U.S. DEPARTMENT OF ENERGY

OCRWM

YUCCA MOUNTAIN PROJECT

DRAFT

STUDY PLAN FOR CHARACTERIZATION OF VOLCANIC FEATURES

YMP-LANL-SP 8.3.1.8.5.1, R0

FEBRUARY 1990

DRAFT

UNITED STATES DEPARTMENT OF ENERGY
NEVADA OPERATIONS OFFICE/YUCCA MOUNTAIN PROJECT OFFICE

STUDY PLAN FOR CHARACTERIZATION OF VOLCANIC FEATURES

B. M. Crowe

Los Alamos National Laboratory

ABSTRACT

Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, describes the purpose and objectives, the technical rationale, the constraints, and the approach and methods of studies required to characterize volcanic features for the Yucca Mountain Project. The study is divided into five activities: volcanism drill holes, geochronology studies, field geologic studies, geochemistry of eruptive sequences, and evolution of basaltic volcanic fields.

The volcanism drill hole activity involves exploratory drilling of aeromagnetic anomalies that may represent either buried volcanic centers or intrusive rocks. The geochronology activity will document the chronology of eruptive activity at the Pliocene and Quaternary volcanic centers of the Yucca Mountain region; a second objective is establishing the chronology of post-Miocene silicic volcanism in the Yucca Mountain region. The field geologic activity will establish the field relations and eruptive history of Pliocene and Quaternary volcanic centers in the Yucca Mountain region and determine the distribution of post-Miocene silicic volcanism in the southwest Great Basin. Studies of the geochemistry of eruptive sequences at Pliocene and Quaternary basalt centers will characterize the geochemical composition of basaltic volcanic units and model geochemically the processes of derivation and evolution of the basalt magma that formed the Quaternary centers. A second objective of this activity will be to identify the source of basalt ash exposed in trenches adjacent to Yucca Mountain. The final activity, evolutionary patterns of basaltic volcanic fields, will examine patterns of variation in time, space, eruptive volume, effusion rate, and geochemical composition of continental basaltic fields. This information will provide a perspective for determining if patterns in the developmental history of volcanic fields can provide insight into the predicted patterns of future volcanic activity in the Yucca Mountain region.

The information obtained from this study will be used primarily to assess the risk of future volcanism with respect to storage of high-level radioactive waste at Yucca Mountain. The strategy for applying this information is presented in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, and Study Plan 8.3.1.8.1.2, Effects of Magmatic Disruption of the Repository.

TABLE OF CONTENTS

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(continued)

TABLE OF CONTENTS
(concluded)

LIST OF TABLES

LIST OF FIGURES

1.0 PURPOSE AND OBJECTIVES OF STUDY

1.1 Objectives

The Yucca Mountain Project (YMP) is conducting volcanism studies to evaluate the possible recurrence of volcanic activity during the post-closure period of a potential repository located at Yucca Mountain. The objective of Study 8.3.1.8.5.1, Characterization of Volcanic Features, is to provide the required field, geochronology, and geochemistry data needed to decipher the history of Cenozoic volcanic activity in the Yucca Mountain area. This information will be used to attempt to predict future volcanic activity and will be supplied to Studies 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, and 8.3.1.8.1.2, Effects of Magmatic Disruption of the Repository. The purposes of these two studies are, respectively, to evaluate the probability of disruption of a repository by future magmatic activity and to develop descriptions of likely future volcanic scenarios for consequence analysis and performance assessment.

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 postclosure period of a repository (DOE, 1988; Crowe et al., 1983a). Final resolution of an 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 regional extent of young (2.9 million years old) silicic volcanism located 100 km northwest of Yucca Mountain (Figure 1). The potential for future basaltic volcanism is more difficult to define. The Yucca Mountain site is located in a diffuse zone of basaltic activity named the Death Valley/Pancake Range volcanic zone (Figure 1; DOE, 1988; Crowe et al., 1986). This zone has been active intermittently since about 6.5 million years ago (Ma), and volcanic activity in the zone may possibly have extended into the Holocene. Four Quaternary volcanic centers (approximately 1.2 million years old) 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, about 45 km northwest of Yucca Mountain. The youngest known 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-phased approach will be used in evaluating the hazards of future basaltic volcanism for the Yucca Mountain site (Crowe, Vaniman, and Carr, 1983a; Crowe, 1986), with the second approach developed from the data foundation of the first. First, standard geologic studies combining field mapping, geochronology, paleomagnetic determinations, geochemistry, and geophysical data will provide comprehensive information 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

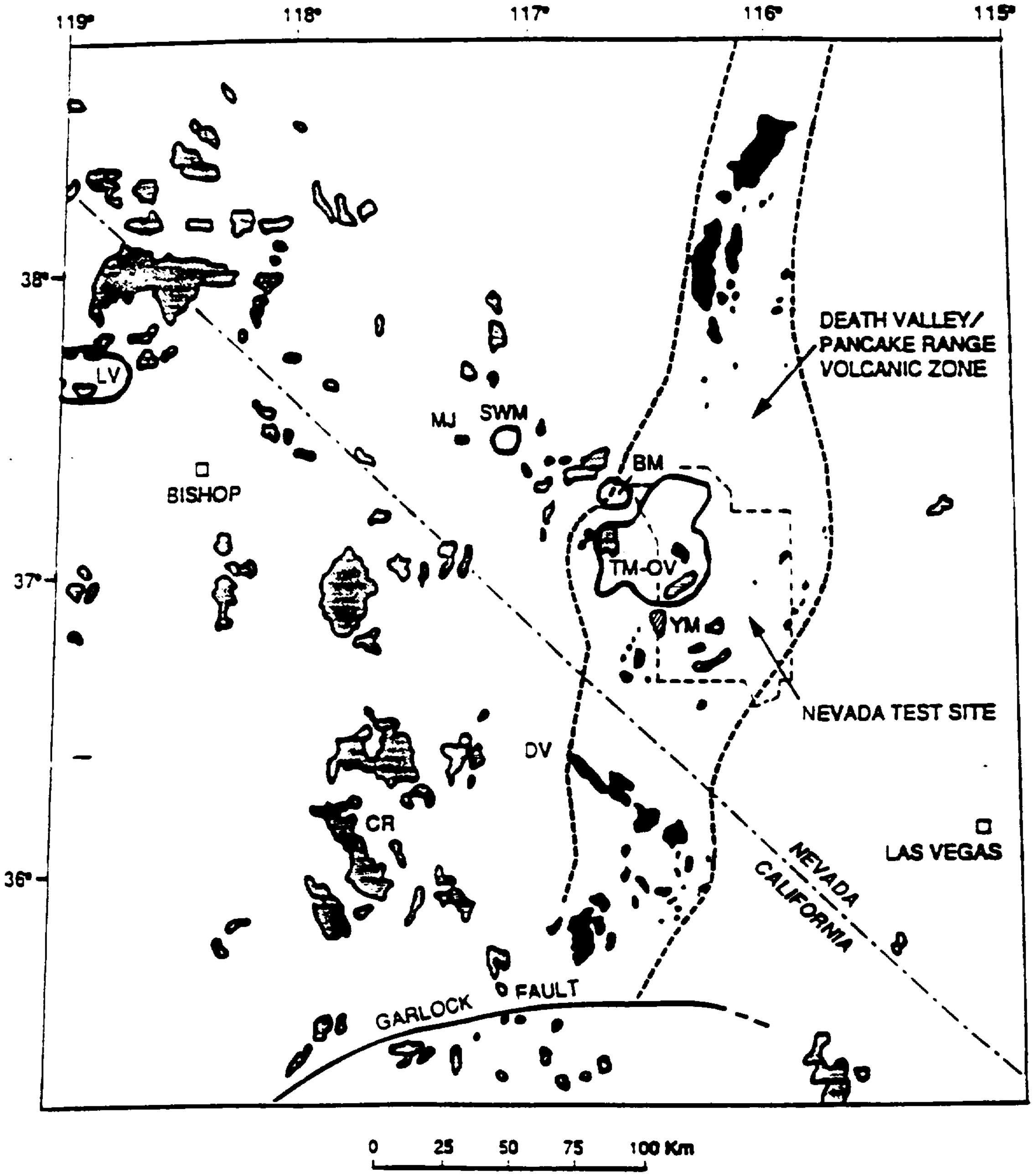

Figure 1. Distribution of post-Miocene silicic (stippled) and basaltic (black) volcanic rocks of the southern Great Basin. Basaltic rocks are inferred to be part of the Death Valley/Pancake Range volcanic zone (Crowe, Vaniman, and Carr, 1983a; Crowe, 1986). An alternative interpretation is that the zone may consist of three unrelated, complex volcanic fields: (1) the Lunar Crater-Reveille range volcanic fields, (2) basaltic and silicic volcanic rocks of the Timber Mountain-Oasis Valley/Black Mountain-Stonewall Mountain volcanic fields, and (3) basaltic and silicic volcanic rocks of southern Death Valley. 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.

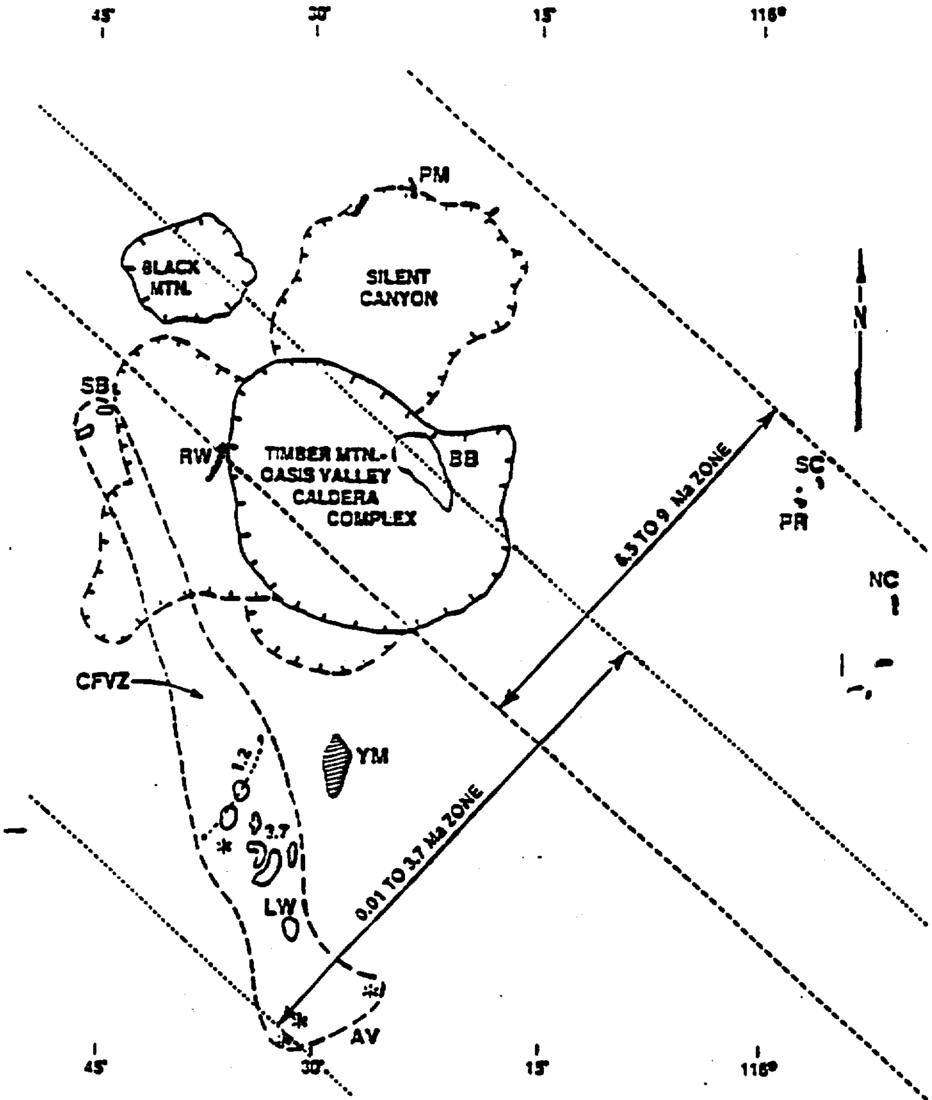

Figure 2. Generalized geologic map of the distribution of the youngest episodes of basaltic volcanism in the Yucca Mountain region. The outlines of the major silicic caldera complexes are shown for scale. The dashed lines spanned by arrows bound the distribution of the older episode of basaltic volcanism; the dotted lines spanned by arrows bound the distribution of the younger episode of basaltic volcanism. The northwest trend of the bounding lines follows the trend of structural elements of the Walker Lane tectonic system in this region; these trends are not defined by the distribution of basaltic volcanic rocks. CFVZ: Crater Flat volcanic zone (Crowe and Perry, 1990); AV: aeromagnetic anomalies of Amargosa Valley; LW: Lathrop Wells volcanic center; 3.7: 3.7-million-year-old Pliocene basalt centers of southwest Crater Flat; 1.2: 1.2-million-year-old basalt centers of Crater Flat; NC: basalt of Nye Canyon; PR: basalt of Paiute Ridge; SC: basalt of Scarp Canyon; BB: basalt of Buckboard Mesa; RW: basalt of Rocket Wash; SB: basalt of Sleeping Butte, including Hidden Cone and Little Black Peak Cone; PM: basalt of Pahute Mesa. Stars are the approximate center of aeromagnetic anomalies inferred to represent buried basalt centers.

consequences of future basaltic volcanism affecting the Yucca Mountain site. The results of past volcanic hazard assessment 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., 1983a and 1983b; Crowe, 1986; Crowe et al., 1986; Crowe et al., 1989; Crowe and Perry, 1990). All work for this study plan is Quality Assurance (QA) Level I unless otherwise noted. Existing data will be qualified as QA Level I on a case-by-case basis if it is judged to be needed in support of a licensing application for the Yucca Mountain site.

This study plan is subdivided into five activities, as follows:

- Investigations, using exploratory drilling, of aeromagnetic anomalies that may indicate the presence of buried basaltic volcanic centers or shallow intrusive rocks of basaltic or silicic composition (Activity 8.3.1.8.5.1.1, Volcanism Drill Holes).

- Refinements of the geochronology of volcanic events in the Yucca Mountain region with an emphasis on basaltic volcanic rocks of Quaternary age. Multiple age measurements using a variety of isotopic and radiometric methods, with cross-checking of results by correlated-age methods, are needed to evaluate and document the detailed geochronology of Quaternary volcanic events (Activity 8.3.1.8.5.1.2, Geochronology Studies).

- Refinements of the field relations and eruptive history of Quaternary basaltic volcanic centers in the Yucca Mountain region (8.3.1.8.5.1.3, Field Geologic Studies). Work in progress suggests that individual centers may have formed through multiple eruptive events separated by significant time intervals (polycyclic volcanism) (Crowe et al., 1989). The studies for this activity will (1) provide samples for Activities 8.3.1.8.5.1.2, 8.3.1.8.5.1.4, and 8.3.1.8.5.1.5; (2) attempt to establish the field relations and eruptive history of Pliocene and Quaternary basalt centers of the Yucca Mountain region; and (3) examine the distribution of post-Miocene silicic volcanism in the southwest Great Basin.

- Evaluations of the geochemistry of eruptive sequences at Quaternary basalt centers in the Yucca Mountain region (Activity 8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences). These deposits need to be studied to characterize geochemically the volcanic units identified from field geologic studies, to define the range of geochemical variations in volcanic units at polycyclic volcanic centers, and to model geochemically the processes of derivation and evolution of basaltic magma. Data from these studies will be used to evaluate the origin and geochemical evolution of basaltic volcanic centers, to constrain the composition of potential future eruptions, and to attempt to identify possible sources of volcanic ash that is interbedded with alluvium in the Yucca Mountain area. This identification will provide age control for ash deposits exposed in trenches cut across faults.

- Assessment of the evolutionary patterns of basaltic volcanic fields of the southwest United States (Activity 8.3.1.8.5.1.5, Evolutionary Patterns of Basaltic Volcanic Fields). This activity will examine spatial, eruptive volume, effusion rate, and geochemical patterns of volcanic fields. These data will be used to evaluate whether there are systematic patterns that could indicate the evolutionary stage of volcanic fields of the Basin and Range province. If these patterns exist, they will be compared to the patterns of volcanic activity in the Crater Flat volcanic field to attempt to assess the stage of development of that field. Such an evaluation, if successful, could provide a more accurate basis for forecasting the composition and volume of future volcanic activity in the Yucca Mountain area. If unsuccessful, forecasts of future volcanic activity will be based on projections of past volcanic activity.

1.2 Regulatory Rationale and Justification

An important element in assessing the suitability or lack of suitability of the Yucca Mountain site is an assessment of the potential for future volcanic activity. A potentially adverse condition with respect to volcanism was judged to be of concern at the Yucca Mountain site (DOE, 1986b) because of the presence of multiple basalt centers of Quaternary age. Volcanism has been identified as a potentially adverse condition at the site based on the regulatory guidance in 10 CFR 60.111 (NRC, 1986). The performance and design issues calling for data from this study are Issue 1.1, Total System Performance; Issue 1.8, NRC Siting Criteria; Issue 1.9, Higher Level Findings for the Postclosure; and Issue 1.11, Configuration of Underground Facilities for the Postclosure. The information from this study provides data for other studies that respond directly to the regulatory requirements (8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, and 8.3.1.8.1.2, Effects of Magmatic Disruption of the Repository).

The performance and characterization parameters for direct releases resulting from magmatic disruption of a repository and the key studies or activities providing data for these parameters are listed in Table 1.

TABLE 1

ACTIVITIES PROVIDING INFORMATION ON DIRECT RELEASES RESULTING FROM MAGMATIC DISRUPTION OF A REPOSITORY

Performance Parameter	Characterization Parameter	Key Activities
Annual probability of magmatic disruption	Location and timing of volcanic events	8.3.1.8.5.1.1, Volcanism Drill Holes
		8.3.1.8.5.1.2, Geochronology Studies
		8.3.1.8.5.1.3, Field Geologic Studies
		8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences
		8.3.1.8.5.1.5, Evolutionary Patterns of Volcanic Fields
	Evaluation of structural controls of volcanic activity	8.3.1.8.5.1.3, Field Geologic Studies
		8.3.1.8.5.1.5, Evolutionary Patterns of Volcanic Fields
Effects of magmatic disruption of a repository	Strombolian eruptions	8.3.1.8.5.1.3, Field Geologic Studies
	Hydrovolcanic eruptions	8.3.1.8.5.1.3, Field Geologic Studies

2.0 RATIONALE

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

2.1 Activity 8.3.1.8.5.1.1, Volcanism Drill Holes

2.1.1 Technical Rationale and Justification

Studies for evaluating the potential of future volcanic activity in the Yucca Mountain region are dependent on the provision of a detailed characterization of the past record of volcanism. One concern with providing the appropriate information for this characterization is the possibility of missing data because of burial of volcanic centers in alluvial basins. The volcanism drill holes activity will evaluate the presence or absence of volcanic or intrusive rocks that may be concealed beneath sediments of the alluvial valleys. The rationale for obtaining this information is to ensure that volcanic risk assessment is based on an adequate characterization of the volcanic record of the Yucca Mountain region. Information from this work will be used to evaluate the potential for future silicic volcanic activity and in Study 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository.

High-quality aeromagnetic data have been obtained for the Yucca Mountain region (Kane and Bracken, 1983), showing a correlation between sites of highly magnetic surface basaltic volcanic rocks and aeromagnetic anomalies. These data also reveal the presence of aeromagnetic anomalies that may be produced by intrusive rocks or buried remnants of volcanic deposits formerly exposed at the surface. The anomalies include a lobate, positively magnetized, aeromagnetic anomaly located in the central part of Crater Flat between and west of the Black Cone and Red Cone basalt centers; a large, dome-shaped, negatively polarized, aeromagnetic anomaly located along the west-central edge of Crater Flat; a positively polarized, aeromagnetic anomaly located immediately south of Little Cones; a negatively magnetized aeromagnetic anomaly with a peripheral magnetic high located south of the town of Amargosa Valley; and two, possibly three, aeromagnetic anomalies in the central part of the Amargosa Valley (Kane and Bracken, 1983; USGS, 1978).

Investigation of the origin of the aeromagnetic anomalies is possible using geophysical techniques or exploratory drilling. Exploratory drilling with recovery of core from penetrated rock intervals of significance provides the only direct means of identifying with a high degree of certainty the origin of the magnetic anomaly. Moreover, recovery of core permits samples to be obtained so that the rocks can be dated using isotopic methods and petrologic studies can be conducted. Geophysical investigations (ground-based gravity and magnetic studies) will be undertaken with the exploratory drilling. These studies are judged to be a necessary supplement to, but not a replacement for, exploratory drilling. The age of the rocks is needed for revised probability calculations (Activity 8.3.1.8.1.1.4; Section 2.4), and petrologic studies are needed for correlation with the study of the evolutionary cycles of basaltic volcanic fields (Activity 8.3.1.8.5.1.5; Section 2.5).

Exploratory drilling of the aeromagnetic anomaly sites, with recovery of core samples of volcanic rocks encountered in the drill holes, is necessary to constrain the origin of the anomalies. The stratigraphy of the drill hole will be established from study of the drill core and correlated to drill hole depths. The magnetic polarity of the anomalies will be established by measurement of core using a flux-gate magnetometer. Age determinations of recovered core will be obtained using the potassium-argon (K-Ar) method if the ages of the drill core samples are in a range suitable for application of this isotopic system. If the drill core samples are suspected or shown to be less than 100,000 years old, consideration will be given to applying one or several of the developmental geochronology techniques that are summarized under Activity 8.3.1.8.5.1.2 of this study plan (Section 2.2). Petrographic analysis will be conducted on the drill core, noting phenocryst and groundmass mineral assemblages, textures, and presence or absence of alteration minerals. After petrographic analysis, the core will be submitted for major and selected trace element analysis. Isotopic analysis of the core may be obtained for selected isotopes. The se-lection of isotopic systems for analysis will depend on the results of studies from Activities 8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences, and 8.3.1.8.5.1.5, Evolutionary Patterns of Volcanic Fields (Sections 2.4 and 2.5). Isotopic analysis of core will be completed if the information is judged to be important for assessing the geochemical evolution of volcanic centers or volcanic fields of the Yucca Mountain region.

2.1.2 Constraints

Exploratory drilling will be conducted outside of the exploratory block and controlled area of Yucca Mountain. No potential impact is anticipated on the site from the drilling activity. The anomaly sites are separate geographically, so that no interferences are expected from activities at the individual drill hole sites. The drill holes will be completed sequentially to provide time for preliminary analysis of data from each hole before proceeding with subsequent holes. Because drilling time is short (weeks), the time required for the drilling program is not expected to be a significant constraint. If exploratory drilling proves unsuccessful in establishing the origin of the aeromagnetic anomalies, analysis of the bore hole and ground-based geophysical data will be conducted. This analysis will be used to determine if a second drill hole is needed or if the aeromagnetic anomaly can be shown not to be produced by the Pliocene or Quaternary volcanic rocks in the Yucca Mountain region.

2.2 Activity 8.3.1.8.5.1.2. Geochronology Studies

2.2.1 Technical Rationale and Justification

A significant new development in volcanism studies, first recognized in late 1986, is the possibility that the scoria cone of the Lathrop Wells volcanic center is significantly younger than associated lava flows (Wells et al., 1988). Further studies have shown that at least three and possibly more of the seven Quaternary volcanic centers in the region exhibit polycyclic activity (brief periods of eruptive activity separated by a few thousand to a few tens of thousands of years of inactivity (Crowe et al., 1989). What needs to be resolved for the Pliocene and Quaternary volcanic centers of the Yucca Mountain region is the detailed chronology of eruptive events and the duration of periods of inactivity. The chronology of volcanic events will be used to establish magma effusion rates for calculating the probability of magmatic disruption of a repository (Study Plan 8.3.1.8.1.1).

A focused geochronology effort is needed to obtain these data, involving application of the conventional K-Ar method, supplemented by developmental work using other radiometric methods (described below). We are following a repetitive approach for establishing the age of volcanic activity through the geochronology studies. That is, the establishment of a chronologic framework of volcanic events will be based on the application of multiple isotopic and radiometric methods with cross-checking using correlated-age techniques. The chronology of volcanic units will be considered to be established with an acceptable degree of certainty when convergent results are obtained from the different but repetitive approaches.

