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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

REGIONAL STRUCTURAL SETTING OF YUCCA MOUNTAIN, SOUTHWESTERN NEVADA, AND LATE CENOZOIC RATES OF TECTONIC ACTIVITY IN PART OF THE SOUTHWESTERN GREAT BASIN, NEVADA AND CALIFORNIA

by

W. J. Carr

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ABSTRACT

The southwestern Great Basin region surrounding Yucca Mountain is divisible into three major structural-physiographic subsections with different structural styles and chronology. Yucca Mountain is located in the tectonically least active of the subsections, the Walker Lane belt. The belt, however, contains a number of structural zones of northeast trend, some of which are moderately active, as shown by Quaternary fault scarps and persistent low-magnitude seismicity. Tectonic activity appears to be favored by northeast fault orientation with respect to the present stress field. In southwestern Nevada, the Walker Lane belt was the source of voluminous middle and late Miocene silicic volcanism, which was located mainly in an area of major right-steps in the northeastern belt margin. The belt originated as a shear and flexure zone in the Mesozoic, when the majority of lateral displacement probably occurred. Tertiary time was characterized by relatively small-scale lateral displacements, accompanied by west-northwest crustal spreading and volcanism. A distinct decrease in the rate of faulting occurred in nearly all areas 9 or 10 m.y. ago. Relatively little tectonic activity has occurred in the Walker Lane belt since about 6 m.y. ago, after silicic volcanism ceased and northwest-striking faults in the belt came under compression as a result of a change in the regional stress field.

The "basin-range subsection" adjoining the Walker Lane belt on the northeast displays typical horst and graben structure, perhaps locally intensified at intersections with the Walker Lane belt marginal shear zones. The long rectangular basins contain rhombic areas of small but deep pull-aparts with as much as 1,220 m (4,000 ft) of alluvium of late Miocene to Quaternary age. The Miocene was the principal period of basin and range faulting, but tectonic definition of the generally narrow troughs and basins continues, although very few Holocene scarps are known.

Southwest of the Walker Lane belt, in California, is the very active Inyo-Mono subsection, whose present physiographic and structural development has occurred largely in Pliocene and Quaternary time, as evidenced by very youthful geomorphology, fault scarps, volcanism, and seismic activity. The

importance of the Furnace Creek-Death Valley fault zone, the boundary between the Inyo-Mono and Walker Lane belt subsections, is emphasized because it marks a major transition in tectonism continentward from the San Andreas fault.

Yucca Mountain and the Nevada Test Site are also located within a diffuse north-northeast trending zone of Pliocene and Quaternary basaltic volcanism termed the Death Valley-Pancake Range basalt belt. It is regarded as a zone of tectonic flux slightly higher than adjacent areas that lies parallel to and just west of the Great Basin symmetry axis. In addition to basalts, the belt is roughly defined or paralleled by topographic, gravity, magnetic, and seismic anomalies. A hiatus in basalt eruptions in the Nevada Test Site region about 4-6 m.y. ago may represent the time of change in the regional least principal stress direction from westerly to northwesterly; early basalts in the belt appear to have reached the surface along north-trending zones, later basalts erupted from more northeasterly striking structures.

Preliminary seismotectonic analysis of the southwestern Great Basin defines several broad areas of seismicity, which agree in general with the regional distribution of Pliocene and Quaternary fault activity, except for the significant exception of important Holocene faults of the Inyo-Mono subsection that presently show very low levels of seismicity. The Yucca Mountain area is one of the least active in the region, but it is flanked on the east by the Spotted Range-Mine Mountain structural zone, an area of numerous small earthquakes and a number of Quaternary fault scarps. Permeability differences of the rocks, i.e., thick volcanic rocks versus fractured Paleozoic carbonate rocks, as well as fault orientation with respect to the stress field, are suggested as important factors in the difference in seismic activity between Yucca Mountain and the Spotted Range-Mine Mountain zone. A continuing problem in evaluation of the natural seismicity of the Nevada Test Site area is the overprint of nuclear test related seismic activity.

One important Holocene faulting event is recognized within about 100 km (62 mi) of Yucca Mountain, excluding the active Inyo-Mono subsection. Other minor Holocene events cannot be ruled out, however, in the region adjacent to Yucca Mountain.

The structural and geohydrologic framework of the Yucca Mountain area rests on a base of pre-Tertiary rocks, whose structure is characterized by thrust faults and folds of Mesozoic age, and by the presence of one and probably two east-trending Mesozoic granitic bodies.

Tertiary structure of the Yucca Mountain area was greatly influenced by volcano-tectonic processes, and the youngest significant faulting appears to be spatially and temporally related to igneous activity. At Yucca Mountain, evidence for general long-term stability is good, as nearly all of the fault displacement occurred prior to about 10 m.y. ago, in harmony with a dramatic decrease in silicic volcanism in the late Miocene. A north-striking pattern of faulting exposed in the area probably continues westward across Crater Flat to Bare Mountain, but interpretation of structure in Crater Flat, aided by geophysics and two drill holes, suggests that the depression is largely related to volcano-tectonic subsidence of the Crater Flat-Prospector Pass caldera complex about 13.5 m.y. ago. Only minor additional tectonic displacements have occurred, except at the east foot of Bare Mountain. Reactivation of the caldera ring-fracture faults is suggested as a partial explanation for the style of basin and range type faults at Yucca Mountain. An area north of Bare Mountain displays a contrasting style of thin-skinned Tertiary deformation that was probably accompanied by listric and detachment faulting.

A few northwest-striking structures are present at Yucca Mountain, but these are generally small faults and fracture zones with evidence of right-lateral displacement; none of these northwest-striking structures appear to have been active in the Quaternary.

Rift-like structures with a north-northeast trend occur southeast and southwest of Yucca Mountain. These appear to have localized some of the small-volume Pliocene-Pleistocene basalt eruptions. A significant synchronous relation exists between minor faulting and at least one Quaternary basalt eruption.

The rate of tectonic activity at Yucca Mountain is less than that for most adjacent regions during the last 10 m.y. or so, although determination of the rate during the last 8 m.y. is hampered by a scarcity of events and deposits to record structural disturbance. Silicic volcanism in the region reached a peak about 13 m.y. ago, was over by 5 m.y. ago, and is unlikely to recur. Basaltic activity began about 12.5 m.y. ago and has not changed greatly in type, volume, or periodicity in the last 5 m.y. or so. The youngest basaltic activity occurred 250,000-300,000 yr ago at two locations, the nearest about 15 km (10 mi) south of the Yucca Mountain site.

Deformation rates at Yucca Mountain during the last approximately 10 m.y. have been roughly 10 times less than those in parts of the Inyo-Mono subsection, and about 4 times less than those in adjacent parts of the basin-range subsection. A rate of 0.01 m/1,000 yr is thought to be a realistic maximum for fault displacement in the Quaternary period at Yucca Mountain. Gentle regional tilting to the south has probably occurred in the last 3 m.y.

Evidence of the timing of faulting at Yucca Mountain is given in a series of tables and maps, which illustrate the dramatic decrease in rate of activity during the last 12 m.y. Nearly all persistent faulting has occurred as reactivation of preexisting faults. Age of volcanic units associated with minor, younger faulting shows, however, that the stress field orientation allowing extension on north-northwest striking faults persisted until at least 9 m.y. ago.

INTRODUCTION

Evaluation of the Yucca Mountain area as a potential site for a high-level nuclear waste repository must consider many factors, including geography and hydrology, but both present and future relative tectonic stability of the site area is one of the most important concerns. This report presents a summary of the regional structure and tectonic development, with emphasis on the Tertiary and some preliminary conclusions concerning the tectonic flux in the region surrounding Yucca Mountain. Much of the information in this report has been presented informally in meetings, and one of the main purposes is to make the data and interpretations available in a single referenceable document. In many cases, however, it has been necessary to refer the reader to published data or details that support or clarify certain discussions. Not all possible hypotheses concerning tectonic problems are considered in this report, nor are all observations completely interpreted.

The southwestern Great Basin of Nevada and California is a complex region of diverse structural trends and styles, which has a long history of tectonic disturbance, although there is much evidence of a general waning of activity in about the last 10 m.y. or so. Neogene tectonic development of the region has resulted in several partly overlapping structural-physiographic subsections whose characteristics are important in placing Yucca Mountain, or other segments of the region, in perspective. These characteristics and the differences between subsections have perhaps not been sufficiently emphasized in previous studies, nor has it been widely recognized that certain segments of the Great Basin, on the order of 10 to 50 km (5 to 30 mi) across, have been distinctly less active tectonically in the last 10 m.y. than adjacent areas. It has been traditional to categorize the entire Great Basin, or a larger region, as tectonically unstable, without consideration of detailed information from the seismologic or volcanic records. This view is particularly favored by geophysicists, who combine this data with other characteristics such as high heat flow, seismicity, thin crust, obvious volcanism, and so forth, to conclude that every part of the region is highly active tectonically.

In order to site a nuclear waste facility in a relatively stable area, it is helpful to recognize important sectional tectonic boundaries and to understand the structural style of each subsection and the timing of tectonic events related to the subsection. Many years of intensive geologic investigations, including much geophysical study and many drill holes in the Nevada Test Site (NTS) region, including Yucca Mountain (fig. 1), have provided considerable insight into the tectonic setting. As a result, it has become clear that generalizations about the larger structural domains in the region must be made with care.

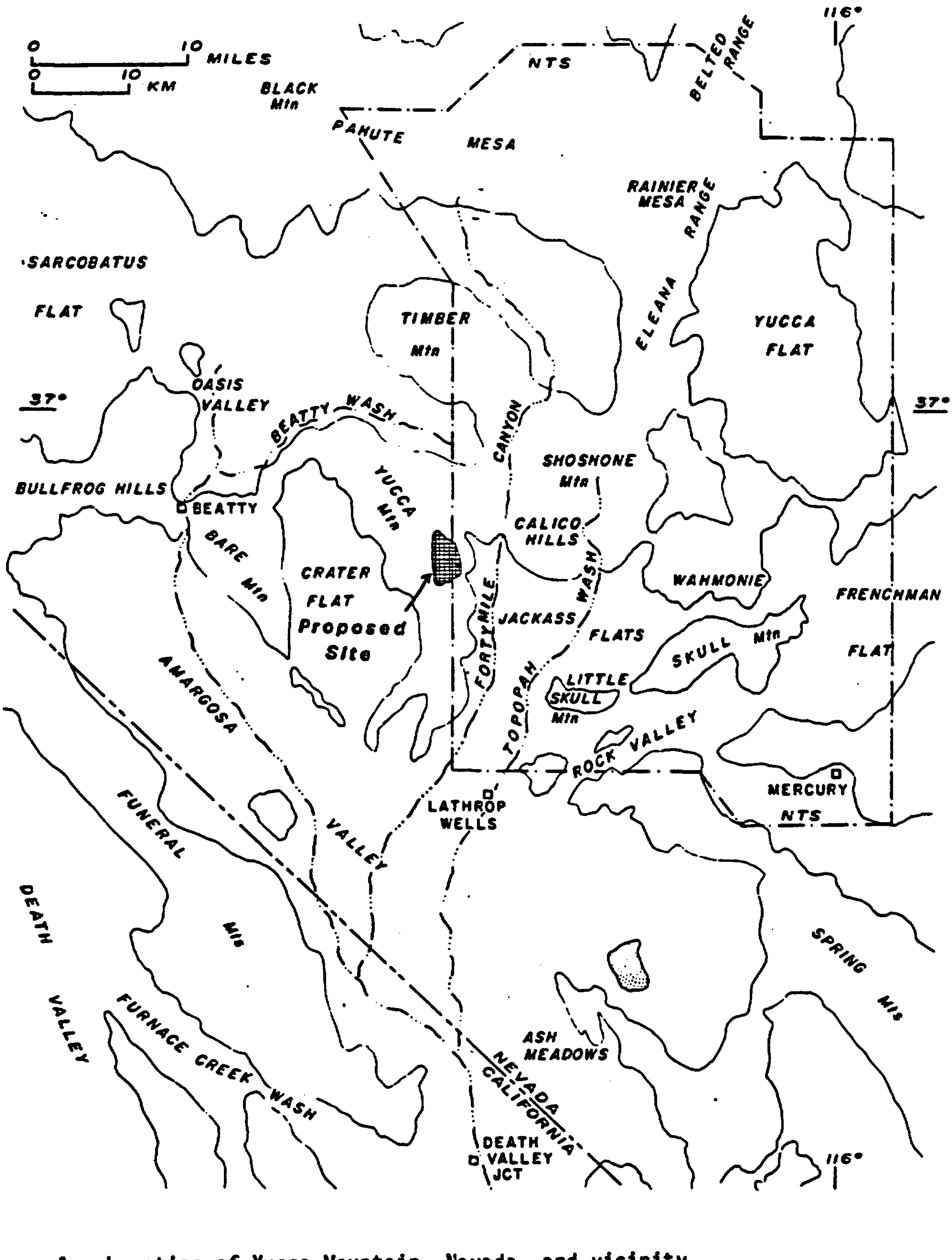

Figure 1.--Location of Yucca Mountain, Nevada, and vicinity.

As stratigraphy is often referred to in this report with respect to timing of structural development, a very generalized stratigraphic column is given in table 1.

The reader is referred to the geologic maps of Nevada (Stewart and Carlson, 1978) and California (Jennings, 1977) and the California portion of the Death Valley sheet (Streitz and Stinson, 1974) for regional geologic background. The only published geologic map of the NTS region (Carr, 1974, fig. 2) is highly generalized and outdated; thus, it is suggested that the reader consult pertinent U.S. Geological Survey geologic quadrangle maps.

The author thanks his colleagues, in particular those studying the seismology of the region, A. M. Rogers, W. J. Spence, and S. C. Harmsen of the U.S. Geological Survey (USGS), and Bruce M. Crowe and D. T. Vaniman of Los Alamos National Laboratory for their contributions to some of the data and conclusions presented in this report. Thanks are also due to C. W. Naeser, B. J. Szabo, J. N. Rosholt, R. J. Fleck, and R. F. Marvin of the USGS for their invaluable assistance in providing numerous critical dates on late Cenozoic rocks of the region. R. B. Scott and K. S. Kellogg of the USGS provided helpful technical reviews. The interpretations presented here, however, are largely those of the author. Editing by V. M. Glanzman greatly improved the report.

Table 1. Generalized major stratigraphic units in Nevada Test Site region, with emphasis on the Yucca Mountain area

Unit		Volcanic center or caldera	Age
Alluvium			Miocene-Holocene
Basalts			Miocene-Quaternary
Tuff of Stonewall Flat		Stonewall Mountain	Middle Miocene
Thirsty Canyon Tuff		Black Mountain	Do.
Rhyolite of Shoshone Mountain		Shoshone Mountain-Fortymile Canyon area	Do.
Rhyolites of Fortymile Canyon		Shoshone Mountain-Fortymile Canyon area	Do.
Tuff of Buttonhook Wash		Timber Mountain	Do.
Timber Mountain Tuff	Ammonia Tanks Member Rainier Mesa Member	do.	Do.
Rhyolite of Windy Wash		do.	Do.
Paintbrush Tuff	Tiva Canyon Member Yucca Mountain Member Pah Canyon Member Topopah Spring Member	do.	Do.
Wahmonie and Salyer Formations		Wahmonie	Do.
Rhyolite lavas and tuffs of Calico hills		Fortymile Canyon area	Do.
Crater Flat Tuff	Prow Pass Member Bullfrog Member Tram Member	Crater Flat-Prospector Pass	Do.
Belted Range Tuff		Silent Canyon (Pahute Mesa)	Do.
Lavas of intermediate composition		Various sources, locations poorly known	
Lithic Ridge Tuff		Various sources, locations poorly known	Do.
Older tuffs and lavas		Various sources, locations poorly known	Early to middle Miocene
Tuffs and sedimentary rocks		Various sources, locations poorly known	Middle Oligocene to Middle Miocene

Table 1. Generalized major stratigraphic units in Nevada Test Site region, with emphasis on the Yucca Mountain area--Continued

Unit	Volcanic center or caldera	Age
Tippipah Limestone and Eleana Formation (aquitard)	Not applicable	Mississippian and Pennsylvanian
Dolomite and limestone (aquifer)	do.	Cambrian-Devonian
Quartzite, shale, limestone, dolomite, locally metamorphosed (aquitard)	do.	Proterozoic and Cambrian

STRUCTURAL-PHYSIOGRAPHIC SUBSECTIONS OF THE SOUTHWESTERN GREAT BASIN

Three major locally overlapping subdivisions or subsections of the southwestern Great Basin are recognizable from their physiography and late Cenozoic structural history (figs. 2 and 3). The term "subsection" as used in this report is a logical subdivision of the physiographic sections delineated by Fenneman and Johnson (1946), who designated the Great Basin as a section of the larger Basin and Range province. Subsections described are: (1) the Walker Lane belt (WLB), which includes several important segments, such as the Spotted Range-Mine Mountain (SR-MM) structural zone; (2) the basin-range subsection of the Great Basin; and (3) the Inyo-Mono subsection.

Walker Lane Belt

The Walker Lane Belt, an important regional zone, includes Yucca Mountain, and has been called the Walker belt by some authors (Stewart, 1980, fig. 3, p. 80). It is viewed (Carr, 1981) as a part of a megastructure or continental-scale lineament that crosses the Basin and Range province from Texas to Oregon. In the southern Great Basin, the belt separates the northwest structural-physiographic trends east of the Sierra Nevada in California from the predominantly north-south trends of the typical basin and range structure of Nevada, as pointed out long ago by Gianella and Callaghan (1934, p. 21). The belt is, as often described, a zone of diversely oriented, relatively low relief hills and valleys dominated by lateral shear rather than vertical tectonics. Shear zones of the belt tend to be poorly exposed, mainly because in the southern Great Basin most of them are tectonically inactive and the traces are largely buried beneath young volcanic rocks and alluvium.

As defined here, the (WLB) of the southern Great Basin is locally more than 100 km (60 mi) wide, and the southwestern boundary is the southern Death Valley-Furnace Creek-Fish Lake Valley fault system (fig. 3). The northeastern limits, less well defined in some areas, are designated as the northeastern-most of a zone of partly en echelon, northwest-striking right-lateral shear zones (figs. 3 and 4). The shear zones are commonly accompanied by right-lateral flexures; the bending along the Las Vegas Valley shear extends several tens of kilometers north of the zone.

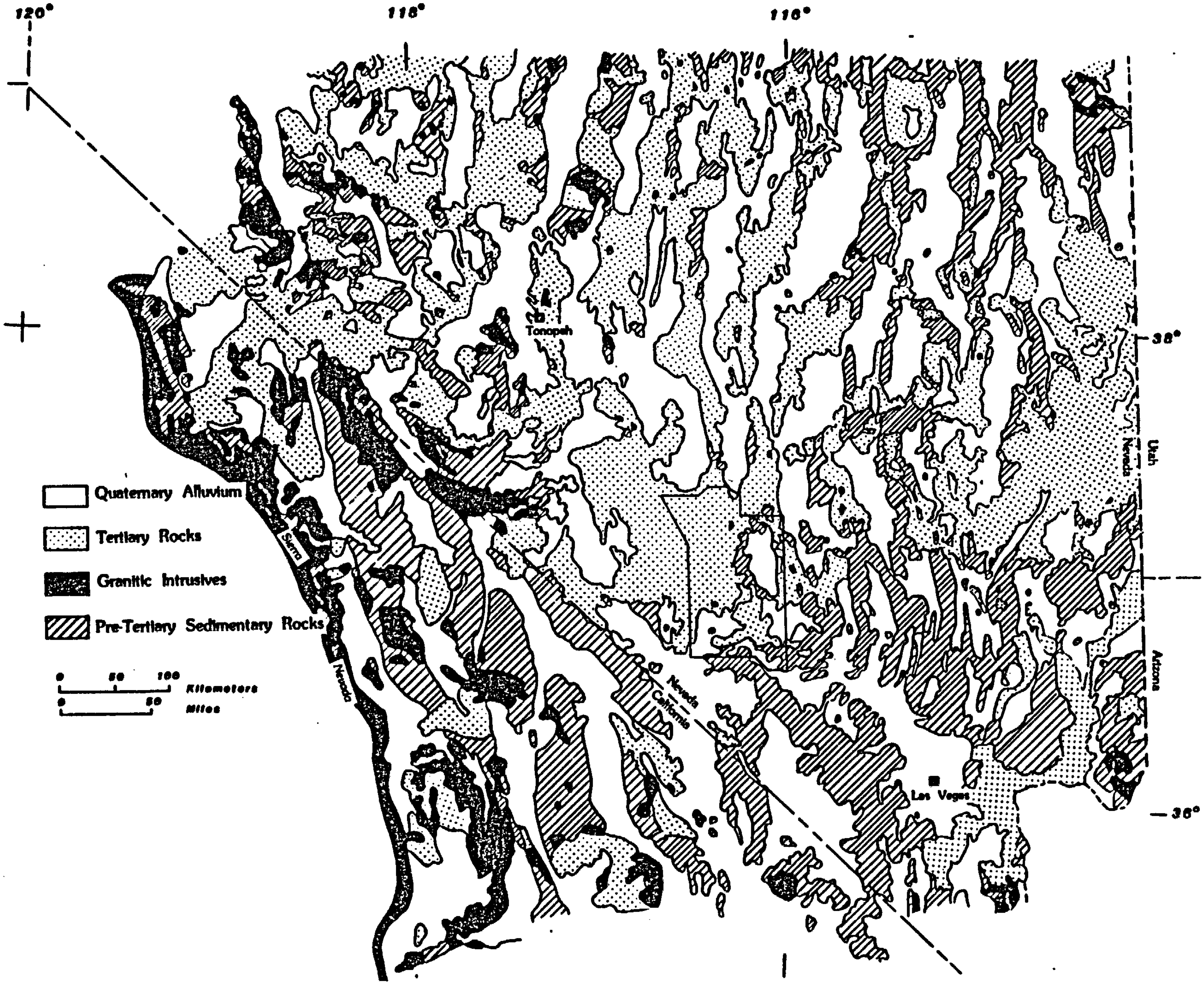

Figure 2.--Generalized geologic map of southwestern Great Basin.

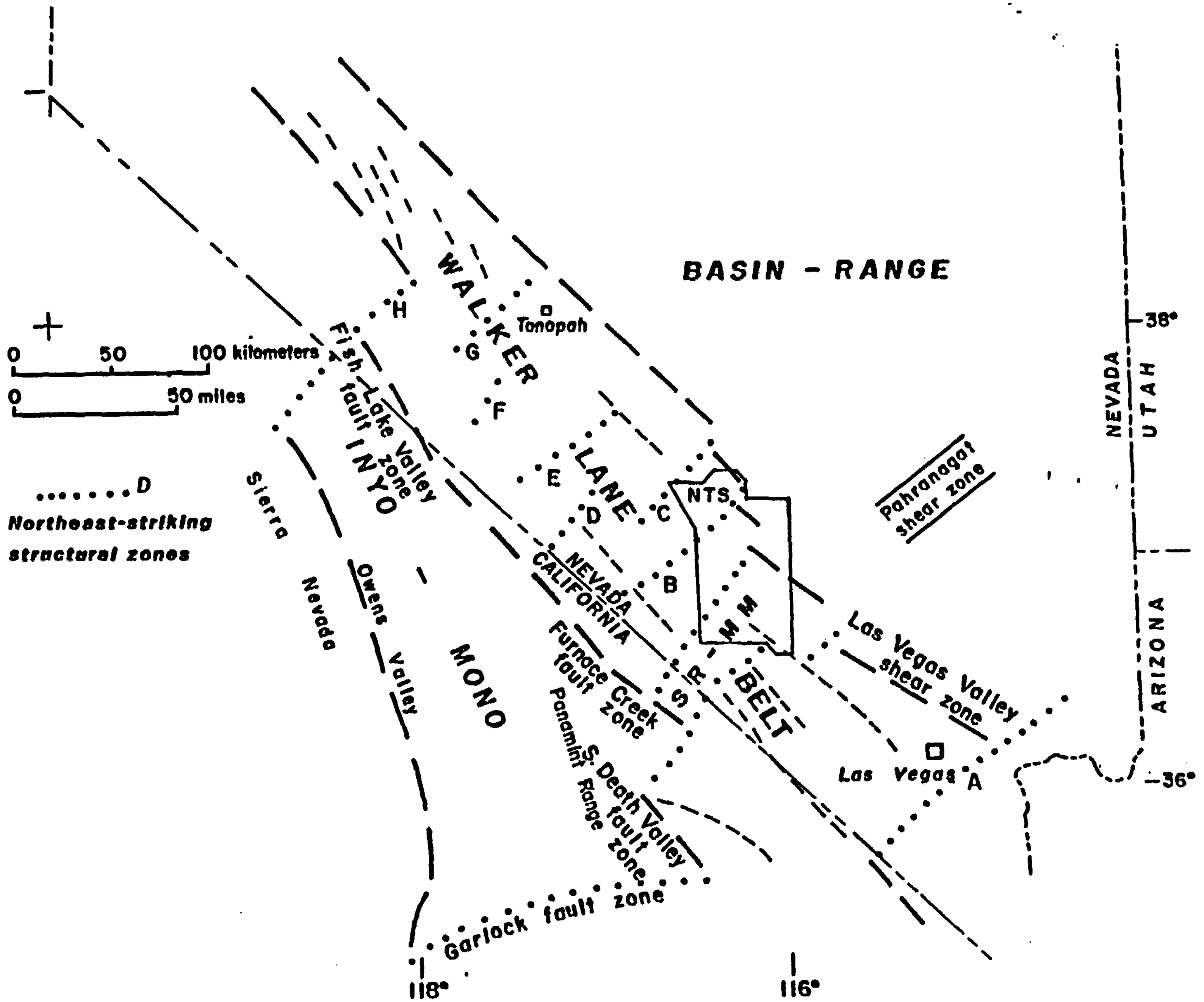

Figure 3.--Structural-physiographic subsections and important structures of the Walker Lane belt.

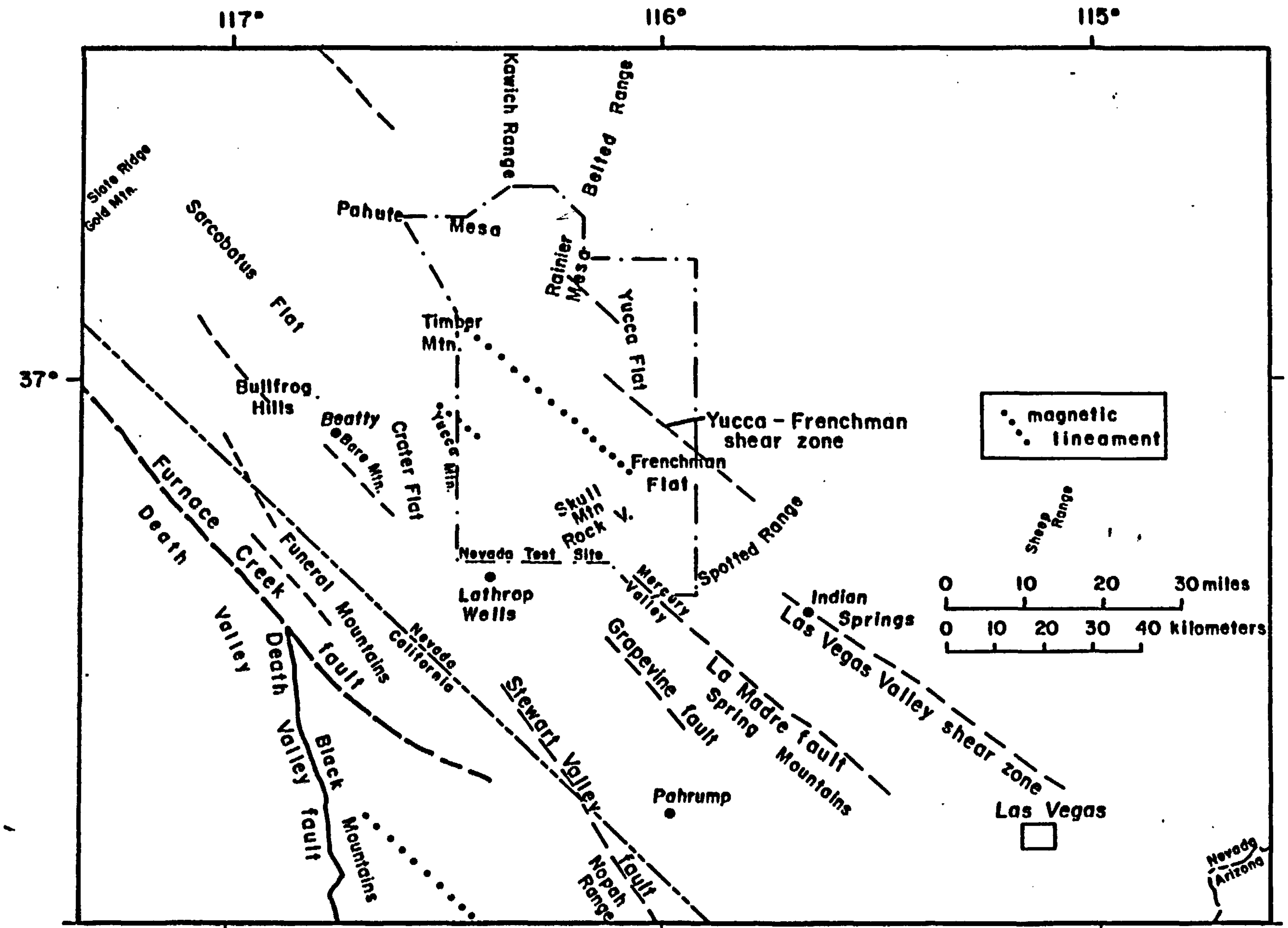

Figure 4.--System of northwest-trending structures and magnetic lineaments associated with the Walker Lane belt.

The shears are transform-like in the sense that they may display greater extension on one side than the other, and they have finite length, typically ending abruptly at north- to northeast-striking structural zones that appear to absorb the right-lateral component by extension on normal or oblique-slip faults. The longest of the northwest-striking shear zones, such as the one in Las Vegas Valley, occur at the belt margins or where the belt is narrow. I restrict the Las Vegas Valley shear zone to a segment about 70 km (45 mi) long between Las Vegas and Indian Springs (fig. 4).

A typical element of the Walker Lane belt system is the Yucca-Frenchman shear and flexure zone (Carr, 1974, p. 35), which extends from the Spotted Range for about 40 km (25 mi) northwestward across northern Frenchman Flat and southwestern Yucca Flat (fig. 4). Where exposed, between Yucca and Frenchman Flats, this zone is expressed by small northwest-striking faults in 11.5-13.5 m.y.[1]-old tuffs, but the main expression is right-lateral flexure of the tuffs, north-northwest trending faults, and buried Paleozoic rocks, as suggested by gravity contours (figs. 5 and 6). Fault displacement and stratal rotation (fig. 5) also suggest a greater amount of extension north of the shear zone than to the south, a style consistent with other shear zones of the WLB, as exemplified by the Las Vegas Valley shear zone (Guth, 1981), and possibly the La Madre fault zone.

The Yucca-Frenchman shear zone is presently a prominent boundary of seismicity associated with northeast-striking faults of the Spotted Range-Mine Mountain (SR-MM) structural zone (fig. 7), suggesting that, even though the shear zone itself is not presently active, it is an important tectonic boundary, and that the triangular-shaped area between the Rock Valley Fault system and the Yucca-Frenchman shear zone is the present focus of basin development in Frenchman Flat.

Large vertical tectonic displacements, however, are not characteristic of the Walker Lane belt, except where the belt structures locally interact with basin and range faults or those of northeast trend, as indicated above for the Frenchman Flat area. Gravity data (Healey and others, 1980a,b; Kane and others, 1979) show that relatively thin Cenozoic deposits are present in most valleys in the WLB. Caldera-dominated areas, such as Crater Flat, owe their prominent negative gravity signatures largely to volcano-tectonic processes (Carr, 1982; Snyder and Carr, 1982) that occurred before 10 m.y. ago.

Other important characteristics of the southern Great Basin portion of the Walker Lane belt are the comparatively low level of seismicity and, significantly, the scarcity of northwest-trending Quaternary fault scarps that parallel the main structural trend (fig. 8). Linear, fault controlled mountain fronts with northwest trend are also scarce. The few scarps of

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[1]Ages given for specific units in this report have been corrected for new K-Ar constants (Dalrymple, 1979).

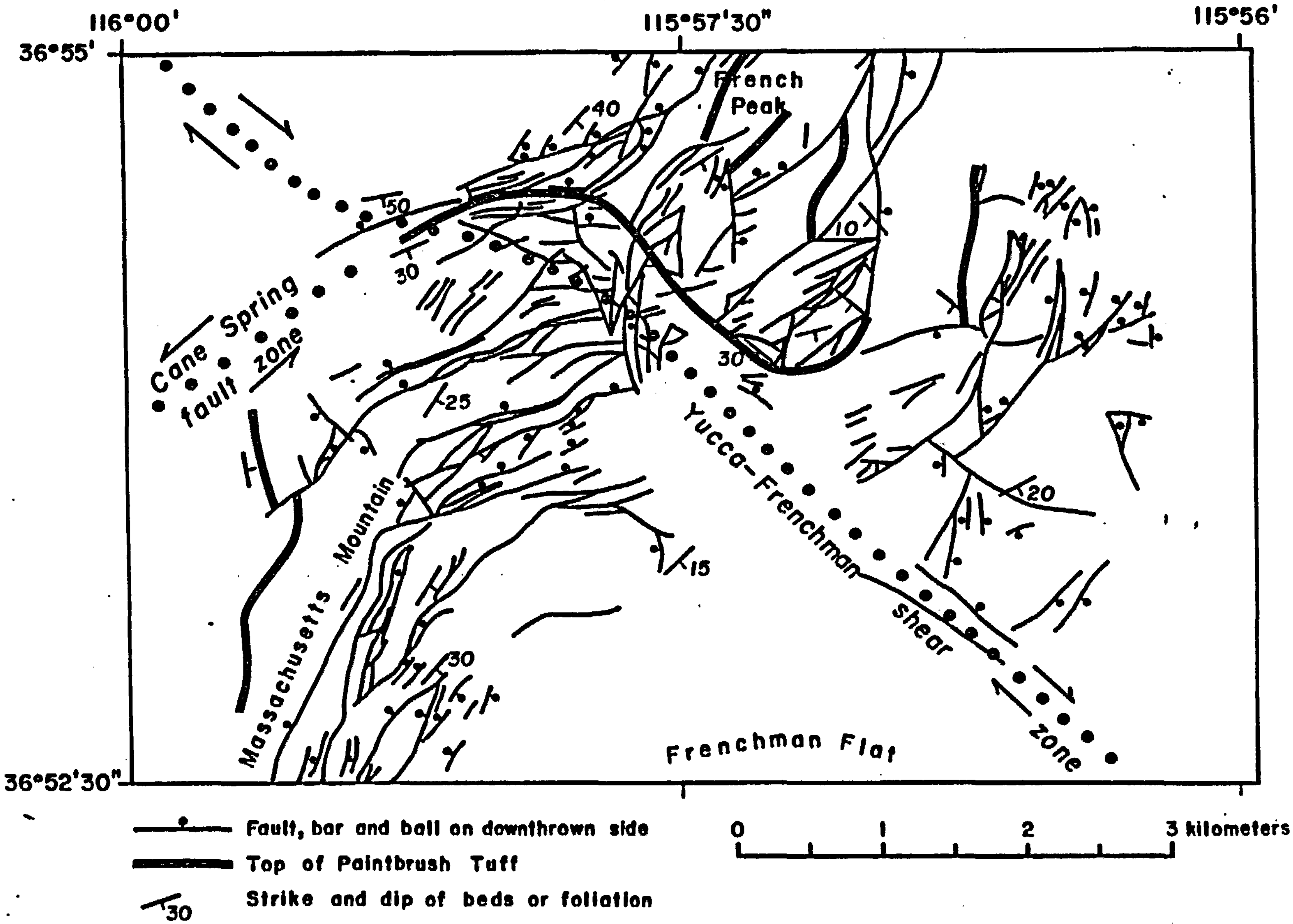

Figure 5.--Structure of a portion of the Yucca-Frenchman shear and flexure zone, northwest Frenchman Flat.

