates. The vent counts assume an exponential time-distribution of events, with no event memory. This limitation can be accommodated by constructing vent counts over an interval that has a causative relationship to magmatic processes. Crowe and Perry (1989) noted that an alternative approach, which is based on a process-based perspective of basaltic volcanism, is to construct a time-volume curve of volcanic activity.

Estimations of recurrence rates for volcanic centers and fields using a time-volume relationship have been determined frequently in the geological literature. Bacon (1982) noted that time-volume behavior of basaltic and rhyolitic volcanism in the Coso volcanic field of eastern California, exhibited time-predictable behavior and he discussed analogies to slip-predictable behavior of earthquake sequences. Kuntz et al. (1986) described volume-predictable eruptions of the Great Rift in the Snake River plains of Idaho. He identified a change in magma-output rates on the basis of a change in slope of the curve of magma-volume versus time. Wadge (1982) described steady-state (volume-predictable) behavior of many polygenetic volcanoes. He used the slope of a time-volume curve to define the effusion rate of volcanoes and speculated that the steady-state behavior was probably controlled by magma-supply rates. Volume-predictable behavior was documented for historical eruptions of volcanoes of Kilauea, Mauna Loa and Piton de la Fournaise (King 1989; Stieltjes and Moutou 1987). Theoretical support for a volume-predictable behavior of volcanoes controlled by magma supply rate was provided by Shaw (1980; 1987).

Magma-output rates for the basaltic volcanic record of the Yucca Mountain region were calculated by Crowe et al. (1982). They range from 210 $m^3\ yr^{-1}$ for Pliocene volcanic activity and decrease to 75 $m^3\ yr^{-1}$ for Quaternary volcanic activity. Revised magma output rates were calculated by Crowe et al. (1989) and Crowe and Perry (1989). These output rates range from 133 $m^3\ yr^{-1}$ for the last 3.7 Ma and 66 $m^3\ yr^{-1}$ (Crowe et al. 1989) and 33 $m^3\ yr^{-1}$ for the Quaternary (Crowe and Perry 1989). The variability in the estimated output rates is attributed to different models of the age and volume of the volcanic centers. Crowe and Perry (1989) noted that the calculations of the magma-output rate are especially sensitive to assumptions concerning the volume of a scoria-fall sheet associated with each center. We are in the process of obtaining revised estimations of the volume of the scoria-fall sheet associated with the Lathrop Wells volcanic center. Until the volume estimations of the scoria-fall sheet are completed, we use published magma-output rates for revised calculations of the recurrence of volcanic events.

Table 7.4 is a compilation of representative magma volume of the volcanic events for the Yucca Mountain region. These values are divided by magma-output rates to yield the predictor attribute, the generation time to produce a volcanic event. The generation time is calculated as different combinations of the mean, median and the geometric mean of the magma volumes of volcanic events during the Quaternary and the YPB. The event rate is equal to 1 over the generation time. The calculation for the next volcanic event using the magma-output rate is given by the formula:

$$N_e = (R_v/O_p) - L_t$$

where N_e is the predicted time to the next volcanic event, R_v is the representative volume of a volcanic event, O_p is the magma output rate and L_t is the time since the last volcanic event (Crowe et al. 1982). The magma-output rate is used from Crowe et al. 1982; 1989; Crowe and Perry 1989). The time of the last event is the age of the main cone at the Lathrop Wells volcanic center which is estimated to be > 40 ka.

Table 7.4 Magma-Generation Rates and Recurrence Rates for Volume-Predictable, Modified Homogeneous Poisson Event Models for Pliocene and Quaternary Volcanic Events in the Yucca Mountain region.

EVENT	AGE	VOLUME	CUMVOL	LOGVOL	Magma output Rates	Gen Time (mean)	Gen Time (geomean)	Gen Time (median)	Period
Thirsty Mesa	4.60E+06	3.00E+09	3.00E+09	9.48	210	3.62E+06	1.79E+06	1.43E+06	Pliocene
Amargosa Valley	4.40E+06	3.00E+08	3.30E+09	8.48	75	1.01E+07	5.01E+06	4.00E+06	Quaternary
CF3.7	3.70E+06	6.80E+08	3.98E+09	8.83	133	5.71E+06	2.83E+06	2.26E+06	Pliocene
Buckboard	2.80E+06	9.20E+08	4.90E+09	8.96	66	1.15E+07	5.70E+06	4.55E+06	Quaternary
CF1.2	1.10E+06	2.30E+08	5.13E+09	8.36	33	2.30E+07	1.14E+07	9.09E+06	Quaternary
Sleeping Butte	3.85E+05	5.90E+07	5.19E+09	7.77		Event Rates (mean)	Event Rates (geomean)	Event Rates (median)	
Lathrop Wells	4.00E+04	1.40E+08	5.33E+09	8.15		2.76E-07	5.59E-07	7.00E-07	Pliocene
	Mean	7.61E+08				9.87E-08	1.99E-07	2.50E-07	Quaternary
	Standard Error	3.91E+08				1.75E-07	3.54E-07	4.43E-07	Pliocene
	Median	3.00E+08				8.69E-08	1.76E-07	2.20E-07	Quaternary
	Geomean	3.76E+08				4.34E-08	8.78E-08	1.10E-07	Quaternary
	Standard Deviation	1.03E+09							
	Variance	1.07E+18							
EVENT	AGE	VOLUME	CUMVOL	LOGVOL	Magma output Rates	Gen Time (mean)	Gen Time (geomean)	Gen Time (median)	Period
CF1.2	1.10E+06	2.30E+08	2.30E+08	8.36	210	6.76E+05	5.90E+05	6.67E+05	Pliocene
Sleeping Butte	3.85E+05	5.90E+07	2.89E+08	7.77	75	1.89E+06	1.65E+06	1.87E+06	Quaternary
Lathrop Wells	4.00E+04	1.40E+08	4.29E+08	8.15	133	1.07E+06	9.32E+05	1.06E+06	Pliocene
					66	2.15E+06	1.88E+06	2.12E+06	Quaternary
					33	4.30E+06	3.76E+06	4.24E+06	Quaternary
	Mean	1.43E+08				Event Rates (mean)	Event Rates (geomean)	Event Rates (median)	
	Standard Error	4.94E+07				1.48E-06	1.69E-06	1.50E-06	Pliocene
	Median	1.40E+08				5.29E-07	6.05E-07	5.36E-07	Quaternary
	Geomean	1.24E+08				9.37E-07	1.07E-06	9.50E-07	Pliocene
	Standard Deviation	8.55E+07				4.65E-07	5.32E-07	4.71E-07	Quaternary
	Variance	7.32E+15				2.32E-07	2.66E-07	2.36E-07	Quaternary
EVENT	AGE	VOLUME	CUMVOL	LOGVOL	Magma output Rates	Gen Time (mean)	Gen Time (geomean)	Gen Time (median)	Period
CF-North	1.10E+06	1.70E+08	1.70E+08	8.23	210	4.08E+05	3.11E+05	2.86E+05	Pliocene
CF-South	1.10E+06	6.00E+07	2.30E+08	8.36	75	1.14E+06	8.72E+05	8.00E+05	Quaternary
Hidden	4.80E+05	3.50E+07	2.65E+08	8.42	133	6.45E+05	4.92E+05	4.51E+05	Pliocene
Black Peak	3.85E+05	2.40E+07	2.89E+08	8.46	66	1.30E+06	9.91E+05	9.09E+05	Quaternary
Lathrop	4.00E+04	1.40E+08	4.29E+08	8.63	33	2.60E+06	1.98E+06	1.82E+06	Quaternary
	Mean	8.59E+07				Event Rates (mean)	Event Rates (geomean)	Event Rates (median)	
	Standard Error	2.92E+07				2.45E-06	3.21E-06	3.50E-06	Pliocene
	Median	6.00E+07				8.74E-07	1.15E-06	1.25E-06	Quaternary
	Geomean	6.54E+07				1.55E-06	2.03E-06	2.22E-06	Pliocene
	Standard Deviation	6.54E+07				7.69E-07	1.01E-06	1.10E-06	Quaternary
	Variance	4.27E+15				3.85E-07	5.05E-07	5.50E-07	Quaternary
	Generation Rate	Event Rate							
Preferred mean	1.00E+06	9.99E-07							
Preferred median	8.72E+06	1.16E-06							
Preferred geomean	8.14E+06	1.23E-06							
Worst Case 1	3.64E+06	2.76E-06							
Worst Case 2	7.27E+06	1.38E-06							

The most difficult attribute to characterize for the magma-volume calculations is the representative volume of the next volcanic event. Table 7.4 shows generation-time calculations for two periods including the YPB (4.5 Ma and younger), and 1.1 Ma and younger. The latter interval is divided into two parts corresponding to the cluster and stress-field models of Table 7.3. Examination of the predicted generation time of representative events for the YPB intervals shows that all values exceed 1,000,000 years, a physically unrealistic value. Figure 7.7 is a plot of magma volume versus time for all volcanic events of the YPB and provides an explanation for the long predicted magma-generation times. The volume of erupted magma has decreased dramatically through time. In fact, the curve from this value, which is the magma output rate may show two populations -- Pliocene output rates and Quaternary output rates (Fig. 7.7). Alternatively, the curve may show two domains for the evolutionary record of basaltic volcanism: 1) an older period (Pliocene) of steady-state (volume-predictable) output rates, and 2) a younger period (Quaternary) of waning magma output rates. The volume of erupted magma of a representative volcanic event has decreased by almost three orders of magnitude since the Pliocene.

A second approach for the magma-volume calculations is to use only the Quaternary eruptive events to establish the representative eruptive volume. This results in decreased predicted intervals for magma-generation times but the intervals are still consistently greater than 600,000 yrs. These values are less than an event rate of 1.7×10^{-6} events yr^{-1}, and are lower than the minimum homogeneous Poisson rates derived from counts of volcanic events. Projection of these rates for the Quaternary and YPB intervals gives predicted event numbers near and less than the minimum event count models.

A third approach is to use representative volumes of events based on the maximum dike event, stress field model (Table 7.4). Here event rates begin to approach but are still less than the homogeneous Poisson event count rates of Table 7.3. The low event rates using magma-output rates are consistent with and confirm the observation that magmatic activity has waned markedly from the Pliocene to the Quaternary. The magma-output rates suggest further that the homogeneous Poisson model using event counts through time gives conservative values that do not account for the decreasing volumes of erupted magma. The most likely value from Table 7.4 is the geometric mean using the stress field model (1.23×10^{-6} events yr^{-1}). An upper bound for this generation rate can be used from the worst case magma output calculations using the volume of the Hidden Cone and the Little Black Peak cone centers as the representative volume (1.4 to 2.8×10^{-6} events yr^{-1}). These centers are the smallest pulse of magma that could be inferred reasonably to have been erupted as an individual volcanic event in the post-Miocene volcanic record of the Yucca Mountain region. The worst case events rates are equivalent to 3 to 5 Quaternary events and 6 to 13 events for 4.6 Ma.

A compilation of the range of E1, the recurrence rate of volcanic events in the Yucca Mountain region, is shown on Fig. 7.8. A geometric mean of 2.6×10^{-6} events yr^{-1} is derived by combining the worst-case repose rate, the most likely values for the Quaternary and YPB recurrence rates based on event counts and the worst-case event rate based on volume-predictable rates. This value is inferred to be the most likely value for the

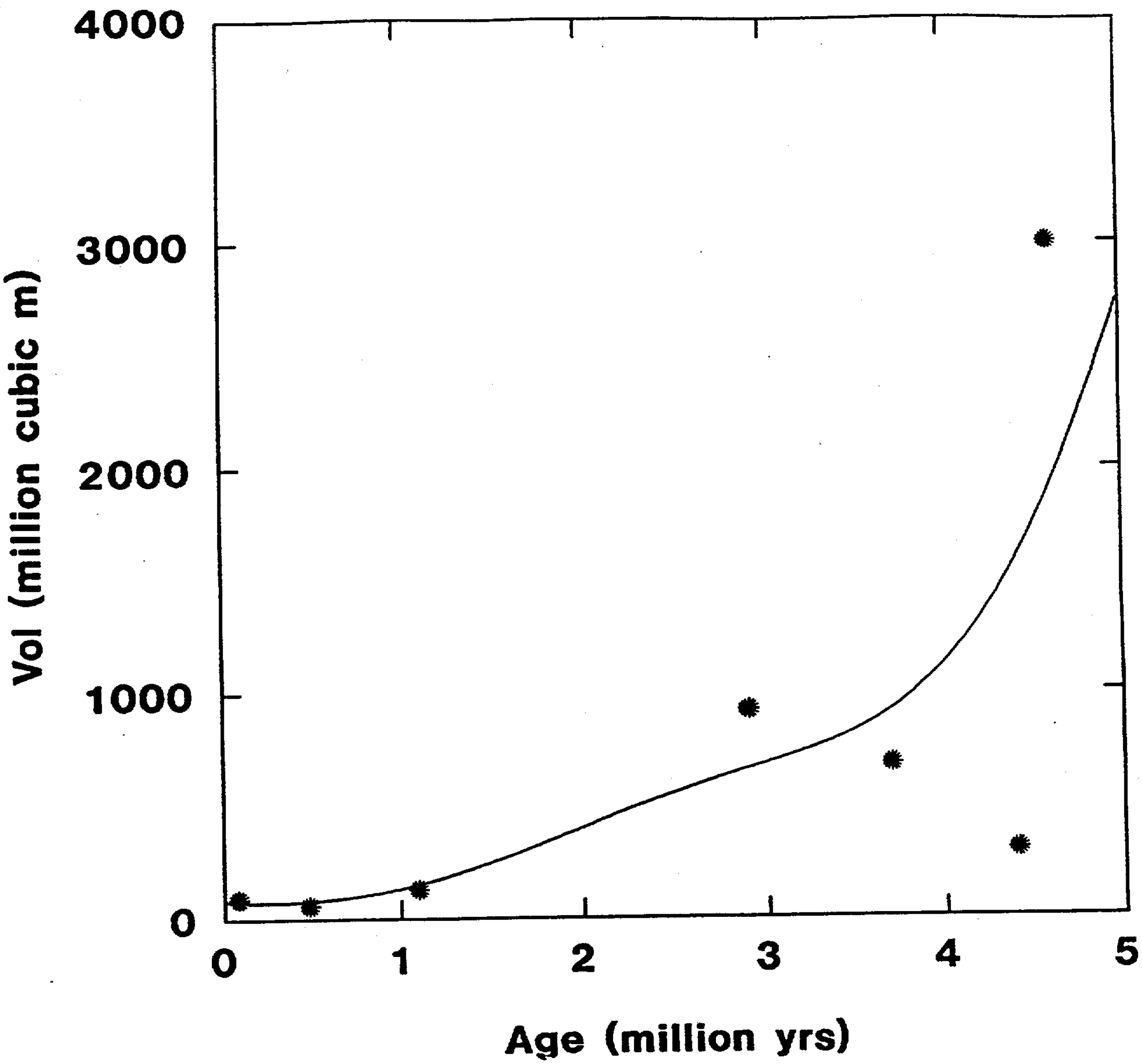


Fig. 7.7 Plot of magma volume (in million cubic meters) versus age (in million years) of the Pliocene and Quaternary volcanic events of the Yucca Mountain region. The volume of erupted magma has declined dramatically from the Pliocene to the Quaternary. The solid line is a distance weighted least squares fit of the data points. An equally valid curve fit is the dashed line of Fig. 7.3. This is a visually fit line that bounds the maximum volume of erupted events; all events fall below this bounding curve. The dashed curve is comparable to the controls or bounds provided by magma-supply rate for volcanic centers (Shaw, 1980; Crowe and Perry, 1989). The slope or first derivative of the bounding curve gives the instantaneous magma-output through time. Magma volumes are calculated as dense rock equivalents using the data of Crowe et al (1983) modified by Crowe et al (1988) and Crowe and Perry (1991).