A problem requiring further evaluation is the inconsistent data that have been obtained from the K-Ar age determinations of lava flows from the Lathrop Wells center and the two Quaternary basalt centers of Sleeping Butte. The results of current studies show significant variance between age determinations, with large analytical uncertainties for individual measurements. Replicate K-Ar ages of the individual lava units may exhibit, however, an apparent reproducible age when a variance weighting data reduction routine is used. The inconsistent results of K-Ar age determinations may necessitate the use of other sample-processing techniques for K-Ar age determinations (mineral separations versus whole rock) or the application of other isotopic methods ($^{40}Ar/^{39}Ar$) to resolve the age of the lava flows.

Two additional problems will be evaluated in the geochronology studies. First, it is extremely important to maximize the accuracy of the geochronology measurements because the chronology data are used to calculate magma effusion rates (x-axis error bars) for the probability calculations (Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository). This may be achieved through a combination of increasing the number of K-Ar determinations (larger value for n); using complementary isotopic methods such as $^{40}Ar/^{39}Ar$, which may provide increased analytical precision (Lanphere, 1988); or applying alternative methods (described below). Second, we have experienced difficulties in obtaining consistent results for K-Ar age determinations of identical samples that have been submitted to separate analytical laboratories (Sinnock and Easterling, 1982). We plan to submit sample splits for K-Ar age determinations to two independent laboratories to investigate the reproducibility of the results.

Additional K-Ar ages are needed for all known Pliocene and Quaternary basalt centers in the Yucca Mountain region to ensure that the chronology of these centers is correctly established. These centers include, in addition to the Lathrop Wells and Sleeping Butte volcanic centers, the four 1.2-Ma Quaternary centers of Crater Flat and the 3.7-Ma basalt centers of Crater Flat. The regulations of 10 CFR 60 (NRC, 1986) suggest that studies of the past record of volcanism should be concentrated on rocks of Quaternary age. That suggestion is generally followed in this study plan. However, the 3.7-Ma basalt centers of Crater Flat represent the first eruptive products of an inferred cycle of basaltic activity (Crowe and Perry, 1990). These rocks will be studied for site characterization activities to ensure that the full record of volcanic activity is used in probability studies. Multiple age determinations are needed for each of these centers to document the age of the centers and to provide confidence in the statistical reproducibility of the ages.

More comprehensive geochronology studies are needed to resolve the question of whether the Pliocene and Quaternary volcanic centers exhibit polycyclic eruptive behavior. Resolution of this question will require assessment of the results of K-Ar and $^{40}Ar/^{39}Ar$ measurements as well as the application of an additional set of methods (described below). The exact number of age determinations for each center cannot be specified now. This will depend on the reproducibility of the individual isotopic and radiometric age determinations, the comparison of results for different isotopic and radiometric methods, and the complexity of the eruptive sequence at each volcano. We estimate from the reproducibility of past age determinations and the known complexity of individual centers that between 5 and 15 age determinations will be needed for each volcanic center. Our goal is to obtain a coherent, geologically defensible set of geochronology measurements for each center.

Additional geochronology studies will be required to establish the ages of scattered basalt sites in the Yucca Mountain region. These sites include the basalt dike of Solitario Canyon, scattered basalt interbedded with Tertiary gravel southeast of Yucca Mountain, basalt penetrated in existing drill holes in southeast Amargosa Valley, and any presently unstudied basalt in the region that may be of Pliocene age or younger. The basalt dike of Solitario Canyon has been dated at about 10 Ma (Crowe, Vaniman, and Carr, 1983a). We intend to obtain additional isotopic-age determinations of the basalt to verify the K-Ar age because the dike is so close to the proposed Yucca Mountain repository location.

The types of additional measurements to be made for the geochronology studies are divided into numerical-age methods, calibrated-age methods, and correlated-age methods, following the classification of Coleman, Pierce, and Birkeland (1987). Numerical-age methods include the isotopic ^{238}U-^{230}Th disequilibrium and $^{3}He/^{4}He$ methods and radiometric methods such as thermoluminescence (TL). Calibrated-age methods include progressive landform modification, soil-profile development, and rock-varnish development. Correlated-age methods include paleomagnetism, field geologic, and tephrochronology studies. These methods are judged to be the most likely to constrain successfully the ages of the basaltic volcanic centers and eruptive events of individual centers in the Yucca Mountain region. If the methods prove unsuccessful or the results inconsistent, there are a variety of other isotopic methods that may in turn be considered. These include but are not limited to ^{238}U-^{226}Ra disequilibrium measurements, other cosmogenic isotopic methods (^{36}Cl, ^{10}Be, ^{26}Al, ^{21}Ne), and ^{14}C dating of rock varnish.

The ^{238}U-^{230}Th disequilibrium measurements are feasible using existing mass spectrometry instrumentation at Los Alamos National Laboratory (LANL). A current limitation of this application is obtaining mineral separates from fine-grained basalt samples with different uranium and thorium ratios to establish an isochron. The techniques for efficient mineral separation are being developed. The $^{3}He/^{4}He$ measurements are feasible using static noble-gas mass spectrometry because of the extreme sensitivity of this technique. The TL-age method has been successfully applied to obtaining ages of archaeologic sites and more recently to sediments in the age range of from 500 to 100,000 years old. With careful selection of samples (surface-exposed soils buried by scoria, sands overlain by aa lava flows), the TL-age method appears promising for age estimates of young volcanic events in the Yucca Mountain region. Preliminary measurements of the TL age of buried soil deposits interbedded with scoria-fall deposits at the Lathrop Wells center indicate the technique is promising for establishing the chronology of young (<50,000 years old) volcanic units of this and other volcanic centers.

The geomorphic parameter and the soils-profile development studies provide semi-independent tests of the reliability of isotopic dating techniques. (These calibrated-age methods are considered to be semi-independent because they conceivably could be tested against the same volcanic sites that were used to establish calibrations. Because of this interdependency, investigators will be careful to avoid using the calibrated-age methods in this way.) These studies have been successfully applied to basaltic volcanic rocks in the Cima volcanic field of the Mojave Desert (Dohrenwend, Wells, and Turrin, 1986). These rocks are similar in age, chemical composition, and geographic and environmental setting to the basaltic volcanic rocks of the Yucca Mountain region.

Measurement of the direction and polarity of remanent magnetization of volcanic units is an accepted technique for establishing the relative ages of volcanic units at a complex volcanic center or field (Tanaka et al., 1986; Kuntz et al., 1986). The geomagnetic field changes as a result of secular variations, which occur at a geologically rapid rate and permit assignment of volcanic units to groups of dissimilar or similar paleomagnetic field directions. Other relative-age methods include field mapping and tephrochronology studies (Activity 8.3.1.8.5.1.3, Field Geologic Studies; Section 2.3).

An unpublished ^{14}C age of about 19,000 years has been obtained for varnish scraped from volcanic bombs at the summit of the Lathrop Wells scoria cone (Dorn, 1987). This age determination is in close agreement with preliminary considerations of the probable age of the formation of the scoria cone. However, the origin and maturation history of carbon in varnish are highly uncertain, and so we regard this single age as unverified. Additional ^{14}C dating and analytical evaluation of the origin and development of carbon in varnish may be undertaken.

2.2.2 Constraints

All samples for geochronology studies will be obtained from outside of the Yucca Mountain site and controlled area (see Activity 8.3.1.8.5.1.3, Field Geologic Studies, for a description of sampling techniques; Section 2.3). No potential impacts on the site from this activity have been identified. The precision and accuracy of isotopic and radiometric methods will provide two constraints. First, the precision and accuracy of the individual measurement procedures and the half-life of the respective isotopic systems will limit the application of the specific measurements. The current approximate estimations of the minimum age limits for the methods are about 100,000 to 200,000 years for K-Ar ages, 5000 to 10,000 years for the ^{238}U-^{230}Th and $^{3}He/^{4}He$ methods, and between 500 and 1000 years for TL ages. Second, the accuracy of isotopic and radiometric ages will partly define the uncertainties of calculations of the magma effusion rate for probability calculations. These constraints are described in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository. Some of the isotopic methods are in a developmental stage, which will result in increased uncertainty in applying and interpreting the results of the analytical measurements. To limit this uncertainty, we will attempt to obtain convergent results between at least two independent isotopic or radiometric methods and use a range of calibrated-age methods to cross-check the results. Current results from the isotopic, radiometric, and calibrated-age methods suggest that the time required for developmental work for these methods should not have an impact on the schedule of volcanism studies. We cannot predict now possible timing impacts if we are unable to obtain convergent results with the isotopic methods. Should this occur, we would follow the logic presented in Figure 8.3.1.8-2 of the SCP (1988).

2.3 Activity 8.3.1.8.5.1.3, Field Geologic Studies

2.3.1 Technical Rationale and Justification

The technical rationale for the field geologic studies is threefold. First, the collection of samples for geochronology studies will be completed as part of this activity. Second, geologic mapping in association with geochronology measurements (Section 2.2) will be used to establish the geologic relations and eruption history of basaltic centers of the Yucca Mountain region. Field geologic studies provide information on the relative ages, the distribution of erupted volcanic material, and the eruption dynamics of the basaltic volcanic centers. Third, field studies will be made on a regional scale of the distribution and field relations of post-Miocene silicic volcanic centers in the Yucca Mountain region. These studies will be part of an assessment of the potential for future silicic volcanic activity.

All the Pliocene and Quaternary volcanic centers (except the basalt of Sleeping Butte and Buckboard Mesa; Figure 2) were mapped at a scale of 1:12,000 on black-and-white aerial photographs (Vaniman and Crowe, 1981). However, the recognition of the possibility of polycyclic volcanism and the requirement for more detailed geochronology data make it important to reexamine the field geologic relations of the Pliocene and Quaternary volcanic centers. Geologic mapping will be extended from the volcanic centers out into the adjacent bedrock, where appropriate, to evaluate structures that may be controlling the location of the basalt centers. The information from the field geologic studies will be used (1) to test for consistency of isotopic and radiometric ages; (2) to provide data for calculation of the magmatic volumes of eruptive deposits (Study 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository); (3) to provide data on structural controls of individual basalt centers for that study, and (4) to provide data on basaltic eruption parameters for Study 8.3.1.8.1.2, Effects of a Magmatic Disruption of the Repository.

Field geologic studies will include geologic mapping of contact relations of volcanic units, tephra studies in soil pits, development of the eruptive history of individual centers, studies of the occurrence and distribution of volcanic crystal fragments in rock varnish, studies of the development of rock varnish on volcanic units, measurement of the geometry (thickness, extent, width) of volcanic deposits, and an evaluation of the original geometry and distribution of older volcanic deposits that have been partly removed by erosion.

Field geologic studies provide the fundamental tool for obtaining information about the stratigraphic sequence and distribution of the volcanic deposits associated with individual volcanic centers or clusters of volcanic centers. The contact relations provide information on the relative ages of volcanic events and can be used to reconstruct the sequence of eruptive events. The distribution of volcanic crystal fragments in rock varnish provides information on the relative age and dynamics of the youngest volcanic eruptions. Mapping of the development of rock varnish on volcanic units can be used to test the validity of the relative ages of geologic units established from field geologic mapping. The geometry of volcanic units will be used in Activity 8.3.1.8.1.1.1, Location and Timing of Volcanic Events; a reconstruction of the geometry and distribution of eroded volcanic deposits is needed for volume calculations in that activity. There are no recognized alternatives to field geologic studies that can be used to obtain the required information.

2.3.2 Constraints

Field geologic studies are a non-surface-disturbing activity. No potential impacts on the site are expected from the work. The information collected by this activity must be sufficiently accurate to identify all major volcanic units ("major" being defined as a measure of the volume of the volcanic unit), to place these units into a correct relative age sequence, and to collect samples for geochronology studies that are correlated to the volcanic units. The precision of the field studies is largely governed by the scale of the geologic mapping. The mapping of Lathrop Wells volcanic center is at a scale of 1:4000. Aerial photographs for the Sleeping Butte and Quaternary volcanic centers of Crater Flat will be obtained at a scale of 1:5000 and 1:6000, respectively. The Pliocene volcanic units of southeastern Crater Flat will be remapped at a scale of 1:6000, using color aerial photography. The mapping scales are judged to allow for adequate precision to obtain the information needed for the field geologic studies. The time requirements for geologic mapping are not a significant constraint.

2.4 Activity 8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences

2.4.1 Technical Rationale and Justification

The possibility of polycyclic activity at the Lathrop Wells center and at other Quaternary volcanic centers of the Yucca Mountain region suggests that eruptive events at individual centers may have been produced by separate batches of basaltic magma (separate batches of magma are required where the time between eruptions exceeds the cooling time of small-volume magma pulses in the shallow crust). A standard approach to studying the geochemistry of basaltic volcanic centers is to sample and analyze only the lavas of the centers and assume that the chemistry of these lavas represents the compositional range of magma associated with these centers. For polycyclic volcanic centers, this assumption may not be correct. The eruption of an individual magma batch may produce only scoria deposits without associated lava flows, and multiple magma batches may have contributed to the formation of the volcanic center. For these reasons, characterization of the magma that produced a polycyclic center requires that all major eruptive units, including both scoria deposits and lavas, be sampled and analyzed. Basaltic scoria deposits, because of their high glass content and high porosity, tend to be easily altered by weathering processes and exposure to volcanic gases near vent areas. As a consequence, these deposits are rarely sampled and analyzed.

Major and selected trace element and isotopic data will be used to attempt to understand, through geochemical modeling, the processes leading to the formation and eruption of multiple pulses of magma at polycyclic centers. An understanding of the formation of polycyclic centers obtained from geochemical data may increase understanding of geochemical patterns of volcanic activity. This may provide constraints on predictions of the composition of future volcanic activity and would be used in assessments of the probability of future eruptions at these volcanic centers. In addition, geochemical studies of eruptive units can provide an independent tool for correlating eruptive units at a volcanic center to unravel the eruptive history of a center.

Basaltic ash occurs as infilling of fractures and in alluvium exposed in trenches cut across faults around the Yucca Mountain site. The most likely source of this basaltic ash is one or several Quaternary basalt centers in the Yucca Mountain region. Correlation of ash deposits in the trenches with a volcanic source could provide information on the age of faulting, where suitable stratigraphic data are present to constrain age relations (Activity 8.3.17.4.6.2, Evaluate Age and Recurrence of Movement on Suspected and Known Quaternary Faults). The geochemical studies of eruptive units at the Quaternary volcanic centers will provide data on the composition of scoria and ash units from the centers.

Samples of all major eruptive events at Quaternary centers (including Lathrop Wells, Crater Flat Centers, and Sleeping Butte) in the Yucca Mountain region will be obtained. Soil pits, constructed around the flanks of scoria cones as part of the geochronology studies, will provide exposure of older tephra units that have been buried by younger volcanic deposits. These samples will be analyzed for their major and trace element compositions using x-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) techniques. Thin section analysis will be done, using transmitted, polarized, and reflected light for petrographic studies. Electron and proton microprobe analyses will be completed for the major and trace element analyses of mineral and glass constituents. Mass spectrometry will be used for conventional isotopic analyses of a selected suite of isotopic systems. The logic for choosing the isotopic systems for analysis will be based on the results of geochemical modeling, the need for data to evaluate mantle source regions and processes of magma generation and evolution, and the results of regional isotopic studies of volcanic fields of the southwest United States (Activity 8.3.1.8.5.1.5, Evolutionary Patterns of Basaltic Volcanic Fields; Section 2.5).

XRF and INAA are standard techniques for analyzing the major and trace element composition of volcanic rocks. Petrographic analysis and electron microprobe studies are standard techniques for conducting petrologic and mineral chemistry studies. The proton microprobe will be used to obtain trace element data of individual ash grains for basalt ash correlation studies. This is one of only a few analytical techniques that can provide trace element analyses of individual ash grains at part-per-million levels. Conventional mass spectrometry measurements will be used for isotopic analysis. A large range of analytical techniques is available for obtaining major and selected trace element data for volcanic rocks. The XRF and INAA techniques have become standard for analyzing geologic samples. Because of the standardization and acceptability of these techniques, they are preferred for this study plan. They provide acceptable precision and accuracy for the geochemical modeling of this activity. The number of samples analyzed for the geochemistry studies of eruptive sequences cannot be specified with certainty. It is dependent primarily on the number of recognized eruptive units at volcanic centers, and secondarily on the results of geochemical modeling. Our current goal is to collect replicate samples for each unit so that the number of samples per unit equals or exceeds the number of mapped geologic units (determined data matrix).

2.4.2 Constraints

Geochemistry studies of eruptive sequences are needed to identify the major, selected trace element, and isotopic compositions of basalt magma for individual eruptive events at the Quaternary volcanic centers in the Yucca Mountain region. All sites for collection of samples are outside the exploration block and controlled area of Yucca Mountain. There will be no impacts on the site from this activity. A potential constraint is the ability to analyze ash grains with a sufficient degree of accuracy to correlate ash deposits in trenches with possible source vents. The proton microprobe has sufficient analytical precision and accuracy to obtain data for ash correlations. However, preliminary data suggest the ash grains are chemically heterogeneous. Because of this, it may be difficult to provide a data set that allows unique correlation of ash-fall events and their source vents for ash deposits in the trenches. The time required for the geochemistry studies is not expected to have an impact on the schedule of the volcanism studies.

2.5 Activity 8.3.1.8.5.1.5, Evolutionary Cycles of Basaltic Volcanic Fields

2.5.1 Technical Rationale and Justification

Prediction of rates of future volcanic activity is based fundamentally on evaluating and extrapolating past patterns of volcanic activity into the future. It is important to assess the continuity of past patterns and to determine if any evidence of changing patterns is recorded in the geologic record. Continental volcanic fields of the western United States (e.g., the Basin and Range province) show considerable evidence that the processes leading to the birth, evolution, and termination of fields are transitory. The lifetime of activity of basaltic volcanic fields generally appears to be bounded by the range of 1 to 10 million years, with most of the fields active for intervals of 3 to 6 million years. Some basaltic volcanic fields are now considered to be inactive (such as the Saline volcanic field in eastern California and the Springerville volcanic field in Arizona). Other basaltic volcanic fields provide clear evidence of spatial migration of activity through time (the San Francisco Peaks volcanic field in Arizona, basaltic volcanism along the Wasatch Front in Utah, the Lunar Crater volcanic field in Nevada). Some fields may be in developmental stages where rates of volcanism can be expected to increase in the future (the Big Pine volcanic field and the Coso Volcanic field in California). The detailed causes of episodes of basaltic volcanism cannot be proved with certainty but are inferred to be related on a regional scale to tectonic-thermal events leading to episodes of mantle melting.

DRAFT

The approach for this activity is to examine the evolutionary stages of basaltic volcanic fields of the southwestern United States to determine if there is any evidence of systematic patterns of development. If these patterns can be recognized and documented, they will be tested against the volcanic record of the Yucca Mountain area. The purpose of this testing is to determine if the volcanism of the Yucca Mountain region is in a recognizable stage of evolution. If this can be established, it provides a potentially improved basis for extrapolating future trends of volcanic activity for the Yucca Mountain region for probability calculations.

Measurement parameters for this activity include determination of the chronology and duration of volcanic activity in volcanic fields of the southwestern United States. The chronology will be established primarily by K-Ar age determinations of volcanic units, supplemented, if required, by other geochronology techniques described in the geochronology studies (Activity 8.3.1.8.5.1.2; Section 2.2). These chronology studies will provide the framework to divide the volcanic fields into major episodes of activity for calculating magma effusion rates. The magmatic volume of the major volcanic episodes will be determined by compiling geologic maps of the geographic distribution of volcanic units and measuring the thickness of those units. The major and selected trace element geochemistry of the volcanic units will be determined by obtaining XRF and INA analysis of representative samples of the volcanic fields.

The K-Ar method for estimating the ages of volcanic rocks is an established standard for determining the chronology of volcanic activity of volcanic fields. Geologic mapping with field measurement of the stratigraphic thickness of volcanic units is the accepted procedure for determining the magmatic volume of volcanic rocks. Measurement of the magmatic volume of basalt units provides a means of assessing the magnitude of volcanic activity through time. Determination of the major and selected trace element composition of volcanic rocks coupled with geochronology data allows an evaluation of the trends in geochemical composition of volcanic fields through time.

2.5.2 Constraints

All studies for this activity will occur outside of the exploration block and controlled area of Yucca Mountain. No impact on the site is expected from the studies. A major constraint for this study is determining how much information is needed at how many volcanic fields. We will be unable to undertake detailed studies of all the volcanic fields of the southwestern United States. A major source of information for many of the volcanic fields of the western United States is the existing geologic literature. That information will be utilized to expedite the schedule of this activity, supplemented by studies associated with this activity that are required to obtain a consistent data set. We estimate that a nearly complete data set may be available for many of the volcanic fields of the southwest United States. The precision and accuracy of field and geochronology data obtained for this study are described in Sections 2.3.2 and 2.2.2, respectively, of the study plan. The precision and accuracy of volume calculations are described in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository.

3.0 DESCRIPTION OF TESTS AND ANALYSES

3.1 Activity 8.3.1.8.5.1.1, Volcanism Drill Holes

3.1.1 Approach

High-quality aeromagnetic data have been obtained for the Yucca Mountain region (USGS, 1978; Kane and Bracken, 1983), showing a correlation between sites of highly magnetic surface basaltic volcanic rocks and aeromagnetic anomalies. These data also reveal the presence of aeromagnetic anomalies that may be produced by intrusive rocks or buried remnants of volcanic deposits formerly exposed at the surface. These anomalies include a lobate, positive aeromagnetic anomaly located in the central part of Crater Flat between and west of the Black Cone and Red Cone basalt centers. This magnetic anomaly was drilled as part of earlier site characterization activities (drill hole USW VH-1; Carr, 1982a). The exploratory drilling penetrated buried basalt lava (reversely polarized) that was dated at about 3.7 million years old (Carr, 1982b). These lavas are correlated with the 3.7-million-year-old basalt unit that crops out in southeastern Crater Flat (Vaniman, Crowe, and Gladney, 1982). Because the 3.7-million-year-old basalt is reversely polarized, it cannot be the source of the positive magnetic anomaly. The exploratory drilling showed, however, that the anomaly is not associated with the Pliocene or Quaternary volcanic rocks of the Crater Flat area. Carr (1982a) speculates that the positive anomaly may be produced by a thickened section of the Bullfrog Member of the Crater Flat Tuff.

A second anomaly is a large, dome-shaped, negative aeromagnetic anomaly located along the west-central edge of Crater Flat (Kane and Bracken, 1983). The probable source of this anomaly was penetrated in drill hole USW VH-2. A sequence of reversely polarized basalt lava was cored in this hole at a depth of about 360 m beneath the surface (Crowe et al., 1986). This basalt was dated at about 11 million years old (Carr, 1984). Because of the similarities in major and trace element geochemical analysis and the matching reversed magnetic signatures, Crowe et al. (1986) correlated the 11-million-year-old basalt in USW VH-2 with a surface basalt located at the south end of Crater Flat (K-Ar age of 10.5 million years; Carr, 1981). Crowe et al. (1986) noted that the surface basalt site is marked by a zone of negative magnetization on the aeromagnetic map of Kane and Bracken (1983). This negative magnetic anomaly extends as an arcuate trough from southern Crater Flat, west-northwest to beneath the Little Cones volcanic center in southwest Crater Flat, and north to the negative magnetic anomaly west of USW VH-2. This suggests that the west and southwest edge of Crater Flat is underlain by 10.5- to 11-million-year-old, negatively magnetized basalt.

A third, positive, aeromagnetic anomaly is present immediately south of Little Cones (Kane and Bracken, 1983). This anomaly has been interpreted to represent a buried basalt center (Crowe and Carr, 1980; Carr, 1982a; Kane and Bracken, 1983).

A fourth aeromagnetic anomaly is present beneath the alluvial deposits of the Amargosa Valley, directly south of the town of Lathrop Wells (Kane and Bracken, 1983; Figure 2). This anomaly is a sharply bounded magnetic low with a peripheral magnetic high. The composite anomaly was interpreted to represent a dipole effect from a shallow buried single source (Kane and Bracken, 1983). The amplitude and width of the anomaly suggest that it could be produced by an extensive basalt lava, by a buried rhyolite center, or by an intrusive body of basaltic or rhyolitic composition.

Two or possibly three additional aeromagnetic anomalies (two positive, one negative) are present in the Amargosa Valley (USGS, 1978; Figure 2). Two are located 15 km southwest of the anomaly south of Lathrop Wells previously discussed; the other is 10 km west of these two anomalies. Two of these anomalies exhibit a dipole effect, suggesting a shallow depth of burial.