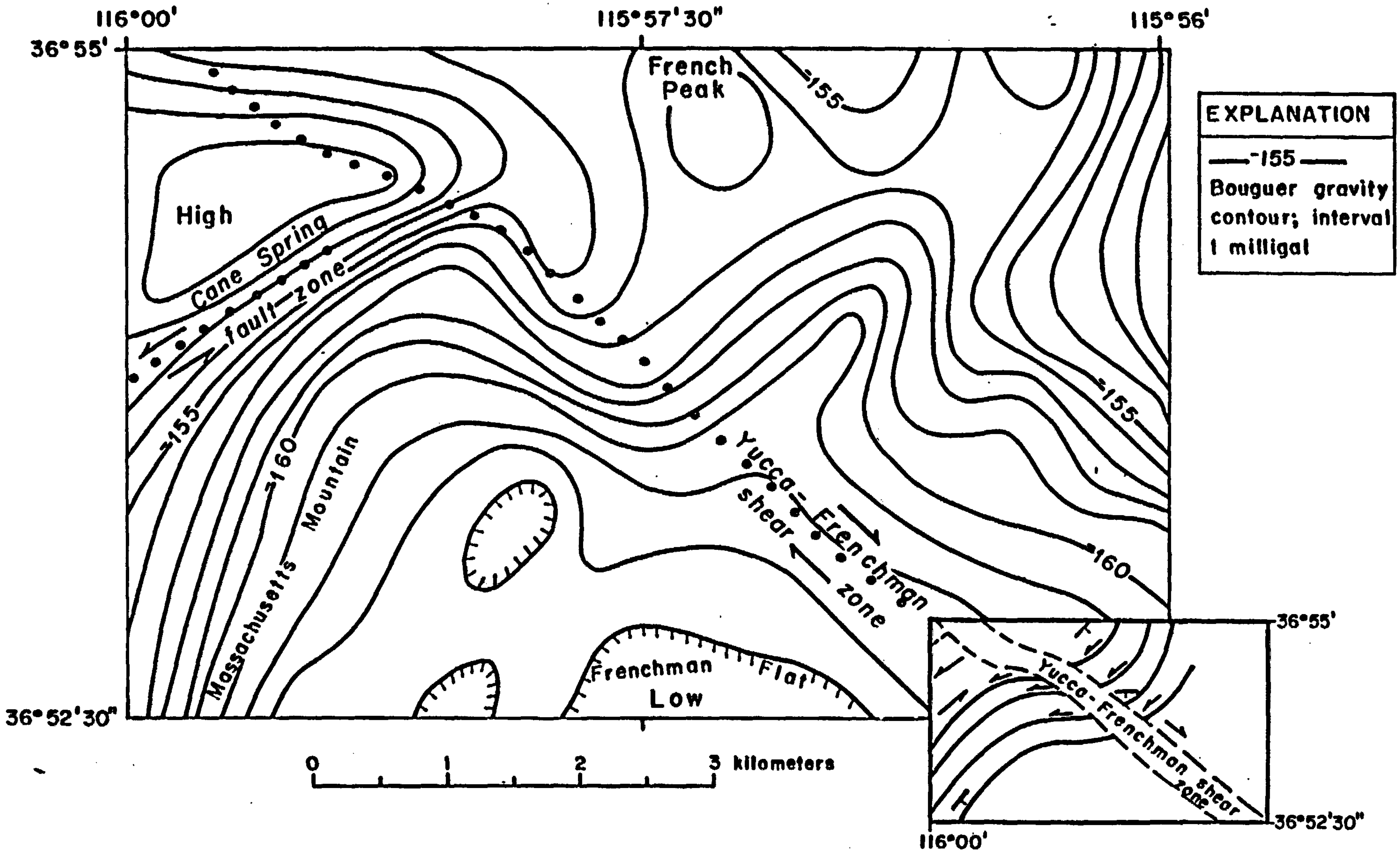

Figure 6.--Bouguer gravity of a portion of the Yucca-Frenchman shear and flexure zone, northwest Frenchman Flat.

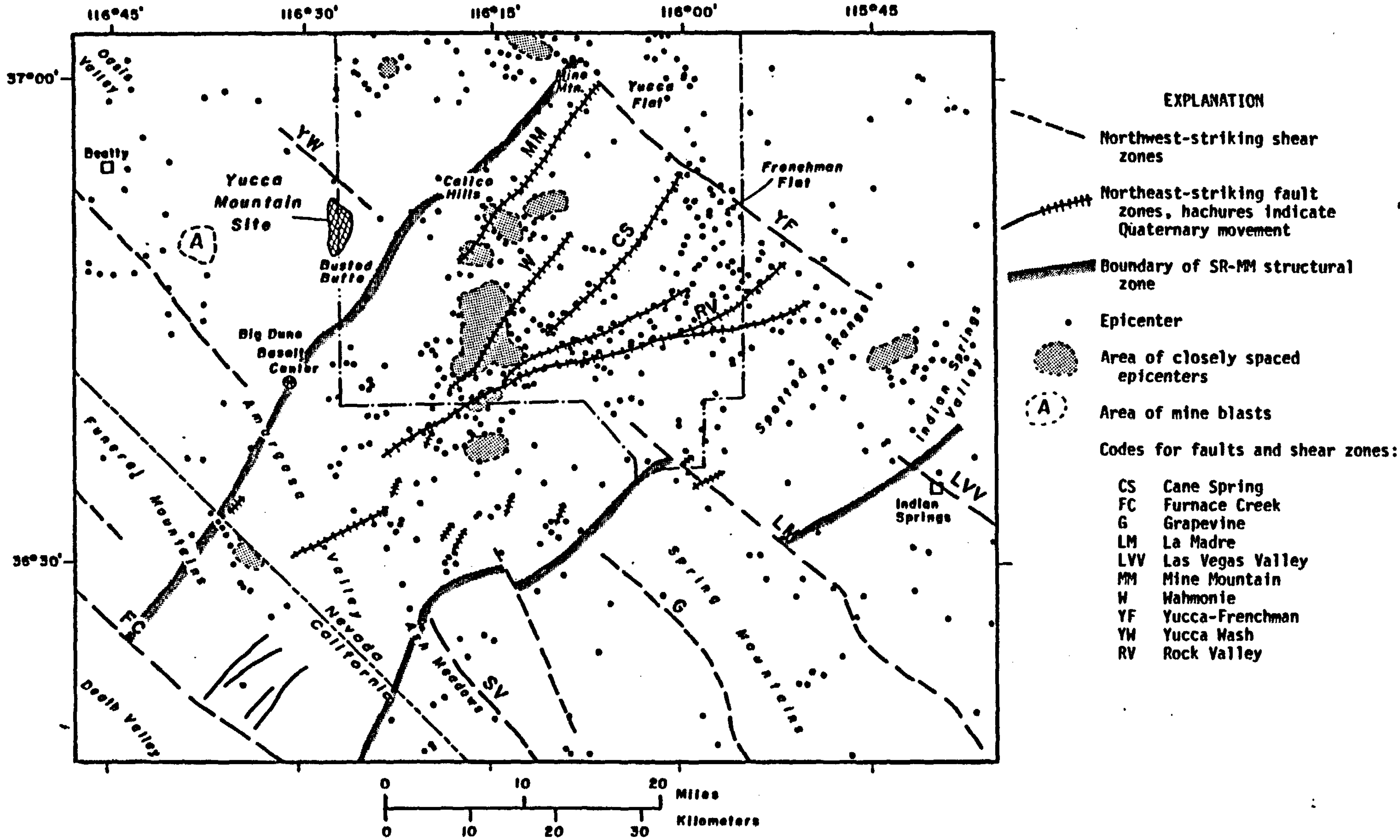

Figure 7.--Spotted Range-Mine Mountain structural zone and included Quaternary fault zones, showing the relationship to seismicity of the southern NTS area, August 1978 through May 1984.

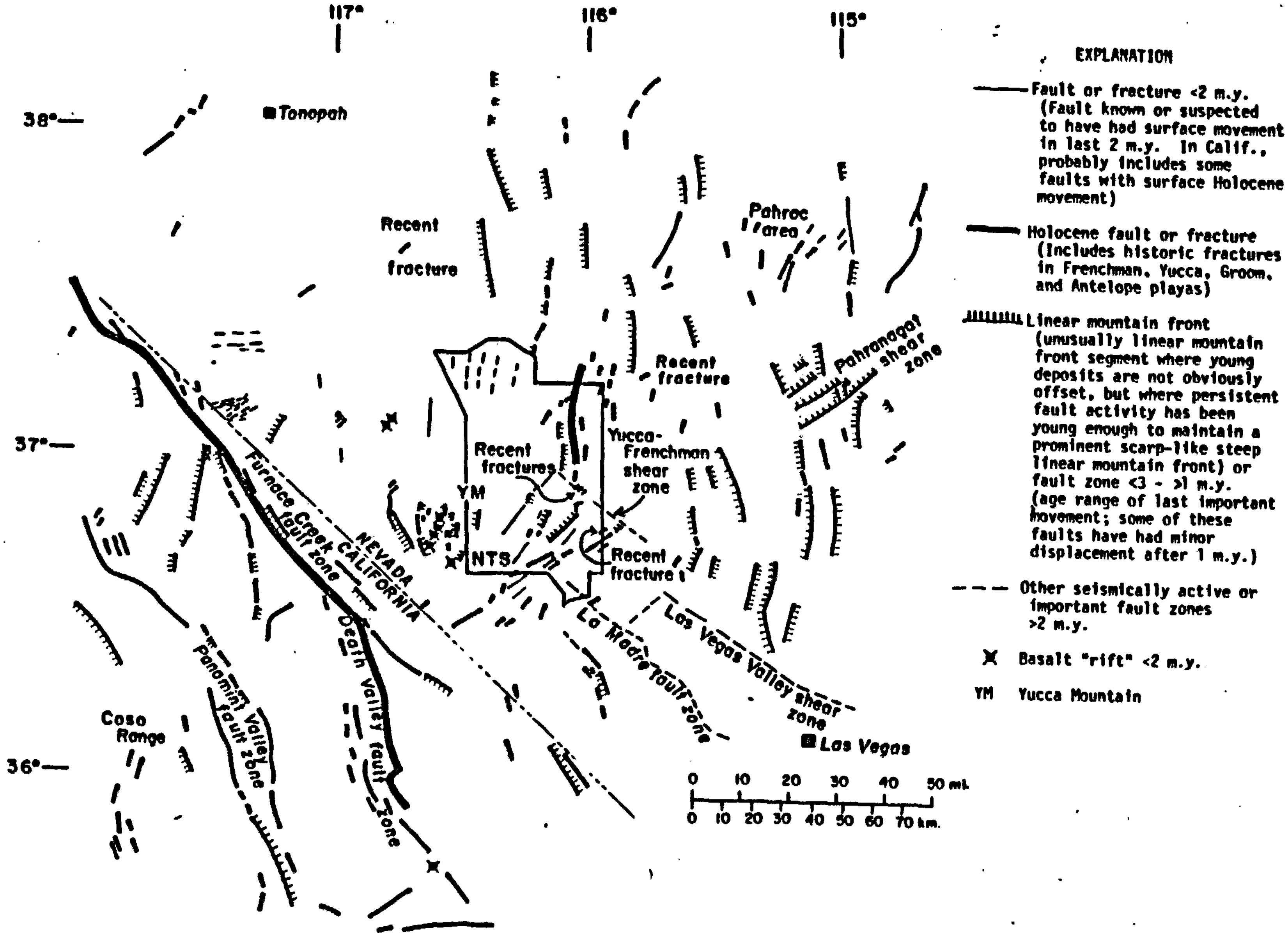

Figure 8.--Generalized map of late Pliocene and Quaternary faults and fractures in the NTS region.

northwest trend that do exist are in the southwestern part of the belt, adjacent to the Inyo-Mono subsection, which contains numerous northwest-trending active faults.

All of the volcano-tectonic features and volcanic centers of the southwestern Nevada volcanic field (fig. 9) are located within the Walker Lane belt, as defined here. The close association of the volcanism with the belt implies a kinematic relationship, as suggested by Carr (1974, p. 5-6) and Christiansen and others (1977, p. 954-955). An appealing structural model for localization of the volcanism is suggested in papers by Hill (1977) and Weaver and Hill (1979), who propose "leaky transform" faulting as the setting for crustal spreading in the Salton trough of southern California. The volcanic centers of the NTS area may have been localized on northeast-trending zones of Tertiary crustal spreading connecting major right-steps of the northeastern boundary of the Walker Lane belt (figs. 4 and 9). The steps progress northward from the Las Vegas Valley shear zone through the Yucca-Frenchman shear zone and the southern Belted Range to the southern Kawich Range area.

Age of the structural development of the Walker Lane belt has long been a subject of discussion and some disagreement. The reader is referred to Longwell (1974), Stewart (1980, p. 86), Burchfiel (1965), Bohannon (1979), Guth (1981), Wernicke, Spencer, Burchfiel and Guth (1982), and Royse (1983) for samples of previous views and analysis of the problem. Longwell (1974) attempted to relate structural rotation of Miocene rocks east of Frenchman Mountain near Las Vegas to the Las Vegas Valley shear zone, but Anderson (1973) showed that the structure in that area is mainly related to a major northeast-striking zone of faults. Establishing the age of inception of the belt is especially difficult. Fleck (1970b) maintained that 15 m.y.-old strata are rotated as much as Paleozoic strata adjacent to the Las Vegas Valley shear zone, and that 10.7 m.y.-old volcanic rocks are undeformed, although he did not give the specific localities for these relationships. In many places in and near the belt, however, the pre-Tertiary rocks are structurally rotated distinctly more than those of Tertiary age. Good examples are around Yucca Flat, particularly on the east side (Byers and Barnes, 1967) and in the Little Skull Mountain-Striped Hills area (Sargent and others, 1970). I briefly discussed (Carr, 1974) some of the aspects of this problem in the NTS area near the northern end of the Las Vegas Valley shear zone, and little new data have emerged to provide a more rigorous time frame. Study of geologic maps and remapping of certain areas in detail, however, such as the Yucca-Frenchman shear zone (Carr, 1974), have demonstrated the right-lateral sense of displacement on several of the northwest-striking shear zones. For example, apparent right-lateral shearing on northwest-striking faults is shown on the Rainier Mesa quadrangle (Gibbons and others, 1963) in both Tertiary and pre-Tertiary rocks on the east side of Rainier Mesa. A prominent set of northwest-striking faults shows progressively less offset up section from the Tertiary-Paleozoic contact; tuffs about 14 m.y. old show about the same amount of displacement as the Paleozoic rocks, but the 11.6 m.y.-old Rainier Mesa Member of the Timber Mountain Tuff shows much less or, on some faults, no offset.

There is large-scale evidence of pre-Tertiary and even pre-mid Cretaceous activity in the Walker Lane belt, particularly oroclinal bending (Albers, 1967) and probable right-lateral displacement of upper Paleozoic rocks (Stewart, 1967; Poole and others, 1967). In addition, some large regional

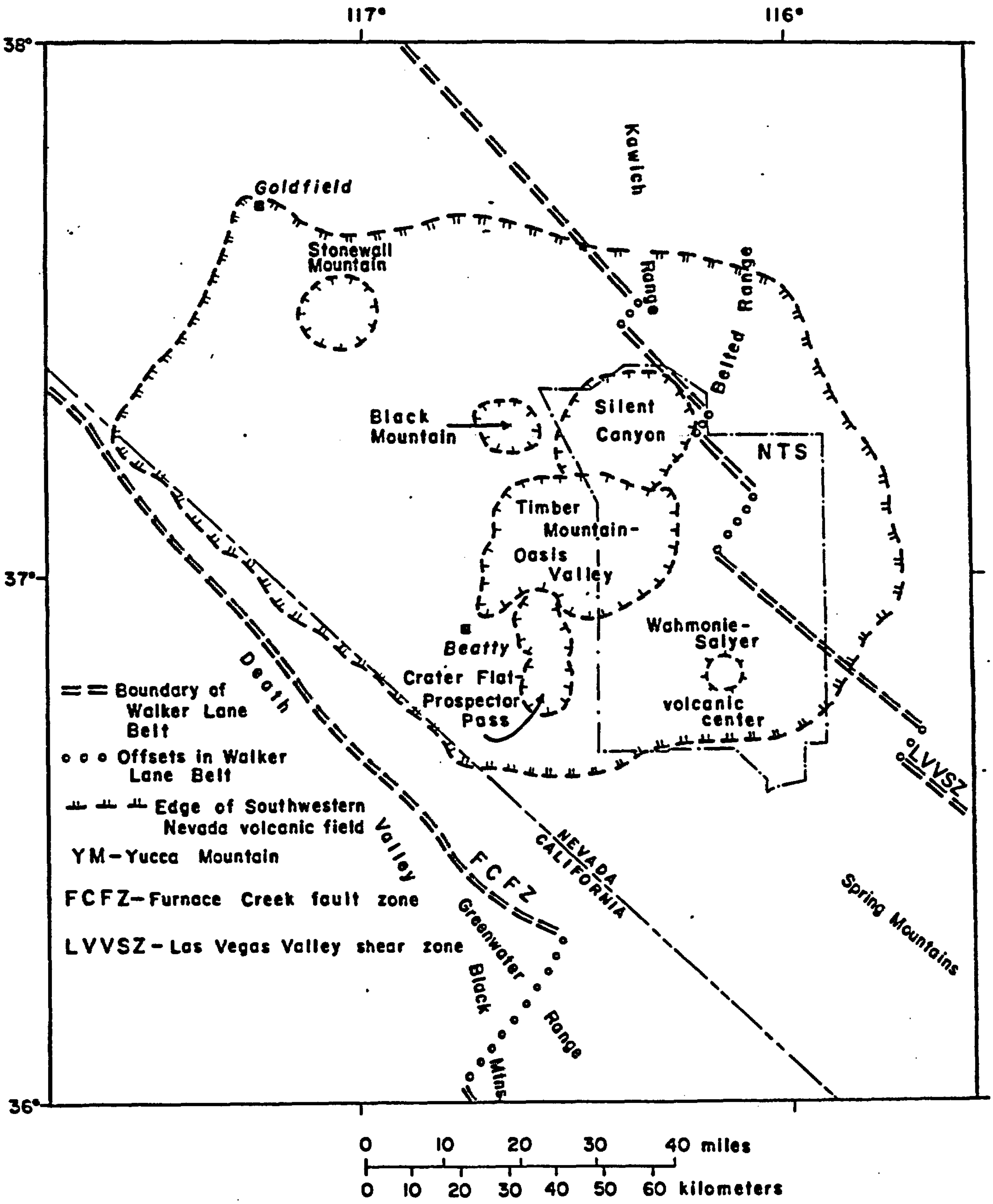

Figure 9.--Location of southwestern Nevada volcanic field and associated calderas and a volcanic center within the Walker Lane belt.

features, such as east-trending Mesozoic granitic pluton trends, and a regional Miocene volcano-tectonic trough, do not appear to be significantly offset, suggesting that the main displacement occurred prior to about 15 m.y. ago, and probably before 100 m.y. ago. This will be discussed further in the section, "Tectonic Setting of Yucca Mountain."

Some new insight has been gained in regard to the ending, or at least the diminishing, of activity on structures of the Walker Lane belt. Seismologic data continue to reinforce earlier conclusions that faults of northwest trend are now essentially inactive (Rogers and others, 1983), and study of Quaternary faulting (fig. 8) in the Walker Lane belt has not identified any northwest-striking faults of Holocene age, although a few older Quaternary faults of northwest-strike have been mapped. In Mercury Valley (fig. 4), near the end of the topographic expression of the Las Vegas Valley-La Madre fault system, alluvium between 1 m.y. and 3 m.y. old is cut by a number of small faults that strike north to northeast, but field and air photo study of the deposits revealed no northwest structural trend, even though a published geologic map (Hinrichs, 1968) places the Las Vegas shear zone in this area.

The Timber Mountain Tuff (as young as about 11.0 m.y.[2]) is the youngest widespread unit of Tertiary age in the NTS area, and it is displaced by northwest-striking faults at a few places, such as the Massachusetts Mountain-French Peak area (fig. 5; Hinrichs and McKay, 1965) and at Rainier Mesa (Gibbons and others, 1963). On Skull Mountain and Little Skull mountain (fig. 4) northwest-striking faults are virtually absent (Sargent and others, 1970; Sargent and Stewart, 1971; Ekren and Sargent, 1965) in all the Tertiary rocks, which range in age from about 14 m.y. to 10 m.y., even though the area lies across projections of northwest-striking fault zones (fig. 4). Elsewhere the scarcity of both northwest-striking faults and rocks younger than the Timber Mountain Tuff provide little close control for the ending or diminishing of structural activity on features of northwest trend.

Timber Mountain (fig. 4), the resurgent dome of the Timber Mountain caldera, which formed soon after eruption of the Ammonia Tanks Member (11.4 m.y. old), is elongated northwest parallel to the Walker Lane belt, and its longitudinal graben is also elongated northwest (Carr and Quinlivan, 1968). The northwest trend of Timber Mountain dome coincides with part of a prominent northwest-trending magnetic gradient (fig. 4) that extends from the dome southeastward nearly to Frenchman Flat (Bath and others, 1983, fig. 1c, p. 42). This gradient could be controlled by a pre-volcanic structure, as could the elongation of the Timber Mountain dome; the elongation could also be the result of the regional stress field in existence at the time (Carr, 1974).

Another shorter magnetic lineament of northwest trend parallels Yucca Wash just northeast of Yucca Mountain (fig. 4; and U.S. Geological Survey, 1979). The magnetic lineament appears to be caused mainly by a buried topographic feature of northwest trend that controlled the deposition of lava

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[2]The youngest units of the Timber Mountain Tuff, mostly confined to the Timber Mountain-Oasis Valley caldera complex, are the tuffs of Buttonhook Wash and Crooked Canyon (Byers and others, 1976b).

of Calico Hills. Exposures of Paintbrush Tuff (12.5-13.5 m.y. old) in and along Yucca Wash indicate some abrupt stratigraphic changes across the lineament, but no major structural effects exist in the Paintbrush, as will be shown later in the section,"Tectonic Setting of Yucca Mountain."

Thus, although the precise time of initiation of the Walker Lane belt structure is particularly difficult to ascertain, there is some evidence that major activity on the system ended by about 10 m.y. ago, and in some areas before 14 m.y. ago or earlier.

Basin-Range Subsection

The basin-range subsection as used here contains the typical north-trending fault-block graben terrain of the region. Along and occasionally south of the basin-range-WLB boundary, local overlap of structural styles occurs, especially in the NTS area. In southern Nevada, the basin-range subsection consists of prominent ranges and relatively deep and narrow alluvium-filled troughs that are mainly the result of latest Miocene, Pliocene, and Quaternary displacement on northerly striking faults. Predominant displacement on these faults is dip-slip, but commonly they have a significant component of right-slip, an interpretation supported by the general stress model for the region, subsurface data (Carr, 1974), and fault plane solutions from earthquakes (Rogers and others, 1983). The subsection as discussed here, corresponds in general to the deformational field I of Wright (1976), which he described as being characterized by mostly high-angle normal faults of north-northeast trend. Gravity data (fig. 10) and drill-hole information (figs. 11 and 12) show that valleys like Yucca Flat and Kawich Valley (Healey and others, 1980a) contain thick prisms of late Miocene, Pliocene, and Quaternary deposits. Extensive subsurface data from Yucca Flat shows that the principal basin development has taken place along east-dipping normal faults located in the middle part of the valley (fig. 11). East-west cross sections indicate stratal rotations in tuff that require an important fault approximately every 450 m (1,500 ft). Detailed data from Yucca Flat show, however, that the formation of such structural depressions is not necessarily a simple downdropping of linear blocks, but rather a combination of faulting and subsidence of relatively small, almost equidimensional or semicircular areas that have behaved somewhat like collapse sinks that have sagged much more than adjacent parts of the basin (fig. 12). The most spectacular structural depression for which good data are available is in southern Yucca Flat where 600 to 1,200 m (2,000-4,000 ft) of alluvium is present in an area less than 3 km (2 mi) across (figs. 11 and 12). Alluvium in other areas in the down-faulted parts of Yucca Flat is only 300 to 600 m (1,000-2,000 ft) thick. The deep depression is tucked into the intersection of the northwest end of the northwest-trending Yucca-Frenchman shear and flexure zone and the southern end of the Carpetbag fault system, a major fault zone controlling the subsurface structure of Yucca Flat (figs. 11 and 12). It appears that west-northwest extension and subsidence of this part of Yucca Flat (Carr, 1974) have been facilitated by the interaction of part of a typical basin and range fault (Carpetbag) and a Walker Lane belt structure (Yucca-Frenchman shear zone).

The fundamental mechanism of formation of the semicircular type of depocenter discussed is not known. Stewart (1971) suggested a model of complex graben formation above a plastically extending substratum. This is a

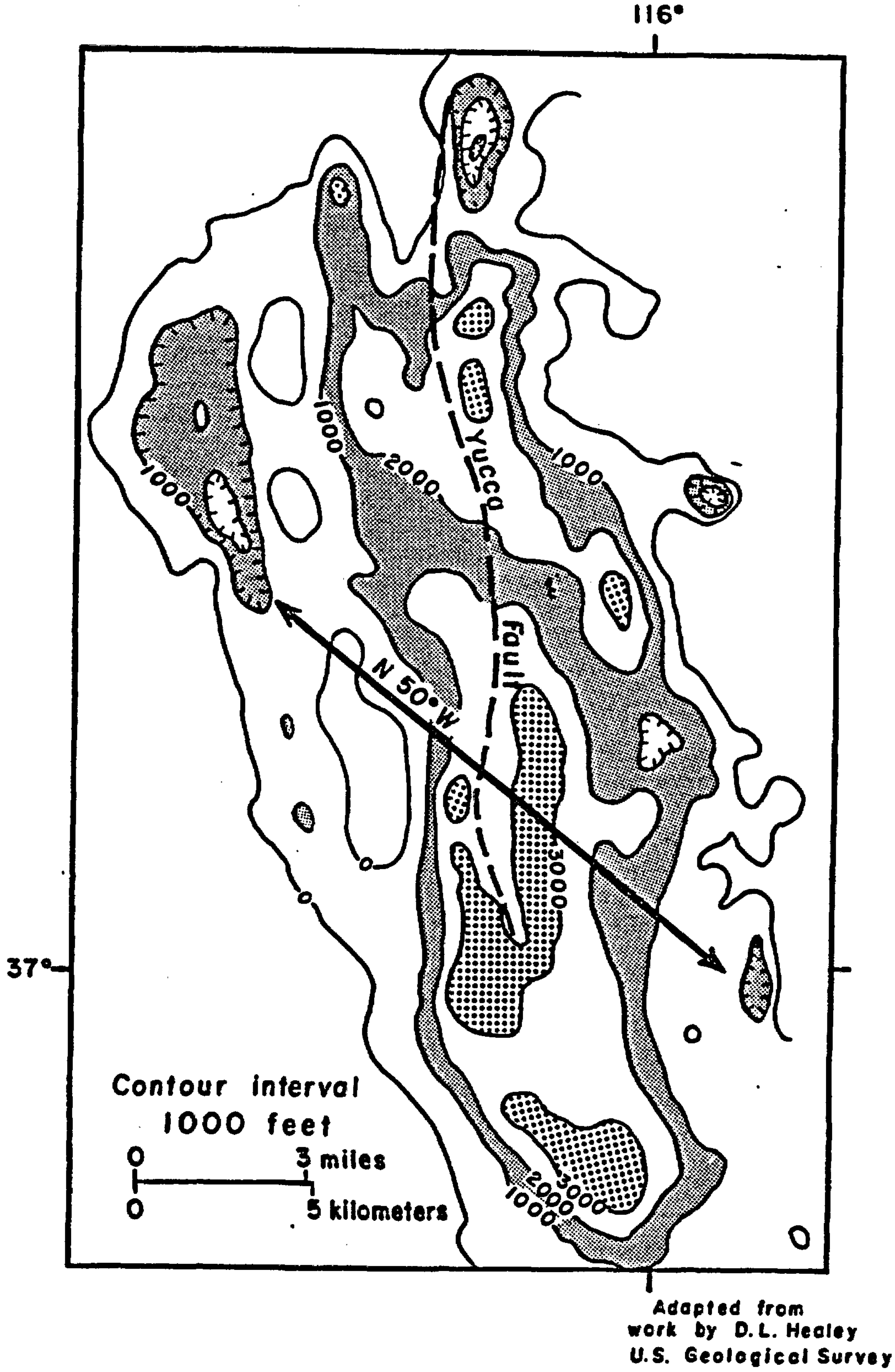


Figure 10.--Three-dimensional gravity controlled diagram of buried Paleozoic surface, Yucca Flat. Intensity of stippling indicates relative depth. Arrow shows direction of extension of area.

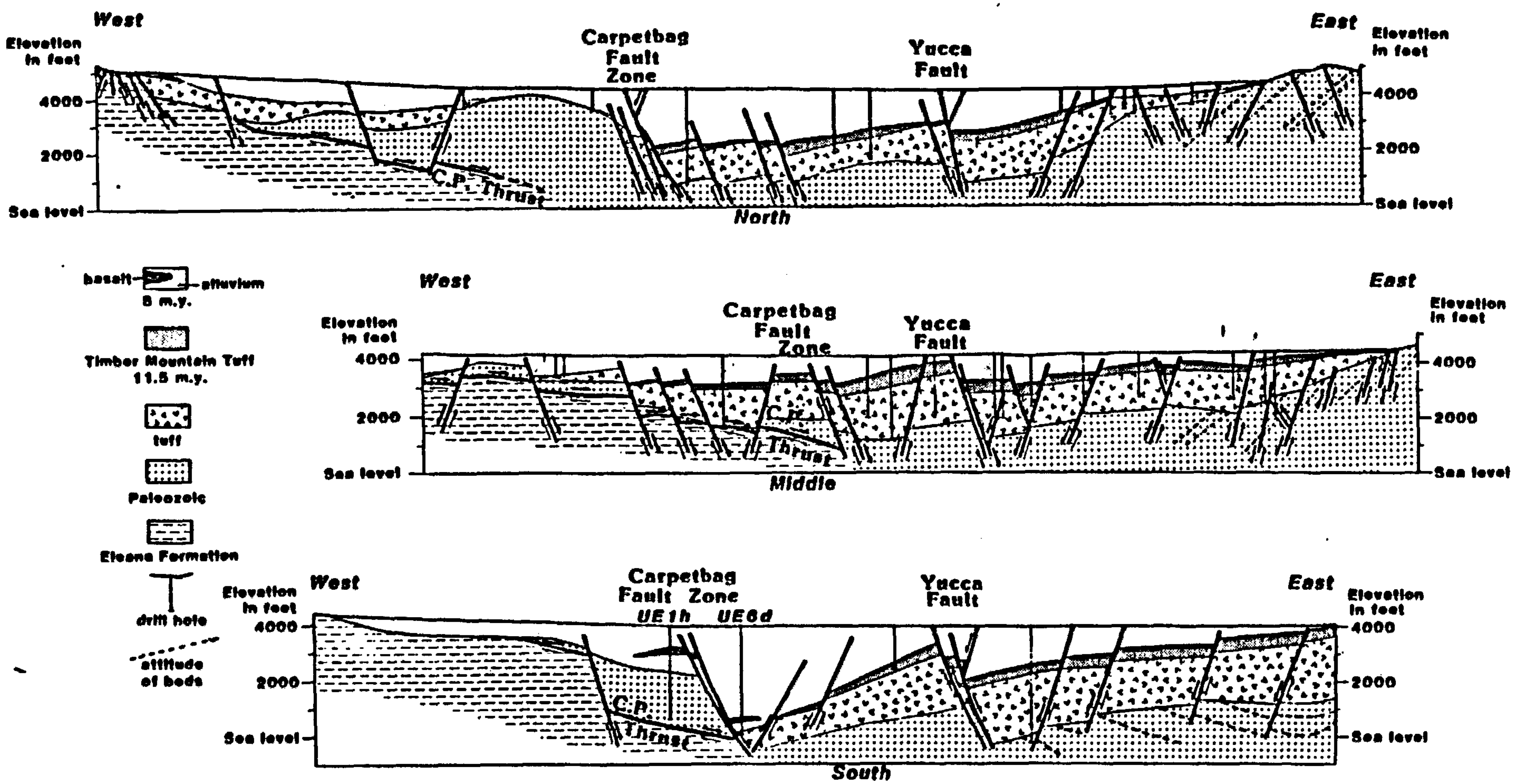


Figure 11.--Typical cross sections of the northern, middle, and southern parts of Yucca Flat.

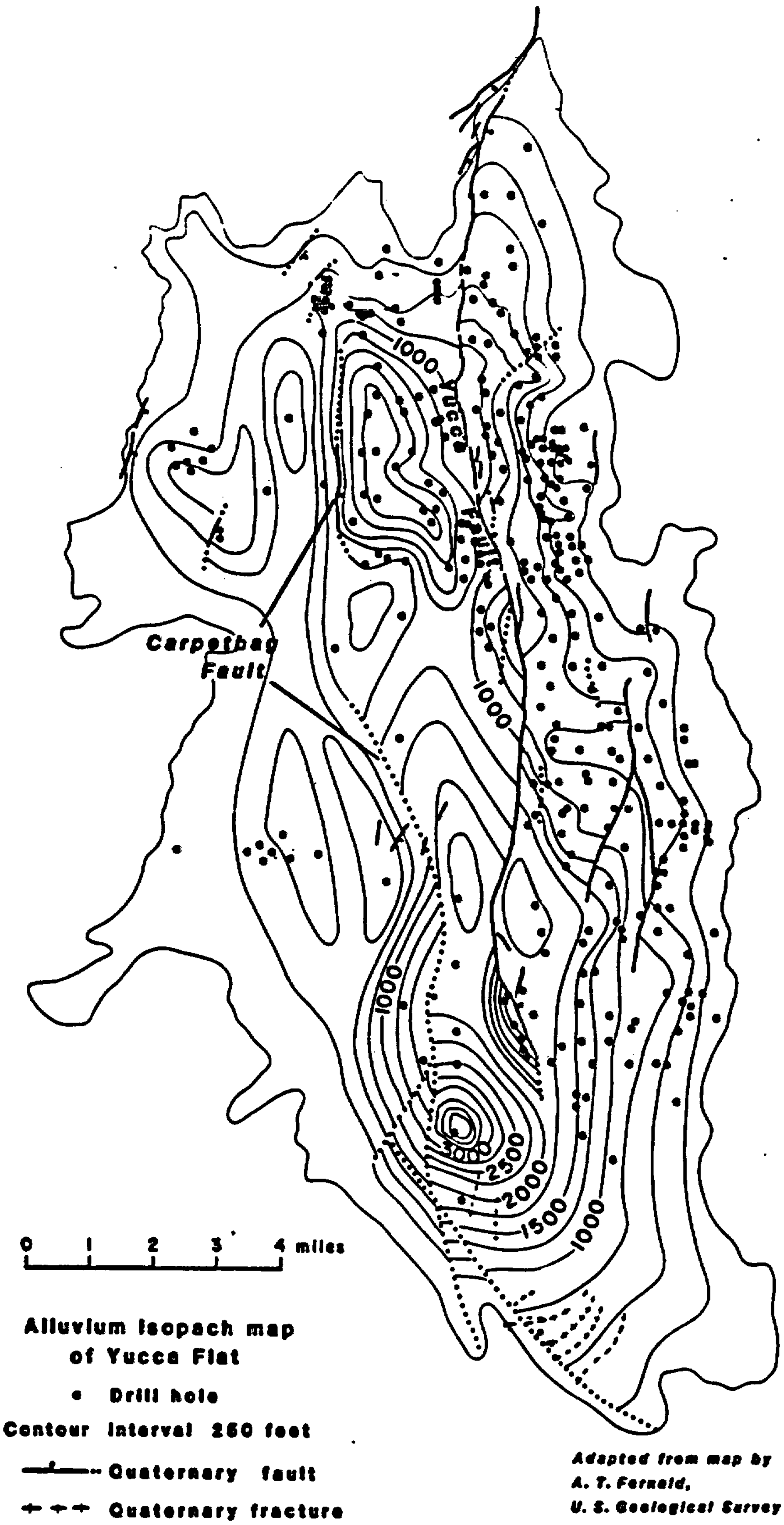


Figure 12.--Alluvium isopach map of Yucca Flat.

reasonable hypothesis which, as Stewart states (1971, p. 108), "seems to be in accord with what is known from geophysical studies....and is similar to structures produced in some small clay models of grabens."

Thus, if Yucca Flat is typical of structural basins in the basins and ranges of this region, as gravity maps suggest (Healey and others, 1980a), the style of basin and range deformation in southern Nevada includes the formation of fairly young structural troughs, in many cases medial to existing valleys. Within these structural depressions the rate of subsidence is quite variable, but is nearly balanced by alluviation, resulting in only moderate relief on most bordering mountain fronts.

Ekren and others (1968) reported some important conclusions regarding the age of basin and range faults in the NTS and adjoining Nellis Air Force Range, and these results are commonly cited in the literature (e.g., Stewart 1980, p. 115). They concluded from the relations between two groups of faults and volcanic rocks of known age in the Belted Range (fig. 4) that (1) an older set of northeast- and northwest-trending faults formed in the Tertiary prior to about 17 m.y. ago, and (2) a younger north-striking, presumably basin and range fault system, began to develop between 17 and 14 m.y. ago. The statement (Ekren and others, 1968, p. 250) that the "north-trending fractures (and faults) appear to have been contemporaneous with the faults that bound the Belted Range on the west," seems reasonable, yet much of the formation of alluvium filled Kawich Valley on the downthrown side of these bounding faults must have occurred at a much later time. These authors (Ekren and others, 1968) also pointed out that the Yucca Flat basin formed mainly after extrusion of the Timber Mountain Tuff about 11.5 m.y. ago, but that the Thirsty Canyon Tuff (about 8 m.y. old) was deposited across terrain not much different from the present. The Thirsty Canyon, which together with the essentially coeval Stonewall Flat Tuff (Noble and others, 1984) is distributed across a wide area in the northwestern part of the NTS region, lies almost entirely within the Walker Lane belt, as used here (fig. 3). In northwestern Frenchman Flat, outside the deeper more active part of the basin, a drill hole penetrated the Thirsty Canyon Tuff at a depth of about 335 m (1,100 ft) (Carr and others, 1975)[3] overlain at a depth of about 275 m (900 ft) by essentially flat-lying basalt that probably correlates with basalts exposed in the nearby Nye Canyon area that are about 7 m.y. old (Crowe and others, 1983).

On the Paiute Ridge (Byers and Barnes, 1967) and Jangle Ridge (Barnes and others, 1965) quadrangles on the east side of Yucca Flat, a prominent north-striking system of faults displaces and tilts Paleozoic rocks a distinctly greater amount than the overlying tuffs, which include units whose maximum age is about 15 m.y.

[3]The "Recent" faults in Carr and others, 1975 (p. 10-16 and fig. 3), originally prepared in 1967, are incorrect. No "Recent" (Holocene) faults are recognized in this area; the term should have been "Quaternary" rather than "Recent."

Thus, in the region under consideration, the age of the basin and range faulting can be readily documented in many areas, and it is clear from this information that there is some local variation in the beginning and end of the major activity. In general, however, most of the important displacement that formed the present structural basins began after the peak of Walker Lane belt activity.

