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THE CNWRA VOLCANISM GEOGRAPHIC INFORMATION SYSTEM DATABASE

Prepared for

Nuclear Regulatory Commission

Contract NRC-02-88-005

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Center for Nuclear Waste Regulatory Analyses
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ABSTRACT

The Volcanism Geographic Information System (GIS) has been developed primarily as a tool for the analysis of natural analogs in the Basin and Range and nearby regions. It is the intent of this report to summarize the current development of the CNWRA Volcanism GIS. At this time, data have been compiled for five volcanic fields in the western United States. These are: volcanoes of the Yucca Mountain Region (YMR), the Cima Volcanic Field, Coso Volcanic Field, Lunar Crater Volcanic Field, and the Big Pine Volcanic Field. Data on two large Colorado Plateau rim volcanic fields, the Springerville Volcanic Field and the San Francisco Volcanic Field, also may be useful in testing specific hypotheses and have been incorporated into the database without any attempt to attain complete geographic coverages. Most of the data compiled and manipulated in the Volcanism GIS originate in the published literature, and include maps, data tables, digitized images, and binary geophysical data. In addition to model development, this GIS also will be useful in evaluating the completeness and adequacy of the DOE volcanism database used to demonstrate compliance with 10 CFR Part 60 requirements relating to igneous activity. The volcanism GIS will provide confirmatory data for addressing issues related to waste isolation, and provide data that may be required to explore safety issues not adequately addressed by the DOE. The Volcanism GIS database currently contains the following data types: vent locations and lava flow outlines, age determinations, fault traces, geochemical analyses, geologic contacts, and topographic data. These data are useful for description and investigation of the tectonic settings, physical volcanology, and petrogenesis of western Great Basin volcanic fields. The Volcanism GIS will provide a substantial data set with which to test and develop probability models of potential volcanic disruption of the candidate repository. Using these data, it will be possible to evaluate probability models more fully, by viewing probability estimates together with structural and related geological data.

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ACKNOWLEDGMENTS

Important technical contributions to this report were made by Kathy H. Spivey, Peggy G. Hunka, Richard V. Klar, and Ronald H. Martin. These contributions include compiling data from the geologic literature, entering data into the Volcanism Geographic Information System, and using Arc/Info to produce maps and tables. Their efficient work with the Arc/Info program is greatly appreciated. Joyce L. Foegelle was instrumental in management of the bibliographic database. Final report preparation was greatly assisted by Cathy Garcia, Esther Cantu, and Corky Gray. H. L. McKague and Wesley C. Patrick provided valuable technical and programmatic reviews.

CNWRA-generated original data contained in this report meets quality assurance requirements described in the CNWRA Quality Assurance Manual. Sources for other data, indicated in the references, should be consulted for determining the level of quality for those data. The Arc/Info® computer code was used for analyses contained in this report. This computer code is not controlled under the CNWRA's Software Configuration Procedures.

This report was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the U.S. Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-88-005. The activities reported here were performed on behalf of the NRC Office of Nuclear Regulatory Research. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

1 INTRODUCTION

Characterization of the frequency and nature of past volcanic events in the Yucca Mountain region (YMR) and assessment of the probability and consequences of future volcanism are critical aspects of prelicensing scientific investigations. The technical objectives of the Volcanic Systems of the Basin and Range research project are to: (i) assess the probability of continued magmatic activity in the YMR, (ii) develop models that better predict the interaction between structure and volcanism in this tectonic setting, and (iii) develop scenarios for the potential impact of volcanism on the candidate Yucca Mountain repository. Effective review of the U.S. Department of Energy (DOE) license application will require insight into volcanic processes operating in the YMR on several scales. These processes include assessment of: western Great Basin tectonic and structural controls on volcanism on local scales (10^2 - 10^3 km^2); the longevity of vent complexes and individual volcanoes in the western Great Basin; and the relationship between specific mappable faults, joints, and fractures, and volcanic conduits such as dikes and dike swarms. The western Great Basin has been the site of recurring small-volume basaltic volcanism throughout the Quaternary (i.e., 1.6 Ma; Palmer, 1983). Modern analogs and theoretical studies have demonstrated convincingly this activity encompasses a variety of eruption styles, from the gentle effusion of lavas to sub-Plinian and Plinian-style activity that has produced large and highly dispersive ash columns (Williams, 1950; McGetchin et al., 1974; Wilson et al., 1978; Wilson, 1980; Amos et al., 1983; Head and Wilson, 1989; Connor et al., 1993). The Volcanic Systems of the Basin and Range research project has been designed to assess the probability of future volcanism in the YMR, taking into account the range of activity and the structural controls on activity that are an inherent part of western Great Basin volcanism.

A principle criticism of current models of volcanism, including probability models of the potential for volcanic disruption of the candidate repository, has been that these models have failed to adequately incorporate basic geologic information in an adequate way (e.g., Trapp and Justus, 1992). This geologic information includes complex geologic processes, such as fault-dike interaction as magma ascends toward the surface and the geochemical evolution of volcanic fields, that may provide clues about waxing or waning trends in volcanism. Models also need to account for relatively straightforward geologic processes such as possible relationships between the occurrence of cinder cone volcanism and topography and the migration of vents through time within a given volcanic field. In order to assess the degree to which these geologic processes can be used to better estimate the probability of volcanic disruption of the repository, it is critical to develop a mechanism for comparison of spatial and temporal information. This is best accomplished through development of a Geographic Information System (GIS) database, within which geologic data can be analyzed for both temporal and spatial patterns.

The Volcanism GIS has been developed primarily as a tool for the analysis of natural analogs in the Basin and Range and nearby regions. This focus on analog volcanic fields has been adopted because it provides an expedient approach to gathering data that will be useful in testing and evaluating conceptual and numerical models of volcanic field development in the western Great Basin, and therefore provide a context in which to evaluate the nature of Plio-Quaternary volcanism of the YMR. Although the Volcanism GIS incorporates a broad range of data types, the database is structured to provide data specifically related to conceptual and analytical probability model development. By structuring the Volcanism GIS around specific types of volcanological data, with specific hypothesis testing in mind, it will be possible to understand the strengths, uncertainties, and shortcomings of these probability models more fully.

It is the intent of this report to summarize the current development of the CNWRA Volcanism GIS. At this time, data have been compiled for five volcanic fields in the western United States. These are: volcanoes of the YMR, the Cima Volcanic Field, Coso Volcanic Field, Lunar Crater Volcanic Field, and the Big Pine Volcanic Field (Figure 1-1). Data on two large Colorado Plateau rim volcanic fields, the Springerville Volcanic Field and the San Francisco Volcanic Field, also may be useful in testing specific hypotheses and have been incorporated into the database without any attempt to attain complete geographic coverages. We anticipate the database will continue to develop as the Volcanic Systems of the Basin and Range Project continues, especially through the incorporation of other, smaller western Great Basin volcanic fields. Tasks 3 and 4 in the Volcanic Systems of the Basin and Range Project are designed for critical review of this database and model development using this database, respectively. These Tasks are currently in progress.

1.1 GOALS OF THE VOLCANISM GEOGRAPHIC INFORMATION SYSTEM

A computerized GIS provides the means necessary to construct models relating quantitative physical data to spatial data. In the volcanism research project, a computerized GIS is being constructed to support conceptual, empirical, and theoretical models of volcanism and tectonism for the Basin and Range Province.

Development of the GIS is necessary in order fully assess volcanic activity in the western Great Basin, primarily because:

- A tremendous range of information on volcanism is found in a broad variety of sources in the geologic literature; these data must be tabulated and evaluated in a consistent manner in order to quantify the spectrum of volcanic activity.

- It is important to be able to easily compare a large amount of complex data, such as petrologic data, from different volcanic fields.

- There is a the need for simple hypothesis testing using a variety of spatial and temporal data.

- It is important to understand the extent and limits of volcanological data in order to guide the license application review in an effective and timely manner.

Most of the data compiled and manipulated in the Volcanism GIS originate in the published literature, and include maps, data tables, digitized images, and complex binary geophysical data. In addition to model development, this GIS also will be useful in evaluating the completeness and adequacy of the DOE volcanism database used to demonstrate compliance with 10 CFR Part 60 requirements relating to igneous activity. The volcanism GIS will provide confirmatory data for addressing issues related to waste isolation, and provide data that may be required to explore safety issues not adequately addressed by the DOE.

1.2 THE ARC/INFO COMPUTER PROGRAM

Arc/Info® is a series of computer programs designed to relate tabular and spatial data using real-world geographic coordinates. Arc/Info also is used by both the U.S. Nuclear Regulatory Commission (NRC) and the DOE as primary GIS software for the Yucca Mountain Project, and is used by the

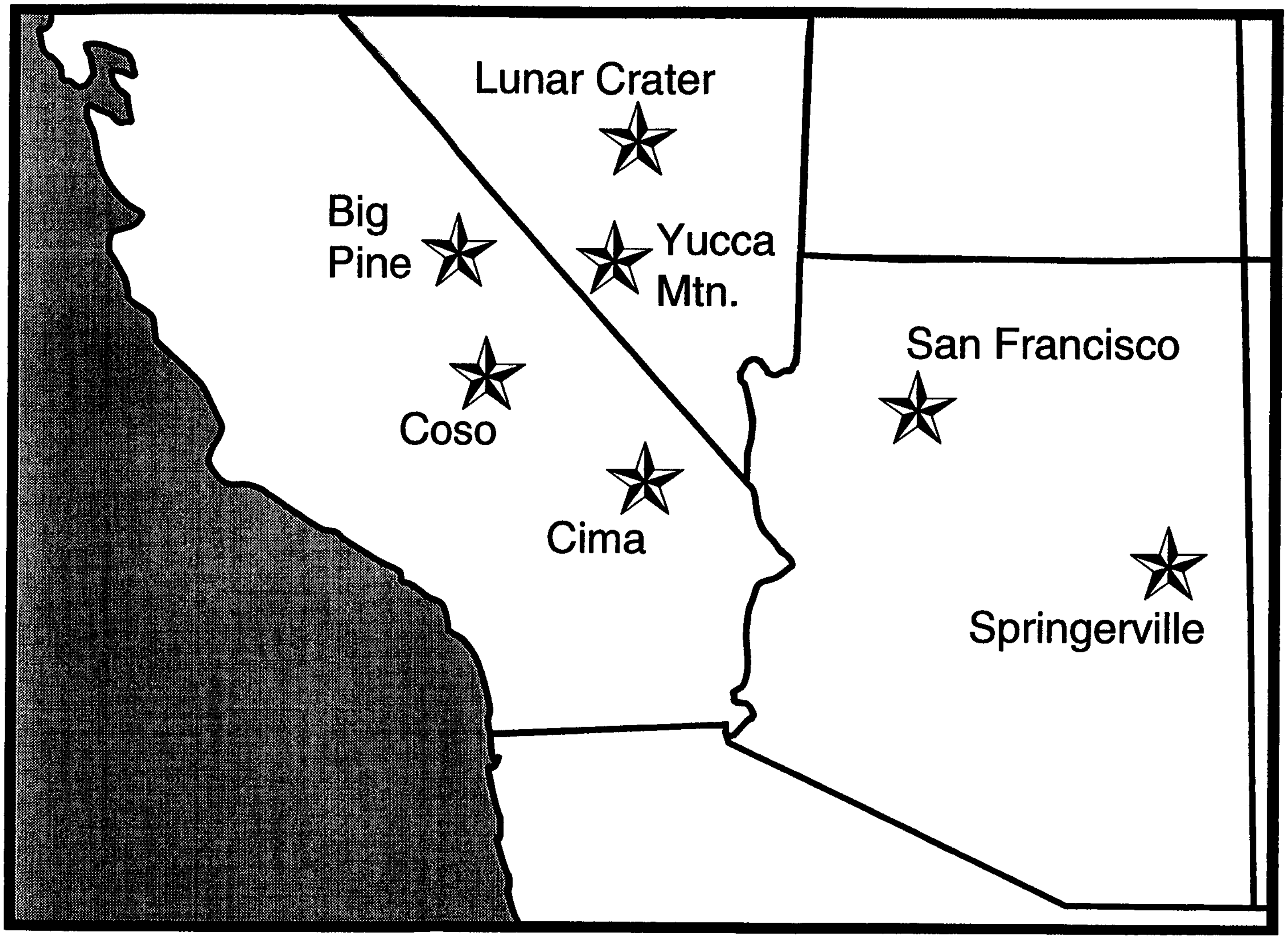

Figure 1-1. Location of volcanic fields incorporated in the volcanism GIS to date.

CNWRA for the Volcanism GIS. Arc/Info is a widely used software package that can plot up to two hundred different layers of information and perform spatial analysis of these data. All types of geologic data, including digitized maps, geophysical data sets, alphanumeric tabular data, and satellite imagery, may be imported and integrated in Arc/Info.

Arc/Info is a complex program that consists of several main subsystems, each of which fulfill a specific function in GIS:

- ARC: The overall GIS program manager, which is used to generate and manage the coverages of interest, converts data from other digital formats into formats compatible with Arc/Info, and creates relational data sets

- ARCEDIT: An interactive graphics editor, which is used to digitize and edit coverages, and to correct errors in spatial and attribute data

- ARCPLOT: An interactive plotting program, which is used to display and query maps and to produce digital maps, which might be exported to a graphics application or printed directly

- INFO: A database manager that is used to enter and reformat tabular data files

- AML: The Arc/Info macro language

Other systems within Arc/Info permit surface modeling and 3D representations and the manipulation of gridded data such as United States Geological Survey (USGS) digital elevation models (DEMs) and satellite imagery.

Arc/Info has approximately 2,500 base commands, most of which are unique to each specific subprogram. Most of Arc/Info is command-line driven, although a graphical user interface is under development by the producers of Arc/Info, Environmental Systems Research Institute (ESRI). Learning to use Arc/Info requires a serious time commitment; the program is essentially inaccessible to a casual user. Once a database is generated, however, these data can be manipulated using a different set of programs called ARCVIEW. ARCVIEW is designed to provide casual users with a vehicle for exploring spatial data sets, such as the Volcanism GIS, without need to develop relational databases or edit data sets.

1.3 REGULATORY BASIS FOR THE VOLCANISM GEOGRAPHIC INFORMATION SYSTEM

Insight gained through the Volcanic Systems of the Basin and Range Research Project will support the following sections of the License Application Review Plan (LARP): (i) Section 3.2.1.9, evidence of igneous activity as a potentially adverse condition; (ii) Section 3.2.2.7, impact of volcanism on groundwater movement; and (iii) Section 6.1, assessment of compliance with the requirement for cumulative releases of radioactive materials. Research is necessary to develop these three sections of the LARP for the purpose of providing the NRC with the methodology and acceptance criteria to determine DOE compliance with 10 CFR Part 60 requirements. Compliance Determination Strategies (CDSs) and Compliance Determination Methods (CDMs) for these LARP sections are currently under development.

However, the CDSs associated with evidence of Quaternary volcanism includes Key Technical Uncertainties (KTU) of Type 5, indicating that independent research by the NRC may be required to evaluate volcanism, and that volcanism poses a high risk of the NRC reaching unwarranted conclusions regarding compliance with 40 CFR Part 191 and 10 CFR 60.122(c)(15).

To date, eight KTUs related to igneous activity have been identified as part of the CDS concerned with evidence of Quaternary igneous activity. These KTUs are:

- low resolution of exploration techniques to detect and evaluate igneous features
- inability to sample igneous features
- development and use of conceptual tectonic models as related to igneous activity
- developing a conceptual groundwater flow model
- prediction of future changes in the hydrologic system (due to tectonism)
- conceptual model representation of the natural and engineered systems
- variability in the model parametric values
- prediction of future system states (disruptive scenarios)

Evaluation of these KTUs will require detailed safety review supported by analyses (Type 4), and detailed safety review supported by independent tests, analyses, and other investigations (Type 5). In addition to evaluation of these KTUs, independent research in volcanism is needed to provide a basis to question how DOE research will address the potential consequences of igneous activity on repository performance, and to evaluate DOE responses to these questions. Development of the Volcanism GIS directly addresses some of these KTUs, particularly those related to the inability to sample igneous features, development and use of conceptual tectonic models as related to igneous activity, assessing variability in the model parametric values, and disruptive scenarios. These KTUs arise largely because volcanic systems of the western Great Basin are complex and seemingly disparate. For example, the petrogenesis of these volcanic fields, their relationship to regional tectonic setting and local structures, and geochronological investigations of the patterns of volcanism in these fields are active topics of research directly focused on resolution of KTUs. These topics of investigation will be greatly assisted by implementation of the Volcanism GIS because this database provides a comprehensive framework to compare and contrast these volcanic processes.

The Volcanism GIS will be utilized in reactive work, including NRC-DOE Technical Exchanges and in the review of Topical Reports, Study Plans, and related reports, where hypotheses must be evaluated in a timely manner. Specifically with regard to this reactive work, the Volcanism GIS is important in order to:

- facilitate NRC and CNWRA staff review of the completeness and adequacy of DOE volcanism research for demonstrating compliance with 10 CFR Part 60 requirements related to igneous activity

- provide confirmatory data for addressing issues related to waste isolation

- provide data that may be necessary to explore safety and isolation concerns that are not adequately addressed by the DOE

The volcanism GIS also will be used to resolve KTUs addressed by other ongoing research projects at the CNWRA. In particular, the volcanism GIS will aid investigations in the Field Volcanism Research Project, an NRC research project that concentrates on eruption energetics, degassing, and controls on magma movement at shallow levels; the Tectonic Setting of the Central Basin and Range Research Project; and Geologic Setting Element technical assistance in conjunction with the Division of High-Level Waste Management on faulting and dike interaction. The Volcanic Systems of the Basin and Range Research Project, together with these associated investigations, will form the basis of volcanism models in Iterative Performance Assessment (IPA). The link between volcanism studies and IPA has been established; the volcanism GIS is being used to develop and test probability models to be implemented during IPA Phase III.

