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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# PRELIMINARY ASSESSMENT OF THE RISK OF VOLCANISM AT A PROPOSED NUCLEAR WASTE REPOSITORY IN THE SOUTHERN GREAT BASIN

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## ABSTRACT

Volcanic hazard studies of the southern Great Basin are being conducted on behalf of the Nevada Nuclear Waste Storage Investigations program. Current work is chiefly concerned with characterizing the geology, chronology, and tectonic setting of Pliocene and Quaternary volcanism in the Nevada Test Site region, and assessing volcanic risk through consequence and probability studies, particularly with respect to a potential site in the southwestern Nevada Test Site.

Young (<5 m.y.) basaltic volcanism in the Great Basin is present along the margins of the province and within a discontinuous, northeast-trending belt that extends through the Nevada Test Site. Basalt volcanic centers in the southern Great Basin are most common in: (1) ring-fracture zones of cauldron complexes, (2) rift grabens that cut cauldron complexes, and (3) rift grabens outside volcanic source areas.

Rates of basaltic volcanism determined for the southwestern Nevada Test Site region vary according to assumptions concerning vent counts and chronology. However, all approaches yield rates on the order of $10^{-6}$ volcanic events per year. Based on this rate, the annual probability of disruption of a 10-$km^2$ repository located within a 25-km radius circle centered at Yucca Mountain, southwestern Nevada Test Site, is $10^{-8}$. A larger area, 50-km radius, yields a disruption probability of $10^{-9}$ per year. Current tectonic zonation studies of the southern Great Basin will reduce the calculated probabilities of basaltic eruption for certain areas.

## INTRODUCTION

An important part of the Tectonics, Seismicity, and Volcanism subtask of the Nevada Nuclear Waste Storage Investigations program is an evaluation of the potential for recurrence of volcanism in the NTS (Nevada Test Site) and southern Great Basin region. Specifically, this investigation is presently assessing the potential risk that future volcanic activity may represent to long-term storage of radioactive waste in the southwestern part of the NTS. Geologic and geochronologic studies of the volcanic history of the NTS region, with special emphasis on the basaltic volcanic cycle of Crater Flat, are being conducted by the USGS (U.S. Geological Survey) and LASL (Los Alamos Scientific Laboratory). This report summarizes the status of the volcanic hazard study, and includes a preliminary evaluation of volcanic-risk assessment with respect to siting of a radioactive waste repository within a block presently being explored in the northern part of Yucca Mountain.

We are using a two-fold approach to the volcanic hazard question. First, geologic studies are directed toward characterizing the geology, chronology, occurrence, and tectonic setting of Pliocene and Quaternary (<5 m.y.) volcanism within the southwestern NTS region. Second, such data are used for risk assessment, examining both the consequences of volcanic disruption of a waste repository site and the probability of such disruption, following a methodology developed for the Waste Isolation Safety Assessment Program (Crowe, 1980).

Volcanism, or magmatic activity, represents a catastrophic type of disruptive event. That is, if magma penetrates a waste repository, disruption is virtually instantaneous and there is a great potential for rapid and widespread transport of radionuclides to and within the biosphere. Volcanic disruption of a repository is clearly of concern, and for this reason we have focused the current studies on attempts to define the range of probability values for magmatic disruption of a repository site at Yucca Mountain. These values can be used to evaluate the safety question of waste storage with several levels of interpretation:

1. Low Probability.--If the probability range is sufficiently small, volcanism may not be a critical safety issue. The value or range of a "sufficiently small" probability remains to be defined.
2. High Probability.--If the probability value is relatively large, risk of volcanism could potentially disqualify a site. Again the magnitude of a large probability is undefined for volcanic risk, but we suggest it may fall in the range of $>10^{-6}$/year.
3. Moderate Probability.--If the probability range is moderate, additional detailed studies such as biodose calculations will be required to carefully define volcanic risk.

## VOLCANISM OF CRATER FLAT

Crater Flat is an intermontane basin 5-20 km west and southwest of the proposed Yucca Mountain site area (fig. 1). It is bounded on the east by Yucca Mountain, on the north by hills of ash-flow tuff and lava fringing the southwest side of the Claim Canyon cauldron segment (Byers and others, 1976), on the west by Bare Mountain, and on the south by an arcuate ridge of volcanic rocks extending between Bare Mountain and Yucca Mountain. Crater Flat is drained to the south through a small gap near the point where the arcuate ridge joins the southern part of Yucca Mountain (fig. 1).

Numerous, small volcanic centers of basaltic composition marked by cones, associated lava flows, and feeder dikes are exposed within the central and southeastern parts of Crater Flat (fig. 1). These are readily subdivided into three age groups on the basis of morphology alone. The location of the volcanic centers is probably controlled by a combination of structural regimes. A northeast-trending structural arc is defined by the alignment of Little Cones, Red Cone, Black Cone, and the northernmost of the volcanic centers (unnamed, fig. 1). These centers consist of small dissected Strombolian cinder cones (10 to 30 percent dissection) that are flanked and partly encircled by blocky aa lava flows. The northeast structural arc of basaltic cones may have occurred along one of a system of faults of this trend that are present along the Walker Lane fault system in the southern NTS area (Carr, 1974). In southeastern Crater Flat a second setting of volcanic centers is marked by north-south trending vent zones that probably follow basin-range faults, as mapped on figure 1. These, the oldest of the exposed centers, consist of north-south trending feeder dikes, near-vent basaltic scoria deposits, and associated lava flows. The deposits represent the eroded roots of older cinder cones, which were probably comparable to the Red Cone-Black Cone centers. The third and youngest center is the Lathrop Wells Cone (fig. 1), which consists of a virtually undissected Strombolian cinder cone flanked to the east and south by aa lava flows. A small area of base-surge deposits exposed on the northwest side of the cone records an episode of phreatomagmatic activity that probably occurred during an early stage of development of the Lathrop Wells center. This cone may be at the intersection of north-south-trending basin-range faults and an inferred arcuate volcanic structure (ring-fracture system?) that may control the arcuate trend of the ridge at the south end of Crater Flat. However, the presence and possible influence of an old, buried-volcano tectonic depression on the localization of basalt centers in Crater Flat remains to be determined.