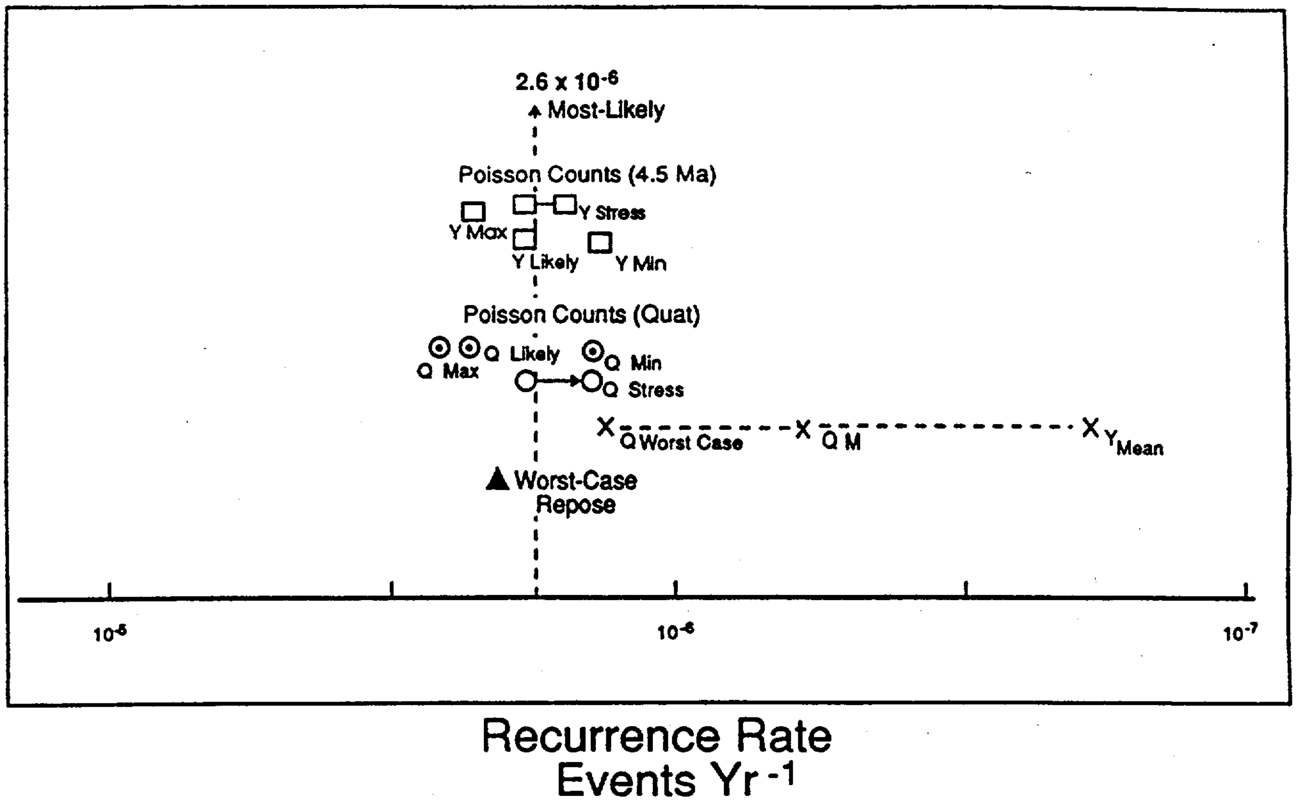


Fig. 7.8 Plot of the distribution of the recurrence rate (E1) for volcanic events in the Yucca Mountain region. The boxes and circles are the location of values for E1 from Table 7.3. Q: Quaternary poisson counts; Y: Younger Post-caldera cycle. The filled triangle is the worst-case value chosen from the minimum repose time of Table 7.2 The X's mark values for the volume-predictable recurrence rates from Table 7.4. Y_{mean} is the geometric mean of recurrence rates using representative values for the Younger Post-caldera basalt cycle. The Q_{mean} is the geometric mean of recurrence rates using representative values for the Quaternary volcanic centers. The Qworst-case is the recurrence rates using the volumes of the Sleeping Butte centers. The wide range in values for the reflects the steep decrease in erupted magma volumes through time. The most likely value represents an attempt to identify the central tendency of the distribution of calculated values for the recurrence rate of volcanic events.

recurrence rate of volcanic events. It may be skewed slightly toward worse case values because two of the event count models (repose rate and magma-generation rate) are based on worst-case models.

3. E2: Disruption Ratio. The second attribute of the tripartite conditional probability of magmatic disruption of the potential repository is E2, the probability of disruption of the repository, the controlled area, or the Yucca Mountain region. This attribute, like E1 the recurrence rate, is difficult to quantify because of the small number of volcanic centers in the region. The small numbers of events mean that there can be an unconstrained number of models of the structural controls of volcanic activity. Further, by virtue of the small number of events, it is difficult to prove or disprove convincingly alternative structural models. Given these difficulties, we use much the same approach applied to estimating the most likely value of E1, the recurrence rate. Multiple structural models of the distribution of volcanic events are assessed. The effect of the alternative models on the disruption ratio is evaluated rather than strengths and weakness of individual models.

The alternative models for the disruption ratio fall into three categories. These include random distribution models, models involving structural controls of volcanic units, and comparative models with analogue basaltic volcanic fields of the basin and range province.

Table 7.5 is a catalog of all calculated values of the disruption ratio obtained in past studies of the probability of magmatic disruption of a potential repository at Yucca Mountain. The values range from 8×10^{-2} to 1.1×10^{-3} (the disruption ratio is a dimensionless ratio). The geometric mean of the data set of Table 7.5 is 3.6×10^{-3}. The published values for E2, like the published values for E1, were established to evaluate the potential disqualification of the Yucca Mountain site. The values tend to be skewed toward higher or worse case values. In the following sections we attempt to estimate most likely values and define the distribution of values about the most likely value.

4. Random Disruption Models. Random disruption models were developed by Crowe et al. (1982) to attempt to bound the disruption ratio. They defined the area of the disruption ratio based on the distribution of basalt centers used to calculate a relevant value for E1. The area was established using a computer program that calculated a minimum area circle and minimum area ellipse enclosing the volcanic centers used to calculate E1 and the potential repository. The circles and ellipses were varied using different combinations of volcanic centers and the resulting areas were compiled into matrices of disruption ratios. Maximum and minimum values were extracted from the data matrices to calculate bounds for the disruption ratio. Table 7.6 is a list of revised disruption ratios for three areas, the repository, the controlled area and the Yucca Mountain region. The Yucca Mountain region is defined arbitrarily as an area enclosing borders that extend 10 km north and south and 5 kilometers east and west of the boundary of the controlled area This area is judged to represent the maximum effect area for direct volcanic effects of either a volcanic eruption or an intrusion. The area may be increased or decreased dependent on the results of more detailed studies of eruption and intrusion effects. The changes to the calculations would be

Table 7.5 Published Values of E2, the Disruption Ratio.

TABLE VOLCANIC RECURRENCE RATE (E1)

PUBLICATION	EVENTS (yr^{-1})	QUATERNARY EVENTS*	RATE MODEL	TIME (Ma)
Crowe and Carr, 1980	4.0E-6	7.2	Poisson: Cone Count	1.8-2.8
Crowe, Johnson, and Beckman, 1982	6.0E-7 to 1.1E-6	1.1 to 19.8	Magma Output (210 m3 yr-1)	1.8-3.7
	9.4E-6	17.1	Poisson: Cone Count	1.8
	6.4E-6	11.5	Poisson: Cone Count	2.8
	8.0E-6	14.4	Poisson: Cone Count	3.7
Crowe et al., 1989	2.8E-5	73	Magma Output (133 m3 yr-1) (Lathrop=130 ka)	3.7
	7.0E-6	12.6	Magma Output (133 m3 yr-1) (Lathrop=20 ka)	3.7
	5.0E-6	9.0	Magma Output (66 m3 yr-1) (Lathrop=130 ka)	1.8
	3.2E-6	5.8	Magma Output (66 m3 yr-1) (Lathrop=20 ka)	1.8
Crowe and Perry, 1990	1.9E-6	3.4	Magma Output (33 m3 yr-1) (Lathrop=130 ka)	1.8
	1.6E-6	2.9	Magma Output (33 m3 yr-1) (Lathrop=20 ka)	1.8
Ho, 1991	2.3E-6	3.7	Weilbull: Episode	12
	5.0E-6	8.0	Weilbull: Cycle	3.7
	6.2E-6	9.9	Weilbull: Cone Count	6.0
	5.5E-6	8.8	Weilbull: Cone Count	1.6
Crowe et al., 1992	3.9E-6	7.2	Poisson Cone Count	1.8
	1.7E-6	3.6	Poisson Cluster Count	1.8
	3.5E-6	5.4	Poisson Cone Count	3.7
	1.3E-6	2.3	Poisson Cluster Count	3.7
	3.2E-6	5.0	Poisson Cone Count	5.0
	1.2E-6	2.2	Poisson Cluster Count	5.0
Ho (1992)	5E-6	8.0	Weilbull:Episode	6.0
	5.5E-6	8.8	Weilbull:Episode	1.6
	1.8E-6	2.9	Weilbull:90% CI	1.6
	1.3E-5	21	Weilbull:90% CI	1.6

* Calculated number of volcanic events projecting the recurrence rate for the Quaternary Period. There were 3 to 7 volcanic events in the Yucca Mountain region in the Quaternary.

Table 7.6 Revised Values for E2, the Disruption Ratio, for Random, Forced Intersection, Intersection and Structurally Bounded Models of the Yucca Mountain Region.

Random Model	Area		Disruption Ratio	Disruption Ratio	Disruption Ratio	E1 Constraint
(equal area probability)	(km2)		Repository	Controlled	Region	
Quat Centers (circle)	2437		2.46E-03	3.53E-02	2.30E-01	3-7 events
Quat Centers (ellipse)	4419		1.36E-03	1.95E-02	1.27E-01	3-7 events
Quat + BB (circle)	2470		2.43E-03	3.48E-02	2.27E-01	3-8 events
Quat + BB (ellipse)	1953		3.07E-03	4.40E-02	2.87E-01	3-8 events
Geomean			2.23E-03	3.20E-02	2.09E-01	
Random Structural Model	Area		Disruption Ratio	Disruption Ratio	Disruption Ratio	E1 Constraint
(equal area probability)	(km2)		Repository	Controlled	Region	
CFVZ (Quat)	1260		4.76E-03	6.83E-02	4.44E-01	2-7 events
CFVZ (YPB)	1480		4.05E-03	5.81E-02	3.78E-01	7-16 events
YPB	1900		3.16E-03	4.53E-02	2.95E-01	7-17 events
Crater Flat Field	650		9.23E-03	1.32E-01	8.62E-01	2-11 events
Strike Slip (a)	1460		4.11E-03	5.89E-02	3.84E-01	3-16 events
Strike Slip (b)	855		7.02E-03	1.01E-01	6.55E-01	3-11 events
Stress-Field Dike (Quat)	1260		4.76E-03	6.83E-02	4.44E-01	3-7 events
Stress-Field Dike (YPB)	1480		4.05E-03	5.81E-02	3.78E-01	5-16 events
Chain Model	360		1.67E-02	2.39E-01	1.56E+00	2-6 events
Pull-Apart Basin	855		7.02E-03	1.01E-01	6.55E-01	3-11 events
Caldera Model	585		1.03E-02	1.47E-01	9.57E-01	3-10 events
NE Structural Zone	1500		4.00E-03	5.73E-02	3.73E-01	5-15 events
Crater Flat + Buckboard	1300		4.62E-03	6.62E-02	4.31E-01	3-12 events
Stochastic dike - NW/NE			6.00E-03	***	***	3-11 events
Stochastic dike -NE/NE			1.00E-02	***	***	3-11 evemts
Lathrop Wells dike			5.30E-03	***	***	1 event
Geomean			5.91E-03	8.19E-02	5.33E-01	
Geomean (intersection)			4.30E-03	6.16E-02	4.01E-01	
Geomean(forced intersection)			6.02E-03	8.63E-02	5.62E-01	
Structural Model	Area	Area	Disruption Ratio	Disruption Ratio	Disruption Ratio	
	repository	control	Repository	Controlled	Region	
	km2	km2	(<<)	(<<)	(<<)	
CFVZ (Quat)	790	890	7.59E-03	9.66E-02	6.29E-01	2-7 events
CFVZ (YPB)	1080	1280	5.56E-03	6.72E-02	4.38E-01	7-16 events
Crater Flat Field	435	480	1.38E-02	1.79E-01	1.17E+00	
Strike-Slip (a)	790	890	7.59E-03	9.66E-02	6.29E-01	2-11 events
Strike-Slip (b)	545	590	1.10E-02	1.46E-01	9.49E-01	3-11 events
Stress Field Dike (Quat)	790	890	7.59E-03	9.66E-02	6.29E-01	2-11 events
Stress Field Dike (YPB)	1080	1280	5.56E-03	6.72E-02	4.38E-01	5-16 events
Chain Model	170	330	3.53E-02	2.61E-01	***	2-6 events
Pull-Apart Basin	545	587	1.10E-02	1.47E-01	9.54E-01	3-11 events
Caldera Model	300	400	2.00E-02	2.15E-01	***	3-10 events
Stochastic dike - NW/NE			6.00E-03	***	***	3-11 events
Stochastic dike -NE/NE			1.20E-03	***	***	3-11 events
Lathrop Wells dike			1.70E-02	***	***	1 event
Geomean			8.82E-03	1.24E-01	6.88E-01	

systematic and thus easily revised. The disruption ratio was constructed using three methods: 1) the random model of Crowe et al. (1982), and 2) inclusion of volcanic centers used to calculate E1 into an irregular polygon bounding the centers and the repository, and 3) bounds from structural models.

The random structural models assume there is an equal probability of a future volcanic event throughout the area enclosing the distribution of volcanic events. The models allow for large scale structural control of the occurrence of volcanic events that is presumed to be reflected in the distribution of volcanic vents, but does not account for local structural controls. The positive merits of the random models are several. First, the calculations are nonarbitrary. The disruption ratio is constrained by the areas encompassing the distribution of all combinations of Pliocene and Quaternary volcanic centers and the potential Yucca Mountain block. Second, the calculations are simple to construct because the model weights equally the spatial probability of occurrence of magmatic events. There are two potential errors in the random structural models. If the structural zones that control sites of volcanic activity do not include the potential Yucca Mountain site, the random model *overestimates* the disruption ratio. In fact the disruption ratios are worse cases because the real probability must be less than the calculated disruption ratio. A factor leading to overestimation of the disruption ratios using the random model is the observation that Quaternary basalt centers tend (but not always) to be located in or along the edges of alluvial basins, not in range interiors. Because the potential Yucca Mountain site is located in a range interior, a random model will overestimate the disruption probability. There are two explanations for the basin versus mountain range distribution patterns. The first is simple lithostatic control. The basalt centers may tend to form in the topographically lowest areas, since they represent the shortest pathways to the surface. Alternatively, the basins and basin edges may be the most tectonically active parts of the present tectonic setting of the Yucca Mountain region and provide the easiest pathways for magma ascent. If the structural zones that control sites of volcanic activity *include* Yucca Mountain, the random model may underestimate the disruption ratio. The amount of underestimation depends on the actual geometry of the structural zone compared to the random zone.

Table 7.6 lists the results of the random structural models of Crowe et al. (1982). The geometric mean of the random model for combinations of minimum area circles and minimum area ellipses enclosing, respectively, the Quaternary volcanic centers and the potential repository, and the Quaternary volcanic centers, the potential repository and the basalt of Buckboard Mesa is 2.2×10^{-3}. The geometric mean would be slightly larger if we also included the Pliocene basalt centers. The disruption ratio for the controlled area for the same combinations of areas is 3.2×10^{-2}. This is consistent with the controlled area being larger than the repository by about an order of magnitude. The disruption ratio for the Yucca Mountain region is generally > 0.1. The latter two ratios are not completely correct because the controlled area and the Yucca Mountain region cover a sufficiently large area that they are not enclosed fully in the minimum area circles and minimum area ellipses.

The second set of random models listed on Table 7.6 are based on structural models for the distribution of basaltic volcanic centers. These models partially incorporate structural controls of the basaltic centers but the structural zones are enlarged somewhat arbitrarily so that the zones enclose the potential repository and/or the controlled area. The random aspect of these models is the assumption that there is an equal probability of occurrence of volcanic events in all parts of the structural zones. This construction differs from the minimum area circles and minimum area ellipses in two ways. First, the geometry and orientation of the random structural zones are based on conceptual models for the structural controls of basalt centers. This means the geometry of the zones is more systematic than the random distribution models. Second, the area of the zones are not fitted to standard geometric shapes (ellipse or circles). The areas are drawn as irregular shapes following the defined structural zone and the zone is enlarged where required to enclose the repository or controlled area.