1.4 RELATIONSHIP TO OTHER DATABASES COMPILED AT THE CNWRA

The Arc/Info system is being used at the CNWRA to construct a number of databases. In addition to the Volcanism GIS database, these include: Geologic Setting / Tectonics, Hydrologic Setting, Aqueous Geochemistry, and Geochemical Analogs GIS databases. All of these databases are used for several purposes, but a common feature of all of them is the requirement to look at different data types on a single, integrated platform. Broadly speaking, the GIS databases under development at the CNWRA can be subdivided into three groups: (i) those dealing with specific issues related to site characterization, (ii) those dealing with a more regional framework, and (iii) those dealing with natural analogs. Databases designed to address site-specific issues are intended to focus on licensing and pre-licensing activities related to understanding the extent and limits of the current DOE database and DOE interpretation of these data. Regional databases are being compiled primarily as a tool for conceptual model development and the evaluation of truly regional processes, such as seismicity, that can impact the candidate repository. Databases that are developed with regard to natural analogs are designed to provide a basis for:

- quantitative comparison of parameters at different sites, and evaluation of the degree to which sites are analogous with the YMR

- conceptual model development and hypothesis testing, particularly with regard to patterns of activity or behavior

- determination of the limits of data availability and the areas in which further data collection might provide the most benefit.

The Volcanism GIS most clearly integrates with the Regional Tectonics database because this latter database provides a regional context for each of the analog volcanic fields. The Volcanism GIS is also site specific because it includes petrologic, geochemical, and related data collected by the DOE and others for the Crater Flat region and other Quaternary to Neogene basaltic volcanoes in the YMR.

The Geologic Setting/Tectonics database currently consists of digital elevation model (DEM) data collected at two scales, regional Quaternary fault traces, and earthquake hypocenter locations, magnitudes, and times. Earthquake data are from the Decade of North American Geology Geophysical Database. This database also includes strain data, and regional aeromagnetic and gravity data sets for North America. In addition, the tectonics database contains the outlines of Plio-Quaternary volcanic fields in the southwestern United States. These volcanic fields are classified on the basis of the ages of most recent activity. The Geologic Setting/Tectonic database is compiled at two geographic scales. The regional scale encompasses much of the southwest United States, including the YMR, the Great Basin, and the Mojave provinces. Faults and cinder cone fields are represented at a scale of 1:2,500,00 in this database and topography is digitized at a 3-arc-second resolution (Young et al., 1993a). The Yucca Mountain regional database covers an area immediately about the candidate repository site, and includes nine 7.5-minute quadrangles. The digital terrain data for this area consists of elevation data collected at 30-m intervals. Additional geologic data, including faults, photo-lineaments, borehole locations, and volcanic vent locations are digitized from large-scale maps of this area (e.g., Young et al., 1993a; O'Neill et al., 1992).

The Aqueous Geochemistry database is a compilation of well and spring chemical analyses collected from approximately 275 sites concentrated in the vicinity of Yucca Mountain, but also includes sites elsewhere in southwestern Nevada and eastern California. Additional data on the chemistry of tuffs and alteration minerals will be incorporated into this database as it becomes available. The purpose of this database is to provide a spatial context for studying variations in groundwater chemistry, and the chemistries of tuff and alteration minerals, in order to better understand spatial and temporal patterns in chemical transport.

The Hydrogeology database consists of data collected from wells and springs in southern Nevada and eastern California. These data include hydraulic head, hydro-stratigraphy, water chemistry, and temperature. The primary function of this database is to provide a regional context of hydrogeologic studies and a comprehensive view of the dynamics of the hydrologic setting.

Because these databases are designed and implemented on the same platform, moving between them in the Arc/Info system is transparent. For example, digital terrain data originally compiled in the Regional Tectonics database is easily utilized in the Volcanism GIS. It is anticipated that as the need arises during the license application review process, a single site-specific database may emerge, which includes all relevant tectonic, volcanological, geochemical, and hydrogeologic data on the site.

2 STRUCTURE OF THE VOLCANISM GIS

Available geologic, geochemical, and geochronological data have been compiled and entered into the Volcanism GIS for the Cima Volcanic Field, California; the Coso Volcanic Field, California; the Lunar Crater Volcanic Field, Nevada; and the Big Pine Volcanic Field, California (Figure 2-1). These volcanic fields have been the sites of numerous geologic studies in the past 25 yr and generally have readily available data. Basic geological and volcanological data exist for the other volcanic fields in Figure 2-1, but the data are less abundant and are contained in less accessible formats such as theses and USGS open-file reports. However, sufficient information exists for these fields to determine volcano distributions, bedrock and regional geology, distribution of major faults, and to characterize volcano ages and compositions. Data from other sites will be entered into the Volcanism GIS as specific investigations warrant.

The Volcanism GIS database currently contains the following data types.

- *Vent locations and lava flow outlines.* Vent locations and lava flow outlines have been identified using a variety of sources, including maps, theses, and published manuscripts. Once identified, these features were digitized using topographic and geological maps. Vent location data are reported in both Universal Transverse Mercator coordinates and Latitude and Longitude; flow outlines may be viewed and shaded in any map projection.

- *Age determinations.* Volcanic rocks have been dated in the western Great Basin using a variety of methods (Hill et al., 1993). In the volcanism GIS, these data are compiled together with sample locations, reported analytical uncertainties, and the type of dating method used. Dating methods include radiometric methods, paleomagnetics, and related techniques. In the case of radiometric methods, the samples are also described (i.e., whole rock samples or mineral separates). Within Arc/Info, these data may be categorized and plotted in a variety of ways. For example, dates may be posted adjacent to sample locations, lava flows may be shaded by geologic epoch or by paleomagnetic epoch, or, where data are sufficient, flows may be shaded by sequence of volcanic activity.

- *Fault traces.* Fault traces have been digitized from published geologic maps. In some cases, where the level of geologic investigation has been sufficient, the direction of fault motion and the timing of most recent fault motion have been included in the database. In other cases these data are not available. Where age data are available fault traces may be patterned by timing of most recent slip. Fault traces may be plotted in any map projection.

- *Geochemical Analyses.* Sample locations, major element, trace element, and isotopic compositions are reported where these data are available. These data have been gathered from the published geologic literature and from theses. An extensive amount of sampling has been done in each of the five volcanic fields. These data may be displayed in tabular form, specific parameters, such as Mg number, may be plotted adjacent to sample locations, or lava flows may be shaded or patterned by their geochemical classification.

- *Geologic Contacts.* Additional geologic contacts, such as contacts within underlying basement rocks or distribution of alluvium, have been digitized from geologic maps. These data can be displayed in any projection and may be shaded or patterned.

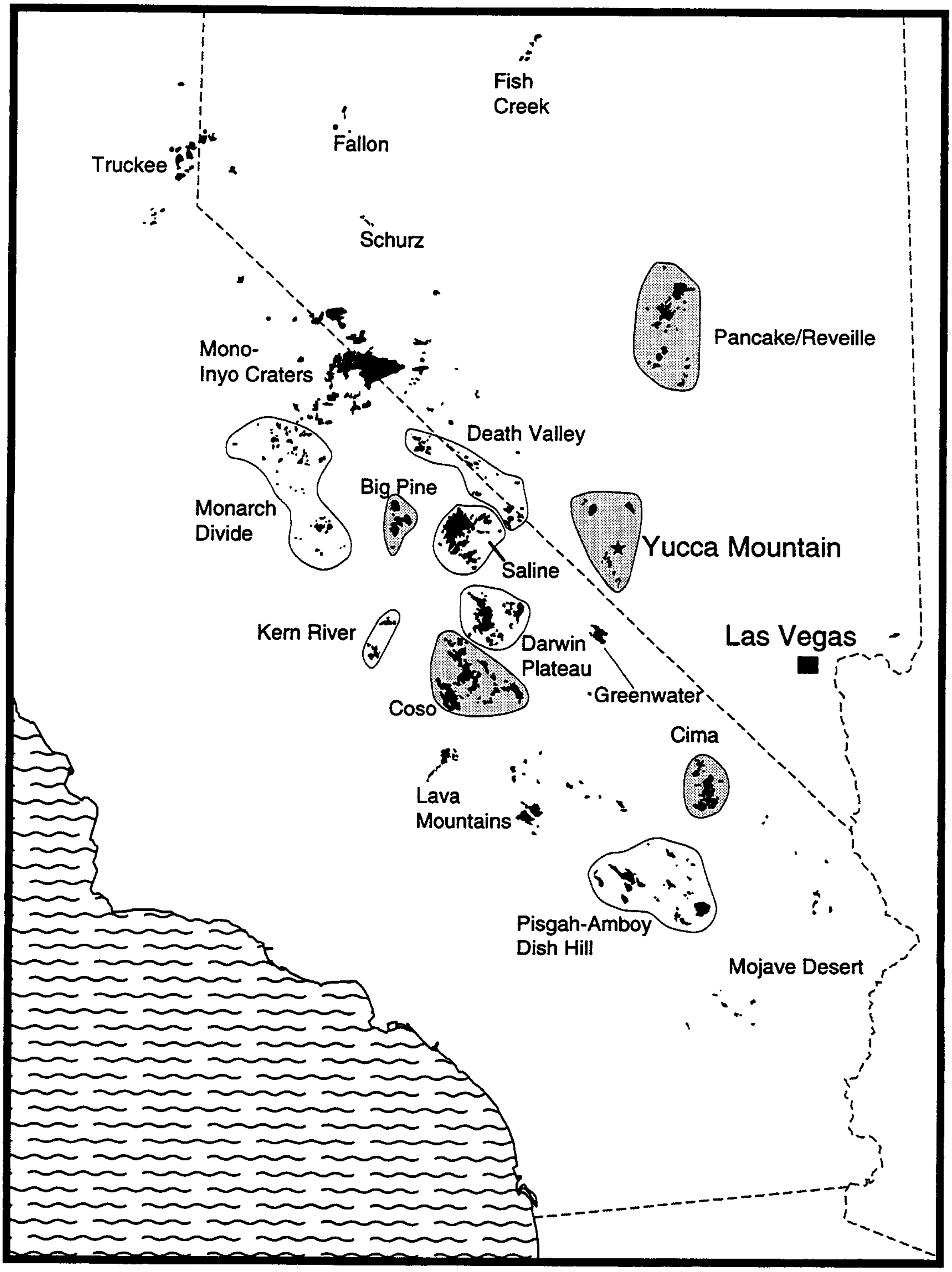

Figure 2-1. Distribution of basaltic volcanic systems younger than 5 Ma, modified from Luedke and Smith (1981). Informal names of labeled volcanic fields from Luedke and Smith (1981) and Smith and Luedke (1984). Shaded areas included in the Volcanism GIS.

- *Topographic data.* Two types of topographic data are available in the volcanism GIS. Digital elevation data from the USGS is available for the entire western United States at a scale of 3 arc seconds. The same type of data are available for the YMR, but sampled at a much finer scale, 30-m sampling intervals. These data are truly digital, in that they may be manipulated as matrices within Arc/Info. In most areas, however, digital elevation data are not available at fine scales. In these areas, contour lines from published 7.5-minute quadrangles have been digitized. Although these data may not be manipulated mathematically without significant interpolation, they do provide an excellent representation of topographic relief within individual volcanic fields.

All data are traceable to their original sources.

Other types of information may be added to the database as specific hypothesis testing and conceptual model development activities progress. These other types of data may include geophysical data, and overlays of probability model results.

The current state of database development for specific volcanic fields is discussed in detail in the following. This discussion consists of an overview of the geology of each area and presentation of representative maps produced using the Volcanism GIS. Additional references not cited in the text but used in the compilation of the Volcanism GIS are provided in Appendix A. Maps used in the database compilation are listed in Appendix B.

2.1 YUCCA MOUNTAIN REGION VOLCANIC FIELD

The YMR volcanic field is located about 125 to 175 km northwest of Las Vegas, Nevada (Figure 2-1). The area around Yucca Mountain has been a locus of rhyolitic and basaltic volcanism between about 15 Ma and 7.5 Ma, forming at least five prominent calderas (Byers et al., 1989). Magmatism in the YMR since about 7.5 Ma has been exclusively basaltic (Crowe and Perry, 1989). Although 2.9 Ma high-silica rhyolite was erupted about 60 km northwest of the YMR at the Mount Jackson dome field (McKee et al., 1989), this activity is not thought to be related specifically to the YMR volcanic system (DOE, 1993). Since about 10 Ma, at least 32 vents (Crowe et al., 1993) have erupted generally alkaline basalt (Crowe et al., 1986) over an area of approximately 8,000 km^2 (Figure 2-2). The youngest volcano in the YMR, Lathrop Wells, is about 0.1 Ma (Crowe et al., 1992; Hill et al., 1993).

The CNWRA Volcanism GIS has not been developed extensively for the YMR Volcanic Field. Much of the available data lack the spatial information necessary for incorporation into a GIS, and there appears to be a significant amount of data that has not yet been published. These data eventually should be available from the DOE GIS which currently is under development. However, some YMR data have been entered into the CNWRA Volcanism GIS in order to develop and test models for volcanism in this area and to provide a template for DOE data.

2.1.1 Overview

The YMR Volcanic Field has been extensively studied because of its proximity to both the proposed high-level nuclear waste (HLW) repository site at Yucca Mountain and the Nevada Nuclear Test Site. Many of these studies have focused on the petrology of Miocene rhyolitic calderas and associated deposits, which are beyond the scope of this report. Detailed geologic maps of the Nevada Test Site were

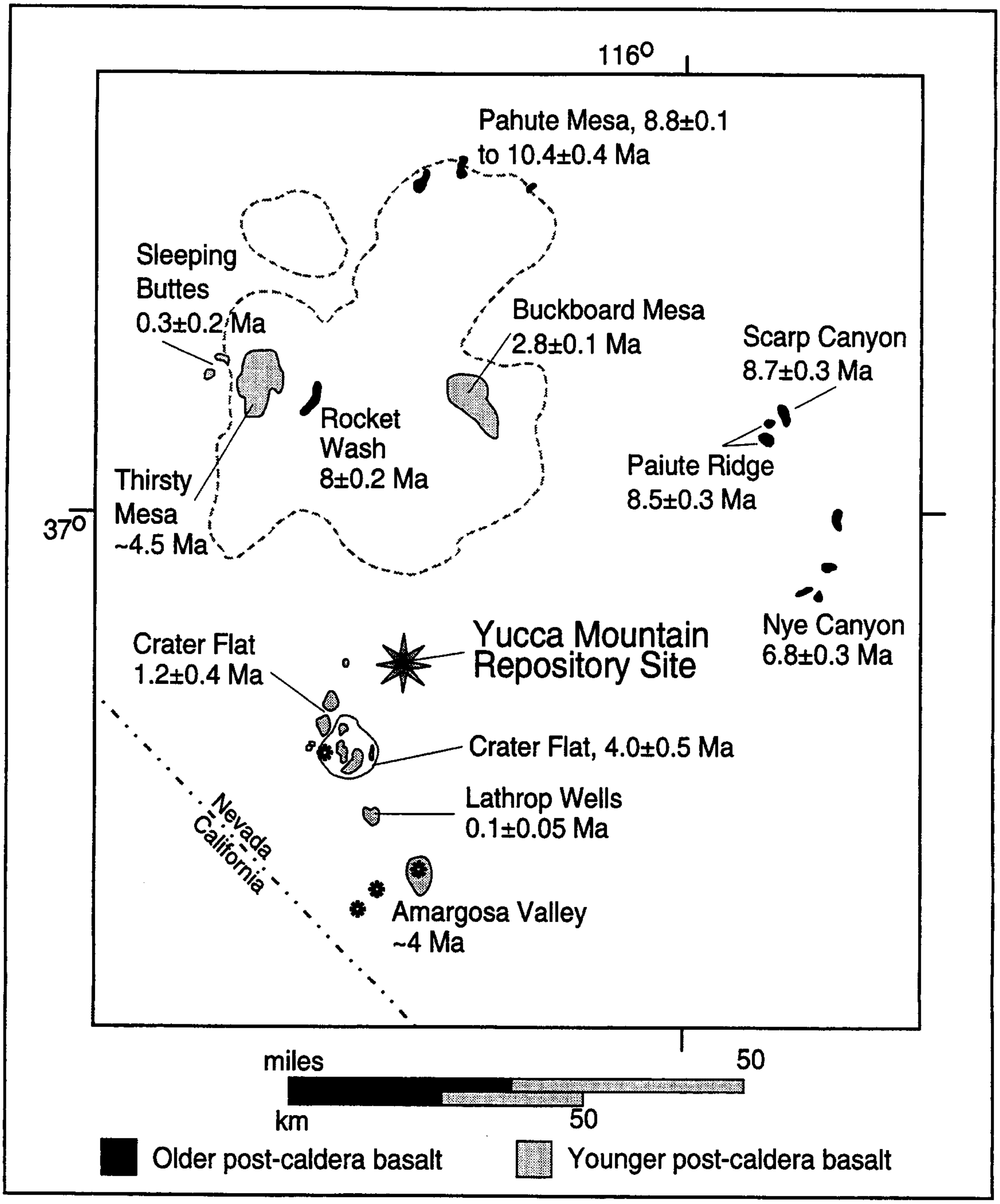

Figure 2-2. Post-caldera basaltic vent locations of the YMR, modified from Crowe (1990). Basaltic units are shaded by relative age, and the average date is shown along with the estimated uncertainty calculated by propagation of analytical error (Hill et al., 1993). Miocene calderas of the Southern Nevada Volcanic Field complex are outlined by the dashed lines. Asterisks denote aeromagnetic anomalies thought to represent buried basaltic volcanoes (Crowe, 1990), and the star indicates the location of the candidate repository site.

produced in the 1960's, 1970's, and 1980's and are compiled by Frizzell and Shulters (1990). Detailed reconnaissance maps that supplement published geologic maps for some basaltic volcanoes have been presented by Crowe and Carr (1980), Vaniman and Crowe (1981), Crowe et al. (1986; 1988), Smith et al. (1990), and Crowe and Perry (1991).

Post-10-Ma basaltic volcanism in the YMR is characterized by eruptions of about 0.1 to 3 km^3 of mildly alkaline basalt (Crowe et al., 1986). Interpreted eruptive styles range from relatively low-energy effusions of lava and agglutinated scoria to high-energy eruptions of fragmented scoria and wallrock (Crowe et al., 1983). In addition, hydromagmatic eruptions have been recognized at Lathrop Wells (about 0.1 Ma) and at some Nye Canyon (about 6.8 Ma) volcanoes (Crowe et al., 1986). Regional studies of YMR basalt have concluded that this system is part of the Western Great Basin (WGB) magmatic province (Fitton et al., 1991). More focused petrogenetic studies have concluded that geochemical variations in this system may be related to a combination of fractional crystallization and differential melting of variably enriched mantle (Vaniman et al., 1982). Detailed studies at Lathrop Wells (Perry and Crowe, 1992) and Red Cone (Smith et al., 1990) have shown that chemically distinct magmas were erupted from these volcanoes.

