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SUMMARY OF TECTONIC AND STRUCTURAL EVIDENCE FOR STRESS ORIENTATION AT THE NEVADA TEST SITE

W. J. Carr

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SUMMARY OF TECTONIC AND STRUCTURAL EVIDENCE FOR STRESS ORIENTATION AT THE NEVADA TEST SITE

By

W. J. Carr

ABSTRACT

A tectonic synthesis of the NTS (Nevada Test Site) region, when combined with seismic data and a few stress and strain measurements, suggests a tentative model for stress orientation. This model proposes that the NTS is undergoing extension in a N. 50° W.-S. 50° E. direction coincident with the minimum principal stress direction. The model is supported by (1) a tectonic similarity between a belt of NTS Quaternary faulting and part of the Nevada-California seismic belt, for which northwest-southeast extension has been suggested; (2) historic northeast-trending natural- and explosion-produced fractures in the NTS; (3) the virtual absence in the NTS of northwest-trending Quaternary faults; (4) the character of north-trending faults and basin configuration in the Yucca Flat area, which suggest a component of right-lateral displacement and post-10 m.y. (million year) oblique separation of the sides of the north-trending depression; (5) seismic evidence suggesting a north- to northwest-trending tension axis; (6) strain measurements, which indicate episodes of northwest-southeast extension within a net northeast-southwest compression; (7) a stress estimate based on tectonic cracking that indicates near-surface northwest-southeast-directed tension, and two stress measurements indicating an excess (tectonic) maximum principal compressive stress in a northeast-southwest direction at depths of about 1,000 feet (305 m); and (8) enlargement of some drill holes in Yucca Flat in a northwest-southeast direction.

It is inferred that the stress episode resulting in the formation of deep alluvium-filled trenches began somewhere between 10 and possibly less than 4 m.y. ago in the NTS and is currently active. In the Walker Lane of western Nevada, crystallization of plutons associated with Miocene volcanism may have increased the competency and thickness of the crust and its ability to propagate stress, thereby modulating the frequency (spacing) of basin-range faults.

INTRODUCTION

In 1972 the U.S. Geological Survey began a review and synthesis of the tectonics and structure of the Nevada Test Site region in order to estimate the present orientation of the regional stress field. This report summarizes geologic information that bears on stress orientation at the test site, including a few stress and strain measurements. Much of the geologic information is presented in the form of maps--one shows the structural features of a large area in and around the test site; the other shows the major structures of the Yucca Flat area, including an interpretation of subsurface structure.

The structural analysis type of approach to current stress field determination has definite limitations as pointed out by Donath (1962), among others, and as recently summarized by Bucknam (1973). A major problem is that a regional map study of structures provides only a two-dimensional view. The problems in using tectonic analysis to determine present stress configuration center in the inhomogeneity of the rocks resulting from subhorizontal discontinuities or layering within the geologic section and other structural planes of weakness, such as faults, folds, and intrusive contacts, some of which may date back to late Paleozoic time. During this span of perhaps 300 m.y. (million years), the structural regimen of the Great Basin in which the test site is situated has changed from general crustal shortening, resulting in large-scale low-angle thrust faults and folding, to crustal extension, resulting in basin-range and strike-slip faulting. The change to dominant regional extension, which produced basin-range faulting, became evident only about 15-20 m.y. ago (Stewart, 1971, p. 1036; Ekren and others, 1968). The geology of the Great Basin is extremely complex and attempts to derive current stress orientation must necessarily concentrate on very young structural features; but because older structures profoundly influence the young ones, the older structural framework must also be well understood. For these reasons this report also presents a brief review of the tectonic setting of the Nevada Test Site region.

I appreciate the valuable assistance given in discussions and the background material provided for this report by colleagues, especially R. C. Bucknam, R. E. Anderson, W. D. Quinlivan, and G. E. Brethauer.

GENERAL TECTONIC SETTING OF NEVADA TEST SITE REGION

The Nevada Test Site lies within the Great Basin, a structural and physiographic region that consists of generally linear mountain ranges and valleys lying between the Colorado Plateau on the east and the Sierra Nevada on the west (fig. 1). The crust of the basin is relatively thin, averaging about 22 miles (35 km) thick. In Mesozoic time it was shortened by complex thrusting and folding, and in western Nevada and eastern California it was extensively intruded by granitic plutons (fig. 1).

A change to dominant regional extension began in the Tertiary. Structures of Tertiary and Quaternary age in the Great Basin may be placed in three general groups that are locally interrelated: (1) horst and graben or block faulting, (2) major zones of dominantly strike-slip faulting, and (3) volcano-tectonic structures.

Some geologists relate most of the basin-range faults to regional lateral shear stresses, and many now believe that the so-called block faulting is a surficial feature confined to the uppermost part of the

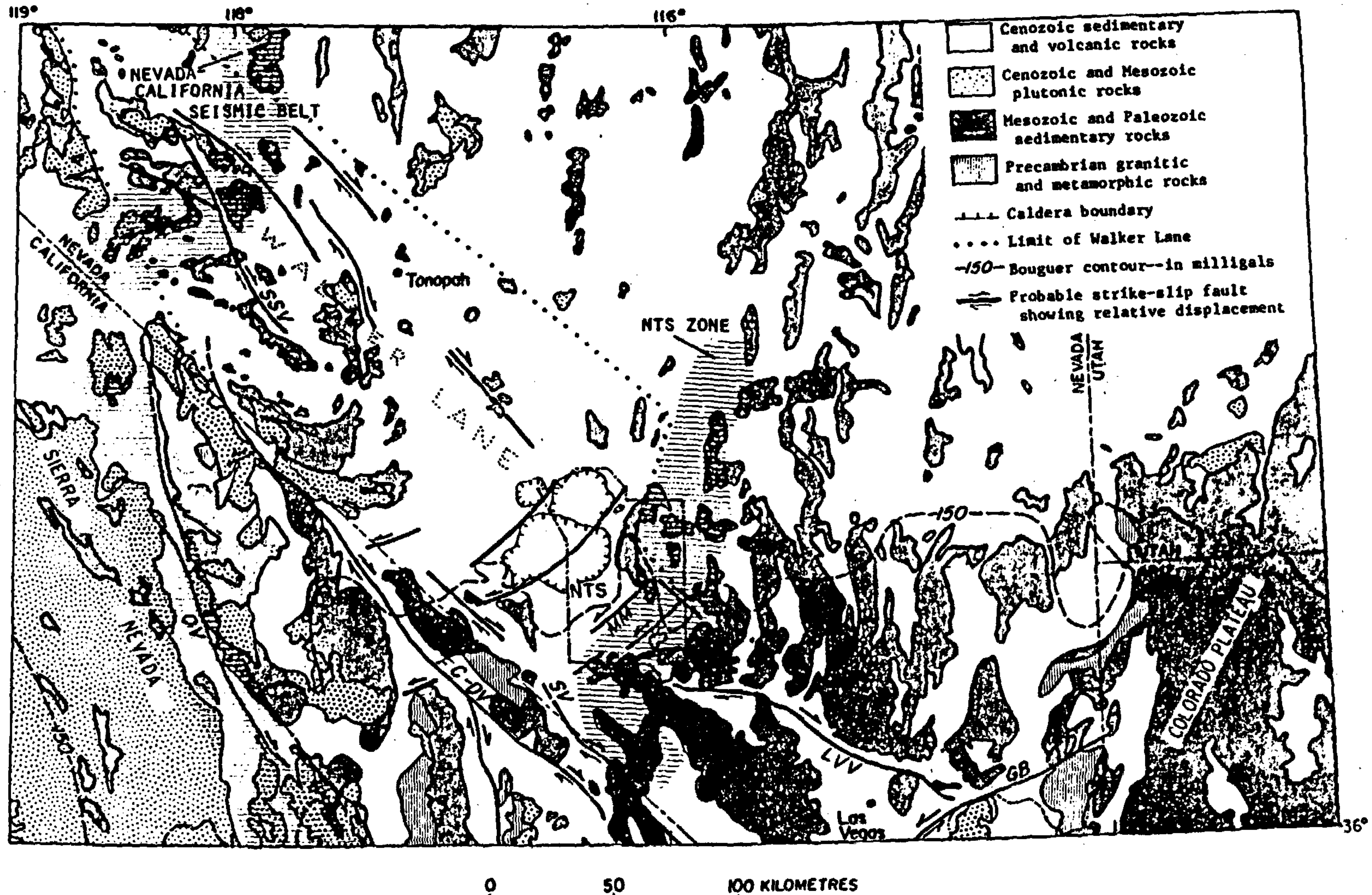

Figure 1.--Distribution of major rock types, southwestern Great Basin, showing system of right- and left-lateral faults in the Walker Lane, and location of Nevada-California seismic belt and NTS zone of Quaternary faulting. Faults and shear zones: CS,-Cane Spring; FC-DV, Furnace Creek-Death Valley; GB, Gold Butte; LVV, Las Vegas Valley: MM, Mine Mountain; OV, Owens Valley; SV, Stewart Valley; and SSV, Soda Spring Valley.

crust. Detailed mapping and modern dating techniques have shown that much of the middle and late Tertiary structural movement is spatially and temporally associated with volcanism, particularly in the western Great Basin (Christiansen and others, 1965).

The generally linear mountain ranges of central Nevada are interrupted in the western Great Basin by several major northwest-striking lineaments (fig. 1), which together form a zone of disrupted topography called the Walker Lane (Locke and others, 1940). These lineaments mark shear zones locally demonstrated to have as much as 30 miles (50 km) of right-lateral offset (Stewart, 1967; Longwell, 1960). These structures are associated with complementary northeast-trending faults, commonly having relatively small left-lateral displacement and large-scale drag folds or oroclinal bends (Albers, 1967) that strike east to northeast. In some areas the Walker Lane shear zones are buried under upper Miocene and Pliocene volcanic rocks; at other places the shear zones may be present at depth but expressed at the surface only by oroclinal bending or low-angle faulting.

Volcanism in the Walker Lane mobile belt is predominantly Miocene in age and tends to be concentrated where the major right-lateral faults die out or display multiple branches and en echelon arrangement. An especially favorable locus appears to be wherever the large right-lateral fault zones step to the right several miles and where their ends are connected by northeast-trending faults, most of which have a small component of left-lateral offset. The northeast-trending faults can be regarded as rifts or spreading centers; commonly they are partially obscured by the products of volcanism. This general idea of rifting and transform faulting has been expressed by Wright and Troxel (1968). Detailed mapping and study of volcanic centers have been insufficient to fully document the structural controls of volcanic centers throughout the Walker Lane, but in the test site area, at least, I feel that the association of eruptive centers and calderas with the ends of right-lateral shear zones and northeast-trending faults (figs. 1 and 2, in pocket) strongly suggests a basic relationship between the volcanism and this structural situation.

In the Walker Lane area large-scale bending and shearing that probably began prior to the basin-range faulting appear to have influenced the trend of that faulting and, hence, the trend of the young basins and ranges. The oroclinal bending (Albers, 1967) associated with shearing in the Walker Lane has not been precisely dated, but there seems no doubt that right-lateral bending and shearing continued into the Pliocene and may still be occurring. At the test site, rocks as young as 11 m.y. are involved in right-lateral flexing and are offset by complementary left-lateral faults. Near Beatty a rhyolite lava dated at 10.8 m.y. (P. P. Orkild, oral commun., 1973) is not displaced by the left-lateral faults that offset the 11-m.y.-old Ammonia Tanks Member of the Timber Mountain Tuff. In the Cane Spring quadrangle, detailed mapping (Poole and others, 1965) has shown that faulting in the Cane Spring left-lateral zone becomes progressively less in tuffs ranging from about 14 to 11 m.y. in age. In the Paiute Ridge (Byers and Barnes, 1967) and Jangle Ridge (Barnes and others, 1965) quadrangles at the east edge of the test site, mapped relations make it clear that north-northwest-trending basin-range faults were well developed prior to the deposition of tuffs older than about 14 m.y.; in many places these tuffs lap onto prominent fault scarps in the Paleozoic rocks and show little or no displacement. In the southern test site the Horse Spring Formation, dated at 29 m.y. in that area, shows considerable structural disturbance, but probably not quite as much as the Paleozoic rocks on which it was deposited, suggesting that structural movements that created the basins of deposition had begun, but perhaps had not progressed very far by late Oligocene time. Ekren, Rogers, Anderson, and Orkild (1968, p. 250) concluded that deposition of the Horse Spring in that area predated structural movements associated with the Las Vegas Valley shear zone. Albers (1967) felt that the apparent scarcity of shearing in Jurassic plutons that follow the curves of the oroclines in Esmeralda County indicates initiation of bending prior to intrusion. R. C. Speed (oral commun., 1973) suggested that the Dunlap Formation of Jurassic age in the Pilot Mountains area of the Walker Lane may record the initiation of transcurrent faulting and bending in the Walker Lane. The Dunlap is unconformable on older rocks and consists largely of locally derived clastic material. On the Death Valley fault zone, McKee (1968) suggested the presence of more than 20 miles (32 km) of right-lateral offset of a granitic pluton of Middle Jurassic age.