Table 7.7 describes the structural models and implications of the structural models for E2 and E1 that are listed on Table 7.6. Two interpretations emerge immediately from examination of the random structural models (Tables 7.6 and 7.7). First, there are

Table 7.7 Summation of Structural Models for the Distribution of Volcanic Events

Structural Model	Evidence for Structural Model	Evidence Against Structural Model
Model 1: Crater Flat Volcanic Zone (Quaternary). This structural model is based on the definition of the Crater Flat volcanic zone of Crowe and Perry (1989). The dimensions of the zone are defined from the distribution of Quaternary volcanic centers.	*Supportive Evidence: northwest-trending linear distribution of volcanic vents, coincidence of the zone and vent alignment with the orientation of the surface of maximum eruption volumes, predominance of northwest structural trends in the Walker Lane structural zone, possible evidence of strike-slip offset of structural features in Paleozoic rocks.*	**Negative Evidence:small number of volcanic centers, distance of gap between Crater Flat and Sleeping Butte centers, secondary northeast alignment of vent clusters.**
Model 2: Crater Flat Volcanic Zone (YPB). Same as model 1 but the dimensions of the zone are defined by the distribution of the Pliocene and Quaternary volcanic centers of the Younger Post-caldera basalt.		
Model 3: Younger Post-Caldera Basalt. This is a non-structurally based zone defined by the distribution of Pliocene and Quaternary basalt centers of the Yucca Mountain region. It is the same as the Area of Most Recent Volcanism of Smith et al. (1990).		

Model 4: Crater Flat Volcanic field: This zone assumes that the major control of the occurrence of basalt centers is the local Crater Flat volcanic field, which is the primary site of Pliocene and Quaternary basaltic volcanism.	*Supportive Evidence: most of the Pliocene and Quaternary volcanic events have occurred in the Crater Flat basin, Crater Flat is the centroid of the distribution of units of the YPB, the Crater Flat basin may a remaining area of active tectonism.*	**Negative Evidence: Three possibly four major occurrences of basalt centers occur outside of the Crater Flat basin, the linear north-northwest alignment of basalt centers is oblique to the trend of the Crater Flat basin.**
Model 5: Strike-Slip Structural Control: Model A. This structural model is based on the inference that the alignment of basalt centers parallels a concealed northwest-trending right-slip fault of the Walker Lane structural system. The model has been described by Schweickert (1989).	*Supportive Evidence: linear northwest alignment of basaltic volcanic centers, proposed offset of structural features of Paleozoic rocks, Walker Lane structural setting, clockwise rotation of field magnetization directions of the Tiva Canyon Member.*	
Model 6: Strike Slip Structural Control: Model B. This structural model is based on the inference that the south-southeast edge of the Crater Basin is bounded by a north-northwest trending, right slip fault. The Pliocene and Quaternary basalt centers are inferred to have ascended along this fault zone and diverted to the northeast, following the maximum compressive stress direction.	*Supportive Evidence: steep gravity gradient paralleling proposed strike-slip fault, presence of north-northwest trending right-slip fault in the arcuate ridge at the south end of Crater Flat, clockwise rotation of field magnetization directions of the Tiva Canyon member.*	**Negative Evidence: extension of the fault to the north shows predominately dip-slip offset, no correlation between volume of basalt centers and proximity to proposed strike-slip fault.**

Model 7: Stress-field Dike: Quaternary centers. This structural model assumes basalt magma ascended along a concealed structure defined by the northwest orientation of vents of the CFVZ. The feeder dike or dikes following this structure diverted at shallow depths to follow the maximum compressive stress direction. The direction of dike propagation is either to the north-northeast or south-southwest.	*Supportive Evidence: coincidence of the zone of maximum erupted volume of magma with the CFVZ, symmetrical distribution of vents about line of center orientation, cluster of the Quaternary basalt of Crater Flat exceeds maximum likely dike extents.*	**Negative Evidence: multiple dikes are required only for the Quaternary basalt of Crater Flat, no recognized correlation between center chemistry and proposed dike systems.**
Model 8: Stress-field Dike: Pliocene and Quaternary centers. This model is identical to model 7. The dimensions of the structural zone are defined by the distribution of Pliocene and Quaternary volcanic centers.		
Model 9: Chain model. This structural model was proposed by Smith et al. (1990). They suggested basalt centers follow northeast-trending chains and the chains form zones of higher risk for future volcanic events.	*Supportive Evidence: northeast-trends of clusters of contemporaneous volcanic centers, parallelism of northeast trends of clusters to bedrock faults of Yucca Mountain, analogue comparison to other basaltic volcanic fields.*	**Negative Evidence: risk zones are unsuccessful as predicators of future events, basalts of the YPB do not follow existing faults, dimensions of chains from analog volcanic fields probably do not apply to the Yucca Mountain setting, inferred chain dimensions exceed maximum cluster lengths of centers.**

Model 10: Pull-Apart Basin: The Crater Flat basin is a pull-apart basin located at the termination of northwest-trending, strike-slip faults of the Walker Lane structural system. The basin is a tectonic basin and the basalt centers occur along extensional structures of the basin (Fridrich and Price 1992).	*Supportive Evidence: discontinuous northwest-trending faults of the Crater Flat area, multiple basalt cycles of the Crater Flat basin (10.5 Ma and Pliocene and Quaternary), gravity data showing steep, northwest-trending gradients, clockwise rotation of field magnetization directions of the Tiva Canyon Member.*	**Negative Evidence: the occurrence of basalt centers is not confined to the pull-apart basins, limited continuity of northwest-trending fault systems.**
Model 11: Caldera Model. This model, which has been described most recently by Carr (1990), ascribes the origin of the Crater Flat basin as a depression formed by caldera collapse associated with eruption of the Crater Flat tuff. Basalt centers are inferred to be following the ring-fracture system of the caldera complex.	*Supportive Evidence: Crater Flat basin is located on the south part of the southwest Nevada volcanic field, basalt centers are located commonly along ring-fracture zones of caldera complexes.*	**Negative Evidence: caldera origin of the basin is controversial, basalt centers occur beyond the confines of the Crater Flat basin, basalt centers occur across the caldera floor and resurgent dome and are not confined to the ring-fracture zone.**
Model 12: Northeast Structural Zone: This is a composite model proposed primarily by Carr (1984; 1990; Kawaich-Greenwater Rift zone) and Wright (1989; Amargosa Desert Rift zone). The potential Yucca Mountain site is included in a diffuse northeast trending, tectonic-volcanic rift zone. Sites of basaltic volcanism are distributed in the zone.	*Supportive Evidence: northeast-trending zone of closely spaced, normal faulting, orientation of caldera centers in the southwest Nevada volcanic field, northeast trending structural trough that is partly delineated by gravity data, concentration of basaltic volcanic centers in the northeast-trending structural zone.*	**Negative Evidence: structural zones may be a composite of multiple different structures, basalt centers are present both in and outside of the structural zone, northwest linear alignment of basalt centers.**

Model 13: Crater Flat and Buckboard Mesa volcanic zone: Smith et al. (1990) proposed that the basalt centers of Crater Flat and the basalt of Buckboard Mesa form a northeast trending zone that extends through the Yucca Mountain area.	*Supportive Evidence: local northeast trends of basalt vents in Crater Flat, existence of the basalt centers of Crater Flat, and Buckboard Mesa.*	**Negative Evidence: Distance of separation between the Crater Flat basalt centers and the basalt of Buckboard Mesa, interruption of the northeast-trends by oblique structures of the Timber Mountain-Oasis Valley caldera complex, northwest-trending vent alignments of the basalt of Buckboard Mesa.**

two classes of models. These include: 1) structural models where the enclosing zone must be expanded to allow for intersection of the repository and controlled area (first 11 models listed under the random structural models of Table 7.6), and 2) structural models that include the repository and part or all of the controlled area in the zone. Second, the structural models cannot be considered independent of E1. Selection of some structural models eliminates individual or groups of volcanic centers from inclusion in the zone. This reduces the recurrence rate for those models, a factor that must be considered in estimations of the probability of magmatic disruption.

The geometric mean of the structural models using forced intersection of the repository is 5.93×10^{-3}. Interpretation of this value requires some judgments. First, a judgment must be made about the structural viability of the geometry of forced intersection. If the geometry of intersection is not realistic, the geometric mean represents a worse case value. Second, a judgment must be made concerning how reasonable the structural models are for the Yucca Mountain setting. The majority of structural models **do not** include the potential repository or the controlled area in the defined structural zones. This is consistent with the geologic record. During the past 4.6 Ma, there has been intermittent basaltic volcanism in the basins of the Amargosa Valley, Crater Flat and in the CFVZ (which includes parts of the basins). None of the events occurred in the potential repository or controlled area. Moreover, the geometry of the structural models indicates these areas lie outside of the controlling zones of basaltic volcanism. The required judgment is whether the models are sufficiently valid to conclude that Yucca Mountain is not located in the structural zones. Third, a judgment is required concerning the likelihood of the continued control of the structural zones on the distribution of future volcanic events. There are two aspects to this judgment. Is there a reasonable degree of confidence that these structural zones will continue to control the sites of future volcanic activity, if such activity occurs? Is the potential for spatial dispersion outside of the zones sufficient to lead to future penetration of the repository or controlled area? The geologic record of the location of past volcanic events provides a reasonable degree of support for positive answers to both questions. That is the structural zones will continue to control sites of volcanism and the sites of volcanism are unlikely to extend into the potential repository or controlled area. The basis for the judgment is the geologic record. There is a 4.6 Ma record of volcanic events supporting these conclusions. The required 10,000 year isolation period of radioactive waste represents a span of only 0.2% of the 4.6 Ma record of basaltic volcanism. We conclude therefore, that the likelihood of significant future changes in the structural controls of volcanism must be extremely low. This means that the geometric mean of 5.9×10^{-3} must be regarded as a worse case value and the most likely value of the disruption ratio must be less than this value.

The intersection models of Table 7.6 represent structural models that include the potential repository site and the controlled area in the structural zones. The geometric mean for these models is 3.8×10^{-3}. A judgment must be made whether this value represents a reasonable likely value or is skewed toward either a worse or best case value. Two lines of evidence support the interpretation that this is a worse case value. First, no past volcanic events have occurred in the potential repository or controlled areas. Second, Yucca Mountain is a mountain range. The volcanic events that define the structural zones that allow inclusion of Yucca Mountain in the zones **all occur in basins in the zones.** All basalt centers of Crater Flat are in the interior of the Crater Flat basin with one event at the range edge (the Lathrop Wells center). The basalt of Buckboard Mesa is located in the moat depression of the Timber Mountain caldera. We conclude therefore that the geometric mean of intersection models is not a most likely value. It is shifted toward worse case values.

The final part of Table 7.6 is a list of structural models without expansion of the areas to include the repository or the controlled area. These models are listed for the insight they provide on the potential range of the distribution of worse case values of the disruption ratio. Because none of the models require intersection of the repository or the controlled area, these values must all be less than the likely value for the disruption ratio. This is consistent with logic of the assembly of data for other parts of Table 7.6. The geometric mean of the structural models is 6.85×10^{-3}. This value is greater than the forced intersection and intersection models of Table 7.6.

Considerable additional insight can be gained on the disruption ratio for the Yucca Mountain region through comparisons with the structural controls of basaltic volcanic fields. The analog fields for comparison, are again, the Lunar Crater and Cima volcanic fields. There are sufficient numbers of centers in these fields to assess the spatial variability of sites of volcanism. Fig. 7.9 is a plot of the location of volcanic vents in the Lunar Crater field. The locations are shown as x,y coordinates transposed from the latitude and longitude coordinates of the vents. The solid line of Fig. 7.9 is the distance weighted least squares regression of the distribution of the vents. The regression curve is near linear reflecting the strong degree of structural control of the vents of the field. That elongation is illustrated on two scales. First, the field is elongate in a north-northeast direction. Second, clusters of vents tend to occur along north-northeast trending fissures. The covariance in the x,y coordinates of the volcanic vents is examined by a constructing bivariate gaussian ellipsoid of the distribution of the vents. Fig. 7.10 is a plot of a bivariate gaussian ellipsoid at the 50% confidence interval.

This provides a good test of whether the vent distribution is normally distributed. The 50% confidence interval should divide the distribution in equal segments with 50% of the vents inside the ellipsoid and 50% outside the ellipsoid. The data for the Quaternary vents of Lunar Crater are divided equally by the 50% confidence ellipsoid. Next, the spatially variability of the vent distribution is examined by constructing ellipsoids at increasing intervals of confidence. A key question answered from these calculations is how do the confidence intervals of the vent distribution change with distance from the field? That is, what is a "standoff" distance from a large volume volcanic field needed to reduce the confidence or likelihood of intersection by a volcanic event?

These questions are examined by Fig. 7.11. First, a separate calculation is used to locate the centroid of the Lunar Crater volcanic field. The small ellipse in the center of the field marks the boundaries at a 90% confidence level of the centroid of the distribution of

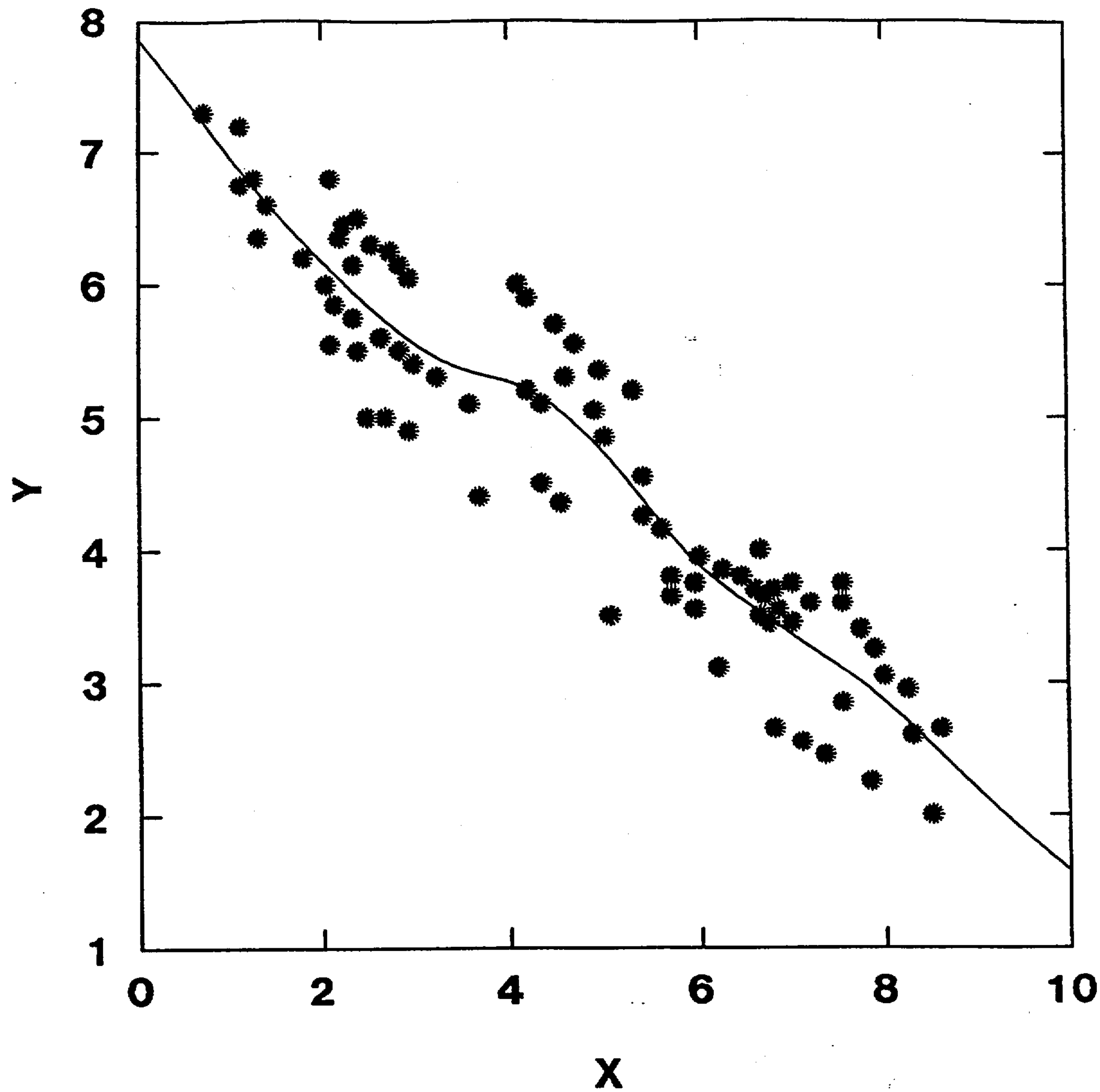


Fig. 7.9 X,Y plot of the location of volcanic vents in the Lunar Crater volcanic field, Nevada. The asterisks mark individual vents. The X and Y axis are the longitude and latitude coordinates of the vents, converted to artificial X,Y coordinates. The solid line is the distance weighted least squares fit of the location of the volcanic vents. The Lunar Crater volcanic field shows strong structural controls in the location of the vents. This is reflected in the linear distribution of the vents and the highly distance weighted least squares fit.