2.1.2 Ages

Most of the post-10-Ma basaltic centers of the YMR have been dated through conventional K-Ar techniques (Figure 2-2). These data are discussed in detail by Hill et al. (1993). Although these dates are representative of the precision and accuracy commonly associated with the K-Ar method, volcanoes older than about 4 Ma generally have only one to three dates and may thus be incompletely characterized. Most of the Quaternary volcanoes have had more than three K-Ar analyses, but these dates have relatively significant errors in precision and accuracy (Sinnock and Easterling, 1983). The youngest volcano in the YMR, Lathrop Wells, has over 110 dates produced through a variety of techniques. $^{40}Ar/^{39}Ar$ dates at Lathrop Wells (Turrin et al., 1991) have relatively large analytical errors, which reflect the difficulty in dating young (i.e., about 0.1 Ma) low-potassium basalt. ^{3}He and ^{36}Cl exposure dates range from about 0.04 to 0.08 Ma (Crowe et al., 1992; Zreda et al., 1993), but U/Th disequilibria dates are about 0.15 Ma (Crowe et al., 1992). Although geomorphologic (Wells et al., 1990) and paleomagnetic (Champion, 1991) studies show that there may have been multiple eruptions from Lathrop Wells, the duration and absolute ages of these eruptions is controversial (Hill et al., 1993).

2.1.3 Physical Volcanology

Post-10-Ma basaltic volcanism in the YMR is characterized by eruptions of about 0.1 to 3 km^3 of mildly alkaline basalt (Crowe et al., 1986). The largest eruptions in this episode occurred at Thirsty Mesa (3 km^3 magma) and Buckboard Mesa (0.9 km^3)(Crowe et al., 1986). Most Neogene (i.e., 1.6 to 23.7 Ma; Palmer, 1983) volcanoes have been moderately to highly dissected by erosion, and some 4 Ma basalt in the southern YMR is completely buried beneath alluvium (Crowe et al., 1993). The Neogene basaltic volcanoes are characterized by relatively low-energy effusions of lava and agglutinated scoria, with several hydromagmatic eruptions at the Nye Canyon volcanic center (Crowe et al., 1986). Cone-to-flow ratios have not been determined for the Neogene volcanoes due to the relatively large degree of erosion.

Quaternary volcanoes of the YMR have interpreted eruptive styles that range from relatively low-energy effusions of lava and agglutinated scoria to high-energy eruptions of fragmented scoria and wallrock (Crowe et al., 1983). In addition, hydromagmatic eruptions have been recognized at Lathrop Wells (Crowe et al., 1986). Most models of eruptive style have generally considered these volcanoes Strombolian (Crowe et al., 1983), although it has been recently recognized (Connor and Hill, 1993; Connor et al., 1993) that eruptions significantly more energetic than Strombolian are possible for these types of basaltic volcanoes. Cone-to-flow volume ratios are relatively high for Crater Flat volcanoes, and anomalously high for the Sleeping Butte and Lathrop Wells volcanoes (Crowe et al., 1983; Wood, 1980). High cone-to-flow ratios may indicate these eruptions are relatively explosive (Wood, 1980), although this relationship has not been well constrained. The presence of amphibole phenocrysts in some Quaternary basalts (e.g., Vaniman and Crowe, 1981), the lack of significant amounts of agglutinated scoria, and the generally well-bedded and unconsolidated character of Lathrop Wells tephra, all indicate these Quaternary eruptions may have been relatively explosive and were capable of ash-transport distances at least tens of kilometers away from the vent (cf. Connor et al., 1993).

2.1.4 Tectonics

A detailed review of the structural setting of the YMR and surrounding Basin and Range region is provided by Stirewalt et al. (1992). In general, north- to northeast-trending, west-dipping normal faults and northwest-trending strike-slip faults are present in the YMR (Scott and Bonk, 1984)(Figure 2-3). Although Quaternary movement apparently has occurred on the northeast-trending faults (Swadley et al., 1984; Scott, 1990), the extent of Quaternary activity is still under investigation. Data from seismic line AV-1 (Brocher et al., 1993) indicate that normal faults may become listric at depth, but nonlistric structural models also can be supported (e.g., Young et al., 1993b).

Teleseismic tomography studies by Evans and Smith (1992) resolved a large low-velocity zone that trends from Crater Flat to east of Yucca Mountain and extends to about 200 km depth. This low-velocity zone may extend as far east as the St. George Volcanic Field in Utah (Stirewalt et al., 1992). Evans and Smith (1992) conclude that this low-velocity zone may represent a zone in the mantle that contains basaltic melt, although additional geophysical data are needed to rigorously support this conclusion. In addition to the low-velocity zone, an upper mantle high-velocity zone extends to a depth of about 200 km beneath the Silent Canyon caldera. Evans and Smith (1992) speculate this zone may represent the cooled residuum of a large Miocene magma system, which supplied the heat and mass required for rhyolitic volcanism.

2.1.5 Petrogenesis

Basaltic magmas in the Yucca Mountain Volcanic Field are petrogenetically distinct from most other basalts in the central Basin and Range. YMR basalts apparently are derived from mantle material that has been metasomatically enriched in incompatible elements, whereas basalts from the central Basin and Range are derived from nonenriched mantle (Menzies et al., 1983; Kempton et al., 1991; Fitton et al., 1991; Livaccari and Perry, 1993). Other volcanic fields that originate from enriched mantle within the WGB include the Big Pine, Coso, Saline Range, and Darwin Plateau fields. Although the major element chemistry between basalts derived from enriched or nonenriched mantle is relatively similar, many of the trace element and isotopic systematics are very distinct between these mantle types (e.g., Livaccari and Perry, 1993). In addition, the magmatic volatile contents could be very different between these mantle types, although this relationship has not been investigated in detail.

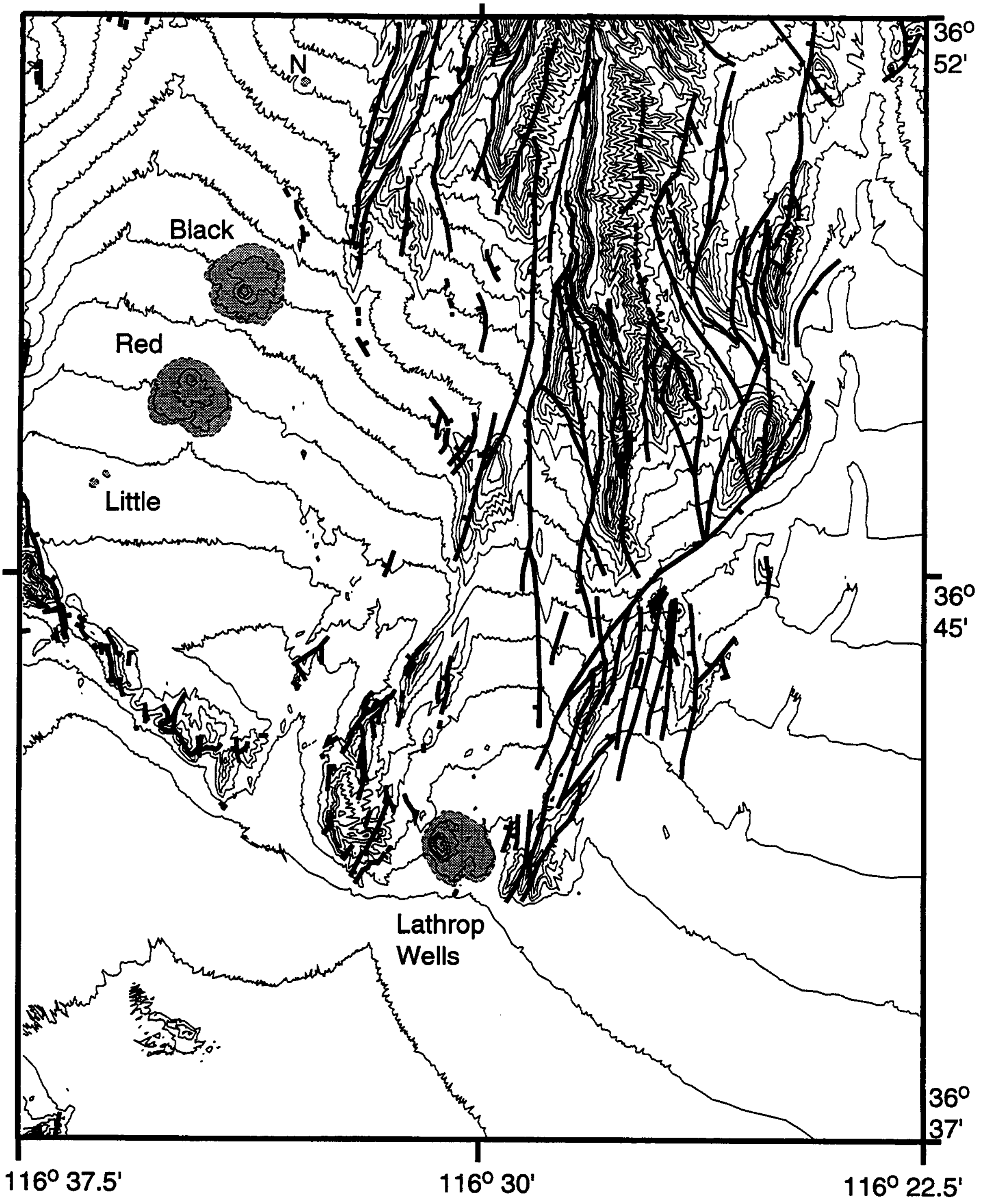

Figure 2-3. Topographic map of the Yucca Mountain area showing mapped faults (Frizzell and Shulters, 1990) and Quaternary basaltic volcanoes (Crowe and Carr, 1980). Topography from USGS Digital Line Graph files for the Amargosa Valley, Big Dune, Busted Butte, and Crater Flat quadrangles. Map produced from the Volcanism GIS. Northern Cone indicated by N.

Geochemical variations in YMR post-caldera basalts are generally attributed to differences in the amount of mantle partial melting and fractional crystallization of olivine, clinopyroxene, and amphibole in a periodically recharged magma system (Vaniman et al., 1982; Crowe et al., 1986). Data presented in Vaniman and Crowe (1981) and Crowe et al. (1986) can be used to show that basalts younger than 2.8 Ma appear petrogenetically distinct from older, post-caldera basalts. The 2.8 Ma Buckboard Mesa eruptions show geochemical and mineralogical evidence of crustal contamination, which is not a characteristic for other post-caldera basalts. Quaternary basalts show wider ranges of geochemical variation than Neogene basalts, and range from nepheline-normative to hypersthene-normative basalt. Although Quaternary basalts lack plagioclase phenocrysts (Vaniman and Crowe, 1981), variations in water content, temperature, and magma composition may control this relationship in addition to increases in pressure proposed by Perry and Crowe (1992).

A detailed petrologic study has been conducted at Lathrop Wells by Perry and Crowe (1992). They concluded that small geochemical variations between Lathrop Wells eruptive units represent the extrusion of compositionally distinct magma batches, which required "many thousands of years" to develop. However, these compositional distinctions are small and are commonly observed at other historic basaltic eruptions such as Tolbachik (e.g., Fedotov et al., 1991). Red Cone also may have compositionally distinct eruptions, whereas Black Cone appears relatively homogeneous (E.I. Smith, pers. comm., 1993).

2.2 COSO VOLCANIC FIELD

The Coso Volcanic Field (CoVF) is located in the Coso Range, immediately north of the Garlock fault and east of Owen's Valley in east-central California (Figure 2-1). Duffield and Roquemore (1988) noted that unlike other ranges in the region, the Coso Range has a nearly equant shape, indicating it is the product of perhaps more complex tectonic processes than has led to the formation of the N-S fault blocks of the Inyo Mountains and other ranges in the vicinity.

2.2.1 Overview

The CoVF is a bimodal volcanic field having erupted both primitive basalts and high SiO_2 rhyolites during its history, often penecontemporaneously (Figure 2-4). Pleistocene eruptions in the CoVF are represented by 38 high-silica rhyolite domes and flows and 14 basaltic centers, which range from 1.1 to 0.04 Ma (Duffield et al., 1980). Current activity in the CoVF is limited to geothermal resources found in this area, and fumaroles which occur at the surface along faults cutting younger dacite-to-rhyolite domes. Because of these geothermal resources, the CoVF has been the site of numerous geophysical investigations, largely in an effort to characterize the structure of the field and to image shallow crustal magma bodies in the region using seismic tomographic and related techniques. Because of bimodal volcanism, the CoVF is not directly analogous to the YMR in several respects. However, the region has been the focus of numerous petrologic, tectonic, and geophysical investigations. Many of the patterns discerned through these studies may provide a basis for interpretation of similar trends, or simply suggest lines of inquiry for the study of the YMR and more analogous regions located elsewhere in the WGB.

2.2.2 Ages

Duffield et al. (1980) collected and dated 36 basalt and mineral separates in the CoVF. A major conclusion from this study was that volcanism in the CoVF has taken place in essentially two stages.

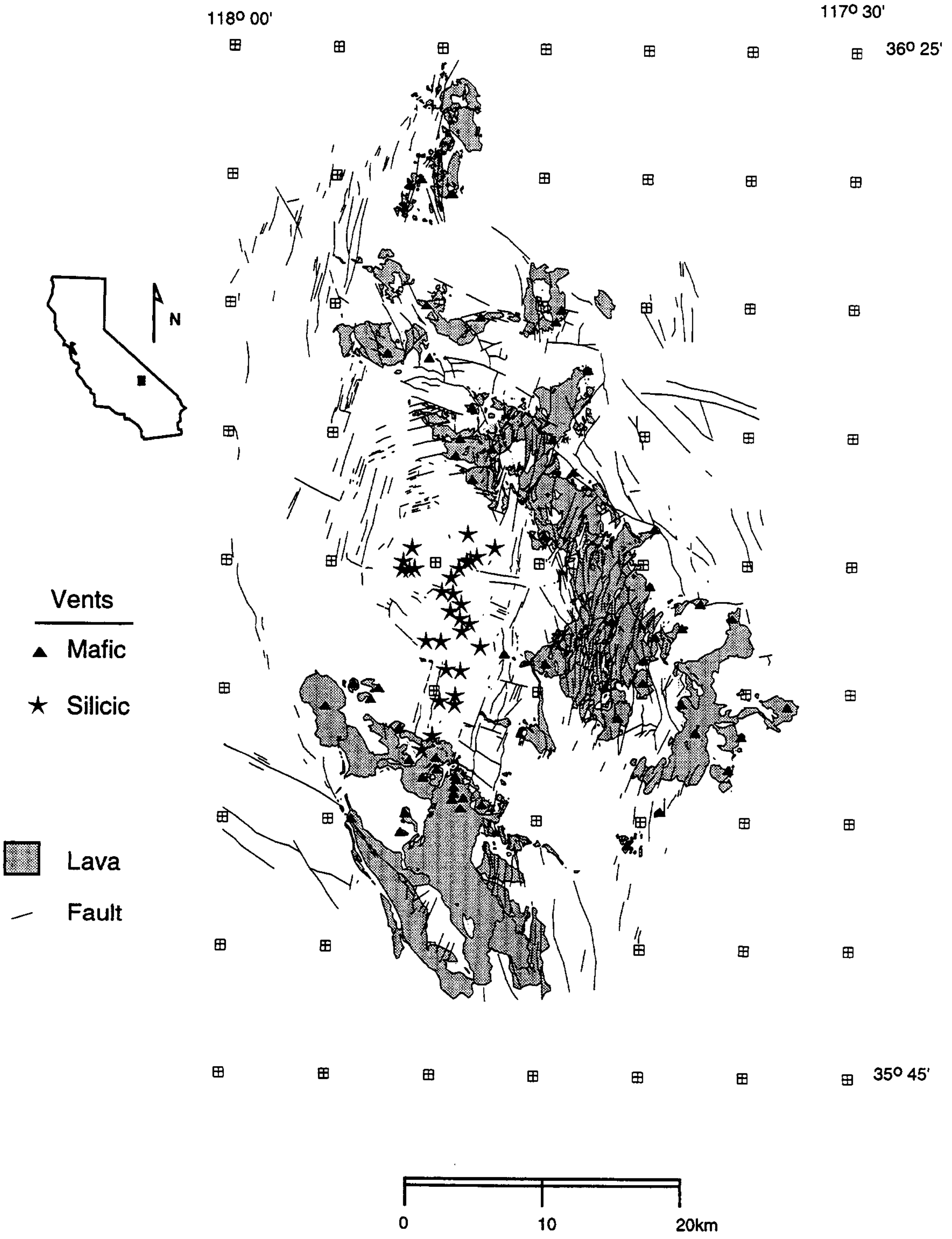

Figure 2-4. Distribution of basaltic vents, silicic vents, basaltic lava flows and faults in and around the Coso Volcanic Field.

Widespread basaltic volcanism began at approximately 4 Ma, with the effusion of basalts over a broad area, which formed an arcuate pattern from southeast to north and west. This Pliocene episode lasted until approximately 2.5 Ma. The most recent episode has lasted from 1.1 Ma to approximately 0.04 Ma and was bimodal. Basalts and rhyolites erupted during this period are located in the southern part of the field (Figure 2-5).

Bacon (1982) found both basalts and rhyolites of the CoVF younger than about 0.4 Ma apparently follow a time-volume predictable pattern. Basalts have erupted at a rate of 2.8 km^3/m.y. since about 0.4 Ma and rhyolites at a rate of 5.4 km^3/m.y. since about 0.25 Ma. Bacon (1982) developed this volume-time relationship using a regression fit on the timing of eruptions and the cumulative volume just prior to eruptions. Extrapolating this regression, a basaltic eruption would be expected in the CoVF sometime in the next 55,000 yr, and a rhyolite eruption would be expected in 60,000 ± 33,000 yr. Bacon (1982) relates his time-predictable pattern to similar patterns in seismology, suggesting that it results from the increase of some parameter at a constant rate until it reaches a critical point, at which time volcanic eruptions occur. Two parameters that may lead to this type of behavior are pressure in the magma reservoir and extensional strain in the overlying rocks (Bacon, 1982). Bacon (1982) favors a relationship to extensional strain, largely because the CoVF is in an area of active extension. In this model, stress in the crust is accommodated by intruding dikes. The greater the volume of intrusions associated with a given eruptive sequence, the more strain is accommodated. As tectonic strain builds at a constant rate, this will result in a longer period of quiescence between successive larger eruptions. Bacon (1982) attributes differences in the rates of rhyolitic and basaltic magmatism to differences in the ways these magmas migrate through the crust, and therefore differences in the way rhyolite and basaltic intrusions accommodate strain.