Thus, the onset of structural activity related to shearing in the Walker Lane is difficult to establish and, whereas much of the movement may have taken place in Miocene and later time, there are strong hints of earlier activity having developed a structural grain by the time of basin-range faulting.

A variety of Tertiary structural styles occurs in the large area of the Nevada Test Site (fig. 2). The structures seem to be influenced by rock type as well as by preexisting structural grain. On the west a dissected volcanic tableland contains three major caldera complexes; caldera structure is closely associated in time with local north-trending basin-range faulting (Christiansen and others, 1965), and with northeast-trending faults having a small component of left-lateral slip. East of the calderas in the Belted and Eleana Ranges, Tertiary faults are scarce to absent; the underlying Paleozoic rocks consist mainly of the lower plates of major thrust faults, which dip steeply westward beneath Rainier Mesa and the Timber Mountain caldera and gently southeastward beneath Yucca and Frenchman Flats. The lower plate Paleozoic rocks, which consist largely of the thick relatively incompetent Eleana Formation, are gently folded north and west of Yucca Flat; but south and southeast of Yucca Flat in the CP and Calico Hills area, low-angle faulting and local tight folding are present. Farther east, in the carbonate rocks of the upper plates of the Mesozoic thrust faults, the frequency and intensity of faulting increases dramatically in the Yucca and Frenchman Flats area. Near Frenchman Flat a strong system of north to north-northwest-trending basin-range faults bends southward to a northeast strike. This bending is in harmony with the regional change in structural trends that occurs throughout the Walker Lane. Similar oroclinal bending probably exists northwest of the obvious trends, along the Las Vegas Valley shear zone within and beyond the area of the Timber Mountain caldera complex, where it is expressed largely by gravity and topographic trends. Paleozoic rocks appear to be bent around the southeastern edge of the volcanic field, and the thrust zone (Barnes and Poole, 1968) along the Belted and Eleana Ranges probably extends westward in an arc to Bare Mountain. Complicated structures associated with the zone of oroclinal bending and basin-range faulting in the southeastern part of the test site consist of two important structural elements--northeast-trending fault zones of small-scale left-lateral offset, such as the Cane Spring and Mine Mountain systems, and northwest-trending fault and flexure zones displaying right-lateral offset or bending. Detailed mapping (W. J. Carr and others, unpub. data, 1967) and seismic records described later show that these two systems mutually offset one another and that they are both locally active. Significantly, the current structural and seismic activity within these fault zones is concentrated near areas of deep-basin formation.

The deep basins, such as those that underlie Yucca and Frenchman Flats, have formed relatively recently in what may represent a new phase of basin-range faulting. The basins consist of deep, relatively narrow troughs superimposed upon but directionally influenced by older basin-range structure. In the Yucca-Frenchman Flats area these basins are mainly post-Miocene in age; they are the sites of thick upper Tertiary and Quaternary alluvial deposits, including local thin basalt lava flows. Development of these troughs is continuing at present, judging from the distribution of seismicity and young fault scarps.

PROPOSED MODEL OF STRESS DIRECTIONS

I believe the evidence that follows herein supports a basic stress model that assumes that the Yucca Flat area, and probably the entire Nevada Test Site region, is being extended along an axis that trends about N. 50° W. (fig. 3). Such a model is consistent with the general tectonic features of western Nevada as described in the preceding section. It is assumed that the principal stress directions are horizontal, or nearly so, but a moderate inclination of these axes from the horizontal is possible. The direction of maximum principal stress in the model trends N. 40° E., the minimum principal stress trends N. 50° W., and the maximum shear directions trend roughly north-south and east-west. Figure 3 also shows sectors within which existing faults are likely to slip in a right- or left-lateral sense. This is based on Bucknam's (1973) analysis of data for granite reported by Byerlee (1967), which shows that slip will occur on a preexisting fault plane, in preference to the formation of a new fracture, if the maximum principal stress lies between 8° and 52° of that fault plane. All the faults cutting alluvium in the test site area fall within the sectors shown; none strikes northwest. It should be remembered that these values are experimental and may not extrapolate directly to test site rocks.

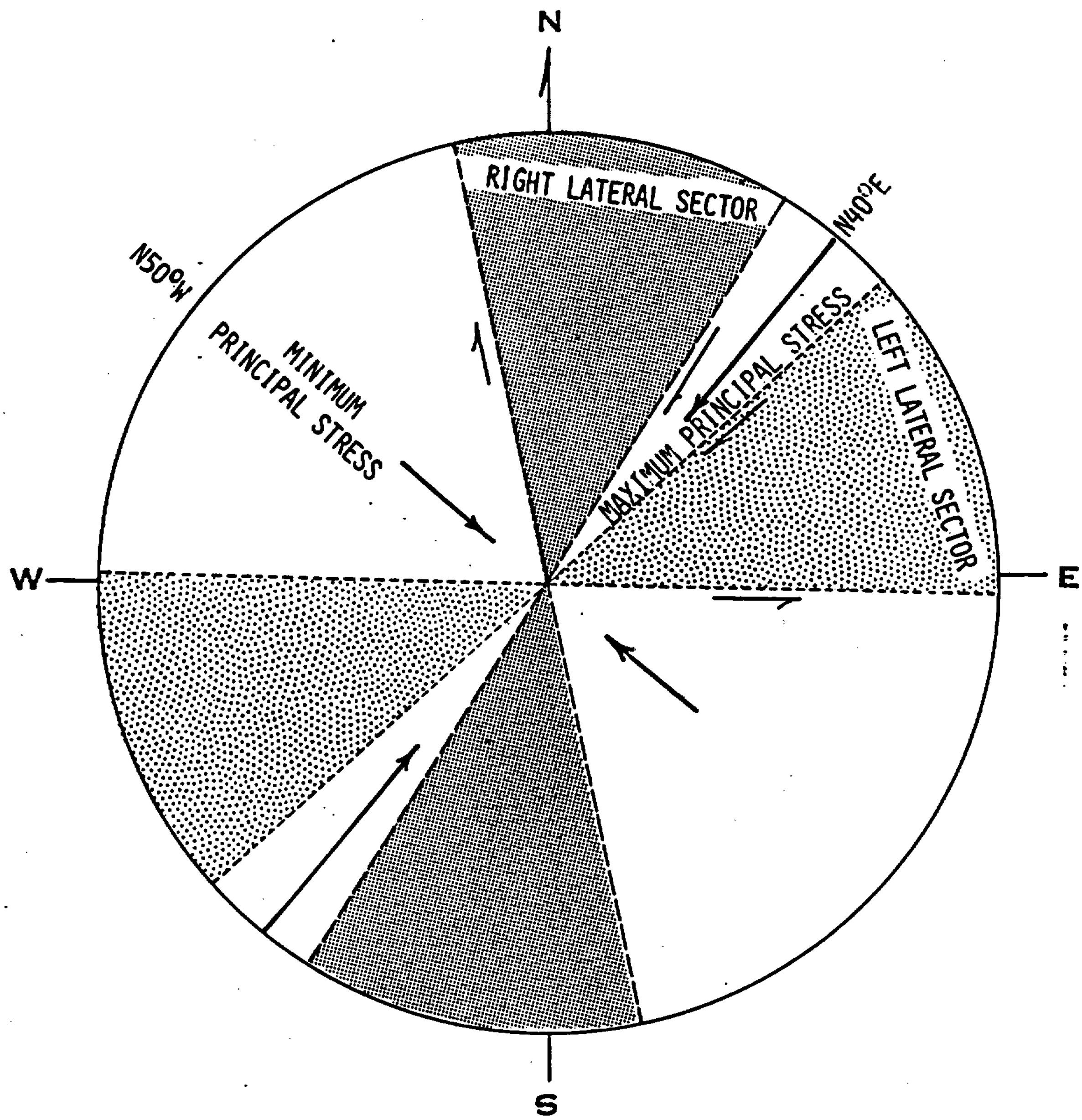

Figure 3.--Stress model for Nevada Test Site area, showing assumed principal stress directions and sectors within which existing faults can slip in a right- or left-lateral sense.

FAULTS AND FRACTURES OF QUATERNARY AGE

Faults in alluvium

Faults of Quaternary age having a northwest trend are not present in the test site area or along the Las Vegas Valley shear zone, but are common to the west and northwest along the Furnace Creek, Owens Valley, and Soda Spring Valley fault zones. Parts of these areas to the northwest are also the loci of much current seismic activity and of historic large earthquakes that caused surface displacements. However, available information (Papanek and Hamilton, 1972; Fischer and others, 1972), suggests to me that much of the stress relief is occurring not on the major faults of northwest trend but near them on northeast-trending faults, particularly where these faults are striking nearly east-west as they approach the main northwest-trending zones (figs. 1 and 2). Additional evidence will be given in the section on seismicity.

In the test site region, faults and fractures of Quaternary age form a zone (fig. 4) flanked on the east and west by areas having very little Quaternary faulting. Few, if any, of the fault scarps within this zone are fresh enough to suggest large earthquakes within the last few thousand years. The scarps nearly all lie in depressed areas that are mainly below 5,000 feet (1,524 m) in elevation. I suggest that the scarps are the surface expression of a seismic belt which currently is relieving stress by fairly numerous small earthquakes but which had been the site of larger earthquakes prior to the last few thousand years. The NTS zone of faulted alluvium is strikingly similar in trend and relative location to part of the Nevada-California seismic belt--a zone

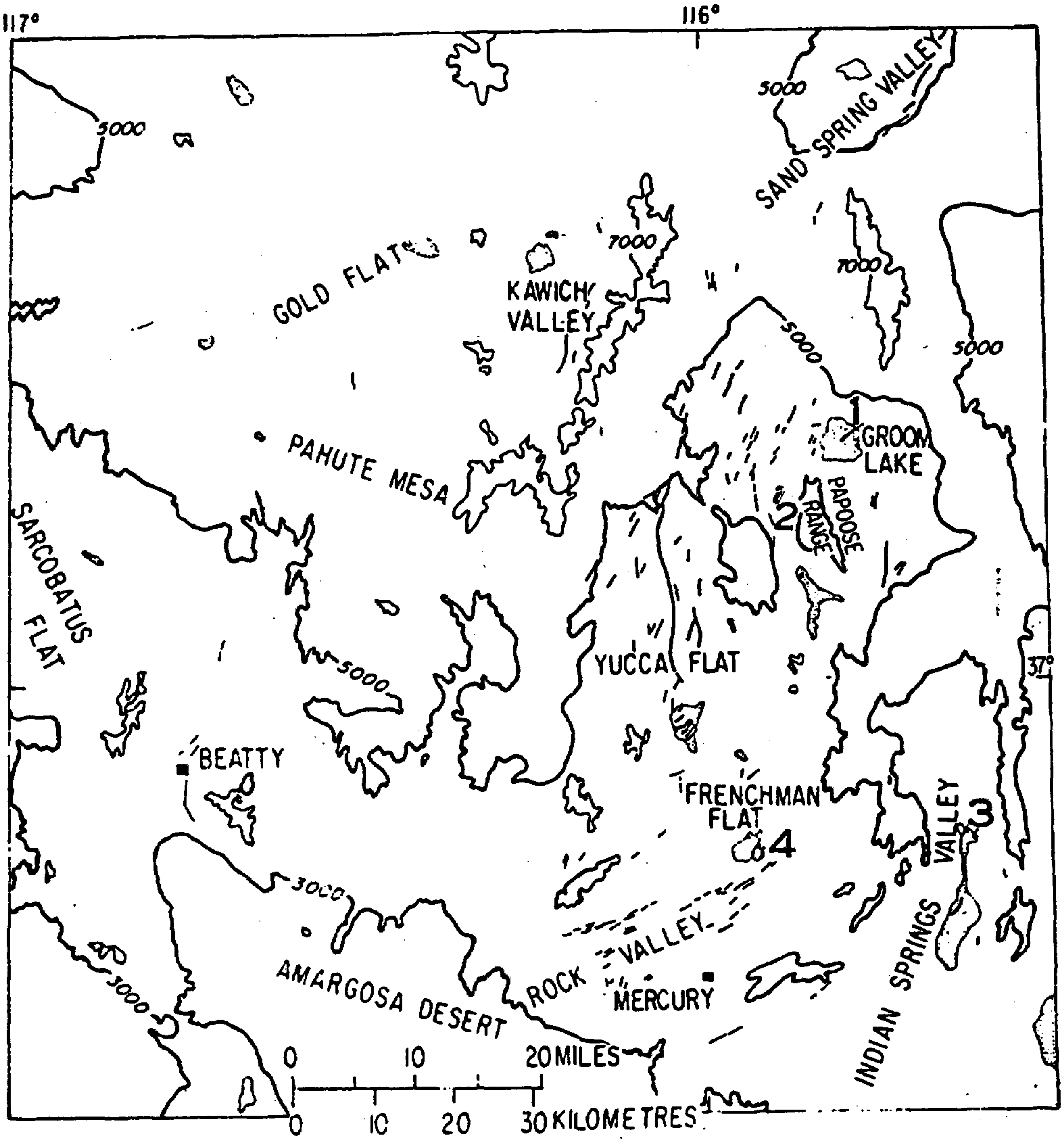

Figure 4.--Quaternary faults and fractures in the Nevada Test Site region and their relation to regional topography. Numbers 1-4 indicate playas having cracks similar to those in Yucca Flat.

of historic large earthquakes that caused surface breakage (fig. 1). Both belts bend to a northeast trend as they cross the Walker Lane, and both appear to show right-lateral oblique slip in their northerly trending portions and left-lateral oblique slip in their northeasterly trending portions. However, at the test site the evidence for left-lateral slip on the northeast-trending faults is mostly in rocks of pre-Quaternary age, even though the faults cut Quaternary deposits. En echelon patterns characteristic of lateral slip seem to be absent from the younger of these northeast-trending faults, but the scarps are old and poorly defined.

