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STUDY PLAN 8.3.1.8.1.2

PHYSICAL PROCESSES OF MAGMATISM AND EFFECTS ON THE POTENTIAL REPOSITORY

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ABSTRACT

The Yucca Mountain Site Characterization Project (YMP) is conducting volcanism studies in order to assess the risk of recurrence of igneous activity during the required isolation period of a potential repository at Yucca Mountain. These studies consist of three main parts: characterization of volcanic and intrusive features, assessment of the probability of recurrence of magmatic activity during repository lifetime, and assessment of the consequences and physical processes of magmatism. The latter is described in this Study Plan, which is divided into three activities. The first activity, "Eruptive Effects," addresses the possible surface release of radioactive waste due to a basaltic eruption (hydrovolcanic or magmatic) penetrating the potential repository. A strategy is described which will allow relatively rapid conclusions based on studies at analog volcanoes in the southwestern United States. The second activity, "Subsurface Effects," addresses the consequences of magmatic intrusions in or near the potential repository, whether these intrusions are accompanied by eruptions or not. A combination of modeling and analog field studies will be used to quantify the processes and estimate the consequences for different intrusion geometries (including dikes and sills) and varying degrees of structural control on the intrusions, mechanical effects that may result in altered country rock properties, hydrothermal activity, and long term effects of intrusions such as perching of groundwater. The third activity, "Magma System Dynamics," will apply modeling and analog approaches to understanding the physical mechanisms and constraints on future magmatic activity at the Yucca Mountain site. The activity will attempt to provide theoretical foundations for probabilistic predictions that are ultimately based on surface (or near surface) observations. Work under "Magma System Dynamics" will focus on such issues as melt generation and segregation in the mantle, magma chamber dynamics, magma transport (e.g., by dikes), and eruption dynamics.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

1.0 PURPOSE AND OBJECTIVES OF STUDY

1.1 Objectives of the Study

The Yucca Mountain Site Characterization Project (YMP) is conducting volcanism studies to evaluate the possible recurrence of volcanic activity during the required isolation period of a potential repository located at Yucca Mountain. The objective of Study Plan 8.3.1.8.1.2 Physical Processes of Magmatic Activity and the Effects on the Potential Repository is to define scenarios of future magmatic activity and evaluate their effects on a potential repository at Yucca Mountain. The primary data to be used as input for this evaluation are provided through Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features and from field, laboratory, and modeling studies associated with this study.

There are two aspects to investigations of the possible recurrence of future volcanism: (1) the potential for future silicic volcanism, and (2) the potential for future basaltic volcanism. The potential for future silicic volcanism, based on current data from site characterization studies of the Yucca Mountain region, is considered to be negligible for the required isolation period of a potential repository (Crowe et al., 1983a, DOE, 1988). Final evaluation of the future potential of silicic volcanism is dependent, however, on the results of drilling of planned volcanism exploration holes and on the evaluation of the significance of young (2.9 Ma) silicic volcanism at Mt. Jackson, located 100 km northwest of Yucca Mountain (Figure 1). Magmatic processes and effects of future silicic volcanic activity on the potential repository will not be considered in this Study Plan because the likelihood of such activity in the Yucca Mountain region is so low. This decision will be reevaluated however, if future work from Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features leads to recognition of an increased likelihood of future silicic volcanic activity.

The potential for future basaltic volcanism in the Yucca Mountain region is more difficult to evaluate. Four Quaternary volcanic centers (approximately 1.2 Ma) are located in Crater Flat, directly west and southwest of the exploration block of Yucca Mountain (Figure 2). Two Quaternary basaltic volcanic centers are located southwest of the Black Mountain caldera at Sleeping Butte, about 45 km northwest of Yucca Mountain. The youngest recognized volcanic center in the region, the Lathrop Wells volcanic center, is located at the south end of Yucca Mountain, 20 km from the exploration block (Figure 2).

A two-phase approach is used to evaluate the potential for future basaltic volcanism at the Yucca Mountain site. First, standard geologic studies combining field mapping, geochronologic, paleomagnetic, geochemical, and geophysical approaches will be used to decipher the history of basaltic volcanism in the Yucca Mountain region. Second, data from these studies will be used to assess volcanic risk, where risk is a combined evaluation of the probability and consequences of future basaltic volcanism affecting the Yucca Mountain site. The results of past volcanic hazard assessments using these two approaches are described in the Site Characterization Plan (SCP), Chapter 1, Sections 1.3.2.1.2 and 1.5.1 (DOE, 1988), and in separate publications (Crowe and Carr, 1980; Vaniman and Crowe, 1981; Crowe et al., 1982, 1983a, 1983b, 1986; Crowe, 1986, 1990; Crowe and Perry, 1989).

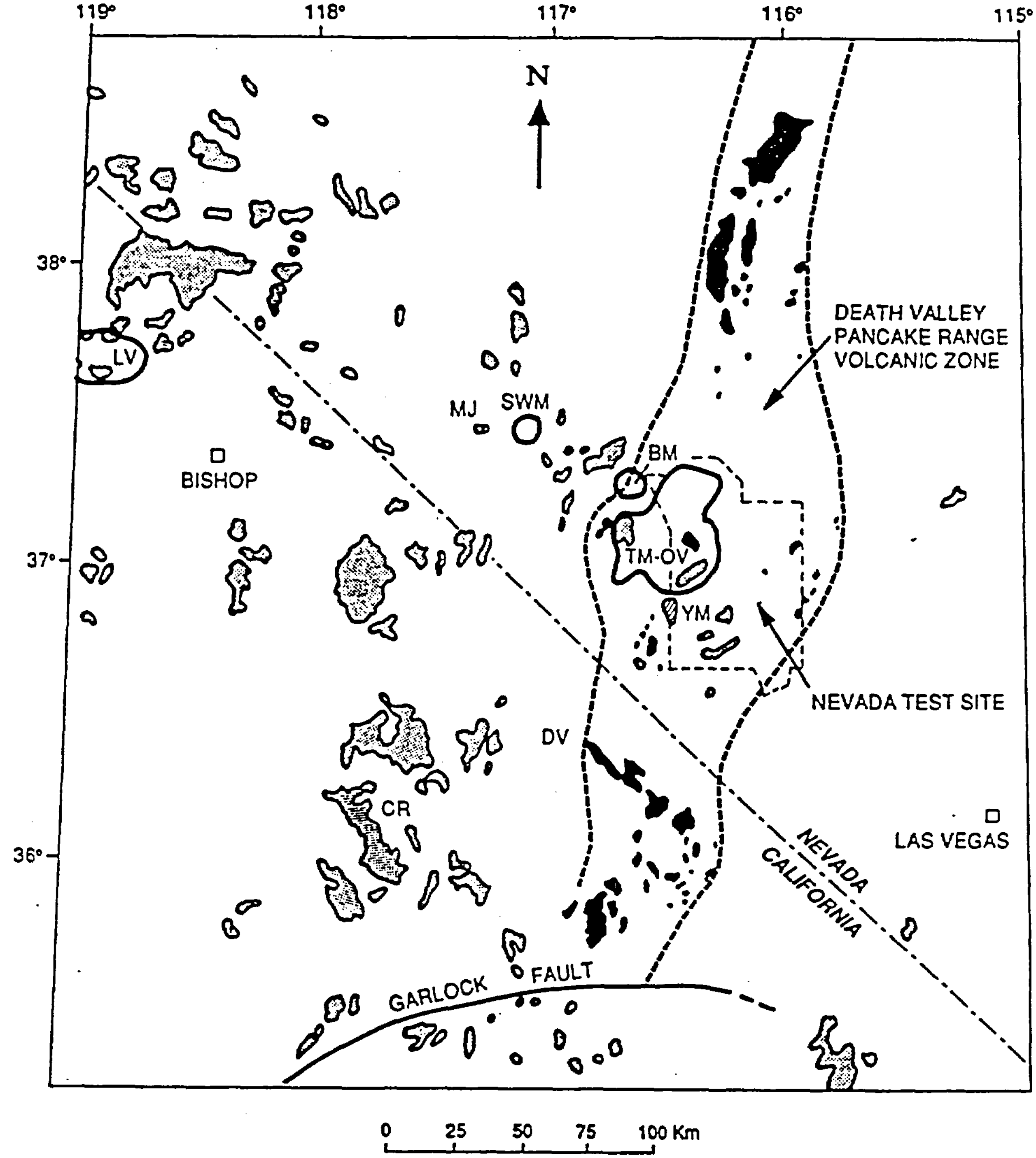


Figure 1. Distribution of post-Miocene silicic (stippled) and basaltic (black) volcanic rocks of the southern Great Basin. Basaltic rocks are inferred to be part of the Death Valley/Pancake Range volcanic zone (Crowe et al., 1983a; Crowe 1986). An alternative interpretation is that the zone may consist of three unrelated, complex volcanic fields. TM-OV: Timber Mountain-Oasis Valley caldera complex; BM: Black Mountain caldera; SWM: Stonewall Mountain caldera; MJ: Mount Jackson dome field; LV: Long Valley caldera complex; CR: volcanic rocks of the Coso volcanic field; DV: Death Valley; YM: Yucca Mountain.