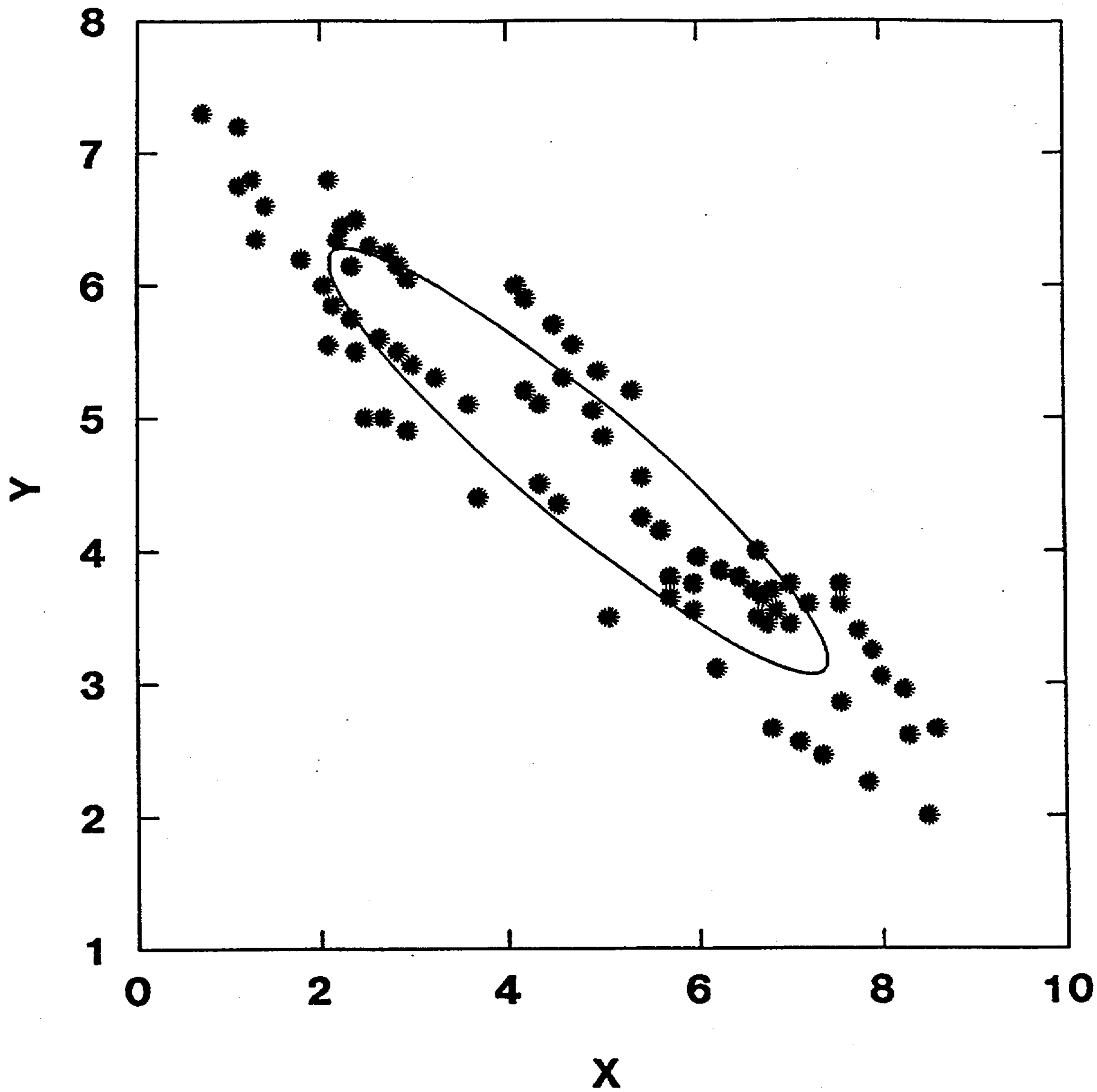


Fig. 7.10 X,Y plot of the location of volcanic vents in the Lunar Crater volcanic field, Nevada, using the same plotting method as Fig. 7.9. The solid line is the bivariate gaussian ellipsoid fitted to the x,y variance of the data at the 50% confidence interval. The ellipsoid divides the data set into two near-equal subsets.

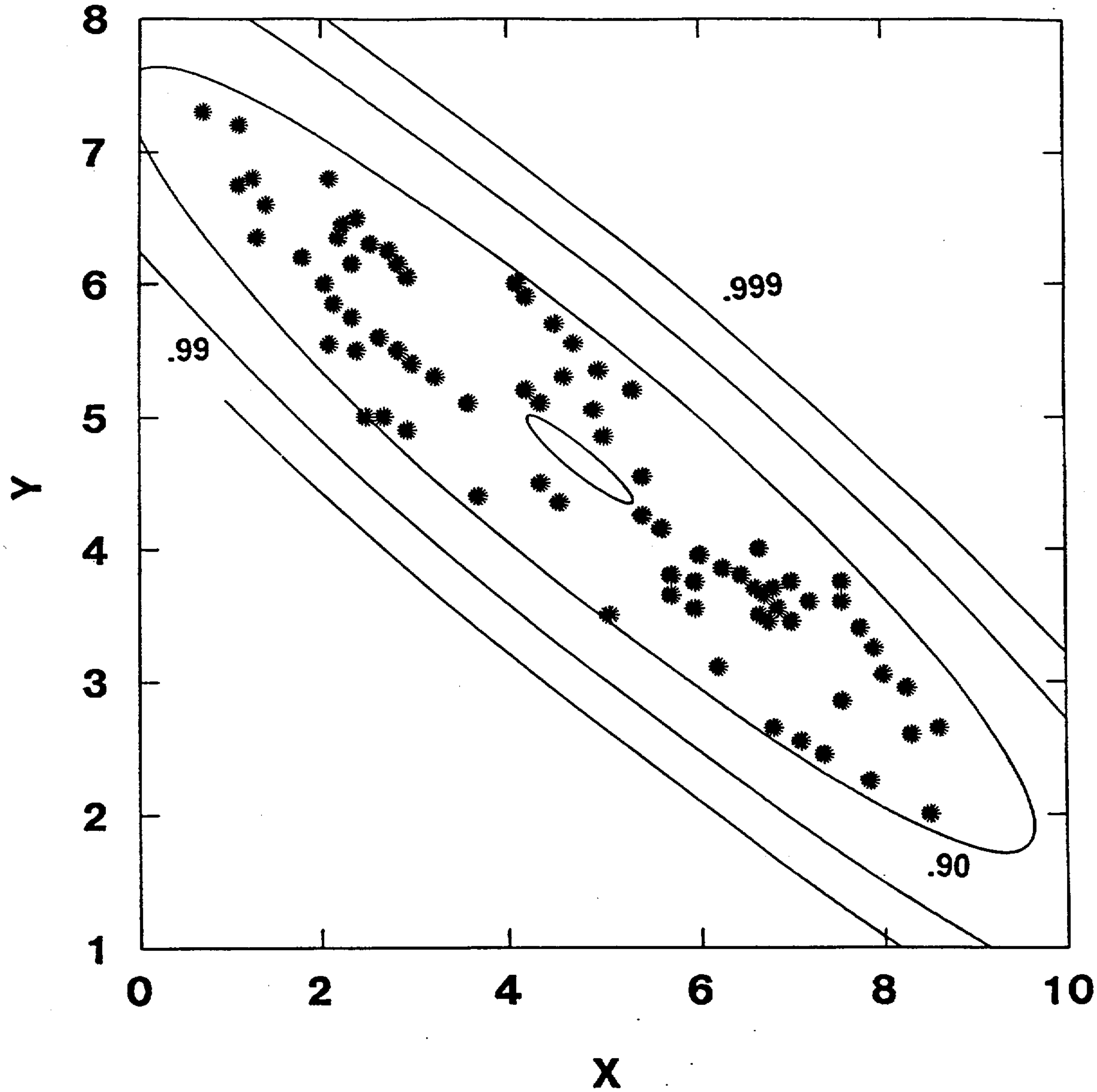


Fig. 7.11 X,Y plot of the location of volcanic vents in the Lunar Crater volcanic field, Nevada, using the same plotting method as Fig. 7.9. The small ellipse is the location of the field centroid drawn at the 90% confidence interval. The enclosing ellipsoids are the .90, .99 and .999 confidence intervals for the x,y variance of the vent locations.

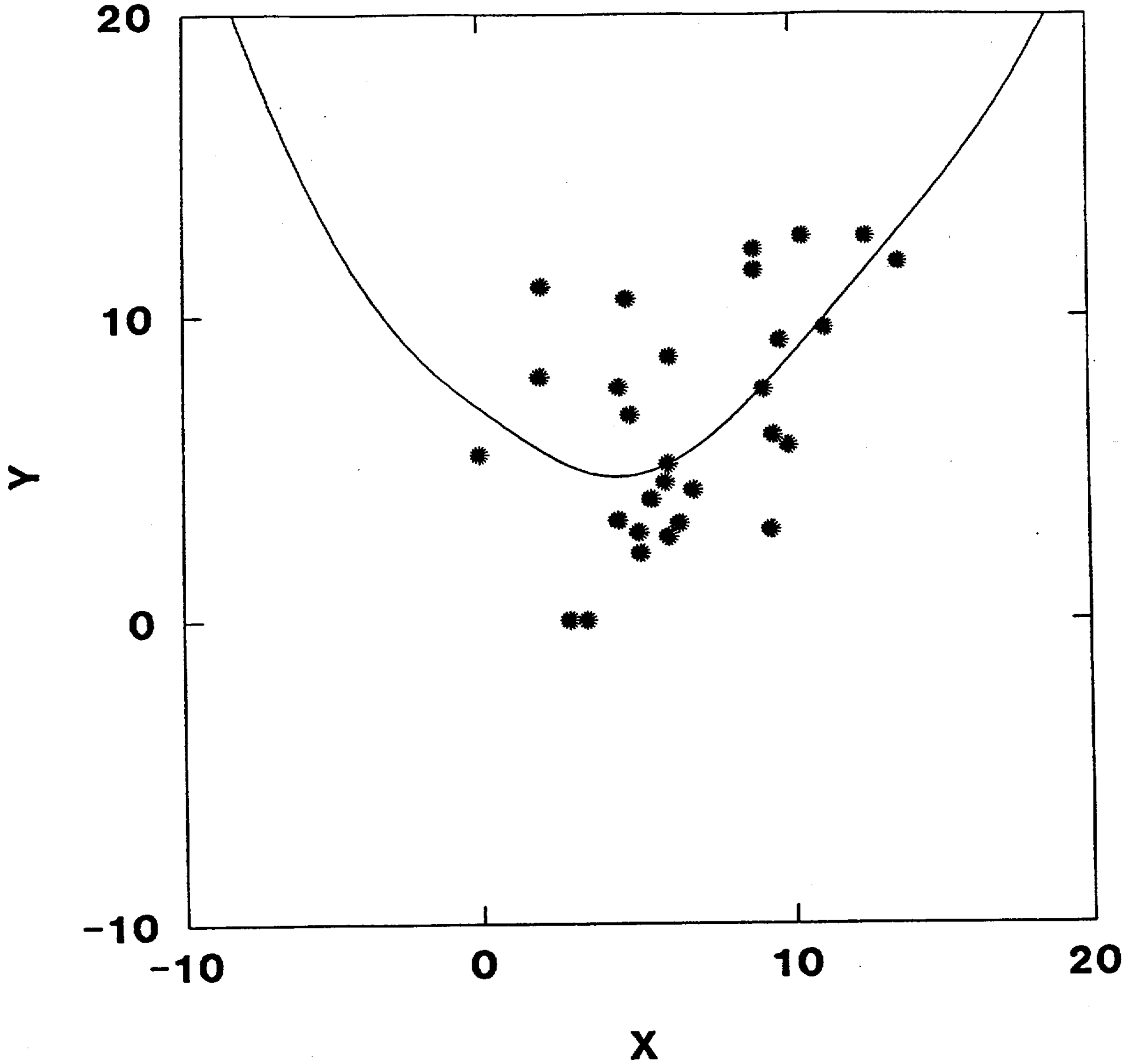


Fig. 7.12: X,Y plot of the location of volcanic vents in the Cima volcanic field, California. The asterisks mark individual vents. The X and Y axis are the longitude and latitude coordinates of the vents, converted to artificial X,Y coordinates. The solid line is the distance weighted least squares fit of the location of the volcanic vents. The Cima volcanic field shows little structural control of the spatial location of the vents as shown by then nonlinear distance weighted least squares fit.

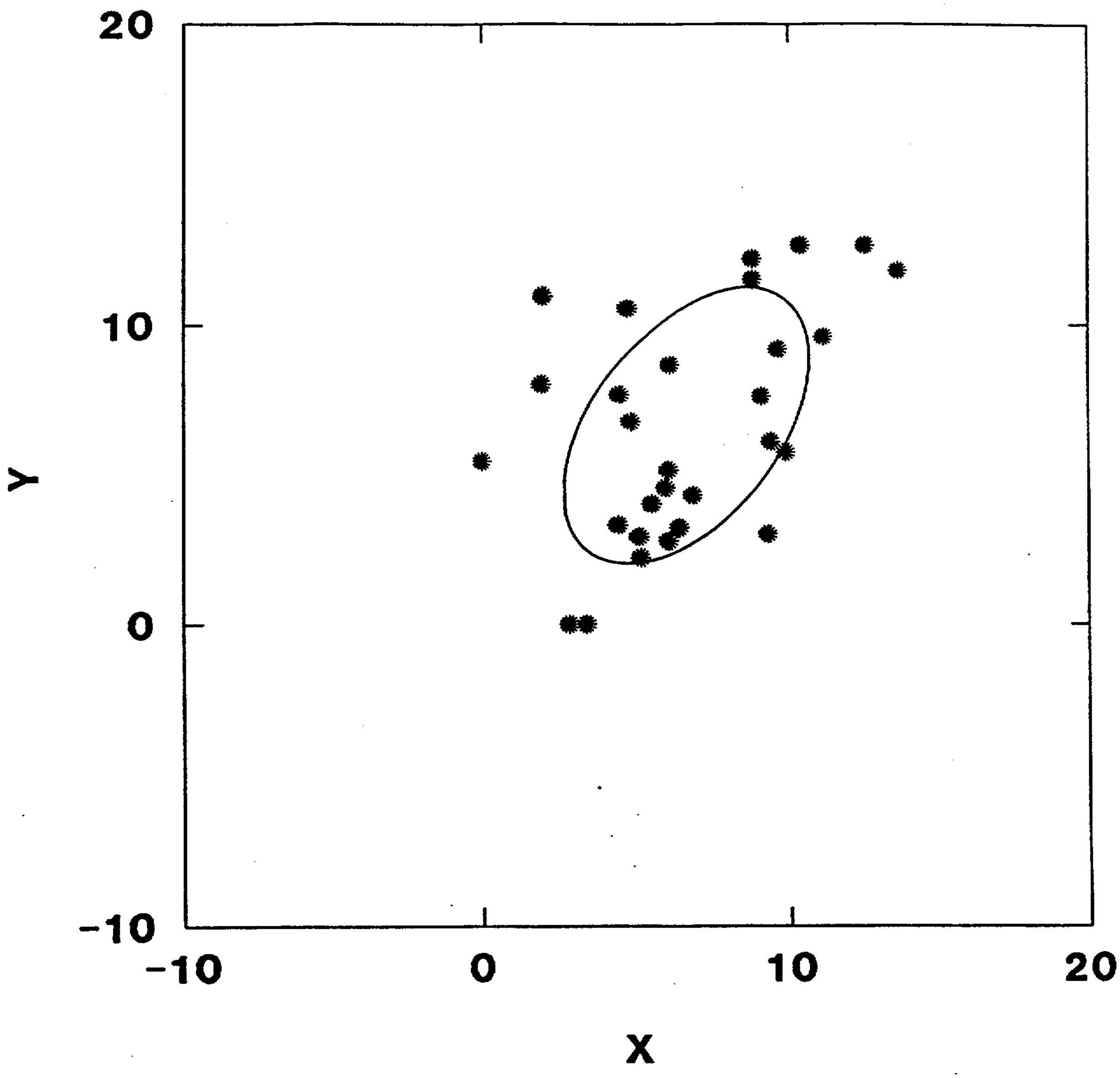


Fig. 7.13 X,Y plot of the location of volcanic vents in the Cima volcanic field, California, using the same plotting method as Fig. 7.12. The solid line is the bivariate gaussian ellipsoid fitted to the x,y variance of the data at the 50% confidence interval. The ellipsoid divides the data set into two near-equal subsets.