The Yucca fault is the only youthful-appearing prenuclear testing fault scarp in the test site area. It will be discussed in detail in the section on page 23.

Fractures in alluvium

Underground explosions at the test site have produced many fractures in the alluvium. The average trend of shot-induced fractures in Yucca Flat is N. 40° E. (fig. 5). This direction is based on 70 occurrences, including prominent long fractures; fractures that are closely spaced in a zone were counted as a single occurrence. If individual fractures had been counted, the frequency of this trend would have been tremendously reinforced because fracture swarms having this trend are much more numerous than those exhibiting other trends. No great difference in fracture trends seems to exist from one part of Yucca Flat to another, although there is a tendency for fractures in Area 3 to trend slightly

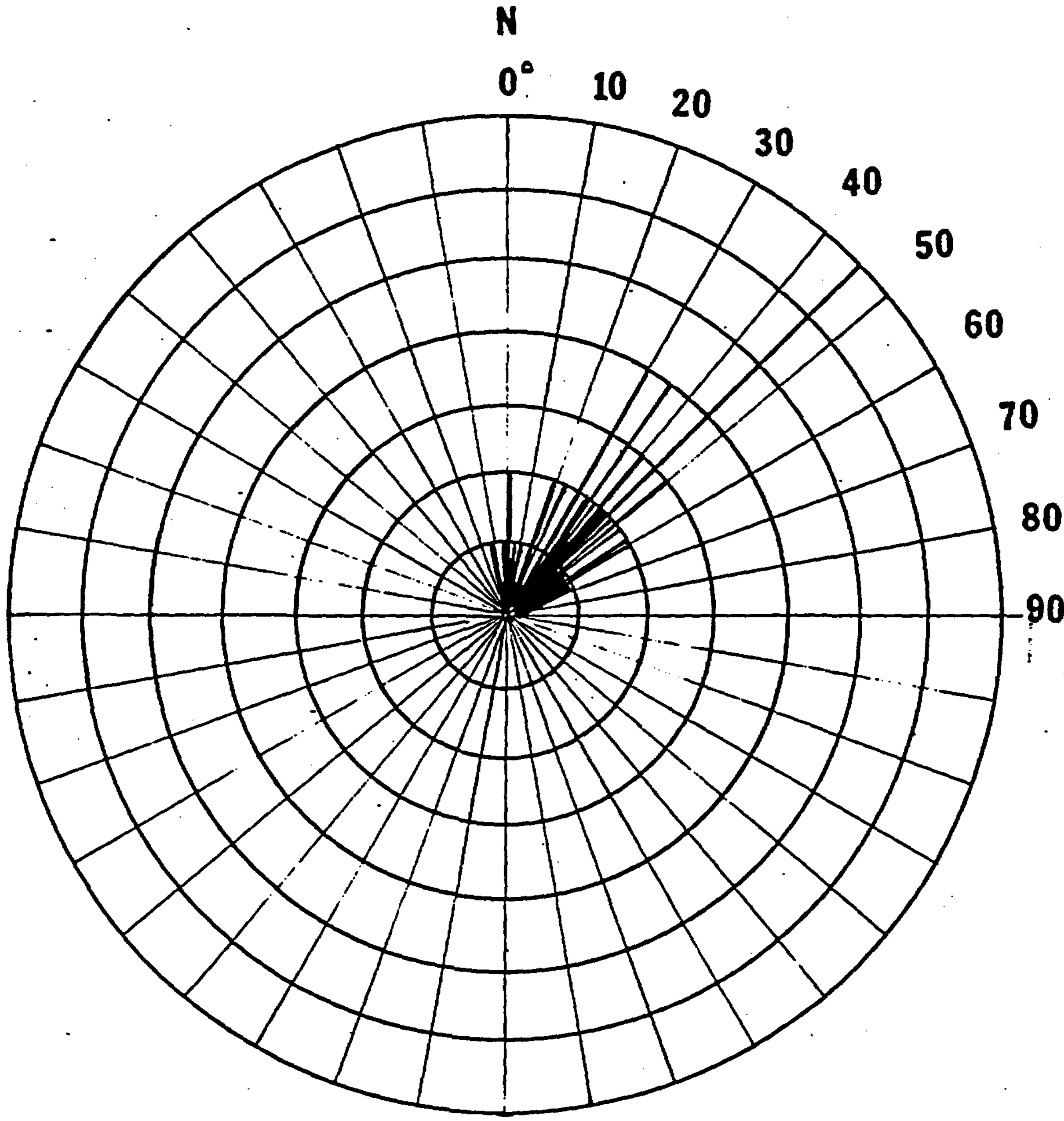

Figure 5.--Rose diagram showing trends of shot-induced fractures, Yucca Flat. Each circle represents one fracture or one close-spaced group of fractures. Does not include fractures concentric or radial to shots or fractures related to known faults.

more northerly than those in the northern part of Yucca Flat. Fractures probably lying along faults were excluded from the count as were fractures that are clearly radial or concentric to shots. There is a minor maximum-of-fracture-trend frequency near north; it is possible that fractures having this trend are fault related. Horizontal separation of an inch or less, normal to the crack, is the usual displacement associated with these fractures. Significantly, the swarm of northeast-trending explosion-related cracks in north-central Yucca Flat crosses the major Yucca fault zone without being obviously affected by it.

Barosh (1968, p. 204-207) showed that in some areas of Paleozoic bedrock around Yucca Flat a well-developed system of northeast-trending joints and very small faults is present, nearly paralleling the trend of shot-induced fractures in alluvium. These joints in Paleozoic rocks are not explosion related. Analysis of the geologic mapping east of Yucca Flat also shows an east-northeast-trending system of small faults in the Paleozoic rocks. No joints or faults of this trend are known in the tuff outcrops adjacent to the fractured alluvium, but outcrops of tuff are sparse and irregularly distributed in these areas and no large underground explosions have been detonated near them. On Banded Mountain, however, a few basalt dikes of late Tertiary or Quaternary age intrude the northeast-trending faults, suggesting that northwest-southeast tensile stress was present at the time of basalt intrusion.

I believe that the described relations indicate that most of the randomly distributed northeast-trending explosion-produced cracks in Yucca Flat are basically unrelated to underlying faults and thus probably do not extend downward more than a few hundred feet. Where they are clustered in a narrow, long linear zone, however, they may reflect the presence of a buried fault.

In the proposed stress model, most of the northeast-trending fractures in alluvium in Yucca Flat would be extension cracks parallel to the direction of maximum principal stress. Alternatively, they could be conjugate shear fractures associated with right-lateral displacement on northwest-trending bedrock faults.

The fact that no consistent shearing has been observed on these cracks and that no significant faults having northwest trends are known in the area of the cracks argue against the conjugate shear interpretation.

Fractures in tuff

On Pahute Mesa several large underground tests have caused extensive fracturing and faulting in tuff. Except for the Benham event, nearly all mapped fractures trend north-northwest to north-northeast and are parallel to or coincident with exposed or thinly buried basin-range faults. At Benham a prominent east-west set of fractures formed, extending outward to a maximum of about 2,300 feet (0.7 km) from ground zero. These fractures may be related to local jointing in the tuff (Bucknam, 1969, p. 2213). Most of the prominent long fractures at Benham, however, are also along northerly trending basin-range faults. According to Bucknam (1969, p. 2215) most of the explosion-triggered lateral displacements on these faults were right lateral. Snyder (1973), however, reported that of 16 target-board measurements of fault creep on basin-range faults on Pahute Mesa, 10 showed left-lateral displacement and 6 showed right-lateral displacement. Shot-induced vertical displacement of several inches to several feet has also commonly occurred on many faults on Pahute Mesa.

Thus, at Pahute Mesa, most fractures follow the known structural trend, and it is likely that the movements represent strain release triggered by the underground nuclear explosions (Dickey, 1968). One explosion, as pointed out by Bucknam (1969, p. 2215), reactivated a pre-Thirsty Canyon Tuff (about 7 m.y. old) fault. Possibly in part because of residual stresses in the tuffs, the fractures and displacements on Pahute Mesa cannot be directly related to the stress model proposed.

Fractures in playas

Desiccation cracks are a well-known feature of desert playas. They tend to be irregular or polygonal and relatively narrow and shallow. Most of the fractures seen in playas of the test site area, and Yucca playa (fig. 6) in particular, are probably not due to desiccation for several reasons: (1) all the cracks of this type identified in this study trend north to about N. 50° E., regardless of playa shape; (2) they tend to be curved, not polygonal; (3) in Yucca playa they trend at right angles to the gravity gradient and to the sides of the basin, contrary to what would be expected if they were due to shrinkage resulting from desiccation of the playa sediments; (4) at least one of the Yucca playa cracks is alined with a small fault in the adjacent