2.2.3 Physical Volcanology

A total of 38 domes and dacite-to-rhyolite flows are located in the CoVF, together with approximately 54 basaltic cones and flows (Figure 2-4). Duffield et al. (1980) identified 14 basaltic centers that formed between 1.1 and 0.04 Ma, each consisting of numerous vents. Very little of the physical volcanology of the basalts at CoVF has been published. Although the Pleistocene cinder cones in the region are nearly pristine, ash blankets associated with these volcanoes have been completely eroded and reworked. Duffield and Roquemore (1988) note, however, that abundant reworked scoria fragments are preserved in thin layers in the Pleistocene soil section, where exposed along shallow road cuts and fault scarps. The range of explosive activity evinced by these cinder cones, cone morphologies, grain-size analyses, and related studies have not been reported. Some work has been done on the dacite and rhyolite domes in the CoVF, and one ash flow and associated Pliocene ash-fall deposit has been mapped (Duffield et al., 1980).

2.2.4 Tectonics

Roquemore (1980) and Duffield et al. (1980) provide summaries of the tectonic setting of the CoVF. The field lies in a tectonically complex area due to the transition in this region from dominantly E-W extension associated with the Basin and Range and strike-slip and oblique-slip deformation west of the CoVF. Evidence of Holocene deformation and active faulting are abundant in the region and include dramatic offsets of Pliocene and in some cases Pleistocene lava flows and historical seismicity within the boundaries of the CoVF.

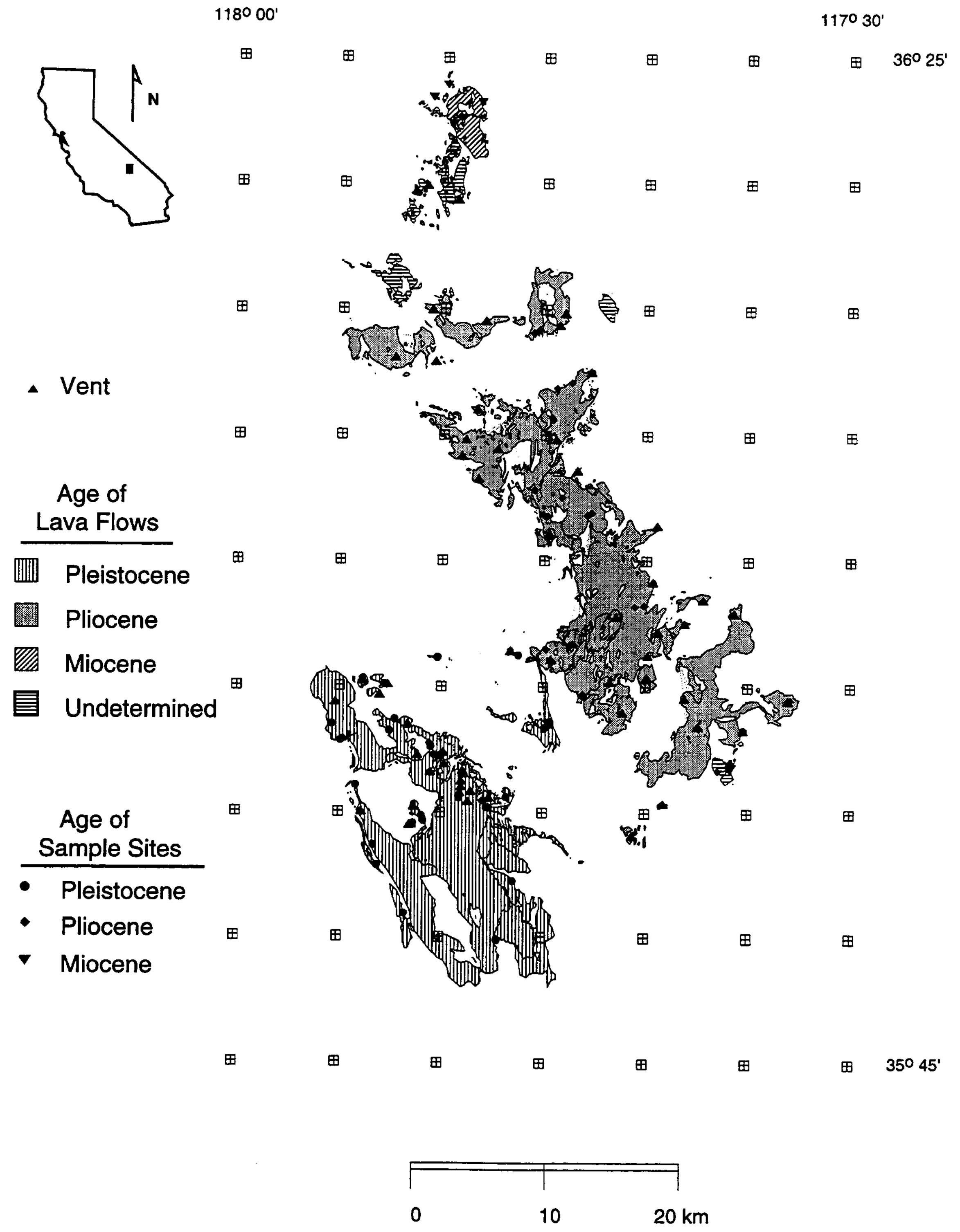

Figure 2-5. Ages of basaltic vents and lava flows in the Coso Volcanic Field. Age symbols posted at sample locations.

Pliocene basalts in the CoVF erupted on relatively gentle topographic surfaces and flows spread in thin, uniform sheets over large areas (Duffield et al., 1980). These lavas now cap mesas in the CoVF. As a result, Pliocene flows provide some control on the average rates of vertical displacement in the CoVF. Duffield et al., (1980) estimated vertical displacements across some N-trending normal faults on the order of 600 m or more. This implies rates of uplift in some areas of 0.1 to 0.8 mm/yr (Roquemore, 1980). Normal faults throughout the CoVF have predominantly N to NE trends and cut all but a few Pleistocene and Pliocene flows. Offset in Quaternary alluvium is common as well. Where exposed, normal faults dip at 60° to 70° at the surface (Duffield and Roquemore, 1988). These normal faults segment the CoVF into a series of roughly N-trending grabens. These trends are also seen in some cinder cone alignments and in the overall distribution of silicic domes (Figures 2-4, 2-6, and 2-7).

Important strike-slip faults in the region include the NNE-trending Airport Lake fault and the NW-trending Little Lake fault. A mafic vent lies along the trace of the Little Lake fault (Figure 2-6). Displacement of flows along this fault indicates a rate of right-lateral offset of about 0.6 mm/yr. Trenching along the Little Lake fault indicates, although slip along the fault is lateral, the fault zone dips to the southwest at the surface (Roquemore, 1981).

In addition to these faults, arcuate fault sets are found in the northern half of the CoVF and are associated with the Pliocene basalts (Figure 2-7). Originally, these faults were interpreted as evidence of caldera formation (Austin et al, 1971), but Duffield (1975) pointed out there are no voluminous tuffs in the area that would indicate the presence of an explosive caldera. Duffield (1975) suggested these faults, that dip steeply toward the center of the field, might be associated with subsidence, possibly related to magmatism. Roquemore (1980) pointed out that it is not unusual to see this type of faulting in areas of mixed strike-slip and normal faulting, and attributed these faults to simple rotation. Roquemore (1980) pointed out cones are associated with some of these arcuate faults, indicating they may have been used as magma conduits. One Pliocene cone, a mafic vent in the northern part of the field, is slightly offset by an arcuate fault, suggesting contemporary faulting and volcanism (≈Lat. 36° 10', Long. 117° 49')(Figure 2-7).

2.2.5 Petrogenesis

Bacon and his colleagues (Bacon et al., 1981; Bacon and Metz, 1984; Bacon et al., 1984; Novak and Bacon, 1986) characterized the petrologic and geochemical setting of the CoVF in an effort to model the petrogenesis of basalts and rhyolites. In general, Pleistocene basalts located close to high-silica domes have been contaminated by crustal interaction and intermingling with more silicic magmas. The degree of this contamination decreases with distance from the rhyolite domes, so far from the domes some of the basalts are relatively primitive. Pleistocene basalts are rich in phenocrysts of olivine, plagioclase, and clinopyroxene, which constitute 30 percent of total volume in some flows. Individual phenocrysts are generally less than 5 mm in length (Bacon et al., 1984). Bacon et al. (1984) found that noncontaminated basalts have SiO_2 contents of less than 50 percent and are mildly alkaline. There is a systematic relationship between eruptive volume and composition in these noncontaminated basalts, suggesting a comparatively simple fractionation history. The most primitive basalts in the CoVF are those with the greatest eruptive volumes, far from rhyolite domes. The most voluminous of these erupted in an episode 0.188 Ma, forming a series of vents along a N-trending fissure system, roughly parallel to other structural trends in the vicinity, near a WNW-trending structural discontinuity in the southern portion of the field (Figure 2-6). These lavas have high Mg, Ca, Sc, and Cr contents and low K, P, Ba, REE, and Th contents. Products of less voluminous eruptions of uncontaminated basalts are low in Mg and high in Fe, Ti, P, Hf, P, Ta, Th, and the HREE. In contrast to the strong correlation with volume,

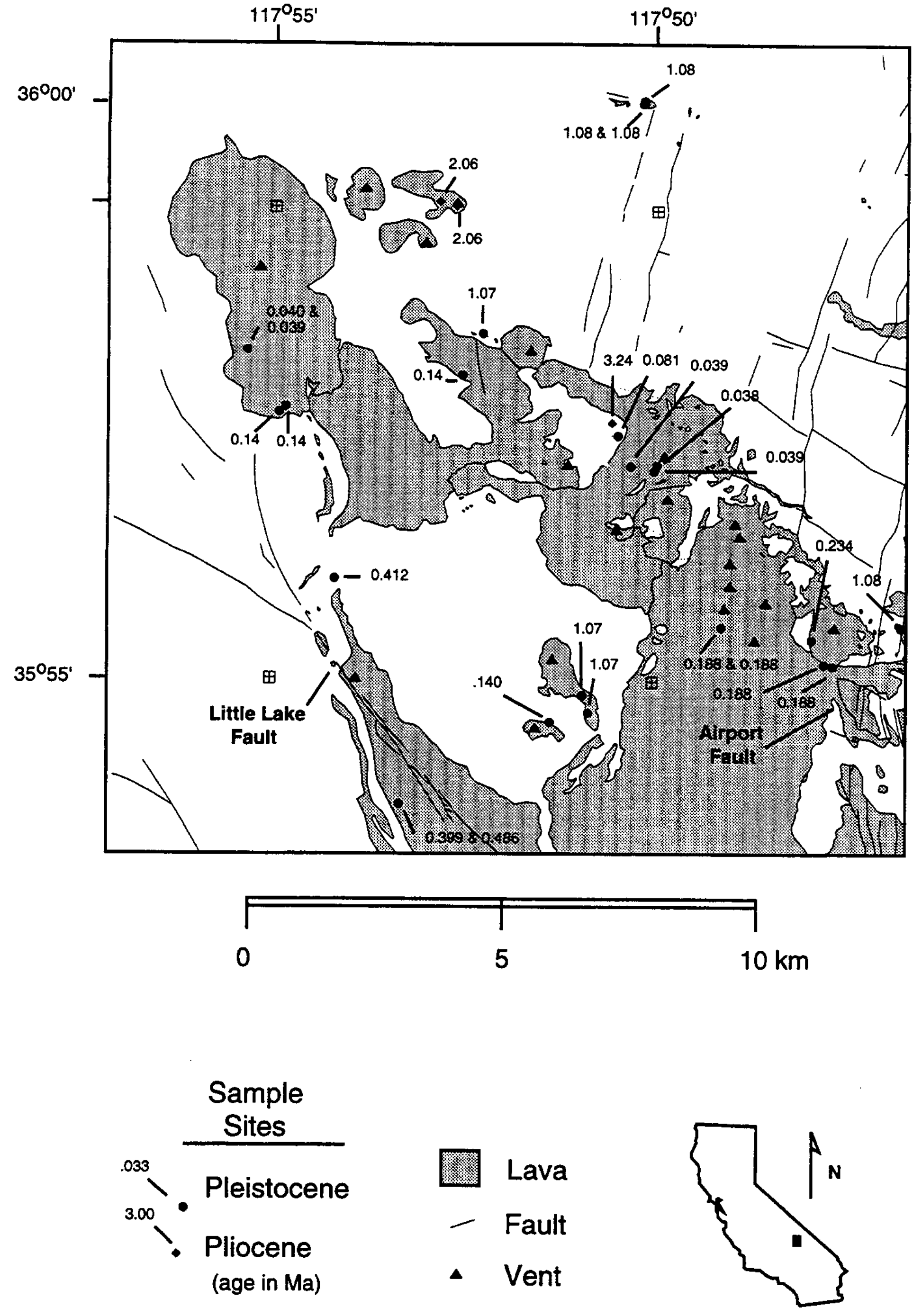

Figure 2-6. Detail of the southern part of the Coso Volcanic Field, showing faults, flows, vents, and age determinations in millions of years. The NW-trending Little Lake fault transects the SW corner of the map; the Airport Fault is a NNE-trending fault set shown on the eastern part of this map.

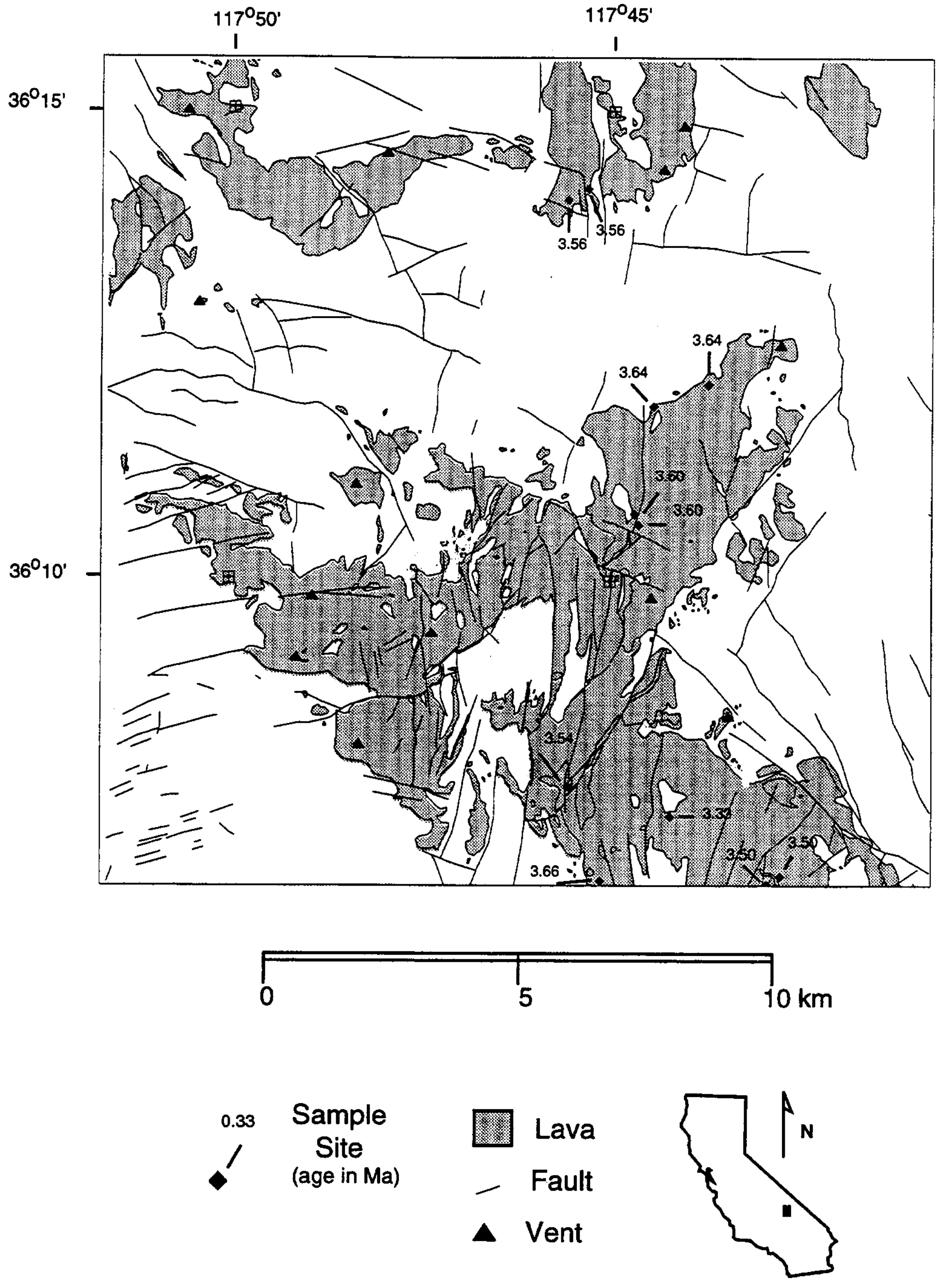

Figure 2-7. Detail of the northern part of the Coso Volcanic Field, showing arcuate faults, vents, and age determinations in millions of years.

no temporal patterns in chemical evolution is apparent in these rocks. Isotopic compositions of the Coso basalts indicate most have experienced some degree of crustal interaction (Bacon et al., 1984). Bacon et al. (1984), however, did identify one flow that has low Sr isotopic ratios ($^{87}Sr/^{86}Sr = 0.7036$) and Pb isotopes indicative of mantle compositions.

Clearly basalts that have mixed extensively with high-silica magmas are not particularly useful for comparison with most volcanoes of the YMR. The comparatively simple fractionation history of basalts located far from the silicic domes and the time-predictable behavior of these basalts make them interesting for comparison with the Crater Flat system and other basaltic volcanoes in the YMR.

