

Status of Volcanic Hazard Studies for the Nevada Nuclear Waste Storage Investigations

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NEVADA NUCLEAR WASTE STORAGE INVESTIGATIONS

by

Bruce M. Crowe, David T. Vaniman, and Wilfred J. Carr

ABSTRACT

Volcanism studies of the Nevada Test Site (NTS) region are concerned with hazards of future volcanism with respect to underground disposal of high-level radioactive waste. The hazards of silicic volcanism are judged to be negligible; hazards of basaltic volcanism are judged through research approaches combining hazard appraisal and risk assessment. The NTS region is cut obliquely by a N-NE trending belt of volcanism. This belt developed ~8 Myr ago following cessation of silicic volcanism and contemporaneous with migration of basaltic activity toward the southwest margin of the Great Basin. Two types of fields are present in the belt: (1) large-volume, long-lived basalt and local rhyolite fields with numerous eruptive centers and (2) small-volume fields formed by scattered basaltic scoria cones. Late Cenozoic basalts of the NTS region belong to the second field type. Monogenetic basalt centers of this region were formed mostly by Strombolian eruptions; Surtseyean activity has been recognized at three centers. Geochemically, the basalts of the NTS region are classified as straddle A-type basalts of the alkalic suite. Petrological studies indicate a volumetric dominance of evolved hawaiite magmas. Trace- and rare-earth-element abundances of younger basalt (<4 Myr) of the NTS region and southern Death Valley area, California, indicate an enrichment in incompatible elements, with the exception of rubidium.

The conditional probability of recurring basaltic volcanism and disruption of a repository by that event is bounded by the range of 10^{-8} to 10^{-10} as calculated for a 1-yr period. Potential disruptive and dispersal effects of magmatic penetration of a repository are controlled primarily by the geometry of basalt feeder systems, the mechanism of waste incorporation in magma, and Strombolian eruption processes.

Three critical questions with respect to volcanic hazard studies are: (1) the degree of confidence in understanding volcanic processes, (2) the areas of uncertainty in hazard assessment, and (3) the procedures for hazard resolution. Volcanic hazard and risk assessment studies based on multiple research approaches show that there is a finite hazard of future volcanism but that the hazard levels are very low.

I. INTRODUCTION

Evaluating the potential hazards of future volcanism is an important part of site investigations that study the suitability of constructing a deeply buried repository to isolate high-level radioactive waste in the southwestern Nevada Test Site (NTS). Volcanism represents one of a number of possible tectonic processes that may cause changes in the environment of Yucca Mountain and adversely affect the ability of the site to isolate waste. The perceived hazard of volcanism is based on the geologic record of widespread and voluminous volcanism in the southcentral Great Basin during Cenozoic time and the local presence of Quaternary volcanic centers in the NTS region. If ascending magma directly intersects a repository, there is a possibility of local-to-regional dispersal of minor-to-significant quantities of radioactive waste elements by surface eruptions. In addition, injection of magma within the immediate vicinity of a repository could alter the geologic and hydrologic setting of the site and change transport pathways of waste elements. The exact nature of the hazard is dependent on the composition of the magma, the geometry of magma/waste intersection, and the timing of the volcanic event with respect to activation of the repository. These factors have been discussed for volcanic processes in general by Crowe (1980) and are discussed briefly for the NTS region by Crowe and Carr (1980). The purpose of this report is to (1) summarize the results of completed volcanic hazard studies through reference to published papers, (2) discuss briefly results of work as yet unpublished, (3) describe plans for future work necessary to complete the volcanism studies for site licensing, and (4) provide expanded discussions of volcanism topics summarized in the Site Characterization Report.

There are two factors in volcanic hazard assessment for the NTS region: (1) future hazards of silicic volcanism and (2) future hazards of basaltic volcanism. Crowe and Sargent (1979) examined the stratigraphy and geochemistry of the youngest major silicic volcanic center in the NTS region, the Black Mountain volcanic center. They note that volcanism associated with this center represents a distinct episode of renewed silicic activity following cessation of the Timber Mountain-Oasis Valley magmatic cycle. This renewal suggests there is a finite, although extremely small, likelihood of recurrence of silicic volcanism. Although the hazard exists, it is considered to be negligible for a number of reasons.

- (1) There has been no silicic volcanism within the NTS region for at least the last 5 Myr. The youngest major silicic center in the region is the Black Mountain caldera, which was active about 7 to 8 Myr ago.
- (2) There has been a dramatic regional decrease, and in-most areas a cessation, of silicic volcanic activity within the central and southern parts of the Great Basin during the last 10 to 20 Myr.
- (3) Silicic volcanic activity of Quaternary age is restricted entirely to the margins of the Great Basin. Regionally dispersed air-fall tuff from future eruptions of silicic centers in the western Great Basin could be deposited in the NTS region. However, such deposits would pose no recognized hazard to a repository.

The judgement of negligible hazards with respect to future silicic volcanism was endorsed in the written responses of the peer review panel, based on the July 1979 meeting on the tectonics, seismicity, and volcanism of the NTS region.

It is much more difficult to define and assess the hazards of future basaltic volcanism as a result of a number of circumstances. First, there is considerable uncertainty in forecasting future rates of volcanic activity. Second, areas under consideration for waste disposal must, according to siting criteria, have low rates of volcanic activity during Quaternary time. By requirement, the Quaternary geologic record used to forecast rates of volcanism is limited. Third, the suitability of data from older volcanic activity is dependent on the degree of preservation of the deposits and the precision of age-determination techniques. Thus, there is not a single and direct approach that yields a clear definition of volcanic hazards. Rather, a number of methods are used and the results from these methods are compared for consistency.

Research methods to date include:

- . geology and geochemistry investigations,
- . tectonic setting,
- . eruptive history,
- . geochemistry and petrology,
- . probability calculations, and
- . consequence analyses (including scenario development and radiation release calculations).

The first five topics are standard techniques of volcanic hazard assessment, and the latter two topics are standard approaches to risk assessment.

In the remainder of the paper, we describe the status of these studies and future research directions.

II. GEOLOGY AND GEOCHRONOLOGY INVESTIGATIONS OF BASALTIC VOLCANISM

Regional geologic studies of late Cenozoic basaltic volcanic centers were undertaken to establish the history and geologic characteristics of volcanic activity in the southern Great Basin. Detailed mapping and sampling of basalt centers of the NTS region have been completed (generally at a scale of 1:12 000). Results of studies of the basalts of Crater Flat, the basalt field located west and southwest of Yucca Mountain, have been described by Crowe and Carr (1980) and Vaniman and Crowe (1981). Crowe and Carr (1980) published a map of all the basalt centers of southern Crater Flat. Vaniman and Crowe (1981) published detailed maps of individual basalt centers of Crater Flat at a scale of 1:12 000, including two maps of deeply dissected basalt centers of the 3.7-Myr basalt cycle, a detailed map of the Red Cone volcanic center (1.4 Myr), and a detailed map of the Lathrop Wells volcanic center (0.3 Myr). The purpose of this work was to characterize the past history of volcanic activity in the NTS region for hazard assessment and to predict rates of future activity for risk assessment.

Reconnaissance geologic mapping (scales of 1:48 000 to 1:62 500) and sampling of volcanic rocks throughout the southern Great Basin have been completed. This work has focused on basalts of the Pancake Range, the Lunar Crater area, the Reveille and Greenwater Ranges, and immediate areas surrounding the NTS. It was directed at establishing the regional character and history of volcanic activity in the southern Great Basin to determine patterns of basaltic activity in the NTS region from a regional perspective.

The regional distribution of basaltic rocks younger than 10 Myr within the southwestern Great Basin of Nevada and California defines two volcanic belts or subprovinces [Fig. 1 in map pocket (compiled and modified from Luedke and Smith, 1981)]: (1) a zone of Quaternary basalt and local silicic centers that are concentrated along and mark the southwestern margin of the Great Basin and (2) a somewhat diffuse but generally continuous belt of Pliocene and younger volcanic activity that extends from southern Death Valley N-NE through the NTS region to central Nevada (Crowe et al., 1980). We refer to this feature as the Death Valley-Pancake Range belt (DV-PR).

Geologic and geochronologic studies of volcanic rocks in the southern Great Basin have defined the timing and spatial evolution of basaltic volcanism

during late Cenozoic time with emphasis on the DV-PR volcanic belt. The belt developed as a recognizable volcanic feature following cessation of silicic volcanism in the southern Great Basin at about 8 to 9 Myr ago (Crowe and Carr, 1980; Vaniman and Crowe, 1981). At this time, basaltic volcanism, which had been relatively widespread but of small volume in the southern Great Basin (Christiansen and McKee, 1978), surpassed silicic volcanism in erupted volume. Sites of active basaltic and minor silicic volcanism shifted progressively toward the margins of the southwestern Great Basin with the exception of the DV-PR. This is shown by the generally westward decrease in age of volcanic activity in eastern California and adjoining areas of western Nevada (Fig. 1). The oldest rocks that succeed voluminous silicic activity include basaltic and silicic centers (predominantly bimodal suites) of 7- to 11-Myr age that extend from northwestern Nye County, Nevada, southeastward to the NTS region, paralleling the Walker Lane structural system (see also Stewart and Carlson, 1978). Rocks in the age range of 2 to 6 Myr, which are predominantly of basaltic to basaltic andesite composition, crop out within an area extending from east-central Nevada S-SW through the Death Valley region to the Garlock fault (Fig. 1). The youngest rocks, less than 2 Myr, crop out along the southwestern boundary of the Great Basin parallel to the eastern boundary of the Sierra Nevada Range (Fig. 1). With rare exceptions (basalts of Silver Peak, Ubehebe Craters, and the DV-PR volcanic belt), there has been no volcanic activity east of the westward migrating zones of volcanism during the period 8 Myr to recent. Thus, regional studies indicate that the DV-PR volcanic belt of the southern Great Basin has been a persistent zone of basaltic activity following cessation of silicic volcanic activity and during a period in which levels of basaltic activity west of the belt declined.

There has been a near continuum in basaltic activity through time for the NTS region, following cessation of the silicic volcanic cycle. Detailed geologic mapping and age determinations have shown that basaltic volcanism can be divided into two cycles:

older basalts that are related spatially to silicic volcanic centers and were generally erupted during the waning stages of silicic volcanism (basalts of the silicic cycle). These basalts are not part of the DV-PR volcanic belt.

younger basalts that postdate and are genetically unrelated to the silicic volcanic cycle (rift basalts). These rift basalts are the

principal volcanic centers of the DV-PR volcanic belt; they are called rift basalts because of their common association with extensional structural features.

The oldest basaltic activity clearly associated with the volcanic belt (rift basalts) in the NTS region includes the basalts of Nye Canyon, Rocket Wash, and Paiute Ridge areas, which have been dated at about 6.5 to 8.5 Myr (Fig. 1). This association is suggested by the straddle-type compositional association of the basalts of Paiute Ridge and Rocket Wash (see Sec. V) and by the parallelism of Nye Canyon basalt vent systems to the trend of the volcanic belt (N-NE). In most other areas of the DV-PR belt, there is a long hiatus between silicic and belt volcanism. For example, basaltic volcanic activity within the Reveille Range (4 to 6 Myr) is much younger than older, voluminous silicic activity (25 to 30 Myr) (Ekren et al., 1974a).

Rates of basaltic activity in the belt have remained relatively constant but generally low. This is illustrated by the distribution of areas of activity during specified periods of late Cenozoic time. For example, sites of Quaternary activity (<2.0 Myr) include the basalt of southern Death Valley, scattered basalt centers in the southwestern and western NTS region (two basalt cycles of Crater Flat and the basalt of Sleeping Butte), and the basalt of the Lunar Crater volcanic field (Fig. 1). Areas of activity during the period 2 to 4 Myr include the northern part of the Greenwater Range, the older cycle of the basalt of Crater Flat, the basalt of Buckboard Mesa, and the southern part of the Lunar Crater volcanic field. This pattern of sporadic volcanic activity in space and time has been maintained throughout the history of belt volcanism. The belt is recognizable as a major geologic feature within the southern Great Basin because of persistent but low rates of activity along its length during late Cenozoic time.

Two distinct types of volcanic fields have been recognized within the DV-PR belt.

Type I: Large-volume ($>2\text{-km}^3$), long-lived (age range of several million years) volcanic fields with a range of basalt types and associated, more silicic, volcanic rocks that were derived by fractionation from the basalts or were produced by melting of the lower crust during the thermal event that produced the basalts.

Type II: Small-volume ($<2\text{-km}^3$ total volume with typical centers of 0.1 km^3 or less), monogenetic Strombolian scoria cones or clusters of scoria cones. These basaltic centers generally formed during brief cycles of activity that were separated by longer periods of inactivity. They generally are of evolved basaltic composition ($\text{Mg}/\text{Mg} + \text{Fe}^{2+} < 0.55$) with no accompanying parental magmas.