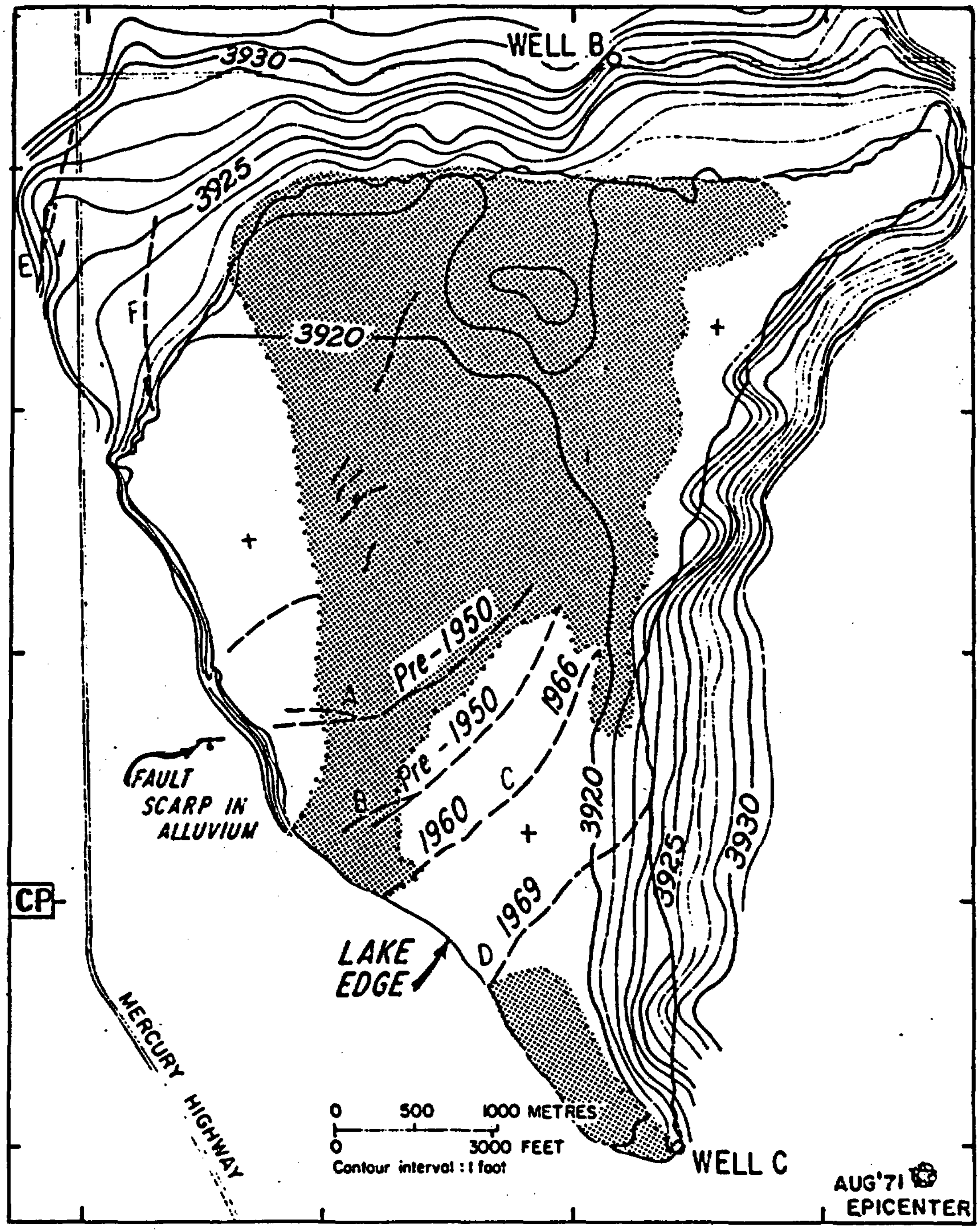

Figure 6.--Map of Yucca Lake playa area showing cracks and detailed topography. Shaded area (-) is apparently depressed with respect to areas marked (+), based on distribution of water in the lake in March 1973; letters identify cracks referred to in text.

alluvium, which in turn trends toward a bedrock fault; (5) topographic data at hand for Yucca playa indicate no subsidence has occurred in the immediate area of cracking; (6) water levels (William Thordarson, oral commun., 1973) in wells B and C (fig. 6) at the edges of the playa indicate no significant lowering of the water table during the last 10 years; and (7) large quantities of water flow into the cracks when they are new, indicating that they go to considerable depth, probably into rocks beneath the alluvium.

Fractures inferred to be of tectonic origin are present in several playas of the region. Six fractures of this type are present on or near the surface of Yucca playa (fig. 6). Four of these (fig. 6, A-D) are subparallel and concave to the northwest; their trend varies from about N. 30° E. to N. 50° E. Two older cracks (fig. 6, E and F) beyond the northwest corner of the playa trend more northerly. The four parallel cracks in the southern part of the playa are about equally spaced and are younger from north to south. The youngest crack (D), still a prominent feature but filling rapidly, formed in 1969; the next crack to the north (C) formed in 1960 and was extended northeastward in 1966. On the basis of aerial photos and degree of obliteration, the third crack (B) probably formed prior to 1950. The fourth and northwesternmost crack (A) is older but of unknown age. None of these cracks shows obvious vertical offset, although the pattern of water distribution on the playa surface suggests that the area surrounding the younger cracks has been elevated slightly with respect to adjoining parts of the playa (fig. 6).

To further investigate the Yucca playa cracks, elevations on a 1965 Holmes and Narver NTS map, scale 1:12,000, were contoured at 1-foot intervals (fig. 6). The area of the playa that contains the four parallel cracks was found to be nearly flat at the time the elevations were determined, except at the northeast end of the subsequent 1969 crack (D). Along the east flanks of the playa, contouring revealed a peculiar topography in positions approximating the northeastward projection of the three pre-1965 cracks; whereas no detectable vertical offset occurred along the cracks on the playa itself, the near flanks of the playa may have subsided several feet along the projections of each of the cracks. An aerial photo taken in March 1973 shows considerable water standing on the playa. Water extends all the way to the north edge of the playa, but the western edge of the playa and a large area around the youngest cracks (B, C, D) appear to be at or above water level. Thus it appears that vertical changes of a foot or so may have taken place since 1964 (fig. 6)--another indication of tectonic adjustments of the playa surface.

In order to establish a more reliable basis for determining vertical and horizontal changes in the playa area, level lines have been requested. These stations will be resurveyed at some future date. Horizontal distances between stations will be measured with the geodimeter.

Four other playas in the surrounding region (locations 1-4, fig. 4) were found to have similar cracks:

1. Groom Lake playa, northeast corner. About 5,900 feet (1,800 m) long, trends N. 47° E.; pre-1952 in age.

2. Small unnamed playa just northwest of Papoose Range, about 4 miles (6.5 km) east of gate 700. Two very faint cracks about 1,000 feet (300 m) and 500 feet (150 m) long, both trending about N. 50° E.

3. North end of playa in Indian Springs Valley, about 18 miles (30 km) north of Indian Springs, 17 miles (27 km) east of Frenchman Lake. Two cracks about 3,000 feet (900 m) long, trending about N. 20° E. and N. 10° E., appear to be at least 20 years old.

4. Frenchman Flat, northeast corner. Two curving cracks, one about 7,000 feet (2,130 m) long, trending N. 5° W. to N. 60° E., the other 2,000 feet (600 m) long trending north to N. 20° E.; both cracks concave to southeast. The easternmost crack is distinctly younger than the western, and looks fresh on photos taken in 1951.

Several other playas in the region were examined on aerial photos and no cracks of this type were detected. None of the photos were low altitude, however, and most were 5-20 years old. Playas on which no cracks were found include Papoose Lake, playas in Kawich Valley and Gold Flat, eastern Sarcobatus Flat, and playas in the valley between the Pintwater and Desert Ranges. The observed cracking in playas occurs within the previously described zone of faulted alluvium that extends northward from the Mercury area at least to Sand Springs Valley north of State Highway 25 (fig. 4).

The playa cracks in the test site region vary somewhat in trend, but nearly all strike northeast. Details of geologic structure in the adjacent bedrock are available only for the cracks on Yucca and Frenchman playas. On Yucca playa the major cracks have two distinctively different trends (fig. 6), suggesting that they may represent two different modes of failure. Both groups of fractures lie on the projection of the Yucca-Frenchman flexure, but the southern group of four curving cracks is nearly at right angles to the northwest trend of the flexure, suggesting that they could be conjugate shears. The two northerly trending cracks at the northwest corner of Yucca playa could be extension cracks near the end of the shear and flexure zone, which appears to be dying out in that area. The curving cracks on Frenchman playa may have a similar origin; they may be extension cracks at the opposite end of the shear and flexure zone.

YUCCA FAULT, ASSOCIATED PARALLEL FAULTS, AND SHAPE OF YUCCA BASIN

The most important Cenozoic structural feature in the central and eastern Yucca Flat area is a series of north-northwest-trending, predominantly east-dipping normal faults (fig. 7, in pocket). They are typical basin-range faults, bounding depressed and elevated blocks in which the beds dip generally westward. The average dip of these faults at the surface is about 60°, based on numerous measurements in quadrangles bordering Yucca Flat and on scattered subsurface information. Dips in Paleozoic rocks exposed between the faults are variable, but the average is about 40° westerly or southwesterly on the east side of Yucca Flat. There is a distinct tendency for dips in the Paleozoic rocks to increase from east to west across a particular fault block (fig. 8); dips of as much as 60° are present along the east edge of Yucca Flat.

In general, the Tertiary tuffs dip less steeply (the average dip in the hills around Yucca and Frenchman Flats is about 20°) but more erratically than the Paleozoic rocks, because the tuffs tend to drape across uneven surfaces and fault scarps on the Paleozoic rocks. The tuffs are commonly less offset by the basin-range faults than are the Paleozoic rocks. Although there are local exceptions, the tuff units, particularly ash-flow tuffs, do not thicken appreciably in the deeper parts of the Yucca Flat basin. The larger exposed faults of the group are spaced from about 1,500 to 3,000 feet (500-1,000 m) apart, but subsurface dips in the tuff beneath Yucca Flat range from 10° to about 35°, indicating that faults are probably more closely spaced in those areas where the dips in the tuff are steep. For dips of about 30° maintained across fault blocks, small faults spaced only about 200 feet (60 m) apart seem required. If, however, dips in the tuffs steepen into the main faults, as seems likely, fewer faults are required. A good case for this phenomenon, called "reverse drag flexing," has been made by Hamblin (1965) and supported by Anderson (1971). It is a mechanism for achieving horizontal extension and implies curving or flattening of the faults with depth. Little evidence of this flattening exists at the test site because of the lack of deep erosion, but the Baneberry fault in northwestern Yucca Flat appears to flatten slightly with depth; at the surface it dips about 65°, and 1,000 feet (300 m)

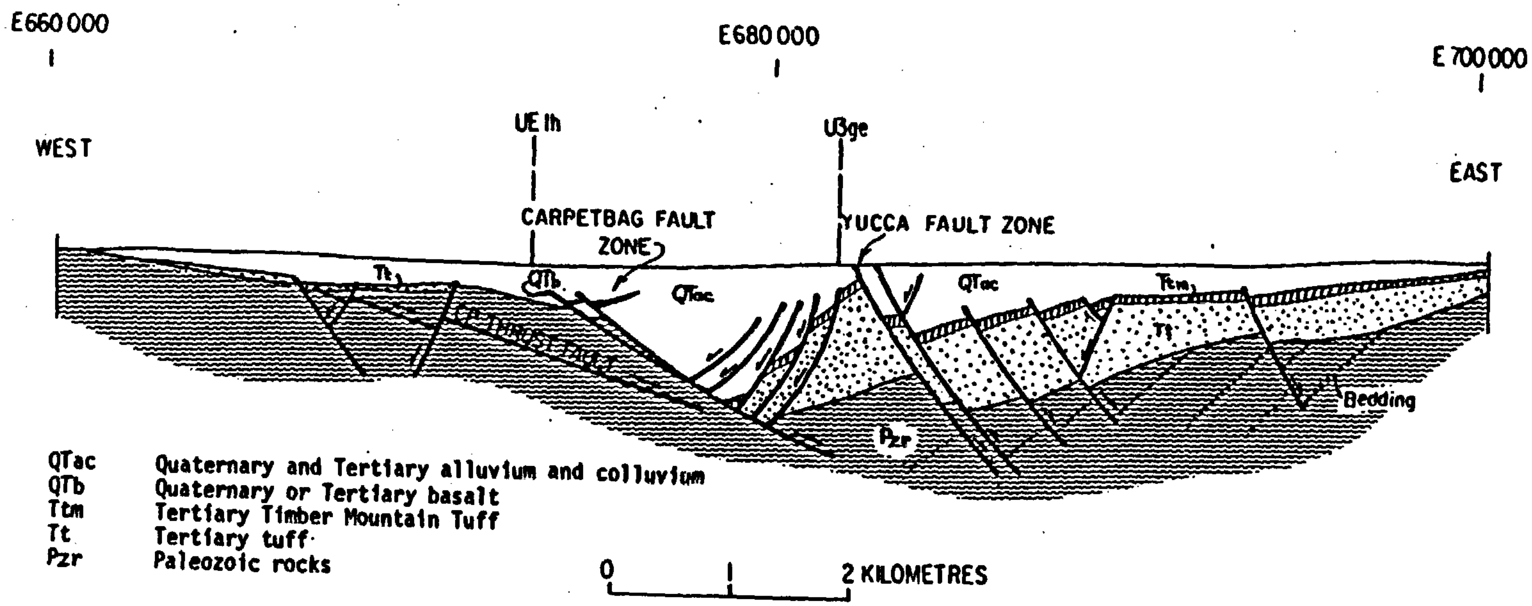

Figure 8.--Schematic section across Yucca Flat along Nevada State coordinate N. 825,000.

lower drill-hole information indicates that it is dipping about 58°. Likewise, the Yucca fault, which at the surface generally dips about 75°-80°, must flatten to 55°-65° in order to fit subsurface geology in some areas. In southwestern Yucca Flat the Carpetbag fault zone may have a low dip, possibly approaching the 40° dip of the Paleozoic surface (fig. 8). Evidence for this will be discussed in a following section.