Aeromagnetic patterns determined from a low-altitude aeromagnetic survey suggest the presence of several volcanic centers buried beneath basalt and alluvial deposits of Crater Flat. These inferred centers, shown as stars on figure 1, are presumed to be of basaltic composition. However, the large amplitude of the aeromagnetic anomaly for the inferred buried center west of Black Cone suggests it may be of more silicic (rhyolitic) composition. Exploratory drilling will be required to establish the complete volcanic history of Crater Flat.

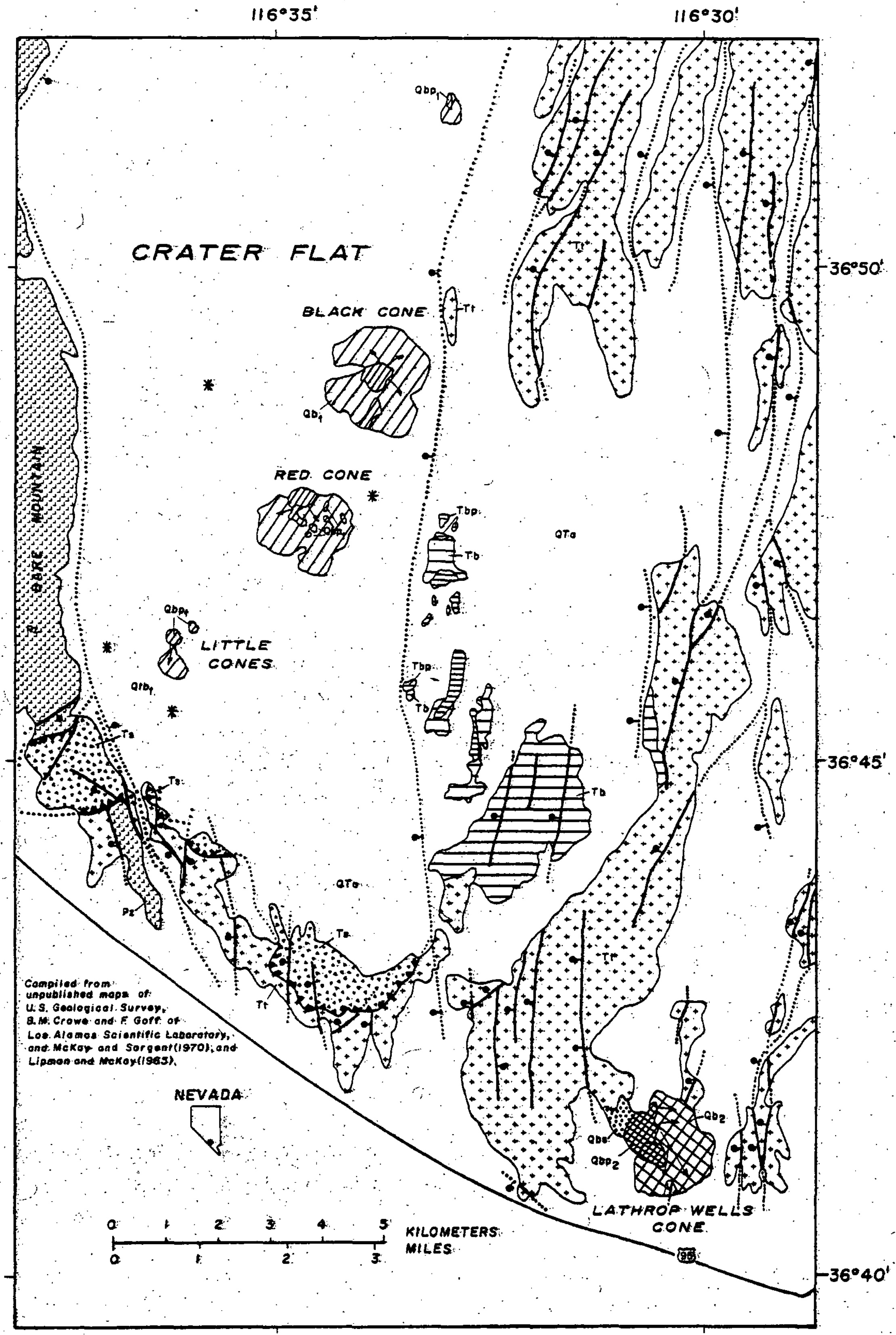
## AGE OF VOLCANISM

K-Ar whole-rock ages for the basaltic volcanic rocks of Crater Flat have been determined for several of the volcanic centers. The ages range from about 1.4 m.y. for the Black Cone volcanic center to about 0.24 m.y. for the lava flows erupted from the Lathrop Wells Center. Magnetic-polarity determinations have been made for all the exposed basaltic centers of Crater Flat. All but the Lathrop Wells center are reversely magnetized. Based on K-Ar ages, the reversely magnetized centers probably fall within the Matuyama reversed polarity epoch (Cox, 1969) and are thus between about 0.7 m.y. and 2.5 m.y. old (ages based on recalculation of K-Ar polarity time scale, necessitated by a change in constants used in K-Ar dating (E. A. Mankinen and G. B. Dalrymple, written commun., 1977)). It is possible that the dissected volcanic centers, in the eastern half of Crater Flat (fig. 1), may be significantly older than the Little Cones-Black Cone arc. The older cones may, therefore, record the Gilbert reversed epoch (>3.4 m.y.). This possibility remains to be tested by K-Ar dating. The Lathrop Wells center is normally magnetized, consistent with its K-Ar age of 0.24 m.y. (Brunhes polarity epoch). The source of an apparent normal magnetic anomaly beneath alluvial deposits just east of Red Cone (fig. 1) must be investigated by drilling.