Characteristics of the field types for the volcanic centers of the belt are summarized in Table I.

III. TECTONIC SETTING

The tectonic setting of volcanic fields of the DV-PR belt and the detailed setting of eruptive centers within individual fields have been examined to evaluate the structural controls of volcanism. Several structural associations are suggested on a regional basis, but their exact relation to the formation of individual fields or the DV-PR belt is not known. First, many of the sites of volcanic activity in the southwestern Great Basin are controlled structurally by extensional or right-slip faults within the Walker Lane structural system. Second, the DV-PR belt is elongate in a N-NE direction that is parallel to the probable Neogene extension direction in the southern Great Basin (Carr, 1974; Wright, 1976; Zoback and Thompson, 1978; Zoback and Zoback, 1980; and Sbar, 1982). Third, the volcanic belt is adjacent and subparallel to a line of bilateral symmetry in the long-wavelength anomalies of the regional Bouguer gravity field. This symmetrical gravity field is a major geophysical feature of the Great Basin and has been attributed to the rise and divergent flow of hot, asthenospheric mantle (Eaton et al., 1978). The axis of gravity symmetry is interrupted to the south, however, at an E-W trending, 90-Mgal step in the gravity field near the latitude of the NTS region (Eaton, 1979). Finally, the belt is parallel to but located about 100 km east of the western boundary of Precambrian crystalline rocks. Regionally, this is an inferred boundary based on strontium isotopic studies of granitic rocks (Kistler and Peterman, 1978). More recent work, using combined neodymium and strontium isotope evidence, suggests that the basement edge may be located about 100 km farther eastward in central Nevada (Farmer and De Paolo, 1983). These limited new data suggest a close association between the location of at least the northern part of the

TABLE I
SUMMARY CHARACTERISTICS OF MAJOR VOLCANIC FIELDS IN THE DV-PR
VOLCANIC BELT OF THE SOUTHCENTRAL GREAT BASIN

<u>Location</u>	<u>Field Type</u>	<u>Description</u>	<u>Age (Myr)</u>
Southern Death Valley, California	II	Small, dissected Strombolian scoria cone with a locally exposed and probably related tuff sheet of pyroclastic surge deposits; lavas of basaltic andesite locally interbedded with fanglomerate.	0.7 and 1.7 ^a
Greenwater and Black Ranges, Death Valley, California	I	Three episodes of volcanic activity, each separated by a major unconformity. Only the uppermost unit, the Greenwater Volcanics and the basalt of the Funeral Formation, are included in the DV-PR belt. This sequence is a bimodal suite of interbedded basalt and rhyodacitic to rhyolitic lavas with local air-fall tuff.	4 to 7.5 ^a
NTS Region (basalts of the silicic cycle)	I	Large-volume lava eruptions with locally thick lava sheets and shield-like complexes. Generally erupted along the periphery of silicic volcanic centers during the waning stages of activity. Examples include the basalts of Basalt Ridge, Dome Mountain, Kiwi Mesa, and Skull Mountain.	9 to 11

TABLE I (Cont)

<u>Location</u>	<u>Field Type</u>	<u>Description</u>	<u>Age (Myr)</u>
NTS region (rift basalts)	II	Monogenetic scoria cones or clusters of cones with associated small-volume lavas. Erupted during discrete pulses of activity. Examples are basalts of Silent Canyon, Nye Canyon, Crater Flat, Buckboard Mesa, and Sleeping Butte.	8.5 to 0.3
Kawich Valley	II	Isolated scoria cones, lavas, and small plugs.	8 to 10
Northern Reveille Range	I	Coalesced scoria cones and large-volume lavas that form lava sheets and local shield complexes. Local occurrence of derivative trachyandesite to trachyte plugs or domal masses.	4 to 6
Lunar Crater volcanic field	I	Numerous monogenetic Strombolian and Surtseyan centers (110 of probable Quaternary age) with small- to large-volume lavas ranging from short flows to fluidal, sheet lavas.	4 to Recent

^aMost of the potassium-argon ages for the southern Death Valley region were obtained from L. Wright, Pennsylvania State University, University Park, PA 16802 (1982 and 1983).

volcanic belt and the western edge of cratonic basement rocks. The exact boundary of basement rocks is poorly known in the NTS region; precambrian basement rocks are exposed only in southern Death Valley.

Crowe and Carr (1980) recognized three structural settings associated with the occurrence of basaltic volcanism within the southern Great Basin. These include, in probable order of decreasing frequency of occurrence,

- (1) N-NE trending zones of extension between active or formerly active NW trending, strike-slip faults,
- (2) ring-fracture zones of inactive cauldrons, and
- (3) basin-range faults.

Not all areas containing these tectonic features are sites of volcanic activity, and sites of future volcanic activity cannot be predicted directly on the basis of tectonic features. However, in a qualitative fashion, the above tectonic settings are areas of relatively higher risk of volcanism than sites lacking these features. There is no consistently predictable relationship between volcanism and local tectonic features. The features may merely provide the structural pathways for the ascent of magma from depth, although a genetic relationship between faulting, for example, and volcanism is possible. The tectonic setting of major basalt centers within the belt is summarized in Table II.

IV. STRATIGRAPHY AND ERUPTIVE HISTORY

Detailed studies were made of Quaternary basalt centers of the NTS region to establish the history, style, and volume of past basaltic eruptions. Such data are necessary to determine potential mechanisms of repository disruption and to determine the processes and potential distances of transport of waste elements by volcanic activity. The predominant type of basalt center in the NTS region comprises moderate-size scoria cones generally flanked by short lava flows. Size dimensions and magma volumes of Quaternary basalt centers of the NTS region are listed in Table III. Scoria-fall sheets inferred to have originally flanked the scoria cones and extended downwind are now largely removed by erosion. The predominant eruption style of Quaternary basalt centers in the NTS region was Strombolian (Crowe et al., 1983). Eruptions typically formed distinct sequences consisting of (1) opening fissure

TABLE II

TECTONIC SETTING OF MAJOR BASALT FIELDS IN THE
VOLCANIC BELT OF THE SOUTHCENTRAL GREAT BASIN

Locality	Tectonic Setting
Southern Death Valley	On the Death Valley fault zone, a major NW trending, right-slip fault.
Greenwater- Black Ranges	An area of volcanic activity located within a possible "pull apart" rift basin between the Furnace Creek and Death Valley fault zones.
NTS region (basalts of the silicic cycle)	Within or flanking cauldron complexes, commonly on ring-fracture systems.
NTS Region (rift basalts)	(1) Caldera ring-fracture systems, commonly at their intersection with basin-range faults, (2) basin-range faults, and (3) N-NE trending zones of extension, possibly located between en echelon segments of NW trending strike-slip faults of the Walker Lane structural system. May be analogous to a "leaky transform" setting (see Weaver and Hill, 1979).
Kawich Valley	Basin-range faults.
Reveille Range	(1) Basin-range faults and (2) N-NE trending extensional zones between N-NW trending, right-slip faults with a probable older history of left-slip offset (Tybo-Reveille fault system).
Lunar Crater volcanic field	Major N-NE trending rift zone that cuts across a major N-S trending basin-range block and older cauldron complexes (20 to 30 Myr). Rift may have followed an older system that localized silicic volcanism (Ekren et al., 1974b). Older basalts were erupted along cauldron ring-fracture zones; younger basalts follow the N-NE trending rift zone.

TABLE III
 SIZE PARAMETERS FOR THE BASALTIC CENTERS OF THE NTS REGION

<u>Volcanic Center</u>	<u>Height (m)</u>	<u>Width (m)</u>	<u>Cone Volume (m³)</u>	<u>Flow Volume (m³)</u>	<u>Vents</u>	<u>Total Magmatic Volume (m³)^a</u>
Lathrop Wells	140	690	1.7×10^7	1.6×10^7	3	5.7×10^7
Little Cone No. 1	43	360	1.5×10^6	3.0×10^6 ^b	1	6.2×10^6
Little Cone No. 2	27	220	3.4×10^5	--	1	7.8×10^5
Red Cone	73	435	3.7×10^6	1.9×10^7	6	2.6×10^7
Black Cone	121	525	2.7×10^7	4.4×10^7	3	1.0×10^8
Sleeping Cone No. 1	63	240	2.7×10^6	4.9×10^6	1	1.1×10^7
Sleeping Cone No. 2	70	562	5.8×10^6	8.1×10^6	1	2.1×10^7

^aMagmatic volume is equal to the volume of the cone plus the volume of an inferred scoria sheet plus the lava volume corrected to magmatic density.

^bCalculated volume of lava flow that is largely buried by alluvium; areal coverage of the flow was determined through interpretation of aeromagnetic data.

eruptions; (2) vigorous pyroclastic activity with several active vents that focus with time to one vent, which becomes the main scoria cone for the basalt center; (3) lava extrusion associated with the maximum magma flux; (4) cone modification and dike injection; and (5) a weakly explosive pyroclastic phase--the general final stage of activity. This eruption sequence can be attributed to variations in the degree of bubble coalescence within the magma column between the sites of volatile exsolution and magma fragmentation (Crowe et al., 1981). This interpretation assumes a feeder conduit of constant dimensions and a mass eruption rate that rises rapidly and declines exponentially over the duration of activity (Wadge, 1981). These observations have important implications. The most likely time of incorporation of significant quantities of radioactive waste debris in basalt is early in an eruptive cycle if rising magma breaks through a repository and establishes feeder pathways to the surface. Early erupted magma may therefore be the most highly waste-element-contaminated material of an eruptive cycle and would be ejected preferentially with the initial pyroclastic phase.

Hydromagmatic or Surtseyan eruptive deposits have been recognized at the Lathrop Wells volcanic center and two of the Nye Canyon centers. This type of activity is associated with an increased degree of particle fragmentation, may transport debris a greater distance than Strombolian deposits, and generally incorporates a greater abundance of country-rock debris. All three factors increase the consequences of magmatic disruption of a repository, and thus, the possibility of Surtseyan eruptions is important to hazard assessment. Crowe et al. (1983) examined the controls of Surtseyan eruptions in the NTS region. They note that the considerable depth to the groundwater table, the absence of surface water, and the probable extremely low flux of water in the unsaturated zone all indicate that maintained Surtseyan eruptions are unlikely at Yucca Mountain (Fig. 2). The only condition that could lead to maintained Surtseyan eruptions is the presence of relatively shallow perched groundwater.

V. REGIONAL PETROLOGY AND GEOCHEMISTRY OF BASALTIC VOLCANISM

Petrologic studies of basaltic volcanism in the southern Great Basin are conducted to establish the character of past basalt types, to examine changes in basalt compositions with time, and to evaluate, where possible, the processes leading to generation of basalt magma. Particular emphasis is given to the

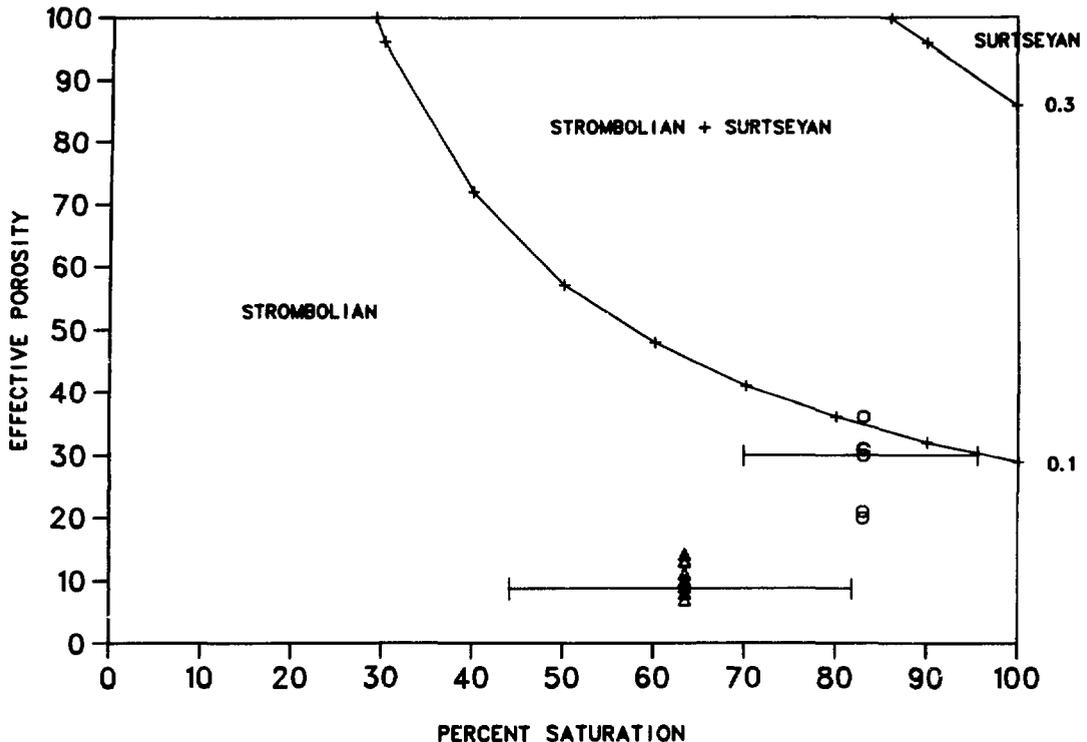


Fig. 2. Strombolian, Strombolian and Surtseyan, and Surtseyan eruption fields plotted with respect to effective porosity and per cent saturation for unsaturated tuffs of Yucca Mountain. Position of the eruption fields is determined by the water-to-magma mass ratio based on the experimental work of Sheridan and Wohletz (1981). As a result of the probable extremely low transport rates of water in the unsaturated zone for the NTS region (Winnograd, 1981) and except in the case of extreme recharge events, the water-to-magma ratio is determined by the resident moisture content. Mixed Strombolian-Surtseyan eruptions are possible only under extreme conditions of high porosity and high per cent saturation. Moreover, even under these conditions, hydrovolcanic eruptions could occur only in the opening eruptive phase because infiltration rates are too low to maintain the water-to-magma mass ratio for continued Surtseyan eruptions.

