# Large-Magnitude Late Tertiary Strike-Slip Faulting North of Lake Mead, Nevada

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*By* R. ERNEST ANDERSON

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*Geologic mapping of 115-square-mile area indicates major northeast-trending fault system with estimated 40-mile left-lateral displacement*

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# LARGE-MAGNITUDE LATE TERTIARY STRIKE-SLIP FAULTING NORTH OF LAKE MEAD, NEVADA

By R. Ernest Anderson

## ABSTRACT

In late Miocene time, in what is now the Lake Mead area of southern Nevada, an andesitic stratovolcano, the Hamblin-Cleopatra volcano, formed at or near the northern boundary of a broad late-Cenozoic volcanic terrain that developed on a platform of Precambrian crystalline rock. The boundary may have been a hinge line or a major fault zone prior to formation of the volcano. After the volcano formed, it was disrupted into three principal parts by as much as 12 miles of left-lateral displacement on a system of northeast-trending strike-slip and oblique-slip faults that now mark the boundary. Other faults of the same system displace Tertiary and pre-Tertiary sedimentary rocks in the area north and northwest of the disrupted volcano. The cumulative displacement on the entire fault zone is estimated at 40 miles.

The area northwest of the disrupted volcano consists of several large blocks that are tilted steeply east or southeast and are separated from one another by complex fault zones of the strike-slip system. Some strike-slip fault traces parallel the general strike of the strata, and in such areas small-scale folds and normal faults that are genetically related to the strike-slip faults are well developed. The small-scale structures bear a geometric relationship to the strike-slip faults analogous to that reported for similar fold and fault structures associated with major strike-slip faults in New Zealand. Where the strike-slip faults cross the trend of the tilted blocks, large-scale first-order drag folds with steeply to vertically plunging axes are developed. Some normal faults in the northwest area are probably equal in rank to the strike-slip faults and are part of a single movement pattern analogous to that reported for the area south of Lake Mead.

South of the northeast-trending shear zone, vertical displacements of about 6,000 feet occurred on north-trending normal faults that were active during at least the late stages of strike-slip displacements. The largest of these normal faults bound the elevated Wilson Ridge mass of the Black Mountains against the structurally depressed Detrital Valley block on the east and the Colorado River block on the west. Where the strike-slip and normal faults intersect there is complex interaction between the two. Some strike-slip displacement seems to be translated into normal displacement, and a simplistic model presented herein interprets the mechanics of that interaction. That area provides an excellent example of diverse types of simultaneous deformation that are produced in the Western United States by strong local inhomogeneities in stress fields.

The Las Vegas shear zone must pass north of the mapped area with possibly as much as 45 miles of right-lateral separation to account for the abrupt southward termination of the compressional structures of the Sevier orogenic belt. If this is so, the rocks between the Las Vegas shear zone and the shear zone that passes through the mapped area have been shifted about 40 miles westward relative to the terrain to the north and south. Such large-scale shift of a narrow crustal belt can be explained best by assuming their transport, piggyback, on a fast-moving current of mantle and possibly lower crustal plastic material that was banked against and deflected around the margin of the Colorado Plateau. An alternative interpretation which does not take movement on the Las Vegas shear zone into account is that the northeast-trending left-lateral shear system is a structural feature that compensates for contrasting amounts of extensional strain as the Basin and Range structural province broadens northward around the Colorado Plateau. An analogous interpretation can be made for the Garlock fault, which has similar trend and sense of displacement.

## INTRODUCTION AND ACKNOWLEDGMENTS

Erosion by the Colorado River in the vicinity of Lake Mead has removed much upper Tertiary and Quaternary basin fill and locally has cut deeply into bedrock, thereby producing excellent exposures within the Basin and Range structural province. The elevation of a pre-Colorado River fossil water table indicates as much as 1,800 feet of downcutting near Hoover Dam in the last 2.6 million years (Anderson, 1969). The excellence of exposures, together with indications of exotic structural relationships revealed in reconnaissance mapping by Longwell (1963) and Longwell, Pampeyan, Bowyer, and Roberts (1965), led in 1969 to a mapping study of transcurrent faults and other structures in the Lake Mead area. The present report results from those studies, as have other published reports (Anderson, 1969, 1971a, 1971b; Anderson and others, 1972).