2.2.6 Seismic Tomography

Several seismic tomographic surveys have been carried out in the CoVF. The P-wave velocity structure of the upper 22 km of the crust beneath the CoVF was studied by Reasenberg et al. (1980). They used 137 teleseismic earthquakes correlated using 40 stations to model velocity in a study volume centered on the CoVF and discretized into three layers of blocks, each with dimensions of 5×5×7.5 km. Their results indicate the presence of a low-velocity volume beneath the rhyolite domes (Figure 2-4) at depths of 5 to 20 km. The maximum velocity contrast of this anomaly is on the order of 6 to 8 percent, and the dimensions of the body are on the order of 5 km. Young and Ward (1980) identified a high-attenuation zone in the same region at depths of 12 to 20 km, which they interpreted to be a magmatic heat source driving the Coso geothermal system. A higher resolution survey by Walck and Clayton (1987) used 4,036 P-waves from 429 local earthquakes to image velocity variations in the upper 10 km of the crust. The model volume in their study was 70×80×10 km and individual block sizes were 2×2×2 km. Their most significant finding was that crust beneath Coso has normal velocities to a depth of 10 km. In other words, there is no evidence of a shallow magma body at Coso with dimensions greater than 2×2×2 km and at depths of less than 10 km. However, Walck and Clayton (1987) did identify a low-velocity zone at depths of 3 to 5 km within alluvium south of the Coso Range. Seismic velocities are 7 percent lower than regional velocities within this zone. Similar conclusions were reached by Sanders et al. (1988) and Ho-Liu et al. (1988) in their studies of the S-wave attenuation structure of the Coso region. These results agree well with petrogenetic models developed by Bacon et al. (1984) in which it is suggested that a rhyolite magma body is present at Coso, but at depths greater than 10 km.

2.3 CIMA VOLCANIC FIELD

The Cima Volcanic Field (CVF) is located in the northeastern Mojave desert, approximately 150 km SSE of Yucca Mountain and 120 km SW of Las Vegas (Figure 2-1). The field is comprised of approximately 40 cinder cones and 60 flows, distributed over an area of approximately 150 km^2 (Figure 2-8 (Dohrenwend et al., 1984; 1986). These features define an episode of volcanic activity that began approximately at 10 Ma and has continued through the latest Pleistocene (Turrin et al., 1985).

2.3.1 Overview

The CVF is one of the most studied volcanic fields in the entire WGB. The field was first mapped by Hewitt (1956), who recognized the Quaternary basaltic field and mapped the areal extent of flows. Barca (1965) mapped the southern part of the Cima field at a scale of 1:62,000 and Breslin (1982) mapped the youngest cone in the field, Black Tank cone (also known as cone C22), at a scale of 1:2,000. Later studies in the field (Dohrenwend et al., 1984; Wells et al., 1985) augmented these maps and

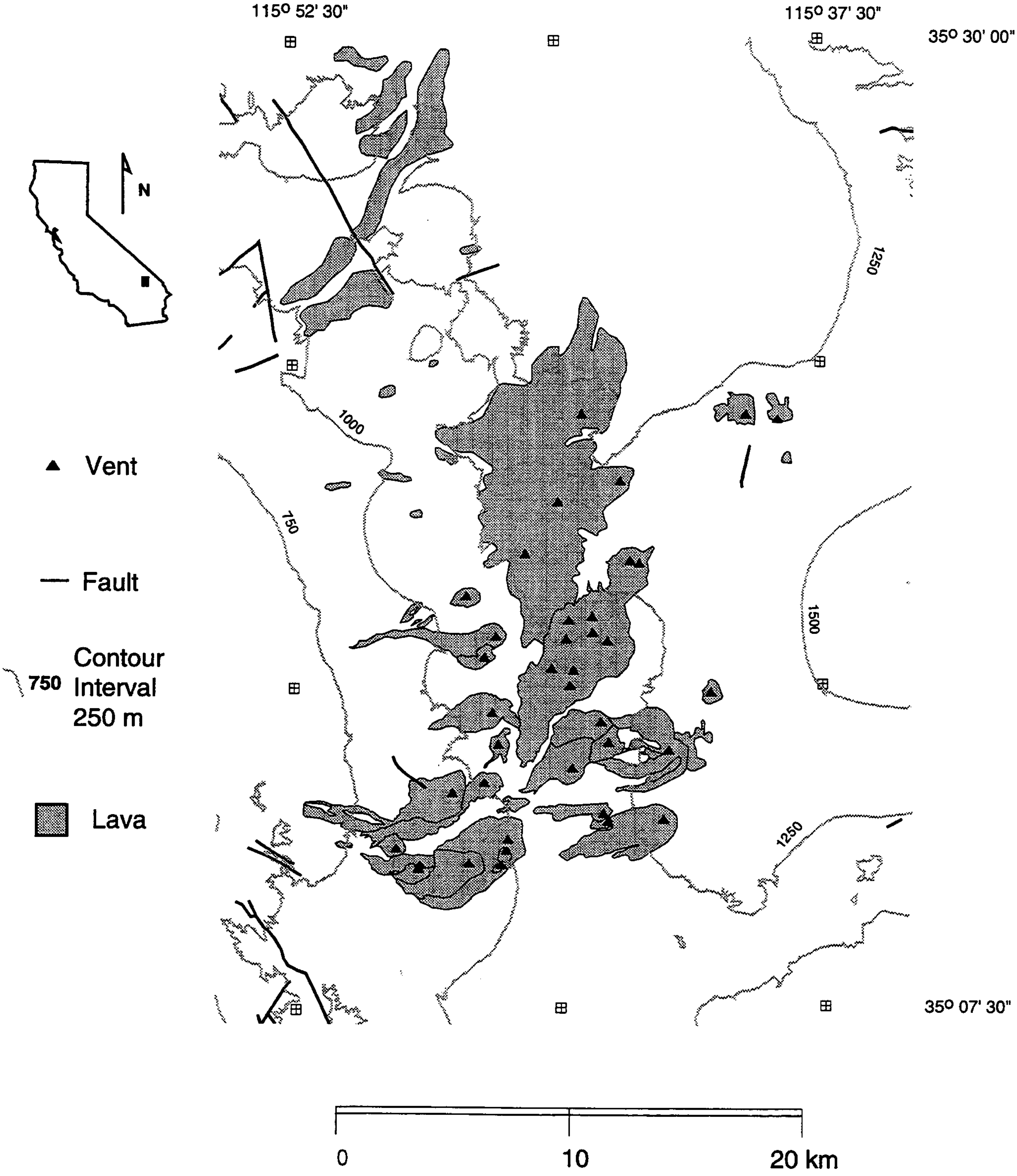

Figure 2-8. Distribution of basaltic vents, flows and faults in the Cima Volcanic Field. Digitized topographic contours are shown (contour interval is 250 m).

provided details of individual flows and vents. Geochemical and petrologic studies of the field include investigations by Katz (1981), Wilshire (1986), and Farmer et al. (1991). The CVF has been the site of intensive geomorphic studies, calibrated by numerous radiometric age determinations (Dohrenwend et al., 1984; 1986; Turrin et al., 1985; Wells et al., 1985).

2.3.2 Ages

Turrin et al. (1985) report 53 high-precision K-Ar dates for the lava flows of the CVF. These data, together with paleomagnetic data collected as part of the same study, provide a very complete record of the timing of basaltic volcanism in this field. Based on these data, Dohrenwend et al. (1984) identified three periods of activity in the field, each lasting approximately one million years: 7.6 Ma to 6.5 Ma, 4.5 to 3.6 Ma, and 1 Ma to the present. The initial period of activity is only represented by a small volume, highly dissected flow and vent complex located on the southeastern margin of the field (Figure 2-9). Eruptions during 4.5 to 3.6 Ma occurred in the northern half of the field and were the most voluminous. Quaternary eruptions occurred in the southern half of the field and have been further subdivided, based on paleomagnetic epochs and the degree of soil development on lava flows from this period (Figure 2-9).

The youngest cone in the CVF is the Black Tank cone, located in the extreme southeast portion of the field. Katz and Boettcher (1980) and Katz (1981) estimate the age of Black Tank cone to be between 300 and 1,000 yr, based on several lines of evidence. A thermoluminescence (TL) date on the youngest flow from Black Tank was 963 ± 145 years before present (y.b.p.). A date of 860 ± 130 y.b.p. was reported (Katz and Boettcher, 1980) based on basaltic glass hydration. A ^{14}C date of 330 to 440 y.b.p. was determined for organic matter excavated from beneath the youngest Black Tank flow Katz (1981). These data, together with the lack of vegetation on Black Tank deposits led (Katz, 1981) and Breslin (1982) to conclude that Black Tank is quite young. In contrast, Dohrenwend et al. (1986) found evidence to suggest that this cone formed at approximately 15,000 y.b.p. These data include ^{14}C dates on desert varnish and cation ratio dates (Dorn et al., 1986). All of these dating methods have limitations (Hill et al., 1993). Although this difference in estimated age is interesting from a geochronological point of view, this difference in age does not have a substantial impact on probability calculations.

2.3.3 Physical Volcanology

Several studies have sought to understand the morphometrics of cinder cones and lava flows in the CVF, largely in an effort to develop conceptual and empirical models of cinder cone and lava flow degradation and as a method of assessing climate variation (Dohrenwend, 1984; 1986; Turrin et al., 1985; Wells et al., 1985). Cinder cones in the CVF range in height from 50 to 155 m and in basal diameter from 400 to 915 m. Crater-width to cone-width ratios in the CVF average 0.48, a typical value for Quaternary cinder cones (Wood, 1980).

Younger cones in the CVF often have thick mantles of ash and unconsolidated cinders. These cinder cones contain strata of varying thicknesses that are normally parallel, or nearly parallel, to the outer cone slope. Juvenile clasts in these strata range from coarse sand to cobble size. Reverse grading in these strata is common. The degree of agglutination in these deposits is also variable. Clasts are unconsolidated in some strata, indicating that clasts were deposited cold. In other strata, clasts are well agglutinated and there is evidence of rheomorphic flow. Bombs are common in the cinder cones of the CVF. These bombs are generally fusiform and vary in size from several cm to 2 m in maximum dimension. These bombs are common both in young cones and in older cones. In some areas, bomb fields can be identified extending out from the bases of the cinder cones.

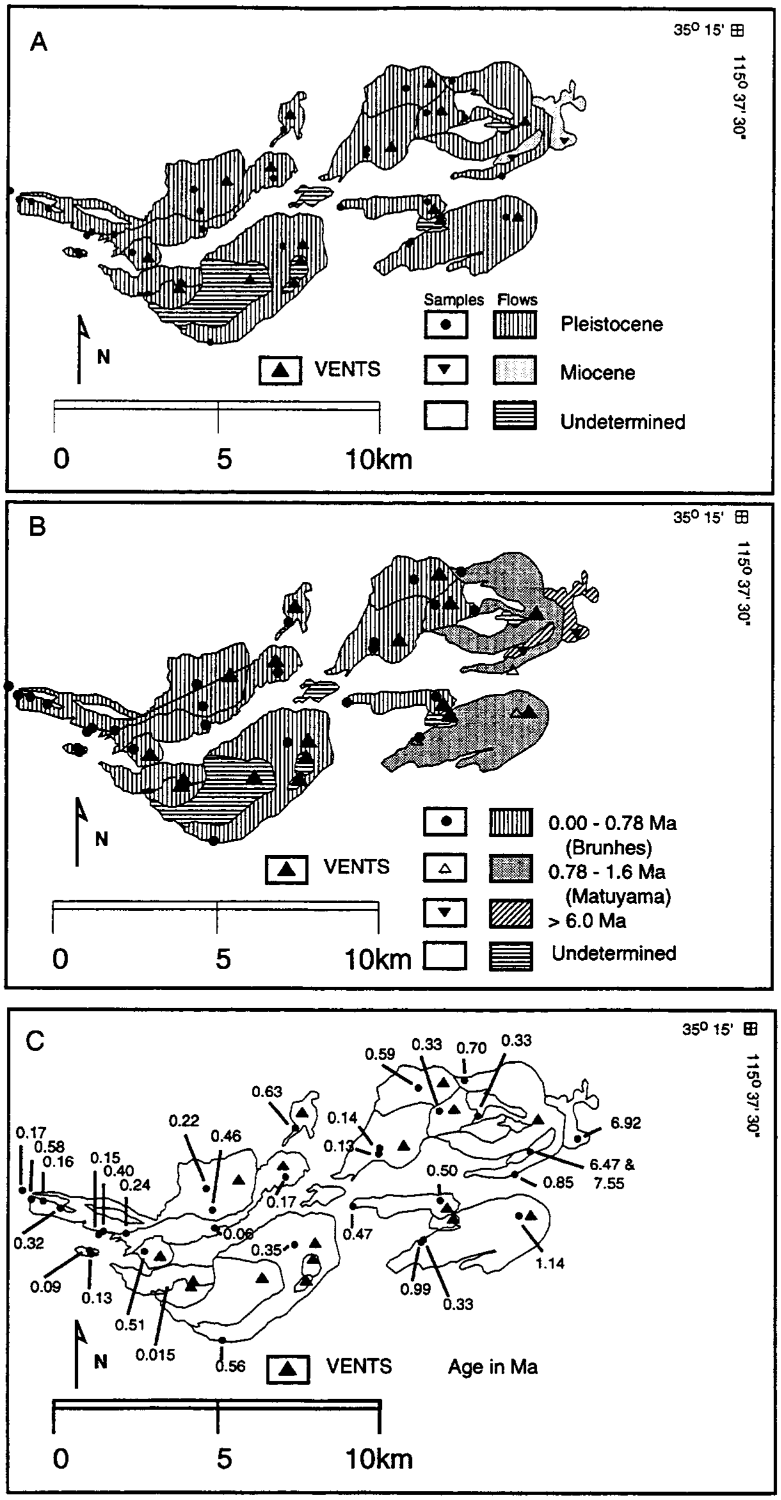

Figure 2-9. Three methods of presenting the same geochronological information in the southern part of the Cima Volcanic Field, by: (a) geologic epoch, (b) paleomagnetic epoch, and (c) posted ages.

Dohrenwend et al. (1984) mapped four tuff rings in the CVF. These are located in the same general area in the south-central part of the volcanic field. Classic antidune structures and low angle cross-bedding are found in these tuff rings, which are the result of base surges, and indicate that these deposits result from explosive magma-water interaction.

Approximately 60 lava flows are mapped in the CVF (Figure 2-8). Flows are associated with all but one cinder cone in the southern part of the field. Flow volumes vary between 10^4 and 10^7 m^3 (Katz, 1981). These volumes are large compared with cone volumes, but are comparable in size to the volume of numerous ash blankets associated with individual cinder cone eruptions where these are preserved in historically active volcanic fields. These flows have been classified into two types by Dohrenwend et al. (1984) on the basis of their morphology. Elongate lava flows in the field are the most common type. These range in length from 2.4 to 9.1 km, have low relief on the order of 2.5 to 4 m, and have pahoehoe to aa textures. These flows typically have gradients of 3 to 6 percent. Equant flows range in length from < 1 to 4 km and are often more than 15 m thick (Dohrenwend et al., 1984). These flows have blocky textures, although individual blocks are comparatively small and are rarely greater than 0.5 m in maximum dimension. Flow gradients in equant flows are 4 to 10 percent, steeper than those of elongate flows. Dohrenwend et al. (1984) suggested that elongate flows tend to form early in a given eruptive sequence and equant flows later in the eruptive sequence. This would suggest that the lava flow morphology may reflect changes in magma properties as eruptions continue.

2.3.4 Petrogenesis

Lavas in the CVF are classified as hawaiities, alkali olivine basalts, and basanites (Katz, 1981; Breslin, 1982). Typically, Cima basalts consist of phenocrysts and megacrysts of plagioclase, clinopyroxene, olivine, and less frequently iron oxides. The groundmass is composed of microcrystalline feldspar, clinopyroxene, magnetite-ulvospinel, hematite-ilmenite, and apatite. Kaersutute and spinel are rare. Xenoliths are common in CVF lava flows. These xenoliths are mafic, ultramafic, granitic, or gabbroic. Breslin (1982) reported alluvial gravels present as xenoliths within a small dome-like mound at the center of the Black Tank Cone crater.

Major and trace element analyses for CVF lavas have been entered into the GIS volcanism database. Most of these data are from Breslin (1982) and Katz (1981). Typical analyses are shown in Figure 2-10. SiO_2 concentrations vary between 46 and 51 percent, and MgO from 6 to 8 percent, in CVF lavas (Katz, 1981). Major and trace element contents do not show systematic variations between flows in the CVF or within individual flows (Katz, 1981). In fact, Breslin (1982) has reported major element variation within a single flow at Black Tank nearly encompasses all of the major element variation in the southern part of the field. Dohrenwend et al. (1984) suggested Pliocene lavas in the CVF tend to have slightly higher SiO_2 and lower MgO contents than basalts from the latest episode of activity.