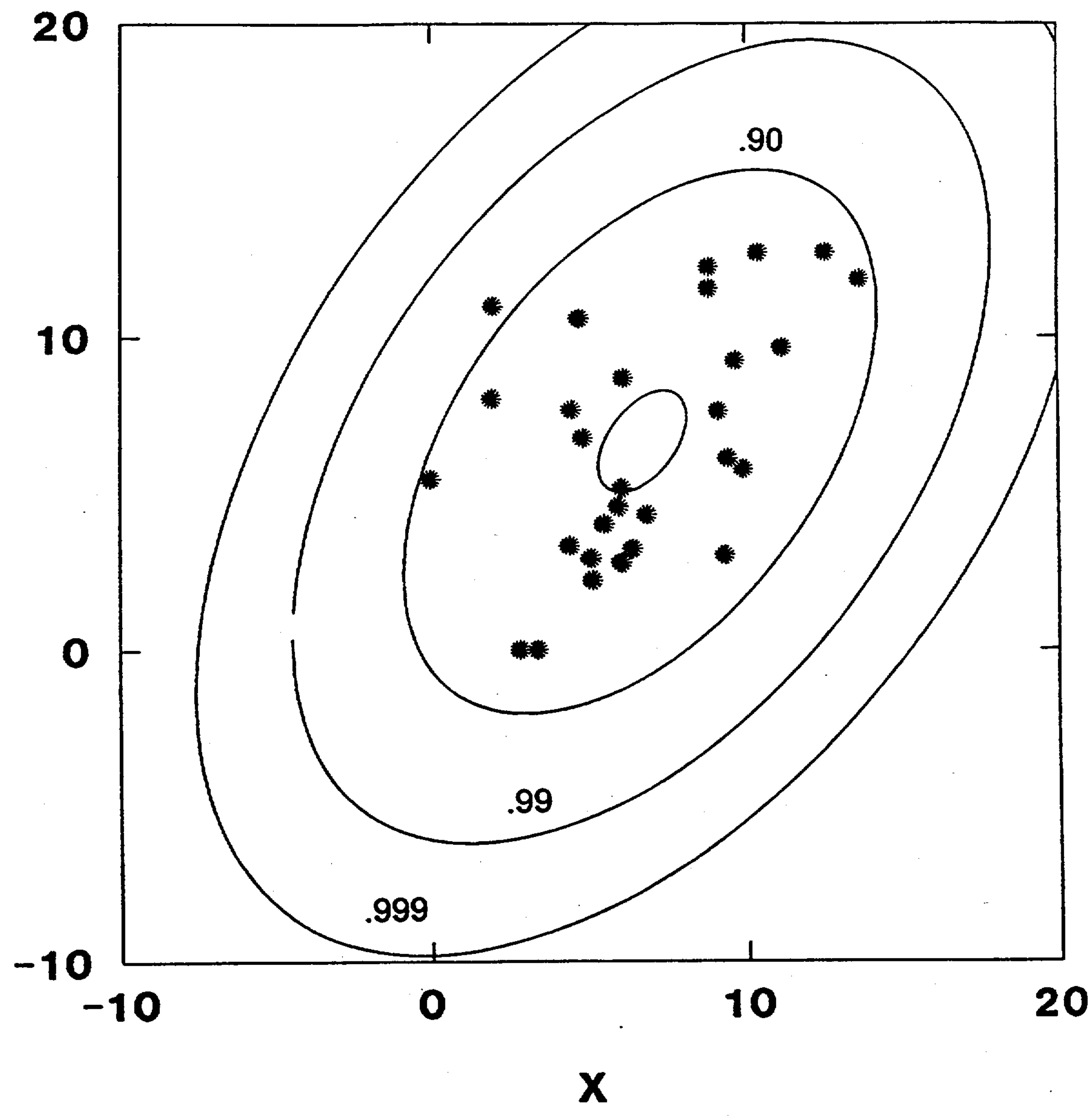


Fig. 7.14 X,Y plot of the location of volcanic vents in the Cima volcanic field, California, using the same plotting method as Fig. 7.12. The small ellipse is the location of the field centroid drawn at the 90% confidence interval. The enclosing ellipsoids are the .90, .99 and .999 confidence intervals for the x,y variance of the vent locations.

the volcanic vents. The location of the field centroid has varied through time; there is evidence of northeast migration of volcanic vents in the field through time (Scott and Trask 1971; Crowe et al. 1986; Bergman et al. 1985). A most likely value of 3.6×10^{-2} is the best approximation for the disruption ratio of the probability of disruption of the controlled area. A most likely value of .34 is used for the disruption ratio of the probability of disruption of the Yucca Mountain region.The selections of values are based on partly judgmental logic derived from the probability table of values of repository disruption (Table 7.6). The geometric mean of the intersection models is 3.8×10^{-3} (Table 7.6). This must be skewed toward the worse case values because alluvial areas are about one-third of the area of the intersection values and all volcanic events are in the alluvial valleys. Additionally, a value of 3.8×10^{-3} is similar to the geometric mean of all published values of the disruption ratio, which as noted above, is skewed toward worse case values. The probability of disruption must be less for the range interiors than the valleys. The potential Yucca Mountain site is located outside of the distribution zones of basaltic centers for most models of the structural controls of volcanic activity. The probability of disruption of the potential repository must be less than the structural control models. The random model may provide a reasonable approximation of the most likely value of the disruption probability.

5. Probability of Magmatic Disruption. The estimates of the most likely values for E1, the recurrence rate of volcanic events, and E2, the disruption ratio can be combined using the exponential equation for the conditional probability of repository disruption. The exponential equation is approximately linear for t = 10,000 years so the events can be multiplied to satisfy the conditional probability. This gives a most likely value for the probability of magmatic disruption of the repository, the controlled area and the Yucca Mountain region. These values are 6.5×10^{-9} yr^{-1} for intersection of the repository, 9.4×10^{-8} yr^{-1} for the controlled area, and 8.8×10^{-7} yr^{-1} for the Yucca Mountain region. These values were calculated primarily for the likelihood of a volcanic eruption through the respective areas of interest **associated with the direct releases of radioactive waste in the accessible environment.** We currently have no evidence to indicate that the probability of intruding the areas is different from the eruption probability. However, the probability of an intrusion is likely to be higher for the case of secondary or coupled releases. The calculated value for this probability case requires data on the geometry of intrusions and is a topic of ongoing studies.

The most likely value of the disruption of the repository **meets or is less than** the requirement of an event occurrence of less than 1 in 10,000 in 10,000 years. The most likely values of disruption of the controlled area and the Yucca Mountain region **do not meet** the requirement of an event occurrence of less than 1 in 10,000 in 10,000 years. These scenario categories will require assessment of the probability of exceeding regulatory releases and/or calculation of the likely releases of radioactive waste in the accessible environment.

The most likely value of 6.5×10^{-9} yr^{-1} for disruption of a repository is not a completely reliable estimate of the probability of magmatic disruption. The exponential combination of most likely values of E1 and E2 leads to a slight but possibly significant **overestimation** of the occurrence probability. This is because the recurrence rate for the most likely value

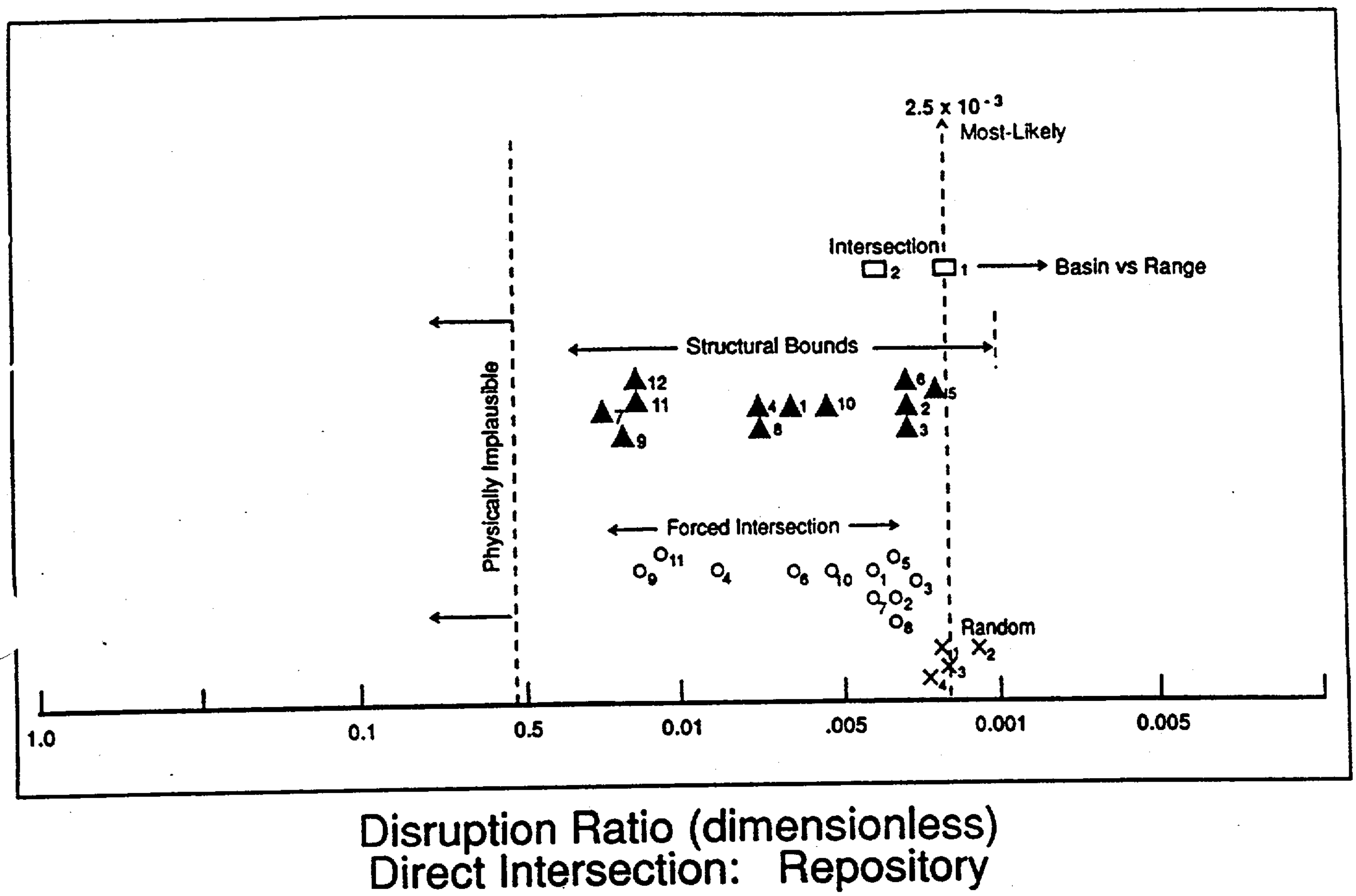


Fig. 7.15 Plot of the distribution of the disruption ratio for direct intersection of the repository. Data models and values for the disruption ratio are from the Table 7.6. The X's mark values using the random models of Crowe et al (1982). The open circles are structural models extended to encompass the repository area. The filled triangles are the bounds established by structural models that do not intersect the repository. The open squares are structural models that incorporate or intersect the repository area. The arrow marks the direction of change in the models if the basin versus range interior controls of the location of centers was included. The dashed line labeled most likely represents the most-likely or the value chosen to represent the central tendency of the distribution of values for the disruption ratio. The line labeled physically implausible represent bounding values that bound the largest possible values of the disruption ratio based on geometric considerations.

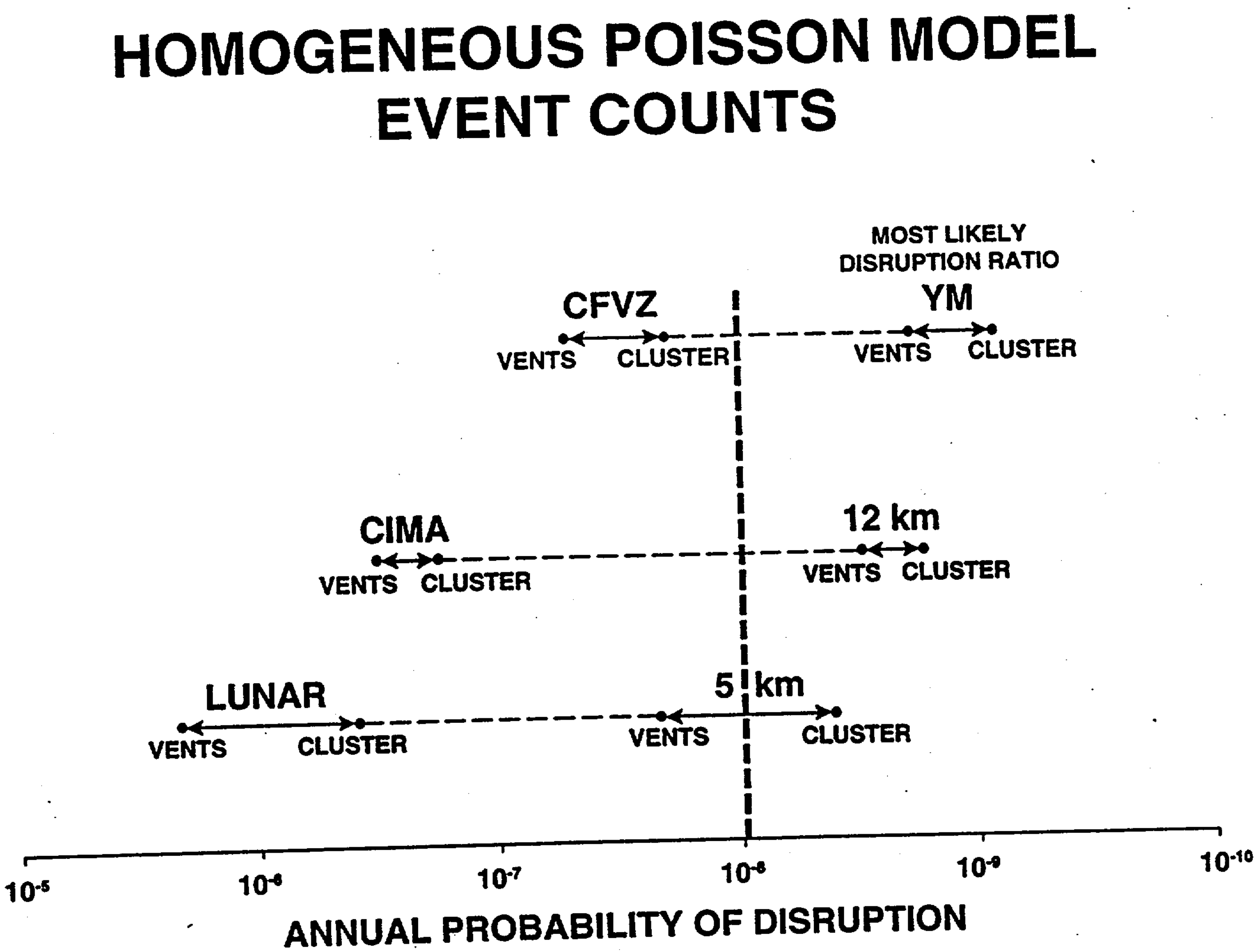
of repository disruption has not been modified for specific models of the disruption ratio. A significant number of structural models used to calculate the disruption ratio exclude some of the volcanic events used to estimate the recurrence rate. Therefore the estimate of the most likely value of the recurrence rate should be smaller than the value used to calculate the most likely value of the probability of magmatic disruption of the repository. This constraint, which is based on the geometry of individual structural models of E2, applies also to the probability of magmatic disruption of the controlled area and to a lesser degree, the probability of disruption of the Yucca Mountain region. Calculation of refined values of the most likely estimate of the probability of magmatic disruption of the respective areas will require further work. These refinements will be undertaken as part of simulation modeling of the probability attribute values and the probability of magmatic disruption of the repository, the controlled area, and the Yucca Mountain region. The most important conclusions from this stage of work are the recognition that the probability of magmatic disruption of the repository is less than 1 in 10,000 in 10,000 years and this value is based on slightly conservative estimations.