Triangles represent average effective porosity and saturation values for the Topopah Spring Member; circles represent average effective porosity and saturation values for the tuffaceous beds of Calico Hills. (Porosity values from Lappin, 1982; saturation values provided by W. Wilson, Water Resources Division, US Geological Survey, Denver, CO 80225, 1982).

petrological and geochemical trends of basaltic volcanism through time within the NTS region because these data aid in predictions of future volcanic activity.

Petrographic features of basalt localities within the NTS region are listed in Table IV. The basalts of the DV-PR belt can be divided into four types.

- (1) Aphyric to moderately porphyritic olivine basalt. These rocks are dominated by olivine as the major phenocryst phase with lesser amounts of plagioclase and clinopyroxene. Preliminary chemical data indicate they are predominantly of hawaiite composition. Examples include the basalts of Crater Flat, the basalts of Buckboard Mesa, and the younger basalts of the northern Greenwater Range.
- (2) Plagioclase porphyritic, clinopyroxene-olivine basalt. These rocks are moderately to strongly porphyritic with rare to abundant megacrysts of sieve-textured plagioclase, resorbed augite, and lesser amounts of olivine. Thin-section studies suggest multiple cycles of megacryst and phenocryst formation based on differing size populations and complex resorption of these crystals. Inclusions in these basalts are glomeroporphyritic clots of gabbroic composition, clinopyroxene-olivine gabbro (\pm phlogopite), and mantle peridotite (rare). Available chemical data indicate these rocks are predominantly hawaiites, alkali-olivine basalts, and basanites. Examples include basalts of the Reveille and Lunar Crater fields and the basalts of Nye Canyon and Silent Canyon.
- (3) Feldspathic clinopyroxene-olivine basalt to basaltic andesite and trachyte. These rocks are plagioclase rich, commonly with sieve-textured plagioclase phenocrysts and megacrysts and subordinate clinopyroxene and olivine. They are associated with Type I volcanic fields. Basaltic andesite and trachyte of this association may be derived by fractionation from the more voluminous basalts. Examples include the basalt of Dome Mountain and scattered trachyte domes of the Reveille Range.
- (4) Quartz-bearing clinopyroxene-olivine basalts. These basalts are porphyritic with phenocrysts consisting of plagioclase, olivine, and clinopyroxene in near equal amounts. Quartz phenocrysts are jacketed by coronas composed of clinopyroxene and glass. Examples include the basaltic andesites of Skull Mountain and the southern Greenwater Range.

TABLE IV
SUMMARY PETROGRAPHY OF MAJOR BASALTIC VOLCANIC ROCKS
OF THE NTS REGION

<u>Name</u>	<u>Description and Occurrence</u>	<u>Petrography</u>	<u>Age^a (Myr)</u>
<u>SILICIC CYCLE BASALTS</u>			
Dome Mountain	Thick sequence of lava flows and flow breccia interbedded locally with fanglomerate. Exposed in Fortymile Canyon in the moat of the Timber Mountain Caldera.	Plagioclase-porphyritic cpx-olivine basalt to mafic andesite. Local sieve-textured plagioclase and gabbroic glomeroporphyritic clots. Moderately to highly porphyritic; textures are intergranular.	~10
Black Mountain	Flank lava flows of the Black Mountain center that underlie and locally interfinger with the Thirsty Canyon Tuff.	Fine-grained, plagioclase porphyritic olivine basalt; textures are intergranular to hyalopilitic	~8-9
Beatty	Deeply dissected scoria cones and lavas in the Beatty area.	Moderately porphyritic cpx olivine basalt ± phlogopite. Textures are intergranular to intersertal.	~10
Older basalt of Crater Flat	Deeply dissected scoria cone, conduit plug, and local lavas exposed at the south end of Crater Flat.	Moderately porphyritic cpx-olivine basalt with glomeroporphyritic gabbro clots; textures are intergranular.	10.5 ± 0.1

TABLE IV (cont)

Name	Description and Occurrence	Petrography	Age ^a (Myr)
Dikes of Yucca Mountain	N-NW trending dike set exposed in the central and northwestern part of Yucca Mountain.	Fine-grained, feldspathic olivine basalt with rare glomerophyritic clots (cpx-bearing); texture intergranular.	10.0 ± 0.4
Skull Mountain	Lava flow sequence that caps Skull and Little Skull Mountains.	Moderately porphyritic quartz-olivine basaltic andesite with sieve-textured plagioclase phenocrysts; textures intersertal to hyalopilitic, rarely intergranular.	10.2 ± 0.5
Kiwi Mesa	Lava flow sequence in the north-eastern corner of Jackass Flat.	Fine-grained, sparsely porphyritic, olivine basalt with rare sieve-textured plagioclase and cpx phenocrysts. Relict opx cores preserved with cpx jackets; texture intergranular.	9.7 ± 0.3
Jackass Flats	Isolated lavas surrounded by alluvial deposits in the center of Jackass Flat. May extend into the Little Skull Mountain area where it interfingers with the basalt of Skull Mountain.	Coarse-grained, moderately porphyritic cpx-olivine basalt; texture subophitic.	11.0 ± 0.4

TABLE IV (cont)

Name	Description and Occurrence	Petrography	Age ^a (Myr)
<u>RIFT BASALTS</u>			
Silent Canyon	Two isolated localities, both consisting of dissected cone scoria with minor lavas in Pahute Mesa.	<p><u>Eastern Locality:</u> plagioclase porphyritic olivine basalt with rare resorbed cpx and plagioclase megacrysts, texture intergranular.</p> <p><u>Western Locality:</u> Porphyritic phlogopite-cpx-olivine basalt with megacrysts of plagioclase, cpx, and rare olivine. Xenoliths of phlogopite-cpx gabbro; Textures intergranular.</p>	<p><u>Eastern Locality</u> 8.8 ± 0.1</p> <p><u>Western Locality</u> 10.4 ± 0.4 9.1 ± 0.7</p>
Paiute Mesa	Basalt intrusions (dikes, sills, and lopoliths), local cone scoria, and lavas. Emplaced within a NW trending zone of normal faults, Paiute Ridge.	Cpx-olivine basalt, diabase, and local pods of derivative augite monzonite within interior parts of thick intrusions.	8.7 ± 0.3 8.5 ± 0.3
Rocket Wash	Deeply dissected scoria cone and lava flows emplaced along the intersection of the western ring-fracture zone of the Timber Mountain caldera with a N-S trending basin-range fault.	Moderately porphyritic olivine basalt with scattered phenocrysts of cpx. Probably olivine accumulative; texture is intergranular.	8.0 ± 0.2

TABLE IV (cont)

Name	Description and Occurrence	Petrography	Age ^a (Myr)
Nye Canyon	Three exposed basalt centers and one buried center penetrated in drill holes in Frenchman Flat. Northern center consists of scoria cone and lavas; the two southern centers are deeply eroded tuff cones filled by lava lakes. The four centers are aligned along a zone of trend N-NE.	Moderately to highly porphyritic cpx-olivine basalt with minor to abundant megacrysts of resorbed cpx and sieve plagioclase. Middle center contains numerous xenoliths of cpx gabbro; southern center contains rare megacrysts of kaersutite; textures intergranular to intersertal.	6.8 ± 0.2 7.2 ± 0.2 6.3 ± 0.2
Crater Flat	Monogenetic scoria cones, lavas, and dissected cones with dikes in scoria. Exposed in and southeast of Crater Flat.	Aphyric to sparsely porphyritic olivine basalt with microphenocrysts of plagioclase. Older basalt cycle contains glomeroporphyritic clots bearing cpx; textures intergranular to intersertal (altered samples) and hyalopilitic.	Three cycles with average ages 3.7, 1.2, and 0.3, respectively.

TABLE IV (cont)

Name	Description and Occurrence	Petrography	Age ^a (Myr)
Buckboard Mesa	Dissected scoria cone and associated large-volume lava flows. Exposed in the northeastern side of the moat zone of the Timber Mountain caldera.	Most of the lavas are aphyric to sparsely porphyritic olivine basalt with microphenocrysts of plagioclase. Rare plagioclase phenocrysts. Cpx present in rare glomeroporphyritic clots. Textures intergranular. Local flows north of the source cone are plagioclase-porphyritic, quartz-kaersutite-bearing olivine basalt. Texture is hyalopilitic.	2.82 ± 0.04 2.79 ± 0.10
Sleeping Butte	Two isolated scoria cones and small-volume lavas near the ring-fracture zone of the Sleeping Butte Caldera segment.	Sparsely to moderately porphyritic olivine basalt and cpx-olivine basalt. Southern center is more porphyritic with abundant cpx, glomerophyritic clots, and rare kaersutite. Textures are hyalopilitic to intergranular.	0.29 ± 0.11 0.32 ± 0.15 0.24 ± 0.22

^aPotassium-argon ages from R. F. Marvin and R. J. Fleck, US Geological Survey, Denver, Colorado. Approximate ages are based on field relations with rocks of known potassium-argon age.

Vaniman and Crowe (1981) discussed the petrologic features of the basalts of Crater Flat, which are located directly west and southwest of the exploration block. They note that the basalts are sparsely to moderately porphyritic with olivine as the major phenocryst phase and lesser amounts of plagioclase (largely microphenocrysts), clinopyroxene, and rare kaersutitic amphibole. Major element data indicate that the basalts are evolved hawaiites and the parental magmas related to the hawaiites were not erupted at the surface. Field, geochronological, and geochemical data indicate three distinct cycles of basalt activity (3.7, 1.2, and 0.3 Myr); each cycle is of hawaiite composition but is unrelated in origin to previous cycles. These data require the repeated generation through time of compositionally similar, but magmatically unrelated cycles of hawaiite magma. The major-element composition of the basalts of Crater Flat range from nepheline to hypersthene normative (Vaniman and Crowe, 1981; Vaniman et al., 1982). Trace-element abundances suggest fractionation from parental magmas by the removal of olivine, clinopyroxene, or amphibole. Such fractionation over a range of depths drives the residual liquid compositions into the hypersthene- or nepheline-normative fields, depending on the absolute percentages of fractionating phases and particularly on the role of amphibole (Vaniman et al., 1982). Trace- and rare-earth element analyses show that the two younger cycles of the basalts of Crater Flat are enriched in incompatible trace elements, particularly strontium. This enrichment may be inherited from their mantle source regions or be caused by crustal contamination. Furthermore, a depletion in rubidium or a lack of rubidium enrichment necessary to be consistent with the general incompatible trace-element enrichment is superimposed on this enrichment. This leads to two important conclusions: First, the rubidium values are too low to generate the high $^{87}\text{Sr}/^{86}\text{Sr}$ values (~ 0.707) measured for the basalts of Crater Flat and for basalts of the surrounding region (Leeman, 1970; Hedge and Noble, 1971). This suggests an ancient enrichment in rubidium for the mantle source rocks, which was followed by a later rubidium depletion. Second, the rubidium values are too low and the strontium values too high to allow derivation of the high $^{87}\text{Sr}/^{86}\text{Sr}$ values by simple crustal contamination without significantly modifying the major-element contents of the basalts. Third, geologic evidence from the NTS region and Greenwater Range, California, indicates that the trace-element enrichment of young basalts (< 4 Myr) and the accompanying rubidium exclusion may be a

regional event (Vaniman et al., 1982). Present petrological studies are focused on the origins of this enrichment event to test whether it has affected the rates of magma generation.