## PROBABILITY CALCULATIONS

Calculation of the annual probability of both the occurrence of an eruptive event and the intersection of a waste repository by that volcanic event is a case of conditional probability:

$$P_{\text{Volcanic Disruption}} = R X A$$

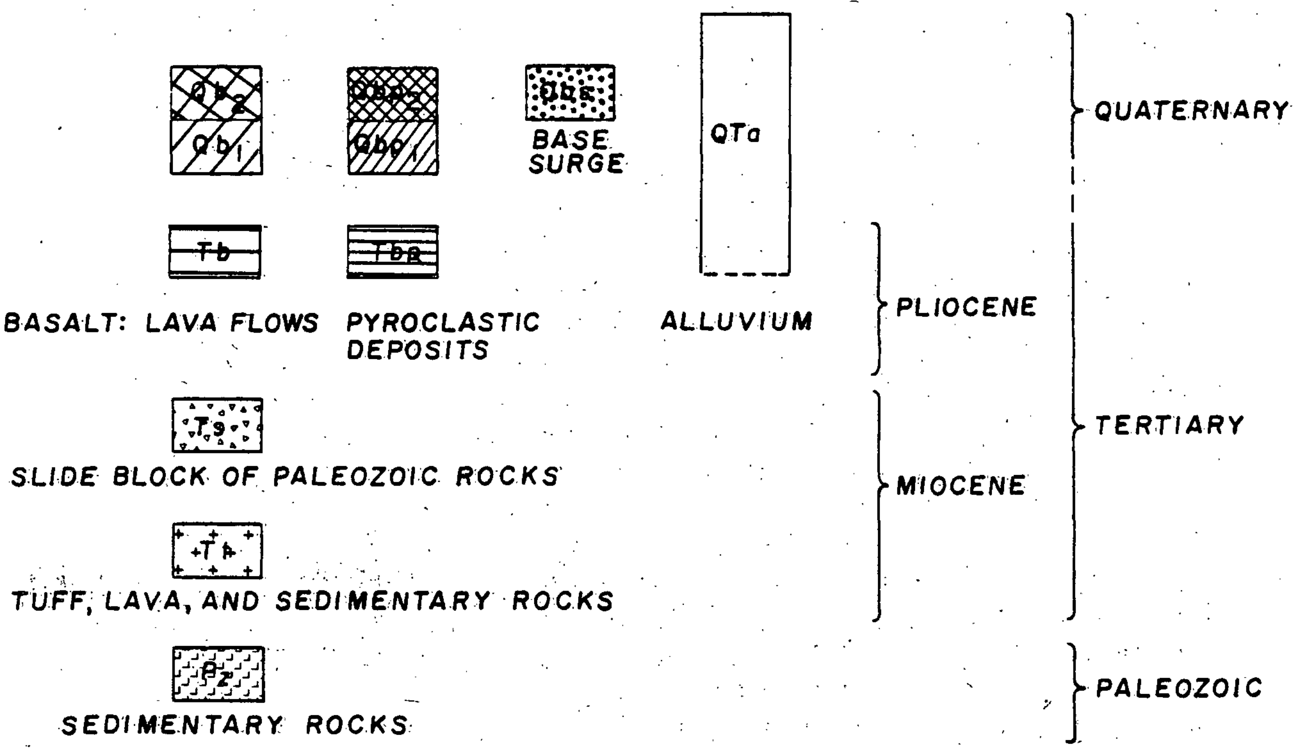


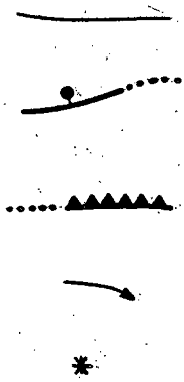
Compiled from unpublished maps of U.S. Geological Survey, B.M. Crowe and F. Goff of Los Alamos Scientific Laboratory, and McKay and Sargent (1970), and Lipman and McKay (1965).

Figure 1.--Generalized geologic map of the southern Crater Flat area.

## EXPLANATION

### CORRELATION OF MAP UNITS





CONTACT

*FAULT, dotted where concealed; bar and ball on downthrown side*

*Base of slide block, dotted where concealed*

*Direction of lava flow*

*Buried volcanic center, located from aeromagnetic anomaly*

Figure 1.--Continued.

where R is a rate of volcanism and A is an area ratio defined as the area of a repository or the area of an appropriate volcanic disruption zone (whichever is larger) divided by the area for which the rate applies. The area ratio (A) can be approximated with some accuracy, although there are numerous assumptions with respect to dimensions of appropriate disruption zones. The major problem with the calculation is establishing a rate of volcanic activity that is applicable for a considerable length of time (>$10^5$ years).