Pending evaluation of ground-based geophysical data, each of the anomaly sites will be drilled, and continuous core of volcanic rock encountered in the drill holes will be recovered. The precise location of the drill holes will be determined from modeling and analysis of ground-based gravity and magnetic data for each anomaly site (for a description of the geophysical studies, see Activity 8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site, in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository). The thickness of volcanic units in each drill hole, the areal extent of each magnetic anomaly, and the geophysical modeling will be used to estimate the subsurface volume of the buried volcanic or intrusive rocks. The volume data will be combined with the results of K-Ar age determinations to add the information from the anomaly sites to the cumulative magma volume/time curve being developed for the Yucca Mountain region. The magma volume/time curve is used to establish magma effusion rates for probability calculations. These procedures, including discussion of the geophysical modeling of the aeromagnetic, gravity, and ground-based magnetic data, are described in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository.

3.1.2 Summary of Methods

Magnetic polarity, petrographic, major element chemistry, and selected trace element and isotopic chemistry data will be obtained for representative samples of the volcanic material. Magnetic polarity measurements require only preserving identified top and bottom segments of the drill core. Oriented samples are not needed for core from the volcanism drill holes.

One drill hole will be drilled at each of the anomaly sites. The exact location of the drill hole will be determined from analysis of the anomaly from geophysical data. We will attempt to locate the drill hole to penetrate the predicted most favorable section of the anomalies to maximize information to be obtained from the drill hole. Continuous core will be obtained from the drill holes, using standard drilling and coring techniques as outlined in the drilling plans (TWS-INC-7-3/86-5).

Detailed drilling plans will be completed for V-3 through V-5 six months before the start of exploratory drilling. The drilling program will follow the established drilling procedures of the Department of Energy (DOE) support contractors.

A major priority of the drilling plan is to core continuously both the upper and lower contact of any volcanic or intrusive rocks so that the nature of the contact relationships can be determined. This is the primary basis that will be used to establish the extrusive or intrusive origin of any volcanic or subvolcanic rocks in the drill holes. Information to be obtained from the drilling program includes (besides the nature of the upper and lower contacts) establishing the presence or absence of volcanic or subvolcanic rocks, the depth of volcanic or intrusive rocks, the presence of stratigraphic contacts within volcanic or intrusive rocks, the lithology of volcanic or intrusive rocks (lava flows, flow breccia, scoria, intrusive breccia, border phase of an intrusive, intrusion interior), and the thickness of volcanic or intrusive lithologies. The thickness and lithology of volcanic rocks, combined with the results of geophysical modeling, will be used to estimate the continuity of units in the subsurface.

Core samples from the drill hole will be logged and stored at the Sample Management Facility. Representative samples will be selected from the drill core for laboratory studies. The selection of samples will be based on visual and binocular examination of the core for lithologic representativeness and presence or absence of secondary alteration. K-Ar ages will be obtained for a minimum of two samples of the drill core per drill hole, following the procedures described in Activity 8.3.1.8.5.1.2, Geochronology Studies; Section 3.2.2.1. If the rocks are younger than or suspected to be younger than 100,000 years old, alternative geochronology measurements, besides conventional K-Ar determinations, will be obtained. Samples of core will be prepared for geochemical analysis by powdering 50 to 100 g of sample in a hardened-steel-ball mill. Whole rock, major element, and selected trace element (strontium, rubidium, and zirconium) chemistry of core samples will be determined by XRF for at least six samples per drill hole. Additional selected trace element chemistry will be determined by INAA for at least three samples per drill hole. The trace element suite for analysis will be the same as specified in Activity 8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences (Section 3.4). Strontium and neodymium isotopic compositions of one sample selected from each drill hole will be determined by solid-source mass spectroscopy. Additional isotopic studies may be required, depending on the results of other studies (see discussion in Section 2.1.1). Thin sections of core samples will be cut into doubly polished mounts. Petrographic characteristics of the volcanic rocks will be determined from the thin section mounts using transmitted, polarized, and reflected microscopy.

3.1.3 Procedures

The following procedures will be used in this activity:

- drilling procedures described in TWS-INC-7-3/86-5;

- Thin Section Preparation Procedure, TWS-ESS-DP-04 (standard procedure);
- Procedure for X-Ray Fluorescence Analysis, TWS-ESS-DP-111 (standard procedure);
- Preparation of Powders from Rock, Cinder, and Ash Samples, TWS-N5-DP-605, R0 (standard procedure);
- Potassium-Argon Dating, NWM-USGS-GCP-06;
- Nevada Test Site Core Petrography Procedure, TWS-ESS-DP-03 (standard procedure);
- Procedure for Volcanism Field Studies, TWS-EES-13-DP-606 (standard procedure) (revised version in technical review);
- strontium and neodymium isotopic procedures (to be prepared when the drilling schedule is established);
- procedures for geophysical investigations for this activity are referenced in Study Plan 8.3.1.8.1.1, Probability of a Volcanic Eruption Penetrating the Repository;
- procedures for exploratory drilling will be implemented through DOE contractors following drilling requirements specified in a Criteria Letter.

3.1.4 Accuracy and Precision

XRF analyses generally have an accuracy and precision of better than 5% for major elements and better than 10% for selected trace elements (strontium, rubidium, and zirconium) that are present above their detection limits. INAA routinely gives accuracies and precision of better than 10% for the elements of interest. Strontium and neodymium isotopic analyses give precision of better than 0.005% with accuracies determined (and analyses corrected if needed) by analysis of standards from the National Institute of Standards and Technology (NIST). The accuracies and precision of the analytical techniques are considered adequate for the purposes of this activity.

3.1.5 Equipment

All the equipment, laboratory facilities, and analytical procedures (with two exceptions, INAA and mass spectrometry measurements) for these studies are now available. This equipment includes

- Olympus petrographic microscopes with capabilities for thin section studies under conditions of transmitted, polarized, and reflected light; one microscope is equipped with photomicrograph capabilities and an automated point-counting stage;
- thin section preparation facilities for constructing 30-micron slides for petrographic studies and polished 30-micron slides for electron microprobe analysis;
- rock-crushing facilities for crushing geologic samples for XRF and INAA;
- sample fusion facilities for preparing glass pellets for XRF analysis;
- Rigaku automated XRF unit for major and selected trace element analysis;
- electron microprobe for major element mineral chemistry;

- potassium/argon instrumentation:
  - 10-cm-radius gas source Reynolds-type mass spectrometer,
  - Kepco high-voltage power supply,
  - filament power supplies,
  - Bell 640-G meter,
  - Carry 401-mV vibrating reed electrometers,
  - magnetic field controller,
  - computer-instrumentation interface,
  - Fluke high-voltage power supply and voltage divider,
  - ion gauges and Ganvill-Phillips controllers, and
  - dual-extraction bottle glass extraction/vacuum systems; and
- California Electronic Model 70 Fluxgate magnetometer.

A research reactor and gamma-ray-counting facilities, including calibration programs, are available at LANL. However, INAA procedures have not been standardized for basaltic volcanic rocks using our equipment. We will contract these analyses to an external laboratory (commercial vendor) that has an established reputation for performing high-precision INAA of geologic samples. The measurement techniques for strontium and neodymium isotopic analyses have been used at LANL. However, the chemical separation facilities and the mass spectrometry instrumentation are not now optimized for these isotopes. We will contract these isotopic analyses to the University of Colorado, Boulder, where a Finnigan-Matt, fully automated, six-collector, solid-source mass spectrometer is available.

3.1.6 Data Analysis

Information from the drilling program and studies of the drill core will be summarized in a drill hole report, which will present a stratigraphic column of any volcanic or intrusive rocks noted in the drill hole. The K-Ar age measurements will follow conventional techniques. If additional chronology studies are required, we will follow the methods described in Activity 8.3.1.8.5.1.2, Geochronology Studies (Section 3.2). Major element data will be listed as oxide percentages, and normative mineralogy will be calculated as an oxide percent and a cation percent. These calculations will use the computer program IGPET, Version 1.1 (Carr, 1986). Evaluation of major and selected trace element data will be through a combination of construction of bivariate graphical plots, evaluation of Pearce diagrams, and application of the computer subroutines of the commercially available programs MAGMA86, Version 1.2 (Hughes, 1987), and IGPET, Version 1.1 (Carr, 1986). Supplemental analysis of geochemical data for fractionation modeling will use the published fractionation code EQUIL (Nielsen, 1985). Statistical analysis of the geochemical data (univariate and multivariate) will use the computer program SYSTAT, Version 4.1 (Wilkinson, 1988). Drill hole, major and trace element, and isotopic data will be archived on a computer using a commercially available data-base system. The computer systems used for these calculations are MS-DOS compatible computers with numeric coprocessors. Data reduction and analysis of geophysical data for this activity are described in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository.

3.1.7 Representativeness

A source of uncertainty for this study is the degree to which the age, volume, and chemical composition of a volcanic center or intrusive rocks are represented by core recovered from a single drill hole. If the aeromagnetic anomalies are produced by buried volcanic centers, we would expect the buried centers to be similar geologically to the exposed volcanic centers of the Yucca Mountain region. They may have formed during multiple eruptive phases and may have been active for a time span approaching 100,000 years. If this is the case, a single drill hole will probably not provide sufficient information to represent the volcanic evolution of the volcanic center. However, the implications of this concern are dependent on the age and volume of the buried volcanic centers. If the centers are older than 2 million years and the volumes do not cause changes in the cumulative magma volume/time curve for the Yucca Mountain region, a single drill hole should provide sufficient information. If the volcanic rocks are younger than 2 million years or change the volume/time curve a sufficient amount to affect calculations of volcanic recurrence rates, additional exploratory drilling may be required at individual sites to provide a more representative sample population.

There are several possible geologic units that may provide the source of the aeromagnetic anomalies. These include the following. (1) The anomalies may be produced by buried basalt units (older than 9 million years) of the silicic episode (Crowe, 1986). These basalt units have been reported in drill holes in the Amargosa Valley (chemical analysis referenced in Crowe et al., 1986). Such basalt units, if present and verified by drilling and geochronology studies, would have no effect on probability calculations for the Yucca Mountain site. They would be considered in models of regional volcanic patterns of the Yucca Mountain region. (2) The anomalies may be produced by buried basalt centers of Pliocene or Quaternary age. The significance of these basalt units for probability calculations is dependent on the age and volume of the individual basalt centers. (3) The anomalies may be produced by basaltic intrusive volcanic rocks. The significance of these rocks is dependent on the age and volume of the intrusive rocks. (4) The anomalies may be produced by buried silicic volcanic centers or silicic intrusive rocks. The significance of these rocks is dependent on the age of the silicic rocks. Any silicic rocks found that are significantly younger than 7.7 million years (the age of the Thirsty Canyon Tuff of the Black Mountain caldera) would necessitate a reassessment of the potential for recurrence of silicic volcanism.

3.2 Activity 8.3.1.8.5.1.2, Geochronology Studies

3.2.1 Approach

The purpose of this activity is to establish the detailed chronology of basaltic and silicic volcanism in the Yucca Mountain region. The data obtained through this activity will be used to refine the chronology of basaltic volcanism in the Yucca Mountain region and to revise, where appropriate, calculations of the magma effusion rate for the probability calculations (Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository). Geochronology studies of basaltic volcanic centers have been under way for several years. The results of these studies are summarized in Chapter 1 of the SCP (DOE, 1988). The primary approach of this activity is twofold. First, the age of basaltic volcanism in the Yucca Mountain region must be measured and documented with the maximum confidence possible. Second, enough geochronology measurements (including repetition of measurements and use of alternative measurement techniques) are needed to provide the maximum precision and accuracy of the techniques. These measurements will constrain the x-axis error bars on a plot of cumulative magma volume versus time for the Yucca Mountain region.

Additional K-Ar age determinations are needed for several problems. First, the age and accuracy of K-Ar age determinations needs to be established for each Pliocene and Quaternary volcanic center in the Yucca Mountain region. Multiple K-Ar ages have been obtained for many of the Quaternary volcanic centers (Crowe, Johnson, and Beckman, 1982; Vaniman, Crowe, and Gladney, 1982; DOE, 1986b). Further work is needed to obtain a uniform level of data coverage for each center. Second, one of the perplexing problems with K-Ar ages is the difficulty of obtaining coherent data sets for samples analyzed at different laboratories. Sinnock and Easterling (1983), for example, submitted samples of basalt collected from the basalt sites in the Yucca Mountain region to three separate analytical laboratories and obtained widely varying chronological results. We intend to obtain duplicate K-Ar age determinations at two separate analytical laboratories to determine the variability of results from different laboratories and to attempt to obtain a coherent and reproducible set of K-Ar age determinations (USGS K-Ar laboratories and the Berkeley Geochronology Center). Third, one of the key problems described in the field geologic studies activity of this study plan (Section 2.3) is the possibility of polycyclic eruptive patterns at the Quaternary and Pliocene centers of the Yucca Mountain region. K-Ar ages may be suitable for documenting age differences of separate cycles of activity at the 1.2- and 3.7-million-year-old basalt centers of the region. A number of K-Ar ages are needed to evaluate the chronology of volcanic activity at these centers.

It is important to establish the age of the youngest volcanic events in the Yucca Mountain region. The youngest events now recognized are small-volume scoria eruptions at the Lathrop Wells and Hidden Cone volcanic centers (Figure 2). These eruptions mantled cone slopes and immediately adjacent areas of existing scoria cones at both centers. The last eruption of the Lathrop Wells scoria cone is estimated to have occurred less than 20 ka (thousand years ago) (Wells et al., 1988; Crowe et al., 1988) and possibly less than 10 ka. These volcanic events are too young to be dated by the conventional K-Ar method. Multiple techniques are being developed to attempt to date the youngest volcanic events and to refine the K-Ar chronology of the Quaternary volcanic centers in the Yucca Mountain region. These methods include ^{238}U-^{230}Th

disequilibrium measurements using solid-source mass spectrometry, measurement of the $^3He/^4He$ ratios of surface volcanic rocks, and TL-age measurements. These methods were chosen from a suite of possible geochronology methods because they are judged to have the maximum chance of success for estimating the ages of the volcanic rocks in the age range of 5000 to 100,000 years.

The age of the youngest silicic volcanic activity in the Nevada Test Site (NTS) region, with emphasis on the Black Mountain caldera or young silicic rocks encountered in volcanic drill holes, needs to be determined. The hazards of future silicic volcanism are considered to be negligible (Crowe, Vaniman, and Carr, 1983a), based in part on the Miocene age of the youngest silicic volcanic center, the Black Mountain caldera complex. Noble et al. (1984) and Weiss, Noble, and McKee (1989) have shown that the zoned ash flow sheets of the Black Mountain center were erupted over a very short period, defined by K-Ar ages, of about 7.7 Ma. Younger silicic volcanic centers are also associated with a northwest-trending zone of potassic and peralkaline volcanic centers extending from Black Mountain to Stonewall Mountain (Noble et al., 1984; Weiss and Noble, 1989; Figure 1). The Stonewall Flat tuff at the northwest end of this cluster of centers has K-Ar ages of about 6.3 Ma. A Pliocene rhyolite center (2.9 Ma) has recently been identified at Mount Jackson, west of Stonewall Mountain (McKee, Noble, and Weiss, 1989). This center is located about 100 km northwest of Yucca Mountain and is the youngest silicic volcanism in the region. Pliocene rhyolite centers may be present in the Monte Cristo Range, in association with the Stonewall Mountain volcanic center, and in the Greenwater Mountains adjacent to the southwest part of Sarcobatus Flat. Additional work (literature review, field and geochronology studies) may be required to evaluate the significance of the occurrence of possible Pliocene silicic volcanism in the Yucca Mountain region. The spatial distribution of Pliocene silicic volcanic centers needs to be placed into the regional perspective with associated sites of silicic volcanism along the western Cordillera rift zone (Smith and Luedke, 1984) and the time-space patterns of migration of silicic volcanism (Stewart, Moore, and Zietz, 1977; Stewart, 1978). If silicic volcanic rocks are encountered in any of the volcanic drill holes, they need to be dated and incorporated in descriptions of the volcanic record of the Yucca Mountain region.

A range of calibrated-age methods will be used to test the consistency of age determinations. These methods include evaluation of the stages of geomorphic degradation of scoria cones and lava flows, evaluation of the degree of soil-profile development on volcanic units, paleomagnetic studies of volcanic units, and studies of the development and geochemical maturity of rock varnish on volcanic units. These calibrated-age methods will be applied cautiously in cross-checking the geochronology results. They will be used primarily to judge whether the results of isotopic and radiometric dating are consistent with the relative age assignments of volcanic units developed from the field studies.

3.2.2 Test Methods

A number of tests will be performed for the geochronology activity. For clarity, each test method will be described separately.

3.2.2.1 Potassium-Argon Age Determinations

The basaltic volcanic rocks of the Yucca Mountain region will be dated primarily by the K-Ar and $^{40}Ar/^{39}Ar$ methods. These are established techniques, described in many papers and textbooks (Dalrymple and Lanphere, 1969; Faure, 1977; Dalrymple and Lanphere, 1971). Multiple age determinations will be obtained for the Pliocene and Quaternary volcanic centers, which include the Lathrop Wells center, Little Cones, Red Cone, Black Cone, Northern Cone, the two basalt centers of Sleeping Butte, and the older basalt episode of Crater Flat. We will obtain separate ages of lava flows at the Pliocene and Quaternary volcanic centers when the results of field studies and relative dating techniques indicate the groups of lava flows may differ significantly (a few tens of thousands of years) in age. Special attention will be focused on obtaining statistically consistent ages for the lava flows of the youngest volcanic centers. Some additional K-Ar ages may be required for silicic volcanic rocks of the Mount Jackson, Stonewall Mountain, and Grapevine Mountain areas.

The technical procedures to be followed are

- potassium-argon dating procedures, described in NWM-USGS-GCP-06; and
- procedures for $^{40}Ar/^{39}Ar$ measurements, to be completed 60 days before the start of work using this technique.

3.2.2.2 Single-Crystal $^{40}Ar/^{39}Ar$ Age Determinations

A single-crystal laser fusion method for determining the $^{40}Ar/^{39}Ar$ ratios of volcanic rocks is being developed through a cooperative laboratory effort with the United States Geological Survey (USGS) Geochronology Laboratory and the Berkeley Geochronology Center. This technique may be used to date basalt and silicic samples obtained from the field geologic studies. The initial application of the $^{40}Ar/^{39}Ar$ method will be to test the feasibility of applying the technique to whole rock samples of basalt. If the technique is judged to be suitable for the geochronology studies, detailed procedures will be developed. These procedures will be in place 60 days before the start of QA Level I work.

3.2.2.3 ^{238}U-^{230}Th Disequilibrium Age Determinations

Specialized isotopic-dating techniques for determining the crystallization age of scoria deposits are needed to date volcanic events younger than 100,000 years. Eruptive events of this age are inferred to be present at the Lathrop Wells and Hidden Butte volcanic centers. Age determinations for rocks of this age will be attempted through uranium series disequilibrium measurements for minerals or phases separated from basalt samples. This technique is based on the chemical fractionation that can occur during geochemical processes and lead to radioactive disequilibrium between uranium parents and some daughter nuclides. For example, ^{238}U can fractionate from its daughter ^{230}Th during magma formation, which makes it possible to date young (<400,000 years old) rocks by measuring the extent of deviation of ^{230}Th from secular equilibrium.

The ^{238}U-^{230}Th dating systematics are based on developing an isochron by plotting $^{230}Th/^{232}Th$ versus $^{238}U/^{232}Th$ for cogenetic minerals or mineral phases of a basalt. The slope of the isochron is proportional to the time elapsed since crystallization. Precise measurements of the thorium and uranium isotope ratios are necessary to constrain the slope of the mineral isochron and to obtain accurate ages of young basalt. These measurements have generally been made using alpha decay counting. However, significant improvements in sensitivity (smaller sample size) and precision can be obtained using solid-source mass spectrometry for the measurements.

Future developmental work will be necessary to obtain high-purity mineral or mineral-phase separates with different U/Th ratios. Scoria and volcanic bomb samples will be collected from the Lathrop Wells volcanic center. These samples will be crushed, and minerals (olivine, plagioclase, and iron-titanium oxides) will be separated using a combination of techniques (hand-picking with a magnet, magnetic separation, and heavy-liquid separations). The present ionization efficiency of the measurements is adequate if it is assumed that reasonable amounts (0.5 to 2 g) of separates can be obtained. If the mass spectrometry procedure is successful and a precise isochron is established, the resulting age determinations will provide the crystallization ages of the youngest volcanic events in the Yucca Mountain region. The developmental work on the mass spectrometry technique for uranium disequilibrium measurements will be covered by TWS-QAS-QP-3.5, Procedure for Documenting Scientific Investigations. When the procedures have been adequately established and the technique has been judged to have a high probability of obtaining a precise crystallization age, detailed procedures will be written. These procedures will be in place 60 days before the start of QA Level I work.

3.2.2.4 Measurement of the ^{3}He Accumulation in Basaltic Volcanic Rocks

Helium-3 is produced in exposed rock outcrops at the surface of the earth by two nuclear processes. The first is cosmic-ray-induced spallation of the major elements, and the second is capture of thermal neutrons by ^{6}Li to produce tritium, which decays to ^{3}He. The ^{3}He concentration has been measured at the surface of lava flows from the Mauna Loa volcano in Hawaii with known ^{14}C ages. The helium isotopic concentrations are consistent with the ages of the lavas, assuming a theoretical production rate of cosmogenic ^{3}He (Kurtz, 1986). These results indicate measurement of ^{3}He is feasible to establish the surface exposure ages of young basaltic volcanic rocks. The major unknown for this technique is the calibrations of the production rate of cosmogenic ^{3}He. Current research to establish the production rates is in progress and appears promising.

The concentration of ^{3}He and $^{3}He/^{4}He$ ratios will be determined by static gas-source mass spectrometry for mineral separates of olivine from scoria collected from selected Quaternary volcanic centers of the Yucca Mountain region. Samples will be collected from surface outcrops that are inferred to have not been significantly eroded or buried by surficial deposits since the time of emplacement. This judgment will be based primarily on the degree of geomorphic preservation of volcanic landforms and the position of outcrops relative to sites of active erosion or deposition. Selected surface outcrops will be drilled to a depth of approximately 1 m using a portable rotary drill. This core will be used to evaluate the ^{3}He profile to determine if the sample site has been stable. Samples and core obtained from the drilling will be returned to LANL and sectioned for sample preparation.

A major effort for the helium work will be calibration of the ^{3}He production rates for the Yucca Mountain area as a function of longitude, latitude, elevation, and time. We plan for this calibration to be accomplished primarily through comparison with volcanic sites of established K-Ar age. However, current results using conventional K-Ar methods may not be sufficiently accurate to provide well-constrained calibrations. We may have to calibrate the ^{3}He production rate using isotopic measurements from the $^{40}Ar/^{39}Ar$ method coupled with results of TL ages for younger volcanic events (<50,000 years old). Special attention will be given to calibration of the $^{3}He/^{4}He$ production rates independent of the ^{238}U-^{230}Th age determinations because we will be attempting to cross-check the results of the two techniques for consistency. An additional concern with the helium work is the possibility of helium loss from diffusion. This problem may be mitigated by choosing coarse-size splits of olivine (this may not be possible for the Lathrop Wells center) and cross-checking the helium measurements with measurements of ^{21}Ne.

The developmental work on the $^{3}He/^{4}He$ studies will be performed according to TWS-QAS-QP-3.5, Procedure for Documenting Scientific Investigations. Technical procedures for the $^{3}He/^{4}He$ measurements will be developed at LANL when the measurement techniques have been adequately established and are judged to have a high probability of obtaining surface exposure ages of sufficient accuracy to use for probability calculations. These procedures will be in place 60 days before the start of QA Level I work.

3.2.2.5 Thermoluminescence Properties and Age Determinations

The TL technique directly dates quartz and feldspar mineral grains by reflecting the time since the sediment was last exposed to sunlight (Wintle and Huntley, 1980). Exposure to sunlight for at least 8 hours eliminates (bleaches) any inherited TL signal. This effectively resets the TL clock to "zero." If the sediment is buried and shielded from further light exposure (by extrusion of lava flows or deposition of tephra), nuclear radiation (primarily from the decay of uranium, thorium, and their daughter products, and potassium) progressively imparts a TL signal. This radiation ionizes electrons of mineral grains, which are subsequently trapped at lattice-charged disequilibrium sites called electron traps. Heating during laboratory analysis or in the natural environment (from emplacement of lava flows) or exposure of the sediment to natural sunlight causes vibration of the mineral lattice and eviction of electrons from the traps. Some of these electrons are conducted to recombination sites from which light is emitted. It is the intensity of this light signal that can be measured to quantify the time since burial of the mineral grain.