The Yucca fault is the youngest natural fault scarp in the test site region. It was studied carefully for clues to the present stress field. A large earthquake must have produced the Yucca fault scarp, which extends in a very narrow zone for a distance of at least 15 miles (24 km) and probably as much as 20 miles (32 km) (fig. 7). At least the southern 10 miles (16 km) of the fault scarp shows no evidence of multiple displacements. Magnetic evidence and surface fracturing show that in places the present scarp lies several hundred feet east of older buried parts of the fault zone. No reliable way has been found to date the formation of the scarp, but degree of erosion in comparison with scarps of known age in similar climate, such as the 100-year-old Owens Valley scarps, permits a rough age estimate of between 1,000 and 10,000 years. Erosion has cut down through the scarp in all gullies, and the scarp has been destroyed completely in a few places. Erosion has destroyed any evidence of lateral offset.

Under the proposed stress configuration (fig. 3), the north-northwest-trending faults strike subparallel to a maximum shear direction and should display a component of right-lateral slip. Evidence for this is summarized in the following discussions.

The main Yucca fault scarp, though nearly continuous, consists in detail of numerous close-spaced en echelon breaks that consistently step to the left (fig. 9), consistent with a component of right-lateral slip. Much of the en echelon pattern is a result of movement caused by underground tests, thus providing a general measure of present stress orientation. Minor departures from the nearly vertical displacements caused by explosions are, in my opinion, due to shoving and jostling of the alluvium by ground motion. However, fairly consistent minor right-lateral offset resulting from testing has been described for at least one underground test (R. E. Anderson and W. D. Quinlivan, written commun., 1966). Barosh (1968, p. 215) concluded that fracturing from another test indicated a slight right-lateral component.

North-trending surface faulting produced by the Carpetbag event (near UE2b, fig. 7) also shows evidence of right-lateral displacement; a road northwest of the shot was dextrally offset about 6 inches (15 cm) across a 4-foot (1.2-m) -high scarp, and en echelon cracking along the scarp steps to the left in a manner similar to that along the parallel Yucca fault scarp. The total amount of right-lateral slip on the Yucca and Carpetbag fault zones is difficult to estimate, but it could easily equal or exceed the average post-tuff vertical component, which is about 700 feet (200 m) for the Yucca and 2,000 feet (600 m) for the Carpetbag fault zone. Right-lateral offset is also indicated (W. J. Carr, unpub. data, 1972) for the Baneberry fault

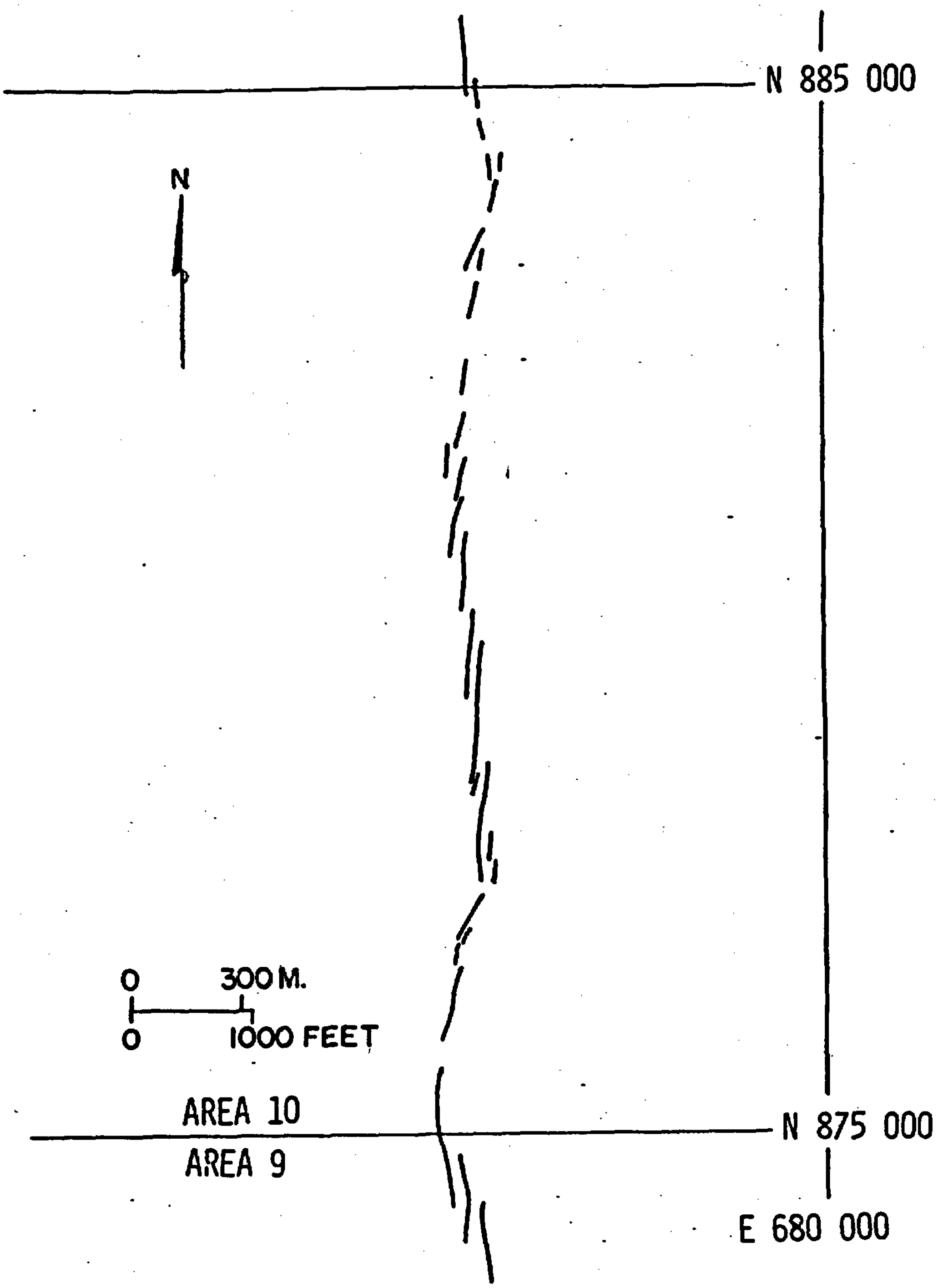

Figure 9.--Diagram of shot-induced scarplets along part of the Yucca fault

(fig. 7), which trends about N. 20° E. The evidence consists of the left-stepping of surface fractures along the scarp, northeast-trending tension cracks near the fault, and mismatch in tuff stratigraphy on opposite sides of the fault.

Additional observations may be cited in support of right-lateral slip on north-trending faults in the Yucca Flat area: (1) scattered subsurface data suggest that Paleozoic formations may be displaced several thousand feet laterally across the northern Yucca and Carpetbag faults (fig. 7); (2) slickensides on a few fault surfaces of north-northwest trend in the hills northeast of Yucca Flat show that oblique right-lateral movement has occurred at some point in the fault's history, but most of the strike faults east of Yucca Flat seem to have had principally dip-slip displacement in the geologic past; and (3) the sides of the medial Yucca Flat depression, as outlined by the buried Paleozoic surface determined from gravity (fig. 10), fit fairly well if shoved back together along a line trending about N. 50° W.

The deep troughs under Yucca Flat (fig. 10) are significant, relatively young structural features, although they are probably controlled in trend by older faults. Their youthfulness is supported by a general lack of thickening of the Pliocene Timber Mountain Tuff but abrupt thickening of the alluvial deposits in the troughs. The vertical and horizontal displacements involved are in general much greater than those recorded by faulting in the tuffs around the edges of the Yucca basin. Thus, these medial troughs seem to represent a relatively young episode of localized deep basin formation, possibly

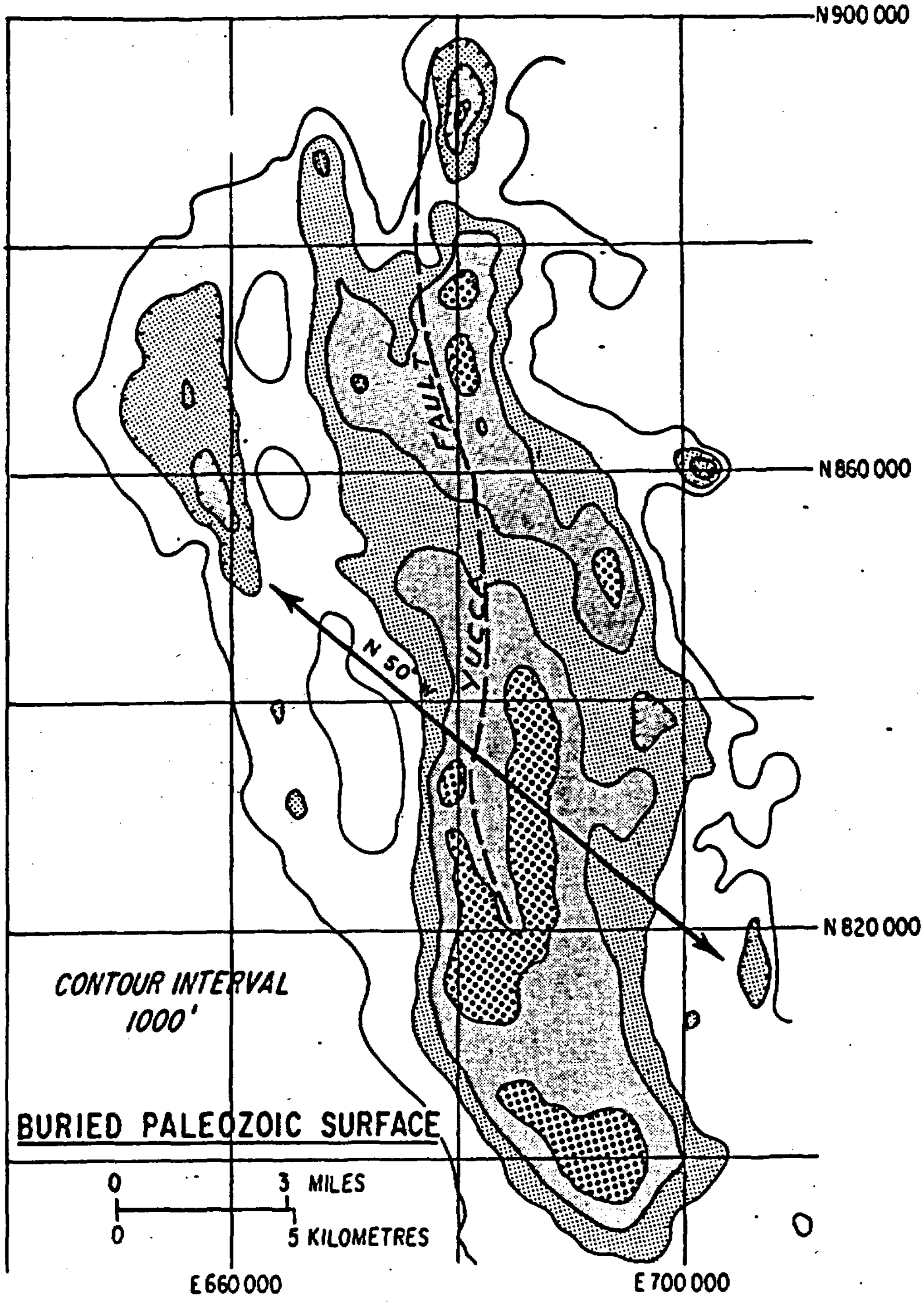

Figure 10.--Three-dimensional gravity controlled diagram of buried Paleozoic surface, Yucca Flat. Intensity of stippling indicates depth. Arrow shows assumed direction of extension of area.

involving a change in stress orientation and mechanism. This period of tectonic activity may correspond to one in the western Great Basin described by Gilbert and Reynolds (1973, p. 2507), which they were able to date as later than approximately 3-4 m.y. ago. They described this deformation as characterized by tilted fault blocks and broad areas of warping; the faults of this episode trend predominantly north as opposed to earlier northeast and northwest trends. Stewart (1971) has suggested that these relatively narrow depressed zones in the Basin and Range province may be due to localized plastic extension in the lower crust.