## Rate Calculations

Numerous assumptions are required to calculate rates of volcanism for the region surrounding the Yucca Mountain (fig. 3) site. The available K-Ar ages of the volcanic centers are insufficient at present to establish a volcanic recurrence interval. Moreover, it may be difficult to obtain sufficient age data to calculate recurrence intervals due to analytical problems inherent in whole-rock K-Ar dating of basalts younger than about 2 m.y. However, approximate rate calculations can be determined using the magnetic polarity time scale.

There are 14 recognizable Pliocene and Pleistocene basaltic volcanic centers, including three buried centers, within a 25-km-radius circle drawn with the center at the northern part of Yucca Mountain. This number may be as great as 18 or as small as 10 (14±4 volcanic centers--a more precise number would require extensive geophysical exploration and drilling). For comparison, a 50-km-radius circle includes about 18 centers. As the oldest centers within the 25-km circle are magnetically reversed, they are probably between 0.7 and 2.5 m.y. (Matuyama reversed epoch) or older than 3.4 m.y. (Gilbert reversed polarity epoch). The age of these basalts will be more accurately defined by K-Ar dating in progress, but for this report we have made the conservative assumption that they are no older than 2.5 m.y. Assuming that the rate of volcanism has been constant for the last 2.5 m.y., and that this rate can be projected into the future, a rate calculation can be made as follows:

$$R_{\text{Rate}}=\frac{\text{14 volcanic centers}}{2.5\text{X}10^6\text{ years}}$$

$$=5.6\text{X}10^{-6}/\text{year}$$

Two things need to be emphasized concerning the assumptions involved in this calculation. First, the available age and polarity data could be interpreted as indicating that the peak of volcanic activity occurred during the Matuyama reversed polarity epoch (2.5 to 0.7 m.y.), yielding a peak volcanic rate of:

$$R_{\text{Peak Rate}}=\frac{\text{12 volcanic centers}}{1.8\text{X}10^6\text{ years}}$$

$$=6.7\text{X}10^{-6}/\text{year}$$

where 12 is the number of volcanic centers occurring in the Matuyama reversed polarity epoch, and $1.8\text{X}10^6$ years is the approximate duration of the polarity epoch. The argument could be made that the present-day volcanic rate is well below the peak rate. In fact, data indicate that only one volcanic center was active in the last 1 m.y. A frequency versus time plot could be attempted to define a density curve and statistically calculate the nonpeak rate, but the limited data makes this calculation meaningless. Moreover, the peak-rate calculation differs by only 16 percent from the uniform rate calculation. Second, to illustrate the range of sensitivity of the rate calculation, the maximum and minimum cone counts can be used:

$$R_{\text{Minimum}}=\frac{\text{10 volcanic centers}}{2.5\text{X}10^{6}\text{ years}}$$

$$=4.0\text{X}10^{-6}/\text{year}$$

$$R_{\text{Maximum}}=\frac{\text{18 volcanic centers}}{2.5\text{X}10^{6}\text{ years}}$$

$$=7.2\text{X}10^{-6}/\text{year}$$

To summarize, a number of volcanic rate calculations can be determined assuming various cone counts for a $2.5\text{X}10^{6}$ year period. Significantly, all the rate calculations fall within the same order of magnitude ($10^{-6}$/year). This is an important point to emphasize in the following sections.

## Area Ratio

The disruption zone for a basaltic volcanic center is limited, based on the assumption of deep burial of a waste repository (>500 m). Geologic field studies of dissected volcanic centers indicate that surface vent zones are fed by relatively narrow dikes (less than 10 m and generally less than 1 m in width). Assuming that the disruptive effects of a basalt dike extend laterally 10 m from the dike margins (a conservative assumption), a disruption width for a single dike may be:

$$\text{Dike Disruption Width}=10\text{ m}+10\text{ m}+10\text{ m}$$

$$=0.03\text{ km}$$

Geologic studies have shown that dikes have a finite lateral extent and a maximum length of about 4 km (B. Crowe and D. Vaniman, Los Alamos Scientific Laboratory, studies in progress). Therefore:

$$\text{Dike Disruption Area}=0.03\text{ kmX4 km}$$

$$=0.12\text{ km}^{2}$$

Finally, field studies of the basalts of Crater Flat indicate that there are an average of three vent zones, each assumed to be fed by a separate dike, at each volcanic center. Thus, the final disruption zone calculation becomes:

$$\text{Dike Disruption Area}=0.12\text{ km}^{2}\text{X3 dikes}$$

$$=0.36\text{ km}^{2}$$

For the purposes of the probability calculations, the area of a repository is assumed to be 10 $\text{km}^2$. Therefore, at Yucca Mountain the area ratio becomes:

$$A=\frac{10\ \text{km}^2}{\pi(25\ \text{km})^2}$$

$$=5.1\text{X}10^{-3}$$

where 10 km$^2$ is the area of an assumed repository. The final probability calculation becomes:

$$P_{\text{Volcanic Disruption}}=\text{RXA}$$

$$=(5.6\text{X}10^{-6}/\text{year})(5.1\text{X}10^{-3})$$

$$=2.9\text{X}10^{-8}/\text{year}$$

Several comments concerning the order of magnitude ($10^{-8}$/year) of this number are required. First, the calculation was designed as a worst case probability and therefore corresponds to an upper limit or maximum probability of volcanic disruption. Second, the calculation assumes volcanism is a random process. That is, it is a necessary requirement of the probability calculation to assume that there is a uniform probability of a volcanic event throughout the 25-km-radius circle centered at Yucca Mountain. Field studies of volcanism at Crater Flat and volcanic studies, in general, have clearly shown that the surface occurrence or localization of volcanism is strongly controlled by existing structural features.