This report describes the results of geologic mapping of about 115 square miles at the north end of the Black Mountains north of Lake Mead (fig. 1). Much of the mapping was detailed reconnaissance with some reliance on photogeologic interpretation, but because the study emphasized the area's structural geology, detailed field mapping was done in numerous structurally critical areas, especially along major fault zones.

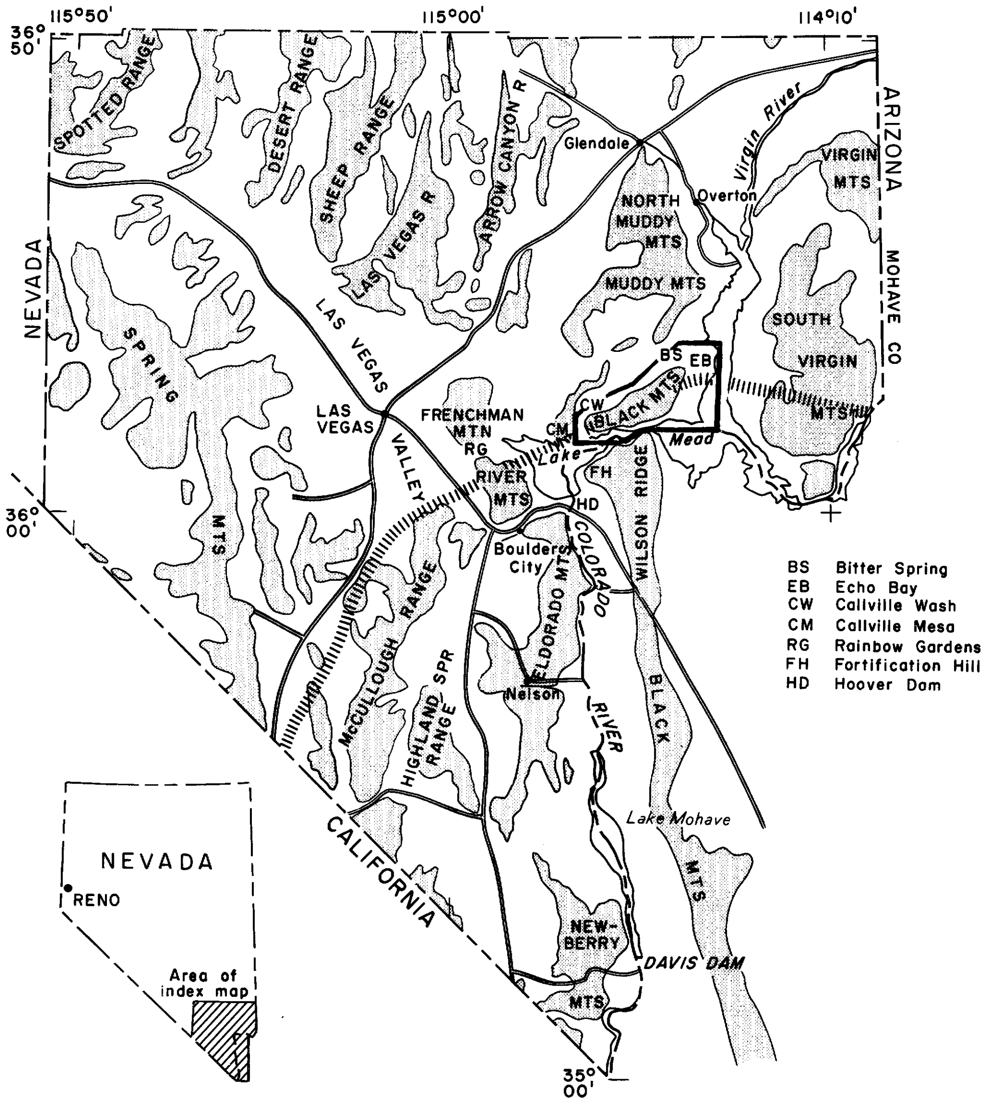


FIGURE 1. — Index map of Clark County, Nev., and part of Mohave County, Ariz., showing location of mapped area (heavy line) and major cultural and physiographic features. Hachured line marks boundary between thick Paleozoic, Mesozoic, and Tertiary sedimentary rocks to the north and Precambrian crystalline and Tertiary igneous rocks to the south.