An additional perspective of the magnitude of the risk of future volcanism for the Yucca Mountain site can be provided by another comparison with analog volcanic fields. The bounds can be examined of the probability of magmatic disruption of a theoretical repository located in either the Lunar or Cima volcanic field. This provides a comparative assessment of volcanic risk for a setting that must exceed the probability of magmatic disruption of a repository at the potential Yucca Mountain site.

Figure 7.16 illustrates the probability of location of a repository within and at set distances from the Lunar Crater and Cima volcanic fields. The annual probability of repository disruption for location of repository in the interior of the highest vent density part of the Lunar Crater volcanic field is 1×10^{-6} yr^{-1}. This is based on a homogeneous Poisson model of event counts (82 Quaternary vents for an event rate of 4.5×10^{-5} events yr^{-1}), a field area of 245 km^2 (disruption ratio of 2.4×10^{-2}) and a repository area of 6 km^2. The gaussian bivariate ellipsoid calculations of the change in likelihood of intersection with distance from the center of the field show that the probability of magmatic disruption is reduced to 1×10^{-7} yr^{-1} at 5 kilometers from the vent centroid of the field and to 1×10^{-8} yr^{-1} at a distance of 7 kilometers from the center of the field. If cluster counts are used for the Poisson model, the respective values are 3.7×10^{-7} yr^{-1} in the field interior, 3.7×10^{-8} at a distance of 5 kilometers and 3.7×10^{-9} events per year at a distance of 7 kilometers from the field center. Comparison against the occurrence criterion of 1 in 10,000 in 10,000 years shows that a repository located 7 kilometers from the center of the Lunar Crater volcanic field would **not be disqualified** because of the risk of volcanism.

The same calculations can be repeated for the Cima volcanic field, a field that shows less structural control of the location of eruptive vents. The homogeneous Poisson model of event counts is 1.6×10^{-5} event yr^{-1}, the disruption ratio is 2.0×10^{-2}, the probability of magmatic disruption of a 6 km^2 repository in the high-cone density part of the field is 3.2×10^{-7} yr^{-1}. The same probability based on cluster counts is 2×10^{-7} yr^{-1}. Siting a repository 12 kilometers from the vent centroid of the field reduces the count-count based probability

Fig. 7.16 Plot of the distribution of the probability of magmatic disruption of the repository for the Lunar Crater, and Cima volcanic fields and the potential Yucca Mountain site. The recurrence rate values for this figure are based on homogeneous poison event counts using the maximum vent and minimum models to constrain the range of the recurrence rates. The positions labeled as Lunar and Cima are the probability of disruption of a theoretical repository located in the Lunar or Cima volcanic fields. The position label CFVZ is the probability of disruption of a theoretical repository located in the Crater Flat volcanic field. The position labeled 5 km on the Lunar Crater line, represents the values of the probability of magmatic disruption for a repository located 5 km from the centroid of the vent distribution. This location straddles the line of probability equal to 1 in 10,000 in 10,000 years. The position labeled 12 km on the Cima line, represents the values of the probability of magmatic disruption for a repository located 12 km from the centroid of the vent distribution. This location meets the criterion of < 1 in 10,000 in 10,000 years. The position labeled YM on the Crater Flat Volcanic Zone line, represents the values of the probability of magmatic disruption of a repository at the Yucca Mountain site. This was calculated using the most likely value for E2 and is a different calculation than those shown for the Lunar and Cima volcanic fields.



of magmatic disruption to 3.2×10^{-8} yr^{-1}. It is reduced to 3.2×10^{-9} yr^{-1} at a distance of 15 kilometers from the vent centroid. The analogous values for the cluster-count model are 2×10^{-8} yr^{-1} at 12 kilometers and 2×10^{-9} yr^{-1} at 15 kilometers. Again, a repository located 15 kilometers from the center of the Cima volcanic field would meet the volcanic occurrence criterion of 1 in 10,000 in 10,000 years.

What is the point of these calculations? They illustrate that the risk of volcanism even near the most active volcanic fields of the basin and range province is very low. There are two reasons why this is true. First, volcanic eruptions in the most active basaltic volcanic fields of the basin and range are infrequent events even compared with the required isolation time of high-level waste. Second, the area of a repository is small compared with the area of volcanic fields. The low event rates coupled with the requirement of direct intersection of a repository makes the conditional probability of a volcanic event occurring and disrupting a repository very low. By comparison this perspective illustrates that it is difficult, even with the increased uncertainty of the small number of volcanic events in the Yucca Mountain region, to obtain a probability of magmatic disruption that exceeds the analogous probability near high-event rate volcanic fields. Collectively the combined methods of analyzing the occurrence probability of direct intersection of a repository by a future volcanic event suggest strongly that this risk does not disqualify the potential Yucca Mountain site from consideration for underground storage of high-level radioactive waste.

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SECTION VIII: STATUS AND IMPLICATIONS OF FUTURE STUDIES

I. INTRODUCTION

Section VIII of the Volcanism Status Report describes, from three perspectives, the current state of information used in assessments of volcanic risk. First, the completeness of information is examined. Second, expectations of how new information may affect the assessment of risk for the potential Yucca Mountain site are described. Third, areas of controversy in volcanism studies are described and their potential affects on risk assessment studies are considered. This section of the Volcanism Status Report is organized following the activity structure of two of the volcanism study plans: 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository, and 8.3.1.8.5.1 Characterization of Volcanic Features. The activities of the third study plan (8.3.1.8.5.1) are described first because it is the data gathering part of the volcanism studies. Finally, this section is written in abbreviated form because substantial discussions of individual topics have been provided throughout the status report.

II. STUDY PLAN 8.3.1.8.5.1 CHARACTERIZATION OF VOLCANIC FEATURES

A. Activity 8.3.1.8.1.1.1 Volcanism Drillholes

Three aeromagnetic anomalies representing buried volcanic centers or intrusions remain to be explored by drilling. Two of the anomalies are in the Amargosa Valley. These anomalies are located in areas where rates of alluvial sedimentation are expected to be lower than the drilled anomaly site south of the town of Amargosa Valley. The latter site has been shown to be 4.4 Ma. It is expected that anomaly sites, if they are buried volcanic centers, are probably > 4 Ma. In this case, the centers would have little effect on the recurrence rate of volcanic events based on magma-output rates. They can have no more than about a 20% effect (increase) on the recurrence rate based on event counts. The anomaly site in southern Crater Flat is unusual because it is a positive anomaly and thus may be reversely magnetized. All of the known basaltic volcanic events in Crater Flat are positively polarized. However, the anomaly, if it is a buried basalt center, is expected to be > 3.7 Ma because 3.7 Ma centers are exposed at the surface of Crater Flat.

A remaining unknown for this activity is whether any of the anomaly sites could be basaltic intrusions. To date none of the drilled anomalies have been shown to be intrusions. The drilling record (cuttings, not core) of one drilled anomaly site in Amargosa Valley does not allow for assessment of intrusive versus extrusive origin. However, because the anomaly is produced by a basalt that is > 4 Ma, the event is insignificant even if an intrusion.

Finally, the issue of recurrence of silicic volcanism will be reexamined if any drilled anomalies are produced by silicic volcanic rocks that are of Pliocene or Quaternary age. This possibility appears unlikely because of the absence of post-8 Ma silicic volcanism in the region, and the small size of the remaining undrilled anomalies.

B. Activity 8.3.1.8.5.1.2 Geochronology Studies

There are three remaining goals of continuing geochronology studies. The first is to establish the age of the basaltic volcanic centers of the Yucca Mountain region with an acceptable degree of confidence. Second, additional geochronology data will be used to continue to test monogenetic versus polycyclic eruption models for the volcanic centers. Resolution of the different eruption models is not significant however, because both models are being considered in Study Plan 8.3.1.8.1.2, Physical Processes of Magmatism and Effects on the Potential Repository. Third, the data used for geochronology assessments must meet the Quality Assurance requirements of the Yucca Mountain Site Characterization Project (YMP). We examine the status of information for these three topics for individual centers of the Younger Post-caldera basalt (YPB).

1. Basalt of Thirsty Mesa. Duplicate samples of basalt lava flows collected from the basal and upper parts of the basalt of Thirsty Mesa have been submitted for K-Ar age determinations using the complete fusion, $^{40}Ar/^{39}Ar$ method. Results from these studies, which will meet the quality assurance requirements, are expected during the first part of calendar year 1993. We do not anticipate any problems establishing the chronology of this center because it is known to be > 4 Ma and the K-Ar method should be reliable for rocks of this age. A remaining uncertainty is whether there is evidence of an extended duration of volcanic activity at this center. The Thirsty Mesa center is largest volume center of the YPB (3 km^3). Should evidence be discovered of an extended duration of activity more detailed chronology work involving primarily acquisition of additional K-Ar age determinations and paleomagnetic data may be required. Only limited data should be needed because this is a Pliocene center and the volume of erupted magma has declined dramatically from the Pliocene to the Quaternary.

2. Basalt of Amargosa Valley (aeromagnetic anomaly). Duplicate samples of cuttings were collected from the exploratory drill hole that penetrated the aeromagnetic anomaly. These samples were submitted for K-Ar age determinations and the results are expected in the first part of calendar year 1993. These data will meet quality assurance requirements. An age of 4.4 Ma has been obtained for the basalt cuttings from this anomaly by workers outsider the Yucca Mountain Project. If this age is verified, no further studies will be required. The drilling of the aeromagnetic anomaly was completed by an independent company and does not meet the quality assurance requirements of the YMP. However, the basalt center is Pliocene in age and has limited affect on risk assessment studies. Little additional work is needed other than qualified data for the age of the volcanic center.

3. Basalt of Southeast Crater Flat (3.7 Ma). Reproducible whole rock K-Ar age determinations of about 3.7 Ma have been obtained by a variety of workers at different analytical laboratories. These data either do not meet current quality assurance requirements or were collected before full implementation of the full quality assurance program. We will obtain additional K-Ar age determinations under the current quality

assurance program to both test and verify past data. No significant changes are anticipated in the chronology of this volcanic event.

4. Basalt of Buckboard Mesa. The basalt of Buckboard Mesa has been dated by the K-Ar method by a variety of workers at independent laboratories. Results of this work are both reproducible and consistent. However, none of the age determinations either meet or were completed under the qualified quality assurance program. We will obtain additional K-Ar age determinations under the current program controls to both test and verify past data. No significant changes are anticipated in the chronology of this volcanic center.

5. Quaternary Basalt of Crater Flat. The Quaternary basalt centers of Crater Flat have yielded largely consistent age determinations by the K-Ar method. These ages were obtained at independent K-Ar analytical laboratories. The data span a range of about 1 Ma although reproducible data have been obtained for individual centers. None of the data meet the current quality assurance requirements except for data collected by the State of Nevada. Recent results using step-heating, $^{40}Ar/^{39}Ar$ release spectra for basalt samples from the Lathrop Wells center show that it is possible to obtain increased precision for age determinations using this method. This method will be applied under full program controls to attempt to resolve the problems of the reproducibility of past age determinations.

A current unresolved problem for these centers is whether separate centers were formed by a single or multiple pulses of magma. If formed by multiple pulses of magma, there are insufficient data to resolve the ages of the magma pulses. Additionally, preliminary soil data show that there may be differences in the degree of soil development on volcanic units of some of the centers (Little and Black Cone centers versus Red Cone center). Additional K-Ar age determinations will be obtained for the Quaternary basalt centers of Crater Flat to obtain fully qualified data and to attempt to resolve the question of possible age differences between individual centers. Additional soils studies will be conducted at each of the four centers to test models of possibly different soil ages of volcanic unit. These studies will be implemented by construction of soil pits. Paleomagnetic data may be obtained for the individual centers if it is judged to be an aid in resolving interpretations of chronology data.

The spans of likely results from future chronology studies for these centers have been incorporated in models of the recurrence rate of volcanic events for the Yucca Mountain area. New results may improve the ability to distinguish different models used for the recurrence rates but are unlikely to change significantly the results of the probability assessments. The primary purpose of additional studies is to provide fully qualified data and to increase confidence in data by application of cross-checking methods.

6. Basalt of Sleeping Butte. K-Ar age determinations of the Sleeping Butte basaltic centers have yielded generally reproducible results consistent with preliminary information on the soils and geomorphic features of the centers. However, the precision of most of the age determinations obtained has been fair to poor. New age data obtained by workers outside the YMP using step heating, $^{40}Ar/^{39}Ar$ release spectra have been encouraging and

application of this method may resolve the precision problems. None of the existing data were obtained under a full quality assurance program. U-Th age determinations using solid source mass spectrometry of a lava flow from the Little Black Peak center should be completed in early calendar 1993. Additional samples will be submitted for K-Ar age determinations under a fully qualified program. We anticipate that these results should be sufficient to establish the chronology of the centers with acceptable confidence. A remaining problem is to attempt to constrain the age of the youngest volcanic event of the Hidden Cone center. This will require trenching at the center to expose cross-sections through the older and potentially younger, cone-slope apron and cone-slope deposits, respectively. We will attempt to date the scoria-fall deposits of the youngest event by the cosmogenic helium method supplemented with soils studies and thermoluminescence age estimates of any appropriate deposits exposed in trenches.

These studies will test the applicability of polycyclic versus monogenetic models of the Hidden Cone center and provide fully qualified, cross-calibrated geochronology data.

7. Lathrop Wells Volcanic Center. The geochronology studies for the Lathrop Wells volcanic center are beginning to converge. We now have sufficient data to bracket the age of the lava flows of the center between 70 and 140 ka. One remaining inconsistency is the interpretation of a thermoluminescence of 25-30 ka for the Ql_3 lava unit. Additionally, the stratigraphic position of the Ql_3 lava has not been completely resolved. The age of the main cone is probably greater than 40 ka and less than the age of the lava flows (< 70 ka). The age of the youngest volcanic event at the Lathrop Wells center, the tephra deposits interbedded with soil, is about 10 ka. We have no reason to suspect that these are not valid age estimations (thermoluminescence measurements). We have been unable to relate the tephra units to a volcanic event and can conclude only that the tephra units were not associated with eruptions of the main cone. We have established that the tephra units are very small volume and local. They are found only on the southeast flank of the main cone. Therefore they are not a major event in the evolution of the volcanic center. Additionally, there is not complete agreement that the tephra events represent a volcanic event. We include the tephra units in polycyclic models of the Lathrop Wells center. We have not included the event in volume-predictable models for calculating the recurrence rate of events. The reason for this is the young age gives longer recurrence times and lower recurrence rates. We will continue to study and assess the importance of the tephra units at the center and factor the event into risk assessment. Acquisition of sets of fully qualified U-Th disequilibrium, cosmogenic helium and thermoluminescence age determinations should be completed for the center in calendar year 1994. K-Ar age determinations of silicic lithic fragments in lavas of the center will be obtained in early calendar year 1993. We anticipate obtaining fully qualified, partial and complete fusion $^{40}Ar/^{39}Ar$ and step heating, $^{40}Ar/^{39}Ar$ release spectra age determinations to complete chronology studies of the center. Soil and geochronology studies of the center should be completed in calendar year 1993.

There is a relatively high degree of confidence that the final geochronology results will not result in major changes in the chronology of the center. The controversy concerning the different eruption models for the center has been solved by using both the monogenetic and polycyclic models in studies of the effects of volcanism on the potential repository.

C. Activity 8.3.1.8.5.1.3 Field Volcanism Studies

Field volcanism studies are nearing completion. Revised geologic mapping has been completed for the Lathrop Wells and Sleeping Butte volcanic centers. A final map of the Lathrop Wells center will be completed in calendar year 1993. Revised geologic mapping will be completed of the Quaternary basalt of Crater Flat and the basalt of southeast Crater Flat in calendar year 1993. The geologic relations of Pliocene basalt centers are adequately represented on published geologic quadrangle maps. No additional work will be required of Pliocene volcanic centers other than possible minor reconnaissance mapping and field checking of the data on the duration of the events that formed the basalt of Thirsty Mesa. Flow edges of buried lavas of the basalt of southeast Crater Flat will be located using ground magnetic data and this data will be used to refine volume calculations for the volcanic unit.