As an approach to examining the sensitivity of the probability calculation, the important parameters can be varied. The disruption area, as previously discussed, is bounded by the assumed repository size (10 km$^2$). The rate of volcanism is dependent on the number of recognized volcanic events, a factor which is controlled both by the area examined and the time period chosen. The latter is largely governed by the geologic history of the area examined. The most significant variable affecting the magnitude of the calculation is, therefore, the area examined. Accordingly, we have repeated the calculation for a 50-km-radius circle centered at Yucca Mountain, which encloses the maximum number of volcanic cones in the NTS region that are 5 m.y. and younger. Using the larger area and the probability formula

$$P_{\text{Volcanic Disruption}}=\text{RXA},$$

the parameter R is defined by a volcanic center count of 18, which includes three cinder cones and associated lava flows southwest of Black Mountain (approximately 0.3 m.y.)(A, fig. 2), and the eroded cone and lava flow of Buckboard Mesa (2.8 m.y.) (B, fig. 2).

$$R_{\text{Rate}}=\frac{18\ \text{volcanic centers}}{2.8\text{X}10^{6}\ \text{years}}$$

$$=6.4\text{X}10^{-6}/\text{year}$$

and the area ratio A:

$$A=\frac{10\ \text{km}^2}{\pi(50\ \text{km})^2}$$

$$=1.3\text{X}10^{-3}$$

The volcanic-disruption probability for a 50-km-radius circle centered at Yucca Mountain is:

$$P_{\text{Volcanic Disruption}} = (6.4\times10^{-6}/\text{year})(1.3\times10^{-3})$$
$$= 8.3\times10^{-9}/\text{year}$$

## CONSEQUENCE ANALYSES

A second important problem with respect to volcanic-hazards analyses is an evaluation of the range of consequences of disruption of a waste repository by volcanic activity. The generalized consequences of magmatic disruption of a waste repository have been described by Crowe (1980). Major variables are:

1. Depth of waste burial
2. Geometry of magma-waste intersection
3. Nature of volcanism
4. Lag time prior to magmatic disruption

Several constraints on volcanic consequences can be applied to the southwestern NTS region based on field studies of the basalts of Crater Flat. First, the most probable magma composition of future volcanic activity is basaltic. This composition limits transport distances, assuming Strombolian and(or) phreatomagmatic eruptive activity (Crowe, 1980). Second, as described in the probability discussions, deep burial of waste (>500 m) would greatly reduce the disruption area attributed to basaltic volcanic activity, based on the observation that basalt centers are generally fed at depth by relatively narrow dikes. Some very simple calculations can be determined on the area of contact of a basalt feeder dike, assuming direct intersection of a repository. Two dissected basaltic volcanic centers are exposed along the northern margin of the Silent Canyon volcanic center, revealing a feeder dike for the westernmost center. The dike is exposed vertically for about 20 m. It is approximately 0.7 m wide and extends about 2.2 km. Assuming three feeder dikes per center (based on field studies of basalt centers at Crater Flat), a total area is calculated:

$$A_{\text{magma-waste contact}} = \text{dike width x extent x 3 dikes/center}$$
$$= 0.0007\ \text{km}\times2.2\ \text{km}\times3$$
$$= 0.0046\ \text{km}^2$$

This figure corresponds to the total disruption area in which waste and magma are in <u>direct</u> contact. Assuming the radioactive waste is uniformly distributed within a 10 km$^2$ area, the percentage of direct contact is:

$$C_{\text{Contact}} = \frac{0.0046\ \text{km}^2}{10\ \text{km}^2}\times100$$
$$= 0.046\ \text{percent}$$

This calculation clearly ignores the wallrock disruption effects due to emplacement of a dike into the repository. Secondary effects due to dike emplacement (for example, ground-water disruption, stress field changes, etc.) may be very important in the consequence analyses.

## REGIONAL VOLCANIC PATTERNS AND TECTONIC CONTROLS OF VOLCANISM

The third approach to an evaluation of volcanic hazards in the Great Basin is analysis of the patterns and tectonic controls of past volcanism, in order to attain a more complete understanding of regional tectonics and volcanism. Much has been learned about the past distribution of Cenozoic volcanism within the Great Basin. We attempt to briefly summarize this knowledge here and point out unsolved problems.

In general, Tertiary volcanism began in the east-central part of the Great Basin region about 40 m.y. ago, and has spread outward toward the edges of that region through time (Armstrong and others, 1969). However, many questions remain concerning the details of time-space migration of volcanism and the relationships to basin-range tectonism and plate-tectonic interactions (Noble, 1972; Christiansen and Lipman, 1972; Scholtz and others, 1971; Suppe and others, 1975; Snyder and others, 1976; Stewart and others, 1977; Christiansen and McKee, 1978; Best and Hamblin, 1978). A southerly or southwesterly migration has been emphasized by some authors (Stewart and others, 1977). There are exceptions, but major silicic volcanism in a given area or volcanic field generally has a lifetime of less than 10 m.y., and, once ended, has not been renewed. In many areas silicic (rhyolitic) volcanism was accompanied by minor basaltic activity after about 15 m.y. ago (Christiansen and Lipman, 1972). Significant silicic volcanism has not occurred during the last 5 m.y., except locally near the margins of the Great Basin. Basalt eruptions younger than 5 m.y. have occurred primarily along the margins of the Great Basin (Best and Hamblin, 1978) and additionally in the south-central part of the basin, including a discontinuous belt that extends through the NTS region northward into central Nevada (fig. 2). Work recently completed for the Nevada Nuclear Waste Storage Investigations program has shown, however, that many of the basalts in this belt are older than 5 m.y. In fact, only four relatively small areas of Quaternary (<2 m.y.) basalts are present; these occur in Death Valley, the Crater Flat-Lathrop Wells area, north of Beatty (A, fig. 2), and the Lunar Crater field of the Pancake Range. The belt may continue north-northwestward across northern Nevada (fig. 2), where it could coincide with the Oregon-Nevada lineament (Stewart and others, 1975), a major structural zone expressed magnetically by volcanic rocks, including significant basaltic flows and dikes. The reasons for localization of the south-central Great Basin basaltic belt of Pliocene and Pleistocene volcanism are not well understood. The belt lies immediately west of a general north-south septum of Paleozoic rocks that is magnetically quiet (Stewart and others, 1977), and which coincides with the axis or median of symmetry described by Eaton and others (1978). This septum of Paleozoic rocks appears to mark a persistent division between volcanic source areas to the east and west, and could mark the eastern, slightly more active edge of a western or subsidiary half of the southern Great Basin (fig. 2).