During the past decade, the TL technique has provided chronological control in a variety of geologic settings for sediments less than 100,000 years old (Forman, 1989). Only recently has the method been successfully extended to geologic studies in the Basin and Range province (Forman et al., 1989). Preliminary analysis of buried soil horizons (AV soil horizon) from the Crater Flat and Cima volcanic fields indicates that the method has the potential for providing chronological control on volcanic events during the past several hundred years to possibly 250 ka.

Preferred materials for TL dating are buried soils or sediments that have been shielded from further light exposure by emplacement of lava flows or deposition of tephra or sediments. Initial analyses will be conducted on samples of fine-grained (4- to 11-micron), polymineral separates. If necessary, we will either optically or physically separate individual quartz and feldspar components for TL analysis. Laboratory procedures will be similar to those outlined in Forman et al. (1989). Principally, we will use the total (Singhvi, Sharma, and Agrawal, 1982) and partial (Wintle and Huntley, 1980) bleach techniques. All samples will be tested for anomalous fading, which undetected could reduce the accuracy of age estimates by 10% to 20%. Error analysis will follow the procedures of Aitken (1986).

An early focus of the TL dating research will be to test the accuracy of the TL technique by dating radiocarbon localities in cores of Lake Mojave, California. The sediments in this lake basin are similar in mineralogy and genesis to sampled stratigraphic horizons in soil units of the Yucca Mountain region. Additionally, a series of modern soil horizons will be dated to ascertain the residence time of fine silt in soil and the maximum resolution of the technique.

The developmental work on the TL technique will be performed according to TWS-QAS-QP-3.5, Procedure for Documenting Scientific Investigations. Detailed procedures for the TL technique will be developed when the TL procedures are judged to a reasonable degree of confidence to provide reliable estimates of the chronology of volcanic events in the Yucca Mountain region. These procedures will be in place 60 days before the start of QA Level I work.

3.2.2.6 Measurement of Scoria Cone and Lava Flow Geomorphic Parameters

Geomorphic research at the Cima volcanic field has shown that progressive erosional degradation of scoria cone slopes and the development of soils on volcanic features can be calibrated for young volcanic fields (Dohrenwend, Wells, and Turrin, 1986). Time curves based on K-Ar age determinations of volcanic rocks were developed at this volcanic field for many geomorphic features. These curves can be used to evaluate approximate ages of volcanic centers and also to establish relative ages of closely spaced volcanic centers. These techniques will be applied to the Quaternary volcanic centers of the Yucca Mountain region, including Lathrop Wells, Little Cones, Red Cone, Black Cone, Northern Cone, and the Sleeping Buttes cones. Curve calibrations will be based on established K-Ar ages of these centers, and the curves established for this region will be compared with the curves developed for the Cima volcanic field. The major advantages of these tests are (1) they can be used to cross-check the chronology of volcanic centers developed by isotopic measurements, and (2) for individual centers in which past environmental conditions were similar (closely spaced features), relative correlations of geomorphic parameters and soil development can be established to test concepts of polycyclic volcanism.

Specific measurements to be made for the volcanic centers include cone height, cone width, cone slope length, maximum slope angle, tangent of the maximum slope angle, apron length, apron slope, drainage frequency, and maximum gully incision (geomorphic parameters). The following technical procedures will be developed for the geomorphic work:

- Procedure for Volcanism Field Studies, TWS-EES-13-DP-606 (standard procedure) (revised version in technical review); and
- Procedure for Geomorphic Studies of Volcanic Landforms (in preparation; to be in place 60 days before the start of QA Level I work).

3.2.2.7 Soils Studies

A large number of published studies demonstrate that the degree of soil development on progressively older landforms typically increases systematically (Birkeland, 1984; Catt, 1986; Buol, Hole, and McCracken, 1989). Without numerical ages for soil parent materials, pedologic data provide relative-age information. However, if numerical-age information can be obtained for soil parent materials, calibrated ages may be obtained for pedologic data (Colman, Pierce, and Birkeland, 1987). Moreover, pedologic data for soil from a given study area can be compared with pedologic data for soils for which numerical-age control is available, a procedure that makes possible derivation of correlated ages in addition to calibrated ages (Colman, Pierce, and Birkeland, 1987). Pedologic dating techniques will be used to derive ages for volcanic landforms and deposits of the Yucca Mountain region by comparing the degree of soil development in this region to that observed in the Cima volcanic field. Several recent studies in this arid region provide numerical-age constraints for volcanic landforms and volcanic deposits that are similar to those in the arid Yucca Mountain region. In order to further evaluate the rates of soil development in the Yucca Mountain region, pedologic data will be collected from other volcanic fields, such as the Lunar Crater field in central Nevada. Specific measurements to be made in the soils of selected study areas include (1) morphologic features (structure, color, field consistency, clay films, mottles, pore development, carbonates, salts, horizon thickness, boundary geometry); and (2) textural, chemical, and mineralogic properties (clay, silt, and sand content of the fine-earth fraction, bulk density, carbonate, soluble mineralogy).

Besides the above measurements, we will attempt to collect pedogenic carbonate and submit samples of it from selected soils and soil subhorizons for isotopic analysis, which may make possible radiometric dating of carbon in this material (Quade, Cerling, and Bowman, 1989) and paleoenvironmental evaluation of the pedologic environment (Cerling et al., 1989).

The following technical procedures will be followed or developed for the soil studies:

- Procedure for Volcanism Field Studies, TWS-EES-13-DP-606 (standard procedure) (revised version in technical review); and
- Procedure for Laboratory Studies of Soils (in preparation, anticipated completion date 3/90).

3.2.2.8 <u>Paleomagnetic Studies</u>

Studies will be conducted on the remanent magnetization of volcanic units identified from field mapping for the Pliocene and Quaternary volcanic units of the Yucca Mountain region. Samples will be collected using a portable rock drill, following the procedures described by Doell and Cox (1965) and McElhinny (1973), except that a sun compass will be used for core orientation. Approximately 6 to 12 samples will be collected per sample site. Outcrops at the sample site will be carefully examined to ensure collection of samples that have not been rotated by volcanic or geomorphic processes after cooling. The number of sample sites at individual volcanic centers will vary with the complexity of eruptive sequence of the individual volcanic centers. We will work in an iterative fashion between the paleomagnetic and the field geologic studies. Volcanic units will be mapped in the field, then sampled and analyzed for remanent magnetization directions. The directions will be compared for the individual units. The assumption for the paleomagnetic studies is that the geomagnetic field changes at a geologically rapid rate (about 4 degrees per century; Champion and Shoemaker, 1977) and is recorded in the rocks during the cooling of volcanic deposits. Measurement of the remanent magnetization direction permits assignment of field units to groups that have similar and dissimilar field magnetic directions. We will group the mapped field units according to the directional populations and compare those groups with the volcanic units from field mapping. Paleomagnetic studies will also be used to focus geochronology studies. Priority will be given to obtaining age determinations for volcanic units that have different field magnetic directions.

The following technical procedure is in effect and will be followed for the paleomagnetic studies at the USGS:

- Rock and Paleomagnetic Investigations, GPP-06, R0 (effective date, 11/01/84).

3.2.2.9 Rock-Varnish Studies

Studies will be conducted of the ^{14}C and the cation ratio compositions of rock varnish on basaltic volcanic rocks. These studies will be applied to a range of tectonic and Quaternary geologic investigations and will also be used in Study 8.3.1.8.1.1, Probability of a Volcanic Eruption Penetrating a Repository. Detailed information on the investigations of rock varnish is provided in Appendix A.

3.2.3 Accuracy and Precision

The accuracy and precision of the K-Ar and $^{40}Ar/^{39}Ar$ tests are controlled largely by the potassium content and the age of the volcanic rocks, with additional factors being the abundance of atmospheric argon (particularly for young volcanic rocks), the possibility of excess argon, and the possibility of argon loss. The uncertainties of these techniques are controlled by the quality of the sample, the precision of measurements, and the accuracy of age calibrations. Of these parameters, the quality of the sample and the accuracy (measured by replicate analysis of separate samples) are generally the major variables that control uncertainty. Sample quality can be affected by the loss or gain of argon, the presence of xenocrysts, and the presence of mixed phenocryst populations with different crystallization ages. Error bars are largest for the youngest volcanic rocks, where measurement precision can be the limiting variable. It is necessary to achieve sufficient accuracy to identify the age of major volcanic events for probability calculations. We will attempt to achieve this goal by using the K-Ar method and supplementing and cross-checking the results with the constraints from (1) field geologic studies, (2) geomorphic parameter and soil-profile development studies, (3) paleomagnetic studies, and (4) investigations of rock varnish.

DRAFT

The uranium/thorium series disequilibrium measurements will be affected by the precision of the measurements performed by mass spectrometry--the major factors will be the ionization of ^{230}Th, the purity (different U/Th ratios) of mineral separates, and the degree of U/Th fractionation between the mantle host and the magma. The measurements may additionally be affected by postemplacement mobilization of uranium.

The precision and accuracy of the ^{3}He measurements will be controlled largely by calibration of ^{3}He production rates. These parameters cannot be specified until measurements of basalt samples are initiated and sites are chosen for calibration. Work conducted in Hawaii suggests an uncertainty of about 20% may be reasonable (Kurtz, 1986). A major uncertainty of the method is the selection of samples. It is important to establish that the surface samples have not been buried (provides shielding) or eroded (removes part of the record of ^{3}He production).

The TL method has the greatest potential for dating young (<50,000 years old) volcanic events. The maximum resolution of the TL method is 500 to 1000 years. Errors associated with TL age estimates will be between 5% and 20%, depending on the dispersion in the data set used to constrain the TL growth functions. A potential important constraint on the accuracy of dating of volcanic events using the TL technique is the correlation of TL ages to volcanic events. The time of acquisition of a TL signal must be correlated with volcanic events to enhance understanding of the geochronology of volcanic centers. The primary control for these studies will be the field geologic studies.

The accuracy and precision of calibrated and correlated ages obtained by geomorphic methods cannot yet be specified. Both depend on calibration of stages of volcanic landform degradation to volcanic sites of known chronology. These calibrations are most advanced for geomorphic studies of the Cima volcanic field (Dohrenwend et al., 1986). Preliminary studies of the Quaternary volcanic centers of the Yucca Mountain region indicate the geomorphic parameter-time curves for the Cima volcanic field can be broadly applied to volcanic centers of the Yucca Mountain region (Wells et al., 1988). Studies are in progress to further assess this question. Two approaches will be followed in applying the geomorphic parameter data to geochronology studies. First, the geomorphic parameters of volcanic centers will be evaluated using geomorphic parameter-time curves to provide estimations of the approximate age of the centers. The increments of the age assignments will be dependent on the approximate age of the volcanic center. For example, age estimates for the Lathrop Wells center will be evaluated for intervals of several tens of thousands of years (>20,000, <20,000). Ages of the 1.2-million-year-old centers of Crater Flat will be estimated in increments of several hundreds of thousands of years. Second, the results of radiometric dating techniques will be compared with the age of estimates from geomorphic parameter studies. The application of this technique is illustrated by our present assessment of the age of the Lathrop Wells scoria cone. K-Ar ages of volcanic bombs from the summit of the scoria cone yield ages of greater than 200,000 years. Preliminary results of a TL age of a soil zone exposed in the quarry at the south end of the scoria cone indicate an age of about 15,000 to 20,000 years for most of the cone-forming eruptions. Geomorphic parameter data for the scoria are consistent with an age of probably less than 20,000 years (Wells et al., 1988).

The accuracy and precision of soils studies cannot easily be established. The method is not intended to date events but to provide constraints on the interpretation of the results of isotopic and numerical geochronology methods. A major factor in applying the method is calibration of rates of soil formation for the Yucca Mountain region. We will attempt to calibrate this method using results from the local sites in the Yucca Mountain region but additionally by cross-checking the results of these studies with regional studies by other workers in Quaternary geology. A major uncertainty for this method is how the soil can be correlated to volcanic events with an established chronology. As noted in Section 3.2.1.7, preliminary studies of soils in the Yucca Mountain region indicate that pedologic parameters determined in the Cima volcanic field can be broadly applied in the Yucca Mountain region. Studies in the Cima volcanic field show that pedologic data can be used to evaluate the age of volcanic landforms and deposits that range from 1000 to several hundred thousand years old. Moreover, the availability of age determinations provided by TL, rock-varnish, and ^{14}C analyses of pedogenic carbonate will significantly enhance our ability to calibrate rates of soil development.

The major concerns with paleomagnetic studies are postcooling rotation of samples obtained for the studies. This can normally be recognized by scatter of directions of magnetization on equal-area diagrams of mean directions of remanent magnetization. The precision of the paleomagnetic measurements has been discussed by Kuntz et al. (1986). They noted a confidence circle of 2 degrees or less about the mean remanent magnetization direction for 1292 cores obtained from 100 sites in the Great Rift of Idaho. If an average motion of the geomagnetic field of about 4 degrees per century is assumed, this precision corresponds to a capability of recognition of 50-year time differences. Assuming an additional error term of about a factor of 2 from rotation or tilting of volcanic deposits yields an accuracy of discriminating volcanic units with time differences of 100 years. This accuracy is more than sufficient for the requirements of the geochronology studies.

3.2.4 Equipment

All the equipment needed for the geochronology activity is available at LANL, the USGS, the University of New Mexico, and the University of Colorado. This equipment is listed below:

- potassium-argon equipment:
  - 10-cm-radius gas source Reynolds-type mass spectrometer,
  - Kepco high-voltage power supply,
  - filament power supplies,
  - Bell 640-G meter,
  - Cary 401-mV vibrating reed electrometers,
  - magnetic field controller,
  - computer-instrumentation interface,
  - Fluke high-voltage power supply and voltage divider,
  - ion gauges and Ganvill-Phillips controllers, and
  - dual-extraction bottle glass extraction/vacuum systems;
- ^{238}U-^{230}Th equipment:
  - Frantz magnetic separator,
  - rock grinder,
  - Class 100 clean laboratory,
  - Mettler semimicroanalytical balance,
  - single-focusing NBS-style 12-in. solid-source mass spectrometer,
  - double-focusing NBS-style solid-source mass spectrometer,
  - filament-degassing rig with turbo pump system,
  - HP integral computer,
  - Q-switched CW TM00 18-W Nd:YAG laser with internal cavity,
  - single-frequency CW ring dye laser, and
  - laminar flow hoods for sample dissolution;
- $^{3}He/^{4}He$ equipment:

- static noble-gas mass spectrometer, model MinnMass, serial number 5;
- gas extraction and purification system;
- double-walled vacuum sample melting furnace;
- sample crusher;
- ultra-clean pumping system;
- electron multiplier stack, Serial #5, with associated gas-handling system;
- cryogenically cooled charcoal finger for separation of noble gases; and
- pressure transducers with traceability to NIST standards for calibration;

• thermoluminescence equipment:

  - TL reader including quartz window photomultiplier tube,
  - optical filters,
  - argon evacuation system,
  - multiple sample (20) irradiator with ^{90}Sr and ^{244}Cm sources,
  - thick-source alpha counters,
  - field portable gamma spectrometer,
  - high-speed centrifuge,
  - Mettler balance, and
  - uranium and thorium standards for calibration;

• soils laboratory equipment:

  - mechanical splitters,
  - Mettler balances,
  - Sartorius analytical balance,
  - hot plates,
  - pH meter,
  - conductivity bridge,
  - glassware for analytical routines,
  - desk top centrifuges,
  - mechanical crushers, and
  - hand magnets; and

• paleomagnetic laboratory equipment:

  The equipment used for the paleomagnetic measurements is described in the USGS detailed procedure Rock and Paleomagnetic Investigations, GPP-06, R0.

3.2.5 Representiveness

A major requirement for the geochronology studies is that the methods used record or bound the crystallization age of basaltic volcanic events. All methods selected for this study were chosen from a suite of potential geochronology techniques because they provide the maximum assurance that the measurements are feasible technically and the results represent the ages of volcanic events. Multiple techniques are used so that the results can be compared for consistency. If agreement is obtained on age determinations using multiple isotopic, radiometric, and calibrated methods, a strong case can be made that the measurements properly record the timing of igneous events.

It is not now known with certainty whether any of the geochronology methods will have the required precision or accuracy to provide ages of late Pleistocene or Holocene volcanic events. However, these techniques are judged to have the greatest potential for successfully tackling this problem.

3.3 Activity 8.3.1.8.5.1.3, Field Geologic Studies

3.3.1 Approach

Geologic mapping will be used to provide samples and geologic controls on the stratigraphic relations of samples for most of the geochronology activities. It will also be used to establish the field geologic relationships, volume of erupted volcanic material, and eruptive history of basaltic volcanic centers in the Yucca Mountain region. Emphasis will be placed on reexamining the field relations of the Pliocene and Quaternary volcanic centers in the region to ensure that the major (major being a function of volume) volcanic events have been correctly identified and to determine how common polycyclic activity is for these volcanic centers. A combination of procedures will be used to establish the eruptive history of individual volcanic centers, including conventional field mapping, studies of tephra in soil pits, determination of field magnetic directions of volcanic units (Activity 8.3.1.8.5.1.2, Geochronology Studies; Section 3.2), evaluation of geomorphic degradation and soil development on volcanic units (Activity 8.3.1.8.5.1.2, Geochronology Studies; Section 3.2), and an evaluation of the degree of development of rock varnish on volcanic units (Activity 8.3.1.8.5.1.2, Geochronology Studies; Section 3.2; see also Appendix A). Additional field studies will be required to investigate the distribution and significance of Pliocene silicic volcanism in the Mount Jackson, Stonewall Mountain, and Grapevine Mountains areas. This will involve primarily reconnaissance field studies of possible sites of Pliocene rhyolite volcanism and collection of samples for geochronology studies.

3.3.2 Methods

An important activity for the field geologic studies will be the collection of samples for the geochronology activity. These samples will be collected during geologic mapping and during special sampling trips in conjunction with investigators involved with individual methods for the geochronology activity. Collection of samples will require establishing the stratigraphic relations of sampled units, evaluating the surface outcrops of a volcanic unit to establish sample representativeness, and avoiding secondary alteration. Samples will be located on aerial photographs and described in field notebooks in accordance with the methods described in the detailed procedure for volcanism field studies (TWS-EES-13-DP-606, standard procedure).

Color aerial photography has been obtained for the Lathrop Wells volcanic center at a scale of 1:4000. Color aerial photographs (stereoscopic) will be obtained for the Sleeping Butte volcanic centers (1:5000) and the basalt centers of Crater Flat (1:6000). Geologic mapping of volcanic units will be completed on the aerial photographs, using a combination of interpretation of stereoscopic photographs and tracing of geologic contacts in the field. The mapping will be successively refined using the results of the range of procedures described in Activity 8.3.8.1.5.1.2, Geochronology Studies (Section 3.2). A particularly important tool for this activity is the paleomagnetic studies. Volcanic units with identical field magnetic directions will be inferred to have formed as a single eruptive event. Volcanic units with different field magnetic directions will be inferred to have formed during time-distinct volcanic eruptions. They will be mapped as separate volcanic units, and we will attempt to determine their age using the techniques described in Activity 8.3.8.1.5.1.2, Geochronology Studies (Section 3.2). A preliminary geologic map of the Lathrop Wells volcanic center has been prepared (Crowe et al., 1988) using partial results from previously conducted geochronology studies. The combination of field and geochronology techniques for studying the eruptive history of this center has proven to be extremely effective. Field studies of silicic centers at Mount Jackson, the Grapevine Mountains, the Monte Cristo Range, and the Stonewall Mountain areas will involve field checking of existing geologic maps and an evaluation of geochronology data for the volcanic units. Studies by other workers are in progress (funded through other DOE programs) that may provide some of the field and geochronology information needed for this task.

Geologic mapping on aerial photographs will be transferred to a topographic base map using PG-2 plotters. Geologic maps of the Lathrop Wells and Sleeping Butte volcanic centers will be produced for the following units: bedrock geology, alluvial and soil units, and air-fall tephra units. A bedrock geologic map will be produced for the Pliocene and Quaternary volcanic centers of Crater Flat.

Soil pits and trenches constructed at selected localities in the Pliocene and Quaternary volcanic centers for Activity 8.3.1.8.5.1.3, Geochronology Studies (Section 3.2), will be evaluated as part of the field geologic studies. Trench sites will be selected to validate contact relations of air-fall scoria and geologic units at the Lathrop Wells volcanic center and to expose contacts between units to look for evidence of soils development. We expect to locate trenches in the cinder quarry area at the southeast end of the scoria cone and along the northeast-trending rift zone immediately north of the scoria cone. One or two trench sites will be selected in alluvium deposits immediately adjacent to the Lathrop Wells center. The purposes of the trench sites in alluvium will be to identify the number of tephra units in alluvium, to examine the thickness and development of soil zones between tephra units, and to attempt to correlate tephra units with ash deposits in the trenches at and adjacent to Yucca Mountain (Activity 8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences; Section 3.4; and Activity

8.3.1.17.4.6.2, Evaluate Age and Recurrence of Movement on Suspected and Known Quaternary Faults; Section 3.4).

3.3.3 Procedures

The following procedure will apply to the field studies:

- Procedure for Volcanism Field Studies, TWS-EES-13-DP-606 (standard procedure) (revised version in technical review).

The skill and experience of the field geologist and the scale of the geologic base map are the main parameters that affect the accuracy of a geologic map. ~~The precision of field geologic studies is probably~~ controlled in part by the scale of the geologic map. The planned map scales are judged to be adequate to produce a precise geology map. A high degree of accuracy of the geologic map will be obtained by multiple cross-checking techniques for selecting map units and establishing the eruptive history of the volcanic centers (combined field and geochronology techniques). Additionally, the compiled geologic maps are field-checked for accuracy through field review by independent field geologists.

3.3.4 Equipment

Standard field equipment for geologic mapping is available at LANL. This equipment includes

- Brunton compass;
- Leitz stereoscopic viewer for photogeology interpretation;
- color aerial photographs of the Lathrop Wells volcanic center, including the American Aerial Surveys, Inc., Lathrop Wells VC-Area 25 photography series, scale 1:4000, August 18, 1987, and EG&G's color aerial photographs 5826, scale 1:7370, September 10, 1987;
- black-and-white aerial photographs of the Crater Flat and Lathrop Wells area, including the American Aerial Surveys, Inc., USGS NTS photography series, scale 1:12,000, September 28, 1978;
- color aerial photography of the Sleeping Butte and Crater Flat centers, already flown and processed; and
- PG-2 plotters available through the USGS.

The field geologic data base will consist of geologic relationships recorded on aerial photographs and topographic maps, as well as observations and measurements recorded in field notebooks. Data reduction will involve compiling geologic information on a topographic base map and interpreting geologic relationships for inferring volcanic eruptive mechanisms and the volcanic history of the centers. The geologic maps will be compiled for individual volcanic centers for this activity. Compilation of geologic maps on a regional scale is described in Study Plan 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, Activity 8.3.1.8.1.1.1, Location and Timing of Volcanic Events.

3.3.5 Representativeness

One of the primary limitations of field interpretations of volcanic centers is the degree of preservation of the volcanic deposits, which is a direct reflection of deposit age. In general, the younger deposits are preserved more completely. The Quaternary volcanic centers in the Yucca Mountain region are well preserved, with the exception of the northernmost volcanic center of the 1.2-Ma volcanic sequence in Crater Flat. A second major uncertainty is the volume of scoria-fall deposits that were produced during scoria eruptions. These scoria-fall deposits are removed by erosion, and their original volumes are difficult to estimate. We have modeled and bounded the likely volumes of these scoria-fall deposits based on the geometry and the relations of thickness versus distance of scoria-fall sheets of young and well-preserved basaltic volcanic centers (Crowe et al., 1983b). Trenching will expose buried tephra units around the flanks of the Lathrop Wells and Hidden Cone centers, and we will construct isopachs of the grain size and thickness of tephra units to evaluate the potential volumes of these units, using the tephra volume calculations of Pyle (1989) and Fierstein and Nathenson (1989).