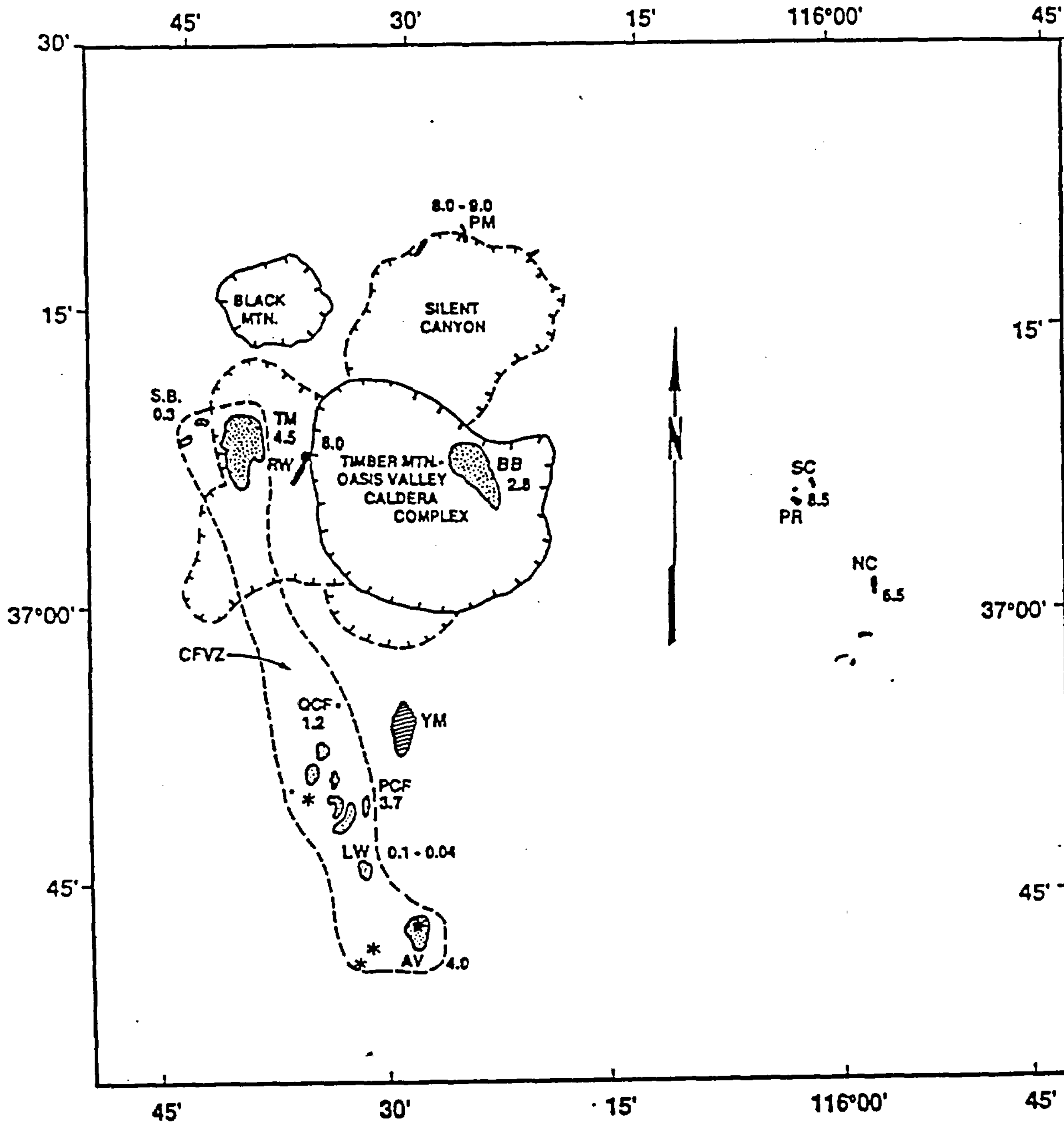


Figure 2. Post-caldera basalts of the Yucca Mountain region. Shaded areas are the Older Post-Caldera Basalts (see Crowe and Perry, 1989), including: RW - basalt of Rocket Wash; PM - basalt of Pahute Mesa; SC - basalt of Scarp Canyon; NC - basalt of Nye Canyon. Stippled areas are the Younger Post-Caldera Basalts (Crowe and Perry, 1989), including: TM - basalt of Thirsty Mesa; AV - basalt of Amargosa Valley; PCF - Pliocene basalt of southeast Crater Flat; SB - basalt of Sleeping Butte; LW - basalt of Lathrop Wells. Asterisks mark aeromagnetic anomalies identified as potential buried basalt centers or intrusions (Crowe et al., 1986). Dashed line encloses the area of the Crater Flat Volcanic Zone (CFVZ). Parallel-line pattern marks the Yucca Mountain site (YM). Outlines of major caldera complexes are indicated for reference. Numbers associated with the symbols for the volcanic units are the age of the volcanic centers in millions of years. Modified from Crowe and Perry (1989).

The basic framework for magmatic risk studies is contained within the following equation which is described in detail in Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository:

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

Pr_{dr} is the magmatic disruption probability, *E1* is the recurrence rate of magmatic events in the Yucca Mountain region, *E2* is the probability that a future magmatic event intersects the repository or is close enough to it to have a significant effect on repository performance, and *E3* is the probability that a given magmatic event will cause release of waste to the accessible environment in quantities that exceed regulatory limits. *E3* is the sum of two components, $E3_e$ and $E3_s$, which denote release to the surface by eruption and release in the subsurface accessible environment, respectively. Pr_{dr} is the primary quantity which will be considered for repository performance assessment in terms of magmatic processes.

Study Plan 8.3.1.8.1.2, Physical Process of Magmatism and the Effects on the Potential Repository is divided into three activities as follows:

-- A reevaluation of previous studies (Crowe et al., 1983b) of the physical processes of Strombolian, mixed Strombolian-Hawaiian, hydrovolcanic, and effusive lava eruptions of basaltic magma. These studies will be used to define and describe the most likely potential eruption scenarios and assess the radiological consequences of any magmatic disruption of the potential repository (Activity 8.3.1.8.1.2.1 Eruptive Effects). The information from this activity will provide $E3_e$.

-- An evaluation of the subsurface effects of emplacement of basalt intrusive bodies through or near a potential repository. This study will include an assessment of mechanisms of incorporation of waste in magma, the geometry of basalt intrusions, and thermal and hydrologic effects on waste isolation of basalt intrusions through or near a potential repository (Activity 8.3.1.8.1.2.2 Subsurface Effects). The information from this activity will provide $E3_s$ which will be considered whether a magmatic event results in eruptions or not. This activity will also provide information that will influence the calculation of *E2* by defining the spatial scale over which an intrusive event can have a significant effect on a repository. A hypothetical example is that if an intrusion has a significant effect on fluid flow for distances of a few kilometers away from the intrusion itself, then this means that the intrusion would not necessarily have to directly intersect the repository but only be within a few kilometers of it, which then affects *E2*.

-- An evaluation of the dynamics of basaltic magmatism. This activity will trace and place bounds on the processes of formation of basalt magma through generation in the mantle, ascent through the mantle and crust, potential storage in mantle and crust, and eruption at the surface of the earth. The study will propose and test physical and mathematically based models for basaltic processes in and beneath the Yucca Mountain area. These models will form a framework for a process-based assessment of the effects of basaltic magmatic activity on a potential repository (Activity

8.3.1.8.1.2.3 Magma System Dynamics). Information from this activity may help to further constrain *E1* and *E2*.

1.2 Rationale for Information to be Obtained and Use of Results

The evaluation of the Yucca Mountain site must include consideration of the possible future tectonic events that could directly or indirectly lead to the release of waste radionuclides. Volcanism has been identified as one potential disruptive event that will be evaluated for site characterization. Regulatory requirements mandate that evaluation of postclosure performance must consider events and processes that can occur within required isolation period of a repository, including estimates of the effects of radiologic releases associated with future events and processes. The objective of this study is to evaluate the possible eruptive scenarios and effects of future magmatic activity penetrating the potential repository or the controlled area during the required period of waste isolation.

The performance allocation process has been used by the YMP to establish appropriate strategies of issue resolution (issues to be resolved are listed in SCP Section 8.2.1). A general discussion of the performance allocation approach is provided in SCP Section 8.1. Issue resolution strategies and details of performance allocation for each design and performance assessment issue are summarized in SCP Section 8.2, and expanded in SCP Sections 8.3.2 through 8.3.5.

The information supplied by this Study Plan will be the most likely scenarios for potential magmatic disruption of the Yucca Mountain site based on field and modeling studies of magmatic processes in the Yucca Mountain region. Additionally, magmatic processes are evaluated on a physical and mathematical basis to ensure that a full range of possible future magmatic processes is evaluated. This Study Plan integrates geology, geochronology, and geochemistry data from Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features and probabilistic studies from Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository. Volcanic scenarios and assessments of effects of magmatic activity on the potential repository will be used in performance allocation.

2.0 RATIONALE FOR SELECTED STUDY

The following sections describe the rationale and constraints for the three activities of this study plan. For continuity, the discussions of these topics are described by individual activity.

2.1 Activity 8.3.1.8.1.2.1 Eruptive Effects

2.1.1 Technical Rationale and Justification

An assessment of the possible effects of magmatic disruption of a potential repository requires identification of the range of eruption processes that could disperse magma after intersection of a potential repository and contamination with high-level waste. The most likely form of a magmatic event that would effect a potential repository at the Yucca Mountain site is intrusion of the repository by basalt magma that is fed through dikes (Crowe et al., 1983b). These dikes would extend through the potential repository and feed eruptions at the surface of Yucca Mountain. As magma moving in a linear dike nears the surface, the body flares locally to form a main or secondary conduit with minor offshoots (radial and concentric dikes). An important issue is whether these intrusive bodies form above the potential repository - this aspect will be studied at analog centers.

Volcanic activity in the Yucca Mountain region during the last 8 Ma has been exclusively of basaltic composition (Crowe et al., 1983b; Crowe, 1990). Basaltic eruptions in the Quaternary formed small scoria-cone complexes that are flanked by lobate lava flows (Crowe, 1990). The most likely scenario of future basaltic eruptions, based on the record of past volcanism in the Yucca Mountain region, is intermixed Hawaiian and Strombolian eruptions forming scoria and spatter cones accompanied by small volume extrusions of aa lava flows. This eruption scenario was used by Link et al. (1982) to estimate the radiological consequences of a basaltic eruption that intersected a hypothetical radioactive waste repository. They assumed a standard Strombolian eruption that distributed pyroclastic deposits from the gas-thrust phase of a fountain eruption to form a scoria cone and scoria-fall sheet. A fine-grained component was distributed upward by a convective cloud and transported by prevailing winds up to several kilometers. Quieter periods of fountaining activity were inferred to have occurred, in association with extrusion of lava flows from flank vents at the base of the cones.

The primary attribute considered in models of the recurrence of future volcanic events is the formation of a new volcanic center. Such events have a defined probability *Pr(E2)* of disrupting the potential Yucca Mountain site. However, a second submodel that needs to be considered for this study plan is the possibility of polycyclic volcanism (Wells et al., 1990; Crowe et al., 1992a,b). This model, the validity of which is still under study, requires that once a new volcanic center is formed, subsequent eruptions occur at the same volcanic center. The recurrence interval of subsequent (polycyclic) eruptions is still being studied (Activity 8.3.1.8.1.5.2 Geochronology studies). However, it may be less than the recurrence time of formation of new volcanic centers. These phenomena raise the possibility that if a new volcanic event penetrates a potential repository during the required isolation period, a subsequent event may be possible on a time scale of a few thousand to several tens of thousands of years. Therefore the consequences of magmatic disruption require assessment of multiple events at closely spaced vents, as well as single events (monogenetic).

The rationale for this activity is that we need to place volumetric bounds of radioactive material that can be carried by ascending magma from potential repository depths to the surface of the earth. This assessment will include both single (monogenetic) and multiple (polycyclic) volcanic events. If the probability of carrying sufficient volumes of radioactive waste from repository depths to the surface $Pr(E3_e)$ multiplied by the probability of magmatic disruption of a potential repository *Pr(E2 given E1)Pr(E1)* is less than $10^{-8}yr^{-1}$ we will conclude our studies of eruptive effects because their contribution to total system performance assessments will be very small (note that even in this case eruptive effects will continue to be incorporated into performance assessment calculations). Note, however, that such a situation would have no effect on assessment of subsurface effects ($E3_s$).