We recognize at least three tectonic settings for Pliocene and Pleistocene basalts in the southern Great Basin: (1) small northeast-trending rift zones or areas of relatively young basin-range extension, (2) caldera ring fracture zones, and (3) right-stepping offsets in northwest-trending, right-lateral shear zones, or intersections of northeast-trending faults with these zones. Combinations of some or all of the above settings may occur, or even be required, to bring basaltic magma to the surface. One of the settings may correspond

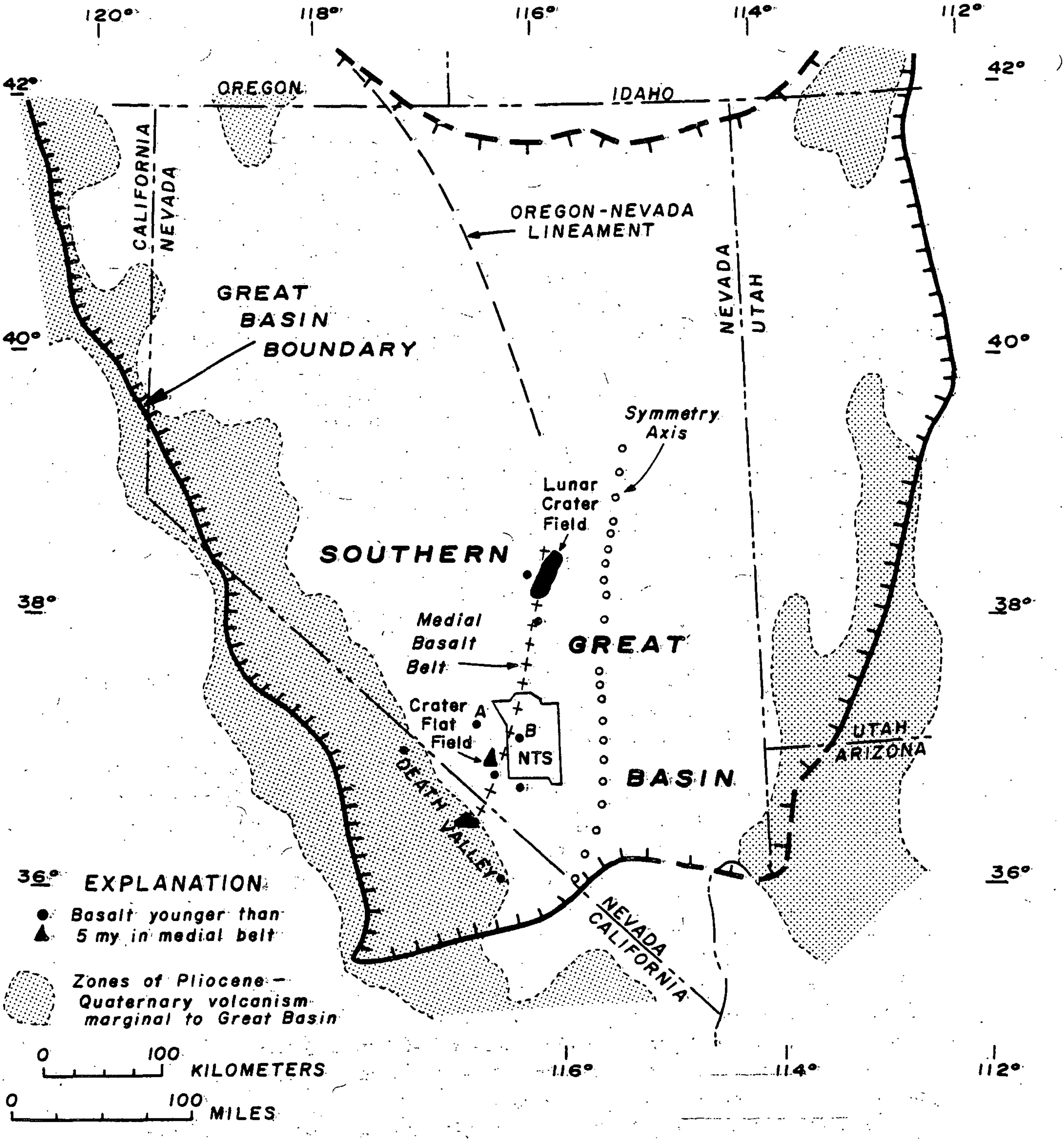


*Figure 2.-- The Great Basin, showing location of marginal young volcanism, medial basalt belt, and septum or symmetry axis.*

to "leaky transform" faults (Weaver and Hill, 1978), which often yield basalts, and which fit well into the overall Pliocene and Pleistocene stress field proposed for parts of the Great Basin (Carr, 1974; Thompson and Burke, 1973; Wright, 1976; Slemmons and others, 1979).