The schematic cross section shown in figure 8 is my interpretation of the general structural character of south-central Yucca Flat. The Tertiary rocks dip westward into the basin from outcrops along the east side of the valley. Dips and strikes obtained from scattered drill holes in Areas 3 and 6 indicate that a westward dip in the tuffs persists into the main deep trough east of the Carpetbag fault zone. Several west-dipping faults, such as the Area 3 fault (fig. 7), form the east walls of the medial trough, but basically the east side of the trough is a downwarp. Drill holes such as UE1h and UE1j, located on the west wall of the trough, go from alluvium directly into Paleozoic rocks. In these two holes identical upper Pliocene or Pleistocene basalt flows intercalated in the alluvium are about 600 feet (180 m) lower to the northwest in UE1j than in UE1h, suggesting a westerly dip of the basalt of about 20° toward the rising surface on the Paleozoic rocks. Thus, a fairly young marker horizon in the alluvium appears to dip westward just west of the Carpetbag fault zone. Dips in the Timber Mountain Tuff in drill hole U3ge immediately west of the Yucca fault are also unusually steep, averaging about 32° to the west. These structural attitudes, in conjunction with the deepest part of the Yucca basin, suggest structural rotation into a relatively low-angle east-dipping fault zone having the appearance of a landslide fault. The strong tendency for large range-front faults in the Basin and Range to be landslidelike or doubly concave, both upwards and toward the downthrown side, has been pointed out by Moore (1960). The deep cleft behind the "slide" or "pull-apart" is the site of deposition of thick alluvium. The basalt intercalated in the alluvium of Yucca Flat is probably late Pliocene or early Pleistocene in age, judged from its similarity to basalts exposed east of Yucca Flat. The postulated structural rotation is, therefore, probably post-late Pliocene in age.

Obviously, other structural explanations are possible, but if this analysis is correct, displacement on the Carpetbag fault zone alone could account for as much as 5,000 feet (1,500 m) of horizontal extension. The parallel Yucca fault may be a more easterly zone of similar deformation that is still forming. The Yucca fault probably has a fairly low easterly dip of 50°-60°, particularly in its southern half. This is suggested by the position of the surface trace with respect to subsurface topography (fig. 10) delineated by gravity. Faults and fractures of the Yucca fault zone can be seen in drill hole U7z-1 (Sargent and others, 1972); they dip from 40° to 60°. If the Yucca fault dips 60°, about 500 feet (150 m) of horizontal extension could be attributed to it, with the amount increasing greatly if a lower fault dip is assumed.

EXPLANATION

Contact between bedrock and alluvium

Fault--Dotted where buried

Fault or fracture of Quaternary age

FEB 19
1973

Earthquake epicenter showing the two fault-plane solutions and pressure axis (heavy line), and date

Aftershock epicenter showing pressure axis

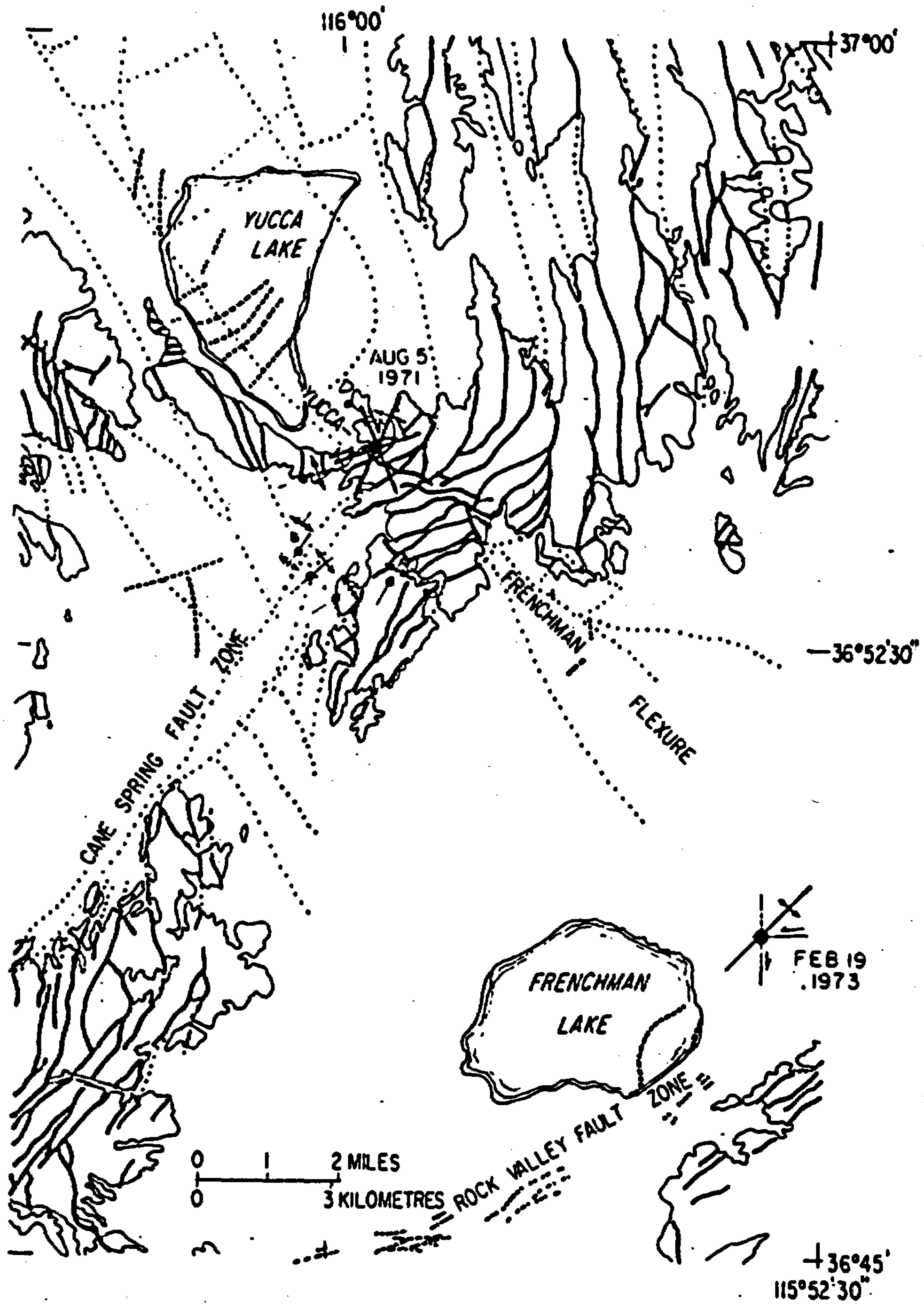

Figure 11.--Southern Yucca Flat and Frenchman Flat area, showing structural pattern, Quaternary faults and fractures, and location of earthquakes, their aftershocks, fault-plane solutions, and pressure axes.

of the southern tip of Yucca playa at a depth of 3 miles (4.6 km) (Fischer and others, 1972). Aftershocks had somewhat deeper hypocenters and were nearly all located in a northwesterly trending zone about a mile and a half (3.2 km) southwest of the main shock. According to Fischer (1972, p. 13) "the axis that bisects the quadrant of compressional first motions, the tension axis, has a near-horizontal, west-northwest orientation for both the main shock and the aftershocks" of the Massachusetts Mountain earthquake. In the main shock the strike of the pressure axis was N. 23° E., and the strike of the tension axis was N. 67° W. For the belt of northwest-trending aftershocks, the pressure axis varied from about N. 30° E. to N. 70° E., the average being about N. 45° E. Of the two fault-plane solutions, one trending N. 22° W. having right-lateral motion, the other trending N. 68° E. showing left-lateral motion, the plane striking northeast seems the most logical choice, as it coincides very closely with a prominent set of faults in the vicinity, many of which have slickensides indicating that the last movement was left-lateral slip. The trend and fault solutions for the aftershocks along a northwest-trending belt at depths of 4-6 miles (6-10 km) fit best with north-northwest-trending faults that cut the nearby CP hogback, but, significantly, the zone of aftershocks parallels a feature called the Yucca-Frenchman flexure (fig. 11 and W. J. Carr and others, unpub. data, 1967). The main shock and a few aftershocks were located very near the flexure at its intersection with the Cane Spring fault zone. The flexure is a right-lateral bend having a probable offset of about a mile (1.6 km). The flexure does not involve large-scale faulting in the tuffs along its trend, but it is well expressed in the gravity (W. J. Carr and others, unpub. data, 1967) and by bending of beds and faults of the Cane Spring system. It is apparent that both the flexure zone and the Cane Spring fault zone have been active concurrently and tend to offset one another. The greater depth of the aftershocks and the fact that most of the belt of aftershocks does not coincide with a mapped fault suggest that a subparallel right-lateral flexure zone may exist at depth across the Cane Spring fault zone but that its strain has not been sufficient to reach the surface in the form of faulting or bending.

The Frenchman Lake earthquake epicenter of February 19, 1973, was located by the USGS on alluvium about a mile (1.6 km) northeast of the Frenchman Lake playa (F. G. Fischer, oral commun., 1973). Preliminary data indicate an intensity and focus depth generally similar to the Massachusetts Mountain quake. Fischer reported the two fault-plane solutions as striking either east-west and having left-lateral slip or north-south and having right-lateral slip. Faults having this trend are not present at the surface in either the alluvium or nearby bedrock, so a choice between the two directions is difficult. The pressure axis, however, has the same trend as nearby faults in the alluvium and bedrock, which trend about N. 50° E. The two cracks in the Frenchman playa are within 1 1/2 miles (2.4 km) of the epicenter, and both the Massachusetts Mountain and Frenchman Lake epicenters lie near the intersection of major northeast-trending fault zones and the Yucca-Frenchman flexure.

Earthquake activity in the southern part of the test site (south of lat 37°) during the last 10 years has been concentrated beneath alluvial areas; of over 50 epicenters recorded for the period 1961-72 in the southern test site area (data supplied by F. G. Fischer; reported by E. B. Ekren, unpub. data, 1972) more than three-fourths of the locations were beneath alluvium, even though bedrock exposures constitute about two-thirds of the area. Thus, present activity is occurring in areas of previous subsidence.

Fault-plane solutions for west-central Nevada, about 200 miles (125 km) northwest of NTS, also suggest a northwesterly oriented minimum principal stress direction and regional extension in a northwest-southeast direction (Ryall and Malone, 1971; Gumper and Scholz, 1971).

Strain measurements

Observations of regional strain variations (Smith and Kind, 1972) from strain meters in the test site region indicate that deformation over a large area occurred episodically in an 8-month period in 1971. In each episode the directions of the principal axes remained the same--northwest and northeast. Although some episodes of northwest extension were recorded during the interval observed, the net effect over the 8-month period was northeast-southwest compression. The apparent lack of correlation of stress relaxation with seismic activity led Smith and Kind to conclude that substantial strain changes can occur in the region without earthquakes. They failed to mention, however, that the Massachusetts Mountain earthquake occurred on August 5, 1971, precisely at the end of their published strain records.

Stress measurements and estimates

The relatively uniform spacing of the four cracks in Yucca playa provides a means for estimating the amount of stress causing them. According to Lachenbruch (1961), a relation exists between crack spacing, crack depth, and amount of stress. Lachenbruch's equations were rearranged by G. E. Brethauer (written commun., 1973) and used to calculate horizontal tectonic tensile stress. The gravitational stress is assumed to be hydrostatic and equal to the weight of the overlying rock. All stress components of a hydrostatic stress field are equal. The formula used by Brethauer is:

$$p = \frac{b\delta}{3.8}$$

where p is the tensile stress in psi, b is the depth of cracking in feet, and δ is the density of the medium in grams per cubic centimetre. Unit conversions are contained in the constant 3.8. The horizontal tectonic stress necessary to produce cracking is assumed equal to the tensile stress, p, minus the horizontal gravitational stress.

The results are given in table 1 for several assumed crack depths and for two densities, which probably include the actual average value for the density of the playa section.

Another possible loading condition, according to Brethauer, would be Poisson's loading criterion, the equation for which would become:

$$p = \frac{b\delta}{3.8} \frac{(\mu)}{(1-\mu)}$$

Table 2 summarizes values for the Poisson gravitational stress for the same crack depth and media densities.

Table 1.--Horizontal gravitational (hydrostatic) and tectonic stress for assumed crack depths

[- indicates tension]

Crack depth (metres)	Crack depth (feet)	Density 1.7 g/cc: Horizontal tectonic stress (kg/cm²)	Density 1.7 g/cc: Horizontal tectonic stress (psi)	Density 1.7 g/cc: Horizontal gravitational stress (kg/cm²)	Density 1.7 g/cc: Horizontal gravitational stress (psi)	Density 2.0 g/cc: Horizontal tectonic stress (kg/cm²)	Density 2.0 g/cc: Horizontal tectonic stress (psi)	Density 2.0 g/cc: Horizontal gravitational stress (kg/cm²)	Density 2.0 g/cc: Horizontal gravitational stress (psi)
365	1,200	-38	-537	34	483	-44	-632	40	568
410	1,350	-42	-604	38	544	-50	-710	45	640
455	1,500	-47	-671	42	604	-55	-789	50	711
610	2,000	-63	-895	56	806	-74	-1,053	66	948

Table 2.--Horizontal gravitational (Poisson) and tectonic stress for assumed crack depths

[- indicates tension]

Crack depth		Density 1.7 g/cc				Density 2.0 g/cc			
		Horizontal tectonic stress		Horizontal gravitational stress		Horizontal tectonic stress		Horizontal gravitational stress	
(metres)	(feet)	(kg/cm^2)	(psi)	(kg/cm^2)	(psi)	(kg/cm^2)	(psi)	(kg/cm^2)	(psi)
366	1,200	-8.5	-121	7.5	109	-10.0	-142	9.0	128
411	1,350	-9.5	-136	8.5	122	-11.0	-160	10.0	144
457	1,500	-10.5	-151	9.5	136	-12.5	-178	11.0	160
610	2,000	-14.0	-201	12.5	181	-19.0	-272	17.0	245

The spacing between cracks A and B (fig. 6) ranges from 600 feet (180 m) to 2,000 feet (610 m), averaging about 1,300 feet (400 m); between cracks B and C from 1,000 to 1,400 feet (305 m to 425 m), averaging about 1,200 feet (365 m); and between cracks C and D from 1,900 feet (580 m) to 2,500 feet (760 m), averaging about 2,200 feet (670 m).