The value of $10^{-8}yr^{-1}$ cited above is based on two sources of guidelines. One of these sources is the set of guidelines in 40 CFR 191 for low probability events. These guidelines are currently being reassessed and if new regulations are different this cutoff value will be altered accordingly. The other source is provided by the Site Characterization Plan (DOE, 1988), Table 8.3.1.8-1b and Table 8.3.5.13-10, where tentative performance parameter goals are provided. Specifically, for the initiating process defined as "Volcanic eruption penetrates repository and causes direct releases to the accessible environment," the tentative parameter goal is "Given occurrence (of initiating event), show <0.1% of repository area is disrupted with a conditional probability of <0.1 of being exceeded in 10,000 yr" (parentheses added). Treating the value of <0.1% of repository area disrupted as a "consequence" of 0.001, and the stated conditional probability of occurrence as $0.1x10^{-4}yr^{-1}=10^{-5}yr^{-1}$, we can interpret this parameter goal as a risk (probability of event multiplied by its consequences) of $10^{-8}yr^{-1}$ which corresponds to our cutoff value stated above. Thus, while we have chosen to base our eruptive release assessment on the quantity of repository debris that could be erupted, which we feel can be better constrained than the area of disruption stated by DOE (1988) because of possible complexities in volcanic plumbing geometries, the criteria are essentially equivalent.

If the probability of eruptive radiological releases based on considerations described in the above paragraphs is greater than 10^{-8} yr^{-1}, more detailed modeling of basaltic volcanic eruptions will be needed. This work will examine and refine potential eruption scenarios that produce small volume scoria cones and associated lava flows, including episodes of hydrovolcanic eruptive activity. The rationale for this activity is to identify eruptive mechanisms that would transport and deposit radioactive waste and the exposure history of that waste from the time of eruption to the end of the required isolation period of the potential repository. If this second part of Activity 8.3.1.8.1.2.1 is judged to be required, we will write a new report following the required outline of the Study Plans to describe the modeling work. That report will be issued in the form of an appendix as a future revision of Study Plan 8.3.1.8.1.2 Physical Process of Magmatism and the Effects on the Potential Repository.

The tests that will be used to constrain the volume of radiological releases and input to models of volcanic eruptions will be based on observations of volcanic centers in the Yucca Mountain region and of analogous centers in the southwestern U.S. Alternative studies including past studies for the Yucca Mountain Project have used parameter constraints derived largely from the geologic literature and partly supported by field data from the Yucca Mountain region (Vaniman and Crowe, 1981; Crowe et al., 1988; Crowe and Perry, 1989). The advantage of this analog approach is that the best representation of future volcanic activity in the Yucca Mountain is obtained from an analysis of the record of past volcanic events in the same region.

The timing of these studies is tied to the schedule of field geologic studies from Activity 8.3.1.8.5.1.2. All geologic studies for the current activity will be conducted outside the boundaries of the potential Yucca Mountain repository. Field studies of the Lathrop Wells and the Sleeping Butte centers (Crowe et al, 1988; Crowe and Perry, 1989) will be used as a basis for further studies at these centers. Detailed geologic mapping of the 1.2 and 3.7 Ma centers of Crater Flat will be conducted as part of Activity 8.3.1.8.5.1.3 Field Geologic Studies. Test methods will include field measurements of dimensions of volcanic features that will constrain parameters used in the modeling studies. These features include, but are not limited to, crater dimensions, cone dimensions, textural data for tephra deposits (thickness, granulometry, bomb size, bedding characteristics, degree of agglutination, clast vesicularity), lava flow dimensions (length, width, thickness, flow shapes) and characteristics of the scoria-fall sheet (thickness, distribution, grain-size). Some of these measurements will be obtained as part of trenching activities at Quaternary volcanic centers conducted through Activity 8.3.1.8.5.1.2 Geochronology Studies. We will examine scoria, hydrovolcanic, and lava deposits at these and other analog centers to establish the abundance and depth of derivation of lithic fragments, which will allow us to constrain the quantity of debris that could be erupted from repository depths (see Sections 3.1.1 and 3.1.2 below).

2.1.2 Constraints on the Study

All studies for this activity are conducted outside the boundaries of the potential Yucca Mountain repository under the established constraints for the environmental program. There are no potential einvironmental, technical, or safety impacts on the site. The study will involve description and study of surface volcanic deposits and possible computer modeling of volcanic eruptions. Field studies will be carried out under standard operating procedures that will ensure the safety of the participants. The are no interferences of this work with other tests, either on-site or off-site. There are no limitations on repeatability of tests because the measurements of volcanic features are non-destructive.

2.2 Activity 8.3.1.8.1.2.2 Subsurface Effects

2.2.1 Technical Rationale and Justification

It is important to understand the effects of magmatic activity within the potential repository block from a repository performance perspective . These effects can be divided into short term processes, which occur during the magmatic event and while the resulting intrusive body cools, and long term effects, which are important after the temperature field in the potential repository block has returned to its ambient value. Short term effects include possible entrainment of waste into intrusions and processes such as hydrothermal flow of both vapor and liquid in response to a magmatic event. Hydrothermal flow may be important because it could provide a fast transport mechanism for radionuclides and because it may result in accelerated waste package deterioration. Hydrothermal processes also play a role in altering the rock properties near a magmatic intrusion, which would relate to the long term effects. Possible long term effects include perching of water due to the presence of dikes and sills, which may produce fast paths for radionuclide migration.

Studies of subsurface effects will rely heavily on a combination of field studies at analog sites and modeling. Analog field studies will focus on small volume basaltic centers where dikes, sills, and volcanic conduits have been exposed by erosion and/or tectonic activity. Special attention will be given to centers such as the Paiute Ridge area (eastern NTS), where basalts intruded and erupted through silicic tuffs, which would be the case if magmatism occurred within the potential repository block at Yucca Mountain. At these analog sites such parameters as intrusion geometry and structural controls on intrusions will be measured and mapped. Deformation of wall rocks in response to the intrusions will also be studied. Samples will be taken at regular intervals within intrusions in order to understand the physicochemical processes that occur during cooling. Where magmas intruded into silicic tuff country rocks, samples will be collected at regularly spaced intervals away from the intrusion margins in order to study hydrothermal alteration and changes in rock properties. Examples of intrusions intersecting groundwater flow (both in the vadose and saturated zones) will be studied for evidence of perching or other effects, such as formation of fast (or slow) paths due to intrusion-induced fracturing, on groundwater movement (see Section 3.2.1). We will make use of existing literature where possible, but the problems of interest here (hydrothermal flow in unsaturated tuffs induced by small volume intrusions) have not been subject to previous extensive study.

Modeling studies will be carried out in two modes. The first will be general sensitivity analysis, where parameters are varied in a systematic manner in order to gain physical insight into important processes. An example of a sensitivity analysis that we will conduct is examining the effects of various intrusion geometries and hydrologic properties on the long term hydrology. This will involve systematically varying the properties of an intrusive body of given dimensions and computing the resulting variations in local groundwater flow. Another example will be to vary country rock hydrologic properties and study the sensitivity of hydrothermal processes to these properties, for a given intrusion geometry. This first mode may be carried out independently from field studies. The second mode will be modeling of specific conditions and geometries observed at analog sites. Calculations of a given field condition will be honed until the results match the observed field characteristics as closely as possible. The purpose of modeling in this mode is to quantitatively understand specific observations.

For subsurface effects studies it is anticipated that the main computer code to be used will be FEHMN (Finite Element Heat, and Mass, code), which has been developed for modeling hydrothermal and isothermal processes in porous and fractured media. For subsurface effects studies FEHMN will be qualified under the LANL Software Quality Assurance Plan.

2.2.2 Constraints

All studies for this activity are outside the boundaries of the proposed Yucca Mountain repository. There are no potential impacts on the site. The study will involve field observations and sampling at analog sites, and computer modeling. The only requirement for simulating of potential repository conditions for the activity is to examine response of the subsurface hydrogeology of Yucca Mountain to thermal and material property perturbations due to intrusions. The required precision of parameters cannot be established at this time. This will be determined through an iterative process with performance assessment studies. We will identify the most sensitive parameters in terms of physical effects on the repository and optimize the measurement precision of those parameters. The analytical methods to support the modeling studies are already developed or are being developed for the computer code FEHMN (Zyvoloski et al., 1991). The applicability of the modeling code FEHMN will be tested by comparing modeling results with analytic solutions and with actual field observations of basaltic volcanic centers from the Yucca Mountain area and from selected sites throughout the southwest United States. Some modeling for this activity will ultimately be used to quantitatively predict effects of magmatic activity on the repository, which will feed directly into performance assessment calculations; for such modeling full software quality assurance measures will be taken. The are no interferences between this work and other tests, either on-site or off-site. There are no limitations on repeatability of tests because the measurements of volcanic features are non-destructive. Drilling may be necessary to test the long-term hydrologic effects of igneous intrusions - if this is the case we will revise the study plan by adding an appendix describing the need and methods of drilling that are appropriate.

2.3 Activity 8.3.1.8.1.2.3 Magma System Dynamics

2.3.1 Technical Rationale and Justification

In order to increase the understanding of volcanic systems in the Yucca Mountain region and to provide a physical basis for probability calculations of future events, it is useful to examine the general physics of magmatic processes and their operation in the Yucca Mountain setting. Theoretical considerations will be combined with petrologic, geochemical, geochronological, and field studies in order to constrain the processes of generation, transport, storage, diversification, ascent, and eruption of magmas. These studies will mainly address three general questions: (1) is magmatic activity in the Yucca Mountain region increasing or decreasing, (2) what processes determine the timing of eruptions, and (3) what mechanisms are responsible for polycyclic volcanism at small-volume basalt centers?

Evidence for decreasing magmatic activity in the Yucca Mountain region includes decreasing eruption volumes through time and geochemical and petrologic data that suggest that magma chamber depth has increased through time due to decreased magma flux (Perry and Crowe, 1992). It is important to understand how mechanisms of melt generation and transport relate to magma flux, depth of magma chamber establishment, and eruption volumes, within the bounds that can be obtained from field and compositional data.

The second issue that is important to address is the mechanism of small-volume polycyclic volcanism. How can a system such as the Lathrop Wells cone, with such small volume eruptions retain a "memory" of eruption locations so that successive eruptive phases vent in proximity to each other? Simple calculations of the cooling times (for solidification) of dikes of a few meters width in the deep crust are on the order of days to weeks, whereas the recurrence interval for small eruptions at Lathrop Wells may be on the order of tens of thousands of years (Wells et al., 1990).

The physical mechanisms that produce polycyclic eruptions may be understood and bounded in a larger context that includes processes of magma generation, separation, transport, storage, and eruption. Generation of basaltic melt in the mantle involves partial melting on spatial scales of a few hundreds to thousands of meters or larger depending on the system of interest. The mechanisms by which these large melting scales are translated into closely spaced eruptions need to be understood in order to support the observations of polycyclic volcanism.

Can the episodic nature of volcanism at Lathrop Wells and at other small polycyclic volcanoes in the region be related to the nonlinear physics of melt segregation and ascent (Fowler, 1990a,b)? Is the generation of melt in the source region a relatively steady process, with melt migration being episodic, or is the generation process itself episodic?