On the basis of present knowledge, one might zone or rate the southern Great Basin as to the risk of recurrence of basaltic volcanism in the following general way, from least probable to most probable: (1) areas that have experienced no Tertiary or Quaternary volcanism whatever; (2) topographically high or structurally positive blocks that (a) were not volcanic source areas in the last 20 m.y., or (b) were not volcanic source areas in the last 10 m.y.; (3) rift grabens outside volcanic source areas; and (4) caldera ring fracture zones or rift grabens within volcanic source areas. Special cases may exist with respect to these general risk zones. For example, resurgent domes of calderas may well be an exception to category (4) above, and may correspond to category (2). One of the authors (Carr) has noted that in the NTS region, in an area of major silicic volcanism ranging in age from about 16 to 7 m.y., basin-range grabens have not significantly penetrated areas underlain by granitic basement rock (fig. 3). In other areas, such as central Nevada, where the volcanic centers are about twice as old, basin-range faulting and graben formation have penetrated and broken through granitic rocks, both within and outside caldera areas. These grabens are the sites of extensive Quaternary basaltic volcanism.

## SUMMARY AND FUTURE DIRECTIONS

Preliminary calculations of the probability of volcanic disruption of a waste repository site at Yucca Mountain have been made. Assuming random occurrence of volcanism within an area enclosed by a 25-km-radius circle centered at Yucca Mountain, an annual probability of volcanic disruption of a waste site of $10^{-8}$ has been calculated. The rate of volcanism for the probability calculations varies, depending on assumptions concerning the number of volcanic centers in the NTS region, but all calculations yield rates on the order of $10^{-6}$ volcanic events per year. A critical parameter to the probability calculations is the area of concern. A second probability calculation for a 50-km-radius circle and a time period of 2.8 m.y. yields a probability of disruption of $10^{-9}$ per year.

Regional studies of the occurrence of young (<5 m.y.) basaltic volcanism within the northeast-trending belt of the southern Great Basin are in progress. These studies will extend the area of interest of the probability calculations and establish a basis for comparing rates of activity for the NTS region with surrounding areas of the southern Great Basin. Additionally, the frequency of occurrence of basaltic volcanic centers with respect to tectonic setting will be determined, and these data will be used to upgrade our classification of volcanic recurrence zones. Field studies will additionally focus on attempts to recognize past tectonic and petrologic controls of volcanism in order to better predict future rates and possible sites of volcanic activity.

Data in hand indicate that the probability of disruption of a waste repository by volcanism is extremely low and, moreover, that the risk can be reduced by locating a site within an area that is less likely to have volcanic activity in the future. Additional work is required concerning the tectonic setting of volcanism within the Great Basin and