No significant changes are anticipated in risk assessment studies based on additional field geologic studies. There should be minor changes in the calculation of the volume of basalt units when data from final geologic mapping is combined with computer-based volume calculations using digital terrain data. We have attempted already to bound these changes by field estimations of the basaltic rocks buried by alluvium or removed by erosion. Additional more detailed work will test and refine existing data.

D. Activity 8.3.1.8.5.1.4 Geochemistry Studies of Scoria Sequences

Collection of samples for geochemistry studies has been mostly completed for the Lathrop Wells, Sleeping Butte, Quaternary basalt of Crater Flat and basalt of southeast Crater Flat. Additional sampling and analyses of the tephra units of chronostratigraphic unit one will be required to attempt to identify the source vent of the units. Additional sampling and analyses of units exposed in the trenching studies of the Sleeping Butte center will be completed. Revised mapping of the basalt of Crater Flat may identify additional units from this unit to sample. Minor and isotopic data have been obtained for these centers under a fully qualified quality assurance program. Additional geochemistry studies will be undertaken for the basalt of Buckboard Mesa, the buried basalt of the Amargosa Valley and the basalt of Thirsty Mesa.

The primary goal of the geochemistry studies is to assess models for the generation and evolution of the basalt magmas that formed the Pliocene and Quaternary volcanic centers of the Yucca Mountain region. Additionally, geochemical data are used to asses monogenetic versus polycyclic eruption models. Existing fully qualified data show that the Lathrop Wells and Black Cone volcanic centers did not form by simple monogenetic eruptions but the Little Black Peak center may be a monogenetic center. These data provide supporting evidence for inclusion of both the monogenetic and polycyclic eruptive models in studies of the effects of volcanism. Geochemical data for clustered volcanic centers will aid in possible discrimination of models of clustered (single pulse) versus individual magma pulses for the basalt of southeast Crater Flat, the Quaternary basalt of Crater Flat and the basalt of Sleeping Butte. These data may allow discrimination of single versus multiple feeder dike models for these same centers. Further studies will be attempted to identify, through petrologic and geochemical analyses, the origin of basaltic ash discovered in trenches near the potential Yucca Mountain site.

The geochemistry studies have just begun to be fully implemented. It is difficult to speculate about the likely results from these studies. The most significant application of the geochemistry data may be in discriminating alternative models used in recurrence rate calculations. The effect of these studies should be to refine rather than expand the distribution of probability values for this attribute. A major emphasis of future geochemical studies will be to test existing models and attempt to develop alternative models of the origin of the basalt magmas. Data from the studies will provide continuing tests of the completeness of alternative models used in risk assessment studies.

E. Activity 8.3.1.8.5.1.5 Evolutionary Cycles of Basaltic Volcanic Fields

Like the previous activity, this activity has just begun to be fully implemented in volcanism studies. There are now sufficient data for the basalt units of Crater Flat to allow development of models of the evolution of the magma cycles of the YPB. A major and still tentative conclusion of these studies is that a variety of evidence indicates magmatic processes associated with the formation of the basalt magmas have waned from the Pliocene to the Quaternary. Additional studies will be conducted to test this conclusion and to develop alternative models of the evolution of basaltic volcanic fields in the Great Basin, basin and range province and marginal areas of the basin and range province.

A major area of future consideration for studies of this activity will be continued testing of possible models for the future patterns of evolution of basaltic volcanism in the Yucca Mountain region. These studies could potentially have a major impact on risk assessment studies. Current models support the interpretation that magmatic processes have and are continuing to decline. This interpretation has influenced partly interpretations of the most likely values of the recurrence rate of volcanic events. The logic for selection and the selection of most likely values of the recurrence rate of volcanic events could be modified if required by future studies of the evolutionary patterns of basaltic volcanic fields. We anticipate that this activity will be a major area of emphasis of future volcanism studies.

III. STUDY PLAN 8.3.1.8.1.1 PROBABILITY OF MAGMATIC DISRUPTION OF THE REPOSITORY

A. Activity 8.3.1.8.1.1.1 Age and Location of Volcanic Centers

The activity involves collation of geochronology and field data for basaltic volcanic centers of the Yucca Mountain region. Potential changes in these data are described under the activities of Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features.

B. Activity 8.3.1.8.1.1.2 Evaluation of the Structural Controls of Sites of Basaltic Volcanism

The primary goal of this activity is to test and develop alternative models for E2, the disruption ratio of the conditional probability of repository disruption. These studies are structured to be iterative. That is, continued reevaluations will be undertaken of the models, their applications, and their affect on E2. This report implements the formal process outlined in the Study Plan to systematically evaluate and refine the distribution of potential values for E2. Yearly updates are planned to incorporate the latest information from site characterization studies.

An area of future development that will affect this activity is refinement of models of the structural setting of the Yucca Mountain region. This will be enhanced by revised field and geophysical studies of the structure of Crater Flat, Yucca Mountain and the Amargosa Valley. We anticipate that all the Quaternary basalt centers of the Yucca Mountain region have been identified. Drilling of aeromagnetic anomalies may add additional sites of Pliocene volcanic activity. However, the location of sites of Pliocene and Quaternary basaltic centers appears well constrained. What could change through additional studies are the interpretations of how the distribution of centers can be related to the structural setting of the Yucca Mountain region. The mechanisms for accommodating these changes are yearly examinations of the most likely values and the distribution of values for the disruption probability.

Increased confidence that the distribution of values of E2 is acceptably bounded awaits primarily the results of ongoing studies through the planned tectonic programs for the YMP. Controversies concerning this activity are concerned with alternative structural models of the distribution of basalt centers. There are two major alternative models: 1) the northwest-trending Crater Flat volcanic zone (CFVZ) that does not include the potential Yucca Mountain site, and 2) northeast-trending structural zones (Kawich-Greenwater Rift, Amargosa Desert rift zone, Crater Flat-Buckboard Mesa zone) that include the Yucca Mountain site. There are strengths and weaknesses of each structural model. Both structural models are supported by reasonable interpretations of tectonic, geologic and geophysical data. We anticipate that there may never be sufficient data to fully resolve the different structural interpretations. The controversy has been resolved and will continue to be resolved by incorporating both models in probabilistic calculations of E2.

C. Activity 8.3.1.8.1.1.3 Presence of Magma Bodies in the Site Vicinity

The primary goals of this activity are twofold. First, determinations must be made whether there is reasonable evidence of the presence of subsurface magma in the Yucca Mountain region. Second, if magma is present, an evaluation must be conducted to assess whether the presence of magma could invalidate the use of the past record of volcanism to forecast future volcanic events and evaluate volcanic risk. Studies implementing this activity have just started. It is too early in the site characterization studies to evaluate the potential impacts of results from this activity.

There are two areas of controversy concerning this activity. First, interpretations of geophysical data using methods of teleseismic tomography suggest the possible existence of magma beneath parts of the Amargosa Valley south of the potential Yucca Mountain site. Second, evaluations have been insufficient to date to establish whether the geophysical data available for this activity are adequately comprehensive to make reasonable assessments of the presence of magma bodies. Assessments of the impact of this controversy await resolution of these two questions. Currently we regard the conclusions supporting the possible presence of subsurface magma to be inconclusive and judge that it does not invalidate the application of the probabilistic methods of risk assessment. This judgment is based on five lines of evidence. First, the spatial occurrence of the possible magma bodies is in an area that has been amagmatic during intense episodes of magmatism and extensional deformation in the Mesozoic and Cenozoic. There appears to be no compelling regional process that would lead to development of maintained magma bodies in this part of the crust. Second, there is a poor correlation between the geometry of the inferred magma body and sites of Quaternary volcanism. The inferred magma body is located south of the sites of Quaternary volcanism. Third, there are a range of alternative interpretations of the anomaly that have not been considered. Fourth, if a magma body is present in the area south of Yucca Mountain, it may have existed for a long period of geologic time. Fifth, no evidence of a magma body was noted in the seismic reflection line in the Amargosa Valley. According, no compelling evidence has been provided why this body either invalidates the use of the past geologic record for volcanic risk assessment or would lead to changes in the patterns of future igneous activity in the next 10,000 years.

The issue of the possible presence of magma in the crust beneath the region is regarded as an important issue. If additional evidence is obtained to invalidate current conclusions or if the present data are regarded as inconclusive, this issue will be reassessed and additional methods of gathering definitive data proposed. This issue will carefully evaluated during the site characterization process. There is a potential major impact on the program if crustal magma is discovered in the Yucca Mountain area. This discovery could invalidate the use of the geologic record to bound future volcanic processes if the processes that produced the magma are active and could effect the site during the next 10,000 years.

D. Activity 8.3.1.8.1.1.4 Revised Probability Calculations and Assessment

The report completes the first phase of formal assessment of the probability of magmatic disruption (eruption or intrusion; Pr(E2 given E1)Pr(E1)) of the repository, the controlled area and the Yucca Mountain region. Future work will focus on yearly updates of the probability assessment including revision of the data matrices developed for the most likely values of E1 and E2 and the methods for combining E1 and E2 into the probability of magmatic disruption. Future work will focus on several areas. First, we will continue site characterization that could lead to the identification of new volcanic centers. Second, we will continue to develop structural models of the Yucca Mountain setting. Third, we will apply formal methods of simulation modeling and expert opinion to attempt to further refine the probability distribution of E1, E2, and E3 and combinations of those events that fulfill the tripartite conditional probability.

The distribution of attribute values for the recurrence rate of volcanic events should be bounded adequately using existing data assuming all volcanic centers have been identified. It is possible that there could be changes in or new distribution models developed for the recurrence rate of volcanic events. These developments are likely to have been bounded by the range of assumptions used in the models of the recurrence rate. However, it is not possible to anticipate the results of new breakthroughs in volcanic recurrence models. They will need to be examined on a case by case basis. We hope that the formal presentation of recurrence rate models in this paper may stimulate further analyses of conceptual models of volcanic processes that could lead to new distribution models.

Discovery of new Quaternary volcanic centers is not expected because known Quaternary centers form conspicuous constructional landforms. The only possible sites of buried Quaternary centers might be along the trace of the Fortymile Wash or at the east side of the Bare Mountain front where sedimentation rates could be greater. However, drape aeromagnetic data and drilling in Crater Flat show no evidence of buried centers. We conclude that current data are sufficiently compelling to argue that it is unlikely to discover new sites of Quaternary basaltic volcanism. The only anticipated way this could occur is if new geophysical data leads to identification of unanticipated sites of basaltic volcanism or subsurface exploration associated with construction of the Exploratory Studies Facility encounters basaltic dikes of Quaternary age. It is less easy to constrain the discovery of new Pliocene volcanic centers. The presently undrilled aeromagnetic anomalies (two, possibly three sites) are judged likely to be Pliocene (or older) volcanic centers. This impact can be constrained somewhat by assessing the impact of discovery of new Pliocene centers on estimation of recurrence rates. This would have a limited effect on time trend models because of the Pliocene age of the events. Additionally, the effect on volume-predictable models would be limited because of the marked decline in erupted volume through time. The effect on cone counts is more direct. Identification of new events will have a 5 to 10% increase on minimum and maximum event models. It would require identification of at least 5 or more centers to have a significant effect on the most likely model.

Changes in the alternative models of the structural controls of volcanic activity are more likely because of the present preliminary stage of studies of the tectonic setting of the potential Yucca Mountain site. The most important potential change would be if structural models were identified that increased the likelihood of a future volcanic event occurring in or near the repository. Identification of additional structural models that do not include the repository is unlikely to change the distribution of E2 because of the large number of existing models.

We will use formal methods of risk simulation to define more rigorously the attribute distributions of E1, and E2 and the probability of magmatic disruption of the repository, the controlled area and the Yucca Mountain region. Modifications of the likely values and distribution of values for E1 will be estimated for individual models of E2. The present likely values of magmatic disruption are slightly conservative for each calculation. Simulation modeling will be conducted to establish the sensitivity of the conclusion that the most likely values of the probability of magmatic disruption of the repository are less than 1 in 10,000 years and to estimate the value where the probability distribution curve intersects the 10^{-8} yr^{-1} decision line. It is unlikely that the most likely value of the probability of magmatic disruption of the controlled area or the Yucca Mountain region will be less than 10^{-8} yr^{-1}. However, the probability distribution of these calculations will be more completely evaluated. These values will be used to establish the occurrence probability of events for input into performance assessment models.

Aspects of the probabilistic assessment of the occurrence of future volcanism require some judgments. We attempted to carefully note these areas in Section VII of this report. We will employ expert opinion to attempt to better identify, constrain and reduce bias for the judgmental aspects of the probabilistic assessment. Formal methods of expert opinion will be used to establish independent estimations of the probability distribution for E1, E2 and the probability of magmatic disruption of the repository, the controlled area and the Yucca Mountain region.

1. Areas of Controversy. There are several areas of controversy involving probabilistic assessment of volcanism. These include: 1) Completeness of the data set used for probabilistic assessment, 2) Selection of probability distribution models, 3) The use of conservative or worst case assumptions in probability calculations, and 4) Uncertainty of probability calculations. The impact of these topics is discussed in their respective order.

a. Completeness of the Data Set. An issue of the completeness of the data set used for probabilistic assessments can always be raised. Arguments can be made that any data set is never complete because there will always be continuous improvements in methods of data collection. For example, the rapidly evolving development of new chronology methods, and refinements of existing methods can lead invariably to improved age determinations. What needs to be emphasized is how the iterative nature of probability calculations makes this area of controversy relatively insignificant. The structured approach used in probability calculations allows for efficient recalculation of probability estimates. There is no inherent danger in conducting probability calculations with an evolving data set. The issue of data completeness is in reality more correctly identified as an issue of when probability studies provide reasonable confidence that a problem has been correctly estimated and bounded. The basis for that judgment should be from sensitivity studies of possible changes in the probability distribution. The bounds for establishing the probability of magmatic disruption of the repository were estimated in 1982. Succeeding work has provided better constraints on the probability distribution but has not resulted in modifications of the probability bounds. We will continue to refine probability calculations and incorporate data gathered from the full duration of site characterization studies.

b. Time Distribution Models. A mildly controversial issue of probabilistic assessment for volcanism studies is the choice of time distribution models for volcanic events. We have selected a homogeneous Poisson model for the distribution of volcanic events as discussed in Section VII. Use of other distribution models is possible. The important point is that the limited record of basaltic volcanic events in the Yucca Mountain region makes it impossible to use goodness of fit tests of the data to select a distribution model. A homogeneous

Poisson model is used primarily for simplicity of underlying assumptions, and because errors introduced by selection of a homogeneous Poisson model can be assessed and bounded. However, this area of controversy is not significant because application of other distribution models does not change significantly the resulting probability calculations.

c. Conservative or Worse Case Probability Assumptions. A third area of controversy in probability calculations is the approach used to choose values for assumptions to support or conduct the probability calculations. A common approach is to use conservative or worse case assumptions. These assumptions provide a measure of confidence that the probability values are not underestimations. The approach has merit, particularly in attempts to bound the probability of events. An often unappreciated problem with this approach however, is that it introduces an element of nonsystematic bias in probabilistic assessment. There is not a standard definition of what constitutes *conservatism* in selection of attribute values. Different workers can select widely different values under the general guideline of maintaining conservatism. A second problem with the selection of worse case values is propagation of conservatism. Probabilistic assessment using conservative assumptions for attributes of conditional probabilities can lead to propagation of assumptions to a point where the calculated values are not physically plausible for the modeled events or processes.

We argue that a more reasonable approach to probabilistic assessment is through assignment of values measuring the central tendency of data attributes. These values are well defined statistically. Underestimation of probability results can be avoided by sensitivity analyses of probability distributions.

d. Uncertainty of Probability Calculations. The final area of controversy in probabilistic assessment is evaluating the uncertainty of the probability assessments. This falls directly into the area of the data paradox for the Yucca Mountain region. *The small number of past volcanic events in the Yucca Mountain region results in a low risk of future volcanic activity but a relatively large uncertainty in calculating that risk. Conversely, if there were more volcanic events, there would be a reduced uncertainty of estimating volcanic risk but an increased risk.*

The probabilistic assessments for volcanism for the Yucca Mountain region can never be regarded as robust statistical calculations. Instead they are attempts to quantify a problem using a structured probabilistic approach. The importance of uncertainty in the calculations is determined by comparison of the uncertainty to the regulatory standards for licensing a repository. The uncertainty cannot be calculated but it can be bounded by comparison with active basaltic volcanic fields. The judgment of the acceptance or nonacceptance of probability estimations should be based on a comparison of probability bounds not on a concept of statistical robustness.