Farmer et al. (1989; 1991) reported Nd, Sr, and Pb isotopic compositions for CVF lavas. Samples from the most recent episode of volcanism have compositions of $\varepsilon Nd = +8$, $^{87}Sr/^{86}Sr = 0.7030$, $^{206}Pb/^{204}Pb = 18.9$ to 19.1, and $^{208}Pb/^{204}Pb = 38.5$ to 38.6 (Farmer et al., 1991). These data are consistent with an ocean-island basalt-type mantle source of these lavas, such as is found elsewhere in the Great Basin associated with lithospheric extension and concomitant upwelling of the asthenosphere. The data are also consistent with mineralogical data presented by Katz (1981) that indicate comparatively little crustal contamination of CVF lavas. In contrast, some of the older lavas in the CVF have variable

SAMPLE NUMBER	02006MC1a	02006MC3	02006MC5a	02006MC12	02006MC20	02006MC21	02006MC25	02006MC29
Vent Number	01				19	31		32
Easting	611323	605231	603400	602816	608374	610956	610317	614888
Northing	3907666	3920017	3916590	3896052	3895729	3898278	3900688	3894733
Age	3.86	4.48	5.12	0.58	0.46	0.63	0.39	0.99
Deviation	0.12	0.15	0.16	0.16	0.08	0.11	0.08	0.07
Technique	K/Ar	K/Ar	K/Ar	K/Ar	K/Ar	K/Ar	K/Ar	K/Ar
Item Dated	whole rock	whole rock	whole rock	whole rock	whole rock	whole rock	whole rock	whole rock
Magn Polarity				normal	normal	normal	normal	reversed
MAJOR ELEMENTS								
SiO2	50.1	50.9	50.9	47.4	48.1	47.1	48.3	47.4
TiO2	2.5	2.3	2.2	2.4	2.3	2.3	2.4	2.4
Al2O3	17.6	17	17.6	16.5	16.7	16	16.6	16.8
FeO*	10.6	10	10.1	9.8	10	9.9	9.5	10.2
MnO	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
MgO	3.7	4.6	3.5	7.6	6.2	8.4	7.4	7.4
CaO	8	7.8	7.4	9	9.1	9.5	8.9	9.1
Na2O	4.8	4.4	5	4.4	4.5	4.1	3.8	4.1
K2O	1.8	2.1	2.3	2	2.1	1.8	2.1	1.8
P2O5	0.7	0.7	0.8	0.7	0.8	0.7	0.8	0.6
Total	100	100	100	100	100	100	100	100
TRACE ELEMENTS								
Rb	33	39	41	42	47	38	39	42
Ba	270	321	356	376	389	336	426	290
Sr	601	545	641	607	609	555	704	636
V	197	182	198	245	246	270	220	257
Cr	21	43	42	175	95	244	188	175
Ni	29	72	38	121	88	129	126	105
La	32	34	35	38	32	27	38	31
Y	37	36	38	29	32	30	26	30
Zr	343	323	394	306	305	283	308	316
Nb	36	40	43	48	45	41	44	45

Figure 2-10. An example of an Arc/Info data output file, summarizing geochronological and geochemical data for selected samples from the Cima Volcanic Field.

isotopic compositions, but in general are more indicative of some crustal contamination, or possibly a different mantle source (εNd = +5.1 to 6.1, $^{87}Sr/^{87}Sr$ = 0.7032 to 0.7050). Farmer et al. (1991) suggest that instead of decreasing crustal contamination through time, the region may be experiencing erosion of lithospheric mantle. Regardless, their preliminary data indicate some geochemical trends exist in the CVF and these could be the result of a variety of tectonic processes.

2.4 BIG PINE VOLCANIC FIELD

The Big Pine Volcanic Field (BPVF) is located in Owen's Valley, California, between the towns of Big Pine and Independence (Figure 2-1). The BPVF straddles Owen's Valley, a deep NNW-trending alluvial basin between the east flank of the Sierra Nevada on the west and the west flank of the White-Inyo Mountains on the east.

2.4.1 Overview

More than 25 basaltic cinder cones of alkaline and subalkaline composition (Ormerod, 1988), and one small-volume rhyolite dome, comprise the BPVF. These cones are scattered over an area of approximately 400 km^2. The Owen's Valley fault extends the length of the Owen's Valley near its topographic center. Several cones lie along the trace of this fault or along nearby fault segments in the BPVF, but most cones are located at higher topographic levels, close to inferred range-bounding faults (Figure 2-11). Moore (1963) mapped the field as part of a regional survey. His map has been further refined and modified by Darrow (1972) and Ormerod (1988), both of whom studied the petrogenesis of BPVF basalts. Martel et al. (1987) mapped a small area around the Fish Springs cinder cone, located in the northern part of the field along the Owen's Valley fault, in detail.

2.4.2 Ages

Bierman et al. (1991) summarized age data on BPVF basalts collected by Cox et al. (1963), Gillespie et al. (1983; 1984), Turrin and Gillespie (1986), and Martel et al. (1987), and reported two-sigma analytical uncertainties where available. Most flows in the BPVF have been dated by K/Ar or $^{40}Ar/^{39}Ar$ methods. Ormerod (1988) produced several additional dates. Age data compiled for the BPVF are illustrated in Figure 2-12. Activity in the BPVF is apparently limited to the Pleistocene. Oldest centers in the field are on the east side of the Owen's valley (1.05 ± 0.08 Ma) and in Oak Creek Canyon in the southern part of the field (1.18 ± 0.05 Ma). Cox et al. (1963) reported a date of 1.3 Ma for the Crater Mountain alkali basalt. This is in sharp contrast to the more recent date of 0.219 ± 0.04 Ma (Bierman et al., 1991). Ormerod (1988) suggested there was a shift in the locus of effusive activity from north to south through time in the BPVF, excluding the Oak Creek basalts. Based on the compilation of Bierman et al. (1991), it is clear most activity in the field occurred less than 0.5 Ma. In the northern part of the field, eruptions appear to have taken place between roughly 1.0 and 0.3 Ma, with Red Mountain, Fish Springs cinder cone, and Crater Mountain erupting penecontemporaneously. Vent alignments in the southern part of the field, on the west side of Owen's Valley extending south to Sawmill Creek, formed slightly more than 0.1 Ma. However, there is considerable uncertainty reported in the age determination of young flows from this alignment (0.13 ± 0.09 Ma). Age determinations for centers in the southernmost field are more variable, ranging from roughly 1.2 Ma to 0.1 Ma.

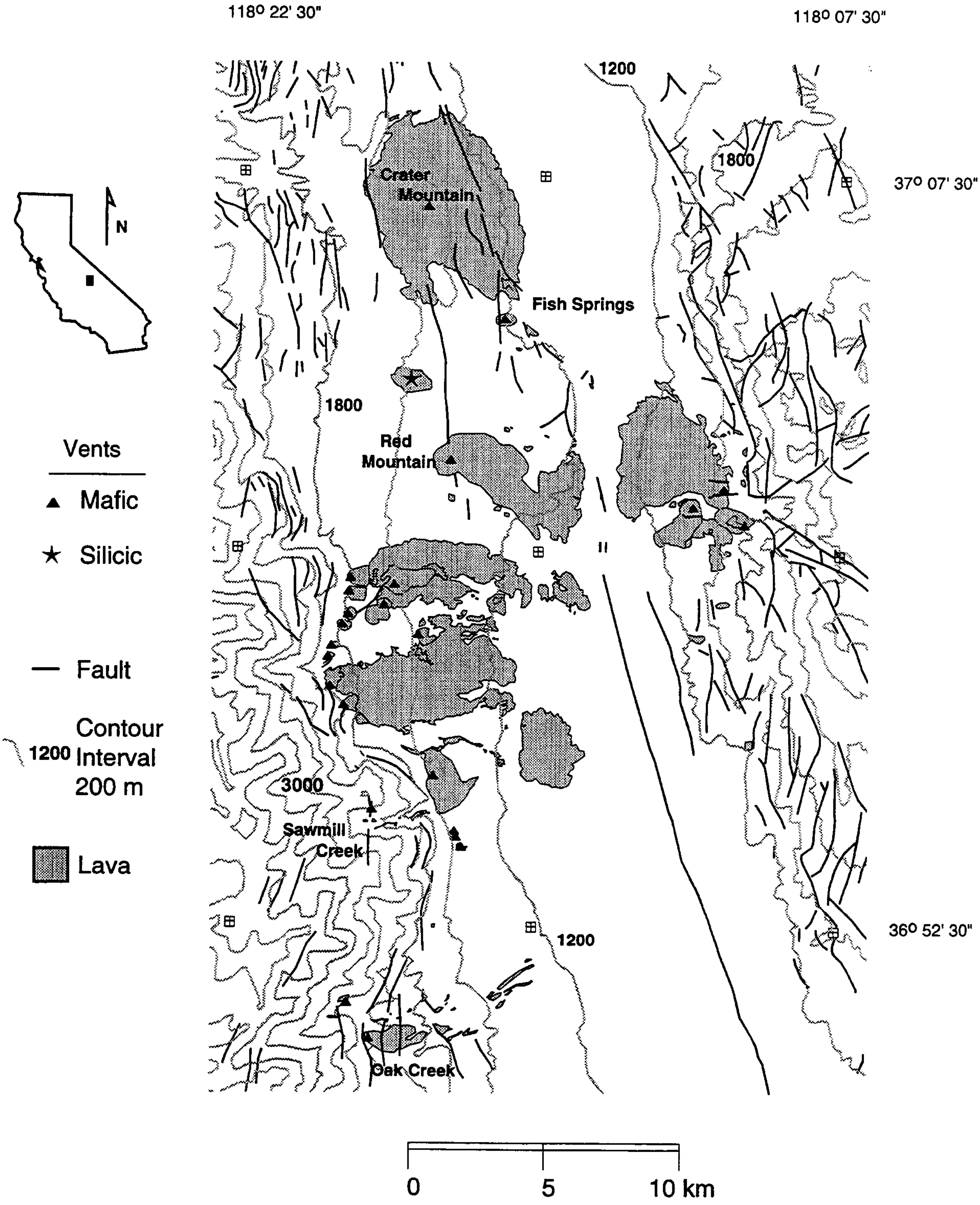

Figure 2-11. Distribution of basaltic vents, flows and faults in the Big Pine Volcanic Field. Digitized topographic contours are shown.

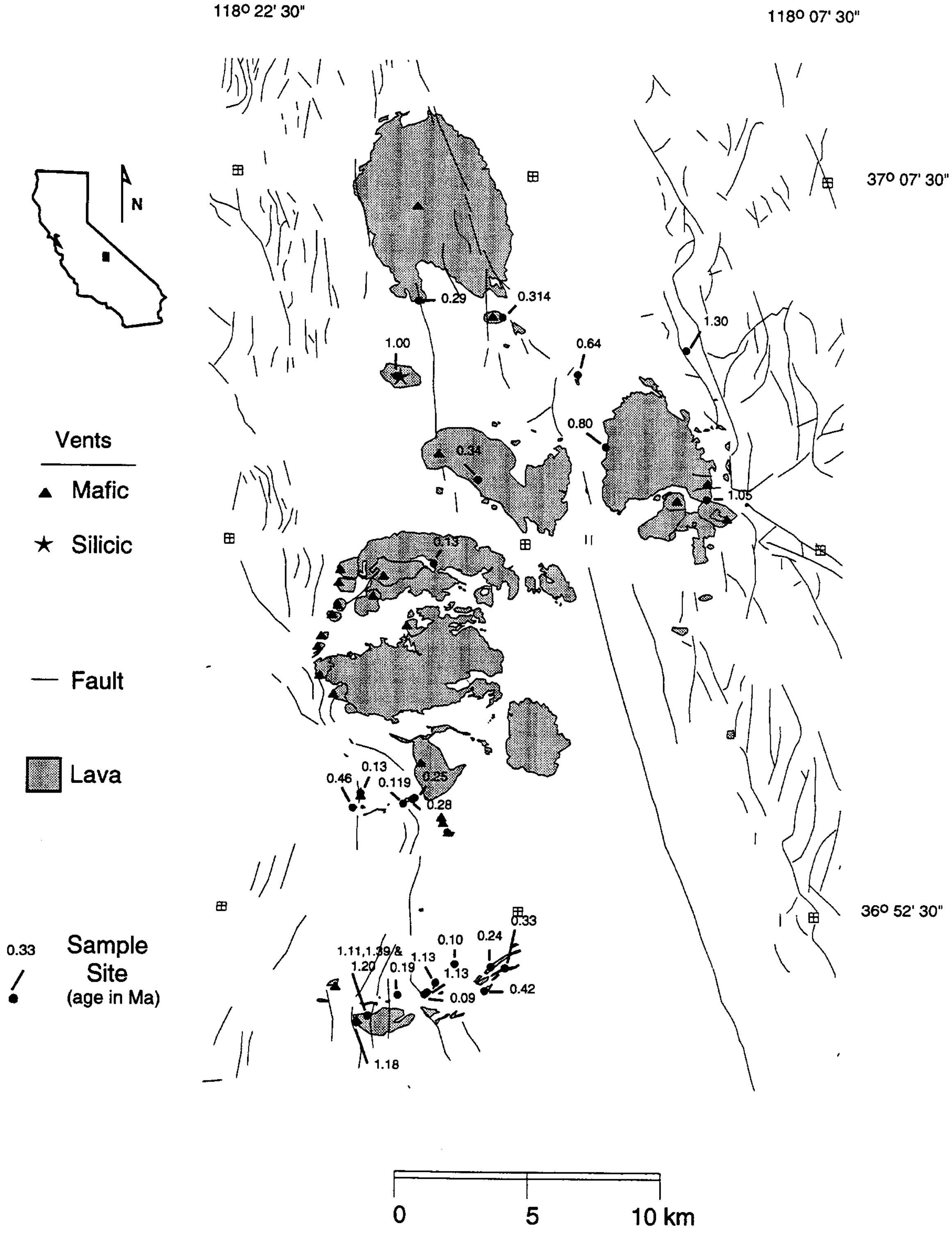

Figure 2-12. A summary of geochronological data complied for the Big Pine Volcanic Field. Sample locations are shown and ages are posted in millions of years.

2.4.3 Physical Volcanology

Essentially nothing has been written about the physical volcanology of the BPVF. Cone heights in the region are up to approximately 250 m and basal diameters up to 1.8 km. Breached cones are common, and generally are the sources of elongate lava flows. There is no report of tuff ring or maar development in the field. Lava flows in the field tend to be aa to blocky in texture. Ormerod (1988) reported pressure ridges up to 10 m in height on some flows, which indicates comparatively viscous flows in the area. Pahoehoe flows have not been reported.

2.4.4 Tectonics

The BPVF offers a remarkable opportunity to study the relationship between basaltic volcanism and extensional tectonism. The field straddles the active Owen's Valley Fault Zone, and several cones in the field are cut by, or overlie, individual fault segments. In particular, the Fish Springs cinder cone has been offset by 78 m as a result of slip since the cone formed 0.314 ± 0.036 Ma (Martel et al., 1987). The Fish Springs fault dips at between vertical and 60°. The Red Cone directly overlies a prominent NNW-trending fault that is also part of the Owen's Valley fault system. Even the earliest workers in the BPVF (e.g., Moore, 1963; Darrow, 1972) reported the dramatic relationship between fault traces and cinder cone alignments in the field, particularly high about the valley floor on the west side of the field.

2.4.5 Petrogenesis

Ormerod (1988) and Ormerod et al. (1991) provide details of the petrology and geochemistry of basalts in the BPVF and offer several explanations for the petrogenesis of these rocks. Basalts in the field are alkali olivine basalts and olivine tholeiites (Figure 2-13). Most alkali basalts are located in the southern portion of the field, with the exception of Crater Mountain, which is the largest volume and northernmost center in the BPVF. Although Crater Mountain is dominated by olivine tholeiites, Ormerod (1988) also reported analyses of alkali olivine basalts at Crater Mountain. Olivine tholeiites are only found in the northern half of the field. Major element trends and phenocryst compositions indicate these suites cannot be related by simple fractionation (Ormerod,1988). The alkali basalts have phenocrysts of olivine and clinopyroxene up to 2 mm in length. In general, these alkali basalts have silica concentrations of between 47 and 50 percent, high Mg contents, and are nepheline normative. Ormerod et al. (1991) found an overall negative correlation between SiO_2 and P_2O_5 and Rb, and suggested these and similar geochemical trends are the result of melt generation by varying degrees of partial melting of a homogeneous lithospheric mantle source. Olivine tholeiites have SiO_2 contents of between 51 and 53 percent. Phenocrysts of plagioclase and olivine are common in these rocks.

Ormerod (1988) proposed several models to explain geochemical patterns in the field. One model is that the early alkali basalt of Crater Mountain formed as a result of partial melting of a deep, asthenospheric source, and subsequent mixing with lithospheric components. Continued heating, likely associated with extension, resulted in partial melt generation at 35–40 km levels and continued mixing with additional asthenospheric melts. Simultaneously, or perhaps later, partial melts of alkali basalt were produced in the southern part of the field, near the lithosphere-asthenosphere boundary. This could have been accomplished either by migration of an asthenospheric plume, or simply due to changes in the depth of the base of the lithosphere and simple heat transfer.

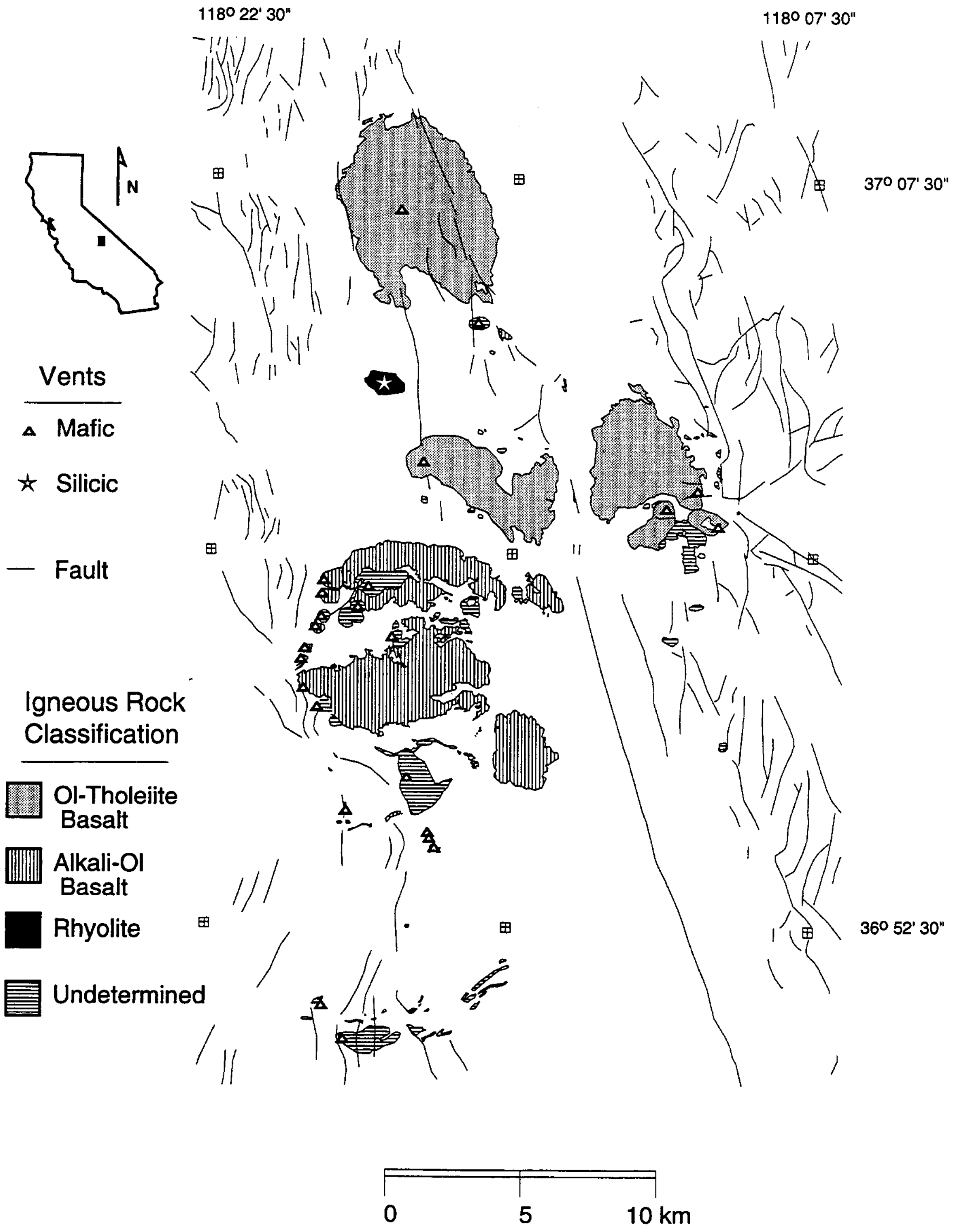

Figure 2-13. Summary of the geochemical classification of lavas in the Big Pine Volcanic Field.