Inyo-Mono Subsection

This spectacular structural and physiographic terrain lies between the Sierra Nevada on the west and the Walker Lane belt on the northeast (fig. 3). As these two boundaries converge northwestward the width of the subsection decreases from about 130 km (80 mi) at the Garlock fault to about 70 km (43 mi) at the north end of the White Mountains. The pronounced northwest structural and physiographic trends are obvious on regional geologic (Jennings, 1977) and topographic maps. The active tectonism of the Inyo-Mono subsection is displayed by many features, including the great relief of the abrupt linear mountain fronts facing Death Valley, Saline Valley, Owens Valley and Fish Lake Valley, the abundant evidence of Quaternary faulting, and the youthful volcanic centers; but the subsection is best characterized by long linear valleys of north-northwest trend that are outlined by pronounced through-going structures with abundant evidence of Holocene and local historic faulting. Most of the eastern margin is well defined by the Death Valley-Furnace Creek-Fish Lake Valley fault zone, a system that has a significant component of right-lateral slip (Stewart, 1967; Stewart and others, 1968; McKee, 1968; Reynolds, 1975; G. E. Brogan, contract with USGS, written commun., 1980), although the amount has been debated (Wright and Troxel, 1967, 1970), particularly with respect to the Death Valley fault zone. Lateral displacement is not as obvious for other faults in the subsection, although it has been indicated for very young faulting in Panamint Valley (Smith, 1979) and Owens Valley (Bateman, 1961; Bonilla, 1968; Slemmons and others, 1968). Despite the important lateral component of faults in the subsection, the obvious relative vertical relief shows that the Cenozoic faulting must have been predominantly dip-slip, especially on more northerly trending segments, such as the southern Death Valley fault zone. In most of the subsection, exposed mountain-front fault scarps are dramatic evidence that major dip-slip faulting has occurred at a rate faster than alluvial deposition at the mountain fronts.

The faults within the Inyo-Mono subsection do not seem to display the adjacent transform-like offsets or large-scale oroflexing (Albers, 1967) common to many elements of the Walker Lane belt. Stewart (1967), however, suggests drag or flexing in Paleozoic rocks on both sides of the Fish Lake Valley-Furnace Creek fault zone.

Boundary between Inyo-Mono and Walker Lane Belt Subsections

The nature of the boundary between the Inyo-Mono and Walker Lane belt subsections is an important fundamental problem of the regional tectonics. As the boundary lies only about 50 km (31 mi) southwest of Yucca Mountain, it is especially important to consider its tectonic significance.

Despite recognition of the abrupt Inyo-Mono subsection-Walker Lane belt transition, a complete explanation of the location and regional extent of the boundary has not emerged. The boundary is apparently near the present northeastward limit of active dextral shear between the North American and Pacific plates, and it crosses considerable diverse geologic terrain between the east end of the Garlock fault and the north end of Fish Lake Valley, a distance of nearly 320 km (200 mi). The close regional association of the Inyo-Mono subsection with the eastern parts of the Sierra Nevada granitic complex invites an explanation that relates the Inyo-Mono structure to west-northwest displacement of the Sierran block (Wright, 1976).

As might be expected, gravity and aeromagnetic anomalies reflect the structural grain of both subsections, but they do not suggest an obvious reason for the boundary between the two structural styles. From seismic refraction studies (Healy and Warren, 1969; Prodehl, 1970; 1979) it is clear that a distinct eastward crustal thinning of 5-10 km takes place in the general area of this structural transition, but data are not sufficient in an east-west direction between the NTS and the Sierra Nevada to determine the closeness of the correspondence between the thinning and the subsection margin. Granitic rocks of the Sierra Nevada batholith extend eastward at least as far as the Panamint Range (Hunt and Mabey, 1966; Hall, 1971) in the southern Death Valley area (fig. 13), but Mesozoic granitic rocks also crop out at several locations on and near the NTS in the Walker Lane belt.

The role of the Garlock fault (fig. 3) in the tectonism of the region remains problematical, even though that fault appears to mark the boundary between regions of greater and less extension (Davis and Burchfiel, 1973). Stewart (1983) suggested that the Panamint Range block has been transported northwestward on detachment surfaces about 80 km (50 mi), based on offsets of rocks across the Furnace Creek and Garlock faults. The sense of the displacement proposed agrees with that shown by turtleback surfaces in Death Valley (Wright and others, 1974), and with west-northwest displacement of the Sierra Nevada block, as envisioned by Wright (1976).

The contrast in structural characteristics between the Inyo-Mono and Walker Lane belt subsections suggests an important fundamental difference may exist in the deformation mechanisms of the two areas. The difference could possibly be related to large-scale detachment faulting in the Inyo-Mono subsection, as postulated by Stewart (1983) for the Death Valley region. Major detachment faults may serve to decouple the late Precambrian and Paleozoic rocks from the older Proterozoic rocks, and provide added inducement for vigorous extension of the brittle upper crust. Such a mechanism might help to explain the earlier mentioned apparent large discrepancy (Wright and Troxel, 1967, 1970) between lateral offset of the Proterozoic rocks versus Paleozoic rocks across strike-slip fault zones of the subsection. In this hypothesis the strike-slip displacement would have affected mostly the upper few kilometers of the crust, and lateral motion at depth would have been partially accommodated by the detachment surfaces, resulting in less relative displacement of the Proterozoic rocks. Detachment faults are not limited to the Inyo-Mono region, however, and they probably extend east of the subsection, as will be discussed in the description of the structural setting of Yucca Mountain.

It seems most reasonable to relate the style and relative youthfulness of the Inyo-Mono deformation to right-lateral shear and west-northwest extension distributed inland from the Pacific-North American plate boundary, but the fairly abrupt cessation of that shearing at the subsection boundary is not

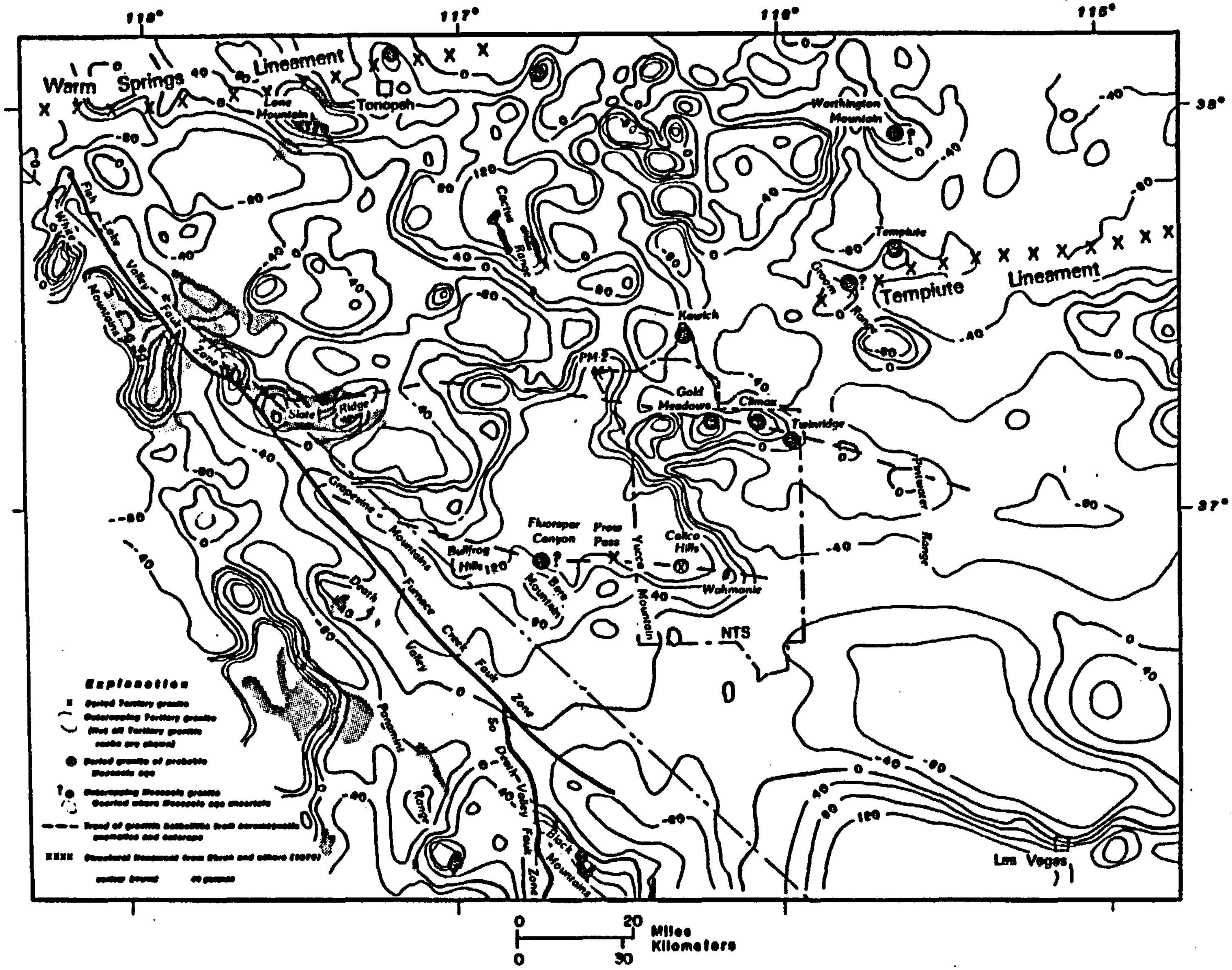


Figure 13.--Aeromagnetic map of southern Great Basin, showing location of Mesozoic and Tertiary plutons and east-trending lineaments.

easily explained. A minor change may occur in the regional stress directions between the Walker Lane belt and the Sierra Nevada; compilations by Zoback and Zoback (1980) suggest a somewhat more westerly direction for the least principal stress in the Inyo-Mono region, as compared with the region to the east, but data are scarce. A more westerly oriented minimum principal stress, combined with the slightly more northerly strike of the major faults in the Inyo-Mono subsection could favor slip on those faults. But perhaps the most significant relationship bearing on the problem of the Inyo-Mono-WLB subsection boundary in southern Nevada is the correspondence between the northwest termination of the Death Valley-Furnace Creek-Fish Lake Valley fault zone (fig. 3) and the beginning of active faults of northwest trend in the WLB northwest of Tonopah. Northwest of the major right step in the boundary (fig. 3, zone H), late Quaternary and historic fault scarps are common in the WLB (Stewart, 1980, fig. 52). From there southeastward in the WLB, Quaternary faults of northwest trend are rare, and those that are present occur along the southwestern margin of the belt. On the basis of scarp morphology and lack of seismicity, these faults of northwest trend appear less active than those in the northern part of the belt. Thus, the Death Valley-Furnace Creek-Fish Lake Valley fault zone itself appears to play an important role in the near absence of active Quaternary structures of northwest trend in the southern WLB, as well as being a factor in the overall lower level of tectonic activity in the southern vesus the northern WLB. In other words, not only is the Death Valley-Furnace Creek fault zone a major slip plane that relieves shear stress generated by the North American-Pacific plate motion, it apparently acts as a tectonic buffer zone tending to suppress strain accumulation in the area to the east and northeast.

OTHER STRUCTURAL ELEMENTS OF SOUTHWESTERN NEVADA

Mesozoic Granitic Rocks

As mentioned previously, Mesozoic granitic rocks crop out at four and probably five locations in the NTS region (fig. 13). The distribution of some of these granitic intrusive rocks and their relation to aeromagnetic anomalies has been discussed by Bath and others (1983). The distribution of the outcrops and the magnetic anomalies strongly suggest two east-trending alignments of mostly buried Mesozoic plutons through the NTS area. The northern one appears to connect with plutons in the Slate Ridge area (figs. 2 and 13), and extends eastward through the Gold Meadows-Climax stock and Twinridge areas, and in the subsurface as far east as the northern Pintwater Range. The southern alignment extends east-southeast from the Grapevine Mountains to northern Bare Mountain, Yucca Mountain, Calico Hills, and the Wahmonie area in the south-central part of NTS. The latter possible granite trend will be discussed in more detail in the section of this report, "Tectonic Setting of Yucca Mountain."

The apparent lack of large-scale offset of these two granite-aeromagnetic trends by the Walker Lane belt in the NTS region is similar to the absence of offset of lineaments by the Walker Lane (Ekren and others, 1976) in west-central Nevada (fig. 13). In contrast, Mesozoic plutons are distinctly offset and dragged in a right-lateral sense, probably more than 30 km (19 mi), by the Death Valley-Furnace Creek fault zone (McKee, 1968; fig. 13, this report) at the northeastern margin of the Inyo-Mono subsection. On the basis of offset of Paleozoic rocks, Stewart (1967) and others have suggested Walker Lane belt right-lateral displacements on the order of 50 km (31 mi) or more. The apparent lack of major offset or large-scale bending of the late(?) Mesozoic lineaments across the Walker Lane belt, supports the conclusion of Albers (1967), who felt that the belt is a relatively old structural zone that affects the Paleozoic rocks much more than those of late Mesozoic or Tertiary age. The large and distinct lateral offset of granitic plutons across the Death Valley-Furnace Creek fault zone, in contrast to the apparent small-scale or lack of offset of similar bodies across the WLB again emphasizes the tectonic importance and relative youthfulness of the Furnace Creek fault zone at the margin of the Inyo-Mono subsection.

Northeast-Striking Structural Zones

The Walker Lane belt contains a number of important northeast-trending structures (fig. 3). One of the most conspicuous of these is the complex Spotted Range-Mine Mountain (SR-MM) zone, which probably spans the Walker Lane belt from the Furnace Creek fault to the Yucca-Frenchman shear zone. Other northeast-striking topographic and structural alinements, nearly all of which appear to coincide with important volcanic centers (fig. 2) can be identified on geologic and topographic maps of the region. These include the Lake Mead fault zone of Anderson (1973), (A, fig. 3) and the "structural knee" of Gilbert and others (1968) in the Long Valley, California-Mina, Nevada, region (H, fig. 3). Both of these major structural zones are the site of important late Cenozoic volcanism (Stewart, 1980, fig. 48). Other similar, but perhaps somewhat less well-defined features include northeast-striking structural lineaments from the Bullfrog Hills across the Timber Mountain Caldera (Christiansen and others, 1965) (B, fig. 3), a similar trend from southern Sarcobatus Flat to Black Mountain Caldera (C, fig. 3), a structural-topographic trend northeastward from Death Valley through the Gold Mountain-Slate Ridge area to Stonewall Flat (Albers and Stewart, 1972) (E, fig. 3), the northeast topographic trend of Clayton Valley (F, fig. 3), and from the northeast end of Fish Lake Valley northeast past Lone Mountain (G, fig. 3). Most, but not all, of these structural zones are seismically active (Rogers and others, 1983), and show some evidence of left-lateral strike-slip offset on faults (Anderson, 1973, Gilbert and others, 1968; Barnes and others, 1982). Several of the zones contain northeast-striking faults with Quaternary movement (Carr, 1974).

The Spotted Range-Mine Mountain zone is one of the widest and most prominent of the northeast-striking structures, and is important because of its proximity to Yucca Mountain, and the fact that it is presently active. The SR-MM zone will be discussed in more detail later, in the section, "Tectonic Setting of Yucca Mountain."

Death Valley- Pancake Range Belt

A regional tectonic feature called the Death Valley-Pancake Range belt (DV-PR) (Crowe and others, 1983, p. 4), though not as clearly defined as the previously described subsections, is nevertheless an important volcanic-structural element of the southern Great Basin (fig. 14). This belt coincides in general with the "medial basalt belt" of Carr and Rogers (1982b, p. 13), and part of the "NTS paleoseismic belt" of Carr (1974, fig. 1) and Carr and Rogers (1982a, p. 7). Best and Hamblin (1978, fig. 14-12) hinted at the belt's existence and placed it within their zone II, which they described as

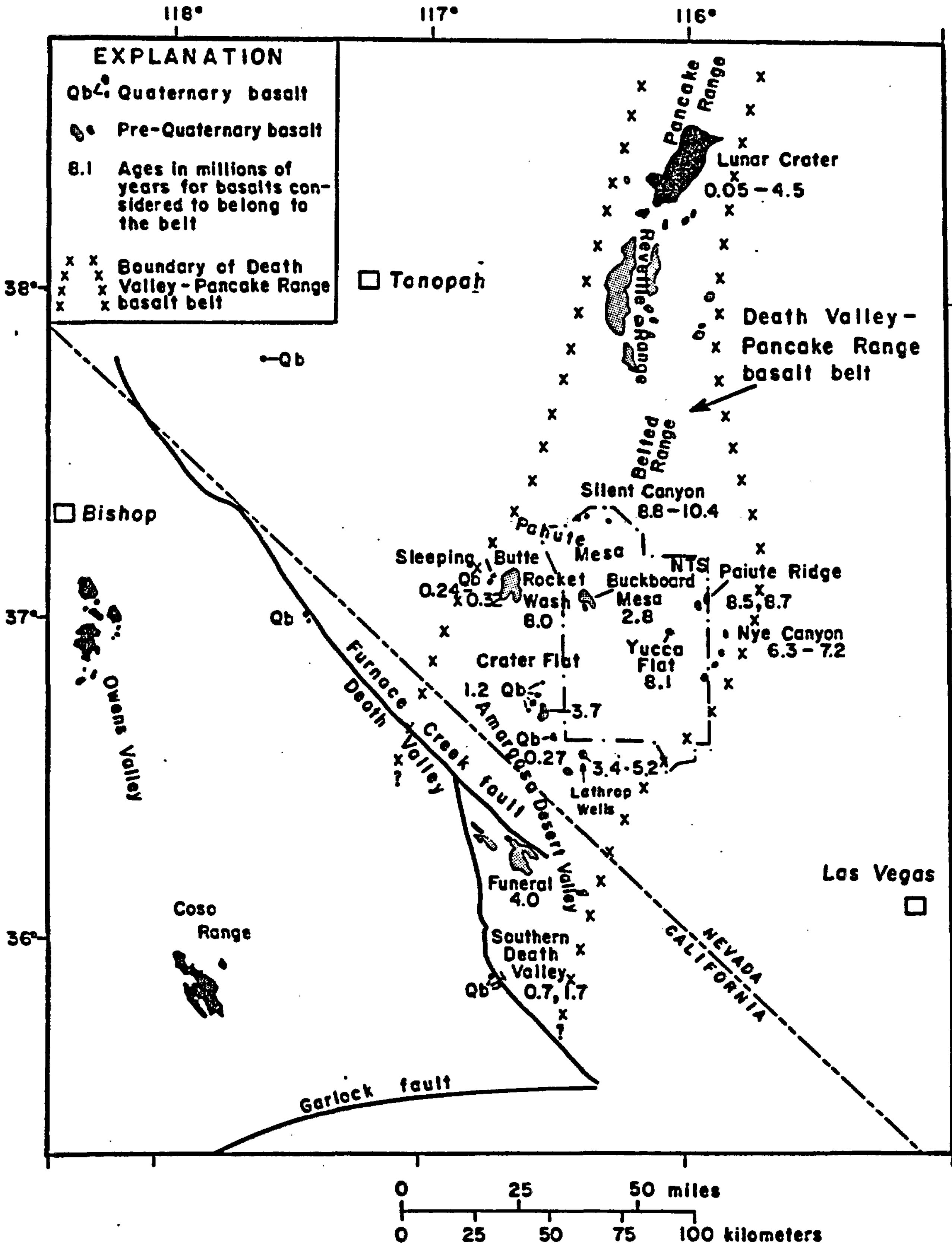


Figure 14.--Location and chronology of the Death Valley-Pancake Range basalt belt. Buried basalt just south of Lathrop Wells has reverse polarity and its age is therefore considered to be roughly that of the Gilbert magnetic epoch. Ages of the Lunar Crater and Reveille basalt fields are based on estimates from reconnaissance by W. J. Carr and two dates: (1) lower flow in Lunar Crater dated at 4.2±0.3 m.y. (R. F. Marvin, U.S. Geol. Survey, written commun., 1981), and (2) flow in the Reveille quadrangle, age reported as 5.7±0.2 m.y. (Ekren and others, 1973).

an area of upwarp, extensional block faulting, and basaltic volcanism. The belt lies just to the west of the Great Basin axis of gravity and topographic symmetry described by Eaton and others (1978).

The Death Valley-Pancake Range belt extends southward from the Lunar Crater basalt field (fig. 14) of central Nevada through the Reveille-Belted Range area, and thence south-southwestward across the southern NTS area and the Amargosa Desert valley to Death Valley (Crowe and others, 1983). The belt widens from about 30 km (19 mi) in the Pancake Range to about 75 km (47 mi) in the vicinity of Lathrop Wells. Extension of the belt westward from Death Valley to include young rhyolites and basalts of the Coso region, California, along the active southwestern margin of the Great Basin, is a distinct possibility, but data to support this are not available at present.

The DV-PR belt is important, especially to the Yucca Mountain area, because it appears to be a relatively youthful zone of slightly higher than regional tectonic flux; that is, compared to adjacent areas, it displays a concentration of Quaternary faulting (Carr, 1974), seismicity (Rogers and others, 1983), and basaltic volcanism (Crowe and others, 1983). In addition, the tectonic activity that characterizes the belt has probably occurred largely in the last 6 or 8 m.y. (Crowe and others, 1983, p.4-5).

Age and Tectonic Setting of Basalts of the DV-PR Belt

Basaltic eruptions of the belt postdate the voluminous silicic and bimodal volcanism of the region that occurred in the late Oligocene and Miocene. The oldest basalts of the belt (fig. 14) closely follow the last major silicic eruptions of the region, those from the Black Mountain and Stonewall Mountain centers (fig. 9) (Noble and others, 1984). These older "rift" basalts (Crowe and others, 1983) occur as dikes and flows in the northwestern Pahute Mesa area where they have yielded ages between 8.8 and 10.4 m.y. (Crowe and others, 1983); these dates appear to be a little too old with respect to the Thirsty Canyon Tuff, which is older than the basalts and has an approximate age of 8.5 m.y. Other older basalts of the belt that occur in the Paiute Ridge, Yucca Flat, and Nye Canyon areas of the eastern NTS area (fig. 14) have been dated from 6.3 to 8.7 m.y.; dikes associated with the flows consistently strike north to about N. 15° W. (Byers and Barnes, 1967; Hinrichs and McKay, 1965). In the Silent Canyon area, however, basalt dikes with trends of north to N. 30° E. (Ekren and others, 1966) are at least as old (fig. 14) as those in the eastern NTS area.

Younger basalts of the DV-PR belt show fairly consistent northeast trends, either in alinement of eruptive centers or as dikes; these basalts are about 4 m.y. old or younger. Examples include the basalts of the Lunar Crater field, and the Funeral basalts near Furnace Creek Wash at the north end of the Greenwater Range (reconnaissance by B. Crowe, D. T. Vaniman, and W. J. Carr, 1980). Feeder dikes or cone alinement for all the basalts in the DV-PR belt that are 4 m.y. old or younger show a consistent N. 20°-30° E. trend. The belt itself, and even the older basalt centers of the Nye Canyon area are alined in a north-northeasterly direction, even though most of the long dikes in the Nye Canyon area trend north.

Thus, several of the older (>6.3 m.y.) basalts of the belt appear to have been erupted in a stress regime that favored intrusion along north to north-

northwest trends, in harmony with a least principal stress direction of west to west-southwest, that probably existed in the western Great Basin before about 6 m.y. ago (Zoback and Thompson 1978; Anderson and Ekren, 1977). Based on basalt trends, change in the regional stress pattern appears to have been underway in the NTS region by about 6 m.y. ago, roughly coincident with the end of silicic volcanism and perhaps with a hiatus in basaltic volcanism from about 6.2 m.y. to 4.2 m.y. ago.

Many basalts of the belt, especially those of larger volume, occur on or close to ring fracture zones of older calderas. Examples include those at Lunar Crater, Silent Canyon, Buckboard Mesa, Sleeping Butte, Rocket Wash, and Crater Flat (fig. 14). In nearly all cases however, the basalts in calderas vented along faults that are not parallel to the ring fractures, suggesting that the deeply penetrating ring fractures provided the initial pathways, but the magma actually reached the surface along faults more favorably oriented in the stress field.

Structural-topographic expression.--Ranges in the eastern half of the Great Basin have a fairly consistent eastward structural tilt (Stewart, 1978, p. 13-15; 1980, fig. 51), and those in the west half tend to have westward tilt. The DV-PR belt lies roughly parallel and just west of this change in tilt direction. In addition, the DV-PR belt is adjacent and parallel to a series of high-standing mountain range blocks with east and southeast structural tilt, which are, from north to south: White Pine Range, Grant-Quinn Canyon Range, Sheep Range, and Spring Mountains. West of these structurally high blocks are a series of prominent topographically low areas, such as Railroad Valley, Sand Spring Valley, Tikaboo Valley, Frenchman Flat, Indian Spring Valley, Pahrump Valley, and southern Death Valley. This trend of high and low topography could be extended west-southwest to include Panamint, Saline, and Owens Valleys and the Panamint Range and the highest parts of the Sierra Nevada around Mt. Whitney.

Quaternary faulting--There is a slight concentration of Quaternary faulting, relative to adjacent regions (Carr, 1974, and fig. 15) that appears to correlate roughly with the DV-PR belt. Very little Quaternary faulting is present west of the belt and south of Tonopah. Numerous older linear mountain fronts occur east of the belt, but there are few young Quaternary scarps in that area.

The amount of faulting that actually accompanied Quaternary basalt eruptions within the belt is generally unknown, but a notable exception is at Crater Flat where trenching has indicated coincident basalt eruptions and surface faulting, probably about a million years ago. (Carr and others, 1983, p 16; Swadley and Hoover, 1983, p. 9-11).

Seismological character.--The general area of the DV-PR has been identified (Carr, 1974, p. 12-14 and fig. 1) as a possible paleoseismic zone resembling in shape the historically active Nevada-California seismic zone (northern portion of the Ventura-Winnemucca zone of Ryall and others, 1966). The DV-PR belt lies within a large relatively active area at present. During at least the last few decades small seismic events have occurred, particularly in the southern part of the belt at a distinctly higher rate than in adjacent areas (Rogers and others, 1983, pl. 1) to the northwest and southwest. Unfortunately, even though nuclear explosions at NTS have been removed from

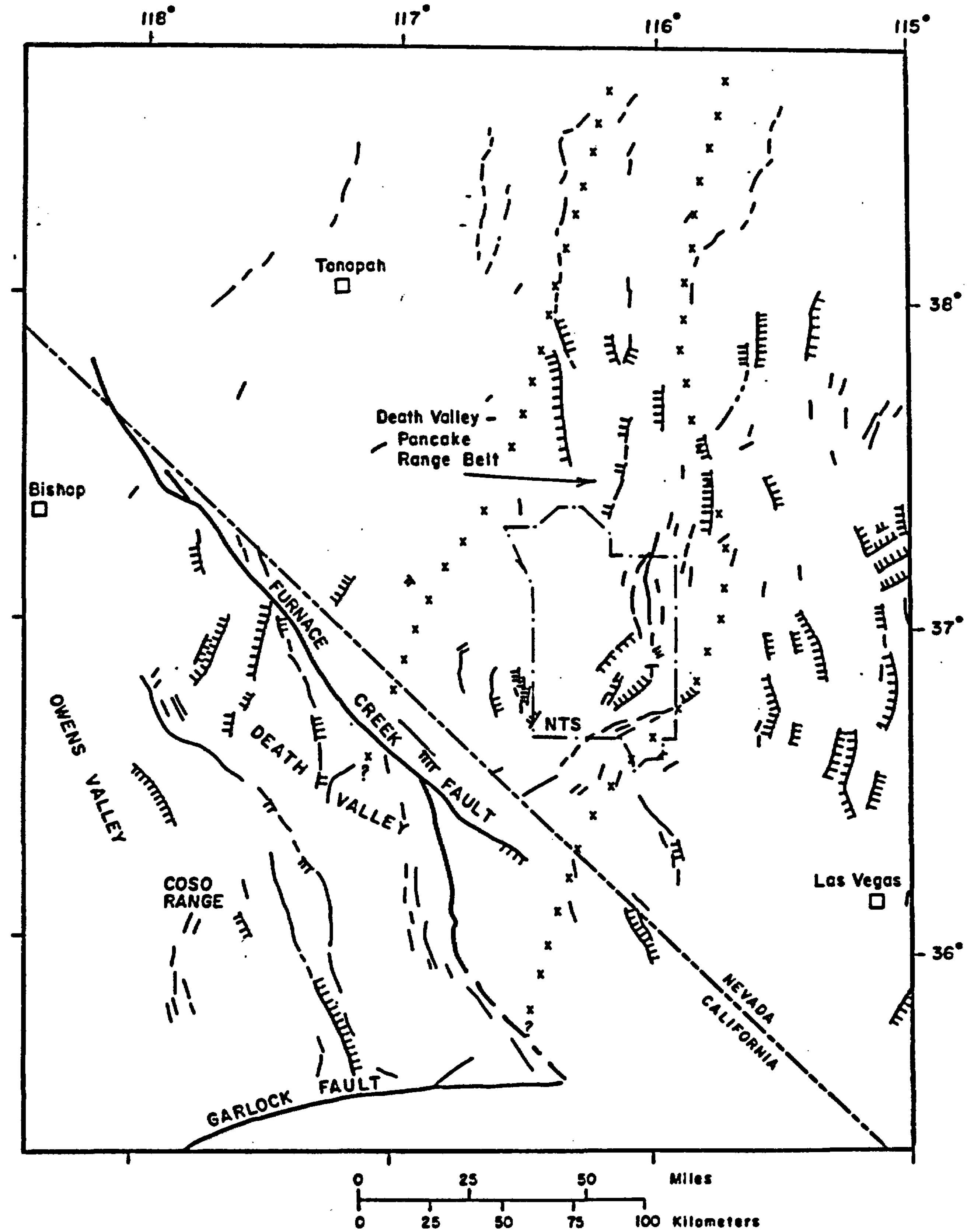


Figure 15.--Late Pliocene and Quaternary faults in the NTS region, and their relation to the Death Valley-Pancake Range belt. Hatched lines are linear mountain fronts or old scarps where young alluvium is not obviously offset but persistent faulting has occurred recently enough to maintain a linear feature. Information is not complete, especially around the edges of the area shown.

the data, many aftershocks triggered by the nuclear events remain in the record in the critical areas of Yucca Flat and Pahute Mesa. In other words, the level of low magnitude (<4) natural seismicity in the eastern and northern parts of NTS remains a question. In the period 1932 through 1958, before sizable underground nuclear tests were conducted at NTS, however, 8 small (magnitude <4) events were recorded (Hileman and others, 1973) in the NTS area by stations in California. During a period half as long, 1959 through 1972, about 20 events were recorded (Hileman and others, 1973) in the same area, but it is difficult to evaluate the effects of nuclear testing and increased recording capability during the latter time. Rogers and others (1977, fig. 1) compiled a map of historic earthquakes of magnitudes =>4.0 in the Nevada-southern California region, which suggests an east-west seismic zone between lat 37° and 38° N. in Nevada, but does not show a definite correlation with the DV-PR belt. Thus, for magnitudes of 4 and above, no clear direct correlation of seismicity with the basalt belt, especially to the north, appears to exist, but good consistent records of lesser magnitude earthquakes have been available for only a few years.

Geophysical anomalies.--The belt itself is not obviously well expressed by geophysical anomalies. However, a north-south axis of geophysical symmetry coincides with, or lies adjacent to the belt on the east (figs. 16 and 17). The symmetry is best expressed in the gravity of the Great Basin (Eaton and others, 1978) but magnetics, heat flow, upper mantle velocity, and seismicity all tend to be symmetrical about a roughly north-south axis lying approximately along long 116° W.

Aeromagnetic data for the southern Great Basin (fig. 16) clearly show a north-south 75-100 km (27-62 mi) wide magnetic "quiet zone" that closely follows the eastern edge of the DV-PR belt. Very few, if any, ash-flow tuff units younger than 20 m.y. cross this zone, despite a pronounced east-west distribution of age groups of volcanic rocks (Stewart and others, 1977). Several east-west-trending magnetic and structural lineaments (Ekren and others, 1976; Stewart and others, 1977; fig. 13) end at the "quiet zone". The zone is deflected southwestward as it crosses the Walker Lane belt in the southern NTS area, in harmony with the structural trend of the SR-MM zone, and appears to continue southwestward through the central Death Valley and northern Panamint Range area in California (fig. 16, and Blake and others, 1978). The basalt occurences of the southern part of the DV-PR belt lie within a somewhat wider regional gravity low that extends from central Nevada to Death Valley (fig. 17). This negative gravity is mostly the result of thick volcanic and subjacent granitic rocks associated with numerous calderas and volcanic centers. On the other hand, a prominent east-west gravity gradient crosses southern Nevada at about lat 37° N., and can be identified within and on either side of the DV-PR belt (fig. 17).

Although the DV-PR belt appears to lie partly within what Lachenbruch and Sass (1978) have called the "Eureka heat flow low", the shape and extent of the heat flow low are poorly controlled, except in the NTS area itself. There is a suggestion in the available data, however, that at least the southeastern part of the NTS area has slightly higher heat flow than adjacent areas (Sass and Lachenbruch, 1982). This higher heat flow could be related to the dominant northeast trend of structure largely in carbonate rocks in the southeastern half of the NTS, which, through favorable orientation with respect to the stress field (Carr, 1974), could allow deeper circulation of

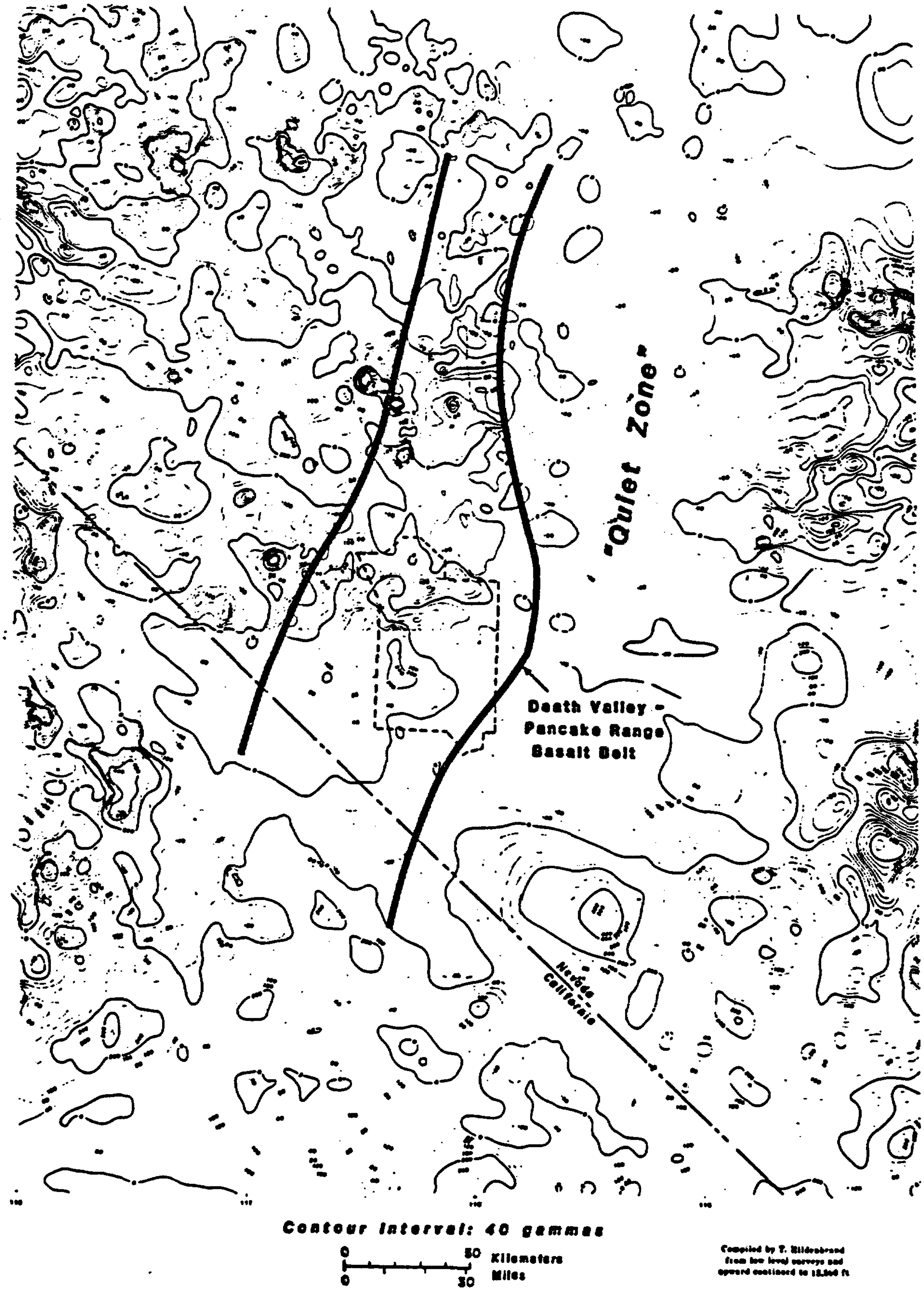


Figure 16.--Aeromagnetic map of a portion of the southern Great Basin, California and Nevada, showing location of Death Valley-Pancake Range belt.