3.4 Activity 8.3.1.8.5.1.4, Geochemistry of Eruptive Sequences

3.4.1 Approach

There are two major approaches to this activity. The first is to sample and analyze the composition of volcanic units recognized from the field geologic studies of the Quaternary basaltic volcanic centers of the Yucca Mountain region. The primary emphasis will be on the Lathrop Wells and Sleeping Butte volcanic centers, the youngest known volcanic centers in the region. We do not currently plan to study the Pliocene basalt of Crater Flat unless the results of field geologic studies indicate that useful information might be obtained from geochemical studies of these centers.

Eruptive units (determined by the field geologic studies) will be sampled and analyzed for their whole rock, major and selected trace element, and mineral compositions in order to understand and document the magmatic evolution of each center. Strontium and neodymium (and possibly lead and oxygen) isotopic analyses may be obtained for selected eruptive units. The choice of isotopic systems for analysis will be based on the results of geochemical modeling and the results of studies from Activity 8.3.1.8.5.5, Evolutionary Patterns of Basaltic Volcanic Fields. Emphasis will be placed on sampling all eruptive units (i.e., both scoria units and lava flows) to ensure that the complete range of chemical variability of eruption products is established. The geochemical data from the complete sequence of eruptive deposits will be used to evaluate geochemical processes of magma formation. Special emphasis will be placed on testing plausible geochemical models that may lead to an increased understanding of the origins of polycyclic volcanic centers. Specifically, are eruptive units at polycyclic centers genetically related, and if so, by what processes? Processes responsible for polycyclic activity may include, but are not limited to, (1) repeated partial melting of a mantle source, (2) fractionation of magma batches in chambers in the lower crust or crust-mantle interface, and (3) polybaric fractionation of magma batches in the mantle and crust. These processes should be distinguishable by analysis of geochemical data (e.g., Allegre and Minster, 1978; Camp and Roobol, 1989). An additional approach to understanding the processes and timing of the ascent of basalt magma from mantle source regions is through analysis of $^{230}Th/^{232}Th$ variations of basalt from different polycyclic episodes. These isotopic variations may distinguish basalt that ascended directly from mantle depths after partial melting and basalt that experienced an interrupted ascent in crustal magma chambers (Condomines, Hemond, and Allegre, 1988). The thorium isotopic data for this analysis will be obtained through Activity 8.3.1.8.5.1.2, Geochronology Studies (Section 3.2).

The second thrust of the geochemistry of eruptive sequences activity is to attempt to identify the source of basaltic ash deposits in trenches cut in alluvium in the Yucca Mountain area. The potential sources for the ash include (1) the youngest eruptive event at the Lathrop Wells center, (2) the pyroclastic eruptive events during the early evolution of the Lathrop Wells center, (3) scoria eruptions associated with the Red Cone volcanic center, (4) scoria eruptions associated with the Black Cone volcanic center, and (5) scoria eruptions associated with the northernmost volcanic center. We will sample scoria and ash deposits from each eruptive event for these sources and will attempt to identify, sample, and analyze (using XRF, INA, and electron and proton microprobe analysis) reworked ash in alluvium from trenched exposures around Yucca Mountain. Samples will be collected and analyzed (using XRF, INA, and electron and proton microprobe analysis) for each ash deposit exposed in the trenches. We will attempt to answer two questions for these deposits. First, were the ash deposits in the trenches formed from one or several volcanic events? Second, what is the volcanic source and age of the ash or ash units in the trenches? This work will be coordinated with Activity 8.3.1.17.4.6.2, Evaluate Age and Recurrence of Movement on Suspected and Known Quaternary Faults.

3.4.2 Methods

Field geology and geochronology studies will provide the necessary framework for choosing samples for each eruptive cycle of the Quaternary volcanic centers. Samples of scoria, ash, volcanic bombs, or lava flows representing each eruptive episode will be collected in order to characterize the magma compositions of each eruptive event. Samples will be prepared for geochemical analysis according to the procedures set forth in TWS-N5-DP-605, R0, Preparation of Powders from Rock, Cinder, and Ash Samples (standard procedure). Whole rock, major element, and selected trace element chemistry will be determined by XRF analysis. Additional trace element chemistry will be determined by INAA. The list of analyzed elements will include (but not be limited to)

- major elements: SiO_2, TiO_2, Al_2O_3, total iron as FeO, MgO, CaO, Na_2O, K_2O, P_2O_5, and MnO; and

- trace elements: Cs, Rb, Ba, Sr, Th, U, Hf, V, Sc, Ni, Co, Cr, Zr, La, Ce, Nd, Sm, Eu, Tb, Yb, and Lu.

Thin sections of samples will be obtained and the petrographic characteristics of the volcanic rocks determined with a polarizing microscope. Mineral chemistry will be determined by electron microprobe analysis. Major and selected trace elements of tephra units will be analyzed by electron and proton microprobe.

3.4.3 Procedures

The following procedures will be used in this activity:

- Thin Section Preparation Procedure, TWS-ESS-DP-04 (standard procedure);
- Preparation of Powders from Rock, Cinder, and Ash Samples, TWS-N5-DP-605, R0 (standard procedure);
- Procedure for X-Ray Fluorescence Analysis, TWS-ESS-DP-111 (standard procedure);
- Microprobe Operating Procedure, TWS-ESS-DP-07 (standard procedure);
- Analysis of Basalt Ash Using PIXE (Proton-Induced X-Ray Emissions) (in preparation; to be in place 60 days before the start of QA Level I work); and
- Procedure for Field Geologic Studies, TWS-EES-13-DP-606 (standard procedure; revised procedure in technical review).

3.4.4 Accuracy and Precision

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 5%. INAA routinely gives accuracies and precision of better than 10% for a range of elements. The accuracies and precision of all measurements are considered adequate for the geochemical modeling of this activity.

3.4.5 Equipment

All the equipment and laboratory facilities needed are currently available, except for those needed to do INAA measurements. This equipment includes

- Olympus petrographic microscopes with capabilities for thin section studies under conditions of transmitted, polarized, and reflected lighting; one microscope is equipped with photomicrograph capabilities and an automated point-counting stage;
- thin section preparation facilities for constructing 30-micron slides for petrographic studies and polished 30-micron slides for electron microprobe analysis;
- rock-crushing facilities for crushing geologic samples for XRF analysis and INAA;

- sample fusion facilities for preparation of glass pellets for XRF analysis;
- Rigaku automated x-ray fluorescence unit for determination of major and selected trace element analysis;
- electron microprobe for determination of mineral chemistry; and
- proton beam microprobe for trace element analysis of individual ash grains.

A research reactor and gamma-ray-counting facilities, including computer calibration programs, are available at LANL. However, INAA procedures have not been standardized for basaltic volcanic rocks with our equipment. These analyses will be performed under contract with an external laboratory that has an established reputation for performing high-precision INAA of geologic samples.

3.4.6 Data Analysis

Major element data will be listed as oxide percentages, and normative mineralogy will be calculated as a weight percent and cation percent. Normative mineralogy will be calculated with the computer program IGPET, Version 1 (Carr, 1986), or an equivalent program whose results can be checked against IGPET. Analysis of major and trace element data will be through a variety of petrologic techniques, including variation diagrams, Pearce diagrams (Pearce, 1968), petrologic mixing models, and application of computer routines found in commercially available programs such as MAGMA86, Version 1.2 (Hughes, 1987), and IGPET, Version 1 (Carr, 1986). Statistical analysis of the geochemical data (univariate and multivariate) will use the computer program SYSTAT, Version 4.1 (Wilkinson, 1988). Drill hole, major and trace element, and isotopic data will be archived on a computer using a commercially available database system. The computer systems used for these calculations are MS-DOS compatible computers with numeric coprocessors.

3.4.7 Representativeness

One uncertainty of the geochemical studies for this activity is whether the information provided by the geochronology and field geologic studies will be adequate to allow recognition and sampling of all major eruptive units at the volcanic center. The combination of field and geochronology methods for mapping volcanic units should provide a high degree of confidence that all significant volcanic units have been recognized. An additional source of uncertainty is whether geochemical modeling can successfully distinguish between variations in basalt compositions that result from mantle processes (melting and high-pressure crystallization) or crustal processes (low-pressure crystallization). These distinctions will aid in forecasts of the nature and composition of future volcanic activity in the Yucca Mountain region. We cannot evaluate the significance of this area of uncertainty until the geochemical modeling has been partly completed. Yet another source of uncertainty in the geochemical studies is the possibility of secondary alteration of scoria and lava so that variance in the geochemical data would not be produced entirely by magmatic processes. We will reduce that uncertainty by choosing samples with the least evidence of alteration. This uncertainty can also be minimized by careful evaluation of data and elimination of samples that exhibit evidence of alteration. The geochemical patterns of basalt fractionation have been well established in many studies. Samples that exhibit patterns deviating markedly from magmatic variation can be readily identified.

The major uncertainty in the second part of this activity is the confidence level at which we can identify uniquely and correlate ash units in fault trenches to their volcanic sources. This is a difficult problem analytically because of the variability of glass compositions, the possibility of multiple sources of ash in the reworked deposits in the trenches, and the multiple possible eruptive sources for the ashes.

3.5 Activity 8.3.1.8.5.1.5, Evolutionary Cycles of Basaltic Volcanic Fields

3.5.1 Approach

Melting of a mantle source to produce basaltic magma occurs when the temperature of the source material rises above its solidus temperature. There are four major mechanisms that can cause this (Wyllie, 1988): (1) temperature increase through regional heating or changes in the stress field, (2) movement of source material by convection, (3) movement of volatile components producing a lowering of the solidus curve below the ambient temperature of the source, and (4) pressure release. Each of these mechanisms is transient for most geologic settings, which leads to the recognition, supported by numerous studies of volcanic fields, that surface volcanic activity is an episodic process. The transitory nature of melting mechanisms requires that the physical and geochemical characteristics of magma erupted in basaltic volcanic fields change through time. This has long been recognized for Hawaiian volcanoes, which erupt alkali magma (nepheline normative) during the early and late stages of development, separated by a long phase of eruption of tholeiitic magma (hypersthene normative).

The approach of this activity is to study the evolutionary patterns (time, space, magma effusion rates, volume, geochemistry) of continental basaltic volcanic fields in the southwest United States to evaluate temporal changes in the fields. We will test two questions that are related to the ability to predict the nature of future basaltic volcanic activity in the Yucca Mountain region. First, are there systematic patterns to the initiation, evolution, and decline of activity in basaltic volcanic fields? Second, can these patterns be used to evaluate the current stage of activity of the basaltic field of Crater Flat and to constrain the likely nature of future activity?

Support for the approach to this activity is provided by past studies of basalt fields of the Death Valley/Pancake Range volcanic zone and studies of the Springerville volcanic field of the Jemez lineament. Crowe et al. (1986) showed that the basaltic rocks of the Lunar Crater volcanic field include eruptions of hy-normative and ne-normative magma during the older stages of activity, with exclusively ne-normative eruptions in the younger stages of activity. They showed that basaltic volcanism in southern Death Valley is marked by a drastic decrease in volume for the post-4-Ma record. Quaternary basalt of the region is small volume, incompatible element enriched, and alkali. Condit et al. (1989) showed that the Springerville volcanic field in eastern Arizona went through a systematic pattern of evolution. Springerville was active for the last 3 million years, with the youngest activity dated at about 0.3 Ma. The major volume of eruptive activity at the field occurred during 2.0 to 1.0 Ma, with a marked decrease in volume less than 1.0 Ma (Crowe and Perry, 1990). Basalt compositions of the field include alkali olivine basalt (and evolved alkalic rocks) during the earliest stages of activity, with mixed alkalic-tholeiitic rocks in the middle stages of activity. The waning stage of activity was characterized by a decline and cessation of tholeiitic activity, with continued eruption but associated volume decline in alkali olivine basalt.

The approach of this study is to compile geologic data from the literature and obtain original data where required on the volcanic evolution of post-Miocene volcanic fields of the southwest United States. The following parameters will be evaluated for individual volcanic fields: (1) age of volcanic activity, (2) location and time-space migration of volcanic vents, (3) volume (dense-rock equivalent) of volcanic units, (4) dimensions of lava flows and scoria cones to constrain magma effusion rates, and (5) the geochemistry of erupted basalts and scoria.

The selection of volcanic fields for study will be based on the following criteria:

- The volcanic fields will be of predominantly basaltic composition.
- The volcanic fields will be in the Basin and Range geologic province or marginal areas.
- Preference will be given to volcanic fields of closest proximity to the Yucca Mountain region. The oldest volcanic activity will be less than 10 Ma.
- Emphasis will be placed on selecting volcanic fields that are the most analogous to the Crater Flat volcanic field (small volume, alkali basalt).
- Emphasis will be placed on choosing volcanic fields that exhibit evidence of being extinct (no eruptive activity for a significant period of time). This will allow us to evaluate patterns of volcanic activity associated with a waning volcanic field.
- Preference will be given to volcanic fields that have available geologic data (age control, chemical analysis, geologic mapping) to reduce the study time required for this activity.

Using the geologic data base for the fields, we will develop a range of models for the evolutionary patterns of volcanic fields. Emphasis will be placed on models that can be tied to mechanisms associated with the initiation and development of episodes of magma generation in the mantle. Predictions from each model will be compared with the geologic data set for the Crater Flat volcanic field to determine how the model could constrain predictions of future volcanic activity.

3.5.2 Methods

The primary method in conducting this activity will be to compile existing data from the geologic literature and identify what data are needed to evaluate the evolutionary patterns of the fields. Field, geochronologic, and geochemical studies of basalt fields will be undertaken where existing data are insufficient to establish the geologic history and geochemical evolution of a particular field. Samples will be collected for K-Ar age determinations and geochemical analysis using the techniques described in Activity 8.3.1.8.5.1.2, Geochronology Studies (Section 3.2), and Activity 8.3.1.8.5.1.4, Geochemistry Studies of Eruptive Sequences (Section 3.4). The number of samples collected for these measurements will depend on the complexity of the volcanic fields. We will attempt to ensure that sufficient samples are measured to establish the age and geochemical record of volcanism for each volcanic field.

Geologic maps will be prepared for the volcanic fields, using literature data, analysis of stereo aerial photographs, and field investigations. The scale of the map compilation will be about 1:50,000 to 1:100,000, depending on the size of the volcanic field. The dimensions of lava flows and scoria cones will be determined from topographic quadrangle maps and from aerial photographs. Samples will be collected where required for major element and selected trace element geochemical analysis using the techniques described in Activity 8.3.1.8.5.1.4, Geochemistry Studies of Eruptive Sequences (Section 3.4).

3.5.3 Procedures

The following procedures will be used in this activity:

- Procedure for Volcanism Field Studies, TWS-EES-13-DP-606 (standard procedure) (revised version in technical review);
- Procedure for Geomorphic Field Studies, TWS-N5-DP-606, R0 (standard procedure) (in review);
- Procedure for Soil Field Studies, TWS-N5-DP-602, R0 (standard procedure) (in review);
- Thin Section Preparation Procedure, TWS-ESS-DP-04 (standard procedure);
- Procedure for X-Ray Fluorescence Analysis, TWS-ESS-DP-111 (standard procedure);
- Potassium/Argon Dating, NWM-USGS-GCP-06;
- Analysis of Basalt Ash Using PIXE (Proton-Induced X-Ray Emission) (in preparation; to be in place 60 days before the start of QA Level I work); and
- Preparation of Powders from Rock, Cinder, and Ash Samples, TWS-N5-DP-605, R0 (standard procedure).

3.5.4 Accuracy and Precision

XRF analyses generally have accuracies and precision of better than 5% for major elements and better than 10% for selected trace elements (strontium, rubidium, and zirconium) that are present above their detection limits. INAA routinely gives accuracies and precision of better than 10% for elements of interest. The accuracies and precision of all measurements are considered adequate for the purposes of this activity.

3.5.5 Equipment

All the equipment and laboratory facilities needed for this study are now available, except for those needed to do INAA measurements. This equipment includes

- Olympus petrographic microscopes with capabilities for thin section studies under conditions of transmitted, polarized, and reflected lighting; one microscope is equipped with photomicrograph capabilities and an automated point-counting stage;
- thin section preparation facilities for constructing 30-micron slides for petrographic studies and polished 30-micron slides for electron microprobe analysis;
- rock-crushing facilities for crushing geologic samples for XRF analysis and INAA;
- sample fusion facilities for preparation of glass pellets for XRF analysis;
- Rigaku automated x-ray fluorescence unit;
- electron microscope; and
- potassium-argon instrumentation:
  - 10-cm-radius gas source Reynolds-type mass spectrometer,
  - Kepco high-voltage power supply,
  - filament power supplies,
  - Bell 640-G meter,
  - Carry 401-mV vibrating reed electrometers,
  - magnetic field controller,
  - computer-instrumentation interface,
  - Fluka high-voltage power supply and voltage divider.
  - ion gauges and Ganvill-Phillips controllers, and
  - dual extraction bottle glass extraction/vacuum systems; and
- Series 151 Image analysis system.

A research reactor and gamma-ray-counting facilities, including computer calibration programs, are available at LANL. However, INAA procedures have not been standardized for basaltic volcanic rocks with our equipment. These analyses will be performed under contract to an external laboratory that has an established reputation for performing high-precision INAA of geologic samples.

3.5.6 Data Analysis

Potassium-argon age determinations and major and selected trace element analysis will be obtained following the detailed procedures described in Sections 3.2.2 and 3.5.3. These data will be evaluated statistically, using selected codes of SYSTAT, Version 4.1. Normative calculations will be obtained for major element data using IGPET, Version 1 (Carr, 1986), and Magma86, Version 1.2 (Huges, 1987). Field geologic maps will be compiled from aerial photographs and from published maps to topographic quadrangles. Lava flow and scoria cone dimensions will be compiled from these maps. The maps will be digitized using a Series 151 Image analysis system. Thickness data will be added to the digitized map data using a combination of contour data from topographic quadrangles and field measurements of thicknesses of volcanic units. The digitized data will be converted into an ASCII format and imported into the SDS, Version 2.0. This software package for three-dimensional surface and contour plotting will be used to define the geometry of the top and bottom surfaces of volcanic units and to calculate the volume of the units.

3.5.7 Representativeness

This activity will attempt to evaluate future volcanic activity in the Yucca Mountain region based on the assumption that past patterns of volcanic activity in other volcanic fields provide a representative model of likely future activity in the Yucca Mountain area. Three major uncertainties are associated with this assumption. First, how many volcanic fields must be examined to determine if there are systematic patterns to the evolution of basaltic volcanic fields? Second, are the patterns of waning volcanic activity at volcanic fields sufficiently systematic that they can be documented with certainty and applied to the Yucca Mountain site? Third, is there a sufficient geologic record of volcanism in the Yucca Mountain region to evaluate the stage of development of the basalt field? The significance of these uncertainties cannot be established until we begin to obtain further data for the Crater Flat volcanic field and other volcanic fields.

4.0 APPLICATION OF RESULTS

The work performed under this study plan will provide information to address (1) 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 and qualifying conditions of the technical guidelines for tectonics provided in 10 CFR 960 (DOE, 1986a).

TABLE 2

INFORMATION FEEDS FROM AND REQUIRED INFORMATION FOR STUDY PLAN 8.3.1.8.5.1, CHARACTERIZATION OF VOLCANIC FEATURES

Study Plan Activity	Information Feeds (Activity Needing Data)	Required Information for Study Plan
Volcanism Drill Holes	8.3.1.8.1.1.1, Location and Timing of Volcanic Events; 8.3.1.8.1.1.4, Probability Calculations and Assessment	8.3.1.17.4.7, Subsurface Geometry and Concealed Extensions of Quaternary Faults at Yucca Mountain
		8.3.1.17.4.12, Tectonic Models and Synthesis
	8.3.1.8.3.1, Analysis of the Effects of Tectonic Processes and Events on Average Percolation Flux Rates Over the Repository	
Geochronology Studies	8.3.1.8.1.1.1, Location and Timing of Volcanic Events	
	8.3.1.8.1.1.4, Probability Calculations and Assessment	
Field Geologic Quaternary Studies	8.3.1.8.1.1.1, Location and Timing of Volcanic Events	8.3.1.17.4.4, Quaternary Faulting Proximal to the Site Within Northeast-Trending Fault Zones
	8.3.1.8.1.1.2, Evaluation of the Structural Controls of Basaltic Volcanic Activity	8.3.1.17.4.6, Quaternary Faulting Within the Site Area
	8.3.1.8.1.1.4, Probability Calculations and Assessment	8.3.1.17.4.7, Subsurface Geometry and Concealed Extensions of Quaternary Faults at Yucca Mountain
	8.3.1.8.1.2.1, Effects of Strombolian Eruptions	8.3.1.17.4.12, Tectonic Models and Synthesis
	8.3.1.8.1.2.2, Effects of Hydrovolcanic Eruptions	

TABLE 2

INFORMATION FEEDS FROM AND REQUIRED INFORMATION FOR STUDY PLAN 8.3.1.8.5.1, CHARACTERIZATION OF VOLCANIC FEATURES
(concluded)

Study Plan Activity	Information Feeds (Activity Needing Data)	Required Information for Study Plan
Geochemistry of Eruptive Sequences	8.3.1.8.1.1.4, Probability Calculations and Assessment	8.3.1.17.4.6, Quaternary Faulting Within the Site Area
	8.3.1.8.1.1.3, Presence of Magma Bodies in the Vicinity of the Site	
	8.3.1.17.4.6, Quaternary Faulting Within the Site Area	
Evolutionary Patterns of Basaltic Volcanic Fields	8.3.1.8.1.1.4, Probability Calculations and Assessment	8.3.1.17.4.12, Tectonic Models and Synthesis

5.0 SCHEDULE

The milestones for Study Plan 8.3.1.8.5.1, Characterization of Volcanic Features, are listed below by activity. A tentative schedule for accomplishing this work is given in Figure 3. As detailed below, many uncertainties influence this schedule. (The milestones and corresponding schedule have not been formally incorporated into the Yucca Mountain Milestone Data Base.) The primary objective of activities for this study is to produce data for Study 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository; reference to that study is required to understand the logic of the activity milestones of this study plan.

The primary use of data from this study is twofold: First, to ensure that the geologic record of significant volcanic events in the Yucca Mountain region is recognized and described as a part of a comprehensive site characterization process, and second, to establish the chronology of those events and the corresponding volume of the eruptive units with an acceptable degree of certainty. These parameters define the y- and x-axes, respectively, on a plot of the cumulative volume of magma versus time. The accuracy in the measurement of these parameters controls the uncertainty of the calculation of magma effusion rates.

The schedule of this study is dependent on conducting a full site characterization plan as described in the SCP (DOE, 1988). The present schedule of initiation of these activities cannot be precisely defined. The first activities we will be performing are to complete detailed chronology studies and field geologic mapping of Pliocene and Quaternary volcanic centers in the Yucca Mountain region. The priorities for this work are established on the basis of the age of the volcanic centers (the centers are studied in order of increasing age) and proximity to Yucca Mountain (the centers are studied in order of increasing distance from the Yucca Mountain site). Based on these criteria, the sequence of study of the volcanic centers is Lathrop Wells, Sleeping Butte, 1.2-million-year-old centers of Crater Flat, 3.7-million-year-old centers of Crater Flat, and Buckboard Mesa. We anticipate completion of the mapping and geochronology of these centers within 3 calendar years of start of work, assuming no significant delays in the development of geochronology methods. The geochemistry of eruptive sequences should be completed within this time. However, two activities could affect the schedule. First, the software and development plans for control of the analytical instrumentation for geochemical analysis are being reassessed. If there are delays in implementing these plans, this activity will be delayed. Second, we cannot currently plan a completion schedule for basaltic ash correlation studies of this activity until more work has been completed on development of analytical techniques and methods of establishing ash-source correlations. The activity on evolution of volcanic fields will extend about 4 years into the study. Its successful completion will depend on how much information is available from the geologic literature. We cannot predict the timing of completion of the volcanism drill holes. We estimate that the task can be completed within 2 calendar years of the restart of the drilling program, if the volcanism holes remain a high-priority task.