Representative major-element analyses of the basalts of the southern Great Basin are listed in Table V. Analyzed rocks range from nepheline to hypersthene normative, and respective basalt names include basanite, hawaiiite, alkali-olivine basalt, and basaltic andesites; hawaiiite is the most common basalt type. These rocks are typical of basalts described throughout the Great Basin (Leeman and Rogers, 1970; Best and Brimhall, 1974; Lowder, 1973; Best and Hamblin, 1978; Moore and Dodge, 1980; and Duffield et al., 1980). The term hawaiiite is used after Best and Brimhall (1974) with the modifications of Vaniman et al. (1982). Hawaiiites are characterized by SiO_2 contents within the higher end of the basalt range, by low $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ ratios (generally <0.55), and by sodium-rich normative feldspar (oligoclase or andesine). Hawaiiites within the NTS region can be further classified as straddle-type basalts of the alkalic suite (Miyashiro, 1978). This is indicated by several lines of evidence.

- (1) Compositions range from slightly nepheline to slightly hypersthene normative.
- (2) Suggested parental compositions, where known, straddle the diopside-olivine join in the basalt tetrahedron diagram (Yoder and Tilley, 1962).
- (3) The basalts show mineralogical affinities to the alkali basalt suite (calcium-rich pyroxene; limited evidence of a reaction of olivine to form calcium-poor pyroxene).
- (4) Basalts plot consistently in the alkali field of the $\text{Na}_2\text{O} + \text{K}_2\text{O}/\text{SiO}_2$ diagram (Fig. 3a).

Hawaiiites are of particular significance to volcanic hazard studies as they are the most common rock type among the younger basalts of the NTS region. The uniformity of hawaiiite compositions and their consistently small volume through time provides support for predictions of future rates of volcanic activity (Vaniman and Crowe, 1981). The dominance of evolved hawaiiites in the NTS region may suggest density trapping of primary magmas, probably at the crust/mantle interface, followed by fractionation of olivine and clinopyroxene, which reduces the residual liquid density (Vaniman et al., 1982; Crowe et al., 1983). As

TABLE V
 MAJOR-ELEMENT AND CIPW-NORMATIVE COMPOSITIONS OF BASALT
 OF THE SOUTHCENTRAL GREAT BASIN^a

No. of analyses	<u>Sierra Nevada and Western Great Basin</u>		<u>NTS-Region Rift Basalts</u>			<u>Pancake Range</u>		<u>Eastern Great Basin</u>	
	<u>Ultrapotassic</u>	<u>Alkaline</u>	<u>Old</u>	<u>Young Ne norm</u>	<u>Young Hy norm</u>	<u>Basanite</u>	<u>Hawaiite</u>	<u>Basanite</u>	<u>Hawaiite</u>
	4	12	12	8	9	15	15	34	163
<u>Major-element composition (wt %)</u>									
SiO ₂	51.0	49.0	48.9	48.2	50.9	44.1	47.8	44.9	49.4
TiO ₂	1.52	1.3	1.74	2.05	1.39	2.34	1.93	2.4	1.7
Al ₂ O ₃	13.1	14.5	15.4	16.2	16.9	15.2	15.2	13.6	15.8
FeO	6.8	7.8	11.4	11.0	9.6	11.2	11.4	12.3	10.5
MgO	8.3	9.9	7.1	5.4	5.1	8.1	7.9	10.5	8.0
CaO	6.7	8.6	9.5	9.3	9.0	10.3	8.9	9.9	8.9
Na ₂ O	2.24	3.0	2.92	3.67	3.42	3.73	3.09	3.4	3.4
K ₂ O	7.2	2.4	1.52	1.89	1.60	1.80	1.13	1.6	1.1
P ₂ O ₅	1.57	0.76	0.76	1.39	1.15	0.65	0.37	--	--
Total	97.4	97.3	99.2	99.1	99.1	97.4	97.7	98.6	98.8

TABLE V (cont)

	Sierra Nevada and Western Great Basin		NTS-Region Rift Basalts			Pancake Range		Eastern Great Basin	
	Ultrapotassic	Alkaline	Old	Young Ne-norm	Young Hy-norm	Basanite	Hawaiite	Basanite	Hawaiite
<u>Normative compositions (cation %)</u>									
Qtz	--	--	--	--	--	--	--	--	--
Or	43.1	14.3	9.1	11.3	9.6	10.8	6.8	9.5	6.5
Pl(An) ^b	10.2(17)	43.1(44)	51.2(48)	51.8(43)	57.4(46)	28.8(69)	53.1(47)	25.1(68)	54.6(45)
Ne	7.2	1.9	--	2.3	--	15.0	--	13.6	0.5
Di	17.3	15.1	14.3	12.1	9.0	22.3	14.3	25.6	15.7
Hy	--	--	5.2	--	13.4	--	1.6	--	--
Ol	15.7	20.9	14.3	14.8	4.7	16.6	18.8	20.9	18.6
Mf	1.1	1.3	1.9	1.8	1.6	1.8	1.9	2.0	1.7
Hm	2.2	1.8	2.4	2.9	2.0	3.3	2.7	3.3	2.4
Ap	3.3	1.6	1.6	2.9	2.4	1.4	0.8	b	b

^aData from Best and Brimhall (1974), Lowder (1973), Moore and Dodge (1980), S. Bergman, Princeton University, Princeton, NJ 08544 (1980), Vaniman et al. (1982), and our unpublished analyses.

^bAn content (%) of the total normative Pl listed in parentheses.

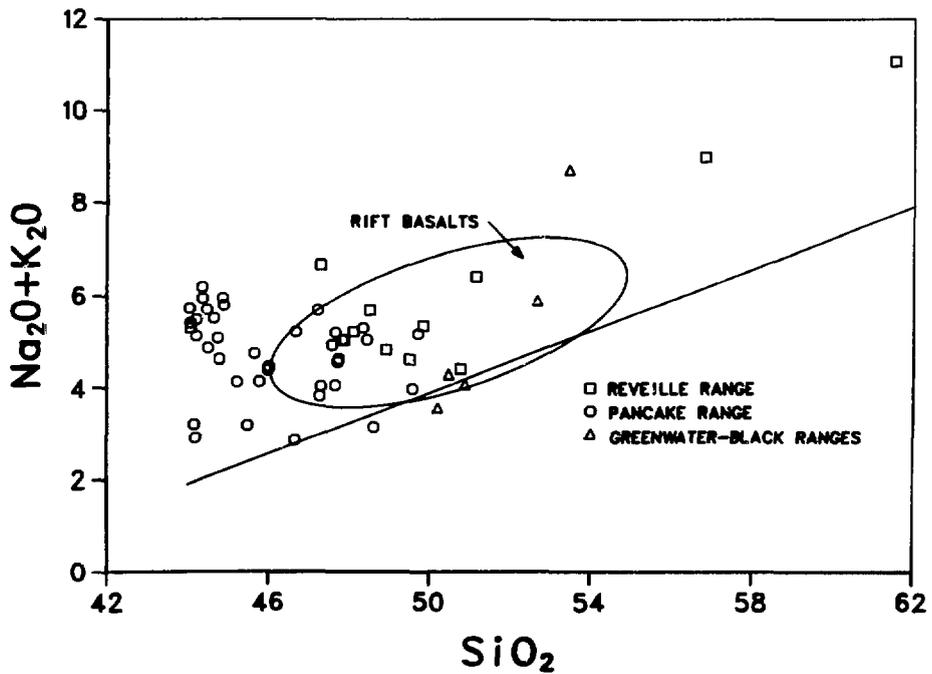
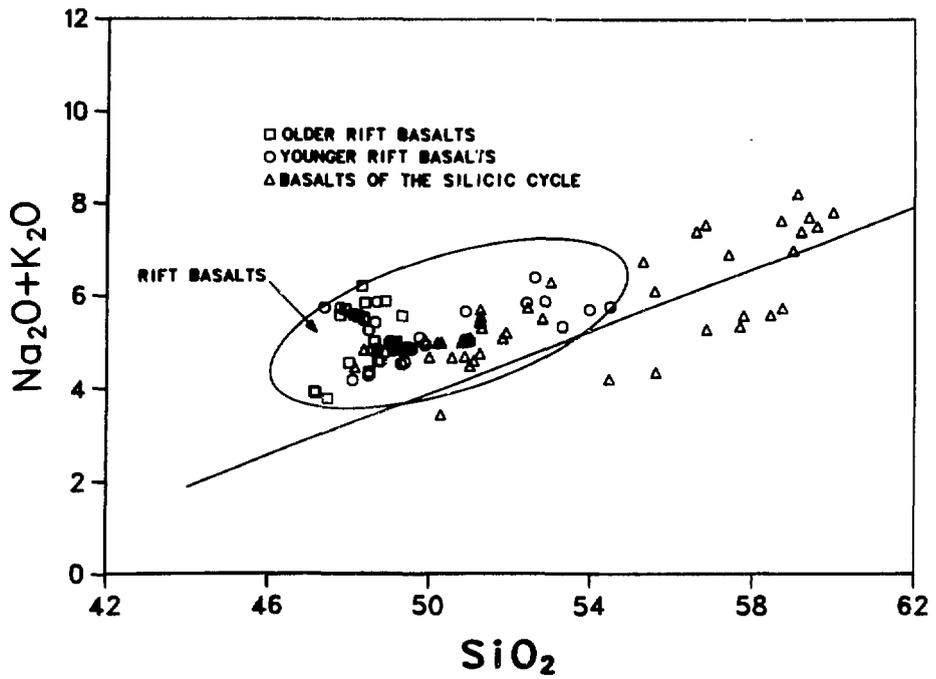
^cNot applicable.

the density of the melt decreases by fractionation, the melt may continue to ascend because of magma buoyancy, the density difference between magma and the overlying rock column. Such a mechanism, which was first suggested by Stolper and Walker (1980), provides a means to explain the evolved nature of hawaiites, the absence of primitive basalts, the absence of early crystallized phenocryst phases (aphyric nature of the basalts), and the absence of mantle xenoliths. These features are particularly prominent in the basalts of the NTS region.

Available geochemical data allow preliminary comparisons of the compositions of basalt of the NTS region with basalt from other areas of the Great Basin. Figures 3a, 3b, and 3c are, respectively, plots of $K_2O + Na_2O/SiO_2$ for basalts from the NTS region, the DV-PR volcanic belt, and the southwestern and southeastern margins of the Great Basin. Rift basalts of the NTS region plot within a relatively narrow area of the $Na_2O + K_2O/SiO_2$ diagram and above the McDonald-Katsura (1964) alkaline line (Fig. 3a). In contrast, basalts from all other localities, although overlapping in composition with the hawaiites of the NTS region, span a greater range of compositions and include minor subalkaline basalt (Figs. 3b and 3c). Figures 4a, 4b, and 4c are plots of samarium vs lanthanum for rift basalts of the NTS region, the volcanic belt, and the eastern and western margins of the Great Basin. Rift basalts of the NTS region plot in two fields with minor overlap. These fields correspond to highly enriched basalts (high samarium and lanthanum) and nonenriched basalts with lower values of samarium and lanthanum. Moreover, the fields are consistent with the age relations of the rift basalts. Younger rift basalts (<4 Myr) are enriched in samarium and lanthanum (as well as other incompatible trace elements), and older rift basalts (>6 Myr) show lower samarium and lanthanum values. Basalts of the volcanic belt plot primarily in the field of the older rift basalts, with the exception of basalts of the northern Greenwater Mountains and the southern Death Valley cone (Fig. 4b). These data indicate a spatial variation in trace-element enrichment as well as the time variation noted for the rift basalts of the NTS region. Basalts of the eastern and western margins of the Great Basin also plot within the field of the older rift basalts (Fig. 4c). This suggests that the older rift basalts have samarium and lanthanum contents typical of most basalts of the NTS region and emphasizes the highly enriched compositions with respect to lanthanum and samarium of the younger rift basalts. Work is under way to further refine our understanding of the origin of the trace-element-enriched basalts.

Fig. 3a. Total alkalis vs silica diagram for basaltic rocks of the NTS region. All the basalts, with the exception of the basaltic andesite of Skull Mountain, plot in the alkaline field of MacDonal and Katsura (1964). The rift basalts cluster in a relatively narrow field (circled). The basalts of the silicic cycle overlap with the field of the rift basalts but exhibit a much greater compositional diversity. Data are from Perry (1983) and our unpublished chemical analyses.

Fig. 3b. Total alkalis vs silica diagram for basaltic rocks of the DV-PR volcanic belt (excluding data from the NTS region). Circled area is the rift basalts from 3a. Basalts of the volcanic belt overlap with the rift basalt field but show a much greater range of compositional variation. Data provided by S. Bergman, Princeton University, Princeton, NJ 08544 (1982) and our unpublished analyses.