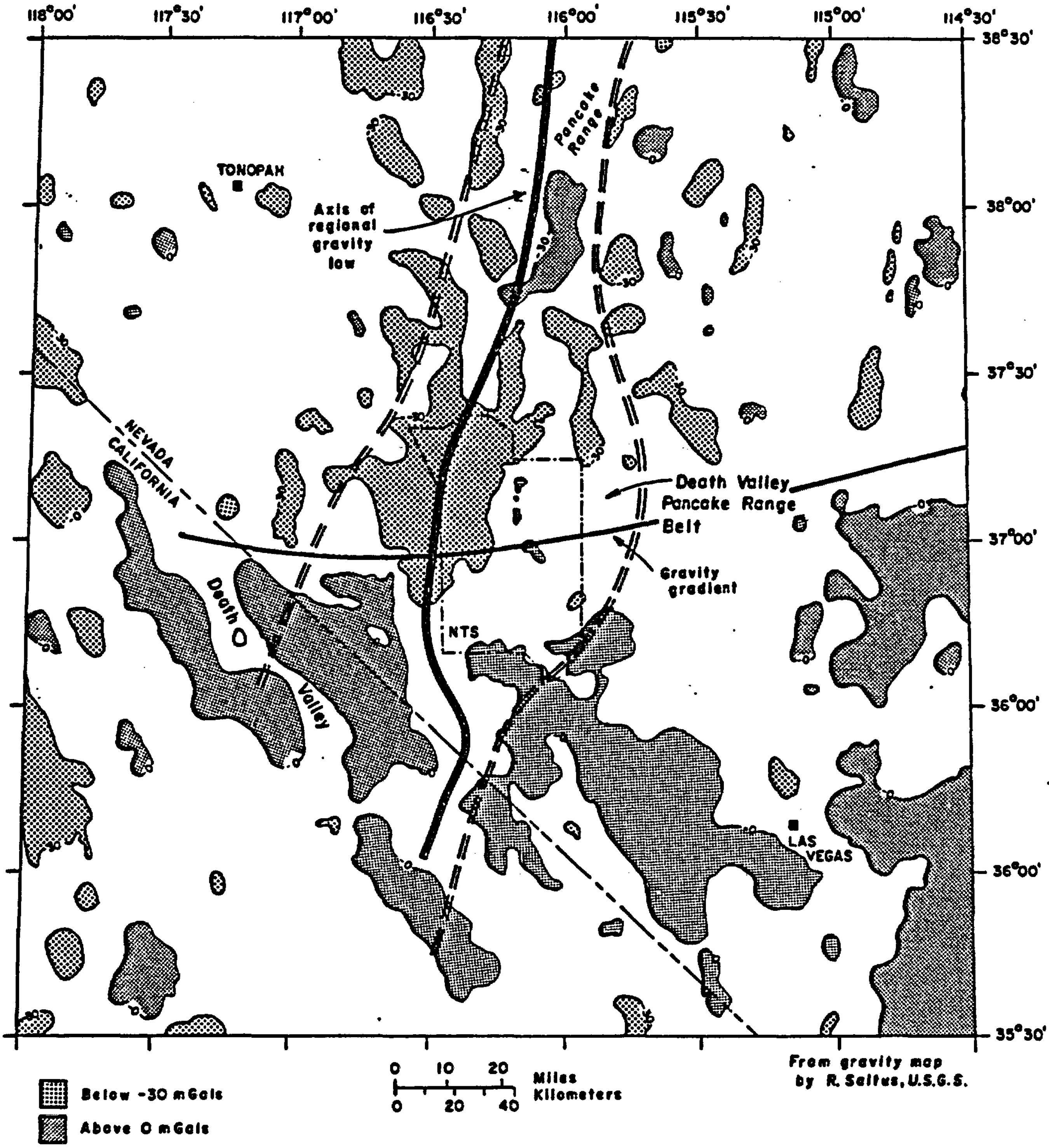


Figure 17.--Areas of high and low Bouguer gravity in a portion of the southwestern Great Basin, showing the relation of gravity to the Death Valley-Pancake Range belt.

ground water and promote higher heat flow. North of the NTS, for a large area along the DV-PR belt, little or no heat-flow data exist. Thus, presently available heat-flow information does not support or refute a slightly higher tectonic flux for the DV-PR belt.

Studies of P-wave velocity yield travel-time anomalies derived from teleseismic sources (Monfort and Evans, 1982, fig. 3e) that suggest an east to west increase, particularly in upper mantle velocity, across the general area of the DV-PR belt; contours of residual velocity are roughly parallel to the belt. The cause of the velocity increase could be a westward increase in older basalt bodies in the lowermost crust or upper mantle. Corresponding westward velocity increase is also suggested by the work of A. M. Rogers (written commun., 1982), who has studied seismic waves from nuclear explosions at the NTS.

Possible northward continuation of Death Valley-Pancake Range belt.--North of the end of the DV-PR belt, aeromagnetic data (Zietz and others, 1978) strongly suggest a continuation of the western edge of the magnetic "quiet zone" flanked by strong positive anomalies over the "Cortez Rift" (Mabey and others, 1978, p. 100) or the Oregon-Nevada lineament (Stewart and others, 1975) (fig. 18). Even though the anomalies in the Cortez Rift are caused by Miocene volcanic rocks that predate the DV-PR belt, the ends of the two features are in alignment near Eureka, Nevada (fig. 18), and together they serve to separate the Great Basin into Bonneville and Lahontan segments, whose general configuration is well supported by the symmetry model (Eaton and others, 1978). Basalts in north-central Nevada, in the northeast part of the Lahontan segment (fig. 18), appear to occupy a similar position to those of the DV-PR belt.

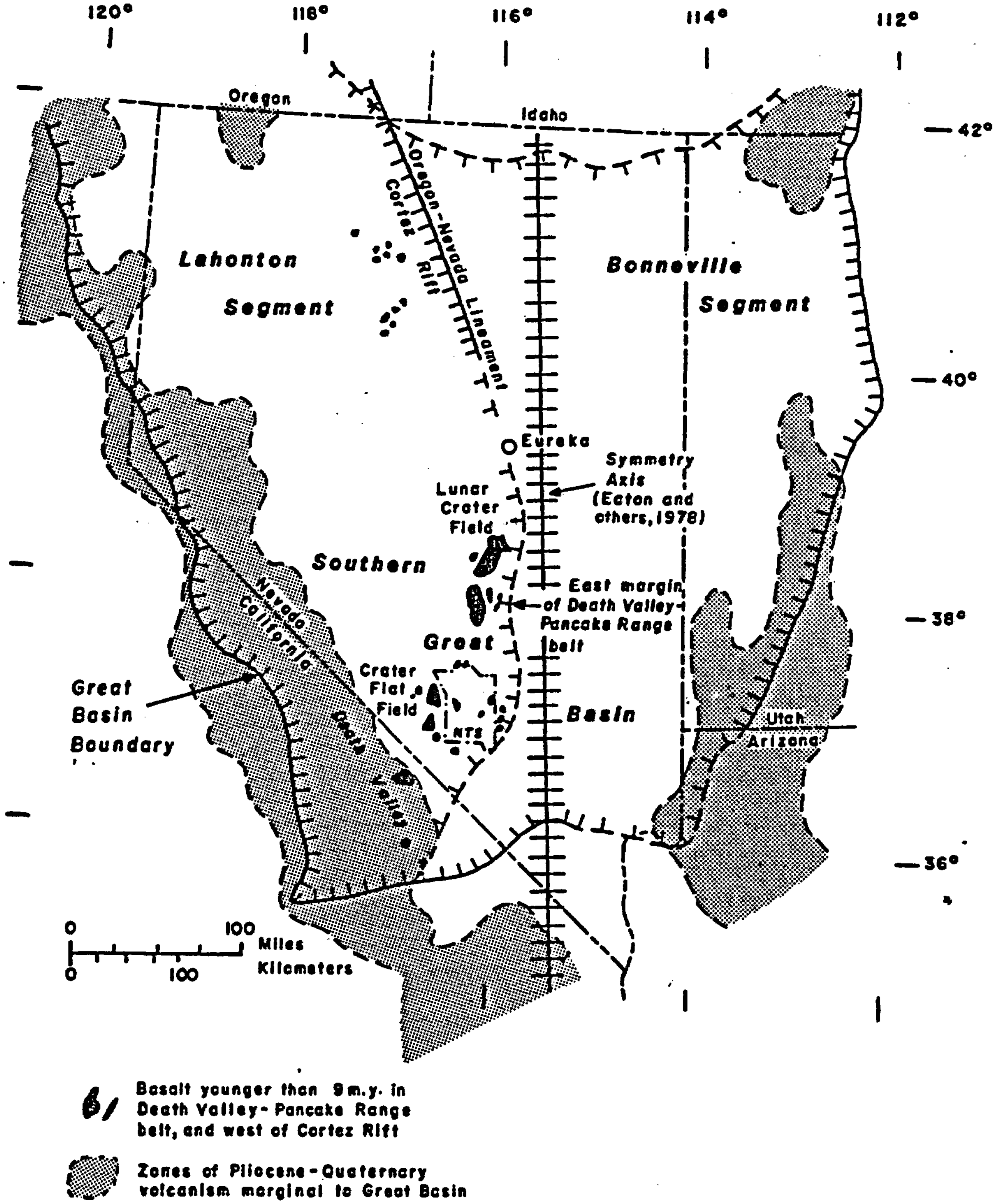


Figure 18.--The Great Basin, showing Lahontan and Bonneville segments, as defined by the Cortez rift and eastern edge of Death Valley-Pancake Range belt.

SEISMOTECTONICS OF THE SOUTHERN GREAT BASIN

A detailed discussion of the complex seismotectonic character of the region is not attempted here, as data are incomplete at present. However, a brief discussion of certain aspects of the subject is given below.

Acquisition of Data

Only in the last few years, after August 1978, have seismicity data, particularly low magnitude earthquakes, of the southern Great Basin been collected in a systematic program with a fairly close-spaced network of stations. In 1978-79 a new seismic net became operational by the USGS. Earthquakes in the NTS area prior to about 1961 were recorded mainly outside Nevada by organizations such as the California Institute of Technology Seismological Laboratory (Hileman and others, 1973). In 1961 the NOAA, in cooperation with the USGS and Sandia National Laboratory began monitoring southern Nevada seismicity (King and others, 1971). During the 1960's and 1970's the network configuration was changed frequently, stations were often far apart, or were installed for special purposes. For example, special studies were made of the seismicity on Pahute Mesa (Hamilton and others, 1972), along the Furnace Creek-northern Death Valley fault zone (Papanek and Hamilton, 1972; Molnar and others, 1969) and at Massachusetts Mountain (Fischer and others, 1972) in the southeastern NTS area.

The new network, installed in the late 1970's, consisted of 47 stations within about 175 km (110 mi) of Yucca Mountain (fig. 19). In 1981, six stations were added at Yucca Mountain to improve detection and location accuracy in the area. The data and preliminary interpretation from the network have been summarized by Rogers, Harmsen, Carr, and Spence (1983).

A continuing problem in attempting to understand the seismotectonics of the region is the overprint in the northern and eastern NTS area of seismicity triggered by underground nuclear explosions. The number of small earthquakes increases markedly after most larger underground tests. Few records exist for small earthquakes in the NTS area prior to the nuclear testing program. Previous studies (Rogers and others, 1977) suggested no apparent effect on seismicity at distances more than about 15 km (9 mi) from the explosion (Hamilton and others, 1972). According to A. M. Rogers (USGS oral commum., 1984), however, there appears to be a statistical relation between many underground tests and the frequency of earthquakes within a larger region. As this problem is critical to defining the actual seismological character of the NTS area, more data and further analysis are needed.

Seismotectonic Zones of the Southwestern Great Basin

The region has been subdivided on the basis of historic seismicity into several seismic zones (Rogers and others, 1983, fig. 2) as shown on figure 20. These were defined by trend and relative activity: (1) The Nevada-California seismic zone, (2) the east-west seismic zone, (3) the eastern Mojave aseismic zone. An additional zone was recognized by its apparent concentration of Quaternary faulting and relatively high level of present seismicity, the NTS paleoseismic zone. The Nevada-California seismic zone, as used here, is part of what Ryall and others (1966) called the Ventura-Winnemucca zone, and is essentially the same as the Nevada seismic zone of Gumper and Scholz (1971). As data accumulate from the current network (figs. 19 and 20), it is apparent that some formerly well-defined boundaries of these zones are becoming less obvious, especially with respect to small earthquakes. In particular, in the last 5 years or so seismicity appears to have spread southeastward from the NTS. The southeast boundary of fairly dense epicenters now extends northeastward from near the intersection of the Garlock and San Andreas faults to the central Spring Mountains, Sheep Range, and on to the southern Clover Mountains near the Nevada-Utah border. Within this zone, the areas of Holocene faulting in southern Death Valley and Panamint Valley and the eastern part of the Garlock fault remain as relatively quiet areas. With the latter exceptions, the pattern of seismicity coincides roughly with the distribution of Pliocene-Quaternary faulting, as shown on figure 20. Within this broad zone, the most intense activity tends to occur in areas of northeast-trending structure, such as the Pahranagat shear zone and Spotted Range-Mine Mountain zone.

Seismicity of the Yucca Mountain Area

On both the pre-1978 and later seismicity maps (figs. 19 and 20), the area of Yucca Mountain continues to be one of the least active in the region. The area of relatively low seismic activity in the western NTS area corresponds quite well with the southern part of the major north-south gravity low (fig. 17), suggesting that the caldera-related volcanic rock section of the low is somehow retarding fault movement. The general impermeability of the volcanic rocks (Winograd and Thordarson, 1975), especially below about a kilometer, may have the effect of reducing pore pressure and therefore slip on the faults. Again because of the unknown state of natural seismicity in the thick volcanic rocks of the nuclear testing and caldera complex areas north of Yucca Mountain, it is difficult to evaluate this suggestion with respect to those areas. However, yearly plots of earthquakes by the California Institute of Technology (Hileman and others, 1973) show no seismic events in the testing areas prior to 1959; conversely, about a dozen events are plotted for the 1960's and 1970's, a period of numerous tests. An earthquake epicenter map of Nevada through 1960 (Slemmons and others, 1964) shows only one earthquake near the Pahute Mesa or Yucca Flat areas, but the minimum magnitude reported in the southern Nevada region is about 4.0. Unfortunately, the NTS area was on the fringes of the regions monitored with instruments prior to underground nuclear testing, and recording capability undoubtedly increased in the later years, so no firm conclusions can be drawn.

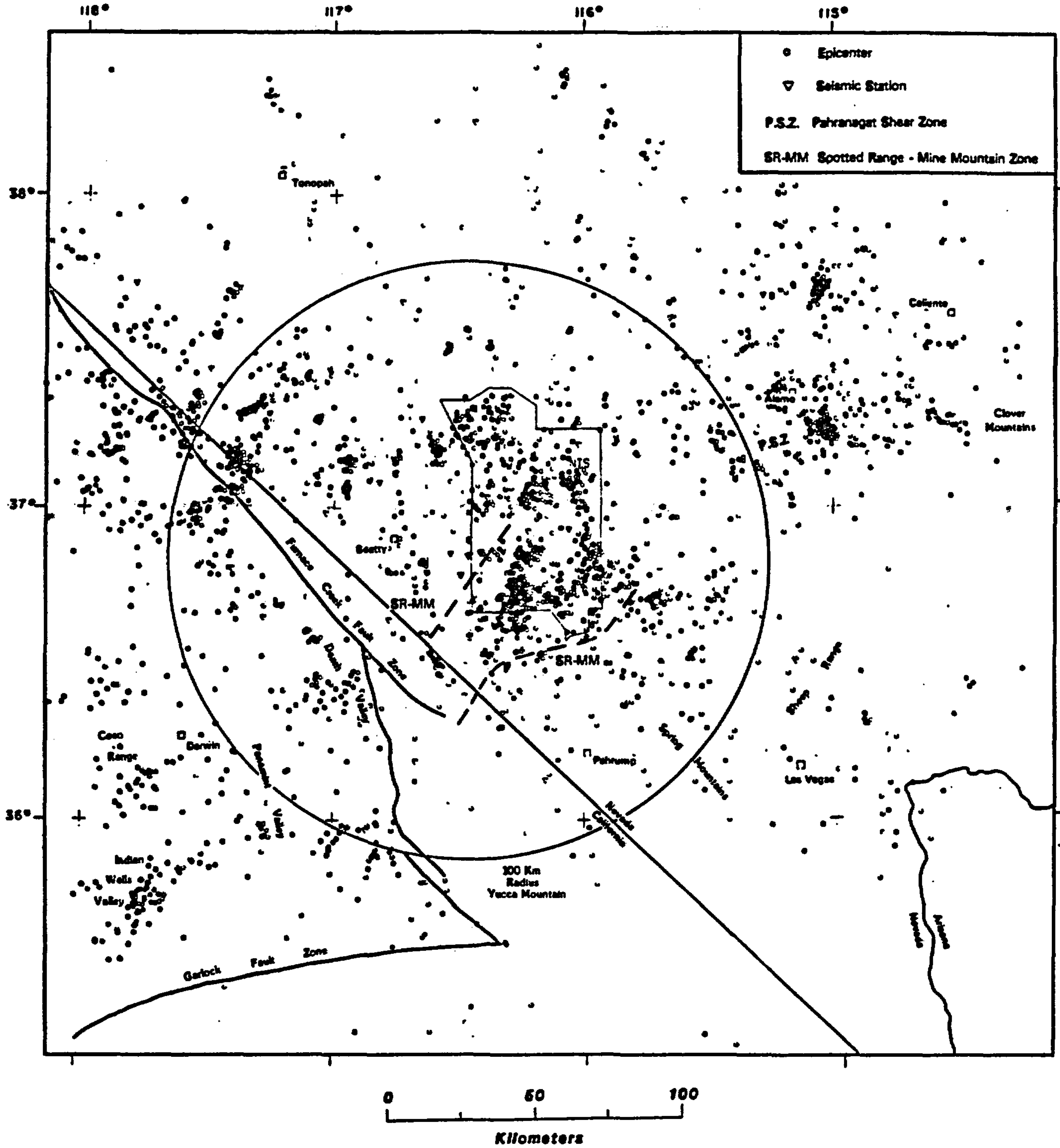


Figure 19.--Seismicity of southwestern Great Basin, August 1978-May 1984.

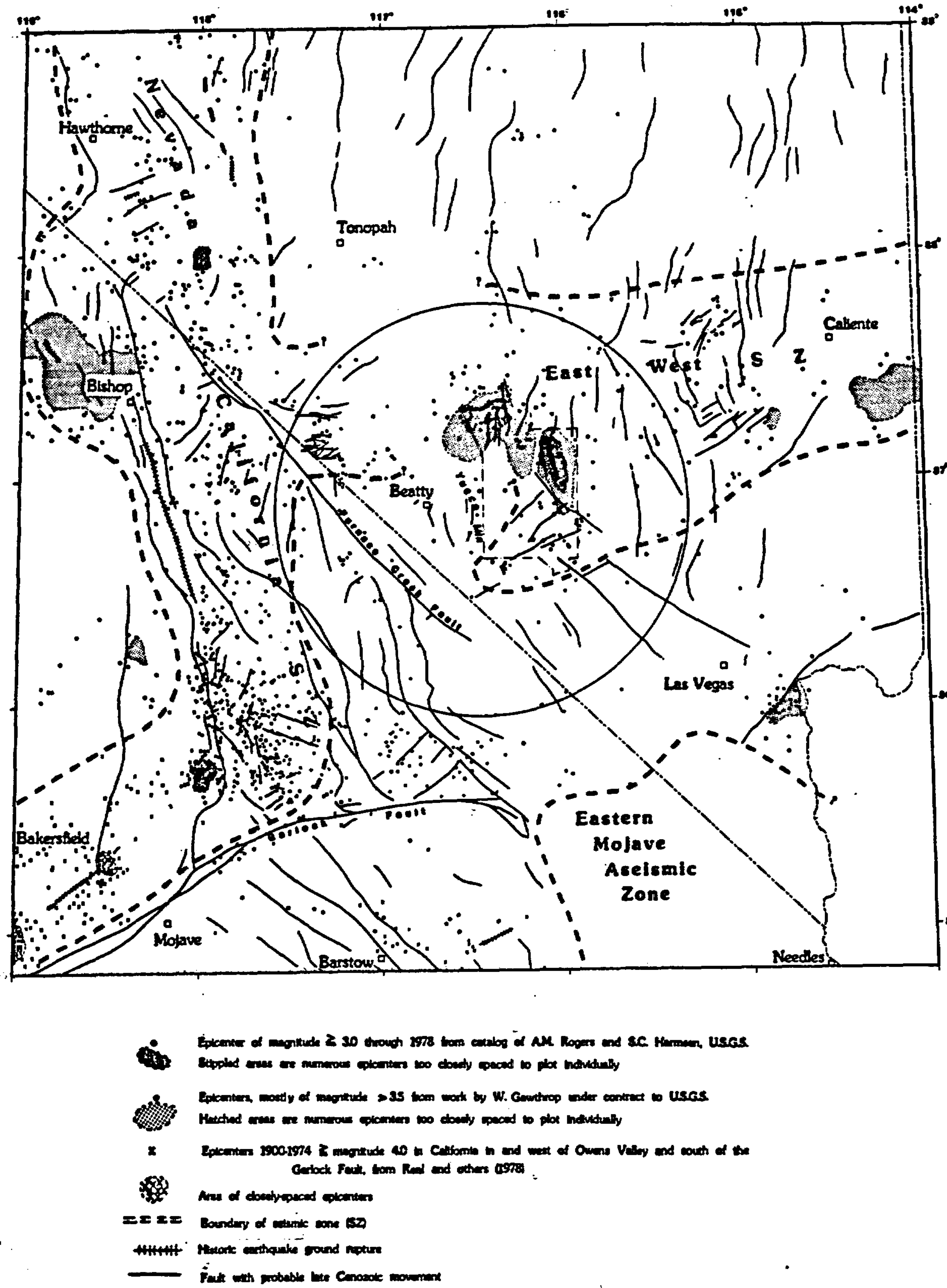


Figure 20.--Preliminary seismotectonic map of southwestern Great Basin, showing earthquakes of magnitude 3.0 or greater, recorded prior to 1978.

Only 7 very small (<1.5 magnitude) earthquakes have occurred within 10 km (6 mi) of the Yucca Mountain site boundaries (figs. 7 and 21) in about 5 years of recording; all of them occurred north or east of the site. Four other events have occurred within about 12 km of the site boundaries (fig. 22). There are not enough events in a 10 km (6 mi) radius to determine a pattern, but a few epicenters to the north near Dome Mountain appear to be related to a system of north to north-northwest striking faults (fig. 21) that extends from just east of the Yucca Mountain site into the moat of the Timber Mountain caldera. Farther south, where the trend changes to more northerly, some of these faults have had minor surface movement in Quaternary time (W C Swadley, USGS, written commun., 1984), probably prior to 35,000 yr ago. Most of the epicenters east of the site lie along the edge of the SR-MM structural zone (fig. 7), and may be related to buried northeast-striking faults.

Several epicenters occur to the west, near the frontal fault on the east side of Bare Mountain (fig. 21); other than that, the entire Crater Flat area is quiescent, as well as nearly all of Yucca Mountain. The area of closely-spaced epicenters on the east side of Bare Mountain corresponds with the location of a gold mine where relatively large blasts occur routinely.

Clusters of epicenters 15 km (9 mi) east and southeast of Yucca Mountain in Jackass Flats (fig. 21) occur as part of the activity in the SR-MM structural zone. Some of the activity may be related to the Mine Mountain fault zone, or faults of similar trend which are not exposed in that area. Other closely spaced epicenters to the southeast near Little Skull Mountain are associated with the Wahmonie fault zone (fig. 7) and related northeast-striking faults.

Quaternary Faulting of the Yucca Mountain Region

Field work and aerial photo study have identified all important fault scarps of Quaternary age within about 100 km (62 mi) of Yucca Mountain, but in most cases, precise age, as well as length and displacement of the faults represented by the scarps have not been determined. In general, many of the scarps are small (less than 3 m or 10 ft high), and most have very low maximum slope angles, generally less than 10°, except in the Inyo-Mono subsection where scarps are more youthful appearing as well as more abundant.

The regional pattern of scarps is shown on figure 8; a slightly more detailed map is presented by Rogers, Harmsen, Carr, and Spence (1983). Quaternary faulting at Yucca Mountain is discussed by Swadley, Hoover, and Rosholt (1984). Additional work, mainly trenching, indicates several small Quaternary fault segments are present in the Yucca Mountain area that are not shown on the regional map by Rogers, Harmsen, Carr, and Spence (1983).

Within a 100-km (62-mi) radius of Yucca Mountain, approximately 180 Quaternary scarps or lineaments have been identified. About one-fourth of these features are linear or curvilinear mountain fronts; the remaining 135 or so are actual scarps or strong lineaments in the alluvium. The long Death Valley-Furnace Creek fault zone was broken into 25-km (15-mi) segments for counting, because preliminary interpretation of unpublished work by G. E. Brogan (written commun., 1980) suggests that this is about the length of most

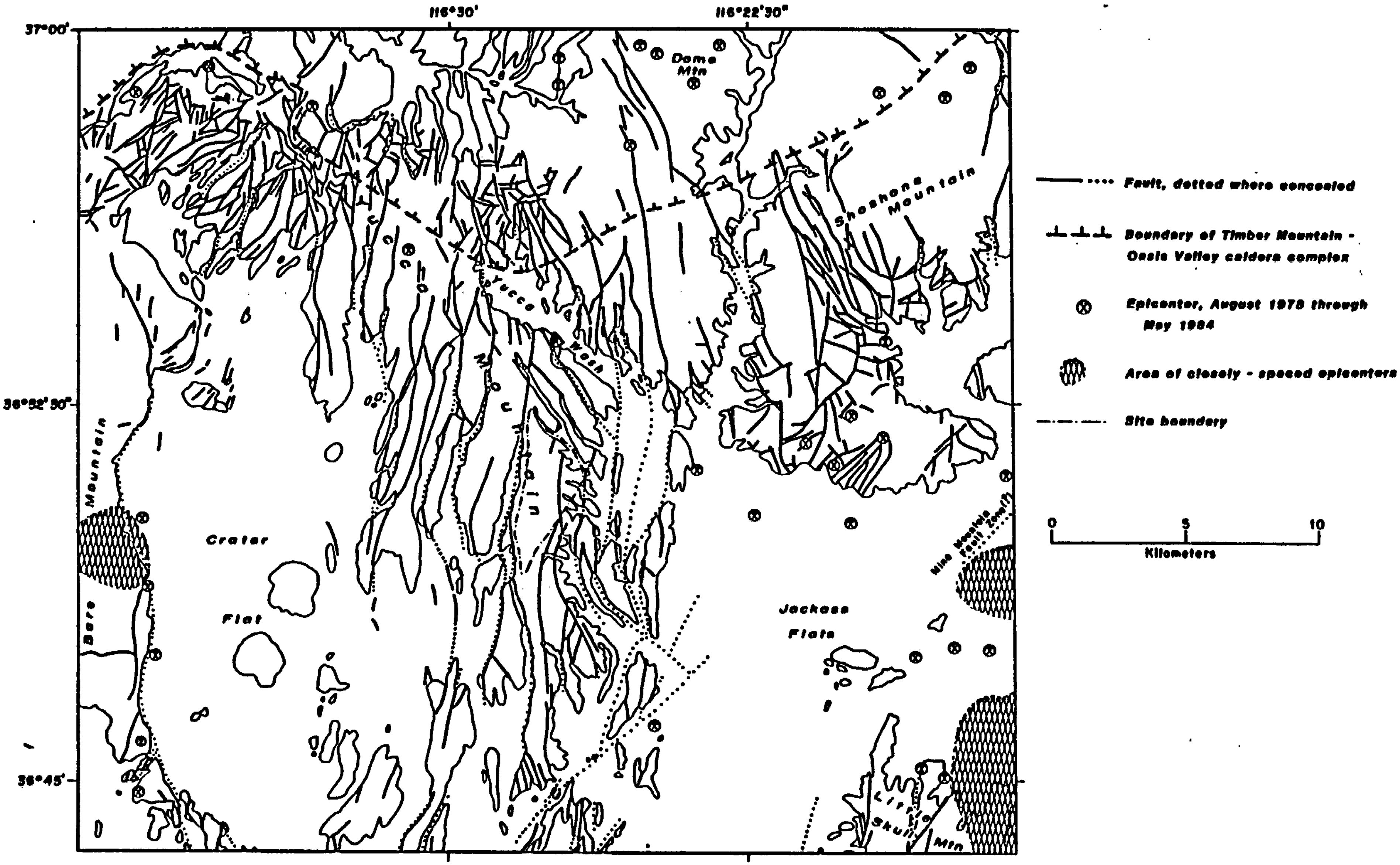


Figure 21.--Relation of seismicity to high-angle fault pattern, Yucca Mountain area.

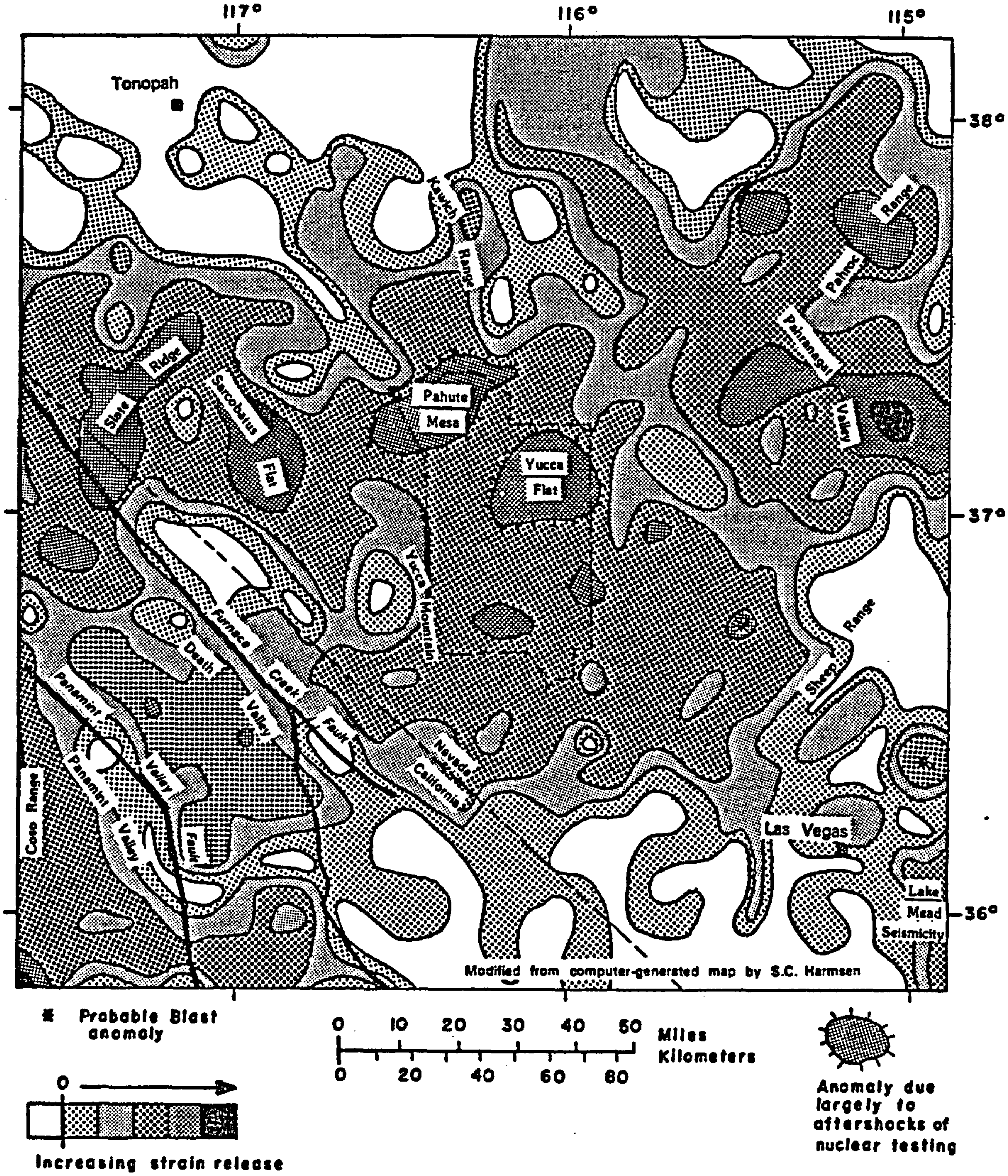


Figure 22.--Preliminary map of strain release from all recorded earthquakes in a portion of the southwestern Great Basin from August 1978 through May 1984. Each contour represents a 32-fold increase in energy. Grid size used for plotting: 7.26' long and 6.18' lat.

segments that ruptured in one earthquake on that fault zone. More than half of the 135 scarps are in the Inyo-Mono subsection, even though that area is only about one-third of the area counted. Outside the Inyo-Mono subsection, only one fault (Yucca fault in Yucca Flat) with probable Holocene displacement (Carr, 1974) has been found although slight Holocene movement cannot be ruled out on several other faults (Szabo and others, 1981).

Seismic Energy

Seismic strain release is one measure of tectonic flux. Maps have been published (Allen and others, 1965; Ryall and others, 1966) that provide a general overview of strain release for the region, although the data available previously did not permit an evaluation for the southern Nevada portion of the Great Basin, comparable with that for southeastern California. Furthermore, much new data has become available in the last 20 years, and seismicity patterns have changed in some areas.

Figure 22 is a seismic energy release map for a large part of the southwestern Great Basin, based on earthquakes recorded from the present seismic network. Although preliminary, the map is believed to represent fairly well the current general tectonic flux of the region. Several features of the map are noteworthy. First, the NTS region is in the middle of a wide east-northeast trending belt of moderately high strain release. A large area including the NTS, however, has a relatively uniform strain release that is interrupted only by a few small areas of higher or lower tectonic flux. This is even more striking if activity of the Pahute Mesa and Yucca Flat nuclear testing areas is removed. This broad area of relatively uniform but high strain release correlates fairly well with the large right-step in the Walker Lane belt described earlier. This could be interpreted to mean that the structural pattern in this part of the WLB tends to spread or even out the strain release by small earthquakes over larger areas instead of concentrating the activity. The northeastern margin of the area of relatively uniform strain release extends northwestward from the northern Sheep Range to the northern Kawich Range (fig. 22). This northwest-striking corridor of lower flux lies in a zone where the basins and ranges have a trend of about N. 25°-35° W., a direction unique in the basin-range subsection of the Great Basin. It is suggested that this correlation may be another indication that the present stress field tends to suppress slip on structures of northwest trend.

To the west, in the Inyo-Mono subsection of California, the southern part of the Furnace Creek-Death Valley fault zone and the Panamint Valley fault zone are within and generally parallel to northwest-trending zones of relatively low strain release; the least active areas tend to be just east of the two fault zones. The obvious association of these linear zones with important Holocene faults indicates a strong seismotectonic relationship, and suggests that either rupture along these fault zones is young enough to have relieved the stress, or stress is building up along the faults because it is not being relieved. Not enough information is available at present to choose between these possibilities.

The regional east-northeast-trending belt flanked by areas of lower strain release is, of course, matched by the regional seismicity distribution (fig. 19), and would be even more prominent if it were not for the temporary quiescence of the Death Valley-Panamint Valley area. The belt alines well with the White Wolf and western part of the Garlock fault zones (see fig. 20), yet there is no obvious structure of this trend across the Inyo-Mono subsection. The northeast-trending belt of relatively high strain release includes the narrower SR-MM structural zone, which is poorly defined on figure 22 by several closed contour areas of slightly higher strain release. Epicenters of the last few years (fig. 19) in the Indian Wells Valley area (fig. 22) north of the Garlock fault display a distict northeast alinement. It appears that, at least temporarily, strain release has shifted northward away from the Garlock fault.

In the vicinity of Yucca Mountain itself, an area of low strain release lies to the west over Crater Flat and extends northward into the Timber Mountain area, generally following the regional gravity low associated with the calderas. To the east, strain release shows up on the map (fig. 22) as a nearly north-south boundary near the eastern edge of the repository site, and appears to coincide roughly with the system of northerly striking faults in that area. Thus, on the basis of preliminary regional strain evaluation, the proposed Yucca Mountain site lies in an area of moderate flux, but it is adjoined on the east by a large area of relatively high strain release. Further evaluation of these factors, and all other tectonic flux indicators is desirable before final judgment of the stability of the Yucca Mountain area is made.

TECTONIC SETTING OF YUCCA MOUNTAIN

The Yucca Mountain area, or site vicinity, is defined as the area within about 35 km (22 mi) of the proposed repository site (fig. 7). Thus, it extends roughly from Beatty and Oasis Valley on the northwest to the Specter Range on the southeast, and from Mine Mountain on the northeast to the Funeral Mountains on the southwest. As discussed previously, the area lies athwart the Walker Lane belt, and is adjacent to the Inyo-Mono subsection on the southwest and the basin-range subsection on the northeast; in addition, the southeastern half of the area lies within the Spotted Range-Mine Mountain structural zone. Superimposed on these structural elements are the major Timber Mountain-Oasis Valley (Byers and others, 1976; Christiansen and others, 1977) and Crater Flat-Prospector Pass caldera complexes (Carr and others, 1984).

Pre-Tertiary Structural Framework

Late pre-Cambrian and Paleozoic rocks are exposed east and west of Yucca Mountain, where they exhibit folds, thrust faults, low-angle probable detachment-type faults, gravity glide blocks, and high-angle normal and reverse faults. In addition, local metamorphism occurs in the Calico Hills, Bare Mountain, and the Funeral Mountains. Much of the complex structure is concealed beneath extensive Tertiary and Quaternary deposits, so that integrating the various structural elements can be done with considerable latitude. Because of the importance of the distribution of the pre-Tertiary rocks, especially in the deep hydrologic flow system (Winograd and Thordarson, 1975), the USGS is continuing mapping and other studies that are designed to help clarify the structural relations.

In general, the pre-Tertiary rocks are distributed in a large structural bend (fig. 23) whose axis strikes northerly in the Yucca Flat-Eleana Range area, to northeasterly in the Calico Hills and Specter Range, and easterly in the Bare Mountain area (Barnes and Poole, 1968; Stewart, 1967). This conclusion is based on both strike of the rocks and continuity of facies trends. Albers (1967) called large sigmoidal bends of this kind along the Walker Lane belt oroflexes. In the Spotted Range-Mine Mountain structural zone of the southeastern NTS, which lies within this larger structure, the trend of much of the Tertiary faulting is controlled or influenced by the structure in pre-Paleozoic rocks; in the Yucca Mountain-Crater Flat-Bare Mountain area this is generally not the case, as Tertiary faults strike northerly, nearly at right angles to the postulated Paleozoic trends.