5.1 Activity 8.3.1.8.5.1.1, Volcanism Drill Holes

The schedule of the volcanism drill holes is tied to the overall drilling exploration program for Yucca Mountain. Current plans are for

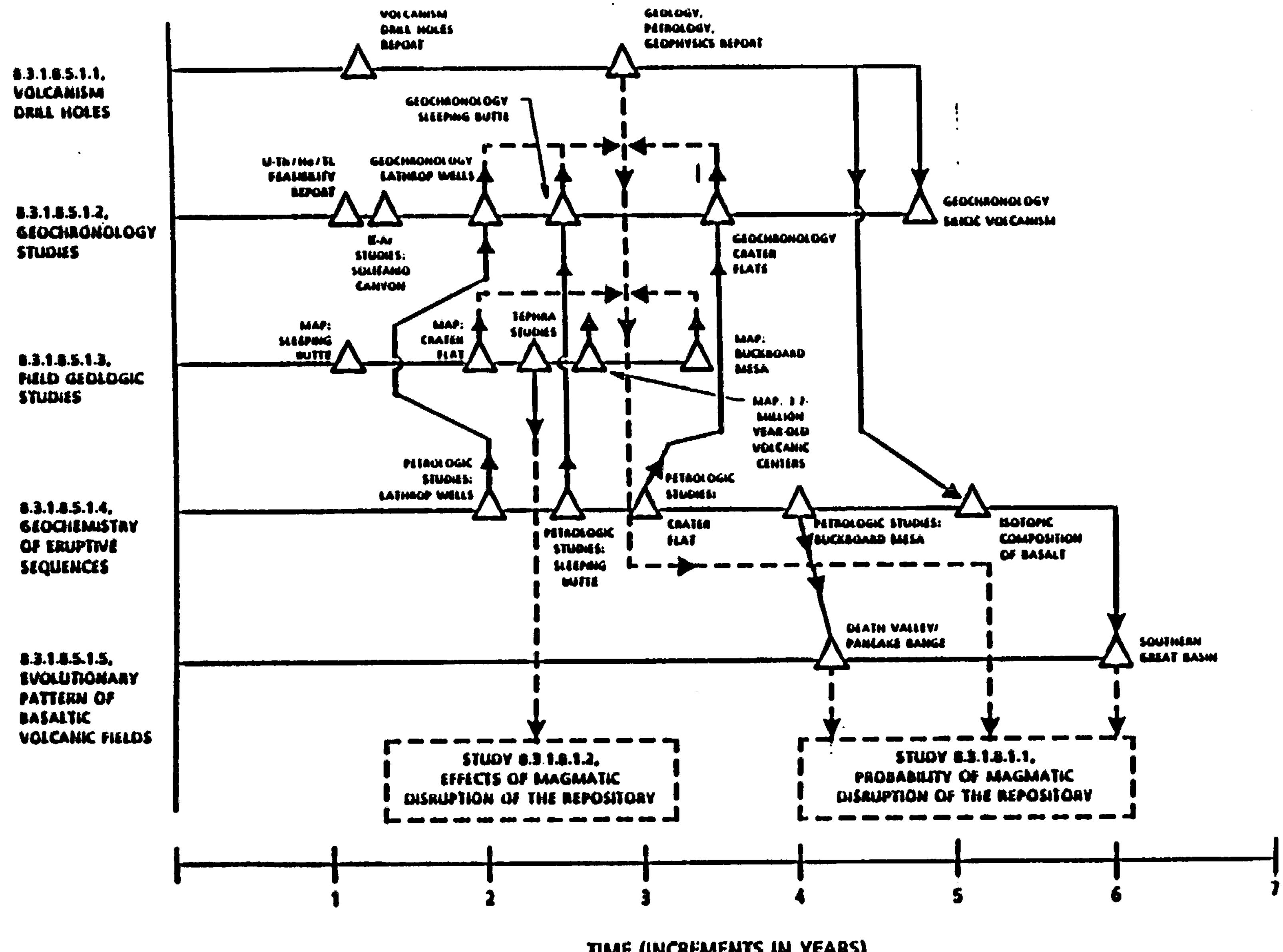

Figure 3. Milestone schedule for characterization of volcanic features.

the volcanism drill holes to be a high-priority task of the drilling schedule; they would be among the first holes drilled when drilling activities resume. The schedule of milestones for this activity is tied to the start-up date of exploratory drilling. Specific dates cannot be provided until the schedule for resumption of drilling is known.

- Report on the stratigraphy of the Volcanism Series holes. This report will be completed 3 months after completion of the drilling of V-5 (or V-4 if V-5 is not drilled; this decision will be based on the results of ground-based geophysical studies at the V-5 site).

- Geologic, petrologic, and geophysical report on Pliocene and Quaternary volcanic rocks in the Volcanism Series holes. This report will be completed 1 year after completion of the drilling of V-5 (or V-4 if V-5 is not drilled; this decision will be based on the results of ground-based geophysical studies at the V-5 site).

5.2 Activity 8.3.1.8.5.1.2. Geochronology Studies

Parts of the geochronology studies require construction of trenches at the Lathrop Wells, Sleeping Butte, and Crater Flat volcanic centers. These activities cannot be started until permission is received to start the full site characterization program.

- Feasibility reports on the application of the U-Th, $^{3}He/^{4}He$, and TL techniques for geochronology studies of the basalt of the Yucca Mountain region.

- Letter report on the results of conventional K-Ar studies of the basalt of Solitario Canyon.

- Summary report on the geochronology of the Lathrop Wells volcanic center.

- Summary report on the geochronology of the Sleeping Butte volcanic centers.

- Summary report on the geochronology of the basaltic volcanic rocks of Crater Flat.

- Summary report on the age of the youngest silicic volcanic rocks in the Yucca Mountain region. This report is dependent on the results of the volcanism drill hole activities. It will be completed 1 year after the completion of the Volcanism Series holes.

5.3 Activity 8.3.1.8.5.1.3. Field Geologic Studies

Parts of the field geologic studies require construction of trenches at the Lathrop Wells, Sleeping Butte, and Crater Flat volcanic centers. These activities cannot be started until permission is received to start the full site characterization program.

- Geologic map and eruptive history of the Sleeping Butte volcanic center.

- Geologic map of the 1.1-million-year-old volcanic centers of Crater Flat.

- Tephra studies of the Lathrop Wells and Sleeping Butte volcanic centers.

- Geologic map of the 3.7-million-year-old volcanic centers of Crater Flat.

- Geologic map of the Buckboard Mesa basalt.

5.4 Activity 8.3.1.8.5.4. Geochemistry of Eruptive Sequences

The schedule for this activity is dependent on revising of the software procedure for operation of analytical instrumentation. If this procedure is delayed, it will result in delays in this activity.

- Report on the petrologic studies of the Lathrop Wells volcanic center (not including isotopic studies).

- Report on the petrologic studies of the Sleeping Butte volcanic center (not including isotopic studies).

- Report on the petrologic studies of the Crater Flat volcanic centers (not including isotopic studies).

- Report on the petrologic studies of the Buckboard Mesa basalt (not including isotopic studies).

- Report on the isotopic composition of Pliocene and Quaternary volcanic centers of the Yucca Mountain region. The schedule of this report is dependent on completion of the volcanism drill holes.

- Report on the identity, composition, and source of basaltic ash deposits in trenches in the Yucca Mountain region. The schedule of this report is dependent on further evaluation of techniques for analysis and correlation of ash units.

5.5 Activity 8.3.1.8.5.1.5. Evolutionary Patterns of Basaltic Volcanic Fields

- Report on the evolutionary patterns of volcanic fields of the Death Valley/Pancake Range volcanic zone.

- Report on the evolutionary patterns of volcanic fields of the southern Great Basin and adjoining parts of the Basin and Range province.

6.0 REFERENCES

Aitken, M. L., 1986. Thermoluminescence Dating, Academic Press, New York.

Allegre, C. J., and J. F. Minster, 1978. "Quantitative Models of Trace Element Behavior in Magmatic Processes," Earth Planetary Sci. Lett., Vol. 38, pp. 1-25.

Birkeland, P. W., 1984. Soils and Geomorphology, Oxford Univ. Press, London/New York.

Buol, S. W., F. D. Hole, and R. J. McCracken, 1989. Soil Genesis and Classification, Iowa State University Press/Ames.

Camp, V. E., and M. J. Roobal, 1989. "The Arabian Continental Alkali Basalt Province: Part I. Evolution of Harrat Rahat, Kingdom of Saudi Arabia," Geol. Soc. America, Vol. 101, pp. 71-95.

Carr, M. J., 1986. IGPET, Version 1.1, Rutgers University, New Brunswick, New Jersey.

Carr, W. J., U.S. Geological Survey, Denver, Colorado, 1981. Written communication to B. Crowe, Los Alamos National Laboratory, Los Alamos, New Mexico.

Carr, W. J., 1982a. "Volcanic-Tectonic History of Crater Flat, Southwestern Nevada, as Suggested by New Evidence for Drill Hole USW-VH-1 and Vicinity," U.S. Geological Survey Open-File Report 82-457, Denver, Colorado.

Carr, W. J., U.S. Geological Survey, Denver, Colorado, 1982b. Written communication to B. Crowe, Los Alamos National Laboratory, Los Alamos, New Mexico.

Carr, W. J., U.S. Geological Survey, Denver, Colorado, 1984. Written communication to B. Crowe, Los Alamos National Laboratory, Los Alamos, New Mexico.

Catt, J. A., 1986. Soils and Quaternary Geology, Oxford Science Publications, Oxford, England.

Cerling, T. E., et al., 1989. "Carbon Isotopes in Soils and Paleosols as Ecology and Paleoecology Indicators," Nature, Vol. 341, pp. 138-39.

Champion, D. E., and E. M. Shoemaker, 1977. "Paleomagnetic Evidence for Episodic Volcanism on the Snake River Plan (Abs.)," National Aeronautics and Space Admin. Tech. Memorandum 78,436, pp. 7-9.

Colman, S. M., K. L. Pierce, and R. W. Birkeland, 1987. "Suggested Terminology for Quaternary Dating Methods," Quaternary Research, Vol. 28, pp. 314-19.

Condit, C. D., et al., 1989. "Patterns of Volcanism Along the Southern Margin of the Colorado Plateau: The Springerville Field," Jour. of Geophy. Res., Vol. 94, pp. 7975-86.

Condomines, M., Ch. Hemond, and C. J. Allegre, 1988. "U-Th-Ra Radioactive Disequilibria and Magmatic Processes," Earth Planetary Sci. Lett., Vol. 90, pp. 243-62.

Crowe, B. M., 1986. "Volcanic Hazard Assessment for Disposal of High-Level Radioactive Waste," in Active Tectonics: Impact on Society, National Science Academy Press, Washington, D.C., pp. 247-60.

Crowe, B. M., and W. J. Carr, 1980. "Preliminary Assessment of the Risk of Volcanism at a Proposed Nuclear Waste Repository in the Southern Great Basin," U.S. Geological Survey Open-File Report 80-375, Denver, Colorado.

Crowe, B. M., M. E. Johnson, and R. J. Beckman, 1982. "Calculation of the Probability of Volcanic Disruption of a High-Level Radioactive Waste Repository Within Southern Nevada, USA," Radioactive Waste Management and the Nuclear Fuel Cycle, Vol. 3, pp. 167-90.

Crowe, B. M., D. T. Vaniman, and W. J. Carr, 1983a. "Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations," Los Alamos National Laboratory Report LA-9325-MS, Los Alamos, New Mexico.

Crowe, B. M., et al., 1983b. "Aspects of Potential Magmatic Disruption of a High-Level Radioactive Waste Repository in Southern Nevada," Journal of Geology, Vol. 91, pp. 259-76.

Crowe, B. M., et al., 1986. "Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations," Vol. II, Los Alamos National Laboratory Report LA-9325-MS, Los Alamos, New Mexico.

Crowe, B. M., et al., 1988. "Volcanic Hazard Assessment for Storage of High-Level Radioactive Waste at Yucca Mountain, Nevada," Proceedings of the Geological Society of America, Cordilleran Section, Las Vegas, Nevada, March, Vol. 20, p. 153.

Crowe, B., et al., 1989. "Volcanic Hazard Studies for the Yucca Mountain Project," Waste Management 89, Vol. 1, pp. 485-91.

Crowe, B. M., and F. V. Perry, 1990. "Volcanic Probability Calculations for the Yucca Mountain Site: Estimation of Volcanic Rates," American Nuclear Soc. Focus 89 Symposium (in press).

Dalrymple, G. B., and M. A. Lanphere, 1969. Potassium-Argon Dating: Principles, Techniques, and Applications to Geochronology, W. H. Freeman, San Francisco, California.

Dalrymple, G. B., and M. A. Lanphere, 1971. "$^{40}Ar/^{39}Ar$ Technique of K-Ar Dating: A Comparison with the Conventional Technique," Earth Planetary Sci. Lett., Vol. 12, pp. 300-308.

DOE (U.S. Department of Energy), January 1986a. "General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories," Code of Federal Regulations, Energy, Title 10, Part 960, Washington, D.C.

DOE (U.S. Department of Energy), May 1986b. "Final Environmental Assessment: Yucca Mountain Site, Nevada Research and Development Area, Nevada," DOE/RW-0073, Washington, D.C.

DOE (U.S. Department of Energy), 1988. "Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada," DOE/RW-0199, Office of Civilian Radioactive Waste Management, Washington, D.C.

Doell, R. R., and A. Cox, 1965. "Measurement of the Remnant Magnetization of Igneous Rocks," U.S. Geological Survey Bulletin, Vol. 1203-A.

Dohrenwend, J. C., S. G. Wells, and B. D. Turrin, 1986. "Degradation of Quaternary Cinder Cones in the Cima Volcanic Field, Mojave Desert, California," Bulletin of Geological Society of America, Vol. 97, pp. 421-27.

Dorn, R., Arizona State University, February 1987. Personal communication with B. M. Crowe, Los Alamos National Laboratory, Los Alamos, New Mexico.

Faure, G., 1977. Principles of Isotope Geology, John Wiley & Sons, Inc., New York.

Fierstein, J., and M. Nathenson, 1989. "Calculation of Tephra Volumes Using Thickness-Area$^{1/2}$ Plots," EOS, Vol. 70, p. 1412.

Forman, S. L., 1989. "Applications and Limitations of Thermoluminescence to Date Quaternary Sediments," Quaternary International, Vol. 1 (in press).

Forman, S. L., et al., 1989. "An Evaluation of Thermoluminescence Dating of Paleoearthquakes on the American Fork Segment, Wasatch Fault Zone, Utah," Journal of Geophysical Research, Vol. 92, pp. 1622-30.

Hughes, S. S., 1987. MAGMA86, Version 1.2, Hughes Magmatics, 3009 Northwest Grant Place, Corvallis, Oregon.

Kane, M. F., and R. E. Bracken, 1983. "Aeromagnetic Map of Yucca Mountain and Surrounding Regions, Southwest Nevada," U.S. Geological Survey Open-File Report 83-616, Denver, Colorado.

Kuntz, M. A., et al., 1986. "Contrasting Magma Types and Steady-State, Volume-Predictable, Basaltic Volcanism Along the Great Rift, Idaho," Geolog. Soc. America, Vol. 97, pp. 579-94.

Kurtz, M. D., 1986. "In Situ Production of Terrestrial Cosmogenic Helium and Some Applications to Geochronology," Geochemica Cosmochemica Acta, Vol. 50, pp. 2855-62.

Lanphere, M. A., 1988. "High-Resolution $^{40}Ar/^{39}Ar$ Chronology of Oligocene Volcanic Rocks, San Juan Mountains, Colorado," Geochemica Cosmochinica Acta, Vol. 52, pp. 1425-34.

McElhinny, M. W., 1973. Paleomagnetism and Plate Tectonics, Cambridge University Press, Cambridge, England.

McKee, E. H., D. C. Noble, and S. I. Weiss, 1989. "Very Young Silicic Volcanism in the Southwestern Great Basin: The Late Pliocene Mt. Jackson Dome Field, Southeast Esmeralda County, Nevada," EOS, Vol. 70, p. 1420.

Nielsen, R. L., 1985. "EQUIL: A Program for the Modeling of Low Pressure Differentiation Processes in Natural Mafic Magma Bodies," Computers in Geoscience, Vol. 11, pp. 531-46.

Noble, D. C., et al., 1984. "Stratigraphic Relations and Source Areas of Ash Flow Sheets of the Black Mountain Stonewall Mountain Volcanic Centers, Nevada," Journ. Geophy. Res., Vol. 89, pp. 8593-8602.

NRC (U.S. Nuclear Regulatory Commission), January 1986. "Disposal of High-Level Radioactive Wastes in Geologic Repositories," Code of Federal Regulations, Energy, Title 10, Part 60, Washington, D.C.

Pearce, T. H., 1968. "A Contribution to the Theory of Variation Diagrams," Contrib. Mineral. Pet., Vol. 19, pp. 142-57.

Pyle, D. M., 1989. "The Thickness, Volume and Grain Size of Tephra Fall Deposits," Bull. Volcanol., Vol. 51, pp. 1-15.

Quade, J., T. E. Cerling, and J. R. Bowman, 1989. "Systematic Variations in the Carbon and Isotopic Compositions of Pedogenic Carbonate Along Elevational Transects in the Southern Great Basin, United States," Geol. Soc. America, Vol. 101, pp. 464-75.

Singhvi, A. K., Y. P. Sharma, and D. P. Agrawal, 1982. "Thermoluminescence Dating of Dune Sands in Rajasthan, India," Nature, Vol. 295, pp. 313-15.

Sinnock, S., and R. G. Easterling, 1983. "Empirically Determined Uncertainty in Potassium-Argon Ages for Plio-Pleistocene Basalts from Crater Flat, Nye County, Nevada," SAND82-2441, Sandia National Laboratories, Albuquerque.

Smith, R. L, and R. G. Luedke, 1984. "Potentially Active Volcanic Lineaments and Loci in Western Conterminous United States," in Explosive Volcanism: Inception, Evolution, and Hazards, Chapter 4, National Academy Press, Washington, D.C.

Stewart, J. H., 1978. "Generalized Maps Showing Distribution and Age of Cenozoic Igneous Rocks in the Western United States," in R. B. Smith and G. P. Eaton, eds., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, Geol. Soc. America Mem. 152, 263, 264.

Stewart, J. H., W. J. Moore, and Isidore Zietz, 1977. "East-West Patterns of Cenozoic Igneous Rocks, Aeromagnetic Anomalies, and Mineral Deposits, Nevada and Utah," Geol. Soc. America Bull., Vol. 88, pp. 67-77.

Tanaka, K. L., et al., 1986. A Migration of Volcanism in the San Francisco Volcanic Field, Arizona," Geological Society of America Bulletin, Vol. 97, pp. 129-41.

U.S. Geological Survey, 1978. "Aeromagnetic Map of the Lathrop Wells Area, Nevada," U.S. Geological Survey Open-File Report 78-1103, Denver, Colorado.

Vaniman, D. T., and B. M. Crowe, 1981. "Geology and Petrology of the Basalt of Crater Flat: Applications to Volcanic Risk Assessment for the Nevada Nuclear Waste Storage Investigations," Los Alamos National Laboratory Report LA-8845-MS, Los Alamos, New Mexico.

Vaniman, D. T., B. M. Crowe, and E. S. Gladney, 1982. "Petrology and Geochemistry of Hawaiite Lavas from Crater Flat, Nevada," Contrib. Mineral. Pet., Vol. 80, pp. 351-57.

Weiss, S. I., and D. C. Noble, 1989. "Stonewall Mountain Volcanic Center, Southern Nevada: Stratigraphic, Structural, and Facies Relations of Outflow Sheets, Near-Vent Tuffs, and Intracaldera Units," Jour. Geophy. Res., Vol. 94, pp. 6059-74.

Weiss, S. I., D. C. Noble, and E. H. McKee, 1989. "Paleomagnetic and Cooling Constraints on the Duration of Pahute Mesa-Train Ridge Eruptive Event and Associated Magmatic Evolution, Black Mountain Volcanic Center, Southwestern Nevada," Jour. Geophy. Res., Vol. 94, pp. 6075-84.

Wells, S. G., et al., 1988. "A Geomorphic Assessment of Quaternary Volcanism in the Yucca Mountain Area, Nevada Test Site, Southern Nevada," Proceedings of the Geological Society of America, Cordilleran Section, Las Vegas, Nevada, March, Vol. 20, p. 242.

Wilkinson, L., 1988. SYSTAT: The System for Statistics, Evanston, Illinois.

Wintle, A. G., and D. J. Huntley, 1980. "Thermoluminescence Dating of Ocean Sediments, Canadian Jour. Earth Sci., Vol. 17, pp. 348-60.

Wyllie, P. J., 1988. "Solidus Curves, Mantle Plumes and Magma Generation Beneath Hawaii," Jour. Geophy. Res., Vol. 93, pp. 4171-81.

APPENDIX A

METHOD FOR ROCK-VARNISH DATING OF GEOMORPHIC SURFACES

METHOD FOR ROCK-VARNISH DATING OF GEOMORPHIC SURFACES
LANL-SP 1.2.3.2.3.A

1.0 PURPOSE AND OBJECTIVES OF STUDIES

1.1 Purpose

The purpose of rock-varnish studies is to define or constrain the timing of geologic events that have affected the Yucca Mountain repository site or its environs, by rock-varnish dating of geomorphic surfaces that have been constructed, deformed, or broken during such events. These geologic events could be erosional, depositional, tectonic, or volcanic. Models for predicting the occurrence of these events or for determining rates for these processes are in large part constrained by the timing (recurrence) of the events over past time. Ages of geomorphic surfaces formed, deformed, or modified during such events provide strong constraints for calculating recurrence intervals.

This appendix defines the nature of rock-varnish studies to be conducted during site characterization in support of several site characterization plan (SCP) (DOE, 1988) studies and activities. Studies and activities in which rock-varnish dating of geomorphic surfaces will provide input include

- 8.3.1.5.1.4, Study: Analysis of the Paleoenvironmental History of the Yucca Mountain Region
  - 8.3.1.5.1.4.1, Activity: Modeling of Soil Properties in the Yucca Mountain Region
  - 8.3.1.5.1.4.2, Activity: Surficial Deposits Mapping of the Yucca Mountain Area
  - 8.3.1.5.1.4.3, Activity: Eolian History of the Yucca Mountain Region

- 8.3.1.6.1.1, Study: Distribution and Characteristics of Present and Past Erosion
  - 8.3.1.6.1.1.2, Activity: Analysis of the Downcutting History of Fortymile Wash and Its Tributaries
  - 8.3.1.6.1.1.3, Activity: An Analysis of Hillslope Erosion at Yucca Mountain

- 8.3.1.8.5.1, Study: Characterization of Volcanic Features
  - 8.3.1.8.5.1.2, Activity: Geochronology Studies
  - 8.3.1.8.5.1.3, Activity: Field Geologic Studies

- 8.3.1.17.4.3, Study: Quaternary Faulting Within 100 km of Yucca Mountain, Including the Walker Lane
  - 8.3.1.17.4.3.2, Activity: Evaluate Quaternary Faults Within 100 km of Yucca Mountain
  - 8.3.1.17.4.3.4, Activity: Evaluate the Bare Mountain Fault Zone

  - 8.3.1.17.4.4.5, Activity: Evaluate Structural Domains and Characterize the Yucca Mountain Region with Respect to Regional Patterns of Faults and Fractures

- 8.3.1.17.4.4, Study: Quaternary Faulting Proximal to the Site Within Northeast-Trending Fault Zones
  - 8.3.1.17.4.4.1, Activity: Evaluate the Rock Valley Fault System
  - 8.3.1.17.4.4.3, Activity: Evaluate the Stagecoach Road Fault Zone

- 8.3.1.17.4.6, Study: Quaternary Faulting Within the Site Area
  - 8.3.1.17.4.6.1, Activity: Evaluate Quaternary Geology and Potential Quaternary Faults at Yucca Mountain
  - 8.3.1.17.4.6.2, Activity: Evaluate Age and Recurrence of Movement on Suspected and Known Quaternary Faults

- 8.3.1.17.4.9.1, Study: Tectonic Geomorphology of the Yucca Mountain Region
  - 8.3.1.17.4.9.1, Activity: Evaluate Age and Extent of Tectonically Stable Areas at and Near Yucca Mountain
  - 8.3.1.17.4.9.2, Activity: Evaluate Extent of Areas of Quaternary Uplift and Subsidence at and Near Yucca Mountain

1.2 Use of Results

These studies will provide basic site characterization data about the present and past surface geologic environment of the Yucca Mountain site, and as such will provide data for investigations in Preclosure (Issue 1.12 and 4.4) and Postclosure (Issue 1.1 and 1.8) tectonics programs. In addition, this study is part of Investigation 8.3.1.8.5 (Studies to Provide the Information Required by the Analysis and Assessment Investigations of the Tectonics Program) as well as Investigation 8.3.1.17.4 (Preclosure Tectonics Data Collection and Analysis). These studies will also provide data for Investigation 8.3.1.6.1 (Studies to Determine Present Locations and Rates of Surface Erosion) and Investigation 8.3.1.5.1 (Studies to Provide the Information Required on Nature and Rates of Change in Climatic Conditions to Predict Future Climates). Data generated by these studies are also used in the design of tests performed by other Project participants and as an aid in interpreting the results of their tests.