2.5 LUNAR CRATER VOLCANIC FIELD

The Lunar Crater Volcanic Field (LCVF) includes alkaline basaltic volcanoes distributed throughout the Pancake and Reveille ranges, roughly 120 km NNE of Yucca Mountain (Figure 2-1).

2.5.1 Overview

The LCVF includes approximately 75 cinder and spatter cones and three maars, distributed over an elongate NNE-trending zone, measuring 100×25 km in area (Foland and Bergman, 1992) (Figure 2-14). Basic mapping in the area was done by Scott and Trask (1971). The focus of studies in the LCVF has been the development of temporal and spatial patterns of volcanism, primarily because of the distinctive migration of vents from southwest to northeast through time in this field, parallel to both regional tectonic and structural patterns.

2.5.2 Ages

Foland and Bergman (1992) report 40 age determinations on LCVF lavas, summarizing, in part, work of Turrin and Dohrenwend (1984), Turrin et al. (1985), and Naumann et al. (1991). The age information available is summarized in Figure 2-15 for the southern part of the LCVF, cinder cones and flows in the Reveille Range, and in Figure 2-16 for the northern LCVF, in the Pancake Range. Alkalic basaltic volcanism has occurred in this area since about 9 Ma, with most activity between 6 Ma and 0.3 Ma. This is a long period of activity compared with WGB volcanic fields, and is comparable to the period of activity in the YMR. Most volcanic activity in the southern part of the LCVF, in the Reveille Range, took place between 4 to 6 Ma. In contrast, activity occurred between 4 and 0.3 Ma in the Pancake Range. Several authors have noted this progression in the occurrence of volcanism (Naumann et al., 1990; 1991; Foland and Bergman, 1992). However, it is clear this is only a general trend, more pronounced than, but similar to, those observed on smaller scales in the YMR, Coso, and Cima volcanic fields. Volcanism may occur at given locations within the LCVF over periods of 3–4 million years and, at a given time, volcanism may occur over areas of several hundred square kilometers (Foland and Bergman, 1992). For example, successive flows associated with the Easy Chair maar have dates of 1.0 Ma and 0.5 Ma. This indicates, although a regional pattern in the migration of eruptive centers exists, local activity persists for long periods of time within small areas.

2.5.3 Physical Volcanology

Cinder cones and spatter cones have varying degrees of agglutination in the LCVF. These, together with three maars in the field, Lunar Lake, Easy Chair, and Lunar Crater (Scott and Trask, 1971), suggest a range of eruptive styles of volcanism from gentle effusive to explosive eruptions. Scott and Trask (1971) report a range of cinder cone basal diameters from approximately 460 to 1700 m, and cone heights from 120 to 360 m. Lava flows in the range often breach cinder cones. Foland and Bergman (1992) report that flow thicknesses range from 3 to 30 m, are often 2 to 3 km in length but sometimes longer on steeper slopes, and have aa to blocky textures. Pressure ridges, squeeze-ups, and clinkery flow surfaces are common. Although Foland and Bergman (1992) report pyroclastic ash sheets about some of the cinder cones, these have apparently never been mapped, nor have physical volcanological studies been made of these deposits.

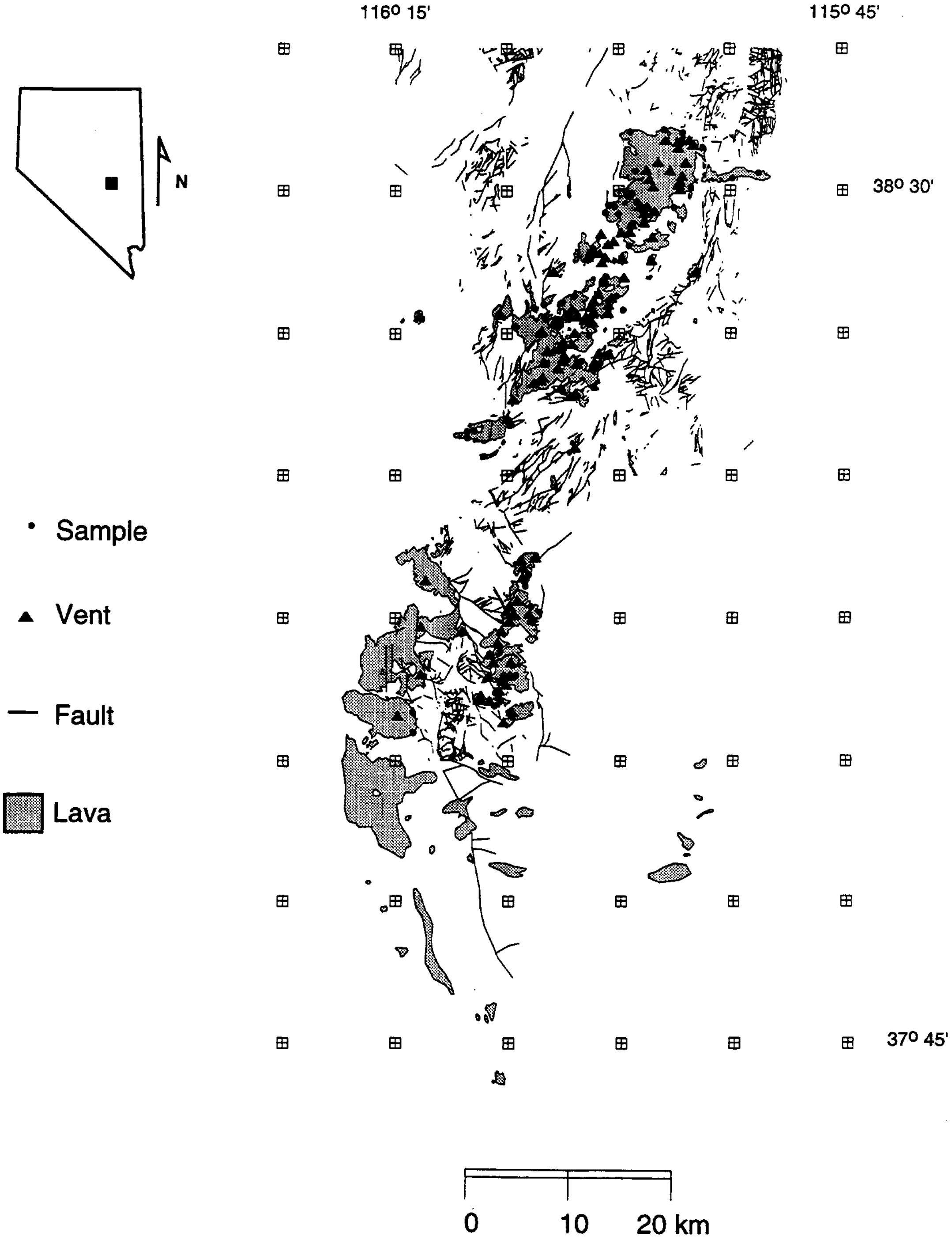

Figure 2-14. Distribution of vents, lava flows, and faults in the Lunar Crater Volcanic Field.

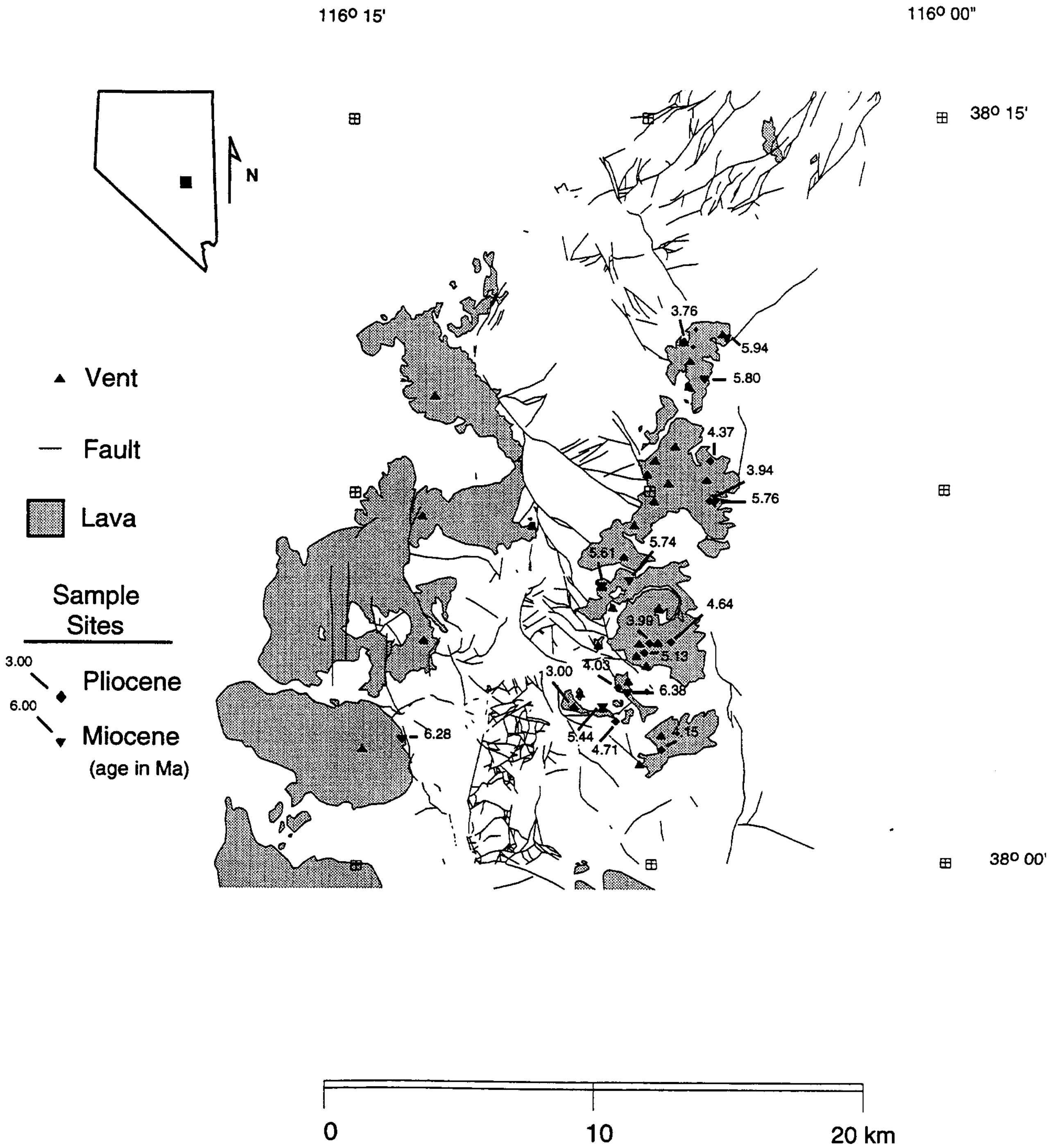

Figure 2-15. A summary of geochronological data complied for the southern half of the Lunar Crater Volcanic Field. Sample locations are shown and ages are posted in millions of years. Faults are also indicated.

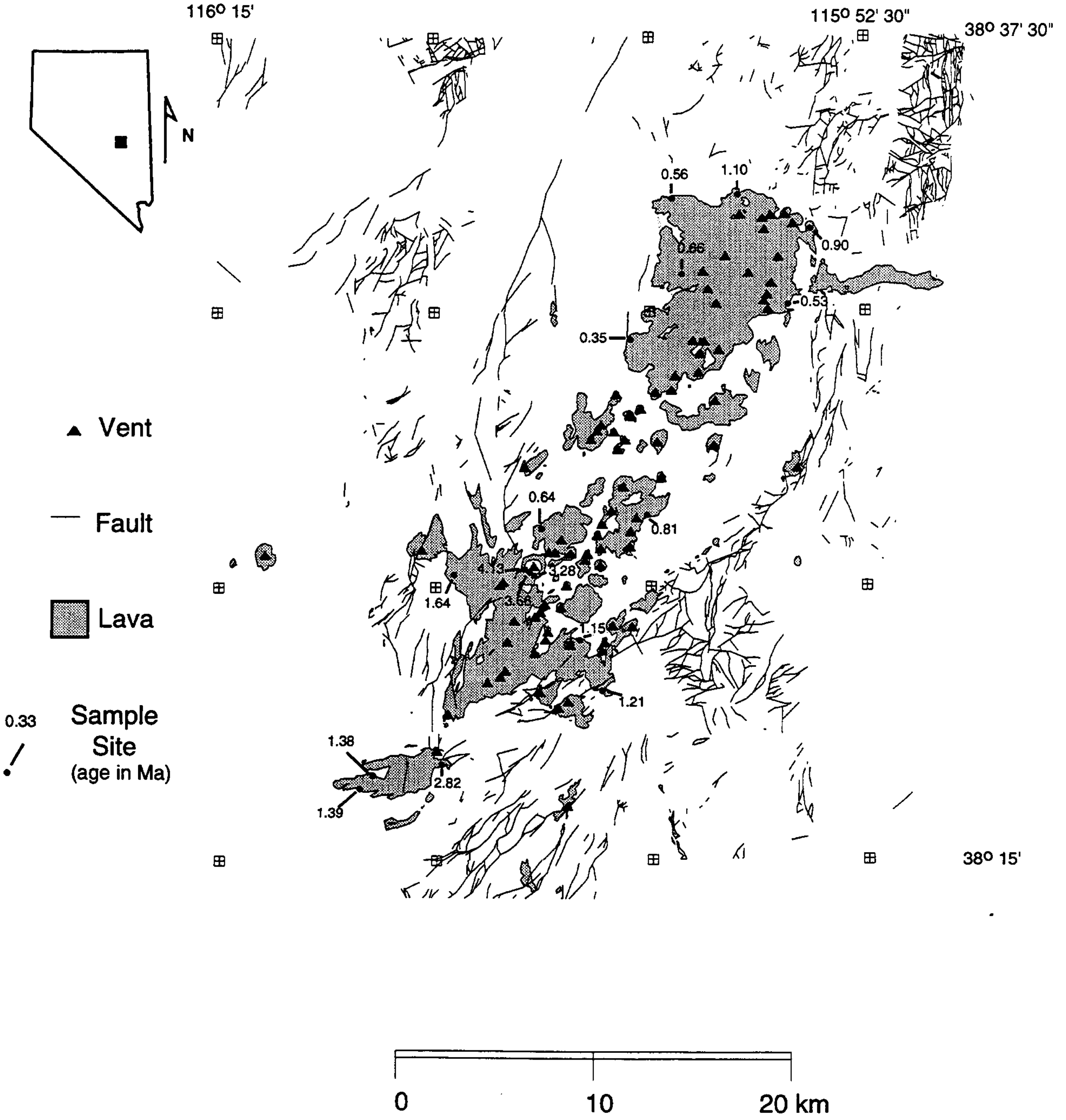

Figure 2-16. A summary of geochronological data complied for the northern half of the Lunar Crater Volcanic Field. Sample locations are shown and ages are posted in millions of years. Faults are also indicated.

2.5.4 Tectonics

Both geochemically and structurally, the LCVF is part of the Basin and Range province, rather than the WGB. The LCVF overlies Paleozoic sediments and Tertiary volcanic rocks (Figure 2-17). These Tertiary units have been deformed by NE-trending normal faults (Figure 2-18). Several authors (e.g., Scott and Trask, 1971; Naumann et al., 1991; Foland and Bergman, 1992) have noted that the overall trend of the volcanic field is coincident with both regional tectonic patterns of deformation and local fault zones. Quaternary lavas in the southern part of the Pancake range are offset by faults, indicating concomitant volcanism and brittle deformation (Figure 2-18).

2.5.5 Petrogenesis

The LCVF consists of alkaline basalts, including basanites, hawaiities, and olivine alkali basalts. Phenocrysts in the LCVF consist of olivine, plagioclase, and augite. Foland and Bergman (1992) analyzed 50 samples collected throughout the area for major elements. Silica content ranges from 43 to 51 percent, Mg numbers range from 40 to 60, and $Na_2O + K_2O$ values of 3 to 6 percent.

Foland and Bergman (1992) found spatial and temporal trends in silica saturation in the LCVF. They found the rocks in the Reveille Range are hypersthene normative, whereas the younger rocks in the Pancake Range are nepheline-normative. Lower Mg numbers also are found in rocks in the Reveille Range compared to the younger, less evolved rocks in the Pancake Range. As is the case with temporal trends, these are generalized patterns and individual centers may vary considerably from these trends. Foland and Bergman (1992) also report significant geographic trends in $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$, indicating a greater degree of crustal contamination in the early, southern basalts, compared with the younger basalts found in the Pancake Range. Similar trends have been related to changes in mantle source composition with time (Fitton et al., 1991).