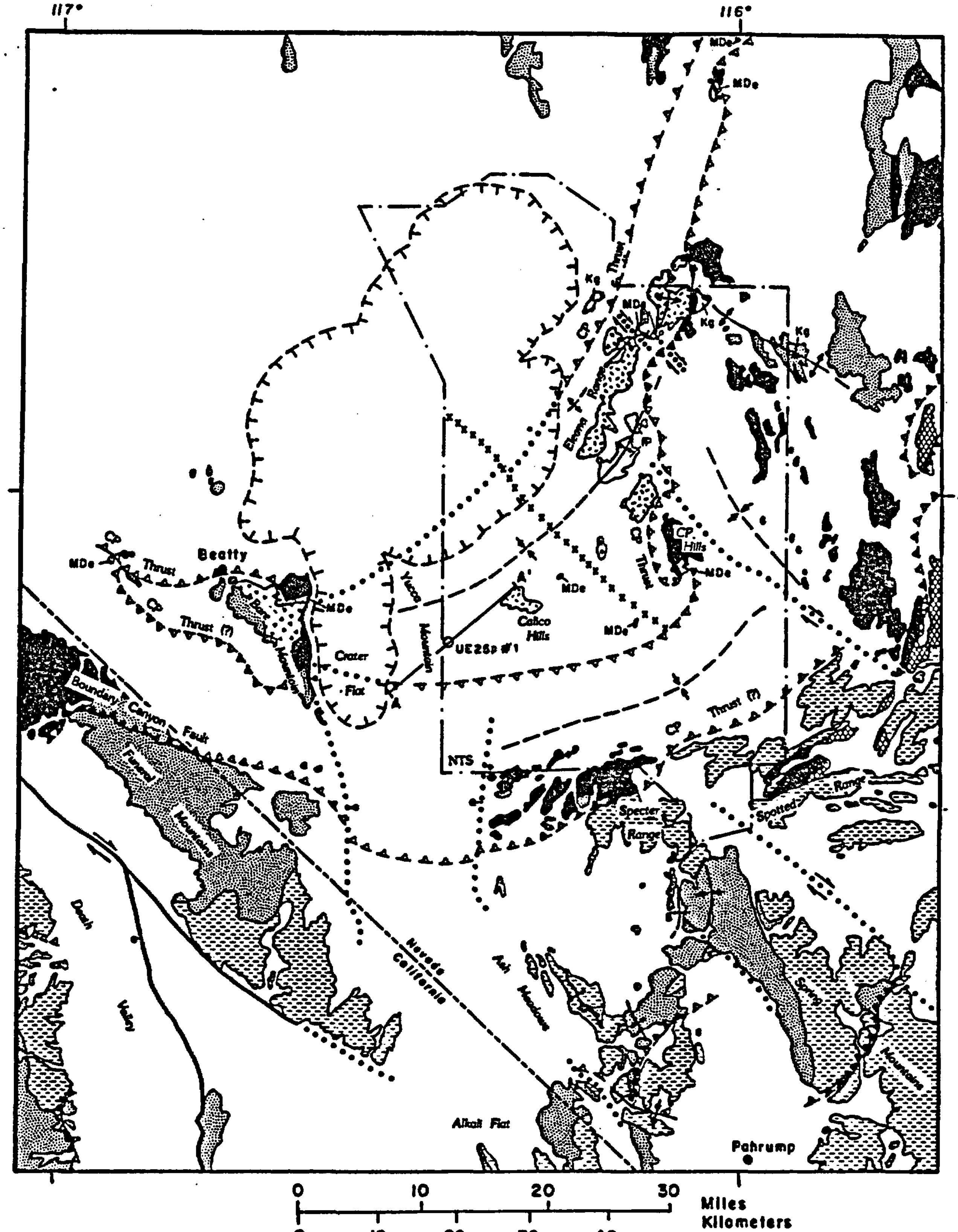


Figure 23.--Inferred configuration of the CP thrust in the NTS region and distribution of carbonate rocks (aquifers) and clastic rocks (aquitards).

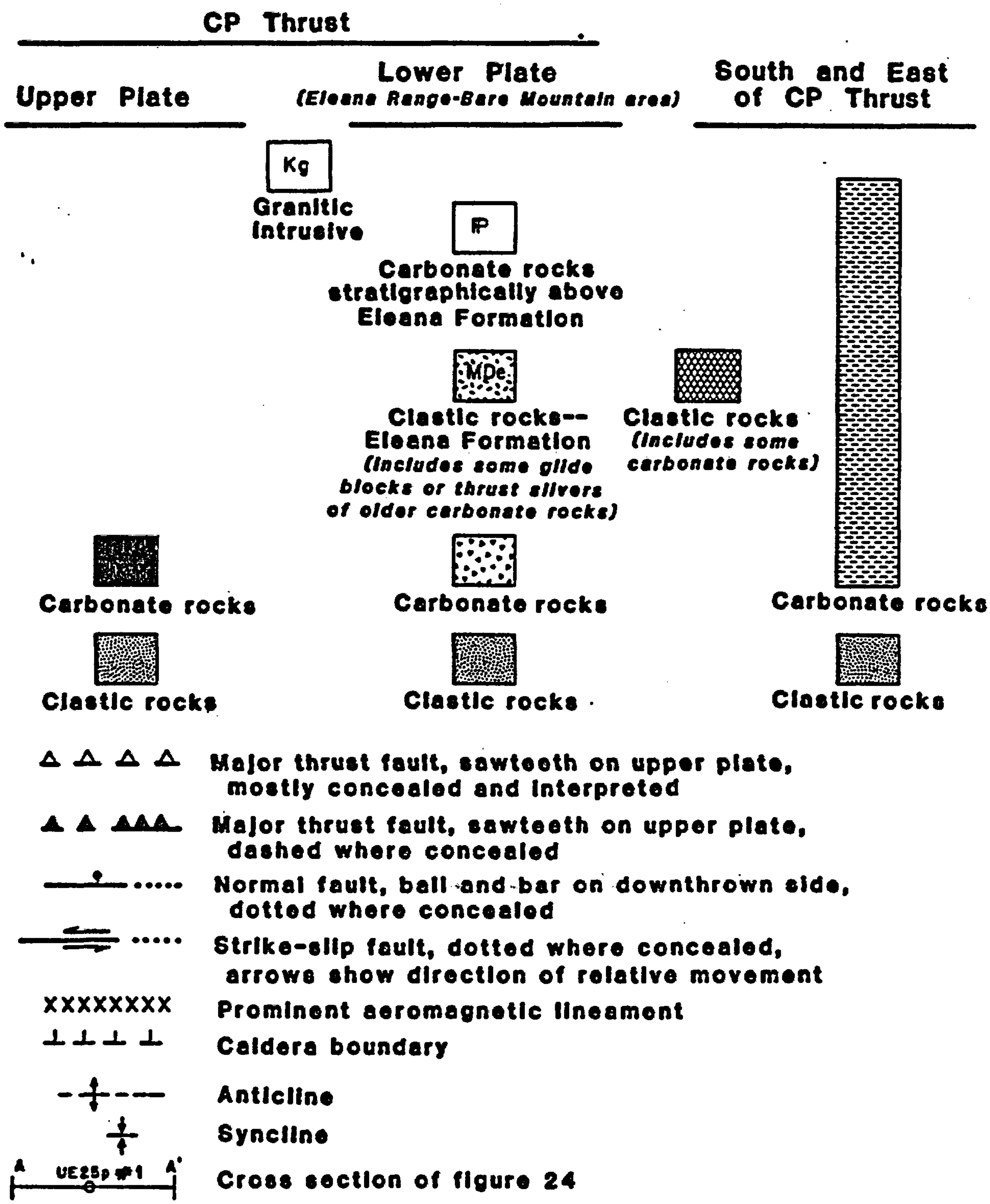
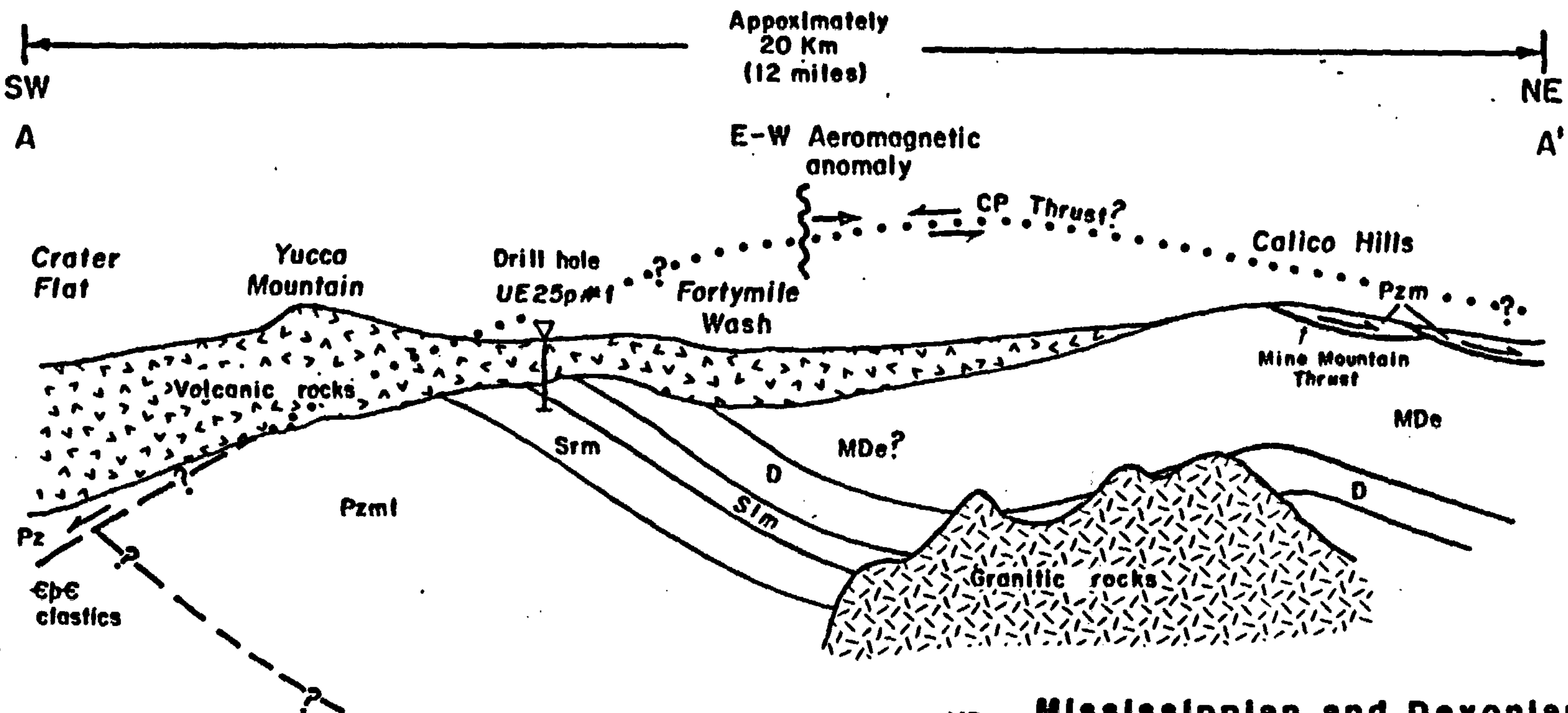


Figure 23.--continued

Thrust Faults

The principal structure responsible for the distribution of the pre-Tertiary rocks in the NTS area is the CP thrust system and related folds (Barnes and Poole, 1968), a major structure that moved older rocks east-southeast over younger rocks, mainly the Mississippian Eleana Formation in central NTS (fig. 23). As originally described, the CP thrust was thought to dip west and be rooted beneath a cover of Tertiary rocks in the Belted and Eleana Ranges, a conclusion based mainly on drill-hole data and geologic mapping at Rainier Mesa (Gibbons and others, 1963). Thrust faults to the southeast in the Spotted Range were considered outliers or klippen of the thrust as it flattened southeastward. Work by Carr (1974 and unpublished) indicates that the CP thrust climbs stratigraphically from the postulated root zone until it reaches the weak Eleana Formation in the Eleana Range, where it flattens and is thrown into a series of large amplitude folds. Farther east the thrust dips beneath Yucca Flat, so that most of the exposed Paleozoic rocks in the eastern and southeastern NTS area are probably in the upper rather than the lower plate (fig. 23). Work in the Bare Mountain area by M. D. Carr and Susan Monsen of the USGS shows that a thrust that could logically correlate with the CP is arched over Bare Mountain, a situation similar to that in the Eleana Range.

A drill hole (UE-25p#1) located on a gravity high near Yucca Mountain, (fig. 23) encountered northward-dipping Silurian dolomites at about 1,220 m (4,000 ft). Evidence that Eleana Formation may have underlain much of Crater Flat is found in the presence of common Eleana-like mudstone fragments in the Prow Pass Member of the Crater Flat Tuff, erupted from the Crater Flat area (Carr and others, 1984, p. 30). This information is used in a hypothetical cross section (fig. 24) between Yucca Mountain and the Calico Hills, where extensive exposures of Eleana Formation occur. In this model, a configuration similar to northern Bare Mountain is postulated, wherein the CP thrust and upper plate rocks were mostly eroded over the anticlinal structure, and rocks penetrated by the drill hole are part of the lower plate. In this model, Devonian rocks exposed in low-angle fault contact (Mine Mountain thrust) above the Eleana in the Calico Hills and Mine Mountain areas (Orkild, 1968; Orkild and O'Connor, 1970) are regarded as thin-skinned or gravity-glide blocks. Thus, in this interpretation the Mine Mountain thrust is not an underlying and earlier thrust, as suggested by Barnes and Poole (1968, fig. 2, p. 236), but is younger than the CP and represents near-surface thrusting or, more likely, gravity gliding after erosion had stripped the upper plate of the CP thrust, especially from the anticlinal areas shown on figure 23. Most of the Mine Mountain-type low-angle faulting is pre-middle Miocene in age, and does not involve Teritiary rocks, but a notable exception occurs at the south end of Bare Mountain where a huge (at least 5 km or 3 mi wide) glide block of lower Paleozoic rocks rests on Tertiary volcanic rocks as young as 10 m.y. old. At the northeast corner of Bare Mountain, however, dikes dated as 13.9 m.y. old (Carr and others, 1984) apparently post-date the low-angle faulting. S. A. Monsen (USGS, written commun., 1983) concluded that the abundant low-angle faults at the north end of Bare Mountain, however, probably moved from



MDe – Mississippian and Devonian Eleana Formation

D – Devonian carbonate rocks

Slm – Silurian Lone Mountain Fm

Srm – Silurian Roberts Mountain Fm

Pzm – Middle Paleozoic carbonate rocks

Pzml – Lower and middle Paleozoic carbonate rocks

€p€ – Cambrian and Precambrian clastic rocks

Pz – Paleozoic rocks

Figure 24.--Hypothetical cross section of Yucca Mountain area based on interpretation of regional structure and data from drill hole UE-25p#1.

southwest to northeast, which suggests the possibility of gravity gliding toward the Timber Mountain-Oasis Valley and Crater Flat-Prospector Pass caldera complexes during a period roughly 15-10 m.y. ago. Thus, low-angle faulting is not necessarily related to the regional thrust system, is variable in age, and very large glide blocks of Paleozoic rocks may be found within and beneath the Tertiary rocks.

Possible Detachment-Type Faulting

In the Funeral Mountains and west of Beatty (fig. 23) in the Bullfrog Hills, major fault zones are present that separate highly metamorphosed terrain from overlying essentially unmetamorphosed Paleozoic rocks (Labotka, 1980; Giarmita and others, 1983, L. A. Wright (Pennsylvania State Univ.) and B. W. Troxel (Univ. of California, Davis), unpublished mapping). This style of faulting, common to "metamorphic core" complexes (Coney, 1980), involves large scale "detachment" of an upper brittle plate, from a more mobile, penetratively deformed and metamorphosed lower plate; commonly the upper plate shows considerable extension by listric faulting. In the Bullfrog Hills where the area of possible detachment faulting is poorly exposed, a small area of highly metamorphosed probable Johnnie Formation (M. D. Carr, USGS, oral commun., 1983) is overlain on a low-angle fault by highly faulted and altered Paleozoic carbonate rocks. It seems reasonable to correlate this occurrence with a similar low-angle fault (Boundary Canyon Fault of Giarmita and others, 1983) that is exposed in the Funeral Mountains (fig. 23). If such a structure is continuous under the northern part of the Amargosa Desert valley and Bullfrog Hills it may have facilitated the considerable extension that took place in that area in the Miocene.

Granitic Intrusive Rocks and Metamorphism

Evidence of granitic intrusive rocks and metamorphism of probable Mesozoic age exist in the Bullfrog Hills, at Bare Mountain and Yucca Mountain, and in the Calico Hills. The relation of possible detachment faulting in the Funeral Mountains and Bullfrog Hills to the structure at Bare Mountain is presently unknown, but work by S. A. Monsen (USGS, written commum., 1983) clearly indicates that in the northwest part of Bare Mountain the metamorphism and related deformation probably occurred in the Mesozoic, before extensional faulting. The metamorphism may be related to granitic intrusives, because a small body (rhyolite porphyry dike of Cornwall and Kleinhampl, 1961) of granite intruding Paleozoic rocks is exposed near the mouth of Fluorspar Canyon. Zircon from this granite yielded a fission track age of 25.4 ± 1.3 m.y. (C. W. Naeser, USGS, written commun., 1983). This date is an annealing age that records the last time the rock was over a temperature of approximately 650°, and is older than any Tertiary volcanism in the area. As there are no earlier Tertiary magmatic events known in the area, Mesozoic age is suggested for the intrusive and associated metamorphism. In addition to the outcrop of granite, a positive magnetic anomaly of about 150 gammas closure (U.S. Geological Survey, 1978) is present over northwest Bare Mountain in the same area where the maximum metamorphism occurs, which suggests a much larger intrusive body than the exposed dike.

Another location in the Yucca Mountain area where significant metamorphism of probable pre-Tertiary age occurs is in the Calico Hills where volcanic rocks about 13.5 m.y. old are deposited on a stripped surface cut across the arched complexly deformed Paleozoic rocks. The Eleana Formation in the Calico Hills contains considerable magnetite and marble (Maldonado and others, 1979) of contact metamorphic origin, and overlying carbonate rocks in low-angle fault contact above the Eleana are locally converted to tactite. No intrusive has been found, but the type of metamorphism, the apparent doming of the area, as well as geophysical anomalies, strongly suggest the presence of an underlying intrusive. The Tertiary volcanic rocks in the same area are hydrothermally altered, probably from minor Tertiary intrusive activity, but the nature of the metamorphism in the pre-Tertiary rocks suggests it occurred at moderate depths and is mostly Mesozoic in age.

As discussed earlier in the report, east-trending granitic bodies of Mesozoic age are an important, though commonly unmentioned feature of the pre-Tertiary structure in southwestern Nevada. An east-west trending zone of Mesozoic (Naeser and Maldonado, 1981) stocks is present in the northeastern NTS area (fig. 13). The evidence for an east-trending granitic body beneath the Yucca Mountain area is partly geophysical (Bath and Jahren, 1984), but the presence of the previously mentioned probable pre-Tertiary east-trending granite dike at the mouth of Fluorspar Canyon near the northwest corner of Bare Mountain (fig. 13) strengthens the evidence. In addition, coarse-grained large (more than 10 cm across) granitic clasts have been noted locally in the Prow Pass Member of the Crater Flat Tuff near Prow Pass (fig. 13), suggesting a granite source buried somewhere in the Crater Flat-Yucca Mountain area. Several igneous features of Tertiary Miocene age are also present, however, along the east-west aeromagnetic trends. Near Wahmonie, on the east, Tertiary intrusives cut a small area of Eleana Formation and rocks as young as the volcanic rocks of Mt. Salyer (±13.2 m.y.); (Ekren and Sargent, 1965). These bodies, which extend eastward nearly to Frenchman Flat (Poole and others, 1965), are probably related to volcanic rocks of the Salyer and Wahmonie Formations, to which they are petrographically similar. Other Tertiary intrusive rocks and rhyolite lava flows lie along the east-west trend, including the rhyolite of Shoshone Mountain and rhyolite of Calico Hills (Orkild and O'Connor, 1970), rhyolite lavas near Beatty, and a huge rhyolite lava center in the eastern Grapevine Mountains (fig. 13). The distribution of some or all of these Tertiary silicic rocks may be unrelated to the postulated east-west Mesozoic trend, however.

Bath and Jahren (1984) analyzed the aeromagnetic anomalies at Yucca Mountain and concluded that the east-west striking magnetic trend through the area is most likely due to magnetized Eleana Formation in alinement with and similar to the metamorphism at Calico Hills. As the Tertiary volcanic rocks at Yucca Mountain, even in 1,830-m (6,000 ft) drill holes, show no obvious evidence of contact metamorphism, the intrusive body that presumably metamorphosed the Eleana predates the Tertiary volcanism.

The presence of granitic rocks of Mesozoic age beneath northern Yucca Mountain cannot be verified without a deep drill hole, but the coincidence of the east-west magnetic trend with a steep gradient in the water table at Yucca Mountain (J. H. Robison, USGS, written commun., 1984) and a change in structural style in surface rocks from south to north across this trend (Scott and others, 1983; Scott and Bonk, 1984) makes such verification important to complete understanding of the tectonic and hydrologic environment at Yucca Mountain. Likewise, the presence of Eleana Formation as well as granite at depth beneath northern Yucca Mountain, a distinct possibility from the evidence at hand, would have an important impact on interpretation of the hydrology. Furthermore, if granite is present beneath northern Yucca Mountain, it may help to explain the greater structural stability and fewer faults and fractures in Tertiary rocks in that area. Also, if carbonate rocks are more or less continuously present beneath the Tertiary section south and east of Yucca Mountain, as suggested by drill hole UE-25p#1 (fig. 23), ground-water flow rates could be affected in the area between Yucca Mountain and the areas of discharge in Ash Meadows, Alkali Flat, and Death Valley.

Tertiary Structure

Structural development of the Yucca Mountain region during the Tertiary was strongly influenced by volcano-tectonic processes related to the eruption of hundreds of cubic kilometers of silicic tuff and lava. The volcanism was concentrated between about 16 and 7 m.y. ago (Marvin and others, 1970, and fig. 25). The youngest known silicic eruptions in the region were lavas 5-6 m.y. old (Fleck, 1970 a) in the Greenwater Range-Black Mountains area 70 km (43 mi) to the south, and in the Stonewall Mountain area (fig. 9) 90 km (56 mi) to the northwest (Foley and Sutter, 1978).

The Yucca Mountain site vicinity can be divided for discussion into six main structural styles or blocks that reflect various types of Tertiary deformation: (1) the Spotted Range-Mine Mountain structural zone (fig. 7) of prominent northeast trends, (2) northeast-striking fault system north of Bare Mountain (fig. 26), (3) the Yucca Mountain-Crater Flat-Bare Mountain block of dominant northerly structural trends (fig. 21), (4) northwest-striking lineaments and faults (fig. 27), (5) volcano-tectonic structures, including the Crater Flat-Prospector Pass and Timber Mountain-Oasis Valley caldera complexes (fig. 9), and (6) structural "rifts" or grabens (fig. 28).

Spotted Range-Mine Mountain Structural Zone

This prominent 30-60 km-wide fault system lies across the Walker Lane belt (fig. 3) in the southeastern NTS area. The northwest margin of the zone crosses the southeastern corner of Yucca Mountain, and probably extends across the Amargosa Desert valley and through the southeastern part of the Funeral Mountains (fig. 7). Northeast of Yucca Mountain the margin of the zone passes through the Calico Hills and continues past Mine Mountain to the edge of Yucca Flat. The southeast margin, mostly concealed by alluvium, extends from Indian Spring Valley (fig. 7) southwestward to the La Madre fault zone near the Spring Mountains, where it jogs northwestward across the Amargosa Desert valley, past Ash Meadows, to the southeast tip of the Funeral Mountains. The margins, as just described, are drawn at the edges of a system of northeast-striking faults, folds, and topographic trends (Streitz and Stinson, 1974; Stewart and Carlson, 1978; Barnes and others, 1982) (figs. 2 and 23). Widening of the SR-MM zone northeastward could be due in part to greater extension in that area, as suggested by numerous faults and development of the structural basin in the Frenchman Flat area (compare faulting in Mercury quadrangle, Barnes and others, 1982; Cane Spring quadrangle, Poole and others, 1965; and Skull Mountain quadrangle, Ekren and Sargent, 1965, with areas to southwest).

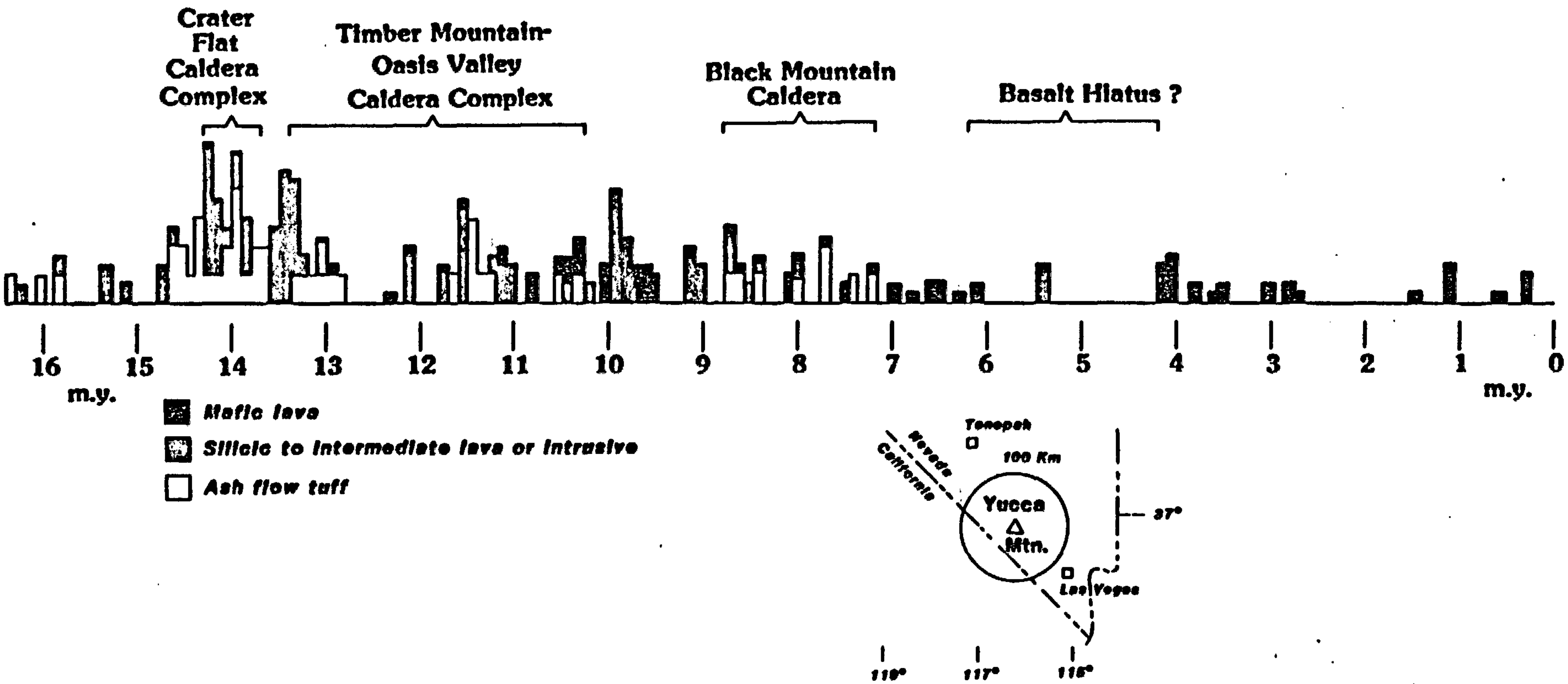


Figure 25.--Histogram of chronology of volcanism, 100-km radius of Yucca Mountain, California and Nevada.

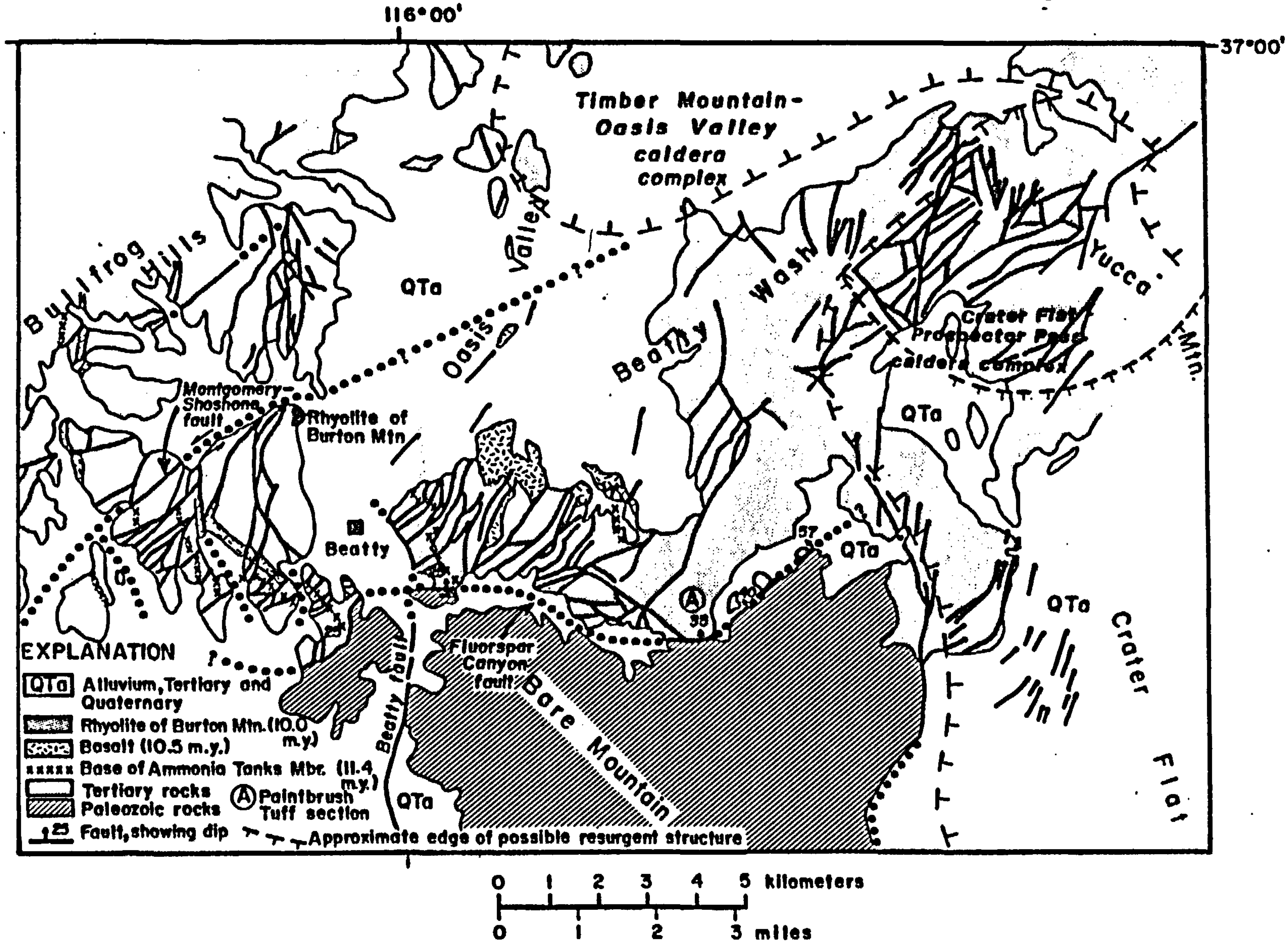


Figure 26.--Sketch map of structure in Cenozoic rocks north of Bare Mountain.

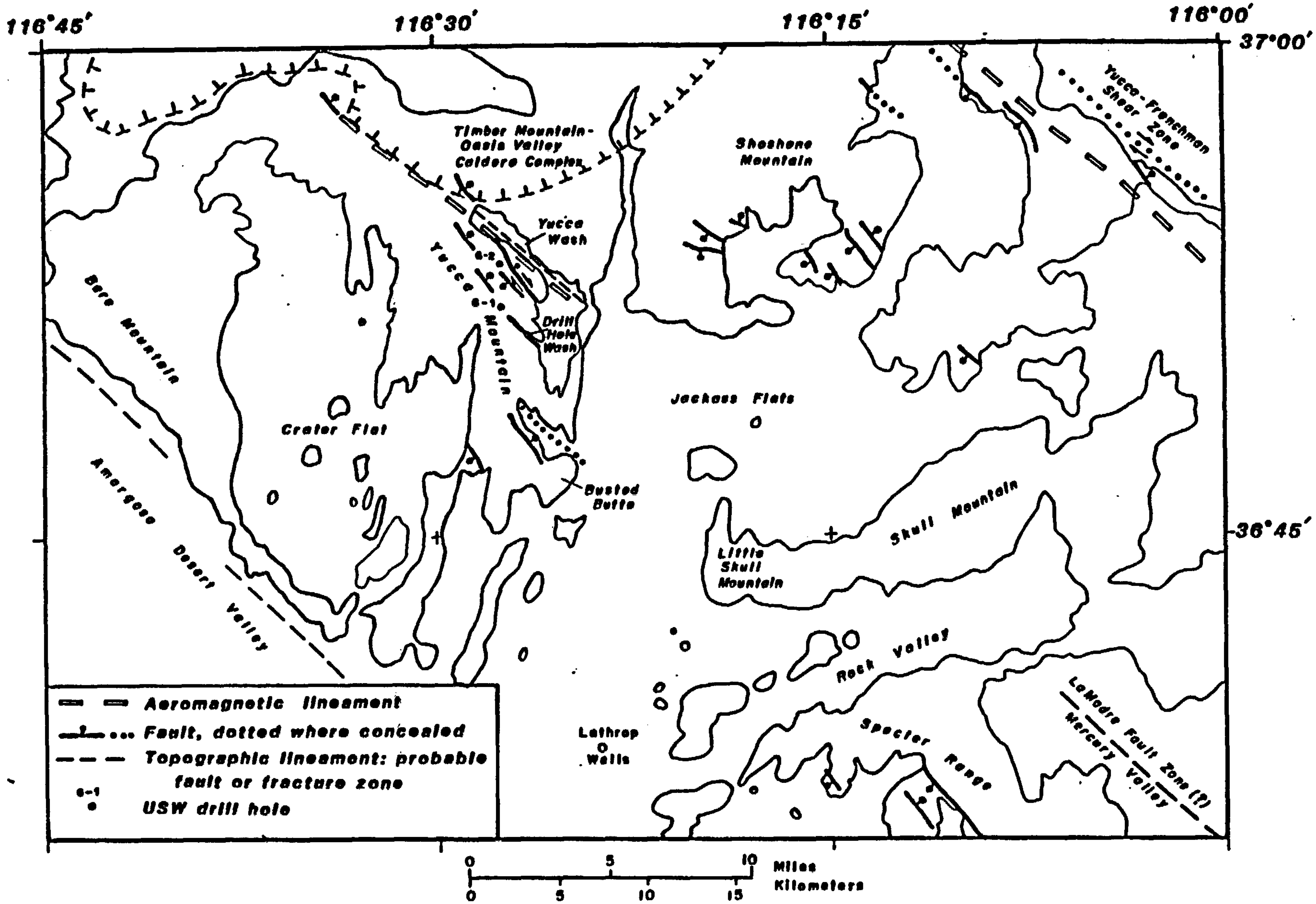


Figure 27.--Sketch map of Yucca Mountain region showing mapped and inferred structures of northwest trend.

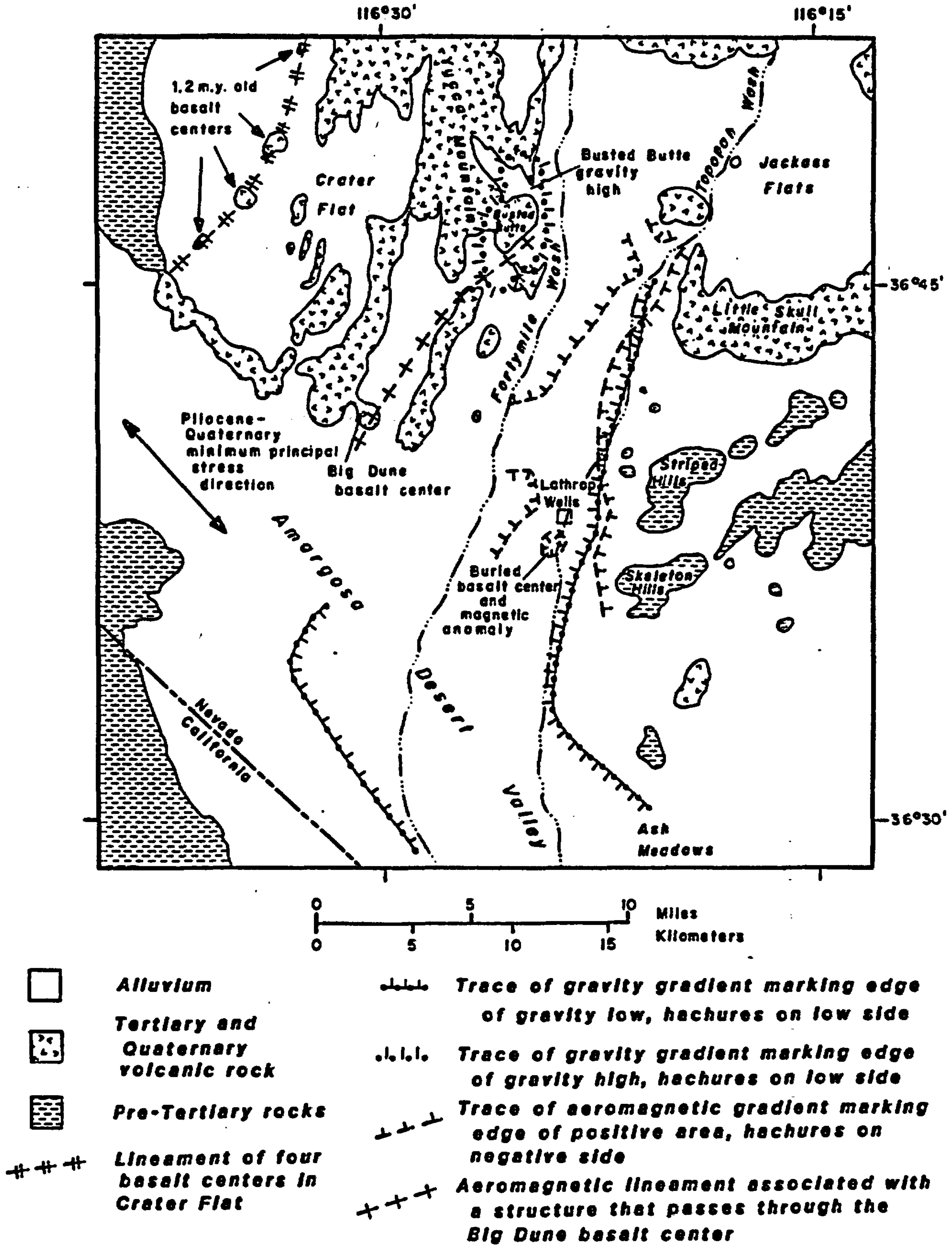


Figure 28.--Expression of rift-like structures in the Lathrop Wells-Crater Flat area.