2.0 RATIONALE

2.1 Approach

The study will involve rock-varnish dating of geomorphic surfaces on and around Yucca Mountain (including alluvial fans, fluvial terraces, hill-slope deposits, lava flows, and pediments) to determine the time of surface stabilization (minimum time since cutting of a fluvial surface, since construction of an alluvial or eolian surface, or since stable surfaces formed on lava flows) and to constrain the timing of events that have formed, deformed, or modified these surfaces.

This study has been subdivided into the following subtasks:

- Tectonic-neotectonic studies, which include the dating of geomorphic surfaces disrupted by faulting or formed by posttectonic deposition. These studies will assist in establishing the number of faulting events and constrain their timing.

- Erosion studies to determine timing and rate of erosion of sediment from the slopes of Yucca Mountain.

- Paleoclimate-paleoenvironment studies using the ages of hillslope, fluvial, and eolian deposits to construct and/or refine a chronology of climatic transitions for the Yucca Mountain area.

- Rock-varnish geochemistry studies to determine the chemical basis and processes operative in rock-varnish formation and in cation depletion within rock varnish through time (with increasing varnish age).

- Studies of rock-varnish chemistry and mineralogy to assess the aerial extent, timing, and complexity of volcanic eruptive episodes at volcanic centers near Yucca Mountain.

2.2 Types of Measurements to Be Made

The following types of measurements will be made in rock-varnish studies for the subtasks noted in Section 2.1:

- Tectonic and neotectonic studies

  - Scanning electron microscope (SEM) analyses of rock-varnish chemistry and the calculation of cation ratio [(K+Ca)/Ti] and estimated ages for geomorphic features and surfaces related to faulting.

  - Mapping of varnish spectral characteristics and correlation of similar aged surfaces based on similar varnish spectral signals to determine areal extent of geomorphic surfaces representing similar times of surface stability.

- Chemical examination of volcanic ash components within varnish at individual volcanic centers to test correlation with volcanic ash in sediments in Crater Flat and other trenches.

• Erosion studies

- SEM analyses of rock-varnish chemistry and the calculation of cation ratios [(K+Ca)/Ti] and estimated ages for hillslope colluvial features and deposits.

- Calculation, using deposit age and elevation above present drainage channel bottoms, of paleotopographic levels.

- Calculation of volumetric erosion rates for hillslopes at Yucca Mountain using paleotopographic levels, remote sensing imagery, and stereoplanimetry.

• Paleoclimatic and paleoenvironment studies

- SEM analyses or rock-varnish chemistry and the calculation of cation ratios [(K+Ca)/Ti] and estimated ages for geomorphic features and surfaces formed under specific sets of differing climatic conditions. These surfaces will be used to define the chronology and timing of climatic transitions in the Yucca Mountain area.

• Rock-varnish geochemistry studies

- SEM analyses of rock-varnish chemistry and the calculation of cation ratios [(K+Ca)/Ti] and estimated ages for geomorphic features and surfaces.

- Electron microprobe analyses of varnish mineralogy at specific sites within or on the surface of the varnish.

- X-ray diffraction (XRD) mineralogy and clay mineral analysis of varnish using either bulk samples extracted from the substrate or using the "in situ" varnish coating on the rock substrate.

- Proton probe analyses of rock varnish to identify and chemically characterize varnish chemistry and mineral grain components and to calculate cation ratios for comparison with those derived by SEM.

- XRF chemical analysis of varnish on the same disk used for SEM analysis. Both the SEM and XRF analyses of rock varnish are nondestructive and do not result in any alteration of the varnish.

- Culturing of microbacteria found on rock-varnish surfaces and chemical analyses of these organisms to determine their role in rock-varnish origin and chemistry.

- Volcanism studies

  - SEM analyses of rock-varnish chemistry and the calculation of cation ratios [(K+Ca)/Ti] and estimated ages for geomorphic features and surfaces of volcanic origin. SEM identification of mineral components of volcanic ash incorporated within the varnish.

  - X-ray fluorescence (XRF) chemical analysis of varnish on the same disk used for SEM analysis.

  - Electron microprobe analyses at specific sites within or on the surface of the varnish to identify and determine the chemistry of mineral components of volcanic ash.

  - Proton probe analyses of rock varnish to identify and chemically characterize volcanic glass and mineral grains incorporated within the varnish layers.

  - ^{14}C dating of organic material in the basal layers of rock varnish.

2.3 Rationale for Choosing Types of Measurements to Be Made

Rock varnish is a manganese- and iron-rich coating commonly found on rock surfaces in arid and semiarid regions. The ratio of several minor elements within the varnish [(K+Ca)/Ti] has been shown to be age-dependent and to decrease with time. Rock-varnish cation ratios (VCR) for geomorphic surfaces that have been isotopically dated are used to construct calibrated VCR curves (area-specific plots of VCR to log of time). A rock-varnish dating curve has been constructed for the Yucca Mountain area, calibrated by potassium-argon (K-Ar) and uranium (U) trend dated surfaces. Rock-varnish dating of these types of surfaces has been shown to be effective over a time range of several thousand to over a million years. Varnish ages from surface clasts represent the surface-exposure time of the clasts. This in turn represents the time that the surface was incised and stabilized, no longer being a surface of active transport. The significance of rock-varnish dating lies in the great variety of geomorphic surfaces and deposits potentially datable with the technique. Many such deposits, especially those composed of coarse clastic material, may not be easily datable by conventional isotopic techniques.

Two techniques are used to prepare and analyze rock varnish within the United States. The first technique was developed by R. Dorn (1983) and involves the extraction of the varnish from the substrate by scraping under a 45-power microscope and analyzing the scraping using proton-induced x-ray emission (PIXE) analyses. The second was developed by Harrington and Whitney (1987), who used a circular core (2 to 2.5 cm in diameter) of the varnish and rock substrate. Harrington and Whitney obtain the bulk chemistry of the varnish on each disk using an SEM equipped with an energy-dispersive x-ray analyzer. They demonstrated the utility of the SEM in the determination of VCRs in varnish on clasts from geomorphic surfaces in the Yucca Mountain region.

The determination of the quantity of any specific element by the SEM may not be highly accurate. A varnish cation ratio, however, is determined as the ratio of [(K+Ca)/Ti]. The accuracy of this ratio depends on the ratio of peak intensities, which are determined by the SEM with great accuracy. Thus, the accuracy of the cation ratio calculations is adequate for this task.

Advantages to the SEM method when compared to the scraping-PIXE method are the following. (1) Varnish is not removed from the substrate for analysis. If an anomalous result is obtained during analysis, then the specific site on the disk may be reexamined to determine the cause of the anomaly. (2) Inclusion of substrate impurities in scraped samples is a possibility, whereas with the SEM technique the varnish is not extracted from the rock. (3) At least 12 sites are examined on each varnished clast in the SEM method and more than 90 sites for each geomorphic surface to be dated. This contrasts to three to four sites used for scraping, followed by analysis of the combined samples. In the SEM method each site is examined and analyzed separately, thus providing a much larger quantity of information about the sample than is obtained from the homogenized sample in the scraping method. Such information gained in SEM analysis includes within-sample chemical variations and between-sample cation ratio variations across an individual geomorphic surface. Rock-varnish cation ratio determinations within the Yucca Mountain Project will use the analytic method of Harrington and Whitney (1987).

Electron microprobe analysis is the only practical technique for determining compositions of primary and secondary minerals within the varnish. The electron beam can be focused on areas ranging from 1 to 25 microns square, and therefore quantitative mineral compositions can be determined for most minerals. Other techniques are not cost effective.

XRF is one of several techniques available for determining major, minor, and trace element concentrations in bulk rock samples. We have chosen XRF over other methods because XRF analyses are rapid and can be obtained nondestructively on the varnish disks. The samples used are the same as for SEM analysis, and these samples are readily archived.

XRD provides an unambiguous identification of mineral phases present and gives a quantitative estimate of mineral abundance. No other technique is suitable for these determinations.

2.4 Constraints

2.4.1 Sampling

A major constraint in this study is our ability to identify and collect for analysis the clasts from each geologic surface that have been acquiring a rock-varnish coating for the longest time period, in order to provide the closest limiting age for each surface. The sampling criteria used in the selection of varnished clasts for analysis are critical in rock-varnish studies. The characteristics that are keys to such recognition as well as the geomorphic and environmental conditions that must be avoided in the selection process are as yet not clearly understood. Thus, a necessary component of rock-varnish studies for site characterization is an investigation of both rock-varnish formation on rock surfaces and surface processes or environmental conditions that result in degradation or alteration of rock varnish on surface clasts. These studies will yield a better understanding of the mechanical, chemical, and biological processes operative on these surfaces and the influence they exert on rock-varnish characteristics and chemistry. Not all geomorphic surfaces lend themselves to rock-varnish dating. Clast lithology is a major factor. Carbonate clasts and clasts that are coarse-grained are not hospitable surfaces for varnish accretion. They either do not readily accept the rock-varnish coating or their surfaces weather and degrade so rapidly that they are not stable for a sufficiently long period of time. The ideal clast is one that is fine-grained and silica-rich, providing a surface that has a micro-roughness on which rock varnish is readily accreted and is not easily weathered. Such surfaces are most likely to have been stable over the time period applicable for varnish age dating.

Refinement of the rock-varnish dating curve for the Yucca Mountain area is imperative in order to (1) extend it into the Holocene and (2) establish adequate error bounds for the curve, especially in the Late Pleistocene (>100,000 years ago, 100 ka), in order to reduce the age uncertainties for dated surfaces. Additional calibration sites in the 100 to 500 ka range are needed as well as calibration site(s) to evaluate the Holocene (<10 ka) part of the curve.

2.5 Additional Factors for Consideration

2.5.1 Impact on Site

The analyses necessary for this study should have minimal impact on the site because samples collected for the study will be obtained only from surface rock outcrops and from rock clasts on geomorphic surfaces or features to be dated. Only a limited number of clasts are removed from each surface (usually about eight per surface being dated), and these represent a small number when compared to the total number of clasts forming a desert pavement on a geomorphic surface.

2.5.2 Required Accuracy and Precision and Limits of Methods

The detection limits, accuracy, and precision of SEM, XRD, XRF, microprobe, and proton probe analyses are sufficient for the needs of this study; techniques of SEM analyses are described in Harrington and Whitney (1987). Efforts to improve the precision and accuracy of SEM analyses and to develop the microprobe and proton probe analyses are ongoing.

3.0 DESCRIPTION OF TESTS AND ANALYSES

The following description of tests and analyses is a more detailed discussion of work being done in support of Investigations 8.3.1.5.1, 8.3.1.8.5, 8.3.1.6.1, and 8.3.1.17.4 of the SCP. Section 1.1 of this method shows how this study relates to activities in the SCP.

3.1 Introduction

Rock varnish begins to accrete on rock surfaces with their exposure at the surface. Thus, the age of the varnish represents the surface exposure time of the clast or outcrop. The composition of rock varnish varies according to locality of formation and age of the rock varnish, but major constituents are iron and manganese oxides and clay minerals. The processes of rock-varnish formation and accretion on rock surfaces are not yet clearly understood but likely involve both geochemical and biological agents.

The age of rock varnish is calculated using a calibrated ratio of minor cations within the rock varnish to construct a rock-varnish dating curve (Dorn, 1983; Harrington and Whitney, 1987). This ratio of mobile to immobile cations [(K+Ca)/Ti] within the varnish has been found to decrease with varnish age and provides a relative-age indicator for rock varnish from a given region. Empirical VCR curves (region-specific plots of VCR to log of time) can be constructed by determining VCRs on surfaces that have been or can be dated by conventional isotopic techniques. Such calibrated VCR curves can be used for the calibrated time interval to estimate the VCR age of deposits and surfaces of unknown age within the region, including many surficial deposits that are not datable by conventional isotopic techniques.

A rock-varnish dating curve (Figure A-1) has been constructed for the Yucca Mountain area and calibrated by K-Ar dated lava flows and U-trend dated fluvial deposits ranging in age from 1.1 million years to 40,000 years (Harrington and Whitney, 1987). Rock-varnish studies have demonstrated that varnish cation ratios, especially when used in conjunction with other dating methods, are effective in correlating and dating geomorphic surfaces in arid and semiarid regions over a time range of several thousand to over a million years (Dorn, 1983; Dorn et al., 1986; Harrington and Whitney, 1987; Detheir, Harrington, and Aldrich, 1988).

Varnish ages from surface clasts represent the surface-exposure time of the clasts. For alluvial surfaces, this in turn represents the time that the surface ceased being one of active transport and was incised and stabilized. Ages calculated from varnish cation ratios also can provide estimates of when specific areas on surfaces became stable (Dethier, Harrington, and Aldrich, 1988). Local erosion and aggradation occur frequently on geomorphic surfaces, and it is often difficult to recognize evidence for such reworking. Under optimal conditions, the lowest varnish (K+Ca)/Ti) ratio from a geomorphic surface provides a

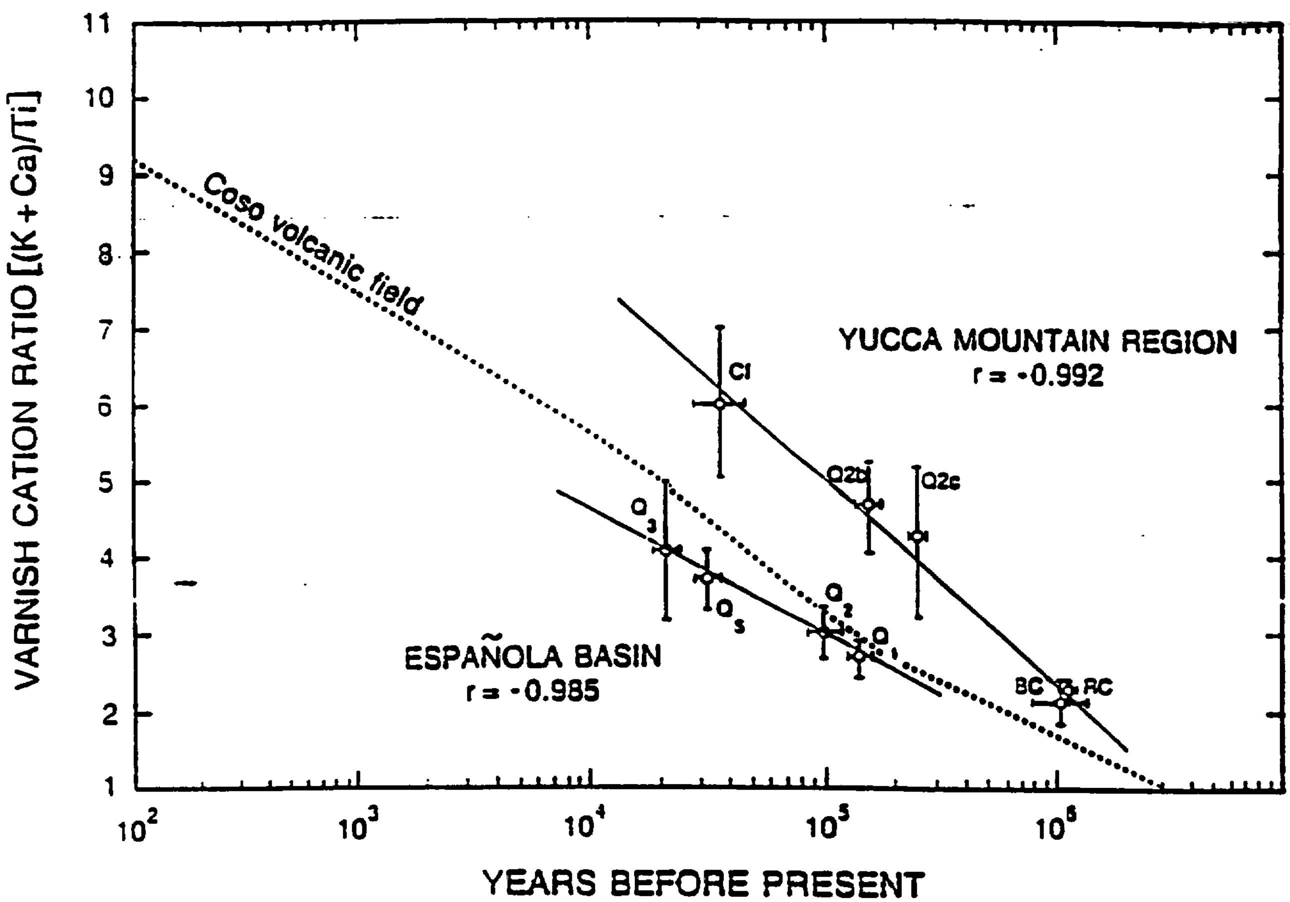

Figure A-1. (K+Ca)/Ti cation ratios from rock varnish versus time for the Espanola Basin, New Mexico (lower curve), and for the Yucca Mountain region, southern Nevada (upper curve). Horizontal bars represent age uncertainties; vertical bars are 1 standard deviation of measured varnish cation ratios. The dotted line is a rock-varnish dating curve for the Coso volcanic field of southeastern California (Dorn, 1983). The symbols identify cation-ratio calibration sites. Cf is a fan surface in Crater Flat, Q2b and Q2c are fluvial terraces along Fortymile Wash, and RC and BC are lava flows at volcanic centers in Crater Flat. Lava flows were dated by K-Ar techniques; the fan surface (Cf) and fluvial terraces (Q2b and Q2c) were dated using U-trend methods. All sites in the Espanola basin (Q_3, Q_s, Q_2, and Q_1) were dated using U-series methods.

close minimum age for formation of the surface (Harrington and Whitney, 1987) and groups of higher ratios on the same surface indicate subsequent periods when other areas of the surface became stable. VCRs can thus be integrated with soil morphology and/or isotopic ages to infer episodes of areas of reworking on such surfaces. The significance of rock-varnish dating lies in the great variety of geomorphic surfaces and deposits potentially datable with the technique. Many such deposits, especially those composed of coarse clastic material, may not be easily datable with conventional isotopic techniques.

3.2 Rock-Varnish Studies

Rock-varnish cation ratio dating is used within the Yucca Mountain Project to provide data and input to a number of specified studies and activities. We have subdivided these into two tasks: (1) dating of geomorphic surfaces and correlation and mapping of surfaces, and (2) studies of rock-varnish chemistry and mineralogy.

Each rock-varnish test will provide data used in predicting the long-term performance of the site and as such is classified as Quality Assurance Level I. The work will be performed in accordance with terraces (Q2b and Q2c) were dated using U-trend methods. All sites in the_Espanola basin (Q_3, Q_s, Q_2, and Q_1) were dated using U-series methods.

3.3 Geochronology Studies--Dating of Rock-Varnished Geomorphic Surfaces

3.3.1 Test Methods

The following technical procedures will apply to the rock-varnish dating of geomorphic surfaces:

- Volcanic Hazard Investigations, TWS-INC-WP-12;
- Thin Section Preparation Procedure, TWS-ESS-DP-04 (standard procedure);
- Operating Instructions for DV-502 Vacuum Evaporator Used in Carbon Coating Samples, TWS-ESS-DP-06 (standard procedure);
- Sample Collection Procedure for Rock-Varnish Studies, TWS-ESS-DP-114; and
- Scanning Electron Microscope Method for Rock-Varnish Analysis (in preparation).

3.3.2 Sample Collection

Rock-varnish samples collected within the YMP will be collected in accordance with TWS-ESS-DP-114 (Sample Collection Procedure for Rock-Varnish Studies) (standard procedure). Rock clasts exhibiting the most strongly varnished rock surfaces will be selected for analysis. These samples may be clasts from aggradational or degradational surfaces or pieces broken from rock outcrops. A suite of from 8 to 10 varnished rock specimens will be collected and analyzed for each geomorphic surface to be dated. We will first collect approximately 20 clasts from a surface or deposit and then cull them to 8 to 10 clasts. Clasts selected will be (1) those away from the edge of the deposit, which minimizes the likelihood of vegetation affecting varnish development or causing erosion of the varnish; (2) the larger varnished clast sizes, as larger clasts are more stable and not easily rotated; (3) those with no varnish on the underside of the clast, indicating the clast has not been overturned since varnish formation began; (4) tabular clasts because this shape is least likely to be overturned; and (5) clasts possessing large, gently sloping surfaces on which extensive varnish coats can accrete. Volcanic rocks will be chosen for study where possible because they have a porous surface texture on which rock varnish is readily accreted. This is done to reduce the analytic variability in varnish cation ratios for an individual deposit. A greater number of specimens will be collected if the surface is complex or if there is potential geologic modification of the surface after initial stabilization of the surface occurred. To reduce potential variability in varnish characteristics, samples are collected as often as possible from (1) stable, well-drained geomorphic surfaces, (2) as few different lithologic substrates as possible, and (3) areas having similar environmental conditions. Samples will not be collected in close proximity to vegetation, from rocks with lichen covers, along cracks in the rock, or from rock surfaces in contact with the soil. Varnish samples collected will be those with the thickest, darkest, and most complete coatings available on the geomorphic surface to be dated.

Sampling for rock-varnish is an iterative process and must be phased, as early results influence the design of the sampling program. In addition, the number and selection of geomorphic surfaces to be sampled for rock-varnish dating are determined by the needs of the specific activity in which the data will be used.

3.3.3 Sample Preparation and Analysis

The preparation of varnished clasts for SEM analysis will follow the methods described by Harrington and Whitney (1987). Clasts are hand washed in deionized water to remove surficial detritus and are air dried. Circular cores of varnish and clast substrate are drilled from areas where the varnish is best developed. The substrate of each core is ground off to produce a disk approximately 0.5 cm thick. Disks are mounted on glass slides varnish-side up and are carbon coated for SEM analysis.

Samples are analyzed using an SEM equipped with an energy dispersive x-ray analyzer. Standard machine settings used are a 40° takeoff angle and a counting time of 100 seconds. Counting dead time is held between 15% and 25%. Accelerating voltages are defined by the voltage required to analyze the total thickness of varnish at each site, as described in Harrington and Whitney (1987). The voltage required to penetrate through the varnish but not into the rock substrate is indicated by obtaining VCR minima at or just below the voltage at which manganese and iron maxima are obtained; these are the values we will select to calculate a VCR for each rock.

3.3.4 Equipment

All of the analytic equipment and laboratory facilities required for these studies are presently available at LANL.

3.3.5 Data Reduction and Analysis

All data on major element, trace element, and varnish cation ratios will be kept both in a computer data base and on paper hard copy. The software package used for rock-varnish analysis and VCR determinations is that specified in the procedure Scanning Electron Microscope Method for Rock-Varnish Analysis (in preparation).

3.3.6 Calculation of Rock-Varnish Age of Deposit (Time of Surface Exposure)

The ratio of (K+Ca)/Ti is calculated for six overlapping sites on a disk (each about 1 cm^2 in area) and the lowest five are averaged, effectively producing an integrated analysis of the varnish on the entire disk. A VCR is calculated for each sample clast by averaging the two disk ratios, unless the two disk VCRs differ by more than 20% of the lowest disk VCR, in which case the lower VCR is used in calculating the VCR for the geomorphic surface. A VCR for a geomorphic surface is determined by averaging the VCR for all sample clasts. If the VCRs for the clasts from a geomorphic surface fall in a tightly clustered group, then all clast VCRs are used to calculate the VCR for the geomorphic surface. If the clast VCRs are highly variable (1) and there is a clustering of VCRs near the lowest VCR and a second higher grouping, then only those clasts in the lower grouping are used to calculate the surface VCR, or (2) no clustering of VCRs is apparent, those clasts whose VCRs vary by less than 25% of the lowest VCR are used for the calculation. Several factors may cause the chemistry of varnish to vary either across individual rock samples or among a group of samples from a geomorphic surface and result in an anomalous VCR (Dorn and Oberlander, 1981, 1982; Dorn, 1983). These factors include (1) retardation of initial varnish formation due to unfavorable rock (substrate) lithology, surface smoothness, or the presence of lichen; (2) removal of initial varnish by organic acids derived from organic materials or microorganisms, or by eolian abrasion, with subsequent revarnishing; and (3) incorporation of detrital minerals with high calcium or potassium concentration in the varnish. The majority of varnishes that result from these varnish-variation processes have higher cation ratios, which produce an apparent younger age than the initial unaltered VCR. Such anomalous high values of VCRs are difficult to recognize during analysis, which may result in their inclusion in VCR calculations. Therefore, in our calculation of a rock-varnish age, we will exclude the highest VCR site on each disk (one out of six). Additionally, under optimal conditions, the lowest varnish (K+Ca)/Ti ratio from a geomorphic surface provides a close minimum age for formation of the surface (Harrington and Whitney, 1987), and groups of higher ratios on the same surface indicate subsequent periods when other areas of the surface became stable. Thus, when VCRs for a geomorphic surface are variable, the lower VCR values will be selected as most representative of the age of the surface.