SECTION IX: CONCLUSIONS

I. ABSTRACT

This final short section of the Issue Resolution Report presents in itemized form the major conclusions of volcanism studies organized by section of the Volcanism Status Report.

II. CONCLUSIONS

A. Section II: Geologic Setting of Basaltic Volcanism

1. Field and geochronology data show that late Cenozoic basaltic volcanic rocks of the Yucca Mountain region are divided into two major episodes: the basalt of the silicic episode (BSE) and the post-caldera basalt (PCB). The latter episode is divided into the older post caldera basalt (OPB) and the younger post-caldera basalt (YPB) cycles.

2. The younger post-caldera basalt is the primary volcanic rocks of concern for volcanic risk assessment for the potential Yucca Mountain site. The younger post-caldera basalt cycle includes four centers of Pliocene age and seven centers of Quaternary age. There is a high degree of confidence that there are no unidentified Quaternary centers in the region. There is a moderately high degree of confidence that there are no unidentified Quaternary intrusions in Yucca Mountain region. There is a moderately high degree of confidence that the only possible sites of buried Pliocene volcanic rocks have been identified on the basis of aeromagnetic data.

3. The Quaternary basalt includes the four basalt centers of Crater Flat (1.2 Ma), the basalt of Sleeping Butte (0.38 Ma) and the Lathrop Wells center (0.14-0.04 Ma). The Quaternary basalt centers may have formed in single or multiple pulses of magma and they may exhibit slight differences in age that cannot be resolved by the K-Ar method. The Little Black Peak center of the Sleeping Butte centers is a monogenetic center; the Hidden Cone center appears to be polycyclic. The Lathrop Wells volcanic center consists of at least two, possibly three, eruptive sequences of slightly different ages. The oldest event is probably between 70 and 140 ka and consists of three or four sites of scoria/spatter cones, fissure eruptions, and blocky aa lava flows. The second event is probably greater than 40 ka and comprises the main scoria cone, a northwest-trending alignment of spatter vents, and a cluster of satellite vents located south of the main cone. The presence of a young (10 ka) volcanic event is suggested by the presence of tephra deposits interbedded with soil but remains speculative because the source vent(s) for the deposits have not been identified.

4. Systematic field and geochronology studies of the basalt units of the younger post-caldera basalt have been conducted beginning as early as 1980. Much of this work has been completed. Two major problems have emerged in characterizing the basalt centers, and are partly solved. First, some of the centers may have formed in multiple, time-separate volcanic eruptions (polycyclic eruptive behavior) and contrast with the conventional single episode (monogenetic) *interpretation of small-volume basaltic volcanic centers. Second, establishing the chronology of the youngest Quaternary basalt centers with an acceptable degree of confidence has proven problematic. The first problem has been solved by considering both monogenetic and polycyclic eruptive models in risk assessment studies (see Section VII). Recent progress at the Lathrop Wells center using multiple geochronology methods shows signs of convergence of results. There is increased confidence that the ages of volcanic centers can be established with reasonable confidence using multiple methods.*

B. Section III: Tectonic Setting of Basaltic Volcanism

1. Yucca Mountain is located in the south part of the Great Basin, a subpart of the basin and range province. The area has been affected by Cenozoic volcanism that was preceded, accompanied and postceded by extensional faulting. Basaltic volcanism in the area is related to the waning stages of extensional faulting and volcanic activity.

2. Important potential processes that shaped the structural framework of the Yucca Mountain area include detachment faulting that preceded eruption of most of the volcanic rocks, the inferred formation of caldera(s) complexes associated with the development of the Crater Flat basin, the possible location of Yucca Mountain in the Kawich-Greenwater rift and/or related Amargosa Desert rift zones, the possible presence of largely concealed northwest-trending strike slip faults of the Walker Lane structural system, and the formation of pull-apart basins during late Cenozoic time that may be associated with the rift zones.

3. The BSE occurs in a broad northwest-band paralleling the Walker Lane structural zone. The OPB occurs in a northwest-trending zone located northeast of the potential Yucca Mountain site. The YPB, except the basalt of Buckboard Mesa, occurs in a narrow northwest-trending zone called the Crater Flat volcanic zone (CFVZ). This zone does not intersect the potential Yucca Mountain site. The location of sites of basaltic volcanic activity of the PCB migrated or stepped to the southwest through time.

4. Basalt vents (both Quaternary and Quaternary and Pliocene) in the CFVZ show a highly correlated (spatially) northwest alignment. This alignment coincides with the surface of maximum volume of erupted magma. The location-volume relationships support the interpretation of ascent of basalt magma at depth along a concealed northwest trending structural feature that must coincide with or control the CFVZ. At shallow depths, the magma diverted from the structure and formed north-northeast trending dikes parallel to the maximum compressive stress direction. These dikes fed clusters of probable coeval basalt centers.

5. A wide range of geophysical data has been collected for the Yucca Mountain region. Seismic data show no direct correlation with sites of Quaternary basaltic volcanic activity. The seismic gap of Crater Flat and Yucca Mountain may show an inverse correlation with sites of Quaternary volcanism. Gravity data are useful for delineating the structural configuration of the Crater Flat basin and Yucca Mountain but bear no direct relationship to the occurrence of the small volume basalt centers of Pliocene and Quaternary age. Aeromagnetic data show anomaly sites that are correlated with the magnetic polarity of Pliocene and Quaternary basalt centers.

The data also reveal anomalies that are probably buried basalt centers. Exploratory drilling of two anomaly sites intersected buried basalt of Miocene (Crater Flat) and Pliocene (Amargosa Valley) age. Seismic data show additional sites of buried basalt units in the Amargosa Valley that are probably part of the BSE. Mid-crustal bright spots on seismic reflection lines are interpreted to be from focusing of energy reflected from the mid-crust by low velocity basin fill. They are most likely not magma bodies. A large low velocity teleseismic anomaly is located in and extends south of the Amargosa Valley. The anomaly could be produced by partial melt, but this is not consistent with the geologic setting and history of the region. Moreover there was not evidence of the magma body on the seismic profile across the Amargosa Valley.

6. Quaternary basalt centers, in contrast to Pliocene and Miocene centers, do not appear to be controlled by or follow shallow surface structures. Structures that penetrate deepest into the crust show the strongest correlations with sites of basaltic volcanism but there is not a genetic relationship between the structures and volcanism. The structures formed potential pathways of more likely sites for ascent of basalt magma. There is a common but not universal restriction of sites of Quaternary basalt centers to alluvial basins. They are uncommon in range interiors.

C. Section IV: Basaltic Volcanism in the Great Basin

1. Pliocene and Quaternary basalt magmas in the Yucca Mountain region are typical of, but of much smaller volume than late Cenozoic alkali basalt of the basin and range province. The basalt originated by small degrees of partial melting of relatively deep mantle sources.

2. Basaltic magma has been concentrated increasingly in time along the margins of the Great Basin with the exception of spatially isolate sites of basaltic activity in the basin interior. Basalt erupted in the last 5 Ma tend to be more silica-undersaturated, with higher Mg0 contents than basalt erupted before 5 Ma. These compositional changes are associated with decreased degrees of partial melting, diminished eruption volumes, high volatile contents, and possibly increased eruption frequency. The latter observation is probably a combined effect of increased crustal density with cooling and higher volatile contents of magma from decreasing degrees of partial melting.

3. Isotopic and trace-element data for the basalt of the southern Great Basin suggest derivation from lithospheric mantle over the last 10 Ma.

4. Basaltic volcanic fields in the southwestern United States exhibit characteristic patterns of evolution reflecting changes in the intensity and depth of partial melting in the mantle. Basaltic volcanism at Crater Flat occurred in three cycles. The mineralogy and trace-element chemistry of the cycles indicate deepening of magma chambers through time and the chambers for the younger two cycles were formed in the deep crust or mantle. The increasing depth of the chambers may be related to a decreasing magma flux through time.

5. Trace element and isotopic data for the Lathrop Wells and possibly the Black Cone centers are inconsistent with derivation from a single magma batch. The data are consistent with the concept of polycyclic volcanism.

D. Section V: Segregation, Transport, and Local Storage of Basaltic Magma

1. Basalt magma in the Yucca Mountain region ascended from the upper mantle and crust through the processes of melt segregation and magma-assisted fracture propagation as dikes. The initial rise and segregation of magma are driven by buoyancy of the melt phase. The equations for two-phase flow accompanied by matrix deformation and compaction have been developed but not applied to all boundary conditions. Computer modeling of modified forms of the equations suggest the presence of solitary wave solutions called solitons. They may contribute to episodic volcanic activity for areas of low melt production, or they may degrade from nonlinearity, diffusion or overprint by processes of magma ascent.

2. Extraction of magma into conduits by melt-fracture requires the melt pressure to exceed the yield pressure of country rock. This occurs at depths as great as 50 km. The form of magma transport has been modeled from a perspective of rock mechanics and the dynamics of magma transport. The latter requires consideration of elastic deformation of the country rock and processes of fracture, magma flow and volatile exsolution at the dike tip.

3. Magma in the form of dikes will rise until it erupts, solidifies, or reaches the level of neutral buoyancy (LNB). The location of the LNB in the Yucca Mountain region may occur at the base of low-density basin fill at 4 to 5 km. Alternatively, the combined low flux of magma and processes such as crack-rate propagation, magma-gas content or concentrations of volatiles in the dike tip may negate the controls of the LNB.

4. Dikes in the region probably followed northwest-trending structure at depth and diverted at shallow depths to follow the direction of maximum compressive stress direction (north-northeast).

E. Section VI: History of Volcanism Studies

1. Volcanism studies began as early as 1979 for the potential Yucca Mountain site. The risk of silicic volcanism was shown at that time not to be a significant issue for storage of high-level radioactive waste.

2. The methods of volcanic risk assessment were conceived and applied to the potential Yucca Mountain site from 1980 through 1983. The bounds of the occurrence probability of magmatic disruption of a potential repository at Yucca Mountain were established in 1982. Scenarios of future volcanic events were established and described in 1983. Radiological releases associated with penetration of a repository and eruption of basalt magma were bounded in 1982-1983.

3. Risk assessment studies of volcanism were summarized as a Chapter in a book on Active Tectonics and presented in the Environment Assessment in 1986.

4. The strategy for resolution of volcanism was presented in the Site Characterization Plan in 1988. Study Plans implementing two major parts of this strategy were completed in 1990 and 1991.

5. Concerns over the confidence in the adequacy of chronology data using the K-Ar dating method on young basaltic rocks developed in 1988. Additionally, evidence was recognized in late 1988 that some small basalt centers may form by multiple, time-separate eruptions (polycyclic activity). Assessments of volcanic risk were revised to incorporate these new concepts in 1988 through 1990.

6. Overview studies by the State of Nevada for volcanism studies of the potential Yucca Mountain site were published in 1990 through 1992. They presented alternative interpretations of the structural controls of sites of volcanic activity. They argued that the recurrence rate of volcanic events and the probability of disruption of the repository were underestimated but their probability calculations were largely similar to previous studies.

7. Divergence of opinions developed over the adequacy and interpretation of K-Ar and paleomagnetic data for the Lathrop Wells volcanic center in 1991-1992. Initial results of alternative geochronology methods were largely in disagreement but have begun to converge with increasing work. Conflicting evidence concerning eruptive models of the centers centered largely on paleomagnetic data. We have carefully examined the measurement precision, and the assumptions of paleomagnetic data. The basis for the different interpretations of eruptive models is not significant and can be resolved through methods of risk assessment.

8. Revised calculations of the recurrence rate of volcanic events using a homogeneous Poisson model were completed in 1992. The rates were bounded by comparison to analog basaltic volcanic fields. The first reassessments of the consequences of magmatic disruption (eruption or intrusion) were completed in 1992. Volcanism work has become focused on finalizing field and geochronology data for the record of volcanism and revising the occurrence probability of magmatic disruption. Future studies will focus on time-trends of basaltic fields and the effects of volcanic activity on a potential repository and the repository system.

F. Section VII: Volcanic Risk Assessment

1. Evaluations of the hazards of future volcanism for the potential Yucca Mountain site are conducted through implementation of a systematic application of methods of risk assessment where risk is defined as a product of the occurrence probability and consequences of future volcanic events.

2. The conditional probability of magmatic disruption of areas of interest associated with a repository and waste isolation system is described by the relationship:

$$Pr = (E3 \text{ given } E2)Pr(E2 \text{ given } E1)Pr(E1)$$

where E1 is the recurrence rate of volcanic events, E2 is the probability of magmatic disruption of the repository, controlled area or the Yucca Mountain region and E3 is the probability of direct or indirect releases of radioactive waste to the accessible environment exceeding the regulatory requirements.

3. The emphasis of the section on volcanic risk assessment is to summarize the results of assessments of probability of magmatic disruption of the repository, the controlled area and the Yucca Mountain region (Pr(E2 given E1)Pr(E1)).

4. The probability model assumes a homogeneous or modified homogeneous Poisson distribution of volcanic events through time. Other distribution assumptions are possible but are hard to justify using the small data set. The Poisson model is conceptually simple, assumptions are well defined and errors can be constrained. The Poisson approach is conservative because of the pattern of waning volcanism in the Yucca Mountain region.

5. The strategy for resolution of the issue of volcanism for the potential Yucca Mountain site involves first determining if the site should be disqualified because of the risk of future volcanism. This issue is examined using probabilistic criteria for the disruption of the repository. The second step (assuming the site is not disqualified) is to establish the occurrence probability and consequences of a range of future volcanic and intrusive scenarios effecting the repository, and/or the waste isolation system of the repository.

6. Revised probability calculations are presented for the recurrence rate of volcanic events using time-trend analyses, cone counts assuming a homogeneous Poisson model, and magma-volume relationships assuming a modified Poisson model. Time-trend patterns are statistically insignificant but the minimum repose period of volcanic events is 285 ka which is equivalent to a recurrence rate of 3.5×10^{-6} events yr^{-1}. Event counts are compiled using multiple alternative models and the most current data from site characterization studies. The most likely event rate is 3.3×10^{-6} yr^{-1}, the maximum event rate is 4×10^{-6} events yr^{-1}, and the minimum event rate is 1.6×10^{-6} events yr^{-1}. The maximum event rate must be less than and cannot approach a bound of 1.2×10^{-5} events yr^{-1} established from analog basaltic volcanic fields. Volume-predictable recurrence rates give long recurrence times because of the dramatic decrease in erupted volume through time. Worse case bounds can be established from the Sleeping Butte centers and give recurrence rates of 1.4 to 2.8×10^{-6} events yr^{-1}. ***The geometric mean of the most likely value of the recurrence rate is 2.6×10^{-6} events yr^{-1}.***

7. The disruption ratio of the tripartite conditional probability is established by combining multiple alternative models based on random and structurally controlled models of the distribution of volcanic events. The structurally controlled models are divided into random, forced intersection, intersection and structurally bounded models. The occurrence probability is considered for disruption of the repository, the controlled area and the Yucca Mountain region. The random model disruption ratio is 2.2×10^{-2}, 3.2×10^{-2} and > 0.1 for the three respective areas. The geometric mean of the disruption ratio using forced intersection of the repository is 5.9×10^{-3}. The geometric mean of intersection models is 3.8×10^{-3}. The geometric mean of the structural bound models is 6.8×10^{-3}. ***The most likely values of the disruption ratio combining all three approaches and using judgment are 2.5×10^{-3} for the repository, 3.6×10^{-2} for the controlled area and 0.3 for the Yucca Mountain region.***

8. The most likely value for the probability of magmatic disruption of the repository is 6.5 x 10^{-9} yr^{-1}. It is 9.4 x 10^{-8} yr^{-1} for the controlled area and 8.8 x 10^{-7} for the Yucca Mountain region. The most likely value of repository disruption meets the criterion of an occurrence probability of less than 1 in 10,000 in 10,000 years. The occurrence probabilities of the controlled area and the Yucca Mountain region do not meet this criterion and volcanic risk must be assessed through addition of consequence analyses. The low probability of repository disruption can be placed into perspective by comparison with analog basaltic volcanic fields. A low risk of disruption from future volcanic events can be demonstrated for sites near the most active basaltic volcanic fields of the basin and range interior. This is because of the long recurrence times between volcanic eruptions and the requirement that a volcanic event must intersect an area that is small compared with the area of volcanic fields.