Continuity of the SR-MM zone beneath the Amargosa Desert valley and across the southeastern end of the Funeral Mountains (fig. 7) is supported by seismicity, Quaternary fault traces (fig. 7; Swadley and Carr, USGS, written commun., Swadley, 1983), and a few northeast-striking faults in the Funeral Mountains (fig. 7; Denny and Drewes, 1965; McAllister, 1971).

The tectonic importance of the SR-MM zone is underscored by the fact that most of the zone consists of thick, highly fractured Paleozoic carbonate rocks, the prinicipal regional aquifer (Winograd and Thordarson, 1975). In addition, the northeast trend of the faults in the zone is essentially normal to the present least prinicipal stress direction for the NTS region (Carr, 1974), a situation that may enhance fracture flow of ground water through the zone toward discharge areas in Ash Meadows. If the zone crosses the Amargosa Desert valley, as proposed here, some ground water from sources to the northeast may bypass Ash Meadows and discharge in the lower Furnace Creek Wash area adjacent to Death Valley.

The SR-MM zone is currently seismically active (fig. 7) and has a long history of tectonic activity. In Rock Valley, moderately to unfaulted Tertiary tuffs and sedimentary rocks as old as 29 m.y. (Barnes and others, 1982) in many places lap onto highly faulted and folded Paleozoic rocks (Hinrichs, 1968), illustrating that much of the structure developed prior to late Oligocene time, but in the nearby Cane Spring quadrangle (Poole and others, 1965) at the east end of Skull Mountain, Miocene rocks are highly broken by northeast-striking faults. Most of the faulting in the Skull Mountain area predates the Timber Mountain Tuff, however, which is about 11.5 m.y. old. At other locations, such as at Little Skull Mountain (fig. 27) (Sargent and others, 1970) and in the Mine Mountain quadrangle (Orkild, 1968), Timber Mountain Tuff is displaced about the same amount as Tertiary rocks several million years older. Small displacements of Quaternary age are common along the SR-MM system, especially in Rock Valley, and current seismicity of the zone (fig. 7) shows that these faults are still active. However, it is also obvious from the lack of deep structural basins in the SR-MM zone that, except for Frenchman Flat, no large cumulative dip-slip displacements have occurred in the last 10 m.y. or so, even though this type of displacement should be favored by the northwest-oriented least principal stress direction that has existed during at least the latter part of that period (Carr, 1974).

Much of the displacement in the SR-MM zone has been left-lateral strike-slip (Ekren, 1968), but the amount is small--1 or 2 km (0.6 or 1.2 mi) or less--on individual faults. Examples are the Mine Mountain fault south of Mine Mountain where the Paintbrush and Timber Mountain Tuffs are displaced about 1 km (0.6 mi) (Orkild, 1968) in a left-lateral sense, and in the Cane Spring area where (Poole and others, 1965) Salyer and Wahmonie Formations are offset a kilometer or so, also in a left-lateral sense. No steeply dipping units are present anywhere on both sides of faults in the SR-MM zone to give a true measure of the lateral displacement, but drag and slickensides consistent with a component of left-lateral offset are evident (Barnes and others, 1982) at many locations.

As mentioned, the northwestern margin of the SR-MM zone appears to pass just to the east of Yucca Mountain. This is based partly on distribution of seismicity (fig. 7) and on the northeast trends of faults in the Calico Hills, near Busted Butte in the southeast corner of the Topopah Spring SW quadrangle

(Lipman and McKay, 1965), and in the Lathrop Wells quadrangle (McKay and Sargent, 1970) 8-12 km (5-7.5 mi) northwest of Lathrop Wells. Little of the northeast-striking structure is actually exposed on the southeast edge of Yucca Mountain, but the topographic trends and aeromagnetic anomalies (U.S. Geological Survey, 1978, 1979) support its existence. In particular, a strong aeromagnetic lineament trends northeast from the Big Dune cinder cone 11 km (7 mi) northwest of Lathrop Wells (fig. 7) to just east of Busted Butte, a distance of 15 km (9.3 mi). This portion of the SR-MM zone is less active seismically than areas farther to the east, although evidence of minor Quaternary faulting is present (W C Swadley, USGS, written commun., 1984).

The abrupt boundary of the SR-MM zone just east of Yucca Mountain may be related to and inherited from a structural grain in the Paleozoic rocks, which are much less deeply buried in that area than they are beneath Yucca Mountain to the northwest (Snyder and Carr, 1982).

Relation of the Spotted Range-Mine Mountain structural zone to the Pahranagat shear system.--There is no evidence, at least in the surface rocks, tlgd dlv WR-MM structural zone connects with the Pahranagat shear system (Tschanz and Pampeyan, 1970) to the northeast (fig. 3) in Lincoln County, but the two zones aline perfectly, even though they are 70 km (44 mi) apart. Tschanz and Pampeyan (1970) concluded that, on the basis of offset features in Paleozoic rocks, the Pahranagat shear system was responsible for about 15 km (9.3 mi) of right-lateral displacement during late Mesozoic or early Tertiary time. However, displacements of the Tertiary (Miocene) volcanic rocks are left-lateral in sense (Ekren and others, 1977). Ekren and others (1977) pointed out that the similarities of style and alinement of the two shear systems suggest the possibility of a regional northeast-trending zone of weakness that predated Tertiary volcanic rocks, but no important structures of this trend have been mapped (Tschanz and Pampeyan, 1970; Ekren and others, 1977) in the Paleozoic rocks exposed at numerous places in the 70 km (44 mi) gap between the two zones.

Age and origin of the Spotted Range-Mine Mountain Structural zone.--Several lines of evidence suggest the SR-MM zone essentially spans the Walker Lane belt, and may be related, but not connected to, the Pahranagat shear system. Some evidence suggests it is a relatively old structure that probably developed prior to and perhaps independently from Tertiary movements in the WLB. Whereas some of the old movement may well be conjugate with the WLB in nature, I believe the considerable length and breadth of the SR-MM zone, the apparent offset of its boundaries by the WLB shears on both sides of the Spring Mountains (fig. 7), and the great number and style of pre-Miocene structures all indicate a pre-Miocene zone of structural weakness. Furthermore, it is difficult to identify a northwest-striking structure within the WLB that could have been responsible for an oroflexural feature (Albers, 1967) the size of the SR-MM zone. Thus, although it has been suggested (e.g., Carr, 1974; Shawe, 1965) that the northeast-trending structures are part of a regional conjugate system with the WLB, the relationships can be interpreted to indicate that much of the SR-MM zone originated earlier than mid-Tertiary time, and that only faults of favorable orientation have been conjugate to later movements in the WLB. If the two systems were well developed before Tertiary right-lateral shearing in the WLB, it is obvious that preexisting faults of northeast trend would have yielded with a component of left-lateral movement in response to north-south or northeast-southwest directed compression (Carr, 1974; Zoback and Zoback, 1980) associated with Tertiary Walker Lane belt activity.

Ekren (1968, p. 17) suggested that "rotary slippage" was a response of the SR-MM zone faults to right-lateral movement on the Las Vegas Valley shear zone, but the Las Vegas Valley and La Madre shear zones do not cross the SR-MM zone, nor is there much indication that northeast-striking faults of the SR-MM zone are significantly curved or bent so as to require such rotation.

In the SR-MM zone, the absence of rocks between Mississippian and Oligocene age makes dating the early development of the system difficult. Armstrong (1968), Burchfiel (1965), Burchfiel and others (1974), and Fleck (1970b), and several other authors have discussed the age and style of events in the Sevier orogenic belt (Armstrong, 1968) and adjacent areas, but even so, little detailed information is available with respect to the age of prevolcanic structure in the NTS region. In general, the major part of the thrusting and folding of the Sevier belt was completed by the beginning of Tertiary time; this age is established by the fact that thrust plates in adjacent portions of California are cut by plutons of late Cretaceous age (Adams and others, 1968; Burchfiel and others, 1974). In the NTS area, the best evidence of the age of thrusting is the age of the Climax stock at the northwest corner of Yucca Flat. Both fission-track and K-Ar techniques have yielded roughly concordant ages ranging from 91 to 107 m.y. (Naeser and Maldonado, 1981). As the granite stock postdates the nearby CP thrust (Barnes and Poole, 1968), a minimum age of about 100 m.y. is indicated for the CP thrust. The thrust involves older rocks thrust east or southeastward over the Eleana Formation and Tippipah Limestone (Mississipian and Pennsylvanian), so the age of the major compressional structures at NTS can be bracketed no closer than between about 300 and 100 m.y. ago. The CP thrust is of particular interest to the tectonics of the southern NTS area and the SR-MM system because southwestward projection of the thrust from Yucca Flat would carry it parallel to or obliquely across the SR-MM zone and probably westward to Bare Mountain (fig. 23, and Poole and others, 1967; Carr, 1974). Structural analysis and extrapolation of the CP thrust is complicated by the fact that the thrust is gently folded and apparently dips eastward beneath Yucca Flat and southeastward beneath Frenchman Flat (Carr, 1974, p. 8-9 and figs. 7 and 8). Problems of its reemergence to the southeast have not been solved, but I believe an attractive hypothesis is that a thrust in the Specter Range (Sargent and others, 1970) parallel to and near the middle of the SR-MM system, is part of the southeastern flank of the downfaulted and warped CP thrust. Barnes and Poole (1968, p. 235 and fig. 1) originally suggested correlation of the type CP thrust with thrust or reverse faults in the Specter Range and Spotted Range. They also suggested several outliers or klippen of the CP thrust are present east of the NTS.

The Spotted Range-Mine Mountain structural zone coincides rather closely with an abrupt change from thick Mississippian clastic rocks of the Eleana Formation to the northwest and much thinner Mississippian clastic rock (Chainman shale or equivalent; Gordon and Poole, 1968) to the southeast in the Spotted Range and eastward into Lincoln County (Tschanz and Pampeyan, 1970). No exposures of rocks stratigraphically higher than Devonian exist in the 35-km (22-mi) wide area between the Spotted Range and CP Hills. Localization of the structurally complex SR-MM zone in the upper plate of a probable regional thrust riding upon a thick, mechanically weak wedge of clastic rocks (Eleana Formation) suggests a relationship between the intense faulting of the rocks above the thrust and the thick and incompetent rocks beneath. Where the lower plate rocks--Eleana Formation and Tippinip Limestone--are best exposed in a large area of the Eleana Range, folding, and reverse faulting is the dominant structural style; high-angle normal faults are not abundant.

The oldest Tertiary rocks in the SR-MM structural zone are generally limestone and siltstone, correlated (Hinrichs, 1968; Barnes and others, 1982) with the Horse Spring Formation of southern Nevada. Biotite from a tuff in the lower part of the Horse Spring in the Southeastern NTS area (Barnes and others, 1982) gave a K-Ar age of a little over 29 m.y. (Marvin and others, 1970, p. 2,665). Fine-grained sediments of the Horse Spring Formation were deposited directly on the eroded surfaces of the deformed Paleozoic rocks. In some places the contact is a fault, but generally without large vertical offset. It is clear, however, that much of the SR-MM zone structure had developed, and considerable erosion had occurred, before mid-Oligocene time when the Horse Spring of the Mercury area was deposited.

Northeast-Striking Faults North of Bare Mountain

This zone (fig. 26), suggested by earlier mapping by Cornwall and Kleinhampl (1961, 1964), has been more recently mapped (Byers and others, 1976a) by the USGS. This zone is similar in trend to the SR-MM system, but the style of deformation is different, no exposed Paleozoic rocks are involved, and there is little or no associated seismicity. Individual faults show left-oblique displacement, generally less than a kilometer, of volcanic rocks as young as a widespread basalt, which is bracketed in age between the tuff of Buttonhook Wash (11.0 m.y.[4]) and the rhyolite of Burton Mountain (10.0 m.y.[5]). The most complex and highly faulted area adjoins Bare Mountain on the north, and is separated from it by the Fluorspar Canyon fault, a low-angle normal, possibly a detachment type fault. The striking abutment of thick volcanic units in the hanging wall directly against the Paleozoic rocks at the north end of Bare Mountain, together with the northeasterly striking left-lateral faults, suggests that the juxtaposition could be the result of westward lateral transport of the Tertiary rocks on the Fluorspar Canyon fault. Very thick Paintbrush Tuff abuts the fault (location A, fig. 26) along the north side of Bare Mountain; the thicknesses of the Topopah Spring and Tiva Canyon Members (Lipman and others, 1966) are nearly as great as those penetrated by drill holes in Crater Flat (Carr, 1982) and on Yucca Mountain (Spengler and others, 1981). Dips measured on the Fluorspar Canyon fault (fig. 26) indicate an eastward steepening near the northeast corner of Bare

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[4]Approximate age from stratigraphic position.

[5]Original K-Ar date of the rhyolite of Burton Mountain was 10.8±0.4 m.y., 11.1 m.y. corrected for new constants (Marvin and Cole, 1978). A more recent zircon fission-track date is 9.0±0.8 m.y. (C. W. Naeser, U.S. Geological Survey, written commun., 1979); an average of about 10.0 m.y. is reasonable based on stratigraphic relationships.

Mountain, which is accompanied by a distinct eastward decrease in the intensity of faulting in the Tertiary rocks. At the location of the 57° dip (fig. 26), slickensides suggest a predominantly dip-slip direction with a minor left-lateral component. This may, however, be only an indication of latest minor movement on a portion of the fault that trends northeast, a direction not properly oriented for strike-slip displacement in the present regional stress field (Carr, 1974).

The northeast-trending swarm of faults near the northwest end of Yucca Mountain (fig. 26) lines up with those just discussed, and could represent a northeastward continuation of a major structural trend toward and possibly beneath the Timber Mountain caldera. Complicating the picture is the possibility that some of this structure, that within the Tram Member of the Crater Flat Tuff (Carr and others, 1984), occurs in a poorly exposed resurgent dome of the Prospector Pass segment of the Crater Flat-Prospector Pass caldera. The resurgent dome may lie within a portion of the caldera which is related to the Tram Member. Some of the northeast-striking faults, however, occur in rocks younger than the Tram.

Dips in the highly faulted Tertiary rocks shown on figure 26 are steep, averaging about 40°, and dips of 60°, 70° and even vertical are common; direction of tilt is consistently east or northeast. The structure is a complicated example of highly extended terrain in the "thin-skinned" manner described by Anderson (1971). The section of volcanic rocks is repeated more than 15 times along an east-west line from the northeast corner of Bare Mountain to Bullfrog Mountain (10 km or 6 mi west of Beatty), a distance of 20 km (12.5 mi). The repetition appears due to a combination of left-lateral oblique movement on northeast-striking faults with small separation, and north to north-northwest-striking faults with principally dip-slip movement. The latter faults are required in some areas, but are not well exposed. The Beatty fault (fig. 26) may be a Quaternary reactivation of one of this set.

The structural pattern of the area north of Bare Mountain differs somewhat from typical extensional terrain in the prominent oblique relationship between the faults and the strike of the volcanic rocks, an angle that is 30°-40° in many places. My interpretation is that the rocks were first broken into blocks that were moderately to steeply tilted east to northeast by northerly-striking faults, probably listric faults, and then cut by numerous northeast-striking relatively high-angle faults whose sense of displacement was partly left-lateral. Displacement on both fault sets was apparently taken up by a component of left-lateral movement on the Fluorspar Canyon fault at the boundary of the block. Both sets of faults were active in a short period of time about 10-11 m.y. ago; one of the most prominent of the northeast-striking faults, the Montgomery-Shoshone fault (fig. 26) is overlapped by rhyolites and tuffs on Burton Mountain immediately northwest of Beatty. Dips in the post-basalt rocks average less than 30° , about half the average in the older volcanic rocks. Thus, much of the fault movement pre-dates the basalt (about 10.5 m.y. old), and the major northeast-trending Montgomery-Shoshone fault, shows no evidence of important displacement after about 10.5 m.y. ago.

The northeast trend of the entire structural zone toward a northeasterly alined lobe of the Timber Mountain-Oasis Valley caldera complex in Oasis Valley (fig. 26), and the close temporal association with the latter part of the major volcanism at Timber Mountain indicates a tie between the faulting and volcano-tectonic events. The magmatic and thermal crustal events likely facilitated rapid and dramatic extension in a west-northwest direction. (For discussion of this mechanism see Lachenbruch and Sass, 1978.)

Yucca Mountain-Crater Flat-Bare Mountain Block of Northerly Structural Trends

Across a wide area, principally between Fortymile Canyon on the east and Bare Mountain on the west, lies a northerly-trending series of high-angle normal faults, most of which are downthrown on the west and gently tilt and repeat the volcanic rock section eastward (Lipman and McKay, 1965). This structural style continues southward to the southern part of Yucca Mountain, but dips in that locality are slightly steeper (McKay and Sargent, 1970). To the north, a few of the faults continue into the Timber Mountain caldera, but displacements of the younger rocks in the caldera (Christiansen and Lipman, 1965) are small. Strike of the faults on Bare Mountain on the west and Shoshone Mountain on the east (fig. 21) are similar to those in the rest of the Yucca Mountain block, but the faults at Bare Mountain are mostly down on the east, have variable dips, and are exposed in pre-Tertiary rocks; those on Shoshone Mountain and north of Yucca Wash have a more northwesterly strike (about N. 20° W.) and show distinctly more offset of post-Paintbrush Tuff units than those in the Yucca Mountain-Crater Flat area. Major faults across Yucca Mountain tend to be spaced 2-3 km apart and have average vertical displacements of about 250 m (810 ft), rarely more than 450 m (1,480 ft). Stratal tilts across the fault blocks average about 15°, rarely exceed 25° over large areas, and in many places particularly on parts of north central Yucca Mountain, do not exceed 10°. Locally, however, extreme rotation of blocks occurs along some of the faults (Scott and others, 1983) where slices of welded tuff are dropped or dragged into the fault zones. Such zones are generally less than a hundred meters (330 ft) wide.

A left-stepping enechelon pattern of faults is apparent on the west side of Yucca Mountain near Crater Flat (fig. 29). Some, but not all, of these faults increase in displacement southward, such as the one bounding the proposed repository site on the west (fig. 30). Most of the faults end or die out northwestward near the margin of the Claim Canyon cauldron (fig. 29), which trends generally northwestward and is alined with Yucca Wash.

A very generalized east-west cross section of the system of faults under discussion is shown by Snyder and Carr (1982, fig. 12); the west end of their cross section is on Bare Mountain, the east end in Jackass Flats. Study of two new drill holes, UE-25p#1 and USW VH-2, located on the east side of Yucca Mountain and in the center of Crater Flat respectively, require some relatively minor modifications of parts of this section. On the basis of drill holes USW VH-1 and -2 (fig. 31), and aeromagnetic data (U.S. Geological Survey, 1979) it seems likely there is even less major faulting in central Crater Flat than shown by Snyder and Carr (1982). Furthermore, faults of the size and style described here do not occur on strike in bedrock exposures along the southwest side of Crater Flat (W C Swadley and W. J. Carr, USGS, written commun., 1984). The western part of the cross section of figure 31 is about 5 km (3 mi) south of the one shown by Snyder and Carr (1982), and crosses the northwestern part of the caldera collapse related to the Bullfrog Member of the Crater Flat Tuff (Carr and others, 1984). The two drill holes

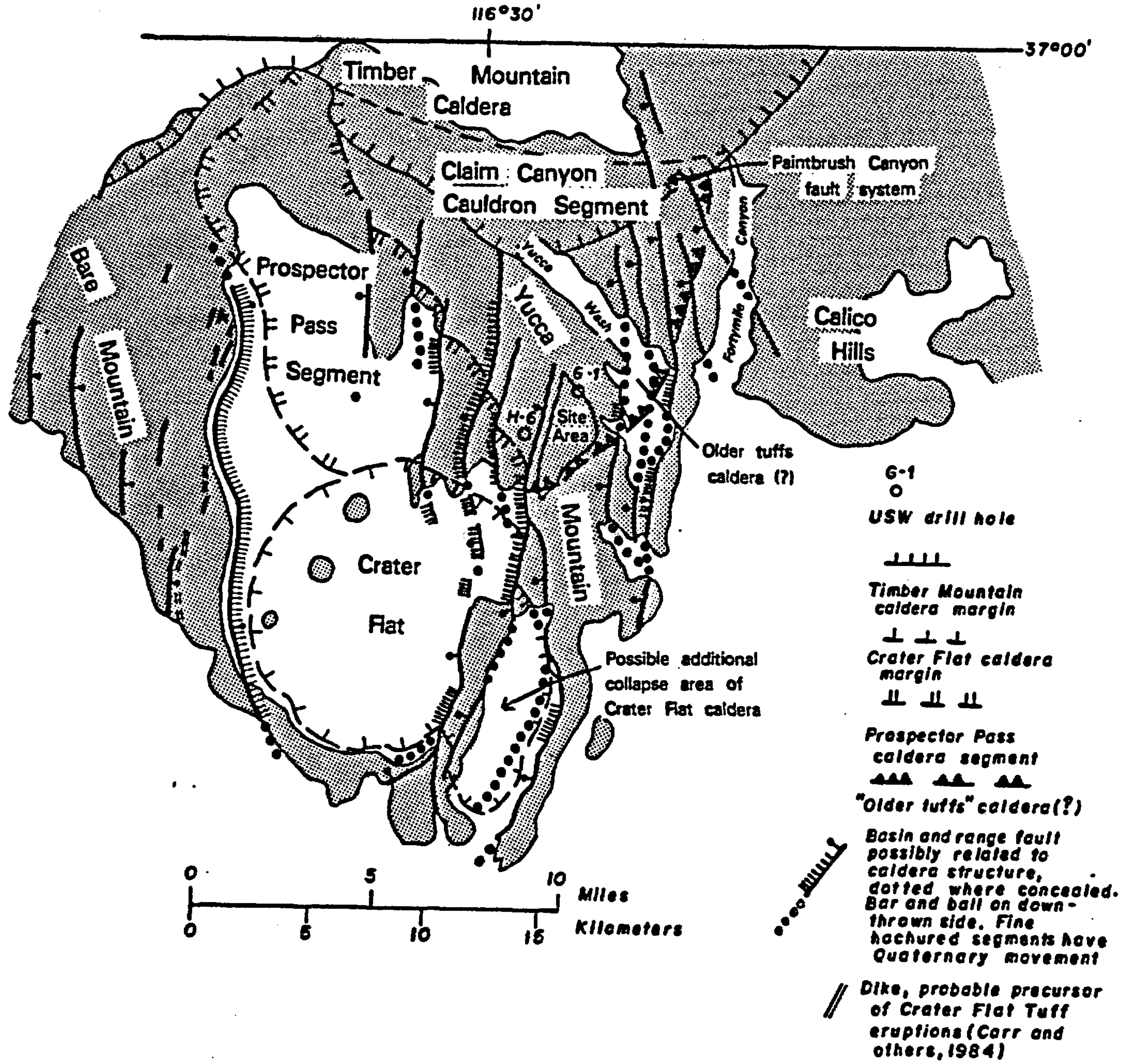


Figure 29.--Relationship between calderas and basin and range type faults, Yucca Mountain area. Stippled area is bedrock.

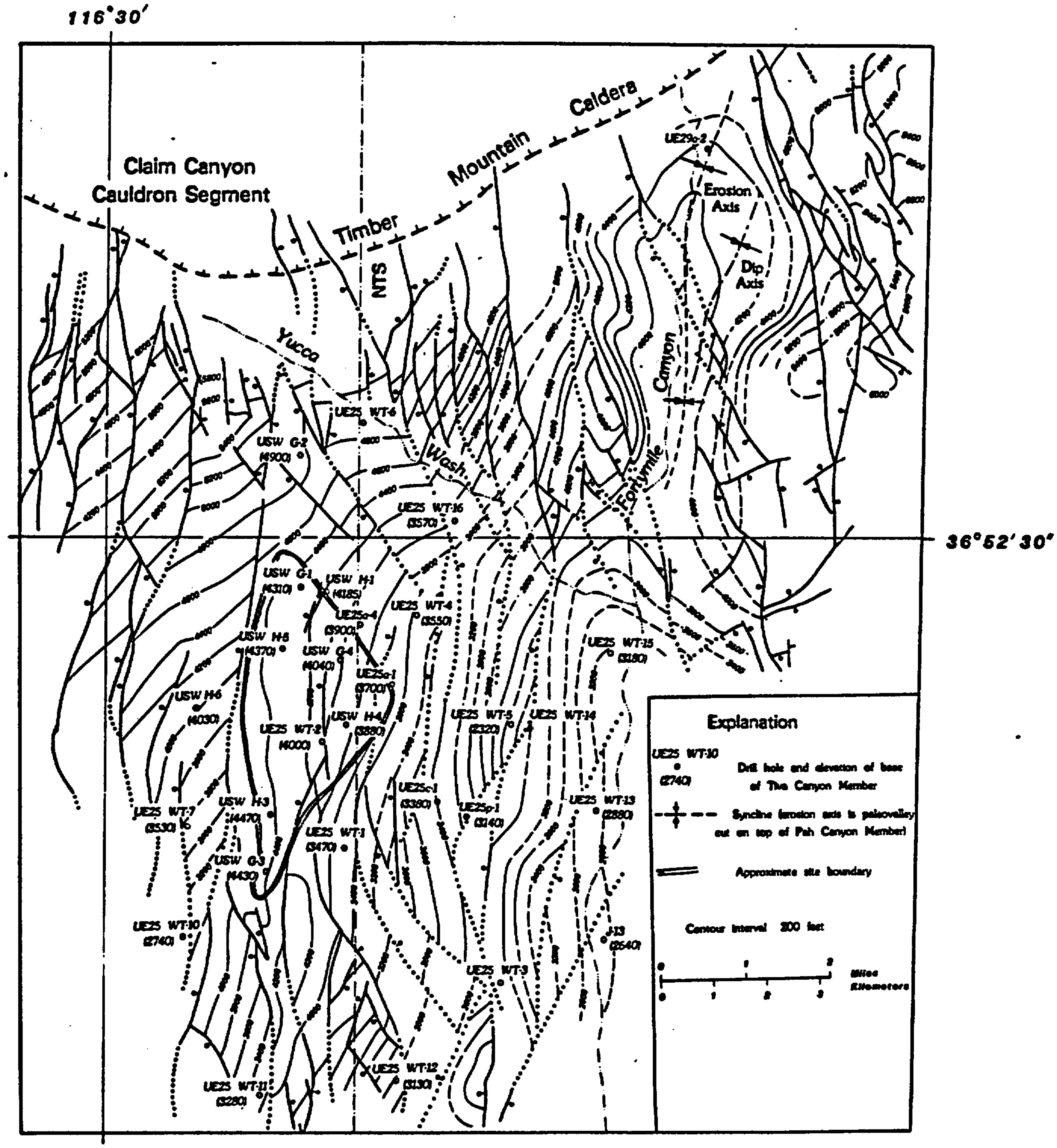
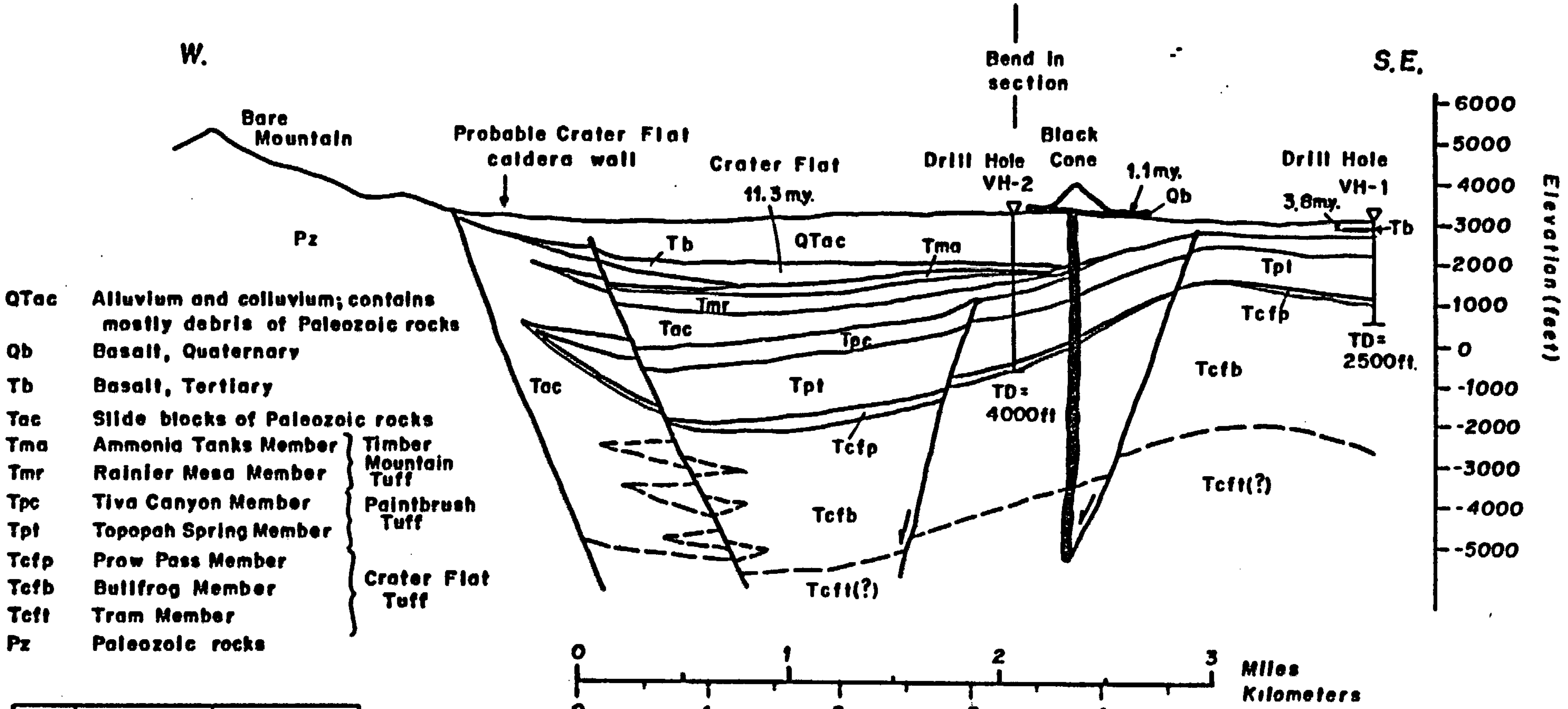


Figure 30.--Structure contour map of the Yucca Mountain-Fortymile Canyon area, drawn on the base of the Tiva Canyon Member (except in Fortymile Canyon area where the contours are on the top of the Pah Canyon Member; contours dashed where control is lacking).



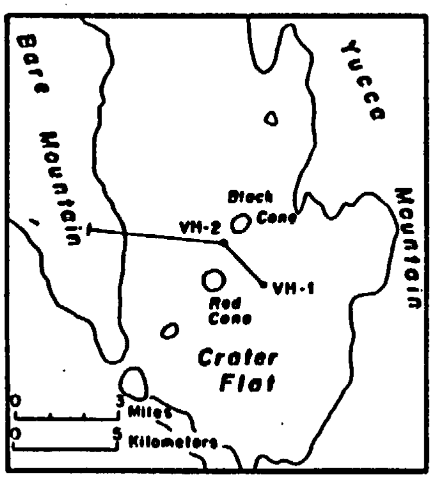


Figure 31.--Cross section of west-central Crater Flat between Bare Mountain and drill hole USW VH-1.

USW VH-1 and -2, together with outcrops, gravity (Snyder and Carr, 1982), and aeromagnetic data (U.S. Geological Survey, 1979) provide reasonably good constraints on the subsurface features in that area, down to a depth of a kilometer or so. No faults of consequence were penetrated in either hole, but in VH-2 much very coarse breccia of Paleozoic rocks was penetrated in the alluvium, and in the interval between the Paintbrush Tuff (Tiva Canyon Member) and Rainier Mesa Member of the Timber Mountain Tuff. The presence of breccia or slide blocks entirely composed of Paleozoic rocks between the Rainier Mesa Member and Paintbrush Tuff suggests that major activity on the east frontal faults of Bare Mountain occurred at the same time as it did on Yucca Mountain; i.e., between the emplacement of Tiva Canyon and Rainier Mesa Members. Furthermore, the stratigraphic section at VH-2 (fig. 31) shows that no deep basin and range type structural depression exists, at least in central Crater Flat; basalt about 11 m.y. old is only about 370 m (1,200 ft) below the surface, and basalt that is 1.2 m.y. old is at the surface. However, a few basin and range type faults of moderate spacing and displacement similar to those on Yucca Mountain may be concealed in Crater Flat.

Volcano-tectonic structures

Two and possibly three major caldera complexes are present in the vicinity of Yucca Mountain (fig. 9): the Crater Flat-Prospector Pass and Timber Mountain-Oasis Valley complexes, and possibly an older, deeply buried caldera related to tuffs older than the Crater Flat Tuff. The youngest, best exposed and understood of the complexes, Timber Mountain, has been described in detail (Byers and others, 1976b); Christiansen and others, 1977). The complex related to the Crater Flat Tuff has only recently been defined and described.(Carr, 1982; Carr and others, 1984); much remains unknown about this episode of volcanism, mainly because it is largely buried by younger volcanic rocks. A pre-Crater Flat Tuff caldera may exist beneath northern Yucca Mountain (Carr, 1982; Carr and others, 1984), but its exact location and history cannot be determined without deep drill holes.

Volcano-tectonic subsidence of the entire area west and north of Yucca Mountain is virtually required by the very thick volcanic section in the Crater Flat, northwestern Yucca Mountain, and the Beatty Wash-Timber Mountain area; the depths to subvolcanic rocks in much of that area are indicated by gravity measurements to be in excess of 3 km (10,000 ft) (Snyder and Carr, 1982). As mentioned earlier, geophysical data and two relatively shallow drill holes in Crater Flat (fig. 31) indicate (Carr, 1982; Carr and others, 1984) that the basin and the negative gravity are largely the result of caldera collapse associated with the Crater Flat Tuff members; the caldera has been modified somewhat, mostly by post-Paintbrush Tuff basin and range faults. Some of these faults, however, may have partially utilized and reactivated the caldera ring fracture faults where these were favorably oriented. This appears especially likely on the east side of Bare Mountain where the trace of the frontal fault zone is curvilinear or gently scalloped. The collapse of the Crater Flat caldera may have been trapdoor-like, with the west side downdropped more than the east. I suspect, but cannot prove, that the enechelon faults that form the western margin of Yucca Mountain facing Crater Flat, are reactivated portions of the eastern ring fracture faults (Carr and others, 1984, fig. 18); i.e., gently curving and scalloped north-trending caldera ring fracture zones may have responded to east-west crustal extension by collapsing in north-trending segments arranged in en echelon fashion (fig. 29). The segments of greatest vertical displacement correspond to the Crater Flat caldera ring fracture segments. The closest deep drill hole to the caldera structure is USW H-6 (Craig and others, 1983) on the west side of Yucca Mountain. This hole penetrated a relatively thin section of Crater Flat Tuff resting on about 250 m (810 ft) of dacitic lavas (Craig and others, 1983). These rocks of intermediate composition are present, but thinner, in several other drill holes on Yucca Mountain to the northeast of H-6 (Carr and others, 1984, fig. 4), and at several other locations centered around Crater Flat, where they occur beneath both the Tram Member and Lithic Ridge Tuff. Both the Tram and Lithic Ridge contain abundant lithic fragments of these lavas. Thus, it is likely that the lavas formed an extensive pile beneath Crater Flat prior to eruption of the Crater Flat Tuff. Carr, Byers, and Orkild (1984, p. 39) also suggested that a series of small 10 m.y. old basalt dikes on Yucca Mountain could mark the general position of the outer ring fracture zone of the complex. These interpretations, together with much more suggestive evidence, indicate a caldera related to the Crater Flat Tuff lies immediately west of Yucca Mountain, but its exact location and dimensions are not well known. That such a caldera is not present in the site area on Yucca Mountain is shown by the absence of abrupt thickening of the members in the area, their generally weak to moderate welding, and the lack of slide blocks or debris in the tuffs that might indicate the proximity of a caldera wall.

A possible additional collapsed or sagged area of the Crater Flat-Prospector Pass caldera complex is suggested (fig. 29) for southwestern Yucca Mountain. The postulated collapse area is adjacent to that indicated by earlier reports on the Crater Flat caldera (Carr, 1982; Carr and others, 1984). Briefly, the evidence, which is not conclusive, consists of the following: (1) aeromagnetic maps (Kane and Bracken, 1983) indicate a sizeable (2-3 km or 1.2-1.9 mi across) negative anomaly is present similar to the one to the west in the southern part of the Crater Flat caldera; (2) The anomaly is matched in general by a structural low containing Ammonia Tanks Member of the Timber Mountain Tuff, but as the Ammonia Tanks has normal magnetic polarity (Bath, 1968) thick underlying units must be the cause of the negative anomaly, namely the Rainier Mesa and Tiva Canyon Members, which produce strong anomalies and have reverse polarities (Bath, 1968; Bath and Jahren, 1984); (3) the presence of features suggesting nearby collapse, such as welded tuff breccia (Carr and others, 1984) in the adjoining section of Crater Flat Tuff; and (4) presence of the young Big Dune basalt cinder cone at the south end of Yucca Mountain, which could indicate proximity to deeply penetrating caldera ring fractures.