Petrologic and geochemical evidence (Perry and Crowe, 1992) suggests that the magmas erupted at Lathrop Wells cone undergo fractionation at pressures exceeding 1 GPa, indicating substantial residence time in a deep (> 24 km) reservoir. Trace element and radiogenic isotope data from eruptive units at Lathrop Wells indicate that several geochemically distinct magma batches were involved in the formation of the Lathrop Wells center. Although all of the erupted magmas are relatively evolved (indicating a large amount of fractional crystallization), the percentage of phenocrysts present is very low (<1%). This implies efficient separation of liquid from fractionating crystals. Closed system fractionation processes can trigger eruption from a magma chamber. Depending on the composition of crystallizing phases, fractionation of basaltic magmas can cause the residual melt to become progressively less dense, due to compositional changes and concentration of volatile phases (note that crystallization of some phases, most notably plagioclase, can cause the density of the residual melt to *increase*; Stolper and Walker, 1980; Sparks and Huppert, 1984). Open magmatic system processes also must be considered for triggering polycyclic eruptions. Injection of new magma (recharge) into a relatively quiet chamber can produce catastrophic processes that lead to eruption, although there may be a time lag between the injection event and the triggering of an eruption (Sparks et al., 1984). An understanding of the mechanisms by which eruptions are triggered at depth in the Yucca Mountain region, based on petrologic and theoretical considerations, may provide some deterministic information and constraints to incorporate into recurrence rate calculations.

If magma chambers form at a level of neutral buoyancy in the lithosphere, decreases in liquid density by the above mechanisms may result in fracturing of the chamber roof and injection of dikes, which are the most prevalent means for transport of mafic magmas through the lithosphere (Turcotte, 1990). As magma flows up through a dike a balance between heat advected with the magma and the heat lost into the wall rocks must be achieved (Bruce and Huppert, 1990) or else the magma will solidify. The equilibrium orientation of dikes is such that the plane of a dike is perpendicular to the local least principal stress. Because principal stresses may rotate with different depths in the lithosphere, an ascending dike may also rotate, although it is not known how rapidly a dike can become re-oriented. It is possible that some dikes erupt at the earth's surface before they can re-orient to the near-surface stress field. A dike may propagate its own fracture, in which case it will always tend toward the equilibrium orientation, or it may follow pre-existing fractures that have suitable orientations (Delaney et al., 1986). In addition, the dike itself can influence the local stress field because the magma exerts a compressive stress on the adjacent wall rocks, causing subsequent dikes to have different orientations (Parsons and Thompson, 1991). All of these factors determine not only the location of an eruption and its orientation if it is a fissure eruption, but also the location and orientation of subsequent pulses of magma in the vicinity. These issues of structural controls are being addressed by Activity 8.3.1.8.1.1.2 Evaluation of the Structural Controls of Basaltic Volcanic Centers (Study Plan 8.3.1.8.1.1 Probability of Volcanic Eruption Penetrating the Repository).

The results of all these magmatic processes are eruption and emplacement of magma as either pyroclastic debris or lava. Eruption and emplacement processes, coupled with petrology and geochemistry, provide the most direct information about the magma dynamic system at depth. Because none of the volcanoes in the Yucca Mountain region are currently active, we must infer the eruption dynamics from the deposits left by prehistoric events. Methods for determining eruption conditions from deposit characteristics will be developed toward this end. These methods will provide information such as magma velocities, discharge rates, and volatile contents (Wilson and Head, 1981; Vergniolle and Jaupart, 1986). Discharge rate and volatile content, and their variations between eruptions, are crucial for constraining the magma conditions at depth and thus may provide information that is valuable for our understanding of mechanisms of waning and polycyclic volcanism in the region. Information for these studies will be obtained in conjunction with information from Study 8.3.1.8.5.1 Characterization of Volcanic Features.

2.3.2 Constraints

All studies for this activity are conducted outside the boundaries of the potential Yucca Mountain repository under the established constraints for the environmental program. There are no potential impacts on the site. The study will involve description and study of surface volcanic deposits, literature review, and computer modeling of volcanic eruptions. Field studies will be carried out under standard operating procedures that will ensure the safety of the participants. The are no interferences with this work with other tests, either on-site or off-site. There are no limitations on repeatability of tests because the measurements of volcanic features are non-destructive. Modeling techniques have already been developed or are currently being developed for eruption modeling (e.g., Valentine and Wohletz, 1989; Valentine et al., 1992a,b) and for magma chamber processes with codes that have been adapted from mantle convection studies (Travis, 1990; Travis et al., 1990).

The theoretical modeling for this activity will serve as a means of analysis and interpretation of observations, and to guide conceptual models related to probability calculations and subsurface and eruptive effects analysis. Because this activity is aimed at analysis and interpretation of observations, the appropriate quality assurance measures are documentation of work in notebooks and competent peer review.

3.0 DESCRIPTION OF TESTS AND ANALYSES

3.1 Activity 8.3.1.8.1.2.1 Eruptive Effects

3.1.1 General Approach

Two main approaches will be used in this activity, both of which will be based on field studies at analog basaltic centers. First, we will examine the depth of derivation of lithic fragments (shallow country rock fragments incorporated in basalt magma) by studying the abundance and lithology of lithic fragments in surface basalts of both magmatic and hydromagmatic eruptions. Second, we will examine the geometry of vent conduits of eroded basalt centers. As a supplementary study to the analog approaches, we will examine through modeling the controls on the depth of magma fragmentation assuming different magma volatile contents, and rates of magma rise and discharge. At depth, basalt magma is transported in narrow dikes (Maaloe, 1989), but as magma rises to shallow levels, volatiles are exsolved until the bubble pressure exceeds the magma pressure and the magma fragments explosively (fragmentation depth; Sparks, 1978). The fragmentation depth may coincide with the depth of conduit flaring and country rock disruption. The modeling approaches will be based mainly on existing models in the literature (e.g., Wilson and Head, 1981). Our main reliance, though, will be on results from field analog studies, primarily because the mechanics of dike and conduit erosion are not well known and thus can not be confidently modeled.

The purpose of the analog approaches is to determine the amount of debris that could be brought up from repository depth in the event of formation of a new volcanic center through and above the repository. This will depend on total eruptive volume and on the mode of eruption (hydrovolcanic explosions, magmatic explosions, or lava effusion). For a given eruptive volume and mode, there will likely be a range of values for the quantity of debris erupted from repository depth. It is likely that most of the dike or conduit wall erosion that entrains debris is concentrated in the uppermost portions of the system near the vent, but this hypothesis is only poorly constrained by existing studies and requires testing in the field. Shapes of basaltic volcanic feeder conduits for explosive eruptions have been reported in the literature (see White, 1991, and references therein), but these have mainly been ultramafic in composition and it is not clear whether they are good analogs for basaltic centers in the Yucca Mountain area. Furthermore, these studies rely heavily on the geometries of eroded feeder systems which record a great deal of complexity due to the closing phases of eruptions. As discussed above, we will study the geometry of some highly eroded centers because they do provide some contraints, but we will also attempt to constrain wall-rock erosion during active eruptive phases by studying lithic fragments within the extrusive deposits and determining their depths of origin. There are some papers in the literature (e.g., Houghton and Schmincke, 1989) which report total lithic content in eruptive products for analogous eruptions, but these are not given in terms of depths of origin. The only study of the type which we will carry out is that of Mastin (1991), but this was for eruptions of rhyolitic composition. Preliminary calculations (Valentine et al., 1992b) show that determining the depth of origin of lithics will have a strong effect on volcanic risk calculations, through the assumption that the amount of radioactive waste erupted in a hypothetical volcano would be proportional to the quantity of debris that can be brought up from the repository level.

3.1.2 Summary of Test and Analysis Methods

The studies of the abundance of lithic fragments in basalt deposits will be based on visual examination and measurement of lithic fragments in 1 m^2 areas. Past studies demonstrated (Crowe et al., 1983b) that lithic fragment abundance can be determined readily in scoria deposits. Multiple sample sites will be studied at basalt centers with a range of eruptive mechanisms from explosive (both magmatic and hydromagmatic) and effusive processes. We will collect and describe sufficient samples to characterize the bulk abundance of lithic fragments in the pyroclastic deposits and lavas. The dimensions of individual lithic fragments will be measured and representative fragments collected. A representative bulk sample of the pyroclastic deposits will be collected for granulometric analysis. The fine-grained fractions (< 2 mm) will be examined under the binocular microscope to establish the abundance of lithic fragments in the small size fractions that may not be readily identified megascopically. The collected lithic fragments will be examined under the binocular microscope and, if required, thin sections will be made to establish the stratigraphic identity of the fragments under the polarizing microscope.

On the basis of the stratigraphic identification, and the percentage and dimensions of the lithic fragments we will convert the data to volume abundance and establish the derivation of lithic fragments as a function of depth below the volcano. For a given type of eruption, the amount of radioactive waste that could be erupted onto the surface above a potential repository will be estimated by the following simple relationship:

$$V_w = F_{rd} V_t F_w \quad ,$$

where V_w is the volume of erupted waste, F_{rd} is the volume fraction of erupted lithic debris that originated at repository depths, V_t is the total volume of an eruption, and F_w is the volume fraction of waste within the repository horizon. Preliminary calculations of this sort have been presented by Crowe et al. (1983b) and Valentine et al. (1992b). This approach involves the assumption that radioactive waste in the wall of a dike has the same probability of being entrained as the wall rocks. This is conservative because the waste is actually much denser than the wall rocks, and because during much of the repository lifetime the waste will remain in packages. The packages have dimensions that are of the same order as expected dike widths (0.5 - 5.0 m), so that waste entrainment would actually be less likely than wall rock entrainment. Thus the volume fraction of erupted wall rock (lithic fragments) in analog volcanoes can be used to provide a conservative estimate of erupted waste.

This type of evaluation of eruptive effects applies both to monogenetic and polycyclic centers. For consideration of eruptive effects of a polycyclic center forming at the potential repository site, each event would be treated individually by the above method.

Examples of each eruptive type, including eruptions driven by both hydrovolcanic processes and by purely magmatic processes (explosive and effusive) and combinations of the two, will likely yield a range of values for F_{rd}. In order to estimate $E3_e$ we will combine these ranges with probabilities of each eruptive mechanism at the Yucca Mountain site using a Monte Carlo technique, for example, so that $E3_e$ will consist of a range of values. The probabilities of each eruptive mechanism will be determined by the number or volume of events of each mechanism divided by the total number or volume of Pliocene and Quaternary eruptive events in the Yucca Mountain region.

Changes in conduit geometry with depth will be studied by using natural outcrops where there are vertical exposures of feeder dikes. Where dikes are exposed and are hosted by silicic tuffs, we will measure the dimensions of conduits and dikes, and thermal and mechanical effects on country rock (see Section 3.2.1). For sites where we make these measurements, we will attempt to establish, using stratigraphic constraints, the depth of the exposure below the original eruptive surface. These studies will provide additional constraints on erosional processes on dike and conduit walls.

The studies for these activities will concentrate on localities where good combinations of rock types and exposures are present. Identified sites for the lithic fragment studies are the Red Cone and Black cone site in Crater Flat. Here drill hole VH-2, located between the cones, provides stratigraphic control on the underlying rock units (alluvial fill, 11 Ma basalt, Timber Mountain and Paintbrush Tuffs). Other candidate sites for both lithic derivation and eroded conduit studies include the Lucero (Baldridge et al., 1987) and the Rio Puerco-Mesa Chivato (Hallett, 1992) basalts in west-central New Mexico, the Vulcan's throne area of the western Grand Canyon, and the San Francisco volcanic field in Arizona. In these areas variably eroded basalt centers overlie the well characterized Paleozoic and Mesozoic stratigraphy of the Colorado Plateau. An alternative area we may examine for the lithic fragment studies is the Lunar Crater volcanic field, north of Yucca Mountain in the Death Valley-Pancake Range volcanic field. Basalt centers in this field erupted through thick sequences of Miocene tuff, analogous to the stratigraphic sequence of the Yucca Mountain setting. Studies of conduit geometry of basalt feeder systems will be conducted at the Paiute Ridge area, east of Yucca Flat, at Vulcan's throne in the western Grand Canyon and at basalt centers of the Fortification basalt units (Smith et al., 1990). An alternative site for this work that may be considered is the southern Reveille range, north of Yucca Mountain.