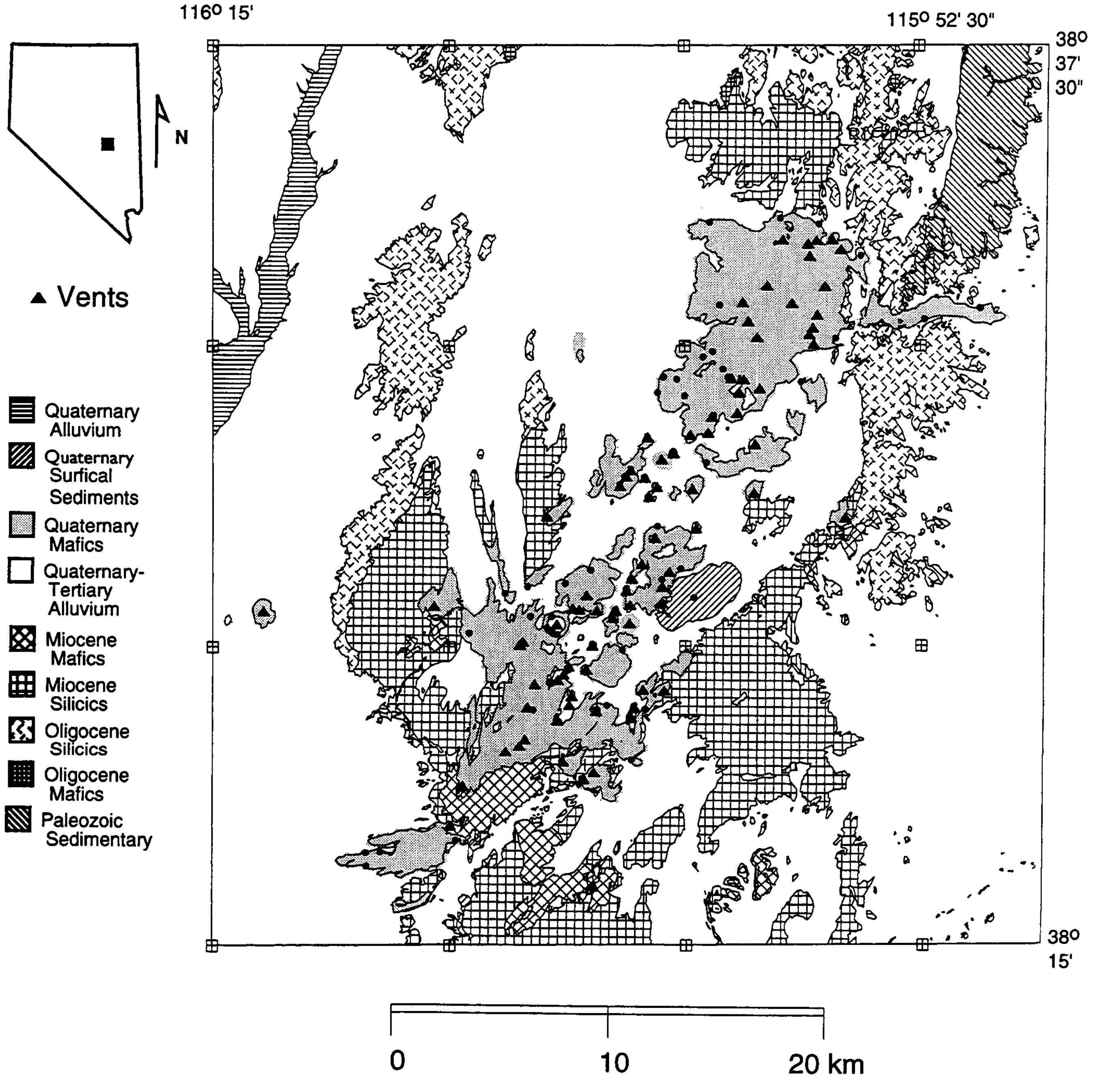

Figure 2-17. Geologic map of the distribution of Paleozoic and Tertiary rocks in the region about the Lunar Crater Volcanic Field.

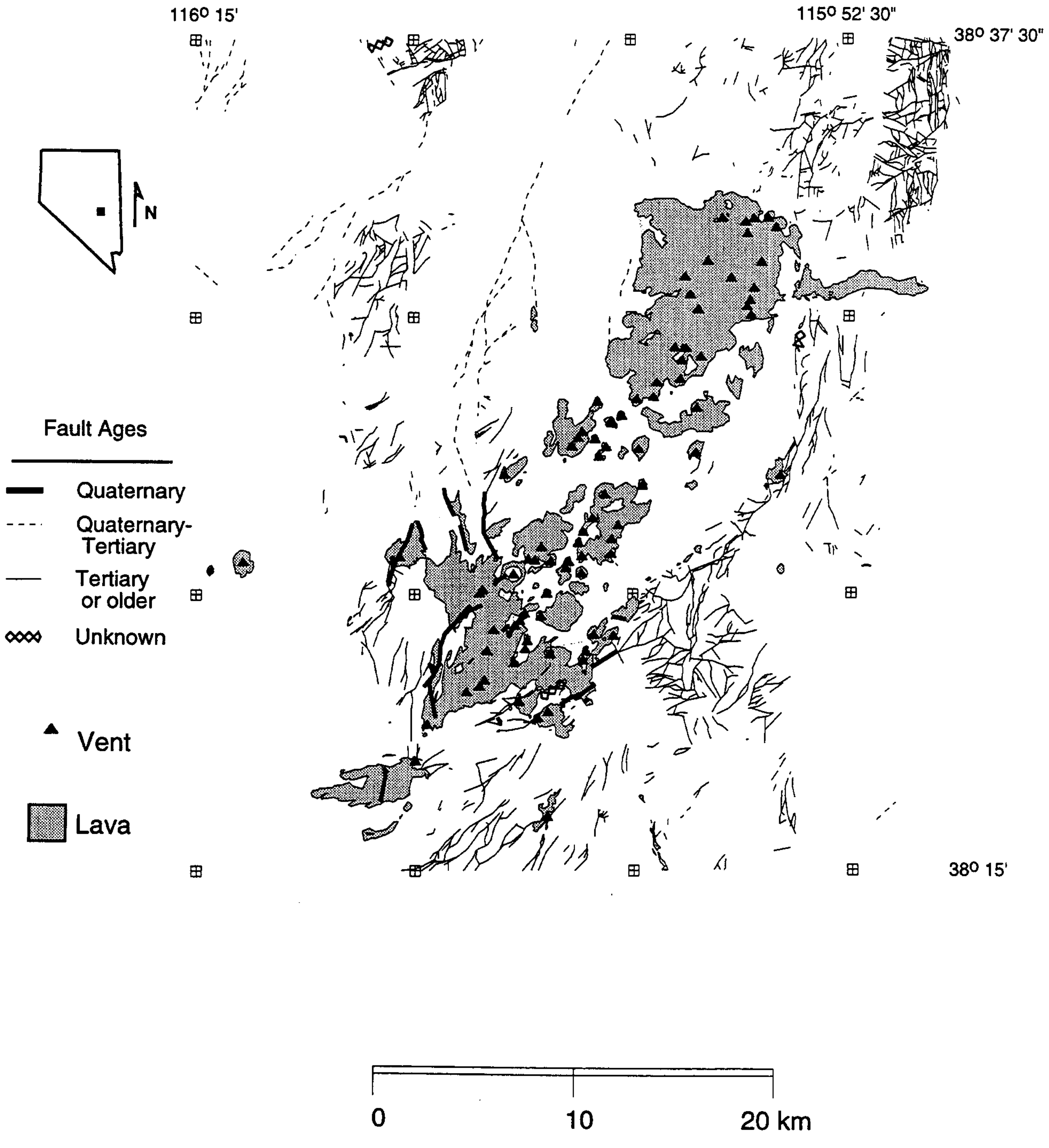

Figure 2-18. **Timing of most recent fault slip in the northern part of the Lunar Crater Volcanic Field.**

3 UTILITY OF THE VOLCANISM GEOGRAPHIC INFORMATION SYSTEM

Assessment of the probability and consequences of potential volcanic activity at or near the candidate repository are critical aspects of prelicensing scientific investigations. KTUs related to volcanism, such as those related to the inability to sample igneous features, development and use of conceptual tectonic models as related to igneous activity, assessing variability in the model parametric values, and disruptive scenarios, must be resolved in the pre-licensing stage in order to assure that these geological problems are fully understood and can be addressed in a scientifically rigorous manner. KTUs related to volcanism arise because volcanic systems of the WGB are complex and have not been studied with regard to the probability of future events in these regions, or with respect to the impact of these events on the near-surface environment. In response to these KTUs, the Volcanic Systems of the Basin and Range Research Project has been designed to provide insight into the probability of continued magmatic activity in the YMR, and into the practical limits of geologic and mathematical models of WGB volcanism. The purpose of the Volcanism GIS is to provide the necessary consistency with which to evaluate models in light of the spectrum of volcanic activity evinced by volcanic fields of the Basin and Range.

Having developed this database, it is now possible to address its utility and limits as a tool used for the resolution of KTUs in volcanism. This primarily involves assessing the utility of the database in understanding problems related to patterns in cinder cone volcanism and probability of future volcanic events. Several approaches to assessing the likelihood of volcanic disruption of the candidate repository have been proposed (Crowe et al., 1982; Ho,et al, 1991; Ho, 1992; Connor and Hill, 1993). These probability models include spatially and temporally homogeneous Poisson models (e.g., Crowe et al, 1982), Weibull-Poisson models for temporal variation in the recurrence rate of volcanism (Ho et al., 1991; Ho, 1992), and spatially and temporally nonhomogeneous Poisson models (Connor and Hill, 1993). The Volcanism GIS provides a platform on which to evaluate these models, largely because of the structure and organization imposed by the database. The value of the Volcanism GIS, however, extends well beyond the ability to rapidly access large amounts of complex data; conceptual, empirical and numerical models for igneous activity that combine both spatial and tabular data can be developed and rigorously tested.

3.1 PATTERNS IN CINDER CONE DISTRIBUTION

One of the most important aspects of probability model development and analysis is the recognition of spatial and temporal patterns in cinder cone distribution. This step provides a basis for the assessment of which probability models are best suited to describe cinder cone distribution, estimate the likelihood of future volcanic eruptions, and estimate the most likely location of future events. Spatial patterns in cinder cone distribution that are widely recognized in the literature include cinder cone clustering and cinder cone alignments. Cinder cone clustering and alignments have been described in widely varying tectonic settings, including the YMR of the WGB (Connor and Hill, 1993), Colorado Plateau rim fields (Connor et al., 1992), and arc settings (Wadge and Cross, 1988; Connor, 1990). The Volcanism GIS will be used to assess the importance of these spatial patterns in cinder cone distribution in the WGB and elsewhere in the Basin and Range. Vent distributions (e.g., Figures 2-4, 2-8) will be used to assess spatial patterns in vent distribution in a quantitative way. Statistical tests used to search for nonhomogeneous Poisson behavior will include the:

- Clark-Evans test, a statistical test based on near-neighbor statistics
- Hopkin's F-test, a Monte Carlo approach based on analysis of variance
- K-function test, a statistical test based on vent intensities

These analytical techniques are well recognized in the spatial statistics literature (e.g., Ripley, 1981) and have been applied to the analysis of vent distribution in the YMR (Connor and Hill, 1993). These three tests are primarily useful for testing for nonrandom distribution, such as the development of cinder cone clusters. Cinder cone alignments also are an important aspect of vent distribution in some areas, including the YMR, and vent alignment development may have an important impact on probability models (Smith et al., 1990). Methods that will be used to test for alignment development in these volcanic fields include the Hough transform and two-point azimuth analysis (Lutz, 1986; Wadge and Cross, 1988; Connor et al., 1992). Where such alignments are identified, the Volcanism GIS will be invaluable for testing models of the development of these alignments, primarily by providing an excellent platform on which to compare geochronological data along the alignment, its relationship to mapped structures, and the geochemical evolution of the alignment.

The Volcanism GIS will also be useful for searching for the development of temporal patterns in cinder cone volcanism. Bacon's (1982) work on temporal trends in erupted volumes in the CoVF suggests that time-predictable variation in magma discharge may provide a valuable geologic constraint on volcanism probability models. Several quantitative methods are available to test for temporal patterns in the occurrence of cinder cone volcanism. Ho et al. (1991) and Ho (1992) have used a Weibull-Poisson model to evaluate temporal trends in volcanism. The robustness of such models will be tested using age determinations in the volcanism GIS.

Sufficient geochronological data are available in several fields, including the CVF (Figure 2-9), the YMR (Figure 2-2), and the Springerville Volcanic Field, in order to test for temporal patterns in volcanism. Elsewhere, the Volcanism GIS can be augmented with additional stratigraphic and numerical geochronological data to provide further examples. For example, the BPVF contains numerous dates. If these data can be augmented by additional age determinations in the eastern part of the field, together with stratigraphic studies, they will provide an exceptionally clear view of the geochronological development of the BPVF. The CoVF and LCVF may prove to be excellent sites also, especially if subsets of the age data are used. For, example if the latest Quaternary data are used, then geochronological information currently available is likely sufficient, but more systematic evaluation of uncertainty in the age determinations and stratigraphy in these volcanic fields will likely be necessary before long-term temporal patterns of the necessary resolution can be discerned with confidence. Volume variations may also be important to constrain in order to fully discern time-predictable patterns in volcanism (cf. Bacon, 1982). These data are generally not available. However, if average flow thicknesses can be deduced using field observations, then the lava flow outlines currently in the Volcanism GIS for the CVF and BPVF might be used to estimate lava flow volumes.

3.2 MODELS OF GEOCHEMICAL EVOLUTION OF VOLCANIC FIELDS

The Volcanism GIS also can be used to test hypotheses about spatial and temporal variations in the petrogenesis of basaltic volcanic fields. For example, Condit et al. (1989) observed that the compositions of lavas in the Springerville Volcanic Field varied systematically with volcano age and location. Early eruptions at Springerville volcanic centers were tholeiitic, whereas later eruptions were more alkaline. In addition, there is an overall eastward migration of alkali basaltic volcanism in the Springerville Volcanic Field (Condit et al., 1989). Similar spatial and temporal trends were observed in the San Francisco Volcanic Field by Tanaka et al. (1986). By using the Volcanism GIS, similar petrogenetic hypotheses can be tested at different areas within the WGB. For example, volcanoes with more tholeiitic affinities may erupt at lower elevations than those with alkaline affinities, or that certain intervals of time produced compositionally distinct volcano clusters.

Current petrogenetic models for the YMR divide basaltic volcanism into early post-caldera and late post-caldera episodes, based on an apparent hiatus in activity between 6.8 and about 4.5 Ma (e.g, Crowe et al., 1986; Crowe and Perry, 1989). These episodes are thought to represent important spatial changes in the locus of YMR volcanism (e.g., Crowe et al., 1993). Using the Volcanism GIS, the petrogenesis of these volcanic episodes can be examined for apparent spatial trends, and for potential relationships to faulting, bedrock geology, or regional tectono-magmatic patterns.

3.3 DIKE-FAULT INTERACTION

Geologic factors may play a role in altering current probability estimates of volcanic disruption of the candidate repository through dike interaction with preexisting structural features, such as joints or fault zones. This could result in lateral transport of magma during the emplacement of cinder cones, and a focusing of magma along or near fault traces at the surface. Such a process, if significant, would increase the probability of volcanic eruptions in fault zones, such as along the Solitario Canyon fault, compared with other regions. This type of scenario has resulted in comparatively high estimates of the probability of volcanic disruption of the repository (Smith et al., 1990). Little is known, however, about the mechanisms by which structures redirect magmas as they ascend, the circumstances under which this type of dike capture might occur, and the magnitude of lateral transport of magma that can occur once the dike has been captured by a fault zone.

Certainly numerous examples of dike-fault interaction have been discussed in the volcanic fields represented in the Volcanism GIS (e.g., Figure 2-11), but perhaps more surprisingly, many vents in these fields show little relation to mapped structures (e.g., Figure 2-8). Several factors likely complicate models of dike-fault interaction. First, current models of dike propagation indicate that the properties of rock surrounding the dike have relatively little or no control on ascent rate or related dike properties. Second, Parsons and Thompson (1991) have noted that the intrusion of dikes into extending lithosphere creates strain in a manner quite similar to faulting. As a result, faulting and related topography is suppressed in regions of active dike intrusion. One result is that it is difficult to determine a relationship between faults and dikes in many active fields.

Investigations currently addressing aspects of the dike-fault interaction problem include the Field Volcanism and Tectonics research projects. Analytical and numeric models, and field data, on fault-dike interaction are being gathered as part of these research projects. The Volcanism GIS will play a critical role in the evaluation of models emerging from these investigations. Fault and vent distributions, and possibly geochronological information, from various volcanic fields represented in the database should provide a sufficient basis to test for direct structural controls on vent distribution and test for changes in vent density distribution around fault zones. In addition, should fault-dike interaction scenarios be incorporated into probability models, the Volcanism GIS will be used to test the adequacy of these probability models relative to less elaborate models, such as those based on vent distribution alone.

3.4 PROBABILITY MODEL DEVELOPMENT

It has often been noted that one of the difficulties inherent in the development of probability models for volcanism in the YMR is that the region contains, perhaps paradoxically, few volcanoes compared to many volcanic fields (e.g., Crowe et al., 1993). This leads to a high degree of uncertainty in estimates of recurrence rate of volcanic eruptions and in selection of the most appropriate model to apply to the region. An important function of the Volcanism GIS will be to provide data on analogous volcanic fields in the WGB and elsewhere in the Basin and Range with which to test probability models developed at the CNWRA, the NRC, and the DOE. This is likely to be the most practical and defensible method of testing probability models of volcanic disruption.

Probability models for potential volcanic disruption of the candidate repository currently under development at the CNWRA include spatially and temporally nonhomogeneous Poisson models and spatio-temporal Markov models. Nonhomogeneous Poisson models use near-neighbor statistics to develop nonparametric estimates of recurrence rate as a function of geographic location and time. For completely spatially and temporally random cinder cone distributions, the nonhomogeneous Poisson model will yield results identical to homogeneous models. However, if significant variation in cinder cone distribution or the timing of cinder cone eruptions occurs within a particular region, the nonhomogeneous Poisson model can account for this variation. Markov process models use some parametric estimate of the time-dependent mean location of volcanic activity in a volcanic field and time-dependent variance in this mean location to estimate probability. Currently, Markov process models under development at the CNWRA use linear square error estimators based on the migration of vents through time and the average time lapse between volcanic eruptions to estimate these parameters.

The Volcanism GIS will provide a substantial data set with which to test and develop these and similar probability models. Not only will vent distributions and age determinations from the database be used in this development, but probability and confidence interval plots will be incorporated into the database. Therefore it will be possible to evaluate models more fully by viewing probability estimates together with structural and related geological data.

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APPENDIX A

Additional References used in Volcanism GIS
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APPENDIX B

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