The question of whether an older caldera is present beneath northern Yucca Mountain is difficult to answer. More than 744 m (2,400 ft) of lava and tuffs underlie the Tram Member in drill hole USW G-1 (fig. 29) (Spengler and others, 1981). Gravity studies indicate more than 3,300 m (10,000 ft) of tuffs underlie Crater Flat and part of Yucca Mountain (Snyder and Carr, 1982, p. 31 and fig. 10), which places the base of the volcanic rocks at least 1.8 km (6,000 ft) below sea level. Therefore, it is evident that some sort of pre-Crater Flat Tuff volcano-tectonic subsidence took place at Yucca Mountain. Carr, Byers, and Orkild (1984, p. 40 and fig. 7) suggested that the Paintbrush Canyon fault and others in that group may mark the eastern edge of a pre-Crater Flat caldera or large tectonic sag beneath northern Yucca Mountain (fig. 29). These faults coincide in general location with the northeastern edge of a lobe of the deep gravity low under Yucca Mountain and Crater Flat (Snyder and Carr, 1982, pl. 1). In this concept, the Paintbrush Canyon fault system on the east edge of the older possible caldera would be analogous to the faults on the west side of Yucca Mountain previously suggested to be partially reactivated segments of the caldera ring fracture zone of the Crater Flat-Prospector Pass complex.

Buried caldera structures in the vicinity of Yucca Mountain assume additional importance when it is noted that several faults on both west and east sides of Yucca Mountain have Quaternary movement (Swadley and others, USGS, written commun., 1984; Swadley and Hoover, 1983). There appears to be a good relationship (fig. 29) between the location of fault segments that have been active in the Quaternary and the proposed location of the caldera margins or ring fracture zones, based on the fault pattern, basalt distribution, gravity, and aeromagnetic maps (Snyder and Carr, 1982; Carr, 1982). Some of the fault scarps are in alluvium, as shown on figure 29, but others occur at the contact between bedrock and alluvium. In nearly all cases, the segments of the faults showing Quaternary movement are near or within inferred caldera margins. In addition, at least some of the Quaternary fault movement can be directly related to basaltic volcanism in Crater Flat, where trenching has documented (Swadley and Hoover, 1983; Swadley and others, USGS, written commun., 1984) the synchroneity of basalt eruption and fault movement by the presence of Quaternary basalt ash in Quaternary fault zones.

Some reinterpretation of earlier ideas about the relationships between volcanic and structural movements seems required by the new surface and subsurface information. Cummings (1968) ascribed the termination of most of the basin and range faults at the Timber Mountain caldera ring fracture zone to the inability of the somewhat decoupled and highly fractured caldera substructure to propagate the faults. Christiansen, Lipman, Orkild and Byers (1965) felt the termination was due to vertical displacement on the basin and range faults being taken up by the caldera ring fracture zone. They also proposed that the basin and range faults were related to broad doming and an associated hingeline that developed preceding Timber Mountain Tuff eruptions and caldera collapse.

First, it has been demonstrated that rocks on the rim of Timber Mountain caldera northwest of Yucca Wash are part of a resurged block of the Claim Canyon cauldron (fig. 29), the probable source of the Tiva Canyon Member of the Paintbrush Tuff (Byers and others, 1976b). The resurgent block was eccentric to the caldera, and uplift occurred along the southern wall, the previously formed caldera outer ring fracture zone. Therefore, most of the circumferential faults of Christiansen and others (1965, fig. 2) are part of the complex resurgent dome structure. The hingeline, as earlier proposed (Christiansen and others, 1965), is not a simple arcuate feature related to doming preceding eruption of the Timber Mountain Tuff, but a more irregular and less continuous boundary that trends northwesterly across Yucca Mountain. Structure contours (fig. 30) suggest that the easterly dips are related to the basin and range faults, as stated (Christiansen and others, 1965), but the southeasterly dips in the Paintbrush Tuff in the northeast part of the Yucca Mountain area are probably a combination of initial dip with perhaps a little tilting related to resurgence of the Claim Canyon block. This conclusion is based on the general slope of the Paintbrush Tuff units away from their resurged source area in a direction that is about 45° to the northerly striking faults in northern Yucca Mountain. The degree of unconformity between the Rainier Mesa Member and underlying units, and the age of latest significant faulting tends to increase in a clockwise arc from east to west, from the southern Shoshone Mountain area (fig. 30) across Yucca Mountain to the north end of Crater Flat. On Shoshone Mountain fault displacements in the Rainier Mesa are commonly nearly as great as those in underlying units (Orkild and O'Connor, 1970); on most of northern Yucca Mountain the Rainier Mesa is absent, but to the south and west it is present at several locations where it was clearly deposited at the foot of already existing fault scarps (fig. 32) and later displaced a minor amount on the north-striking faults. In the northwestern part of Yucca Mountain, the Rainier Mesa and precursor lava flows were deposited unconformably across the tilted blocks of Paintbrush Tuff and older rocks (Byers and others, 1976a), resting on units as old as the Tram Member of the Crater Flat Tuff in the Beatty Wash area northwest of Timber Mountain (Carr and others, 1984). In the area north of Yucca Wash, no Rainier Mesa is present, but the rhyolite lavas of Fortymile Canyon, whose age is bracketed at about 9.5 m.y., are locally sharply unconformable on the Paintbrush Tuff. The lavas are in turn faulted a moderate amount. The zone of faults striking N. 15°-20° W. (fig. 30) between Shoshone Mountain and the northeast edge of Yucca Mountain is spatially and temporally associated with the area of the youngest voluminous volcanic eruptions, the lavas of Fortymile Canyon, Dome Mountain, and Shoshone Mountain. In addition, Fortymile Canyon, in the middle of this zone, is near the axis of a structural low (fig. 30) developed after emplacement of the Timber Mountain Tuff. All Paintbrush and Timber Mountain Tuff Members, except the Pah Canyon Member, thin drastically or are absent in the Fortymile Canyon area, yet the canyon is now the site of a sharp erosional and structural syncline (fig. 30). The location of the canyon is controlled, not by faulting, but by drainage and erosion that was localized along the axes of the syncline.

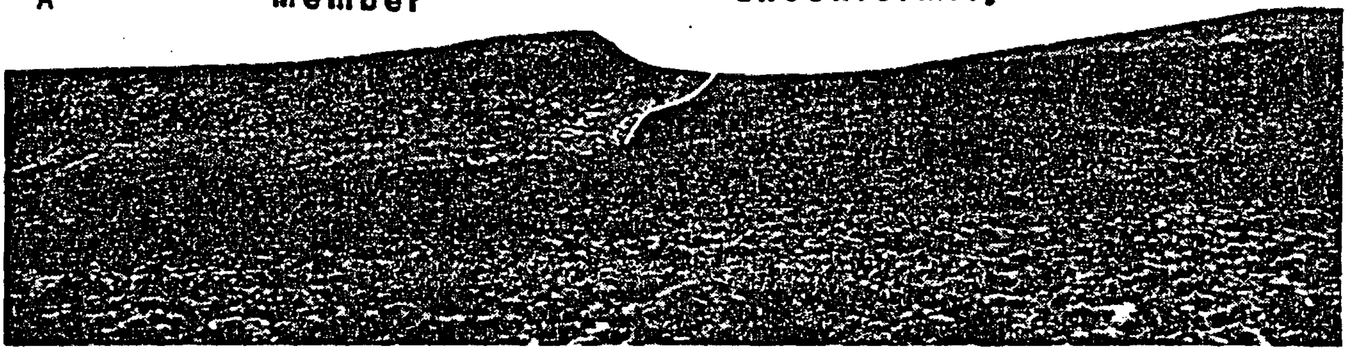
In summary, the history of Miocene tectonic activity in the Yucca Mountain area is complex, but decipherable, and it is clear that structural development of most of a large block exemplified by Yucca Mountain was directly related to volcano-tectonic processes including doming, sector graben or linear sags, and caldera collapse, but the mechanisms are perhaps not as simple or as well understood as earlier reports suggest. Clearly, the youngest significant tectonic adjustments occurred in the area of the youngest volcanic eruptions. Finally, in the author's view, portions of the basin and range style faults on and near Yucca Mountain are reactivations of parts of the older caldera structures.

Northwest-striking Structures and Lineaments

Location of Yucca Mountain within the Walker Lane belt, and its position in line with projection of the Las Vegas Valley and La Madre shear zones (fig. 27) lends special importance to structures of northwest trend. Nevertheless, in the Yucca Mountain area, northwest-striking faults and lineaments are the least developed major structure.

Structural features on figure 27 are generalized from geologic quadrangle maps and aeromagnetic maps (U.S. Geological Survey, 1978 and 1979), and include all features whose strike lies between N. 30° W. and N. 60° W. A few of the structures, such as the Yucca-Frenchman shear zone (Carr, 1974) and

A



B

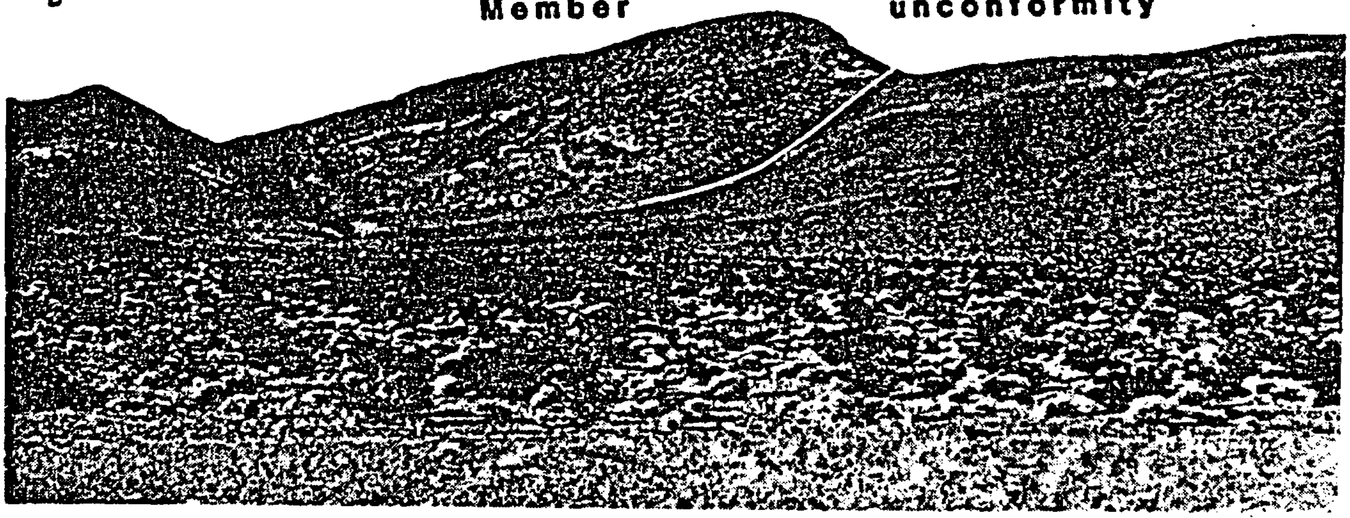


Figure 32.--Onlap of Rainier Mesa Member on structural blocks of Paintbrush Tuff near Dune Wash (A), and at the south end of Yucca Mountain near U.S. Highway 95 (B).

faults near Yucca Wash (R. B. Scott, USGS, oral commun., 1983) have been shown to have had a component of right-lateral slip. In the present regional stress field, with west-northwest oriented minimum principal stress (Carr, 1974; Zoback and Zoback, 1980) these faults should generally be under compression and should not be active. This is supported by a virtual absence of seismicity on northwest-striking faults (Rogers and others, 1983) and a lack of Quaternary fault scarps of northwest trend in the Yucca Mountain area.

At Yucca Mountain, several washes and canyons, including Yucca, Drill Hole, and Dune Washes (fig. 27) trend northwest. Faults parallel or subparallel to several of these have been mapped (Scott and Bonk, 1984); Christiansen and Lipman, 1965; Lipman and McKay, 1965). The most prominent topographic feature, Yucca Wash, has no important exposed northwest-striking faults, and none of consequence are required between Paintbrush Tuff exposures on both sides of the wash (fig. 30). Nevertheless, an aeromagnetic lineament (U.S. Geological Survey, 1979) and alinement of the Claim Canyon cauldron wall (fig. 29) suggest the presence of a pre-Paintbrush Tuff structural boundary that probably influenced distribution of older tuffs and lavas.

Several faults of northwest trend have been mapped (Christiansen and Lipman, 1965; Scott and Bonk, 1984). Some of these faults were penetrated in drill hole USW G-2 (Maldonado and Koether, 1983) where their dips were about 55^{o}-70^{o}; total vertical displacement on the faults is probably less than 50 m (165 ft). Slickensides on associated fractures in the core indicate a component of lateral movement on many of the faults (Maldonado and Koether, 1983). Detailed surface mapping (Scott and others, 1983; Scott and Bonk, 1984) has documented a component of right-lateral displacement on northwest-striking faults at Yucca Mountain.

Other small faults of similar northwest strike occur between Yucca Wash and Drill Hole Wash (fig. 27), although the evidence for a significant fault in and parallel to Drill Hole Wash is not compelling; more likely the wash is the site of a wide northwest-striking fracture zone, because drill holes USW G-1 (Spengler and others, 1981) and USW H-1 (fig. 30; Rush and others, 1983) and geoelectric studies (Smith and Ross, 1982; Flanigan, 1981), together with good exposures along the sides of the canyon do not require an important fault, at least in the upper part of the wash. However, many small faults found in the drill holes showed components of lateral displacement (Spengler and others, 1979, 1981), but the strikes of the faults were variable and the general sense of movement could not be determined. Spengler and Rosenbaum (1980) concluded, from detailed study of core from holes in the wash, that a very small wrench fault or shear fractures occupy the wash. They felt, based on magnetic work on samples of the Topopah Spring Member, that rotation of blocks indicated a left-lateral component. Subsequent magnetic data obtained from the Topopah Spring Member revealed, however, that much variation in magnetic vectors exists in the Topopah Spring. Thus, the Topopah Spring cannot be relied upon for information about structural rotation (J. G. Rosenbaum, USGS, oral commun., 1984). Spengler and Rosenbaum (1980) pointed out, however, that exposures of the base of the Tiva Canyon Member in the upper parts of Drill Hole Wash indicate very little or no vertical displacement has occurred.

Another fault zone of northwest strike, also poorly exposed, is present in and near Dune Wash, which trends northwest from Busted Butte (Lipman and McKay, 1965; Scott and Bonk, 1984), but does not cross Yucca Mountain.

A few faults of northwest trend are mapped in the Shoshone Mountain area, but the only other important structures of this strike are the Yucca-Frenchman shear zone, topographic lineaments in Mercury Valley, and west and south of Bare Mountain (fig. 27). A possible buried fault of northwest trend in Mercury Valley, which may be an extension of the La Madre fault on the northwest side of the Spring Mountains, does not cut alluvium of probable Pliocene age. The faults shown along the west side of Bare Mountain are based largely on the topographic trend and the termination of east-west strikes in the Paleozoic rocks on Bare Mountain.

Structural-Volcanic Rifts

Several linear, north-northeast-striking structural features that are associated with basaltic volcanism are present in Crater Flat, southern Yucca Mountain, and the Lathrop Wells area (fig. 28). Though not well expressed topographically, the structures have some characteristics in common with rifts, and are therefore referred to as such in this report.

Gravity (Snyder and Carr, 1982; Healey and others, 1980b) and aeromagnetic maps (U.S. Geological Survey, 1978 and 1979) indicate the presence of a buried but geophysically prominent structural trough that extends northward from the northwest end of Ash Meadows to Lathrop Wells (fig. 28), and thence north-northeastward to southern Jackass Flats, a distance of about 30 km (19 mi). Topopah Wash follows the eastern edge of the feature quite closely. The east edge of the graben is linear and well defined geophysically; the west edge is identifiable from the magnetic and gravity gradients, but is more diffuse and embayed. About 1.5 km (approx. 1 mi) south of Lathrop Wells is a striking negative aeromagnetic anomaly (fig 28 and U.S. Geological Survey, 1978) that is roughly circular and about 1.5 km (approx. 1 mi) across. I attribute the anomaly to a shallowly buried, reversely magnetized basalt center similar to those exposed in the Crater Flat area. The basalts in Crater Flat are at or very near the surface; the basalt at Lathrop Wells may be less than 30 m (100 ft) below the surface (G. D. Bath, USGS, oral commun., 1981). As the basalt at Lathrop Wells is buried by Quaternary alluvium and is reversely magnetized, it is almost certainly older than 730,000 yr, the end of the last major magnetic reversal. The lack of surface expression of both the basalt and the rift or graben in which it lies also suggests that the basalt is relatively old and could belong to either the Matuyama reversed polarity period, which began about 2.47 m.y. ago, or the Gilbert, which ended about 3.4 m.y. ago. It seems reasonable, therefore, to assign the buried basalt at Lathrop Wells to either the 1.2 m.y. or 3.8. m.y.-old basalt eruptive cycles because of the general contemporaneity of many basalts in this region (Crowe and Carr, 1980).

In general, the Lathrop Wells rift is flanked on the east by Paleozoic rocks that are exposed in the Striped Hills, Skeleton Hills, and several other scattered locations . Paleozoic rocks are not exposed on the west side, but are at depths less than 1,220 m (4,000 ft) in the Busted Butte area (Snyder and Carr, 1982), which is part of an elongate, subdued gravity high on the west side of the rift. Depth to pre-Tertiary rocks was estimated by Snyder and Carr (1982; fig. 8) to be about 1,300 m (4,260 ft) at a point 3 km (2 mi) north of Lathrop Wells. They assumed about 200 m (650 ft) of alluvium is present at that location. The gravity gradient along the east side of the rift can be reasonably attributed to a parallel fault or fault zone that has a throw of at least 1,000 m (3,280 ft). Although no faults or lineaments are visible in the alluvium, nearly all the area is covered by Holocene sand sheets (Swadley, 1983) that could obscure small Quaternary fault scarps. The area has persisted into the Quaternary as a subtle structural low, however, as shown by the general parallelism of modern Fortymile and Topopah Washes with the edges of the rift. The fact that Fortymile Wash has maintained a parallel, but entirely separate course from Topopah Wash mostly outside the rift suggests, however, that this structure is no longer tectonically active. On the other hand, R. L. Hay and R. Pexton (USGS, written commun., 1984) report that some minor (1-2 m or 3-6.5 ft displacement) faulting has occurred in late Pliocence lake beds in the Ash Meadows area near the southern end of the rift (fig. 27).

In contrast to gravity, aeromagnetic gradients (Kane and Bracken, 1983) are about equally well defined on both sides of the rift. The positive aeromagnetic anomaly is not as easily explained as the gravity, however. I believe the best explanation is that the aeromagnetic anomaly defines a paleovalley of Topopah Wash filled with fine volcanic debris and magnetic sand washed out of the Calico Hills area. This reworking process probably concentrated magnetic particles along the flatter, lower reaches of the drainage. The present course of Fortymile Wash, which lies west of, but parallel to the west side of the anomaly, and is incised 15-25 m (50-80 ft) into Pleistocene alluvium, is believed by D. L. Hoover (USGS, oral commun., 1984) to have been established about 300,000 yr ago, probably as a result of capture of the Timber Mountain caldera drainage by headward erosion of Fortymile Canyon.

Two other possible rift structures striking slightly more northeasterly (about N. 35° E.) are present in Crater Flat and across the southern Yucca Mountain area (fig. 28). The one in Crater Flat is a curvilinear alinement of four basalts whose age is about 1.2 m.y. (Crowe and Carr, 1980); the other is marked by the previously mentioned magnetic lineament that extends northeastward from the 0.3 m.y.-old Big Dune basalt center[6] (11 km or 7 mi northwest of Lathrop Wells) to just east of Busted Butte. The magnetic lineament appears to be produced by a combination of downfaulted, reversely magnetized Tiva Canyon Member, and onlapping Rainier Mesa Member.

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[6]This basalt center was originally called the Lathrop Wells cone (Crowe and Carr, 1980, fig. 1), but is here called the Big Dune basalt center to distinguish it from the probable buried basalt at Lathrop Wells.

In general these rift-like structures are distributed across the large regional gravity trough in the Paleozoic surface that has previously been discussed. The northeast trend of the structures along which the basalts reached the surface, however, is consistent with a N. 50°-60° W. minimum principal stress direction proposed for this region (Carr, 1974) in about the last 5-7 m.y. Localization of the basalts in Crater Flat and northwest of Lathrop Wells may also have been influenced by the presence of ring fractures of the Crater Flat caldera, but the buried basalt at Lathrop Wells is not on a known or suspected caldera structure.

RATE OF TECTONIC ACTIVITY IN THE YUCCA MOUNTAIN REGION

Determination of the tectonic flux in the NTS part of the southwestern Great Basin during the last 10 m.y. is important to assure safe nuclear waste storage. The future stability of Yucca Mountain must be predicted largely from the geologic record--a record with very few data points and even fewer precisely dated events in the Pliocene and Quaternary. The general rate of volcanic activity can be determined, and numerical estimates of the rate of movement of certain faults are possible, and several such estimates will be presented here. The present amounts of heat flow and seismic energy release previously discussed can be theoretically determined, but, except for brief notes, are beyond the scope of this report.

The following discussion attempts to summarize the present state of knowledge with respect to the timing and rate of late Cenozoic tectonic events in the Yucca Mountain region.

Volcanism

In the region within about 100 km (62 mi) of Yucca Mountain, volcanic eruptions began about 26 m.y. ago. The earliest activity was in the northern part of the region, although some earlier ash-flow tuffs found in that area probably had their sources farther north or northeast. The earliest widespread volcanism to occur within 100 km (62 mi) of Yucca Mountain consisted of lava flows of intermediate composition erupted across much of the northern part of the region (Ekren and others, 1971, table 5 and pl. 1) about 17-18 m.y. ago. The first major silicic eruptions known to have had their source within the region, produced the Fraction Tuff, and occurred about 16 m.y. ago in the Kawich Range about 90 km (56 mi) north of Yucca Mountain (Ekren and others, 1971, table 5). Figure 25 shows graphically the record of volcanism from 16 m.y. ago. Nearly all of the major volcanic eruptions in the region are plotted, although some bodies, particularly lavas, may be unknown because of burial by later deposits. In general, the younger the units on the diagram, the more accurate the record, although the ages throughout the period are well controlled by many K-Ar dates and detailed stratigraphy (see Marvin and others, 1970; Crowe and others, 1983). The rate of silicic volcanism reached a peak about 13-14 m.y. ago, and the last silicic eruptions occurred more than 5 m.y. ago. More significant perhaps, is that the longest detected period without silicic volcanism prior to 5 m.y. ago was about 1 m.y. Bimodal volcanism began about 12.5 m.y. ago in the Yucca Mountain region, but basalts were insignificant in relation to rhyolites until near the close of activity at the Timber Mountain-Oasis Valley caldera complex about 10.5 m.y. ago. Except for a possible hiatus about 6-4.5 m.y. ago, basalt eruptions have continued at a fairly constant rate (fig. 25). The youngest volcanic activity in the region is basalt erupted at Sleeping Butte and the Big Dune center 11 km (7 mi) northwest of Lathrop Wells (Crowe and Carr, 1980) 250,000-300,000 yrs. ago.

Deformation Rates

For most of the region, including Yucca Mountain itself, major faulting ended by about 10 m.y. ago. At about that time, subvolcanic silicic bodies cooled, the crust probably became more brittle, perhaps allowing fractures to penetrate more deeply, permitting basalt magma to reach the surface in certain favorable environments. During the last 10 m.y., variation has occurred in the timing of the diminishing of activity and in the rate of younger tectonism of the region, however, so that areas like the Inyo-Mono subsection have continued to deform at a rate higher than that of much of the central Great Basin. One of the most widespread late Tertiary stratigraphic units of the region, the Timber Mountain Tuff (approx. 11.5 m.y. old), is a useful marker for determining the amount of faulting since that time. The amount of structural disturbance affecting the Ammonia Tanks and Rainier Mesa Members of the Timber Mountain Tuff is quite variable from place to place. For example, detailed mapping and drill-hole information in the Crater Flat-Yucca Mountain area show that the Timber Mountain Tuff was deposited largely on the low-standing side of existing north-striking basin and range style fault blocks (fig. 32) (Lipman and McKay, 1965; McKay and Sargent, 1970; W C Swadley and W. J. Carr, USGS, written commun., 1984); relatively minor displacement occurred on these faults after deposition of the Timber Mountain Tuff. On Bare Mountain, 13.9 m.y.-old dikes are little affected by major faults that offset the Paleozoic rocks 300 m (approx. 1,000 ft) or more. In many other areas of the region, however, the Timber Mountain Tuff is displaced nearly as much as underlying units. This is true for the Pahute Mesa area and active basins such as Yucca and Frenchman Flats, and for some northeast-trending structural zones, such as the Bonnie Claire-Gold Mountain area west of Sarcobatus Flat (D, fig. 3), where the Timber Mountain Tuff is highly faulted. Thus, in many areas much of the faulting occurred in a relatively short period of time immediately following emplacement of the Timber Mountain Tuff, but in other areas such as at Yucca Mountain and Crater Flat, the major fault movement occurred slightly earlier, immediately following emplacement of the youngest member of the Paintbrush Tuff about 12.9 m.y. ago.

Regional Comparison

A comparison can be made with respect to deformation rates for portions of the subsections of the southwestern Great Basin described earlier. Because dateable measurements of actual displacement on individual faults are rarely available in the late Cenozoic of the region, several of the examples (table 2) used here are based on a rate of subsidence or burial of dated beds in a structural basin. Areas listed (table 2) include Crater Flat and the Amargosa Desert valley, where rates of deformation during the last 1-3 m.y. range from less than 0.01 m per 1,000 yr, to the Coso Range area, California, where the rate is possibly as high as 1.8 m per 1,000 yr.

Yucca Mountain itself has a rate of deformation similar to that of the Amargosa Desert valley and Crater Flat, assuming that no more than 10 m of offset has occurred on faults in the last 2 m.y., a conservative assumption considering the distribution of alluvium and lack of prominent young scarps at

Table 2.--Approximate rates of relative vertical tectonic adjustment or burial at selected locations in the southwestern Great Basin during the late Neogene and Quaternary

Location	Rate, m/1000 yr (mm/yr)	Comment
S. Amargosa Desert valley[1]	[2]<0.01	Based on an ash bed in lake deposits about 5 m below the surface; "Ewing" clay pit, just north of Ash Meadows
Crater Flat, central	[2]<0.01	Basalt dated by K-Ar at 1.2 m.y. (Crowe and others, 1983) is at the present surface and has not been deformed or subsided into the basin
Crater Flat, eastern	[2]<0.01	Based on an offset in alluvium at trench 1 (allowing for 0.6 m of erosion) of 3.0 m in 1.1 m.y.[3] Swadley and Hoover, 1983
Crater Flat, southeastern	<0.02	Offset of alluvium in trench 3 in a minimum time of 40,000 yr. Actual time was probably closer to 260,000 yr (Swadley and Hoover, 1983)
Crater Flat, USW VH-2 drill hole	0.03	Burial of basalt about 11 m.y. old (R. F. Marvin. U.S. Geol. Survey, written commun., 1983)
Yucca Mountain	0.03	Based on maximum of 460 m of offset of Tiva Canyon Member in last 12.8 m.y. For the Quaternary, a very conservative estimate is <0.01 m/1000 yr, based on maximum credible amount of displacement (10 m) in Quaternary time. (see text)
N.W. Frenchman Flat[1]	0.06	Burial of ash bed at depth of 195 m in drill hole UE5n; not in most active part of the Frenchman Flat basin

Table 2.--Approximate rates of relative vertical tectonic adjustment or burial at locations in the southwestern Great Basin during the late Neogene and Quaternary--Continued

Location	Rate, m/1000 yrs (mm/yr)	Comment
S. Yucca Flat	0.16	Based amount of displacement of a basalt in drill holes UE1h and UE6d (fig. 11); basalt is 8.1 m.y. old from K-Ar date (R. F. Marvin, U.S. Geol. Survey, written commun., 1980)
Searles Valley[1]	0.22	Burial of ash bed in core at depth of 691 m
Death Valley-foot of of Black Mountains	0.3	Based on displacement of Artist's Drive Formation, which is 6-8 m.y. old according to Fleck (1970a). Estimated here to be about 1,525 m (5,000 ft) in 5 m.y.
Sierra Nevada-Owens Valley-White-Inyo Mountains	0.4	Average of 9 estimates (range 0.2-1.0 m/1000 yr) from various sources[4]. Quaternary rate is probably higher
Coso Range-Rose Valley	1.8	Offset of 2.5 m.y.- old lava flow (Roquemore, 1980; Healy and Press, 1964).

[1] Relative rate of subsidence or burial is based on an ash bed that occurs at these three locations, and is believed to correlate (Izett, 1981; Sarna-Wojcicki and others, 1980; R. L. Hay, written commun., 1979); the ash is dated at about 3 m.y. by paleomagnetic, stratigraphic, K-Ar and fission-track techniques (Liddicoat and Smith, 1979).

[2] Maximum rate; figures using additional decimal places are considered to imply unrealistic accuracy.

[3] The age of 1.1 m.y. assumes that basalt ash in the fault in this trench came from one of four centers in Crater Flat of this age (Crowe and others, 1983). Logic supports this conclusion (Swadley and others, U.S. Geological Survey, written commun., 1984), but does not rule out the possibility that the ash came from the 0.3 m.y.-old Big Dune Center. If the latter is the case, the rate becomes 0.01 m per 1,000 yr.

[4] Owens Valley--Bachman (1978); central Sierra Nevada--Curry (1971), and Huber (written commun., 1980); Mono Lake basin--Gilbert and others (1968).

Yucca Mountain. The rate and age of deformation at Yucca Mountain will be discussed in the next section of this report.

Several physiographic and geologic lines of evidence strongly suggest that the southwestern Great Basin has undergone a moderate southward or southeastward tilting after about 8 m.y. ago. Prior to that time, during the period 8-15 m.y. ago, when the majority of the volcanic activity occurred in the NTS region, ash-flow tuffs from centers located at Crater Flat, Timber Mountain, and Pahute Mesa were asymmetrically distributed, mainly to the north and west; all units pinched out abruptly southward, suggesting a regional northward or northwestward slope of the surface on which the volcanic rocks accumulated, or perhaps more likely, a topographic barrier trending eastward from the Funeral Mountains to the Spotted Range. In any case, the present situation is the reverse, one of regional southward drainage and lowering altitude (Eaton and others, 1978, p. 56) from a regional topographic high in central Nevada.

In addition to southward sloping of the region toward Death Valley and the Colorado River, there is a progressive south or southeastward decrease in altitude of the top of apparently continuous late Pliocene and Quaternary lake and playa deposits in Las Vegas Valley, Pahrump Valley, Amargosa Desert valley, and northern Death Valley. Data for the four valleys are summarized in table 3. In Las Vegas Valley the altitude of the upper limits of continuously outcropping playa or lake deposits decreases from about 1,100 m (3,600 ft) west of Indian Springs to about 730 m (2,400 ft) near Las Vegas, a distance of about 80 km (50 mi) in an east-southeast direction. This yields a slope of about 4.5 m per km (24 ft per mi). The age of the sloping fine-grained sediments in these valleys varies, and some playa deposits are obviously accumulating locally today at the southern ends of the valleys. Death Valley obviously is a special case with respect to the other valleys, because the large frontal faults at the foot of the Black Mountains are the dominating structure. An estimation of the time of regional tilting can be obtained from the age of the oldest lake beds, which is a little over 3 m.y., based on dated ash beds (table 2).

Perhaps significantly, most of the fine-grained sediments had been deposited by about 2.5 m.y. ago, shortly after establishment of the integrated through drainage of the Colorado River (Lucchitta, 1972), suggesting that regional tilting may have contributed to establishment of the Colorado and Amargosa River drainages, and the diminishing of lake bed and playa deposition by gentle tilting and drainage of the basins.

The general tendency for the present lowest spots or playas in this region to occur at the south ends of valleys is, in some cases, accompanied by evidence that, during the time of alluvium accumulation (approximately the last 10 m.y., based on drill-hole data from Crater, Yucca, and Frenchman Flats) the depocenters have shifted southeastward. This is particularly well displayed in Yucca (fig. 12) and Frenchman Flats, and by the unnamed playa located in the Amargosa Desert valley, 25 km (15.5 mi) southeast of Lathrop Wells, where the present playas are located several kilometers southeast of the minimum points of gravity lows (Healey and others, 1980a, b) caused by thick alluvium, suggesting that the tilting is continuing.

Table 3.--Change in elevation of the top of relatively continuous fine-grained sediments in some major valleys of the southwestern Great Basin

Valley	Maximum altitude of fine-grained sediment							
	Northern limit ft	m	Southern limit ft	m	Distance mi	km	Slope ft/mi	m/km
Las Vegas	3,600	1,100	2,400	73	50	80	24	4.5
Pahrump	3,000	915	2,500	760	30	48	17	3.2
Amargosa Desert	2,800	855	[1] 2,100	640	40	65	18	3.4
N. Death Valley	[2] 2,600	790	[3] 0	0	70	113	37	7.0

[1] Near Eagle Mountain, 10 km (6 mi) south of Death Valley Junction.

[2] Vicinity of Ubehebe Crater, northern Death Valley.

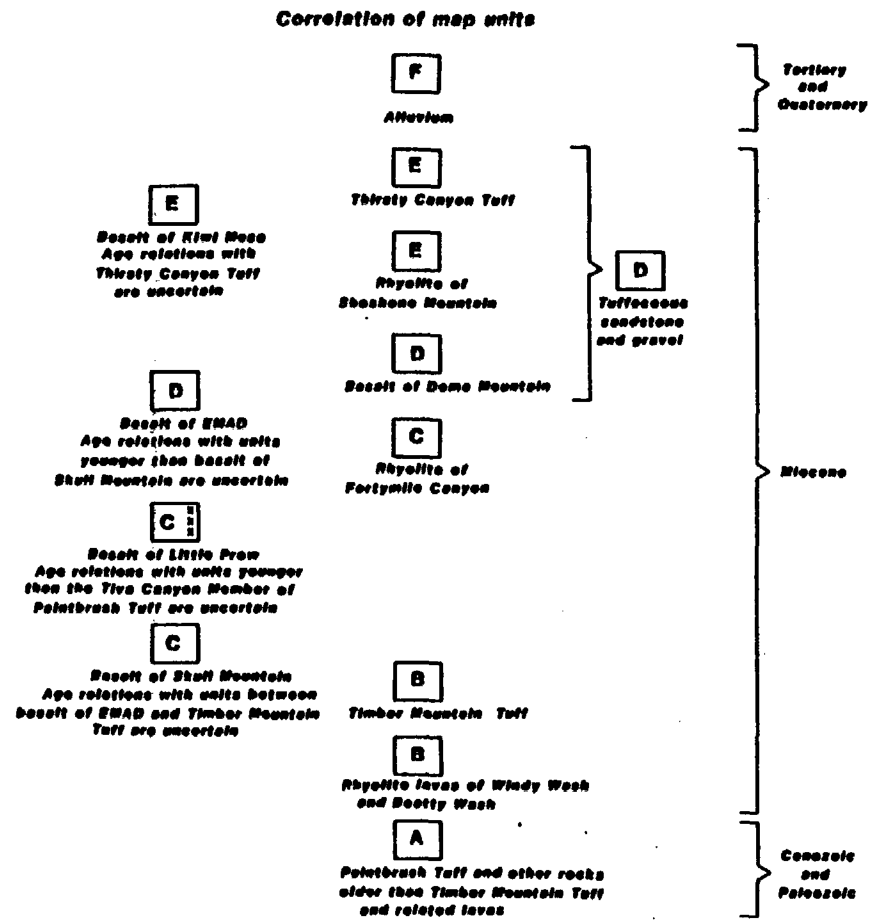
[3] Near Badwater, south-central Death Valley ; lowest point but not the southern limit.

In their synthesis of regional vertical crustal movements in the last 10 m.y., Gable and Hatton (1983, map D) show the NTS area within a broad zone that has deformed at a rate of 0.2-0.4 m/1000 yr, a rate that appears to be well in excess of local measurements discussed in this paper. In fact, a rate of 0.2-0.4 m/1000 yr is more like the rates reported (table 2) for the obviously active Inyo-Mono region of California, but for that area Gable and Hatton (1983, map D) show rates of 1 to more than 2 m/1,000 yr. Part of the discrepancy appears to be due to their use of the higher and possibly accelerating rates of vertical deformation along the Sierra Nevada front during the Quaternary; the rates for that region given in table 2 are generally for a greater period of time. Even if one accepts the lower rates of deformation for the Inyo-Mono region, it is apparent that rates in the NTS region have been less than one-half those in the California area. The higher, mostly Quaternary rates for the Inyo-Mono region are on the order of 10 times greater than those in the NTS and Yucca Mountain region. It should also be pointed out that map B of Gable and Hatton (1983) suggests that the central Great Basin, including most of the NTS region, has been subject to distinctly more vertical movement than nearly all of the Inyo-Mono region, including most of the Death Valley-Panamint-Owens Valley region. This is not a valid generalization, at least for the NTS region. Even using the greatest regional difference in elevation of the 11.6 m.y.-old Rainier Mesa Member in the NTS area, the maximum difference is only 1,830 m (6,000 ft) between Rainier Mesa (elev. 2,134 m or 7,000 ft) and the lowest structural point of the same unit (elev. 325 m or 1,000 ft) beneath southern Yucca Flat, one of the most active basins of the area. Furthermore, much of the 1,825 m (6,000 ft) difference in elevation, perhaps half, is due to a gradual depositional slope away from the rim of Timber Mountain caldera. Inspection of a representative geologic map (Byers and Barnes, 1967) on the east side of Yucca Flat shows the Rainier Mesa has a maximum altitude there of only about 1,675 m (5,500 ft), so the actual maximum amount of structural down-dropping beneath Yucca Flat is only about 1,350 m (4,500 ft), a rate of about 0.12 m/1,000 yr.