Theoretical estimates of conduit erosion as a function of depth can be made under some simplifying conditions. If it is assumed that the pressure in a rising magma is approximately equal to the local lithostatic pressure, and that the concentration of a volatile species (mainly H_2O and CO_2) dissolved in the melt at a given depth is equal to the solubility at that pressure, then the volume fraction of the gas phase can be computed if the volatile concentration at the deep reservoir is known. Coupled with hydrodynamic equations describing conservation of mass and momentum, the conduit width at any given depth for a specified mass flux can be determined. This type of analysis involves assumptions of homogeneous, equilibrium multiphase flow (Wilson and Head, 1981), which is only a rough approximation of actual basaltic systems (Vergniolle and Jaupart, 1986). We will use the approach of Wilson and Head (1981), and in light of the simplifications of this approach the modeling will only be used insofar as it can supplement the analog studies described above.

Procedures - This work will be conducted under notebook control following QP-03.5, Procedure for Documenting Scientific Investigations. A detailed procedure will be written on methods used for study of lithic fragments in basalt deposits. This procedure will be written after approval of the Study Plan. Studies of conduit geometry will utilize simple field measurements. Field studies will follow DP-606, Procedure for Volcanism Field Studies, and sample control will follow DP-607, Procedure for Volcanism Sample Storage and Control. Theoretical analysis will involve use of published analytic and numerical solutions of "equilibrium" conduit geometry based on the solubility of volatiles in basaltic magma as a function of depth, and on fluid dynamic considerations (e.g., Wilson and Head, 1981; Spera, 1984; Vergniolle and Jaupart, 1986).

3.1.3 Equipment List

Equipment used for these studies will include standard topographic maps (1:62500 and 1:24000), geologic quadrangle maps where available, aerial photographs, steel tape, geologic compass, binocular microscopes, and petrographic microscope with automated point counting equipment. The sieve analyses will be conducted with commercial sieve equipment that meets required ANSI standards. Data reduction, compilation and computer modeling will be accomplished using desktop computers, workstations, and mainframe computers depending on problem sizes. Statistical analysis will be done using a commercial software package.

3.1.4 Tolerance, Accuracy, and Precision

The accuracy of the lithic fragment studies involves two factors. First, we will establish the precision of lithic fragment abundance by establishing the reproducibility of replicate measurements. The precision for these measurements will be described using standard univariate descriptive statistics. The accuracy of identifying the depth of derivation of lithic fragments cannot be presently defined. It will be dependent on thickness and stratigraphic variability of rock units below the basalt centers. In light of this we will focus on analog sites where the subvolcanic stratigraphy is not only well constrained, but exhibits as much variability in rock types as is feasible. We will construct representative cross-sections of the locations and identify the depth constraints for lithic assemblages.

Field measurements of conduit geometry will be made using largely tape and compass methods. If greater precision is needed for specialized localities, we will survey the sites using the laser theodolite.

To ensure representativeness, we will only select volcanic centers of similar volume, composition, and eruptive type to basaltic centers in the Crater Flat Volcanic Zone. Centers with a wide range of basement rock types will be studied in order to study the effect of this variable on conduit wall erosion.

The accuracy of theoretical analyses will be assessed by comparing the simplifications of the models with observations of real eruptions (e.g., Wolfe et al., 1987). While existing theoretical models (Wilson and Head, 1981) will provide some guidance, it is anticipated that field studies described above will provide the most rigorous constraints on conduit geometry and erosion because of the predominance of nonequilibrium, multiphase flow processes in basaltic eruptions (e.g., Vergniolle and Jaupart, 1986, 1990).

3.1.5 Test Results

The validity of the test results for this work is based on examination of analog basalt centers. We argue that the best representations of the possible effects of future basalt eruptions are provided by studies of older basalt centers. The degree of representativeness of these studies, however, is dependent on how closely analog centers represent possible future eruptions in the Yucca Mountain region. We will maximize the application of studies for these activities by choosing basalt centers for study that are either located within the Yucca Mountain region, or represent basalt centers that are compositionally similar to centers located near the potential Yucca Mountain site. The most difficult factor to control is the composition of underlying rock units. Eruptions through competent basement rock may have different geometry and abundance of lithic fragments than eruptions through moderately consolidated alluvium. We will attempt to account for these effects by including studies of basalt centers erupted through sections of welded and nonwelded tuff. Also, we will attempt to locate basaltic centers where the feeder dike(s) and conduits intersect one or more layers of rock that is poorly consolidated and less competent than surrounding layers. This situation would be analogous to a dike intersecting backfill material at the potential repository horizon, which may result in increased erosion relative to that in the surrounding intact rocks.

The results of these studies will provide us with information on how wall rock erosion varies with depth, which will be used directly to estimate the amount of repository material that could be erupted if a volcanic event penetrated the potential repository as described above. These estimates will be used as a basis for high-level performance assessment calculations.

3.2 Activity 8.3.1.8.1.2.2 Subsurface Effects

3.2.1 General Approach

The purpose of this study is to define scenarios and determine the subsurface effects of igneous activity. These effects can result from stress variations associated with intrusion emplacement, hydrothermal activity accompanying cooling of intrusions, and possible alterations to the "ambient" hydrologic flow field after the thermal pulse has decayed away. The approach will involve parallel studies of analog sites and numerical studies. The effects of potential polycyclic intrusive complexes will be accounted for by treating each event individually.

Intrusion Geometry
The geometry of intrusive bodies must be characterized in order to understand possible subsurface effects. Crowe et al. (1983b) provided data on intrusion geometry, which we will refine by further literature review and field studies of selected analog sites. Intrusive bodies that are

of interest for this study are those that occur at depths less than about 1 km, which, if emplaced within or directly below Yucca Mountain, might affect the potential repository. Intrusions between 1 km and the surface are dominated by linear dikes whose orientations are determined mainly by the regional principal stress directions, subhorizontal sills, and radial dikes around volcanic conduits. Orientations of radial dikes are determined mainly by the stress field that is induced by an intrusion itself. In many cases, a linear dike or set of *en echelon* dikes will locally swell to form conduits or plug-like bodies, where most eruptive activity is focused. The mechanisms of this swelling include locally enhanced erosion or melting of the dike walls (Delaney and Pollard, 1981; Bruce and Huppert, 1990). Intrusion geometry is important for repository performance because it determines how much of the repository horizon is accessible for an intrusion, the heat transfer rate from the intrusion, and the form of convective flow that may develop around the intrusion.

The general approach for constraining intrusion geometry will consist of the following: (1) literature review with special emphasis on literature from the Basin and Range tectonic environment; and (2) field observations of sites (selected from literature review) in the southwestern U.S. Field observations will include length and thickness of basaltic intrusive bodies (e.g., dikes, plugs, sills), variations in thickness, and any possible correlations of these features with the character of the surrounding rocks. When necessary, samples will be collected to constrain the composition of the intrusive rocks. Sites will be selected on the basis of the range of exposed depths in the intrusive body and the degree of similarity between the tectonic regime at the time of intrusion and the present-day regime in the Yucca Mountain region.

Structural Controls on Intrusion Paths

It is known that the location and distribution of igneous intrusions can be strongly influenced by geologic structures such as faults. In the Basin and Range Province, many volcanic fields are located within basins. Long axes of the fields are commonly subparallel to nearby normal faults. In exposures of eroded shallow intrusive complexes, dikes are commonly subparallel or coplanar with normal faults (Smith et al., 1990; Valentine et al., 1992b).

Much of the information on structural controls will come from Activity 8.3.1.8.1.1.2 Evaluation of Structural Controls of Basaltic Activity and from literature review. Also, field observations made during studies related to the topic *Intrusion Geometry* will include relationships between intrusive bodies and structural features such as faults and bedding planes.

Dikes vs. Sills

In some locales, dikes flare horizontally into tabular, subhorizontal sills at shallow depths. A good example is the 8 Ma Paiute Ridge basalt complex in the eastern Nevada Test Site, where sills formed within Miocene tuffs (Byers and Barnes, 1967). The planes of tabular intrusions are usually perpendicular to the least principal stress, so it would appear that formation of a horizontal sill would require a vertical least principal stress.

It is important to define the conditions that allow the formation of sills from dikes and to address whether or not these conditions may occur within the Yucca Mountain structural block. The subsurface processes that accompany a sill may differ from those accompanying a dike. As with studies for *Intrusion Geometry*, most of the information will be obtained from literature review and from field studies at analog sites that are chosen from the literature. In many cases, these sites will be the same ones that are used for *Intrusion Geometry* . If this work indicates that sill formation, given a magmatic event, at Yucca Mountain has a low probability, then modeling studies of $E3_S$ for sill geometries will be terminated.

Mechanical Effects onWall Rocks
When an intrusive body is emplaced, the local stress field is altered; this may have an effect on the wall rocks (e.g., Delaney and Pollard, 1981). For example, even though dikes are most commonly emplaced in extensional tectonic regimes, the emplacement of magma in a dike causes local compression in the wall rocks (Parsons and Thompson, 1991). Ahead of a propagating dike tip, local tension can cause the formation of dike-parallel fractures. Since Yucca Mountain consists of silicic tuffs at potential repository depth, it is important to understand specifically the effects of intrusions on such tuffs. The local compression and heat of an intrusion may cause contact welding of tuffs immediately adjacent to an intrusion (the term "contact welding" is used here to distinguish effects of heat and compression due to a nearby intrusion from welding of pyroclastic rocks that occurs during cooling just after emplacement, although the mechanisms for the resulting collapse of pore space and development of lineations are essentially the same in both cases). This is likely to alter the hydrologic properties of the tuff, especially in nonwelded units below the repository (e.g., Calico Hills tuffs).

For this study it is important to focus on igneous intrusions into rocks that are similar to those in the potential repository block; thus basaltic intrusions into silicic tuffs will be targeted as analog sites. Such sites will be chosen from literature review; they will include the Paiute Ridge basaltic complex, the Nye Canyon centers, and the Pahute Mesa basaltic dikes (these sites are on the Nevada Test Site). Samples of tuff wall rocks will be collected at regular intervals away from contacts with intrusions in order to study welding and other effects on physical properties. Identification of dike-induced parallel fractures is anticipated to be somewhat difficult because tuffs tend to be fractured to begin with. If we do find unambiguous examples of dike-induced fractures in tuffs we will measure fracture densities as functions of distance from the intrusions. Evidence constraining entrainment of wall rock debris into intrusions, which relate to waste entrainment, will be studied as part of this focus.