If it is assumed from Lachenbruch's study that the crack spacing is approximately equal to crack depth, an estimate of stress is possible from the figures in tables 1 and 2. The tectonic tensile stress would range from about 42 kg/cm^2 (600 psi) to about 77 kg/cm^2 (1,100 psi) in the hydrostatic condition, and from about 9.1 kg/cm^2 (130 psi) to about 15.8 kg/cm^2 (225 psi) if the Poisson loading criterion is used. The latter method gives distinctly lower values but is considered more realistic in terms of the physical properties of the medium.

Stress measurements have been made by the USGS and U.S. Bureau of Mines in two tunnels under Rainier Mesa. In U12t.02 at a depth of 1,175 feet (360 m) the principal compressional stress direction is N. 28° E. and the maximum excess (tectonic) horizontal stress is 41 kg/cm^2 (586 psi) (H. W. Dodge, Jr., oral commun., 1973). The axis of maximum principal stress is inclined about 3° from the horizontal. In U12n.07 bypass drift, at a depth of 1,250 feet (380 m) the direction of maximum principal stress is N. 47° E. and the excess horizontal stress is 68 kg/cm^2 (972 psi) (V. E. Hooker and others, written commun., 1971). This direction is inclined about 20° from the horizontal.

It has been suggested (V. E. Hooker and others, written commun., 1971) that the stress directions are influenced by the free face of Rainier Mesa, to which the maximum principal stress direction is roughly parallel. Such an influence is possible, but perhaps not very likely, because the measurements were taken more than 2,000 feet (600 m) from the nearest point on the face of the mesa.

Other stress-measurement data were reported by Obert (1963, 1964) from tunnels at Rainier Mesa and in the granitic rock of the Climax stock near the northwest corner of Yucca Flat. These data are being analyzed by G. E. Brethauer, who reports (oral commun., 1974) variations of several hundred psi, some of which is probably due to local geologic effects and some to measurement techniques. Additional data reported by Wright (1967) for the Climax stock have not been evaluated.

Drill-hole enlargement

Since the discovery that some drill holes in Yucca Flat are preferentially enlarged, directions of enlargement have been determined for six holes (R. D. McArthur and W. D. Quinlivan, written commun., 1972):

U9ck	northwest to west
U9ITSw24.5	northwest to west
U9cg	N. 20° W. to N. 60° W.
U9ci	northwest
U10ax	east-west to west-northwest
U2bs	N. 60° W. to N. 80° W.

In addition, caliper logs show that many other, but not all, holes in Yucca Flat are enlarged in an unknown direction. Of 96 holes having six-arm caliper logs, about 40 percent show no preferential enlargement.

The average direction of enlargement for the six holes that have been determined is roughly N. 60° W., a direction very compatible with other information assuming that the direction of enlargement represents the direction of minimum principal stress. In the few cases where the enlarged hole has been photographed or viewed by downhole television, the enlargement takes the form of planes of spalling in the northwest and southeast quadrants of the hole, leaving the northeast and southwest quadrants virtually undisturbed.

Other geologic evidence of extension

Two additional pieces of evidence may be cited in support of northwest-southeast extension. W. D. Quinlivan has pointed out an interesting possible analogy to the enlarged drill-hole phenomenon: the Timber Mountain caldera complex, which might be comparable to a huge drill hole in a stress field, has a northwest elongation (fig. 2), the direction being about N. 55° W. The Timber Mountain caldera formed about 11 m.y. ago.

A large Tertiary pluton, which probably underlies much of the northwestern part of the test site area as magnetically defined, has a very distinct northwest-southeast elongation (fig. 2). Interestingly, the Cretaceous plutonic rocks, including the connected Climax and Gold Meadows stocks, trend more nearly east-west, a direction that could have been related to the general development of a Mesozoic structural grain of the test site area. Possibly the same mechanism of spalling in the direction of minimum principal stress could operate during emplacement of a shallow pluton to produce an elongation of the intrusive body in that direction.

DISCUSSION AND CONCLUSIONS

The evidence for a northwest-southeast axis of minimum principal stress for the test site appears good. After I had proposed the stress model for the test site area, a paper was published by Thompson and Burke (1973) that further strengthens this conclusion. Their paper discussed the rate and direction of spreading in Dixie Valley, Nev., which lies in the Nevada-California seismic belt in west-central Nevada (about 37 mi., 60 km north of fig. 1) and occupies a position north of the Walker Lane similar to that of Yucca Flat. Dixie Valley is one of the large north-northeast-trending basins of western Nevada, and lies about 40 miles (65 km) north of the north edge of the Walker Lane. Shawe (1965) has summarized the evidence revealed by historical faulting for strike-slip control of basin-range structure in western Nevada. He noted that deformation changed southward toward the Walker Lane from predominantly dip-slip on the north to strike-slip on the south.

By study of slickensides on fault planes exposed on the west side of Dixie Valley, Thompson and Burke (1973) concluded that the spreading direction for Dixie Valley is N. 55° W. to S. 55° E., and that the north-northeast-trending basin as a whole has a slight right-lateral component of displacement within it. They commented that this direction appears to be fairly consistent over a wide region of the Basin and Range province. Evidence presented in this report strongly supports this general statement, but it should be remembered that the area being considered is not the entire Basin and Range, but rather the Walker Lane and adjacent part of the Great Basin.

There is evidence suggesting that the structural style that probably began to develop in Pliocene time in the test site area with the formation of relatively narrow deep troughs is continuing at present, which, if correct, suggests that the present general stress configuration has existed for several million years. There is a strong hint that present seismic activity in the southwestern Great Basin is generally avoiding Paleozoic and older rocks and is concentrated in areas currently receiving alluvium. In some areas seismic activity is occurring in areas of volcanic rocks of Miocene and Pliocene age, in particular, in areas of volcanic centers or calderas.

Alluvial deposits are very rare, but unconformities are present within the volcanic section in Yucca Flat and elsewhere in the test site region, indicating a period of from roughly 17 to 7 m.y. ago, in which there were few, if any, deep closed basins of the type that now exist. Conglomerates intertongue with mainly the lower parts of the volcanic section near the edges of the volcanic fields, but these gravels are typically fluviatile in appearance and are locally associated with lacustrine limestones. These sediments are unlike the detritus now accumulating in the basins. In the subsurface in Yucca and Frenchman Flats is a widespread deposit of very tuffaceous alluvium postdating the Ammonia Tanks Member of the Timber Mountain Tuff. This unit is present nearly everywhere in the deeper parts of the basins. It contains very few Paleozoic clasts and represents a period of stripping of the tuff from the Paleozoic rocks. In northern Frenchman Flat on the flanks of the Frenchman basin, part of this alluvium underlies the Thirsty Canyon Tuff, which is about 7.5 m.y. old. It can also be shown that most of the highly tuffaceous alluvium was accumulated and much of the subsidence and accompanying faulting of the northern part of the Frenchman basin occurred between about 10 and 2 m.y. ago, because of the presence in the alluvium of nearly flat-lying basalt lavas above the steeply dipping and faulted volcanic rocks (W. J. Carr and others, unpub. data, 1967). In southwestern Yucca Flat, however, there is evidence that deep basin formation may be somewhat younger, because basalt flows intercalated in the alluvium are apparently tilted northwestward and faulted (fig. 8). Both Frenchman and Yucca playas are about 3 miles (4.8 km) southeast of the deepest parts of the two basins. The site of playa sediment deposition has migrated southeastward, but young regional tilting of any magnitude seems unlikely because of the lack of tilting of Pliocene or Pleistocene basalt flows in some areas.

Although precise relations between the stress pattern and structures at the Nevada Test Site cannot be demonstrated, much evidence is in accord with the general idea of northwest-southeast extension, at least along and adjacent to the Walker Lane, and with the idea of the formation of deep basins, within the last 10 m.y. and locally within the last 4 m.y. The localization of basin development implies a fundamental change either in the mechanisms generating the stress or in the physical character of the crust. Locally these basins are undergoing extension and subsidence at the present time. The lack of young faults having a northwest trend in the test site region suggests that the minimum principal stress lies in the northwest-southeast direction, and that stress relief is occurring by bending or in small increments. It is suggested that postvolcanism crystallization of large plutons of granitic rocks beneath and adjacent to the many volcanic centers of the central Walker Lane may have played a part in the initiation of this phase of basin-range development by increasing the capability of the crust to transmit stress and by "spot-welding" the upper crust to the infrastructure, thereby better translating the deep lateral stresses to the surface rocks. The spacing of active basin-range faults may thus be related to the effective thickness of competent crust, the effect of the crystalline rocks being to modulate the spacing of basin-range faults and, hence, basin formation.

None of the very general conclusions of this report should be taken as obviating the need for stress measurements at the test site and elsewhere in the Great Basin. Ideally, quantitative stress measurements should be made in alluvium, tuff, and Paleozoic rocks at several places in the test site so as to determine what local variations may exist. Measurements should be made in highly faulted areas, such as along the east side of Yucca Flat, and in areas of minor faulting, such as the northern Eleana Range and in the southwestern Frenchman Flat area where the structural grain is different from that farther north. Measurements should also be made in zones having a history of right-lateral and left-lateral faulting, such as the Yucca-Frenchman flexure and Cane Spring fault zone.

REFERENCES CITED

Albers, J. P., 1967, Belt of sigmoidal bending and right-lateral faulting in the western Great Basin: Geol. Soc. America Bull., v. 78, p. 143-156.

Anderson, R. E., 1971, Thin skin distension in Tertiary rocks of southeastern Nevada--Reply: Geol. Soc. America Bull., v. 82, p. 3533-3536.

Barnes, Harley, Christiansen, R. L., and Byers, F. M., Jr., 1965, Geologic map of the Jangle Ridge quadrangle, Nye and Lincoln Counties, Nevada: U.S. Geol. Survey Geol. Quad. Map GQ-363.

Barnes, Harley, and Poole, F. G., 1968, Regional thrust fault system in Nevada Test Site and vicinity, in Nevada Test Site: Geol. Soc. America Mem. 110, p. 233-238.

Barosh, P. J., 1968, Relationship of explosion-produced fracture patterns to geologic structure in Yucca Flat, Nevada Test Site, in Nevada Test Site: Geol. Soc. America Mem. 110, p. 199-217.

Bucknam, R. C., 1969, Geologic effects of the Benham underground nuclear explosion, Nevada Test Site: Seismol. Soc. America Bull., v, 59, no. 6, p. 2209-2220.

______1973, Some factors relevant to the determination of in situ stress by analysis of geological and geophysical data: U.S. Geol. Survey rept. USGS-474-168, 20 p.; available only from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Byerlee, J. C., 1967, Frictional characteristics of granite under high confining pressure: Jour. Geophys. Research, v. 72, p. 3639-3648.

Byers, F. M., Jr., and Barnes, Harley, 1967, Geologic map of the Paiute Ridge quadrangle, Nye and Lincoln Counties, Nevada: U.S. Geol. Survey Geol. Quad. Map GQ-577.

Christiansen, R. L., Lipman, P. W., Orkild, P. P., and Byers, F. M., Jr., 1965, Structure of the Timber Mountain caldera, southern Nevada, and its relation to basin-range structure, in Geological Survey research 1965: U.S. Geol. Survey Prof. Paper 525-B, p. B43-B48.

Dickey, D. D., 1968, Fault displacement as a result of underground nuclear explosions, in Nevada Test Site: Geol. Soc. America Mem. 110, p. 219-232.

Donath, F. E., 1962, Analysis of basin-range structure, south-central Oregon: Geol. Soc. America Bull., v. 73, no. 1, p. 1-16.