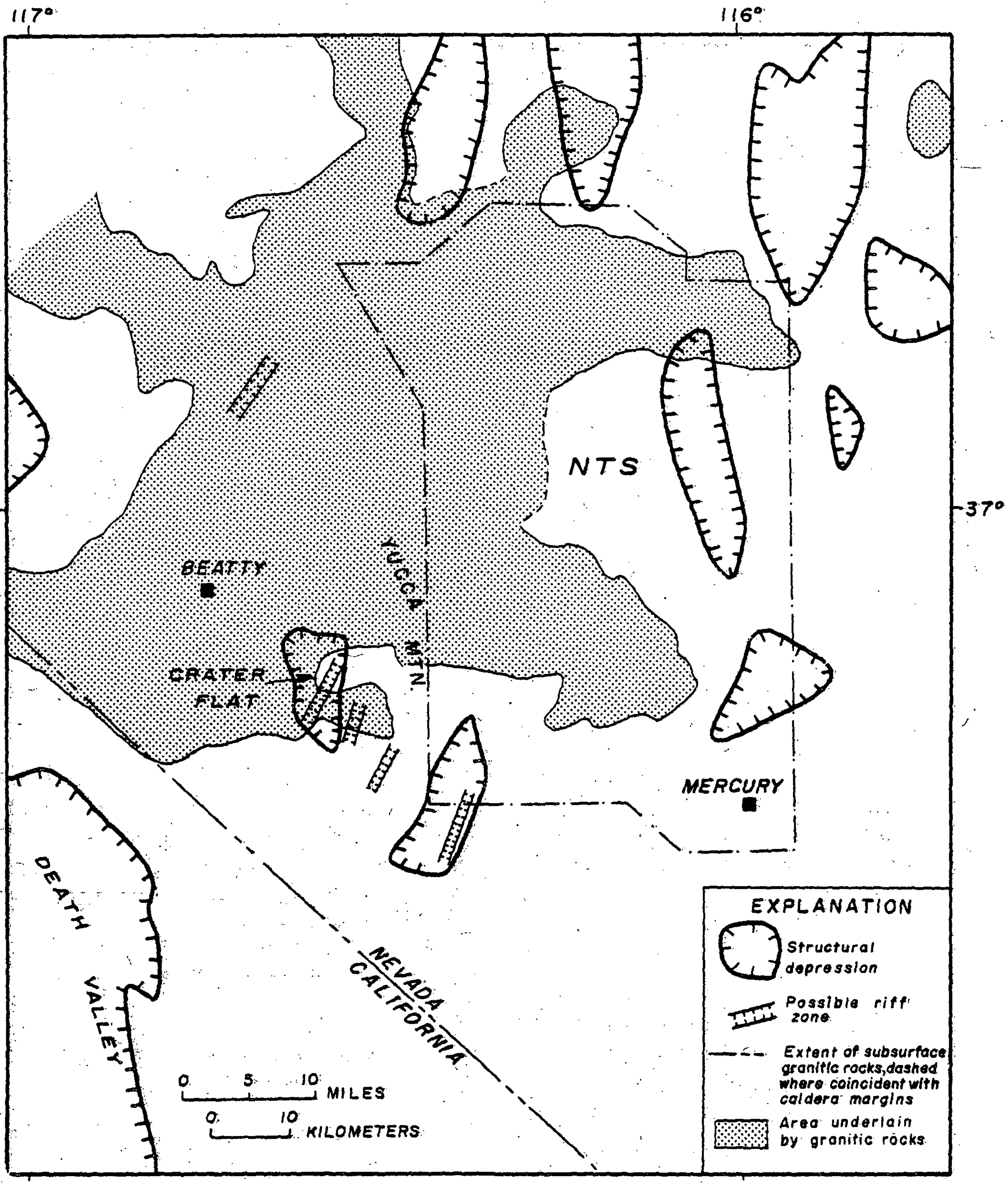


Figure 3.--Nevada Test Site (NTS) region, showing areas underlain by granitic rocks, structural depressions tectonically active in Quaternary time, and possible rift zone associated with Quaternary basalts. Granitic basement based on geology and aeromagnetics.

the local tectonic setting of possible sites, and volcanic consequence analyses are needed to further understand the impact of volcanic hazards on siting of a waste repository in the southwestern NTS region.

## REFERENCES

Armstrong, R. L., Ekren, E. B., McKee, E. H., and Noble, D. C., 1969, Space-time relations of Cenozoic silicic volcanism in the Great Basin of the western United States: American Journal Science, v. 267, no. 4, p. 478-490.

Best, M. G., and Hamblin, W. K., 1978, Origin of the northern Basin and Range province: Implications from the geology of its eastern boundary: Geological Society of America Memoir 152, p. 313-340.

Byers, F. M., Jr., Carr, W. J., Orkild, P. P., Quinlivan, W. D., and Sargent, K. A., 1976, Volcanic suites and related caldrons of the Timber Mountain-Oasis Valley caldera complex, southern Nevada: U.S. Geological Survey Professional Paper 919, 70 p. 21-38.

Carr, W. J., 1974, Summary of tectonic and structural evidence for stress orientation at the Nevada Test Site: U.S. Geological Survey Open-file Report 74-176.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States; Part II, Late Cenozoic: Philosophical Transactions of the Royal Society of London, ser. A, v. 271, p. 249-284.

Christiansen, R. L., and McKee, E. H., 1978, Late Cenozoic volcanic and tectonic evolution of the Great Basin and Columbia Intermontane regions: Geological Society of America Memoir 152, p. 283-311.

Cox, A., 1969, Geomagnetic reversals: Science, v. 163, p. 237-245.

Crowe, B. M., 1980, Disruptive event analyses: Volcanism and Igneous Intrusion: Battelle Pacific Northwest Laboratories Report (in press).

Eaton, G. P., Wahl, R. R., Prostka, H. J., Mabey, D. R., and Kleinkopf, M. D., 1978, Regional gravity and tectonic patterns: Their relation to late Cenozoic epeirogeny and lateral spreading in the western Cordillera: Geological Society of America Memoir 152, p. 51-92.

Lipman, P. W., and McKay, E. J., 1965, Geologic map of the Topopah Spring SW quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-439, scale 1:24,000.

McKay, E. J., and Sargent, K. A., 1970, Geologic map of the Lathrop Wells quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-883, scale 1:24,000.

Noble, D. C., 1972, Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, western United States: Earth and Planetary Science Letters, v. 17, p. 142-150.

Scholtz, C. H., Barazangi, M., and Sbar, M. L., 1971, Late Cenozoic evolution of the Great Basin, Western United States, as an ensialic interarc basin: Geological Society of America Bulletin, v. 82, p. 2979-2990.

Slemmons, D. B., Van Wormer, D., Bell, E. J., and Silberman, M. L., 1979, Recent crustal movements in the Sierra Nevada-Walker Lane region of California-Nevada: Part I, rate and style of deformation: Tectonophysics, v. 52, p. 561-570.

Snyder, W. S., Dickinson, W. R., and Silberman, M. L., 1976, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States: Earth and Planetary Science Letters, v. 32, p. 91-106.

Stewart, J. H., Walker, G. W., and Kleinhample, F. J., 1975, Oregon-Nevada lineament: Geology, v. 3, p. 265-268.

Stewart, J. H., Moore, W. J., and Zeitz, Isidore, 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: Geological Society of America Bulletin, v. 88, p. 67-77.

Suppe, J., Powell, C., and Berry, R., 1975, Regional topography, seismicity, Quaternary volcanism, and the present-day tectonics of the western U.S.: American Journal of Science, v. 275-A, p. 397-436.

Thompson, G. A., and Burke, D. B., 1973, Rate and direction or spreading in Dixie Valley, Basin and Range Province, Nevada: Geological Society of America Bulletin, v. 84, p. 627-632.

Weaver, C. S., and Hill, D. P., 1978, Earthquake swarms and local crustal spreading along major strike-slip faults in California: Pure and Applied Geophysics, v. 17, p. 51-64.

Wright, L. A., 1976, Late Cenozoic fault patterns and stress fields of the Great Basin and westward displacement of the Sierra Nevada block: Geology, v. 4, p. 489-494.