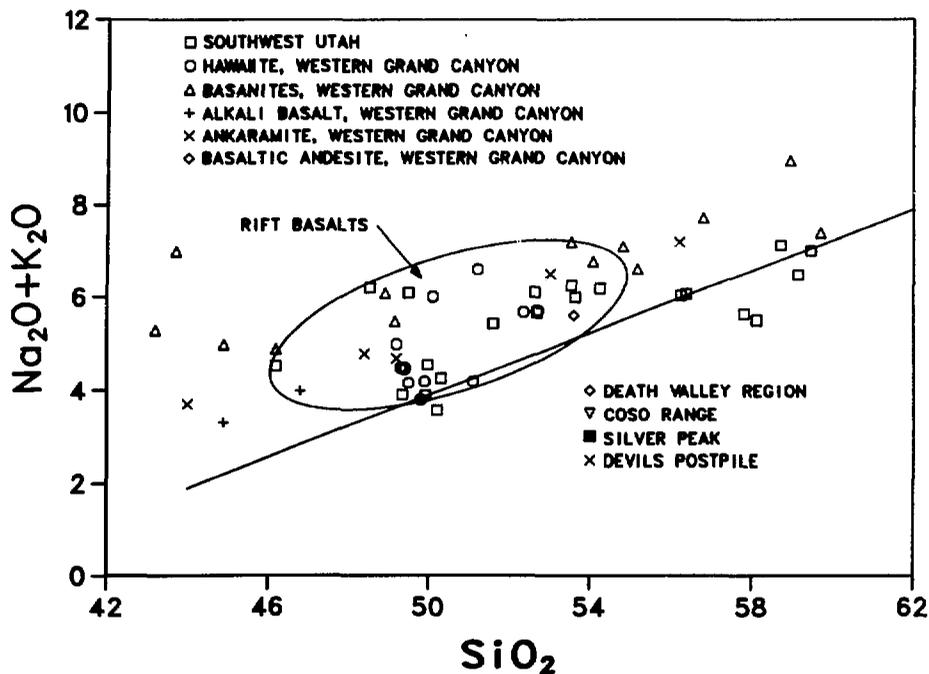


Fig. 3c. Total alkalis vs silica diagram for basaltic rocks of the southeastern and southwestern parts of the Great Basin. Data are from Best and Brimhall (1974), Lowder (1973), Duffield et al. (1980), Robinson (1972), Huber (1967), and our unpublished analyses.

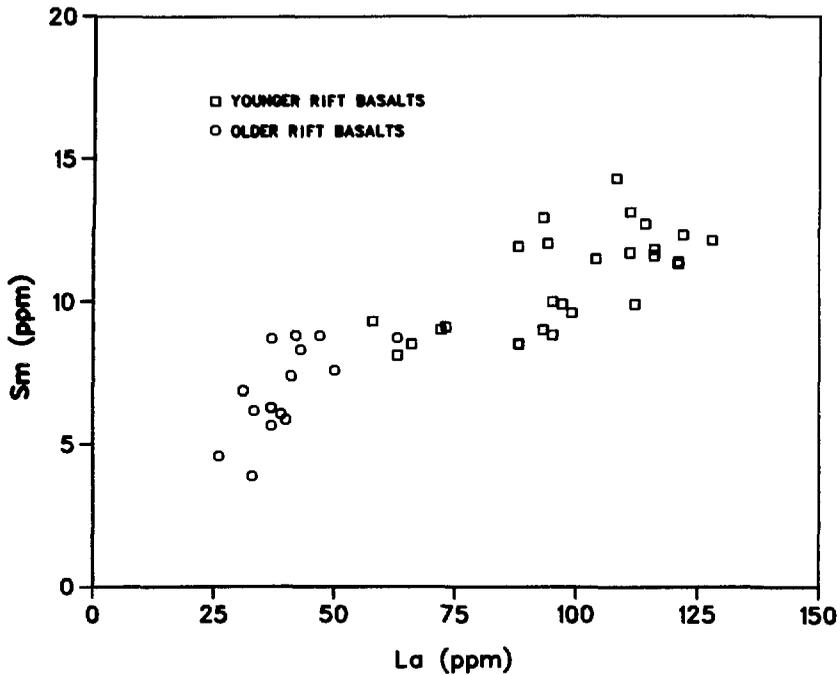
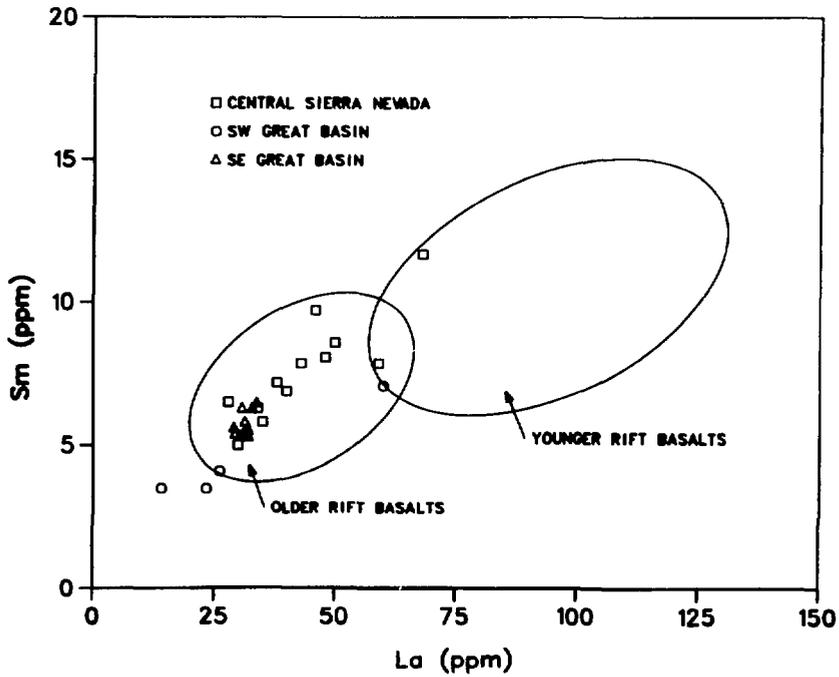
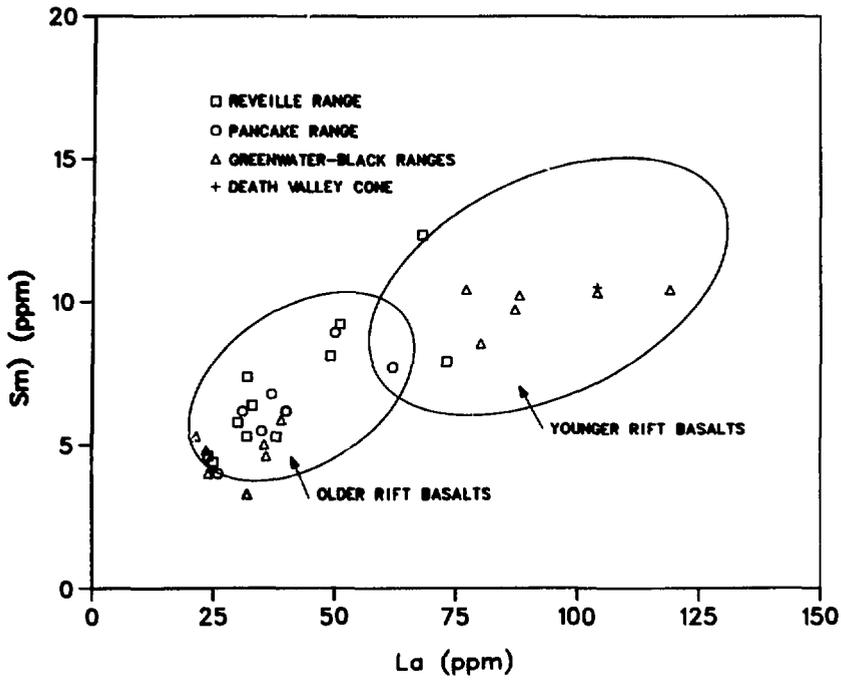


Fig. 4a. Samarium vs lanthanum diagram for the rift basalts of the NTS region. Younger rift basalts are distinctly enriched in samarium and lanthanum (two representative incompatible elements) with respect to the older rift basalts. The two cycles define separate fields with only minor overlap. Data are from our unpublished analyses.

Fig. 4b. Samarium vs lanthanum diagram for basalts of the DV-PR. Circled areas are the fields of the older and younger rift basalts of the NTS region from Fig. 4a. The majority of the basalts plot in the field of the older rift basalts with the exception of the Death Valley cone and younger basalts of the northern Greenwater Mountains (<4.0 Myr). Data were provided by S. Bergman, Princeton University, Princeton, NJ 08544 (1982) and our unpublished analyses.

Fig. 4c. Samarium vs lanthanum diagram for basalts of the central Sierra Nevada Range, the southwestern Great Basin, and the southeastern Great Basin. Circled fields are the younger and older rift basalts from Fig. 4a. The majority of the Great Basin basalts plot in the field of the older rift basalts, which is the predominant field with respect to incompatible element abundances for nearly all basalts of the southern Great Basin. Data are from Lowder (1973), Von Kooten (1981), and our unpublished analyses.



VI. VOLCANIC RISK ASSESSMENT

An assessment of volcanic risk has been completed for the NTS region by using the definition that Risk = Probability x Consequences.

A. Probability

Crowe and Carr (1980) calculated the probability of volcanic disruption of a repository located at Yucca Mountain by using a method developed largely by Crowe (1980). The probability model was formulated as a case of conditional probability and requires determination of a volcanic rate and a disruption ratio. The rate was established through counts of volcanic cones (treated as volcanic events) whose ages were based on potassium-argon dating and magnetic polarity determinations. The disruption ratio was established as the area of a repository divided by the area of a circle of specified dimensions, which is centered at Yucca Mountain. Resulting calculations of the annual probability of repository disruption were designed as a worst case approach:

$$\begin{aligned} &2.9 \times 10^{-8} \text{ for a circle of 25-km radius, and} \\ &8.3 \times 10^{-9} \text{ for a circle of 50-km radius.} \end{aligned}$$

Crowe et al. (1982) refined the volcanic probability calculations for the Yucca Mountain area. The mathematical model they used for the calculations is

$$\text{Pr [no disruptive vent before time } t] = \exp^{-\lambda tp} ,$$

where λ is the rate of volcanic events and p is the probability of repository disruption, given an event. The parameter p is estimated as a/A , where a is the area of the repository and A is some minimal area that encloses the repository and the area of the volcanic events. A computer program was developed to find either the minimum area circle or minimum area ellipse (defined as A) that contains the volcanic centers of interest and the repository site. This allows A to accommodate tectonic controls for the localization of volcanic centers, and it attempts to constrain λ to be uniform within the area of either the circle or ellipse. The rate of volcanic activity was calculated by determinations of the annual rate of magma production for the NTS region and by cone counts using refined age data. A significant finding from the studies of magma volume through time is an apparent decline in the rate of magma production (surface eruptive products calculated as magma volume equivalents) for the NTS region during the last 4.0 Myr. The rate of magma production for the NTS region

during the previous 4.0 Myr is $430 \text{ m}^3/\text{yr}$, calculated as the average rate. A more realistic rate can be determined by calculating a regression line through the data points on a volume vs time plot (Fig. 5, $r^2 = 0.80$). The resulting rate of magma production is $210 \text{ m}^3/\text{yr}$ and reflects the decline in magma production with time. For comparison, the average rate of production of basalt magma on the island of Hawaii is $\sim 0.2 \text{ km}^3/\text{yr}$ ($10^8 \text{ m}^3/\text{yr}$; Shaw, 1980). The rate of production of basalt during the previous 0.5 Myr in the Cosco Range area is $2.8 \times 10^3 \text{ m}^3/\text{yr}$ (Bacon, 1982).

Resulting probability values using the refined mathematical model were calculated for times of 1 and 10 000 yr by using the two procedures for rate calculations (Crowe et al., 1982). The annual probability of volcanic disruption of a waste repository located at Yucca Mountain falls in the range of 4.7×10^{-8} to 3.3×10^{-10} . These numbers provide probability bounds where the worst and best cases are defined by the extremes of the probability range. Collectively, the calculations indicate that the probability of volcanic disruption is very low.

B. Consequence

Consequence studies have been conducted as part of the volcanism studies. These fall within two general areas: scenario development (Crowe and Carr, 1980; Crowe et al., 1983) and consequence studies that examine the radiological consequences of basaltic volcanism (Logan et al., 1982).