Ekren, E. B., Rogers, C. L., Anderson, R. E., and Orkild, P. P., 1968, Age of basin and range normal faults in Nevada Test Site and Nellis Air Force Range, Nevada, in Nevada Test Site: Geol. Soc. America Mem. 110, p. 247-250.

Fischer, F. G., Papanek, P. J., and Hamilton, R. M., 1972, The Massachusetts Mountain earthquake of 5 August 1971 and its aftershocks, Nevada Test Site: U.S. Geol. Survey rept. USGS-474-149, 16 p.; available only from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Gilbert, C. M., and Reynolds, M. W., 1973, Character and chronology of basin development--Western margin of the Basin and Range province: Geol. Soc. America Bull., v. 84, no. 8, p. 2489-2510.

Gumper, F. J., and Scholz, Christopher, 1971, Microseismicity and tectonics of the Nevada seismic zone: Seismol. Soc. America Bull., v. 61, no. 5, p. 1413-1432.

Hamblin, W. K., 1965, Origin of "reverse drag" on the downthrown side of normal faults: Geol. Soc. America Bull., v. 76, no. 10, p. 1145-1146.

Hamilton, R. M., and Healy, J. H., 1969, Aftershocks of the Benham nuclear explosion: Seismol. Soc. America Bull., v. 59, p. 2271-2281.

Lachenbruch, A. H., 1961, Depth and spacing of tension cracks: Jour. Geophys. Research, v. 66, no. 12, p. 4273-4292.

Locke, Augustus, Billingsley, P. R., and Mays, E. B., 1940, Sierra Nevada tectonic patterns: Geol. Soc. America Bull., v. 51, p. 513-540.

Longwell, C. R., 1960, Possible explanation of diverse structural patterns in southern Nevada: Am. Jour. Sci., v. 258-A, p. 192-203.

McKee, E. H., 1968, Geology of the Magruder Mountain area, Nevada-California: U.S. Geol. Survey Bull. 1251-H, p. 36-37.

Moore, J. G., 1960, Curvature of normal faults in the Basin and Range province of the western United States, in Short papers in the geological sciences: U.S. Geol. Survey Prof. Paper 400-B, p. B409-B411.

Obert, Leonard, 1963, Static stress determinations; Shot Hardhat: W.T. 1804; available from U.S. Dept. Defense, Washington, D.C.

______1964, In situ stresses in rocks, Rainier Mesa, NTS: W.T. 1869; available from U.S. Dept. Defense, Washington, D.C.

Papanek, P. J., and Hamilton, R. M., 1972, A seismicity study along the northern Death Valley-Furnace Creek fault zone, California-Nevada boundary: U.S. Geol. Survey rept. USGS-474-141, 37 p; available only from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Poole, F. G., Elston, D. P., and Carr, W. J., 1965, Geologic map of the Cane Spring quadrangle, Nye County, Nevada: U.S. Geol. Survey Geol. Quad. Map GQ-455.

Ryall, Alan, and Malone, S. D., 1971, Earthquake distribution and mechanism of faulting in the Rainbow Mountain-Dixie Valley-Fairview Peak area, central Nevada: Jour. Geophys. Research, v. 76, no. 29, p. 7241-7248.

Sargent, K. A., Dixon, G. L., and Spengler, R. W., 1972, Lithologic logs and stratigraphic identification of exploratory and emplacement drill holes in Area 7, Nevada Test Site: U.S. Geol. Survey rept. USGS-474-152, 70 p.; available only from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Shawe, D. R., 1965, Strike-slip control of basin-range structure indicated by historical faults in western Nevada: Geol. Soc. America Bull., v. 76, p. 1361-1378.

Smith, S. W., and Kind, Rainier, 1972, Observations of regional strain variations: Jour. Geophys. Research, v. 77, no. 26, p. 4976-4980.

Snyder, R. P., 1973, Recent fault movement on Pahute Mesa, Nevada Test Site, from May 1970 through June 1973: U.S. Geol. Survey rept. USGS-474-137, 28 p.; available only from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Stewart, J. H., 1967, Possible large right-lateral displacement along fault and shear zones in the Death Valley-Las Vegas area, California and Nevada: Geol. Soc. America Bull., v. 78, p. 131-142.

______1971, Basin and range structure: A system of horsts and grabens produced by deep-seated extension: Geol. Soc. America Bull., v. 82, no. 4, p. 1019-1044.

Thompson, G. A., and Burke, D. B., 1973, Rate and direction of spreading in Dixie Valley, Basin and Range province, Nevada: Geol. Soc. America Bull., v. 84, no. 2, p. 627-632.

Wright, F. H., 1967, In situ rock stress, Shot Pile Driver: W.T. 4005; available from U.S. Dept. Defense, Washington, D.C.

Wright, L. A., and Troxel, B. W., 1968, Evidence of northwestward crustal spreading and transform faulting in the southwestern part of the Great Basin, California and Nevada [abs.]: Geol. Soc. America Program, 64th Ann. Mtg. Cordilleran Sec., 1968, Tucson, Ariz., p. 131-132.

FOR MAP SEE SCP REF # 64

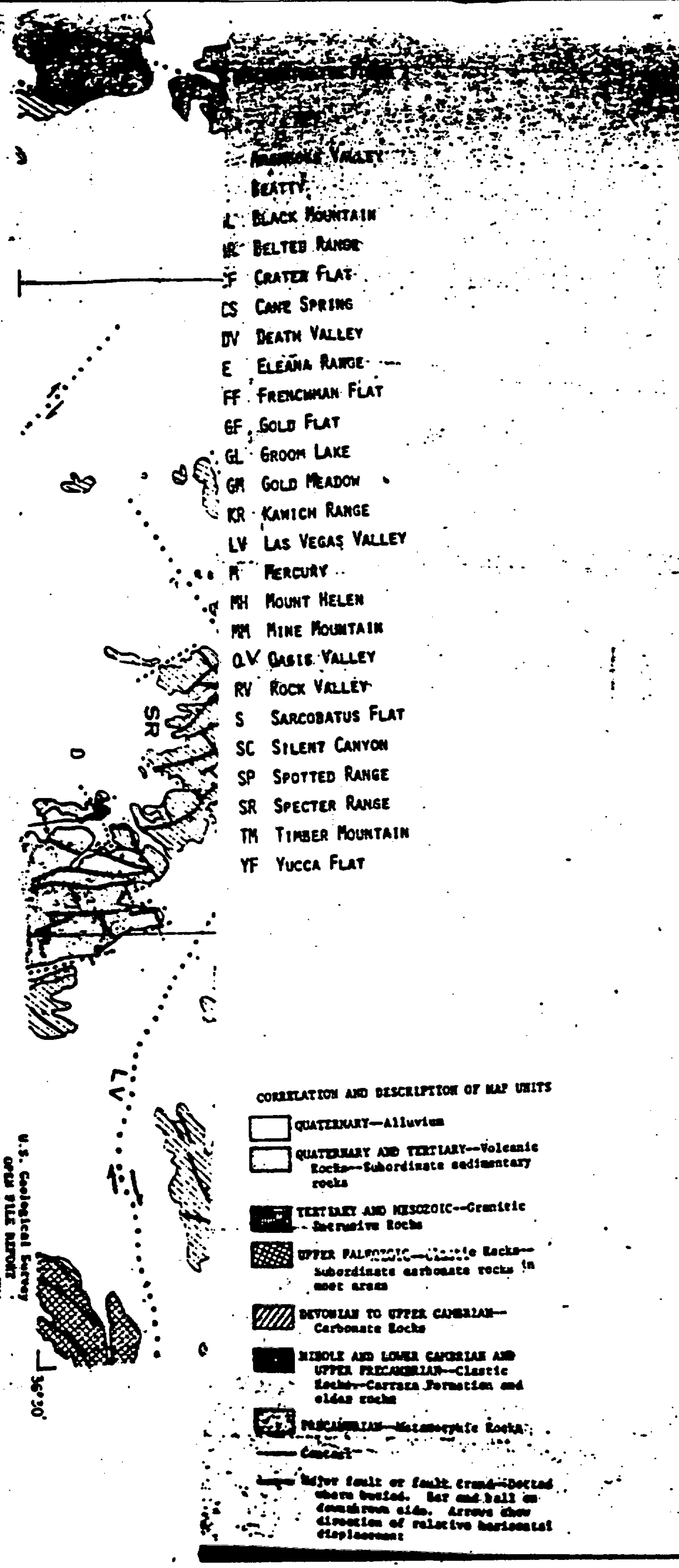

Figure 2.--Generalized structure of Nevada Test Site region.

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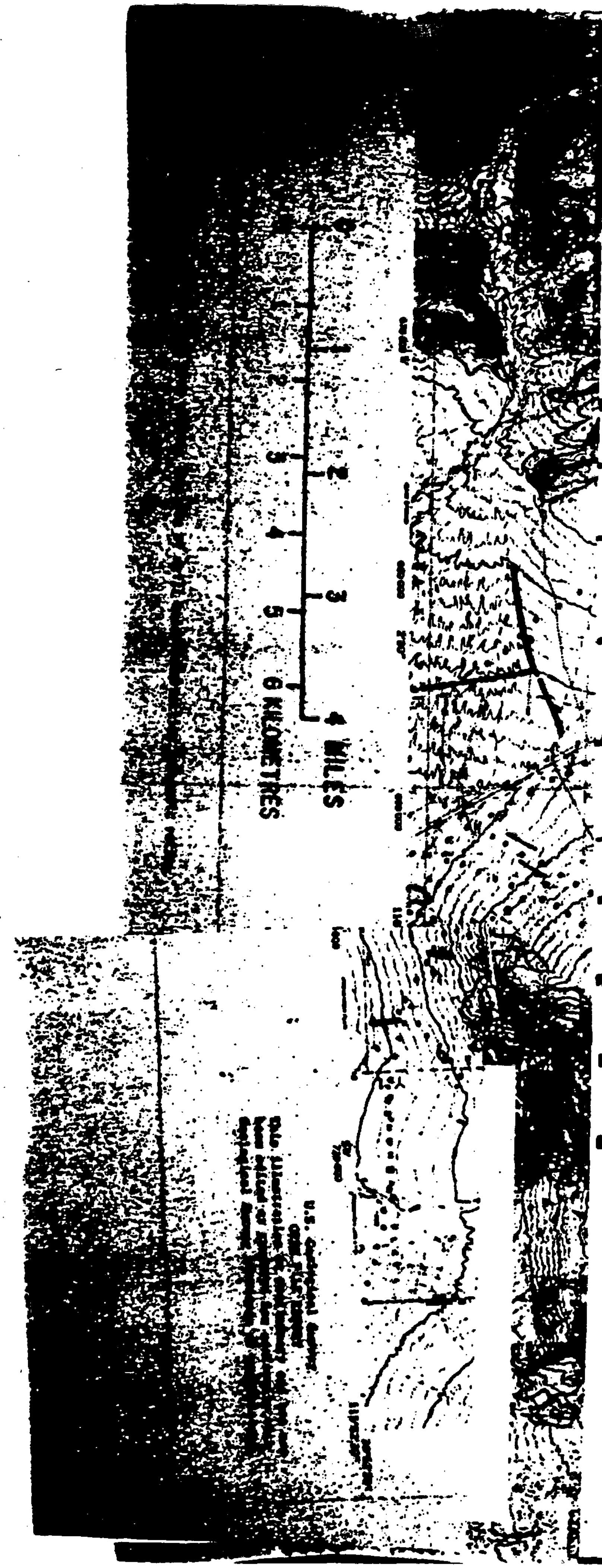
This map is preliminary and has not been edited or reviewed for conformity with Geological Survey standards.



FOR MAP SEE SCP REF # 64

EXPLANATION

Faults and fractures of Quaternary age:

Fault—Shot-induced movement

Fault of Quaternary age—Ball on downthrown side

Fracture or fracture zone—Natural or shot-induced

Fault—Dotted where buried; ball or D on downthrown side

Thrust fault—Broken where buried; teeth on upper plate

Anticlinal axis

Synclinal axis—Dashed where buried or doubtful

Approximate trace of Eureka Quartzite—Probable subsurface dip directions show by arrow

Approximate trace of Dunderbe Shale of Hopah Formation—Probable subsurface dip directions shown by arrow

Approximate trace of Zabriski Quartzite—Probable subsurface dip directions show by arrow

Ue 2od

Drill hole

Upper plate

Devonian through Precambrian rocks—Predominantly carbo

Lower plate

Mississippian and Devonian ro Predominantly clastic

Cretaceous intrusive rocks