Hydrothermal Activity
The hydrothermal activity associated with a possible intrusion into the potential repository block can also affect repository performance. Below the water table, intrusion heat can cause local boiling and convective flow (Bixler and Carrigan, 1986; Carrigan, 1986) and possible changes in water table level. In the unsaturated zone, the heat of an intrusion can drive very localized water flow away from the intrusion and possibly can drive slow convection of water at farther distances. In addition, appreciable vapor-phase convection can occur in the unsaturated zone, which may result in

transport of volatile radionuclides. Hot groundwater may increase the corrosion of waste packages. Volatiles released from the magma itself may be especially corrosive.

Most of the literature on hydrothermal systems surrounding mafic intrusions is concerned with large, relatively long-lived intrusions (e.g., Norton and Knight, 1977; Manning and Bird, 1991, Travis et al., 1991), but examples for smaller systems such as might occur in the Yucca Mountain region will be sought from the literature. Studies at analog sites will be carried out in parallel with those for *Mechanical Effects on Wall Rocks*. Degree of welding at a given temperature is sensitive to the presence of water. The effects of hydrothermal fluids on contact welding can be studied by a combination of numerical modeling and studies of welding distribution from the above study. Numerical modeling with the Los Alamos computer code FEHMN will be carried out as general parameter sensitivity and as specific case studies for particular observations in the field.

Long-Term Hydrologic Effects
After the thermal pulse of an intrusion has decayed away the groundwater flow field may establish itself at conditions that are different from the pre-intrusion state. For example, wall rocks of a dike that were originally unwelded tuff but are now contact-welded may have much lower matrix permeabilities and be more prone to fracture flow than before the intrusion. If dike-rock has a very low permeability compared to surrounding rocks, the dike may cause local perching of groundwater that may in turn result in a fast path for radionuclide migration. It is likely, though, that the hydrologic properties of dikes can vary from nearly impermeable to highly permeable, depending on local circumstances of emplacement, cooling, and post-intrusion events. For example, some dikes have very low water storage capacities but very high fracture permeabilities (e.g., Boonstra and Boehmer, 1986; Boehmer and Boonstra, 1987). Thus, even if the porosity of a dike is very low compared to surrounding country rocks, its fracture permeability may be much higher than that of the country rocks so that there are no major effects on the groundwater flow field. If a fractured dike is surrounded by other fractured rocks, such as welded tuffs, the dike rock and country rock may have nearly identical properties.

Geochemical and mineralogical alteration of tuffs due to hydrothermal processes may impact the natural barrier system at the Yucca Mountain site. Such alteration would be particularly important in highly zeolitized units such as the Calico Hills tuffs, where the zeolites are efficient sorbers of many radionuclides that will reside in the potential repository. Most zeolites are unstable at temperatures above about 100 C (Fisher and Schmincke, 1984). Thus the zone around an intrusion which is heated above this temperature could loose its sorption potential. As a first approximation, we will estimate, using numerical simulation, the zone around intrusions of various geometries that exceeds this temperature (and other temperatures that may be relevant for particular sorbing minerals) and assume that sorption from these minerals becomes negligible. Groundwater transport calculations will then be carried out using this information. If such calculations, within the context of probabilistic risk assessment for volcanism, indicate that significant radionuclide releases could result from alteration effects, we will revise this study plan by adding an appendix describing detailed field and modeling studies needed to better constrain alteration processes associated with basaltic intrusions into silicic tuffs.

Some of the information that will be needed to address these issues will be gathered in the course of studies for *Mechanical Effects on Wall Rocks*; these will constrain the changes in hydrologic properties of the country rock. Analog sites where intrusive bodies intersect groundwater flow paths will be sought out, mainly from the literature, in order to determine whether such features can cause perching of groundwater. Analog sites that may be studied in the field include the Paiute Ridge area and Solitario Canyon on the west side of Yucca Mountain, where a Miocene dike was emplaced in tuffs. In addition, the computer code FEHMN will be used to model the effects on groundwater flow of various intrusion geometries, both in the saturated and in the unsaturated zones.

3.2.2 Summary of Test and Analysis Methods

Test methods will include standard volcanological field studies as described in DP-606 Procedure for Volcanism Field Studies; samples will be stored and controlled under DP-607 Procedure for Volcanism Sample Storage and Control. Samples of tuff wall rock will be cut into cubes of known dimensions and weighed in order to determine their densities (which relate to contact welding and porosity changes from intrusion); a detailed procedure will be written for this work after approval of this study plan. We will then use permeability values obtained from tuffs with similar degrees of welding (these values can be found in the literature and, in addition, are being obtained for general hydrologic studies of the Yucca Mountain site). Chemical analyses will be carried out with LANL analytical equipment, such as the x-ray fluorescence (XRF) spectrometer and the electron microprobe. The following detailed procedures will be used as appropriate: DP 130 Geologic Sample Preparation; DP-07 Cameca MBX Electron Microprobe Operating Procedure; and DP-111 Procedure for X-Ray Fluorescence Analysis. Petrographic work will follow existing DP-03 Petrography Procedure using thin sections that have been cut into doubly polished mounts according to DP-130 Geologic Sample Preparation.

Numerical analyses which are used to directly predict the effects of magmatism on the repository will be carried out using the Los Alamos code FEHMN as implimented under the Los Alamos Software Quality Assurance Plan. Numerical analyses for this activity which are used to interpret field data and to help build conceptual models for subsurface effects will be subject to the following quality assurance procedures: (1) QP-03.23 Preparation and Review of Technical Information Products and Study Plans; (2) QP-03.5 Procedure for Documenting Scientific Investigations; and (3) QP-03.7 Procedure for Peer Review.

3.2.3 Tolerance, Accuracy, and Precision

Field measurements will be made using largely tape and Brunton methods. If greater precision is needed for specialized localities, we will survey the sites using the laser theodolite.

XRF analyses generally have accuracies and precision of better than 5% for major elements and better than 10% for selected trace elements that are present above their detection limits. Microprobe analyses of minerals and basaltic glass have accuracies and precision of better than 10% for a range of elements. The accuracies and precision of all measurements are considered adequate for the compositional data needs for this activity.

To ensure representativeness, we will only select volcanic centers of similar volume, composition, and eruptive type to basaltic centers in the Crater Flat Volcanic Zone. Eroded centers where basaltic magmas intruded silicic tuffs will be especially emphasized because such centers would be most analogous to a possible intrusive event at Yucca Mountain.

3.2.4 Equipment List

Equipment used for these studies will include standard topographic maps (1:62500 and 1:24000), geologic quadrangle maps where available, aerial photographs, steel tape, geologic compass, binocular microscopes, petrographic microscope, and a balance. Data reduction, compilation and computer modeling will be accomplished using desktop computer, workstations, or mainframe computers depending on problem size. Statistical analysis will be done using commercial software. We will use geochemical analytical equipment such as an x-ray fluorescence spectrometer and an electron microprobe, and attendant sample preparation facilities.

3.2.5 Test and Analysis Results

Results from this activity will be used for study 8.3.1.8.2.1 Study Plan for the Analysis of Waste Package Rupture due to Tectonic Processes and Events, and for input into performance assessments and scenario development. The results will constrain the short-term hydrothermal effects of intrusions into the potential repository block, and the long-term effects of intrusions on the hydrologic flow field including possible formation of fast paths for contaminant transport.

3.3 Activity 8.3.1.8.1.2.3 Magma System Dynamics

3.3.1 General Approach

The physics of magmatic processes provides important constraints on the overall magmatic system that produces small basaltic centers in the Yucca Mountain region. The data being collected on these centers, including geochronology (Wells et al., 1990; Crowe et al., 1992a), geochemistry/petrology (Vaniman et al., 1982; Perry and Crowe, 1992), physical volcanology (Crowe et al., 1983b; Valentine et al., 1992b), and geophysics (Evans and Smith, 1992), provide information on the timing of eruptions including the possibility of polycyclic centers (Crowe et al.,1992b), compositional variations, magma source regions, depths of reservoirs, presence of partial melts, volumes of eruptions, and eruption conditions. Theoretical analysis of relevant physical processes, as constrained by the data listed above, can provide a framework that will increase our confidence probabilistic predictions. For this Activity we will trace the physics of relevant magmatic processes, such as melt formation and segregation in the mantle, storage and evolution in crustal reservoirs, ascent through dikes, and eruption.

Melt Generation and Segregation - Ultimately, the source of basaltic magmas at depth is partial melting of mantle rocks. Melting can be caused by lowering of the solidus temperature by adiabatic decompression or introduction of volatile species (metasomatism), or by increasing the temperature of rock while keeping pressure and composition constant. Previous work by Vaniman et al. (1982) suggests geochemical and eruption volume trends can be explained by a decreasing degree of partial melting with time (presumably from decreasing heat supply in the mantle). Once partial melting has occurred in the mantle, the melt phase must separate from the residual crystalline matrix. This can occur either by migration of melt into fracture networks, which may in turn coalesce and propagate upward to feed lithospheric chambers, or by percolation of melt through slowly deforming matrix to some reservoir level. The nonlinear processes involved in melt migration can produce waves or "shocks" of melt migrating upward, even if the melting process itself is relatively steady state. Such processes can have important bearing on magma chamber dynamics and even eruption triggering. There is much evidence that magmatism is waning in the Crater Flat volcanic zone (Perry and Crowe, 1992), so an important aspect to address is how melt migration processes may change with changes in melt production. It is also possible that the production rate of partial melt at depth may not parallel changes in eruptive activity.

Data pertaining to the possible presence of partial melt will be obtained from Activity 8.3.1.8.1.1.3 Presence of Magma Bodies in the Vicinity of the Site (Study Plan 8.3.1.8.1.1 Probability of Volcanic Eruption Penetrating the Repository), from recent teleseismic studies (Evans and Smith, 1992), and from the general geologic literature on the Basin and Range Province. In addition, geochemical data from Activity 8.3.1.8.5.1.4 Geochemistry of Eruptive Sequences (Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features), particularly trace element compositions, will be used to estimate degrees of partial melting in the mantle that have fed the Crater Flat basalts (Allegre and Minster, 1978; McKenzie and O'Nions, 1991) as well as to constrain the relative importance of various melting processes. Theoretical analysis of melt migration will follow the approach laid out by Fowler (1990a,b) and references therein. Analysis of metasomatic processes will follow the concepts reviewed in Spera (1987). If necessary, the theory will be solved numerically. Specifically, we will attempt to constrain whether the degree of partial melting implied by the data can give rise to episodic or continuous migration into the crust, and what effect this may have on the timing of eruptive activity at the surface and on the formation of polycyclic centers.

Magma chamber dynamics - Based on ongoing petrologic and geochemical studies (Perry and Crowe, 1992), several constraints on magma chamber processes at Crater Flat have been obtained. Eruptive volumes have declined with time. Phase assemblages of eruptive products suggest that magma chambers have been deepening with time during the past 4 million years, with the most recent products of the Lathrop Wells center erupting from chambers in excess of about 24 km depth. At the Lathrop Wells center, isotopic and trace element compositions indicate that extensive fractionation of two or more separate magma batches has occurred, with little contamination by crustal rocks. In addition, the paucity of phenocrysts in eruptive products at the Lathrop Wells center indicates efficient separation of crystallizing phases from the residual melt in the chamber(s). All of these observations provide constraints on physical processes that can occur within the magma reservoirs.