Volcanic scenario development consists primarily of examining the processes involved in the disruption of a repository by basaltic magmatism. These were described in a preliminary fashion by Crowe and Carr (1980), who emphasize that the most probable type of future volcanic activity in the NTS region is basaltic. Further, they suggest that the disruption zone of basaltic activity is relatively small, assuming deep burial of waste ($>300 \text{ m}$). This is based on the field observation that surface basalt centers are fed at depth by relatively narrow dikes. Crowe et al. (1983) further refined this work. They traced basalt magmatic processes from generation at depth through upward migration and surface eruption. This report served two purposes. First, the range of known data with regard to magmatic processes of basaltic activity was examined, and the potential effects of repository disruption by these processes were evaluated. Second, data necessary to calculate the radiological consequences of repository disruption by basaltic volcanism were provided. These

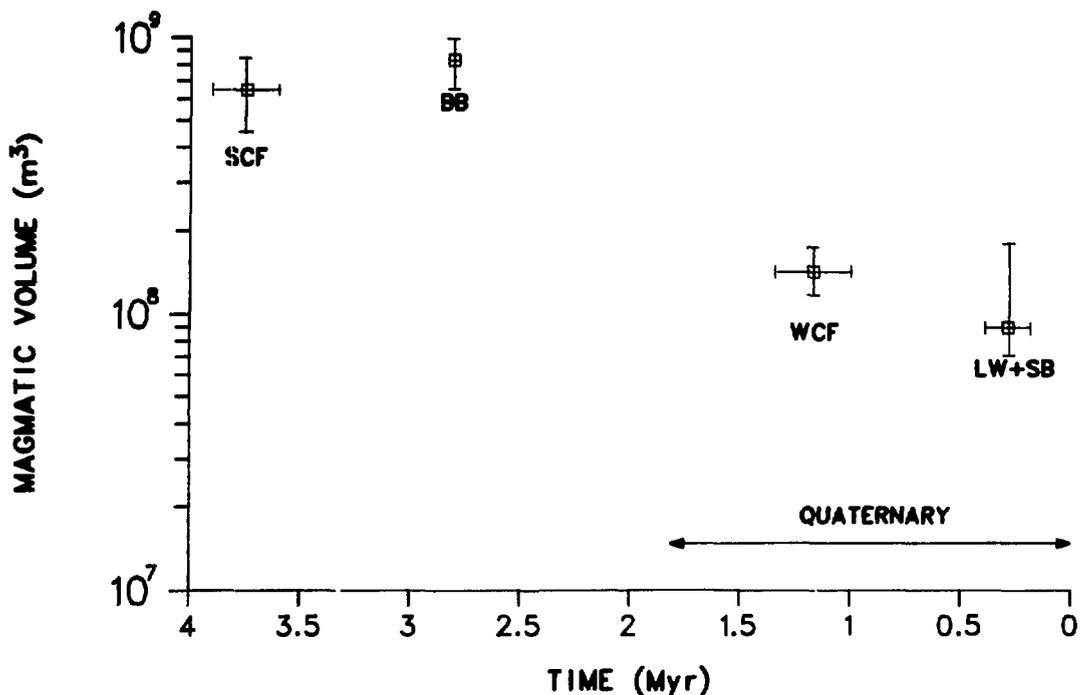


Fig. 5. Plot of magmatic volume vs time for basaltic magmatic cycles of the NTS region. SCF: southeastern Crater Flat basalt cycle; LW+SB: combined Lathrop Wells and Sleeping Butte basalt cycles; BB: basalt of Buckboard Mesa; and WCF: western Crater Flat basalt cycles (from Crowe et al., 1982).

radiological calculations were conducted by Los Alamos Technical Associates and Sandia National Laboratories as part of performance assessment (Logan et al., 1982).

The principal conclusions of the disruption studies (Crowe et al., 1983) are listed below.

- (1) Basalt has been the predominant type of volcanic activity in the NTS region during the last 8 Myr. Magmatic volumes of past eruptions are generally small ($<0.1 \text{ km}^3$), and the eruptions occur as distinct pulses or cycles.

- (2) Past and probable future basalt eruptions will be of hawaiite composition. Data concerning triggering mechanisms or detailed conditions leading to generation of basalt magma are insufficient at present and are unlikely to become available soon.
- (3) Basalt magma ascends rapidly (tens of centimeters per second) through the upper mantle and crust along narrow conduits. Mantle-derived basalt melts are likely to be trapped temporarily, fractionate at the base of the crust, and then ascend to the surface. Small-volume basalt cycles of the NTS region reflect the low magma flux within the southern Great Basin during late Cenozoic time.
- (4) Surface basalt centers are fed through narrow linear dikes with aspect ratios in the range of 10^{-2} to 10^{-3} . Approximately two to three dikes are associated with each basalt center. In some cases, shallow sill-like intrusions may form (at 200- to 300-m depth). The formation of intrusions may be favored by emplacement of volatile-poor magma within low-density tuff and stress conditions associated with active extensional faulting.
- (5) Basalt centers in the NTS region were formed predominantly by Strombolian eruptions. Major products are moderate-size scoria cones and relatively short lava flows (<2 km). Scoria-fall sheets associated with the cones but removed by erosion probably extended for distances of 5 to 12 km from the cones.
- (6) Waste incorporated in magma will be dispersed by surface eruptions with the major pathway being the pyroclastic component. Magma pathways can be approximated, assuming that waste dispersal follows the dispersal patterns observed in studied deposits of country-rock lithic fragments. Accordingly, the major occurrences of dispersed waste are in the scoria sheet (5 to 12 km) with lesser amounts deposited in the cone (near vent) and regionally dispersed (>12 km).

VII. ISSUES AND THEIR RESOLUTION

The hazards of future volcanism are an important information need with respect to the tectonic processes that provide reasonable potential for disrupting a repository or altering the waste-element travel times between a repository and the accessible environment. This can be phrased as a single major question:

What are the hazards of future volcanism with respect to disruption of a radioactive waste repository located within the southwestern NTS area?

This question is divided into three subquestions to discuss the possible hazards of future volcanism.

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

Subquestion 1

Can the processes of basaltic volcanism be understood with a sufficient degree of confidence to define the potential hazards of future volcanism?

There are major uncertainties in predictive geology, particularly for complex geologic processes such as volcanism. The history of volcanism, particularly Quaternary volcanism, can generally be determined for a region. However, the reliability of predictions based on that history is controlled in large part by the adequacy of the geologic record (the degree of preservation of the past products of volcanism) and by the accuracy with which the geologic record can be deciphered using established geologic techniques. It is extremely difficult to quantify with a reasonable degree of numerical certainty the processes that lead to the surface record of past volcanism. Data indicate that rates of volcanism for a particular site are related in a direct but as yet poorly understood way to the state of stress and strain of a region. That is, rates of volcanism, much in the manner of rates of regional seismicity, probably reflect the degree of tectonic activity of a region. Nakamura et al. (1977) and Nakamura (1977) recognized a relationship between the orientation of volcanic belts and dike systems that are associated with volcanic centers and the regional stress field. This indicates that pathways of basalt injection were controlled by the regional stress field. Shaw (1980) has related

rates of magma production for Hawaii to seismic moment (a term reflecting total volume change). He assumed that the potential energy available in a tectonic system may be released through both seismic radiation and the generation and ascent of magma. Although the balance ratios are poorly known, the concept has profound implications and suggests that magmatism may be an important factor in regulating mantle stress levels (Shaw, 1980, p. 259). Thus, it may be possible to correlate past and future rates of volcanic activity to rates of stress and strain within varying tectonic settings. This suggestion has been supported by two studies. Feigensen and Spera (1981) noted a relationship between a transition from tholeiitic to alkalic basalt (trace element enriched) and eruption frequency. They relate magma generation to shear-stress deformation (viscous deformation of Shaw, 1973) and suggest that a reduction in shear stress causes a decrease in the degree of partial melting and an increase in the time between eruptions. Bacon (1982) described a time-predictable relation for the eruption of basalt and high-silica rhyolite (<0.5 Myr) in the Coso volcanic field. This could be possible if the rate of magma production is controlled by a constant rate of strain (extensional deformation) with a minimum strain value required (failure strength of the crustal rocks) to cause fracturing and trigger magmatic ascent. Two points require emphasis. First, rate calculations described above were determined for areas with high levels of magmatic activity (10 to 10^4 times the calculated rates of activity for the NTS region). Second, the relationship between volumes of surface magma and volumes of magma produced in the mantle are poorly known. It should be dependent upon the percentage of partial melt, the fracture mechanisms of magma ascent, the integrated total volume of magma and volume change that is caused by fracture, and the tectonic setting (extensional vs compressional). Thus, although present geologic knowledge provides tantalizing hints of the controls of magma production, the knowledge is insufficient to calculate future rates of volcanic activity with a reasonable degree of confidence. This is perhaps most true for regions with low rates of volcanic activity, such as the NTS region.

Lacking such predictive capabilities, we have chosen to assess the potential hazards of volcanic activity through a variety of approaches. The consistency of results from these approaches provides a degree of confidence in the understanding of basaltic volcanism for the NTS region. A variety of geologic and geochronological data summarized in previous sections show that the NTS region is located within a belt of volcanic activity that has been active

during Quaternary time. Further, the existence of this belt indicates a finite potential for recurrence of basaltic activity within the NTS region in the near future. (Near future is used here in the context of geological time and therefore means 1 to 2 Myr.) Past Quaternary volcanic activity has occurred within ~20 km of the Yucca Mountain exploration site. Geologic data are inadequate to predict future sites of activity with confidence. Regional studies of the structural controls of surface basaltic activity indicate an increased frequency of basalts along ring-fracture zones of calderas, N-NE trending zones of extension, and basin-range faults. Exploration data suggest the possibility that the northern part of the Yucca Mountain block may overlie an old caldera (Snyder, 1981; Carr, 1982). Moreover, the exploration block is cut locally by basin-range faults (Lipman and McKay, 1965). The increased probability of basaltic volcanism at Yucca Mountain, which is the result of the presence of these structures, cannot be quantified. Regionally, some are pathways for basalts; the majority are not. Collectively, the above studies indicate that there is a finite hazard of future volcanism with respect to storage of high-level waste at Yucca Mountain.

Detailed studies of volcanism indicate that the actual hazard levels of future volcanism are extremely small. Rates of basaltic volcanic activity have been uniformly low for the DV-PR volcanic belt since its inception about 7 to 8 Myr ago. Based on cone counts, rates of volcanic activity during Quaternary time are $4 \times 10^{-9} / \text{km}^2 / \text{yr}$ for the NTS region and $9 \times 10^{-10} \text{ km}^2 / \text{yr}$ for the entire volcanic belt. Based on erupted volumes of basalt during the last 4 Myr, the rate of magma production for the NTS region ranges from 3.1×10^{-11} to $8.5 \times 10^{-11} \text{ km}^3 / \text{km}^2 / \text{yr}$ (Crowe et al., 1982). Such low rates of volcanic activity are consistent with low levels of tectonic activity as indicated by studies of seismicity and Quaternary faulting (Rogers et al., 1981). Basaltic activity has characteristically been of small volume and short duration, which has resulted in the formation of monogenetic scoria cones or clusters of scoria cones. Erupted magmas are predominantly of hawaiite compositions. These magmas have erupted repeatedly throughout the NTS region for the last 9 Myr with no recognizable changes or trends in either the composition or volume through time, with the exception of a relatively recent (3- to 4-Myr) trace-element-enrichment event. The probability of disrupting a repository site by basaltic volcanism is very low. Calculated values for a 1-yr period range from 10^{-8} to 10^{-10} . The radiological consequences of repository disruption

are limited, based on calculated release values that were determined by assuming a generalized scenario of basalt feeder dikes intersecting a repository, directly incorporating waste, and carrying the waste to the surface where it is dispersed by Strombolian processes. These consequences reflect the small subsurface area of basalt disruption zones and the limited dispersal of eruptive material by Strombolian mechanisms. Thus, the combination of volcanic hazard studies and risk assessment consistently indicates a very low hazard of future volcanism with respect to geologic disposal of high-level radioactive waste in the Yucca Mountain exploration block.

A number of studies are still in progress. Although the hazards of future volcanism are considered to be extremely small, additional information from these studies may be required to increase confidence in this conclusion.

Field studies are complete. However, one critical question remains that may require additional detailed field work: What is the mechanism of formation of shallow intrusions of basalt magma at some localities? Field studies have shown that the majority of basalt centers are fed at depth by narrow linear dikes. At several localities, basalts formed shallow sill and lopolith intrusions within country rock. Such intrusions, if formed within the Yucca Mountain site, should follow a repository tunnel complex and greatly increase the amount of waste incorporated by magma. The mechanism of formation of intrusions in the Paiute Ridge area of the NTS is only partly constrained (Crowe et al., 1983). They may have formed through a combination of (1) basalt injection during active extensional faulting, (2) lifting of the fault-bounded country-rock roof by combined magma hydrostatic pressure and yield strength, and (3) trapping or stagnation of the rise of basalt within low-density tuff, which is caused in part by the low volatile content of the magma.