Faulting in the Yucca Mountain Area

Timing of faulting in parts of the Yucca Mountain area can be studied by means of maps of faults involving groups of successively younger units (figs. 33 and 34A-F) during the period after about 12 m.y. ago following deposition of the Paintbrush Tuff. Even though the distribution of younger rocks is not sufficient to show overlap of older structures for all time periods, several conclusions can be readily drawn from the information: (1) there has been a dramatic decrease in the frequency of new faulting and in the rate of displacement on new and preexisting faults during the last 12 m.y., particularly after 9.5 m.y. ago; (2) nearly all the faults cutting younger units are reactivations of preexisting faults; (3) faults and basalt dikes cutting rock group C (fig. 34C) (approximately 9.5 m.y. old and includes the rhyolite lavas of Fortymile Canyon) have a strong north-northwest trend, a direction of faulting not favored by the present stress field (Carr, 1974); this can be interpreted as a further indication that the change in extension direction believed to have occurred in this part of the Great Basin in the late Cenozoic (Zoback and Zoback, 1980) from nearly east-west to northwest-southeast occurred after about 9.5 m.y. ago. Minor movement on this fault set also affected rocks as young as unit E (fig. 34E), which includes the rhyolite of Shoshone Mountain, whose age is approximately 9.0 m.y. (fig. 33). The lavas of Shoshone Mountain vented mainly along a zone of dikes and plugs that

Rock group	Stratigraphic unit	Age of unit by isotopic methods m.y.[1]	Age of unit by stratigraphic relations m.y.
F	Alluvium		<8.0
E	Thirsty Canyon Tuff	8.0[2]	
	Basalt of Kiwi Mesa	9.7[3]	< 9.3
	Rhyolite of Shoshone Mountain	9.0[4] & 9.3[5]	
D	Basalt of Dome Mountain		8.8-9.3
	Basalt of EMAD[6]	8.8	
C	Rhyolite of Fortymile Canyon		10.0-9.3
	Basalt dike, Little Prow	10.0	
	Basalt of Skull Mountain	10.2	
B	Timber Mountain Tuff — Ammonia Tanks Member	11.4	
	Timber Mountain Tuff — Rainier Mesa Member	11.6	
	Rhyolite lavas of Windy Wash and Beatty Wash	11.6	
A	Pre-Timber Mountain Tuff rocks		>11.6



[1]Ages reported prior to 1979 (Marvin and others, 1970; Kistler, 1968) have been converted to new constants (Dalrymple, 1979)

[2]Unit mapped is probably the Spearhead Member (Christiansen and Lipman, 1965), but date given is a rerun of anorthoclase from a sample of the underlying Rocket Wash Member which previously gave an age of 7.5 m.y. (Marvin and others, 1970). The 8.0 m.y. age is considered here to be a good approximate age for the Thirsty Canyon Tuff, based on other stratigraphic information.

[3]Date does not agree with stratigraphic position above rhyolite of Shoshone Mountain; thus, date is too old.

[4]Fission track on zircon from small plug in Calico Hills (C. W. Naeser, written commun., 1980)

[5]Whole rock date on vitrophyre base of rhyolite of Shoshone Mountain (R. F. Marvin, written commun., 1980)

[6]Basalt in Jackass Flats and Little Skull Mountain area mapped (McKay and Williams, 1964; Sargent and others, 1970) previously as basalt of Kiwi Mesa and Skull Mountain.

Figure 33.--Explanation of age control for units on figures 34A-F.

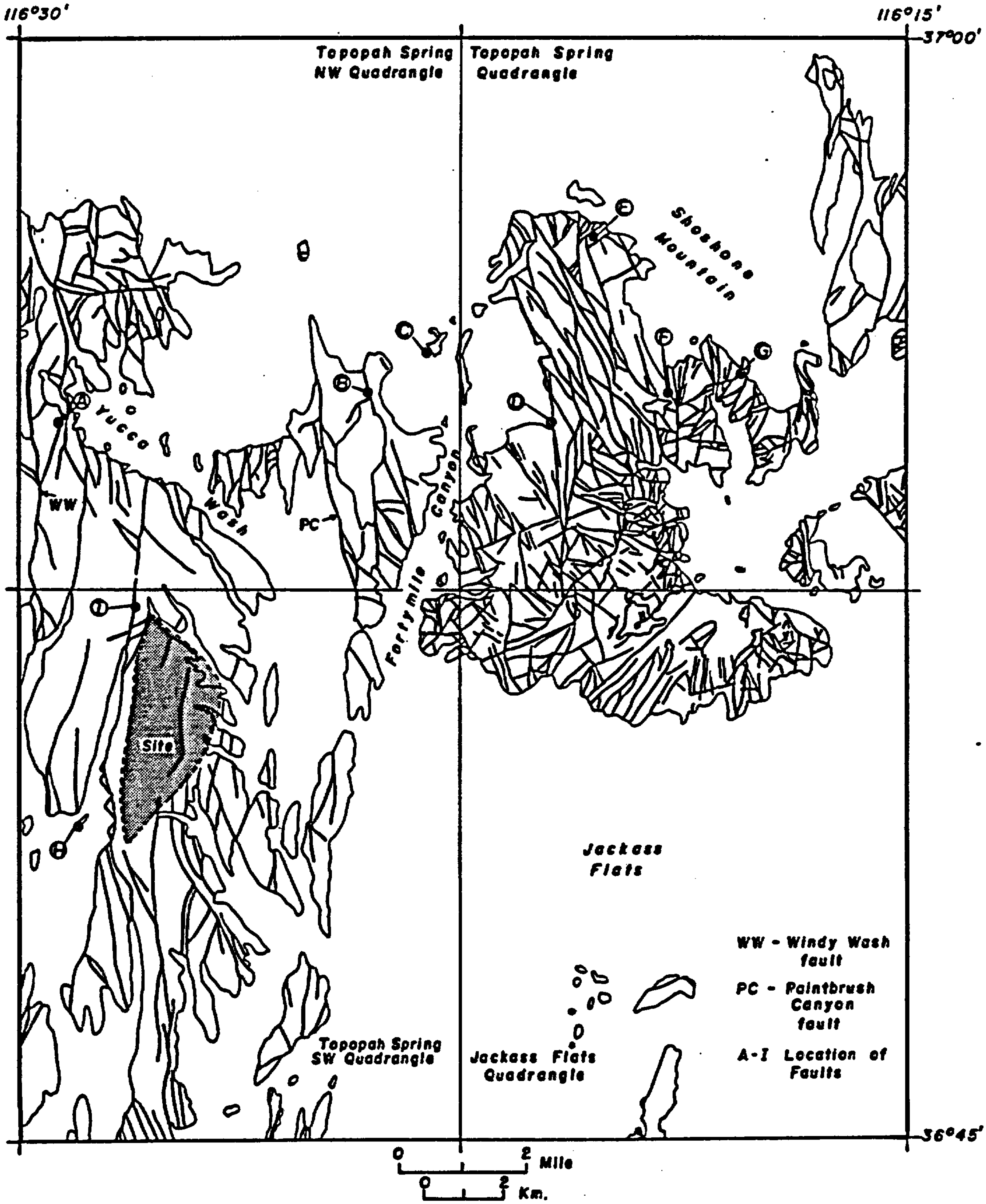


Figure 34A.--Distribution and faulting of group A, rocks older than 11.6 m.y.

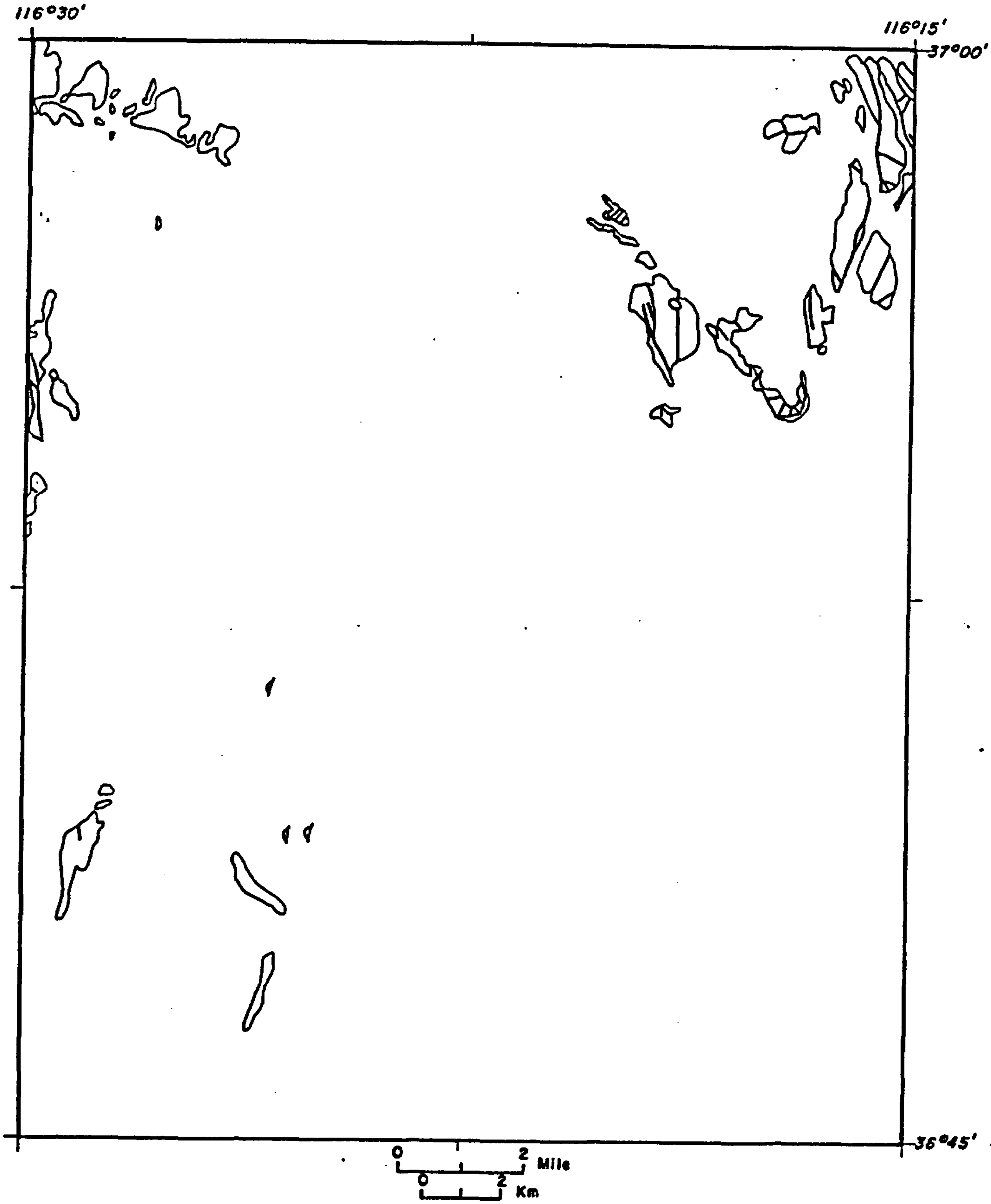


Figure 34B.--Distribution and faulting of group B, rocks 11.6-10.2 m.y. old.

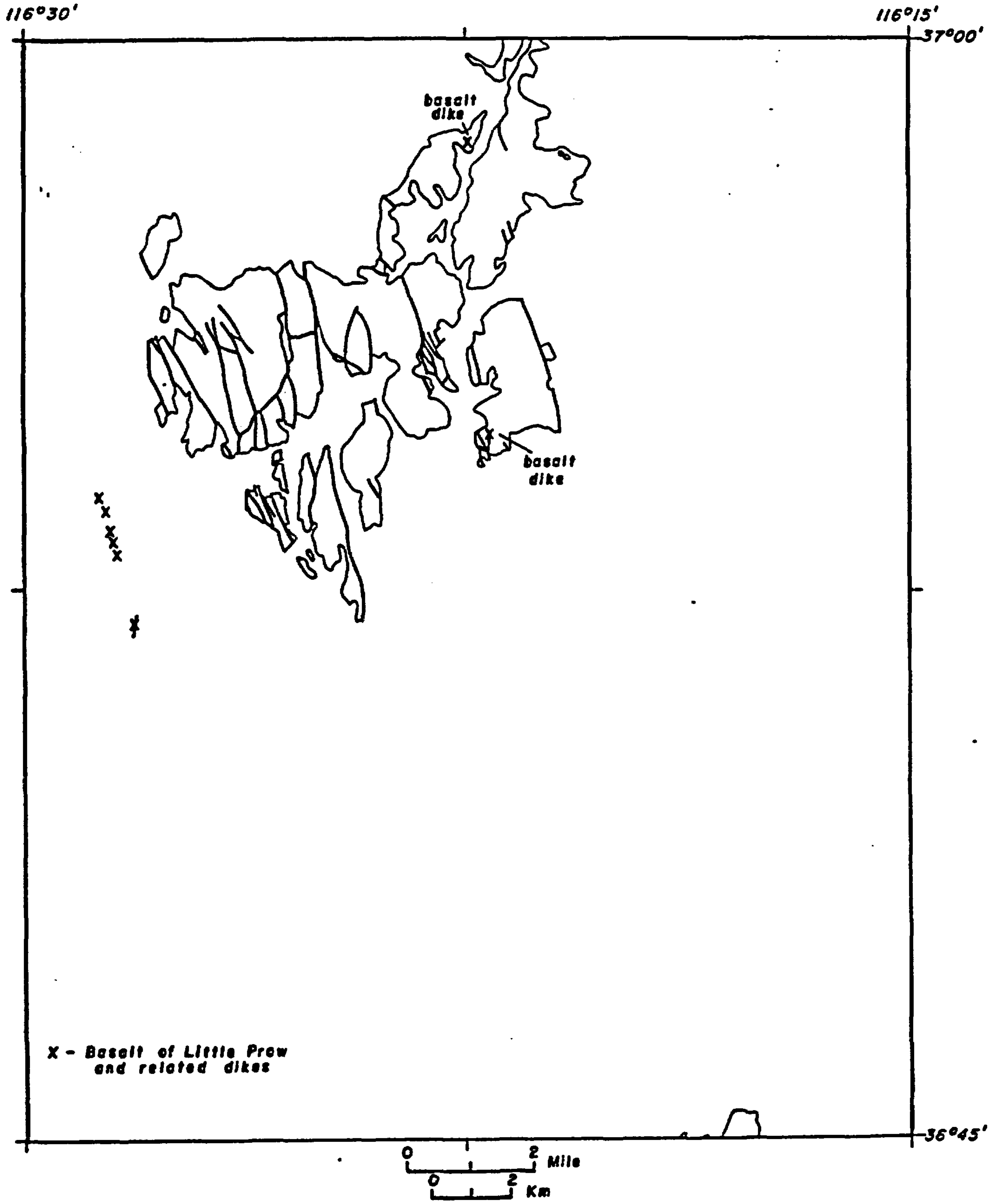


Figure 34C.--Distribution and faulting of group C, rocks 10.2-10.0 m.y. old.

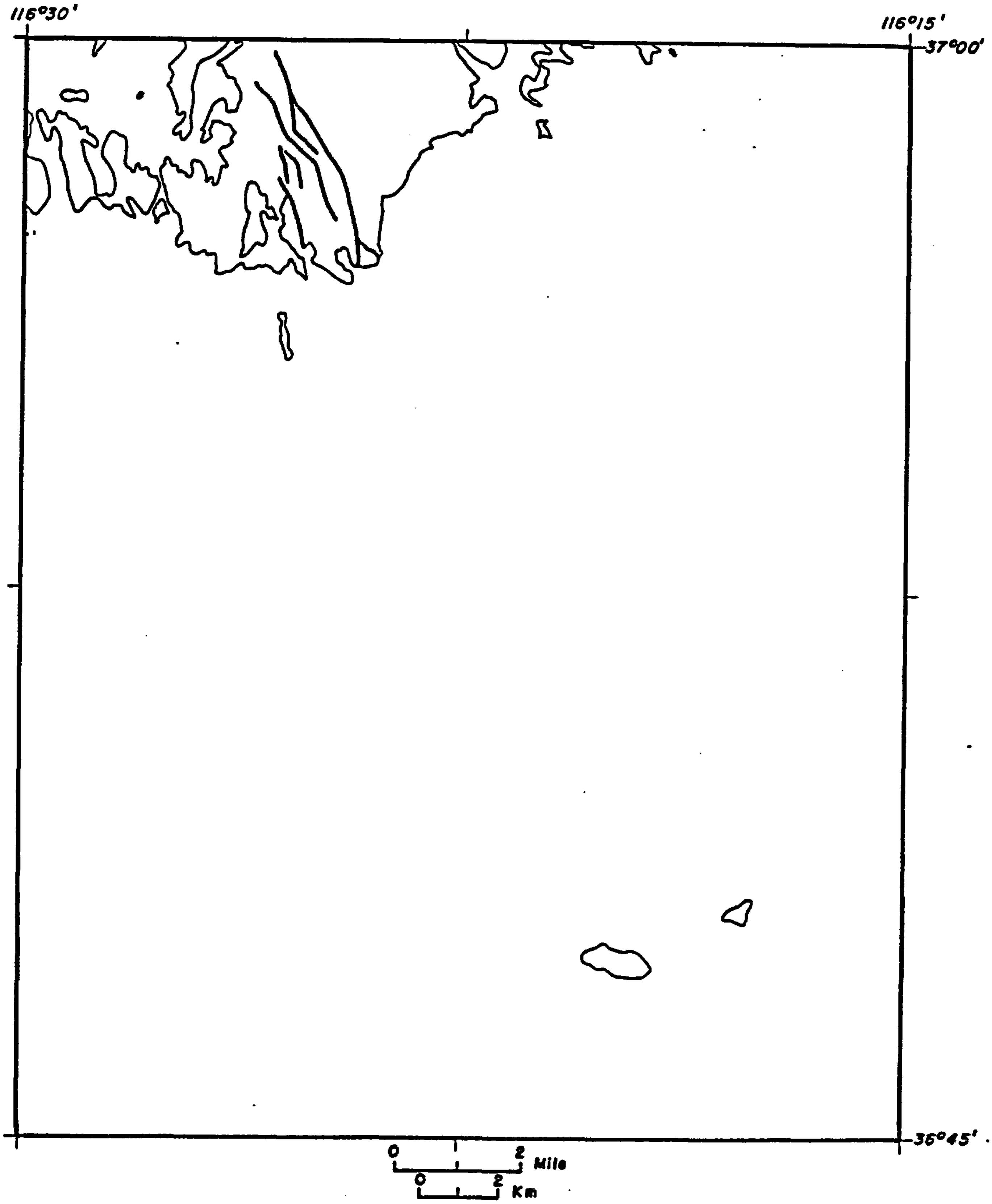


Figure 34D.--Distribution and faulting of group D, rocks 10.0-9.3 m.y. old.

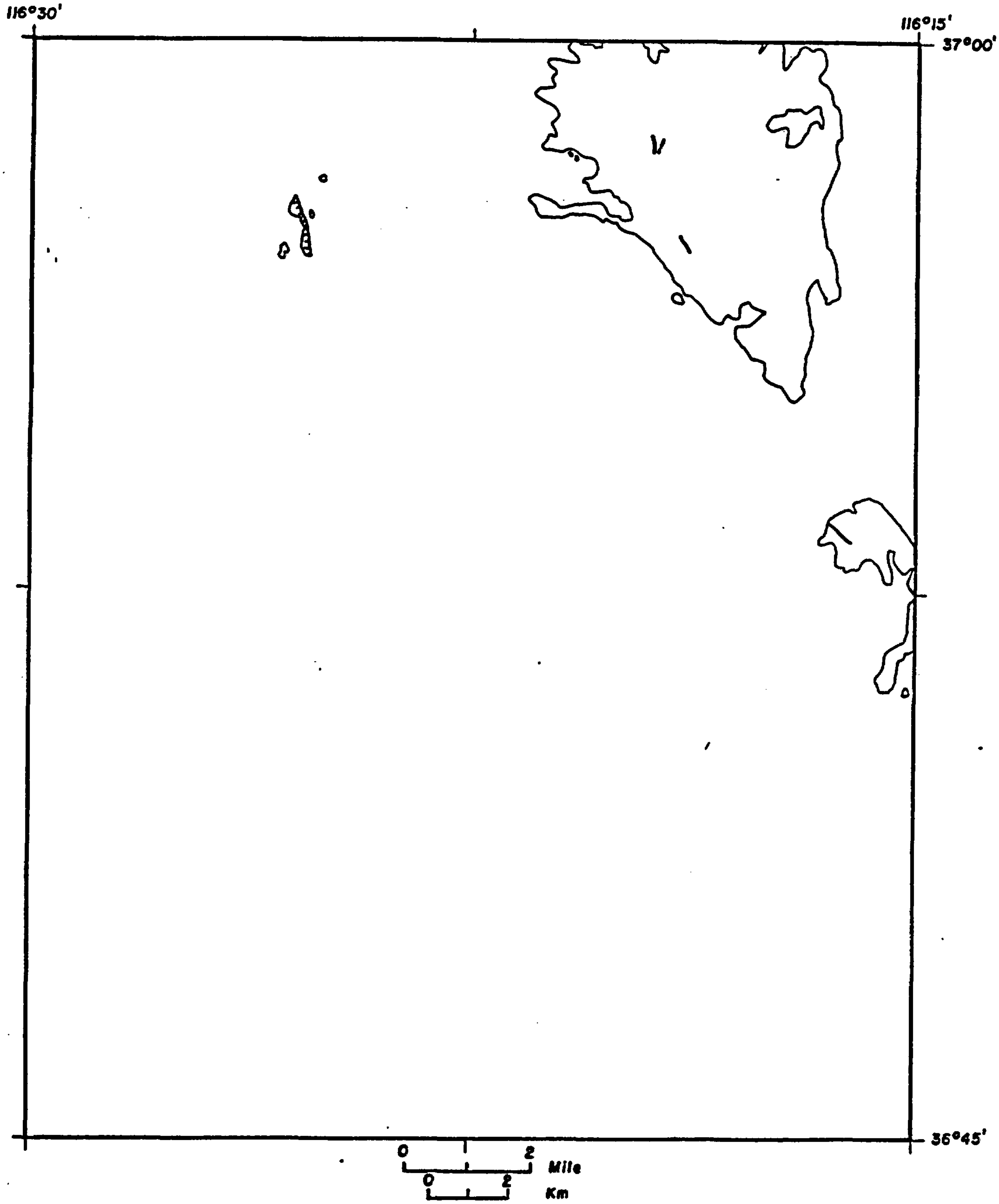


Figure 34E.--Distribution and faulting of group E, rocks 9.3-8.0 m.y. old.

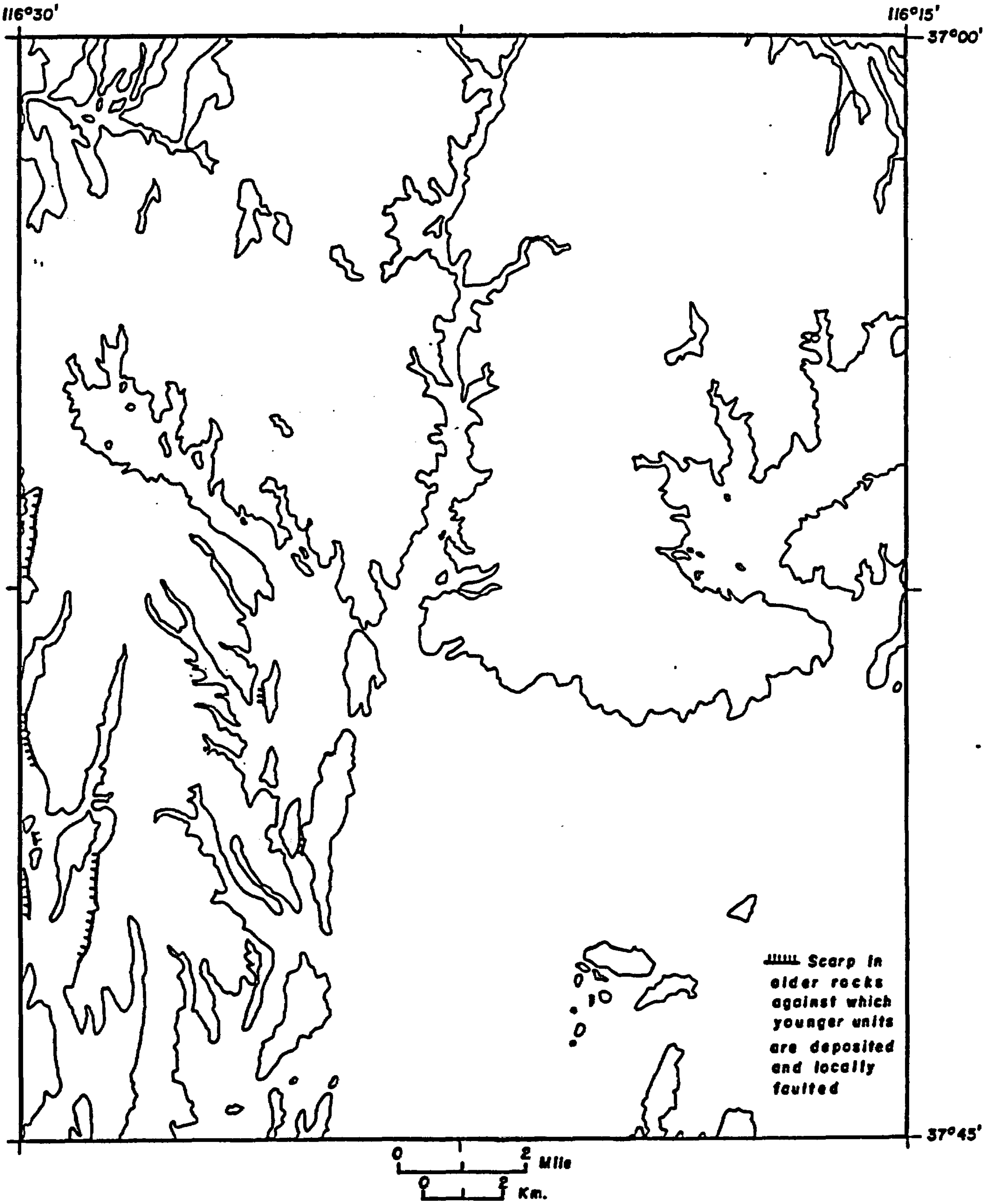


Figure 34F.--Distribution and faulting of group F, rocks younger than 8.0 m.y. old.

trends about N. 30° W (Orkild and O'Connor, 1970). Thus, there is good evidence that the stress field orientation allowing extension on north-northwest striking faults persisted until at least 9 m.y. ago in the southwest NTS area.

Tables 4 through 6 give data illustrating the record of fault movement in the Yucca Mountain area. Table 4 shows the frequency of faults by age group, and attempts to compensate for the large differences in aerial distribution of the various groups of units by reporting the number of faults per million years per square kilometer. The table illustrates in another way the great decrease in frequency of faulting, particularly after about 9.3 m.y. ago.

Good examples of typical faults overlapped by younger units, or showing significantly less displacement in younger units, are listed in table 5. In most cases, about half the total offset occurred during Paintbrush Tuff time, a period of less than 0.5 m.y. In the case of faults B, E, and G (table 5) no mapped displacement occurred after the rhyolites of Fortymile Canyon and Shoshone Mountain were emplaced. One of the most significant of these locations, with respect to the proposed repository site, is the fault at I, which offsets the Tiva Canyon Member about 15 m (50 ft) (Scott and Bonk, 1984), but has, by conservative estimate, less than 2 m (7 ft) of offset of a 10 m.y.-old basalt dike intruded into the fault. A trench about 2 m (7 ft) deep across the fault at this location showed that the basalt is tectonically brecciated, but allowing for minor erosion, the amount of post-basalt offset is probably less than a meter or two. A few hundred meters to the south the basalt dike is unbrecciated by the same fault (Schneider and others, 1982; p. 7).

Finally, table 6 shows calculated rates of displacement for two of the longest and largest faults at Yucca Mountain, the Paintbrush Canyon and Windy Wash (PC and WW, fig. 34A) faults. These two faults cut successively younger units ranging in age from 12.9 (Tiva Canyon Member) to less than 10 m.y. (alluvium). Again, by far the greatest displacement occurred soon after emplacement of the Tiva Canyon Member. Even if the higher rates of pre-Group B displacements are included, the average rate of displacement has been less than 0.03 m/1,000 yr for the Paintbrush Canyon fault, and less than 0.11 m/1,000 yr for the Windy Wash fault.

It should be noted that the displacement of alluvium (Group F) is an estimate based on the assumption that a scarp of more than about 10 m (33 ft) of displacement produced in the last 0.5 m.y. would be highly obvious. Such prominent scarps are not present, although subdued scarps a few meters high are present in several places between highly resistant welded tuff bedrock and adjacent alluvium, and trenching confirms (W C Swadley and others, USGS, written commun., 1984) that small movements have occurred in the last few hundred thousand years. Determination of the amount and rate of displacement in the Quaternary at Yucca Mountain is a difficult problem. At the present time, no way has been found to accurately measure the amount of offset in the last 2 m.y. It is obvious that Quaternary movement has occurred on a few of the faults at Yucca Mountain, but the amount cannot have been very large for the following reasons: (1) at most of the locations where Quaternary displacements occurred, old alluvium is faulted against welded tuff bedrock; both units, especially the tuff on the upthrown block, are highly resistant to erosion, and no steep scarps more than a meter or two high are present, except

Table 4.--Frequency of faults by age group in the Yucca Mountain Area (figs. 34A-F)

Group	Age, m.y.	Estimated percent of area	Sq km	Number of faults[1]	Number of faults /m.y./sq km
F	7.5-0.0	35	215	7	0.004
E	9.3-7.5	8	49	8	0.090
D	9.6-9.3	8	49	13	0.887
C	10.2-9.6	9	55	58	1.767
B	11.6-11.2	5	31	50	1.150
A	>11.6	35	215	[2]>650	[3]1.778
		Total	614		

[1] Obtained by counting the number of mapped faults in each rock age group

[2] Minimum, as not all small faults were counted.

[3] Nearly all the faults shown on figure 34A moved after 13.3 m.y. ago, the age of the Topopah Spring Member of the Paintbrush Tuff; thus, the period used for the calculation was 1.7 m.y.

Table 5.--Examples of faults in the vicinity of Yucca Mountain that are overlapped by younger units, or have significantly less displacement in younger units. (For details of faulting and stratigraphy refer to geologic maps: Christiansen and Lipman, 1965; Orkild and O'Connor, 1970; McKay and Williams, 1964; Lipman and McKay, 1965; Scott and Bonk, 1984).

Fault[1]	Offset, m	Unit	Age m.y	Offset of younger unit, m	Unit	Age, m.y.[2]
A	30	Base of Topopah Spring Member	13.3	15	Base of rhyolite of Windy Wash	11.6
B	30	Base of Pah Canyon Member	13.1	10	Base of rhyolite of Delerium Canyon	9.5
B	30	Base of Pah Canyon Member	13.1	0	Base of rhyolite of Comb Peak	9.3
C	60	Pah Canyon Member	13.1	20	Rhyolite of Waterpipe Butte	9.4
D	150	Top of Topopah Spring Member	13.3	60	Base of rhyolite of Delerium Canyon	9.5
E	150	Base of Pah Canyon Member	13.1	0	Rhyolite of Shoshone Mountain	9.0
F	45	Base of Tiva Canyon Member	12.9	15	Base of Ammonia Tanks Member	11.4
G	60	Base of Pah Canyon Member	13.1	0	Base of rhyolite of Shoshone Mountain	9.0
H	30	Tiva Canyon Member	12.9	<5	Base of Rainier Mesa Member	11.6
I	15	Tiva Canyon Member	12.9	<2	Basalt of Little Prow (dike)	10.0

1 For location see figure 28.

2 Age of younger unit. Some ages have been adjusted slightly to better agree with stratigraphic relationships; all ages are corrected for new K-Ar constants (Dalrymple, 1979)

Table 6.--Amount and rate of displacement in late Cenozoic time of two major faults near Yucca Mountain

Group and offset unit	Offset of unit, m	Offset between units, m	Time interval, m.y.[1]	Time m.y.	Rate m/1000 yr
Paintbrush Canyon fault (PC, fig. 34A)					
		[2]<10	0.5-0.0	0.5	<0.02
Group F, alluvium	<10				
		35	7.5-0.5	7.0	.005
Group E, Thirsty Canyon Tuff	45				
		25	9.3-7.5	1.8	.014
Group D, basalt of Dome Mtn.	70				
		20	9.6-9.3	.3	.067
Group C, rhyolite of Waterpipe Butte	90				
		110	12.9-9.6	3.3	.033
Group A, Tiva Canyon Member	200				
	Totals	200		12.9	
Windy Wash fault (WW, fig. 34A)					
		[2]<10	0.5-0.0	0.5	< .02
Group F, alluvium	<10				
		50	11.6-0.5	11.1	.005
Group B, rhyolite of Windy Wash	60				
		390	12.9-11.6	1.3	.300
Group A, Tiva Canyon Canyon Member	450				
Totals		450		12.9	

[1] Approximate time during which the faults could have had the displacement indicated.
[2] Displacement is estimated maximum; see text.

the high topographic ridges themselves, which are largely the result of pre-Rainier Mesa Member faulting; (2) a 10 m.y.-old basalt dike in a fault along the west side of Yucca Mountain (see fig. 34C) is faulted but not greatly disturbed; a trench across this location showed fault contacts and brecciation of the basalt, but no scarp is present at the fault zone and displacement cannot have exceeded 2 m (7 ft) at a place where offset of the Tiva Canyon Member is about 15 m (50 ft); (3) no fault scarps have been found on Yucca Mountain, or in the adjacent area, that are demonstrably younger than about 35,000 yr (W C Swadley and others, USGS, written commun., 1984). Whereas, a few small Quaternary movements have occurred on faults at and near Yucca Mountain, repeated movements of any consequence would surely have left prominent scarps, especially considering the arid conditions that have prevailed much of the time.

Another kind of evidence bearing on the age of tectonic movements at Yucca Mountain is the age of calcite deposited in fractures in the welded tuff. Table 7 summarizes the results of dating calcite from fractures in three drill holes at Yucca Mountain.

The data of table 7 show some variation, but with one exception they indicate relatively old ages, well over 100,000 yr, for the deposition of calcite in fractures at Yucca Mountain. Most of the samples were selected from fractures that were filled with megascopically crystalline, undisturbed calcite, and as such are believed to represent the latest time the fracture was open to receive calcium carbonate or opal deposits. Theoretically, any important tectonic movement would have reopened the fractures and provided space for deposition of new and younger calcite.

Heat Flow

As heat flow is a factor in evaluation of tectonic flux in a region, a brief summary of information for the Yucca Mountain region is presented here. Lachenbruch and Sass (1978) and Lachenbruch (1979) have pointed out that anomalous heat flow at volcanic centers and elsewhere in the Basin and Range province can be accounted for by variations in the extensional strain rate. In tectonically active areas, heat flow observed at the surface may result from a combination of convection and conduction. The Basin and Range in general is a region of relatively high heat flow, but the NTS is situated on the southern edge of an area called the "Eureka heat flow low" (Sass and others, 1971; 1980). The relatively low values in the Eureka low are attributed to downward and lateral hydrologic disturbance of the regional heat flow (Sass and Lachenbruch, 1982). At the NTS the more typical Basin and Range heat flow values of 1.6-2.2 HFU (heat flow units) occur mainly in the southeastern part of the area where the volcanic rocks are thin or absent; conversely, the lower values (1.5 HFU or less) occur mainly where the volcanic rocks are thick. However, in one deep drill hole (UE20f) on Pahute Mesa, although low heat flow was encountered in the upper 1.5 km, more typical Basin and Range values were determined below 3 km. Between 1.5 and 3 km is a zone that appears to be disturbed by complex water flow. In general in the Yucca Mountain area, the same situation occurs: temperature profiles in the deeper parts of drill holes reflect minimal water movement, but above about 1 km or so depth the profiles are disturbed by complex ground-water movement (Sass and Lachenbruch, 1982). From the data reported (Sass and others 1980; Sass and Lachenbruch, 1982), it appears that the Eureka low could be extended south-

Table 7.--Uranium-series age dates obtained from minerals in cavities and fractures in core from drill holes at Yucca Mountain

Drill hole	Depth, m	Age, 10^3 yr	Remarks
UE-25a 1[1]	34	>400	Calcite filling fracture
	283	>400	Calcite filling fracture
	611	>400	Calcite filling fracture below water table
USW G-2[2]	280	>400	Calcite crystals filling cavity
	347	189±30	Fine-grained calcite lining fracture
	349	142±20	Calcite crystals filling cavity
	359	170±18	Calcite, fraction A
	359	185±18	Calcite, fraction B
	359	>400	Uraniferous opal separate
USW GU-3[2]	63	227±20	Calcite filling fracture
	131	26±2	Calcite from calcite-opal mixture filling fracture
	318	>400	Calcite filling fracture

[1] Szabo, Carr and Gottschall, 1981.

[2] J. N. Rosholt and B. J. Szabo, U.S. Geological Survey, written commun., 1982 and 1983.

southwestward from Pahute Mesa across Timber Mountain to the northwestern part of the Yucca Mountain area, following the prominent gravity low associated with the very thick volcanic rocks of the caldera complexes at NTS.

The following conclusions are drawn from available heat-flow data at NTS: (1) nearly all drill holes measured exhibit fairly steep temperature gradients, but normal to low heat-flow values with respect to the Basin and Range in general; (2) perturbation of temperature profiles by ground-water flow occurs in the upper thousand meters or so of most drill holes; and (3) additional measurements are needed in properly completed drill holes, particularly in intrusive rocks, before the conductive heat-flow regime in the Yucca Mountain area can be throughly evaluated. Thus, at present heat-flow information at Yucca Mountain does not indicate any unusual thermal conditions, but the data have more hydrologic than tectonic significance.

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