The time of surface exposure of clasts (the time over which surface clasts in a deposit have been stable) on a geomorphic surface is calculated using the formula $VCR_E = 10.466 - 2.667 \log_{10} t$ for the calibrated rock-varnish dating curve for the Yucca Mountain region (Harrington and Whitney, 1987), where t is in thousand years before the present (ka) and VCR_E is the varnish cation ratio [(K+Ca)/Ti]. Refinement of this curve may result in a modification of the curve formula.

3.3.7 Required Accuracy and Precision

These studies require high accuracy and precision in determining the ratio [(K+Ca)Ti] within rock varnish, but high precision on individual element amounts is not required. Relative abundances of elements are based on relative x-ray peak intensities. The determination of the quantity of any specific element with the SEM may not be highly accurate. A varnish cation ratio, however, is determined as the ratio of (K+Ca)/Ti. The accuracy of this calculation depends on the ratio of peak intensities, which are determined by the SEM with great accuracy.

Rock-varnish internal textural relationships are determined by visual inspection using the SEM. A certified geologist familiar with the instrument will have no difficulty identifying textural relationships.

3.3.8 Rationale for Analytic Procedure

The rationale and advantages for selecting the SEM method of Harrington and Whitney (1987) for rock-varnish analysis over the method of analysis used by Dorn (1983) are discussed in Section 2.3. The SEM analytic method for rock-varnish dating is considered to still be under development. Review and refinement of both the analytic method and the calibrated rock-varnish dating curve are ongoing.

3.4 Geochemistry Studies of Rock Varnish and Rock-Varnish Origin

3.4.1 Test Methods

The following technical procedures will apply to the studies of rock-varnish geochemistry and origin:

- Volcanic Hazard Investigations, TWS-INC-WP-12;
- Thin Section Preparation Procedure, TWS-ESS-DP-04 (standard procedure);
- Operating Instructions for DV-502 Vacuum Evaporator Used in Carbon Coating Samples, TWS-ESS-DP-06 (standard procedure);
- Microprobe Operating Procedure, TWS-ESS-DP-07 (standard procedure);

- Siemens X-Ray Diffraction Procedure, TWS-ESS-DP-16 (standard procedure);
- Clay Mineral Separation and Preparation for X-Ray Diffraction Analysis, TWS-ESS-DP-25 (standard procedure);
- Procedure for X-Ray Fluorescence Analysis, TWS-ESS-DP-111 (standard procedure);
- Procedure for Infrared Spectroscopy Analysis of Rock Varnish (standard procedure) (to be prepared, completion estimated to be by 6/90);
- Sample Collection Procedure for Rock-Varnish Studies, TWS-ESS-DP-114 (standard procedure);
- Scanning Electron Microscope Method for Rock-Varnish Analysis (to be prepared, completion estimated to be by 10/89).

3.4.2 Sample Collection

Samples to be used in studies of rock-varnish geochemistry and origin will be collected in accordance with technical procedure TWS-ESS-DP-114, Sample Collecting Procedure for Rock-Varnish Studies (standard procedure). Collection of rock-varnish samples for this study will follow all the criteria described in Section 4.2 of the above procedure. Two additional criteria will also be used, namely (1) the selection of clasts having the largest smooth surface area of maturely developed rock varnish to work with and (2) the selection of multiple rock-varnish substrate lithologies from an alluvial surface, where possible. If there are two alluvial surfaces judged to be of the same age in the area, each displaying well-developed rock-varnished surface clasts and differing only in the number of lithologies that can be found within the desert pavement on the surfaces, the surface having the greatest lithologic diversity will be chosen. Geomorphic surfaces at localities throughout the southern Nevada region will be selected for sampling for this study. In many cases the selected surfaces will be those already selected for sampling under the geochronology studies described above, in order to remove the age of the varnish as an unknown variable in the study of rock-varnish geochemistry. An attempt will be made to include a wide range of varnish ages in the study, ranging from varnishes of mid-Holocene age (~6000 years old) to those of Early Pleistocene age (>700,000 years old).

The amount of rock-varnish surface area needed from a geomorphic surface for geochemistry studies is not yet known, but it will be greater the thinner the rock varnish on the varnished surface clasts. In general the greatest surface area of rock varnish will have to be collected from surfaces that are geologically young, with progressively less varnish surface area needed the greater the age of the sampled geomorphic surface.

In all cases, both the number of varnished clasts and the size of the varnish surface area per clast will exceed that required for deriving an estimate of the age of the varnish for the geomorphic surface. The number of clasts needed will be dictated by field conditions.

The total number of surfaces that must be sampled for the geochemical studies will be determined as the work progresses and will be a function of how variable the chemistry of the rock varnish is both with increasing age of the varnish and regionally in the area of Yucca Mountain and across southern Nevada. Initial studies will use approximately 150 samples from approximately 20 localities in southern Nevada to test the feasibility of the analytic techniques and to provide baseline data on variations in rock-varnish chemistry caused by varnish age and substrate lithology.

3.4.3 Sample Preparation and Analysis

Our approach to the analysis of varnish characteristics lies in a varied, thorough, and systematic examination of all samples. For each sample the following analytic procedures will be used:

3.4.3.1 Thin Section Analysis

Polished thin sections will be made perpendicular to the varnish-substrate interface. The varnish will be stabilized with epoxy prior to grinding. Sections will be thinned to allow transmission of polarized light and will be studied for any visible optical variation in the varnish and in the upper part of the substrate. Such variations will be documented for later analysis with electron probe microanalysis (EPM) and SEM with energy dispersive x-ray analysis (EDX). EPM will be used to quantitatively measure elemental contents along numerous transects across the varnish profiles. SEM-EDX will be used to document textural and elemental changes throughout the varnish. Image analysis-enhancement routines will also be used to analyze these changes.

3.4.3.2 Oxide Analysis

Using procedures outlined by Potter and Rossman (1979), we will examine oxides of varnish scrapings using infrared spectroscopy (IR). IR is used because it is sensitive to amorphous components and those with short-range order, thus yielding a more complete description of materials such as manganese oxides, where crystalline disorder may be encountered. In addition, with a micro IR spectrometer attached to an optical microscope, oxides will be studied both on in situ surfaces and in cross sections of varnishes. XRD analyses of in situ varnish surfaces have rather broad peaks for oxide phases. Analysis of rock varnish using a cobalt x-ray source will reduce fluorescence background and increase sensitivity. Both in situ samples and scrapings will be analyzed by XRD with a cobalt source. Other oxide phases incorporated within the varnishes will be examined and documented with SEM-EDX.

3.4.3.3 Silicate Analysis

Silicate phases will be analyzed directly by XRD of in situ varnish surfaces and XRD of residues removed from varnish surfaces following extraction of oxide phases using both dithionite-citrate (Potter and Rossman, 1979) and oxalic acid (Lakin et al., 1963) dissolution procedures. Morphology of silicate phases will be studied both pre- and postextraction using SEM-EDX.

3.4.3.4 Enhanced Mineralogic and Elemental Profiling

Two techniques are available that provide additional information concerning mineralogic and elemental profiling beyond that achieved analyzing thin sections. With an ion etcher the varnish surface will be eroded across the entire surface of a disk prepared for SEM analysis, removing the youngest accreted varnish first. Periods of etching will be used to remove certain depths of varnish in steplike fashion until all varnish is removed and the substrate exposed. The length of the etching period will be a function of the hardness of the varnish, which is in turn a function of varnish composition. Less resistant organic structures, when present, should be readily observable. After each etching period, the occurrence and distribution of minerals across the etched varnish surface will be determined with XRD and SEM-EDX. In addition, energy dispersive x-ray fluorescence analysis of the surfaces exposed by ion etching will document elemental variations with depth. With duplicate samples etched for an equivalent period, oxides will be extracted and the extraction as well as the residual minerals adhering to the substrate will be analyzed for variations in varnish chemistry.

A second technique of mineralogic and elemental profiling in varnish is to epoxy seal a varnish sample duplicate of that being ion etched and, in steplike fashion, slowly remove the varnish by polishing (Dragovich, 1988). In this case the topographically high areas will be removed first, ultimately exposing the highest points on the varnish-substrate interface. Surrounding each exposed point of substrate will be halos, with the oldest varnish nearest the substrate-varnish interface. Elemental variations will be mapped across the polished surface(s) using SEM-EDX and image analysis to determine mineralogic variations with varnish depth. Micro IR will be used to determine zonation of oxide phases. Transitions from weathered to unweathered substrate will also be examined and analyzed.

3.4.3.5 Elemental Analysis

The profiling procedures will define mineralogic and major element distribution within varnish. However, other analytic approaches will be required to determine minor and trace element distribution. When desired, a suite of analytic techniques will be used to measure the chemical composition of iron and manganese oxide extracts, mineralogic residue still adhering to substrate following extraction of oxides, and untreated varnish scraped from the substrate. Analytic techniques to be used may include but may not be limited to atomic absorption, instrumental neutron activation analysis, and ultraviolet through visible spectrophotometry.

3.4.3.6 Substrate Analysis

Critical to understanding relationships between varnish form and occurrence, and the substrate on which it occurs, is a thorough examination and characterization of substrate texture and mineralogy. Therefore, the substrate will be examined petrographically, with XRD, and by chemical analysis using SEM and electron microprobe. In addition, relationships between varnish texture and composition and substrate mineralogy will be determined by SEM-EDX. Finally, the surface texture of substrate, prior to varnish accretion, will be determined by SEM examination of unvarnished faces (such as the underside) of varnished clasts. Weathering rinds formed on the substrate, when present, will be analyzed in the same manner as other substrates but will be treated as separate, distinct lithologies from the underlying, unaltered substrate.

3.4.4 Equipment

All of the analytic equipment and laboratory facilities required for these studies are presently available at LANL.

3.4.5 Data Reduction and Analysis

All data on major element, trace element, and varnish cation ratios will be kept both in a computer data base and on paper hard copy. The program QUANT5 will be used initially to reduce all intensity data obtained on the x-ray diffractometer to determine weight percents of individual minerals. QUANT5 performs either internal or external standard analysis using standard data collected on the diffractometer. Integrated intensity data used as input to QUANT5 will be obtained using software provided with the diffractometer. X-ray fluorescence data will be reduced using the program XRF-11 written by Criss Software, Largo, Maryland. This program calculates elemental concentrations by comparing measured x-ray intensities to a library of intensities for rock standards of known compositions. The program uses fundamental parameters to make matrix corrections for x-ray absorption and fluorescence effects. Future enhancements in XRD data reduction may incorporate Rietveld methods and/or simultaneous linear equation methods coupled with XRF chemical data.

Electron microprobe data will be collected and processed using the Sandia TASK8 operating system. This system incorporates the empirical Bence and Albee method for correcting mineral compositions for differential matrix effects. Atomic number, adsorption, and fluorescence data reduction is also available for the microprobe.

SEM data will be reduced as described above. Qualitative SEM data consists of peak identification performed by Tracor Northern's IDENT program on energy dispersive data.

3.4.6 Required Accuracy and Precision

These studies require high accuracy and precision in identification of minerals present in rock varnish, but high precision on individual amounts is not required for most minerals. XRD routinely provides qualitative determinations of the presence or absence of minerals if these minerals are present above the detection limits. Detection limits are a function of what mineral is being determined and of experimental conditions but are generally 1% to 5%. Future advances in data reduction should improve precision.

Both XRF and electron microprobe analyses generally have relative accuracies and precisions of better than 5% for major chemical constituents and 20% for minor constituents. These errors can exceed 100% as detection limits are approached. For the purposes of these studies, the precision and accuracy for XRD, XRF, and electron microprobe analysis are considered adequate.

Rock-varnish internal textural relationships are determined by visual inspection using the SEM.

3.4.7 Rationale for Analytic Procedure

XRD provides an unambiguous identification of mineral phases present and gives a quantitative estimate of mineral abundances. No other technique is suitable for these determinations, particularly for the fine-grained clay mineral material within rock varnish.

XRF is one of several techniques available for determining major, minor, and trace element concentrations in bulk-varnish samples. We have chosen XRF over other techniques because it has acceptable levels of accuracy and precision, because XRF analyses are rapid and nondestructive, and because the samples are readily archived.

Electron microprobe analysis is the only practical technique for determining compositions of primary and secondary minerals in the rock-varnish groundmass. The electron beam can be focused on areas ranging from 1 to 25 microns square, and therefore quantitative mineral compositions can be determined for most minerals. Other techniques are not cost effective and offer no substantial improvement in precision and accuracy for major chemical components.

SEM inspection of rock-varnish samples allows determination of textural relationships at a much finer scale than can be achieved by binocular microscope. Qualitative chemical analyses useful for mineral identification can be made on grains or clay minerals that are too small for electron microprobe analysis.

4.0 SCHEDULE

The schedule and milestones are presented below. The milestones in this method are tabulated in the SCP in activities into which rock-varnish data will be incorporated. These activities are those listed in Section 1.1 of this method. Milestones will be prepared in collaboration with investigators responsible for conducting these studies/investigations.

Milestone	Description
M698	Report on the preliminary evaluation of the paleoenvironment of Yucca Mountain.
M892	Final 1:24,000 surface deposits map of the Yucca Mountain region.
Z272	Report on the synthesis of the paleoenvironmental history of the Yucca Mountain region.
M395	Report on the Quaternary history of Yucca Mountain.
Z425	Report on the origin of hillslope deposits.
Z288	Report on the analysis of hillslope erosion.
Z287	Report on the analysis of the downcutting history of Fortymile Wash and its tributaries.
Z290	Report on the evaluation of the impact of future climatic conditions on locations and rates of erosion.
Z292	Report on the evaluation of the impact of future uplift/subsidence and faulting on erosion at Yucca Mountain and vicinity.
NEW	Progress report on rock-varnish dating at the Lathrop Wells center.
Z321	Report on the evaluation of the Bare Mountain fault.
Z322	Report on the evaluation of structural domains and the charac-terization of the Yucca Mountain area with respect to regional patterns of faults and fractures.
P880	Report on the evaluation of Quaternary faulting within 100 km of Yucca Mountain.
Z323	Report on the evaluation of the Rock Valley fault system.
Z325	Report on the evaluation of the Stagecoach Road and Cone Springs fault zones.
Z238	Report on the age and recurrence of movement of Quaternary faults at Yucca Mountain.

Milestone	Description
P880	Report on the Quaternary geology and faults of Yucca Mountain.
Z341	Report on the extent of areas of Quaternary uplift and subsidence at and near Yucca Mountain.
Z350	Report on the evaluation of tectonic processes and tectonic stability at the site.
R484	Report on progress on rock-varnish studies.
NEW	Report on rock-varnish dating at the Scarp.
NEW	Report on refinement of the rock-varnish dating curve of the Yucca Mountain region.

5.0 REFERENCES

Dethier, D. P., C. D. Harrington, and M. J. Aldrich, 1988. "Late Cenozoic Rates of Erosion in the Western Espanola Basin, New Mexico--Evidence from Geologic Dating of Erosion Surfaces," Geologic Society of America Bulletin, Vol. 100, pp. 928-37.

DOE (U.S. Department of Energy), January 1988. Site Characterization Plan, Yucca Mountain Site, Nevada Research and Development Area, Nevada: Consultation Draft, Office of Civilian Radioactive Waste Management, Washington, D.C.

Dorn, R. I., 1983. "Cation-Ratio Dating: A New Rock Varnish Age-Determination Technique," Quaternary Research, Vol. 20, pp. 49-73.

Dorn, R. I., and T. M. Oberlander, 1981. "Microbial Origin of Desert Varnish," Science, Vol. 213, pp. 1245-47.

Dorn, R. I., and T. M. Oberlander, 1982. "Rock Varnish," Progress in Physical Geography, Vol. 6, pp. 317-67.

Dorn, R. I., et al., 1986. "Cation-Ratio and Accelerator Radiocarbon Dating of Rock Varnish on Mojave Artifacts and Landforms," Science, Vol. 231, pp. 830-33.

Dragovich, D., 1988. "A Preliminary Electron Probe Study of Microchemical Variations in Desert Varnish in Western New South Wales," Earth Surface Processes and Landforms, Vol. 13, pp. 259-70.

Harrington, C. D., and J. W. Whitney, 1987. "Scanning Electron Microscope Method for Rock-Varnish Dating," Geology, Vol. 15, pp. 967-70.

Lakin, H. W., et al., 1963. "Variation in Minor Element Content of Desert Varnish," in Short Papers in Geology and Hydrology, U.S. Geological Survey Prof. Paper 475-B, pp. B28-B31.

Potter, R. M., and G. R. Rossman, 1979. "The Manganese and Iron Oxide Mineralogy of Desert Varnish," Chemical Geology, Vol. 25, pp. 79-94.

APPENDIX B

QUALITY ASSURANCE SUPPORT DOCUMENTATION

The Quality Assurance Level Assignments (QALA) included in this appendix were approved in 1986 and are not completely consistent with Table B-1. At the time the work for this study fell under WBS number 2.3.2.3.1.A and also included SCP Studies 8.3.1.8.1.1, Probability of Magmatic Disruption of the Repository, and 8.3.1.8.1.2, Effects of Magmatic Disruption of the Repository. Since that time, the work for these three studies has been separated. Revised QALAs for this study and for the two studies are currently being developed using new procedures that implement NUREG-1318. When the revised QALAs are approved, they will supersede the 1986 QALAs and will be provided through controlled distribution as a revision to the study plan.

Table B-1 lists the applicable NQA-1 criteria for this study and explains how they will be satisfied.

TABLE B-1

APPLICABLE NQA-1 CRITERIA FOR SCP STUDY 8.3.1.8.5.1
AND HOW THEY WILL BE SATISFIED

NQA-1 Criterion	Documents Addressing These Requirements		Anticipated Date of Issue
1. Organization	The organization of the Office of Civilian Radioactive Waste Management (OCRWM) program is described in Section 8.6 of the SCP. The LANL QA program is described in the LANL-YMP-QAPP and includes a program description addressing each of the NQA-1 criteria. The LANL QA program contains quality administrative procedures (QP) further defining the program requirements.		
	TWS-QAS-QP-01.1	Interface Control	1/31/89
	TWS-QAS-QP-01.2	Stop Work Control	1/31/89
	TWS-QAS-QP-01.3	Conflict Resolution	2/21/89
2. QA Program	The LANL QA program is described in the LANL-YMP-QAPP and includes a program description addressing each of the NQA-1 criteria. An overall description of the YMP QA program for site characterization activities is described in Section 8.6 of the SCP.		
	TWS-QAS-QP-02.1	Personnel Selection, Indoctrination, and Qualification	1/31/89
	TWS-QAS-QP-02.2	Personnel Training	1/31/89
	TWS-QAS-QP-02.3	Readiness Review	5/31/89
	TWS-QAS-QP-02.4	Management Assessment	5/31/89
	YMP AP-5.4Q	Assignment of Quality Assurance Level	1/24/89
3. Design and Scientific Investigation Control	This study is a scientific investigation. The following QPs apply:		
	TWS-QAS-QP-03.1	Software QA Plan	4/30/89
	TWS-QAS-QP-03.2	Technical and Policy Review	4/30/89
	TWS-QAS-QP-03.3	Preparation of SCP Study Plan	5/31/89
	TWS-QAS-QP-03.5	Documenting Scientific Investigation	2/29/89
	TWS-QAS-QP-03.6	IDS Design and Interface Control	5/31/89
	TWS-QAS-QP-03.7	Peer Review	5/31/89

TABLE B-1

APPLICABLE NQA-1 CRITERIA FOR SCP STUDY 8.3.1.8.5.1
AND HOW THEY WILL BE SATISFIED
(continued)

NQA-1 Criterion	Documents Addressing These Requirements		Anticipated Date of Issue
	TWS-QAS-QP-03.8	IDS Technical Assessment Review	5/31/89
	TWS-QAS-QP-03.11	Software Configuration Management	6/16/89
	TWS-QAS-QP-03.12	Scientific and Engineering Software and Software Libraries	6/16/89
	TWS-QAS-QP-03.13	Auxiliary, Commercial, and Utility Software	6/16/89
	TWS-QAS-QP-03.14	Design Input for ESF	2/3/89
	TWS-QAS-QP-03.15	TMO Design and Interface Control	5/31/89
4. Procurement Document Control	TWS-QAS-QP-04.1	Procurement	12/14/88
	TWS-QAS-QP-04.2	Acceptance of Procured Services	1/31/89
	TWS-QAS-QP-04.3	Qualification of Suppliers	1/31/89
5. Instructions, Procedures, and Drawings	TWS-QAS-QP-05.1	Preparation of QPs	12/14/88
	TWS-QAS-QP-05.2	Preparation of DPs	12/14/88
6. Document Control	TWS-QAS-QP-06.1	Document Control	1/31/89
7. Control of Purchased Material, Equipment, and Services	Applicable parts of this criterion are covered in item 4 (see above).		
8. Identification and Control of Materials, Parts and Samples	TWS-QAS-QP-08.1	Identification and Control of Samples	5/31/89
	TWS-QAS-QP-08.2	Control of Data	5/31/89
9. Control of Special Processes	This criterion has been determined to be inapplicable to the scope of work of the LANL YMP.		
10. Inspection	This criterion has been determined to be inapplicable to the scope of work of the LANL YMP.		
11. Test Control	This criterion has been determined to be inapplicable to the scope of work of the LANL YMP.		

TABLE B-1

APPLICABLE NQA-1 CRITERIA FOR SCP STUDY 8.3.1.8.5.1
AND HOW THEY WILL BE SATISFIED
(concluded)

NQA-1 Criterion	Documents Addressing These Requirements		Anticipated Date of Issue
12. Control of Measuring and Test Equipment	The control of instrument calibration and data collection is described in the technical procedures referenced in Section 3 of this plan. The following QPs also apply:		
	TWS-QAS-QP-12.1	Measuring and Test Equipment	5/31/89
	TWS-QAS-QP-12.2	Control of Operator-Calibrated Equipment	5/31/89
13. Handling, Storage and Shipping	TWS-QAS-QP-13.1	Handling, Shipping, and Storage	3/17/89
14. Inspection, Test and Operating Status	This criterion has been determined to be inapplicable to the scope of work of the LANL YMP.		
15. Nonconforming Materials, Parts or Components	TWS-QAS-QP-15.1	Nonconformances	12/14/88
16. Corrective Action	TWS-QAS-QP-16.1	Corrective Action	4/28/89
	TWS-QAS-QP-16.2	Trending	5/31/89
17. Quality Assurance Records	TWS-QAS-QP-17.1	Resident File	12/14/88
	TWS-QAS-QP-17.2	Records Processing Center	12/14/88
18. Audits	TWS-QAS-QP-18.1	Audits	4/28/89
	TWS-QAS-QP-18.2	Surveys	3/17/89
	TWS-QAS-QP-18.3	Auditor Qualification	3/31/89

QUALITY ASSURANCE LEVEL ASSIGNMENT SHEET (QALAS) AND QUALITY LEVEL ASSIGNMENT CRITERIA SHEET (QLACS)

SIP No. 2/3/1-TV

Rev. 0

Activity Tectonics and Volcanism

Tasks: Volcanism

TABLE B-2
QUALITY ASSURANCE LEVEL ASSIGNMENTS FOR STUDY 8.3.1.8.5.1

NNWSI QUALITY ASSURANCE LEVEL ASSIGNMENT

Items/Activities	QA Level	QA Requirements	Technical Justification
Tectonics and	I	1,2,3,4,5,6,7,8,	NNWSI SOP-02-02; para 5.2.1b
Volcanism		10,11,12,13,15, 16,17,18	(activity will provide site characterization data) and
		See attached QLACS	Step 2 of QA level Assignment Checklist

APPROVALS (Signature and Date)

PI Bruce Crowe 9/3/86 TPO [signature] 9-3-86
QAL [signature] 9/3/86 WMPO(TECH) [signature] 9-4-86
QAIM [signature] 9/3/86 WMPO(PQM) [signature] 9/4/86

PI FINAL REVIEW Bruce Crowe 10/16/86