The literature on magma chamber dynamics (e.g., reviews by Sparks et al., 1984; Turner and Campbell, 1986; Marsh, 1989; Valentine, 1992), especially related to basaltic systems, will be reviewed to provide guidance for modeling the dynamics of chambers that feed the Crater Flat Volcanic Zone. Geologic and geochemical data produced under Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features will provide constraints on theory, including factors such as crystallinity, degree of magma evolution, importance of magma recharge and wallrock assimilation (DePaolo, 1985), and depth and size of magma chambers. We will attempt to constrain the internal dynamics of magma chambers that control observed magma compositions and crystallinity, and the time-scale of magma chamber evolution and maintenance. Much of this study will center on numerical simulation of the thermal and chemical evolution of magma chambers, where we will account for convection, different types of boundary conditions, phase change (Travis, 1990). An understanding of these processes will clarify the mechanisms responsible for polycyclic eruptions in the Yucca Mountain region, and the triggering of eruptions.

Magma Transport - Dikes are the main means by which basaltic magmas traverse the lithosphere. Studies from Magma Chamber Dynamics, described above, will provide insight into processes that may initiate dike propagation from a chamber (e.g., Parfitt and Wilson, 1993). In order for basaltic magma to be transported to shallow depths or to be erupted at the surface, there must be a balance between the heat advected with the magma, the added heat from any crystallization that occurs during ascent, and the heat lost to the wall rocks, otherwise the magma would stagnate at depth and solidify. On the basis of on this balance, we can estimate the transit time for a dike feeding an eruption or intrusion of a given volume, and the relative volumes of magma that solidify in transit as opposed to the amount that flows to shallow depth or the surface.

Data pertaining to dike initiation, magma transport time, and dike cooling time will be gathered from the existing geologic data, from the literature, and from computer modeling of dike initiation, transport dynamics, and cooling dynamics. Most of this information will be obtained with Activity 8.3.1.8.1.2.2 Subsurface Effects. Mechanisms of dike initiation, if related to magma chamber dynamics (discussed above), may be directly related to the mechanics of polycyclic eruptions in the Yucca Mountain region. The timing of eruptions at basaltic centers, obtained from geochronology studies (Activity 8.3.1.8.5.1.2 Geochronology Studies), will constrain modeling of dike initiation mechanisms.

Eruption Dynamics - The style and quantitative characteristics of an eruption can provide direct information on the dynamics of the magma system below, including mass flux rates and volatile contents. For prehistoric eruptions such as those in the Crater Flat volcanic zone we must use characteristics, or facies, of the eruptive products to learn about eruption dynamics. Basaltic volcanoes in Crater Flat have produced both lava flows and pyroclastic material, the latter forming the main cone constructs and more widespread fallout sheets. These facies are produced by eruptions of gas and magma clots. The eruptions may take the form of relatively steady jets and fountains (Hawaiian eruptions), or of intermittent or frequently repeated bursts of material that form short-lived fountains and ballistically ejected bombs (Strombolian eruptions). The development of a given facies depends on the local accumulation rate of clasts and their temperature (Head and Wilson, 1989). The distribution of these facies, which reflects the spatial variations in accumulation rate and temperature, depends on the eruption dynamics, namely, the magma discharge rate, volatile content, vent radius, and clast size.

This study will involve a combination of modeling and field studies. Modeling, using two-phase hydrodynamic simulation codes (e.g., Valentine and Wohletz, 1989; Valentine et al., 1992a,b), will be conducted to quantify how accumulation rate and clast temperature vary as functions of eruption conditions. Techniques for quantifying facies will be developed; these will be simple methods for estimating the percentage of clasts that are welded to surrounding clasts. These techniques will be used to estimate accumulation rate and clast temperature at time of deposition, which will be compared with model results to estimate the range of eruption conditions that produced the volcanoes at Crater Flat. This will be combined with the studies described above to provide a framework for the magma dynamic system.

Work carried out for *Eruption Dynamics* will initially be only indirectly related to Activity 8.3.1.8.1.2.1 Eruptive Effects, which has the primary focus of addressing the very specific issue of how much waste could be erupted onto the surface by a volcanic event penetrating the repository. As described in Sections 2.1.1 and 5.0, if eruptive releases are large enough to exceed a critical value within a probabilistic risk assessment then detailed studies of dispersal mechanisms will be carried out (under a revised version of this Study Plan). In this case the work for *Eruption Dynamics* will play an extremely important role because of constraints it will provide on volatile contents and other parameters that determine dispersal processes.

3.3.2 Summary of Test and Analysis Methods

Except for field data pertaining to facies analysis, most of the information used in this Activity will be derived from studies in Study Plan 8.3.1.8.5.1

Characterization of Volcanic Features. Test methods for facies analysis will be notebook controlled and will include standard volcanological field studies as described in DP-606 Procedure for Volcanism Field Studies; samples will be stored and controlled under DP-607 Procedure for Volcanism Sample Storage and Control.

The literature review and theoretical modeling for this activity will serve as a means of analysis and interpretation of observations. Numerical modeling using multiphase hydrodynamics and convection codes will be carried out as necessary. The results of this activity will be used to guide conceptual models related to probability calculations and subsurface and eruptive effects analysis. Because this activity is aimed at analysis and interpretation of observations, the appropriate quality assurance measures are documentation of work in notebooks and competent peer review. These measures are embodied in the following quality assurance procedures: (1) QP 03.23 (Preparation and Review of Technical Information Products and Study Plans); (2) QP-03.5 (Procedure for Documenting Scientific Investigations); and (3) QP-03.7 (Procedure for Peer Review).

3.3.3 Tolerance, Accuracy, and Precision

Field measurements will be made using largely tape and Brunton methods. If greater precision is needed for specialized localities, we will survey the sites using the laser theodolite.

To ensure representativeness, we will only select volcanic centers of similar volume, composition, and eruptive type to basaltic centers in the Crater Flat Volcanic Zone for study.

3.3.4 Equipment List

Equipment used for these studies will include standard topographic maps (1:62500 and 1:24000), geologic quadrangle maps where available, aerial photographs, steel tape, geologic compass, binocular microscopes, and petrographic microscope, and a balance. Data reduction, compilation and computer modeling will be accomplished using desktop computers, workstations, and appropriate mainframes. Statistical analysis will be done using commercial software.

3.3.5 Test and Analysis Results

Results from this activity will be used for Study 8.3.1.8.1.1 Probability of Volcanic Eruption Penetrating the Repository, and for input into performance assessments and scenario development.

4.0 APPLICATION OF RESULTS

The work performed under this study plan will provide information to address (1) the information needs for Issue 1.1 related to the performance of the mined geologic disposal system, (2) information needs for Issue 1.8 related to favorable and potentially adverse conditions required by 10 CFR 60.122 (NRC, 1986), and (3) information needs for Issue 1.9 related to qualifying conditions of the postclosure system guidelines and the disqualifying or qualifying conditions of the technical guidelines for tectonics provided in 10 CFR 960 (DOE, 1986). Information provided by this study plan will also be used directly in total system performance assessment calculations and by Study Plan 8.3.1.8.1.1 Probability of Volcanic Eruption Penetrating the Repository.

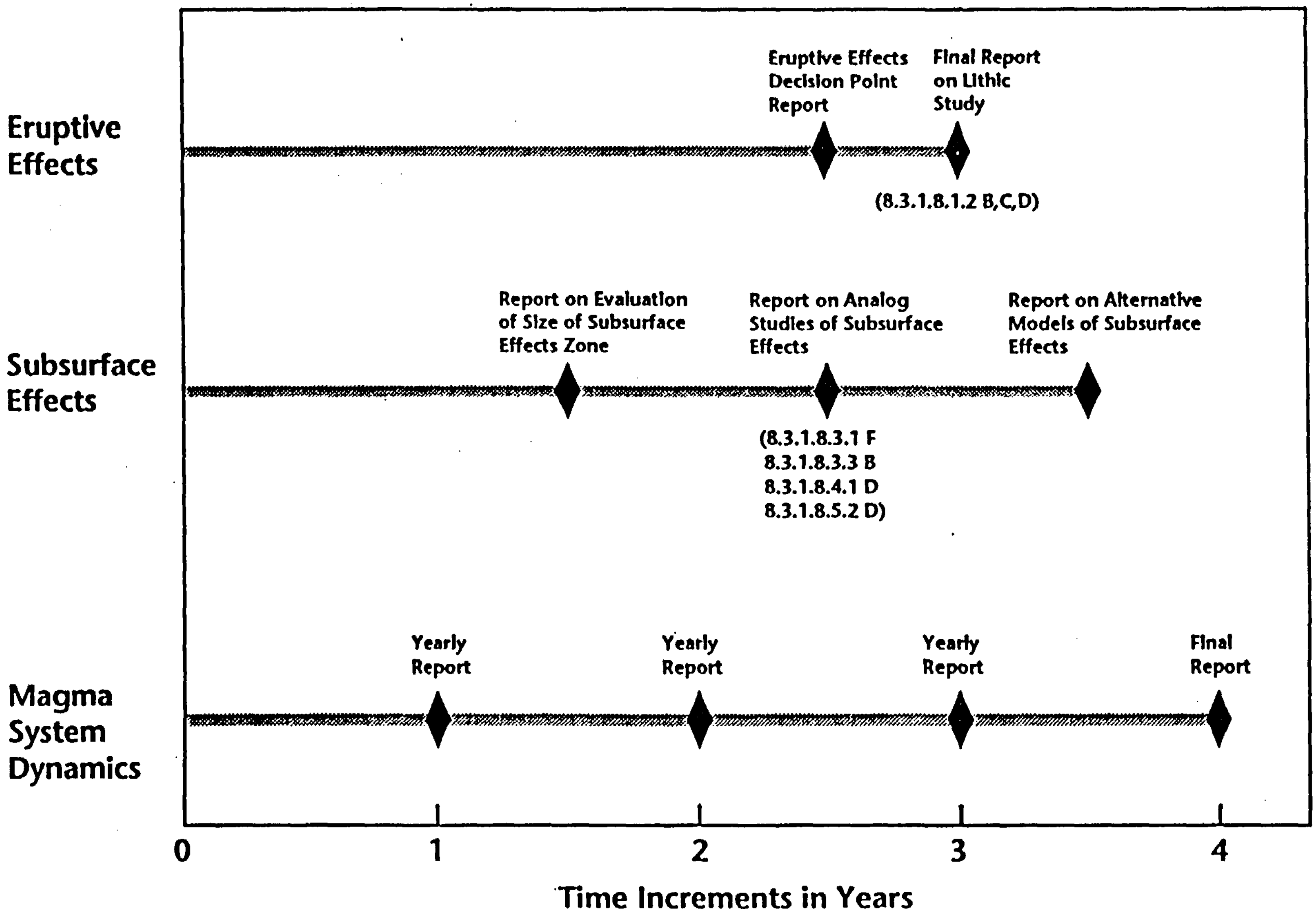
5.0 SCHEDULES AND MILESTONES

The milestones for Study Plan 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository are listed in this section by activity and are also shown in Table 1 with reference to milestones given in DOE (1988). This study is loosely tied to timing of Study Plan 8.3.1.8.1.1 Characterization of Volcanic Features in that to a large extent the information that is needed from the latter is laready available because that study has been in progress for some time. The timing relative to Study Plan 8.3.1.8.1.1 Probability of Volcanic Eruption Penetrating the Repository is more important in that studies of subsurface effects will define the appropriate area that is used in probability calculations. This issue is the first subsurface effects issue that will be addressed in the current study plan.