Geochemical studies have been completed for the basalts of Crater Flat. Work is under way to extend this knowledge to all basalts of the NTS region. Additional reconnaissance geochemical data will be obtained for all volcanic fields of the DV-PR belt. These data allow examination of several remaining questions with respect to volcanism.

- (1) Compositional Changes in Volcanic Fields with Time: What are the compositional trends of major (large-volume, long-lived) basalt fields? Are there consistent geochemical trends among the erupted lavas of the fields through time? How does the composition of the large fields compare with studied hawaiite basalts of the NTS region?

Is there any evidence to suggest that the basalt fields of the NTS region (particularly the basalt of Crater Flat) could evolve through time to form large-volume fields with higher rates of volcanism?

- (2) Bimodal Basalt-Rhyolite Fields: Bimodal volcanic fields (coexisting basalt-rhyolite magmas) are present at one locality in the volcanic belt (Greenwater Range) and at several localities along the western edge of the Great Basin. The possible existence of bimodal volcanism in the NTS region must be considered. Field studies provide no evidence of bimodal volcanism in the Plio-Pleistocene geologic record of the region, with one possible exception. A pumice collected from alluvial deposits in southern Crater Flat has been dated at ~6 Myr. The source of this pumice is not known. Drill Hole USW VH-1 was sited in Crater Flat to investigate the history of basaltic volcanism within the valley and to search for the possible presence of a buried but relatively young silicic center. The existence of a small silicic dome or domes buried by alluvium within Crater Flat is permissible at several localities, based on aeromagnetic data (Carr, 1982). Drill Hole VH-1 did not penetrate such a body. Additional holes may be needed to investigate sites of other aeromagnetic anomalies. Geochemical data are being gathered to examine the compositions of basalt and rhyolite at bimodal localities in the southern Great Basin. The presence of a young rhyolite center within the NTS region would change the results of probability and consequence analyses because of the larger size of disruption zones and larger range of dispersal distances of eruptions of silicic magma.
- (3) Incompatible Element Enrichment: Geochemical studies of basalts of the NTS region and preliminary data from basalts of the Greenwater Range and southern Death Valley, as discussed previously, indicate that younger basalts (<4 Myr) of the southern part of the volcanic belt are enriched in incompatible elements (with the exception of rubidium) relative to older basalts (>6 Myr). The mechanism and timing of this geochemical event must be resolved more completely and causative processes must be examined. It is critical to determine if there is an increase or decrease in rates of volcanic activity associated with or following this event. Field and geochronologic data to date provide no evidence of rate changes. Further geochemical studies are in progress.

Subquestion 2

What are the areas of uncertainty in volcanic hazard assessment?

There is a degree of uncertainty in many aspects of the volcanic hazard studies because of the geological techniques used to gather data. For example, potassium-argon ages of rocks include uncertainty in both precision and accuracy; geochemical analyses have varying uncertainties, depending upon the element. Areas of uncertainty are inherent to many research programs across the complete scope of the Nevada Nuclear Waste Storage Investigations (NNWSI) and are generally recognized in applications of gathered data. However, a less well-defined and potentially greater uncertainty exists for studies that do not have standard and instrumentally verifiable investigative procedures. These include:

- (1) Predictive Geology: There are large uncertainties of undefined magnitude in predictions of future rates of volcanic activity, which are based on rates of past activity. Volcanic rates are subject to change with changes in the tectonic setting, and the processes that may lead to these changes are not well known. This has been discussed for geologic prediction in general as applied to waste disposal (Bredehoeft et al., 1978, p.11). They suggest that "...estimates (predictions) of probabilities of future events be recognized for what they are--estimates only."
- (2) Probability Calculations: A significant degree of uncertainty is present in the probability calculations as a result of the geologic assumptions required for the rate calculations and their dependence on predictive geology. (Future rates are calculated from past rates of volcanism.) Because of this uncertainty, probability calculations are presented as a range spanning several orders of magnitude, and additional research approaches are used for hazard assessment. Particular attention must be paid to the time sensitivity of the probability method. Field observations that provide the data base for the probability calculations are limited, and gathered data span a lengthy time period (3.7×10^6 yr). Therefore, they are most valid for long-range predictions (10^6 yr) and increasingly less valid for shorter periods of time. In particular,

because of the small number of data points used in the probability calculations, the approach may be insensitive to short-term rate changes such as the time period required for waste containment.

(3) Consequence Analyses: A large range of uncertainty exists in the consequence calculations because of the unknowns concerning the processes of basaltic volcanism. Some of the more important areas of uncertainty include:

- the mechanism of intrusion of a repository by basalt magma. A variety of intrusion scenarios can be supported by field data. These range from dikes intersecting the repository with the volume of intrusion within the repository limited to the dike volume to injection of magma along the repository tunnel system with magma filling existing void spaces;
- mechanisms of waste/magma interaction. Magma may follow a repository tunnel and incorporate all waste canisters, or it may chill against and physically isolate waste from the ascending magma column. The magma may incorporate waste as discrete fragments and disperse them at the surface, or there may be complex dissolution and geochemical dispersal of waste elements within the magma;
- partitioning of waste within the differing types of Strombolian eruptive processes;
- energetics of the Strombolian eruptive processes; and
- production of fines (<65 μm) in a Strombolian eruption.

Subquestion 3

What are the procedures to resolve the issue of potential volcanic hazards for geologic disposal of radioactive waste within the NTS area?

Volcanism studies have been presented at numerous reviews, including formal peer review sessions in 1979, 1980, and 1981. Pending approval by the US Department of Energy, the studies will use the methodology for issue resolution outlined in the Volcanism Licensing Topical Report. To date, neither individual reviewers nor formal peer review groups have considered volcanism a disqualifying factor to repository siting in the NTS. It must be

emphasized that the question of volcanic hazards is not a simple problem with an established method of resolution. Although an abundance of data suggests the hazard level is low, the hazard nonetheless exists. Its final impact on the suitability of the NTS region for geologic disposal of high-level waste must be based on a combination of scientific research, determination of acceptability levels of risk as established by the national program for waste disposal, and the acceptability levels of geologic hazards as perceived within the public domain.

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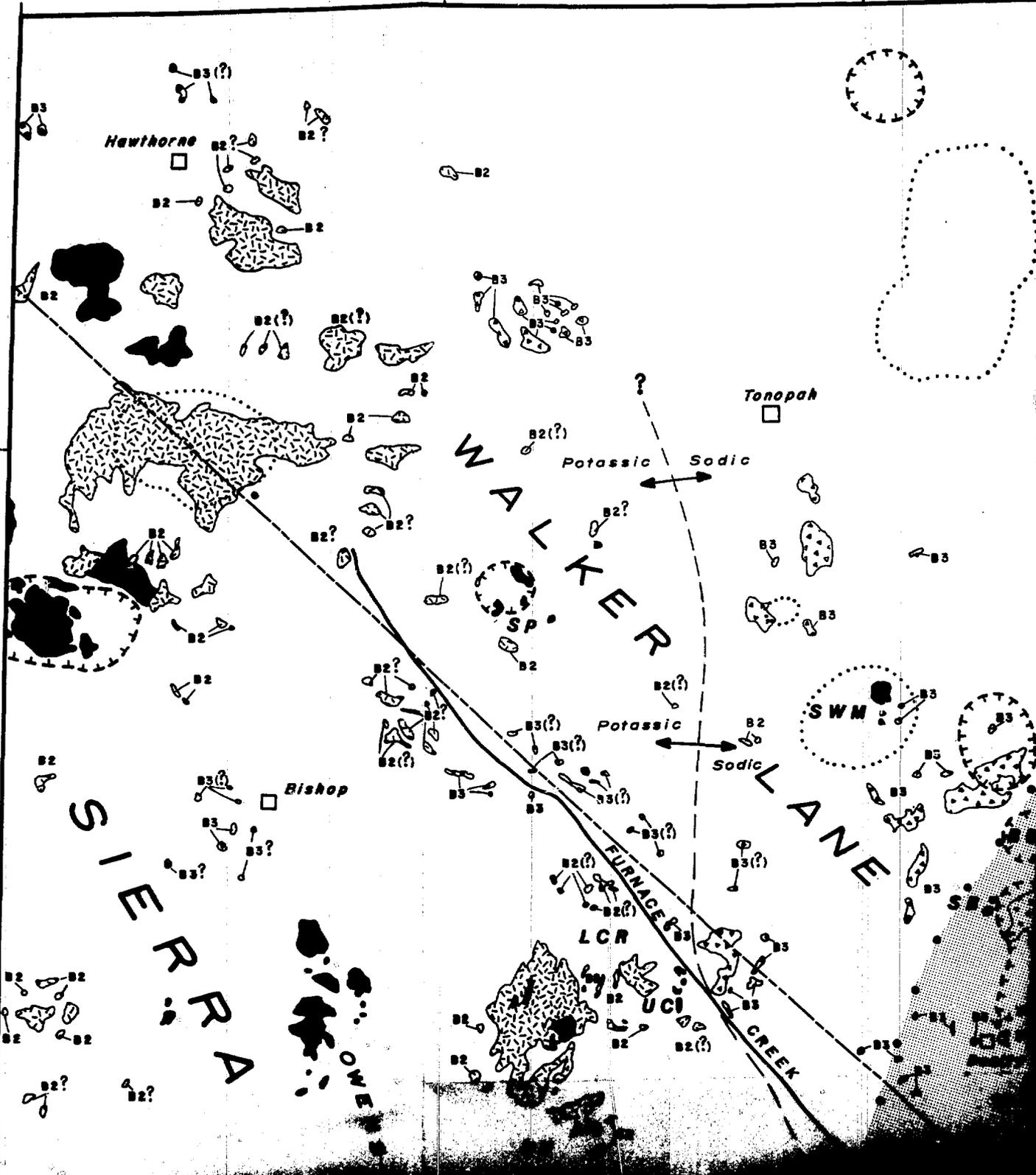
119°