The primary objectives of this study plan are the following: 1) Evaluate the effects of magmatic disruption of a potential repository associated with surface eruption of basalt magma (scenario of direct eruptive effects), 2) Evaluate the effects of subsurface emplacement of magma with or without an associated surface eruption. This scenario will be examined for the potential repository area, the controlled area and an area extending beyond the controlled area. The area of the latter will be dependent on results of modeling of thermal and hydrologic effects of magmatism. Assessments of these scenarios will include cases of formation of basalt intrusions both below and above a potential repository. 3) Evaluate the physical processes responsible for volcanic features in the Yucca Mountain region.

The schedule for this study is dependent on implementation of the overall site characterization program as described in the SCP (DOE, 1988). The results of work described in this Study Plan will be used to aid in several critical decisions. First, bounding data will be obtained on the depth of derivation of lithic fragments found in pyroclastic and lava deposits of basaltic eruptions of the type occuring near Yucca Mountain. These data will be used to attempt to constrain the probability ($E3_e$) of eruptive radiological releases associated with direct magmatic disruption of a potential repository exceeding regulatory limits. If $E3_e$ is significantly less than 1, then the combined probability of the recurrence rate ($E1$), the probability of disruption ($E2$) and the probability of eruptive releases ($E3_e$) can be shown to be $< 10^{-8}$ yr^{-1} (see Section 2.1.1), barring any new infomation which alters the values of $E1$ and $E2$ which could warrant a reevaluation of $E3_e$. If $E3_e$ is not significantly less than 1, then detailed release calculations may be required to evaluate the significance of eruptive effects. We would, upon reaching this conclusion, revise Study Plan 8.3.1.8.1.2 Physical Processes of Magmatism and Effects on the Potential Repository.

Milestones and Schedule for Physical Processes of Magmatism and Effects on the Potential Repository [1]



[1] *Numbers in parentheses are study numbers from DOE (1988). Letters refer to milestones for respective studies, as listed in Table 8.3.1.8-9 of DOE (1988)*

A new appendix would be written describing plans to undertake expanded eruption modeling of surface eruptions to provide more detailed consideration of the pathways and release mechanisms of radionuclides carried to the surface by a volcanic eruption.

Key issues for Activity 8.3.1.8.1.2.2 Subsurface Effects will include: (1) Determining the distance from the potential repository within which an intrusion would have an effect on the potential repository. This distance will be used in Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository for revised probability calculations for subsurface effects. (2) Determination of the magnitude of effects of hydrothermal activity and magmatic volatiles at the potential repository horizon. (3) Determination of whether significant perching of groundwater can result from the presence of intrusive bodies.

The key issues for Activity 8.3.1.8.1.2.3 Magma System Dynamics are to identify magma processes that may provide sensitive controls on the generation, evolution, ascent and eruption of basalt magma. Our goal is to apply a mechanistic perspective to magma system dynamics to test whether concepts and assumptions developed through Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository and Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features are both soundly based and consider a full range of alternative models.

5.1 Milestones for Activity 8.3.1.8.1.2.1 Eruptive Effects

A report on the preliminary results of studies of the abundance and depth of derivation of lithic fragments in eruptive deposits of basalt centers will be completed in 2.5 years. This report will provide the basis for making a decision of whether to conduct detailed eruption modeling for release calculations. If no detailed modeling is needed, the final report will be completed three years after approval of this Study Plan. This single milestone will fulfill the original SCP milestones B,C, and D for Study 8.3.1.8.1.2 (Table 8.3.1.8-9 of DOE, 1988). Two possible options will be followed based on this milestone.

Option 1 -- $E3_e << 1$: Documentation in a formal report of estimated or bounding values of $E3_e$. Upon acceptance of these values work on Activity 8.3.1.8.1.2.1 will conclude.

Option 2 -- $E3_e \sim 1$: Study Plan 8.3.1.8.1.2 will be revised and expanded section will be developed on detailed plans for modeling of a range of potential surface eruptions and evaluation of the potential pathways and exposure history to the biosphere of waste radionuclides.

5.2 Milestones for Activity 8.3.1.8.1.2.2 Subsurface Effects

The initial work on this project will focus on identification of the scale of operation of coupled processes associated with emplacement of dikes or intrusive bodies of basalt magma. We will evaluate, using a combination of field studies and computer modeling, the area of disruption in both time and space in proximity to basalt intrusions. A report will be completed describing the size of these zones and the magnitudes of disruptive effects within them, both physically and temporally. This report will be completed by 1.5 years, and will attempt to answer the questions such as the following:

1. What is the maximum depth below the potential repository where basalt intrusions could affect the waste isolation system?

2. What are the maximum distances, both hydrologically upgradient and downgradient of the potential repository that basalt intrusions could affect the waste isolation system of both the saturated and unsaturated zone?

On the basis of the bounds provided from answering these questions, we will begin analog analysis of basalt processes to evaluate the range of operation of basalt systems in the Yucca Mountain region in comparison to these bounds. A second milestone report will be issued discussing these evaluations at 2.5 years. This single milestone will fulfill original SCP milestones F of Study 8.3.1.8.3.1, B of Study 8.3.1.8.3.3, D of Study 8.3.1.8.4.1, and D of Study 8.3.1.8.5.2 (Table 8.3.1.8-9 of DOE, 1988).

A third element of subsurface effects studies will be an assessment of the completeness of alternative models investigating coupled effects of intrusive magmatic activity. We will produce a third report at 3.5 years that will examine this question. We will produce a set of effects scenarios, based on field and literature studies of basalt processes, that will be used as input for performance assessment studies.

5.3 Milestones for Activity 8.3.1.8.1.2.3 Magma System Dynamics

This activity is designed to provide cross-checking information for Study Plan 8.3.1.8.5.1 Characterization of Volcanic Features, and Study Plan 8.3.1.8.1.1 Probability of Magmatic Disruption of the Repository. We will produce yearly reports based on studies of magma system dynamics to describe the results of literature review and analysis for the following questions:

1. Are constraints on the mechanisms of generation, ascent, storage and eruption of basalt magma consistent with the results of geochronology studies of basalt systems (Activity 8.3.1.8.5.1.2 Geochronology Studies)?

2. Are eruptive models for small volume basalts (Activity 8.3.1.8.5.1.3 Field Geologic Studies) compatible with concepts of magma system dynamics? This will address specifically the issue of polycyclic versus monogenetic eruptions and models of the time gap between basaltic eruptions for polycyclic eruptions.

3. Are geochemical models for the evolution of individual volcanic centers consistent with physical constraints on magma system dynamics (Activity 8.3.1.8.5.1.4 Geochemistry of Eruptive Sequences)?

4. Are current understanding of process of magma generation, storage, ascent and eruption consistent with the time, space, and compositional patterns of basaltic volcanic fields of the basin-range province (Activity 8.3.1.8.5.1.5 Evolutionary Patterns of Basaltic Volcanic Fields)?

5. Are constraints on the location and structural controls of sites of basaltic volcanic activity consistent with current understanding of the dynamics of magma ascent and eruption in the shallow crust of the Basin and Range province (Activity 8.3.1.8.1.1.2 Evaluation of the Structural Controls of Basaltic Volcanic Activity)?

6. Are models of the recurrence rate of volcanic events consistent with current understanding of the mechanisms of evolution, ascent, storage, and eruption of basalt magmas (Activity 8.3.1.8.1.1.4 Probability Calculations and Assessment)?

6.0 QA APPENDIX

The work performed under this study plan is graded in Los Alamos Grading Report 32, Postclosure Tectonics, WBS 1.2.3.2.5.

Quality Assurance requirements are stated in Title 10 of the Code of Federal Regulations, Parts 50, 60, 71, and 72. The Office of Civilian Radioactive Waste Managment issued the Quality Assurance Requirements Document (QARD) to provide a framework consistent with implementing quality assurance programs at every level within the Civilian Radioactive Waste Management Program. Los Alamos National Laboratory implements the requirements of the QARD through Quality Administrative Procedures (QPs). The following QPs apply to the work performed under this study plan:

TWS-QAS-QP-01.1, Procedures for Interface Control
LANL-YMP-QP-01.2, Stop Work Control
LANL-YMP-QP-01.3, Conflict Resolution
TWS-QAS-QP-02.3, Procedure for Readiness Review
TWS-QAS-QP-02.4, Procedure for Management Assessment
LANL-YMP-QP-02.5, Selection of Personnel
TWS-QAS-QP-02.7, Personnel Training
LANL-YMP-QP-02.9, Personnel Proficiency Evaluations
LANL-YMP-QP-2.11, Personnel Orientation
TWS-QAS-QP-03.5, Procedure for Documenting Scientific Investigations
TWS-QAS-QP-03.7, Procedure for Peer Review
LANL-YMP-QP-3.23, Preparation and Review of Technical Information Products and Study Plans
LANL-YMP-QP-3.24, Submittal of Design and Test-Related Information
LANL-YMP-QP-03.25, Review of Design and Test-Related Information
LANL-YMP-QP-04.4, Procedure of Commercial-Grade Items and Services
LANL-YMP-QP-04.5, Procurement of Noncommercial-Grade Items and Services
LANL-YMP-QP-06.1, Document Control
LANL-YMP-QP-06.2, Preparation, Review, and Approval of Quality Administrative Procedures
LANL-YMP-QP-06.3, Preparation, Review, and Approval of Detailed Technical Procedures
LANL-YMP-QP-08.1, Identification and Control of Samples
LANL-YMP-QP-08.3, Transfer of Data
LANL-YMP-QP-12.1, Control of Measuring and Test Equipment
TWS-QAS-QP-13.1, Procedure for Handling, Storage, and Shipping Equipment
TWS-QAS-QP-15.2, Deficiency Reporting
LANL-YMP-QP-16.2, Trending
LANL-YMP-QP-16.3, Deficiency Reports
LANL-YMP-QP-17.4, Records Preparation
LANL-YMP-QP-17.5, Records Processing
LANL-YMP-QP-18.1, Audits

LANL-YMP-QP-18.2, Surveys
LANL-YMP-QP-18.3, Auditor Qualification and Certification

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"Physical Processes of Magmatism and Effects on the Potential Repository"

DP 606	Procedure for Volcanism Field Studies
DP 607	Procedure for Volcanism Sample Storage and Control
DP 130	Geologic Sample Preparation
DP 07	Cameca MBX Electron Microprobe Operating Procedure
DP 111	Procedure for X-Ray Fluorescence Analysis
DP 03	Petrography Procedure

ENCLOSURE 2