118°

117°

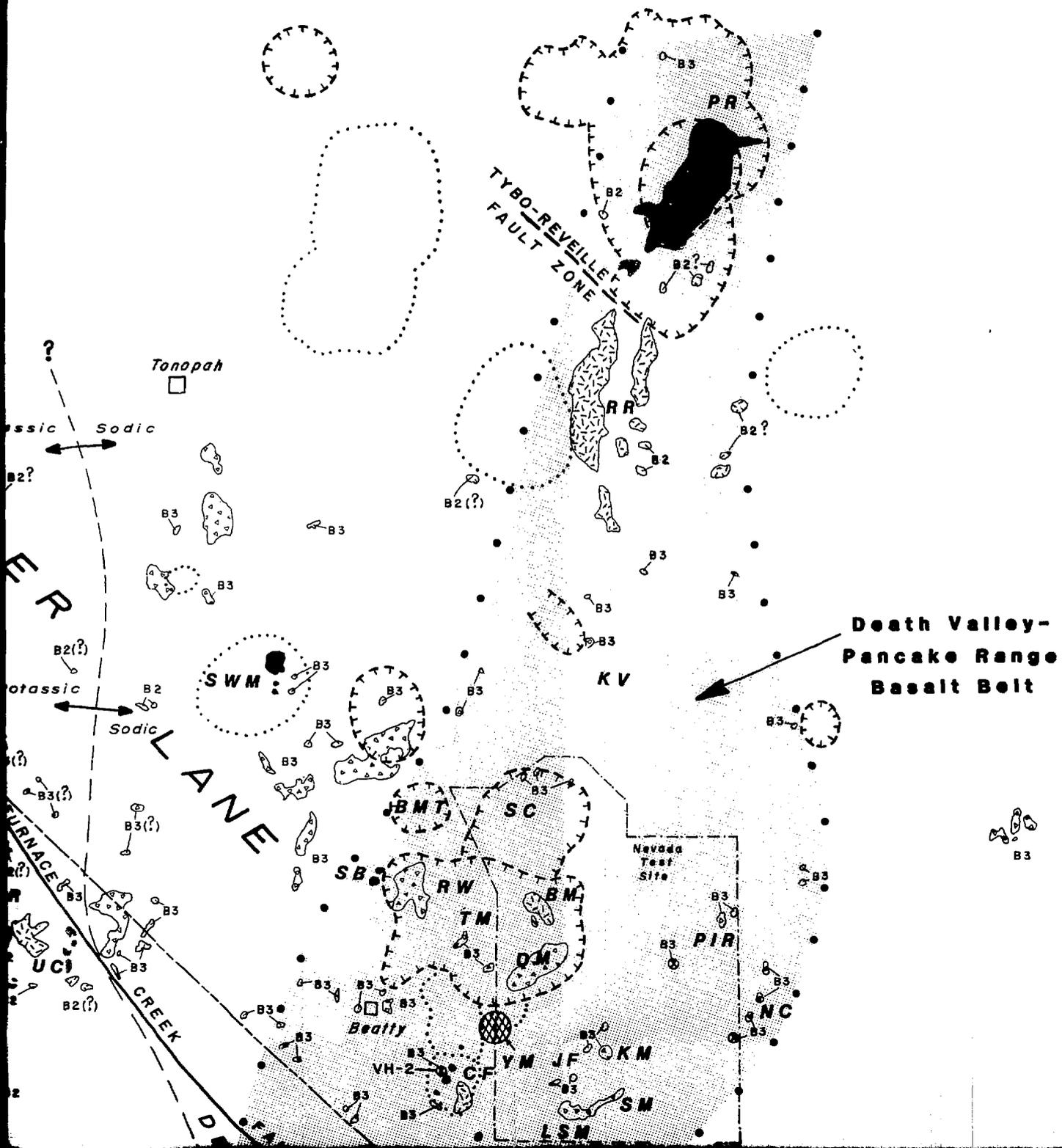
38°

37°



117°

116°



115°

alley-
Range
Belt



EXPLANATION

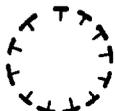
 *Rhyolite younger than 6 my*

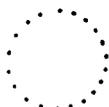
Basalt ages

 0-2my *Quaternary*

 2-6my *B2* } *Late Miocene*

 >6my *B3* } *and Pliocene*

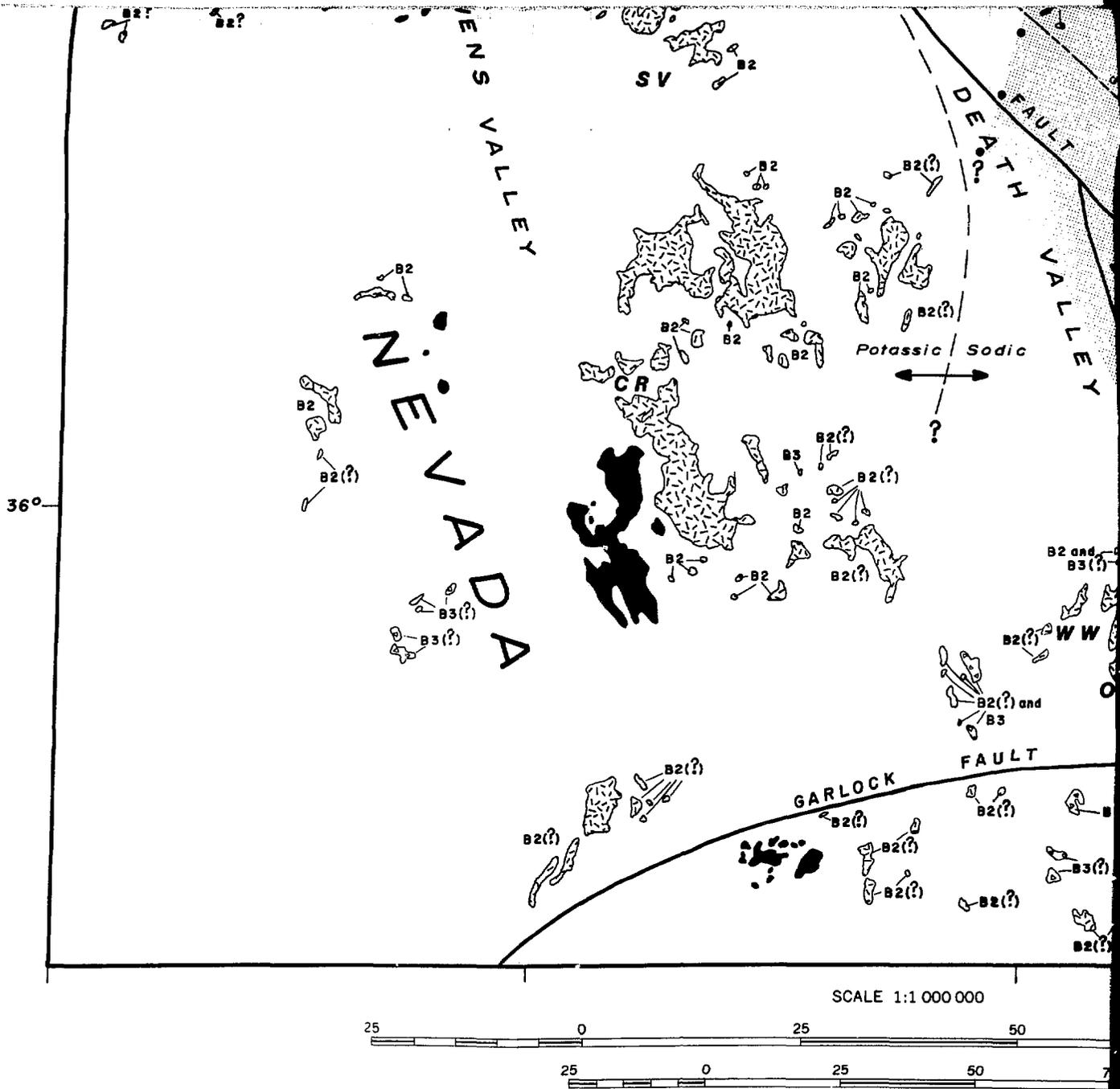
 *Caldera*

 *Probable caldera*

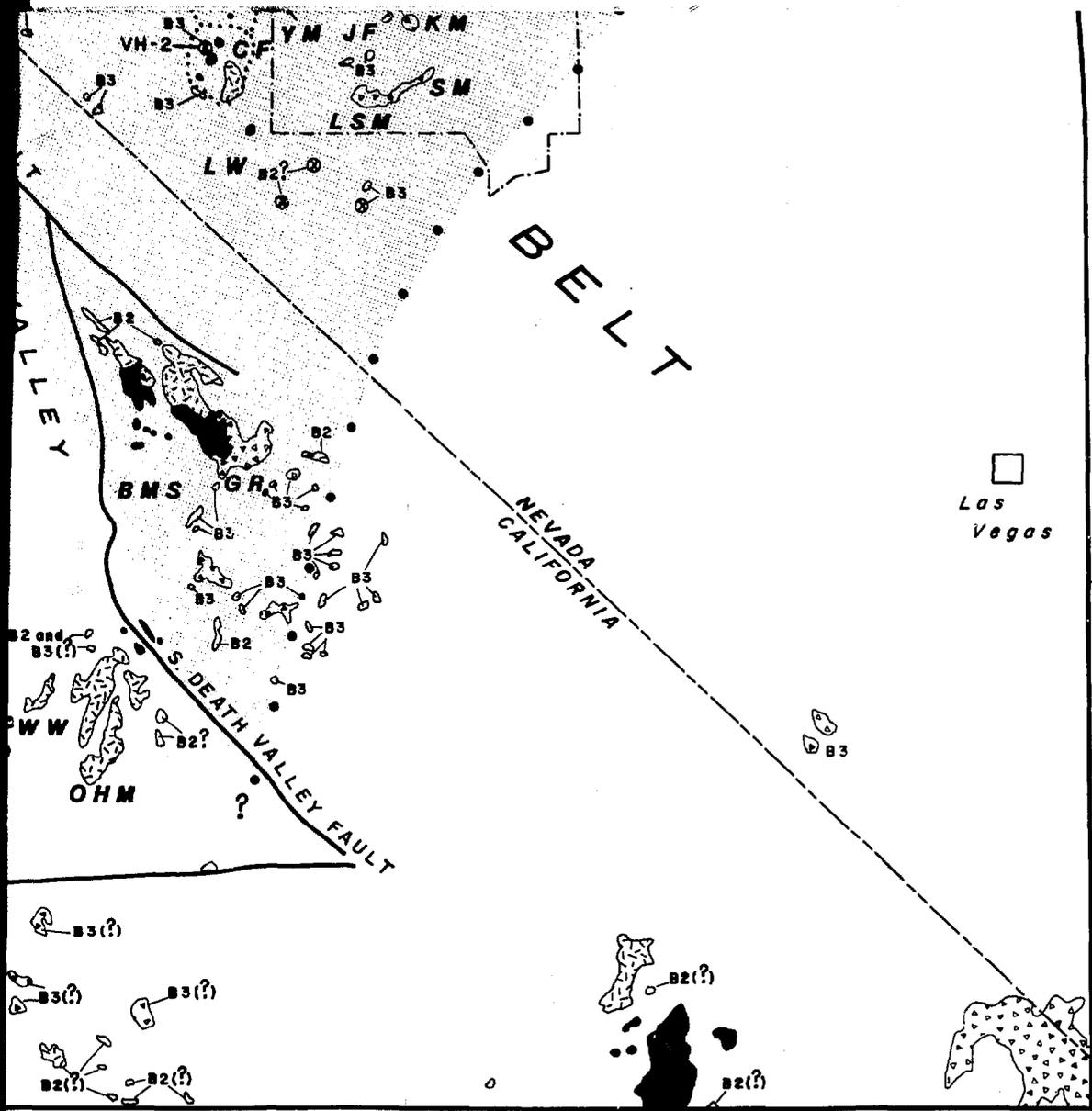
? — — ? *Approximate boundary
between potassic and
sodic basalts*

 *Subsurface basalt recognized
from drill hole and/or
geophysical data*

VH-2 *USW VH-2 drill hole*



Basalts, rhyolitic to dacitic lavas younger than 6my
Includes some bas



- BM-
- BN-
- BM-
- CF-
- CR-
- DM-
- GR-
- JF-
- KM-
- KV-
- LC-
- LCR
- LSM
- LW-
- NC-
- OHM
- PIR
- PR-
- RR-
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- SC-
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- SP-
- SV-
- SWM
- TM-
- UC-
- WW-
- YM-

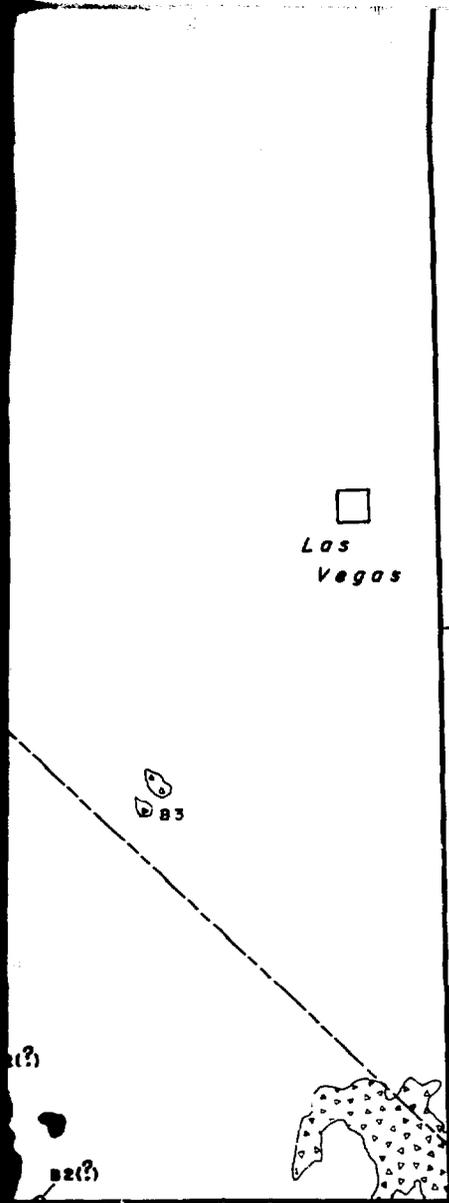
Compiled in part and modified from Luedke and Smith (1981)

75 100 MILES

75 100 KILOMETERS

5my, and calderas of the Southwestern Great Basin, basaltic andesites

VH-2 USW VH-2 drill hole



Compiled in part and modified from
Luedke and Smith (1981)

- BM---Buckboard Mesa
- BMS--Black Mountains
- BMT--Black Mountain
- CF---Crater Flat
- CR---Coso Range
- DM---Dome Mountain
- GR---Greenwater Range
- JF---Jackass Flats
- KM---Kiwi Mesa
- KV---Kawich Valley
- LC---Lunar Crater
- LCR--Last Chance Range
- LSM--Little Skull Mountain
- LW---Lathrop Wells basalt center
- NC---Nye Canyon
- OHM--Owlshhead Mountains
- PIR--Paiute Ridge
- PR---Pancake Range
- RR---Reveille Range
- RW---Rocket Wash
- SB---Sleeping Butte
- SC---Silent Canyon
- SM---Skull Mountain
- SP---Silver Peak Range
- SV---Saline Valley
- SWM--Stonewall Mountain
- TM---Timber Mountain
- UC---Ubehebe Crater
- WW---Wingate Wash
- YM---Yucca Mountain

Southwestern Great Basin, Nevada and California