The area consists of Precambrian crystalline rocks, about 6,000 feet of Permian and Mesozoic sedimentary rocks, and a variegated sequence of Tertiary volcanic, plutonic, and sedimentary rocks, some sections of which exceed 3,000 feet in thickness (pl. 1). The area lies across a northeast-trending join between a broad area of thick Paleozoic, Mesozoic, and Tertiary sedimentary rocks to the north and a broad area of Precambrian crystalline and Tertiary volcanic and plutonic rocks to the south (fig. 1). This report describes the nature of this join north of Lake Mead and comments on its regional tectonic significance.

Geologic mapping was conducted on a part-time basis, during the winters of 1970 and 1971, as other commitments would permit. I am grateful to W. S. Twenhofel for his continued interest in this work. I am also grateful to personnel of the National Park Service who provided me with boat shuttle service to areas of difficult access along the shores of Lake Mead.

C. R. Longwell and R. C. Bucknam read an early version of the manuscript and made several helpful suggestions. Harley Barnes and Robert L. Smith provided technical reviews that were very helpful, and I thank them.

## STRATIGRAPHY

The following brief discussion of stratigraphy outlines salient features and suggested correlations that together form a basis for subsequent structural interpretations.

Precambrian, Paleozoic, Mesozoic, and Cenozoic rocks crop out in the mapped area. Gneiss, schist, and pegmatite of Precambrian age occur as scattered xenolithic masses within the Wilson Ridge pluton (Anderson and others, 1972) that forms the south-central part of the mapped area. Only the largest mass is shown on the geologic map (pl. 1). Precambrian rocks also occur as horses and breccias along some of the major faults. Some masses are several hundred feet across; the only one shown is east of Callville Wash (pl. 1). Many resemble the rapakivi-type granites mapped and described by Volborth (1962) in the Gold Butte area about 10 miles east of the mapped area.

Rocks ranging from Cambrian through Pennsylvanian are not exposed in the mapped area. Inasmuch as they are exposed to the west on Frenchman Mountain and to the east in the South Virgin Mountains, they probably occur in the subsurface of the north-central part of the mapped area. Permian and Mesozoic rocks are exposed widely in the north-central part. These sedimentary strata were briefly described for the Clark County area by Longwell, Pampeyan, Bowyer, and Roberts (1965, p. 29–42) and for the South Virgin Mountains by Morgan (1968). Although numerous formational and lower stratigraphic rankings are recognized in these strata, the geologic map (pl. 1) shows only divisions into Permian, Triassic, and Jurassic(?) rocks.

### PERMIAN ROCKS

Highly faulted limestone that resembles the upper part (Permian) of the Callville Limestone (Longwell and others, 1965) occurs in the southwestern part of the Echo Hills. These rocks are probably the oldest Paleozoic rocks exposed in the mapped area. They are overlain by at least 1,000 feet of faulted and steeply tilted red beds that are probably equivalent to strata mapped by Longwell, Pampeyan, Bowyer, and Roberts (1965) as Permian red beds. Similar structurally disturbed strata occur north of Hamblin Mountain. At both localities the dominant lithology is slightly calcareous red, gray, and pink crossbedded sandstone. The red beds are overlain by light-brown to grayish-orange thin-bedded slightly calcareous sandstone in which planar crossbed sets a few feet thick are conspicuous. These rocks resemble the Coconino Sandstone, but their thickness — in excess of 300 feet north of Hamblin Mountain and in excess of 100 feet in the Echo Hills — is anomalously large for the Coconino in this area (Longwell and others, 1965, p. 36; Morgan, 1968, p. 22).

Permian rocks in the area are mostly limestone of the Toroweap Formation and the overlying Kaibab Limestone. These rocks are resistant to erosion and form the higher parts of such prominences as Pinto Ridge, the Echo Hills, and the hills north of Hamblin Mountain. The lower part of the Toroweap Formation is well exposed north of Hamblin Mountain and in the Echo Hills. North of Hamblin Mountain, the lower part of the Toroweap consists of about 50 feet of weakly resistant sandstone, shale, and gypsum. In the Echo Hills it consists of 40 feet of medium- to thick-bedded pink, yellow, and tan calcareous sandstone with dark limestone interbeds a few inches thick; gypsum is sparse to absent. At both localities the Toroweap rests with apparent conformity on the Coconino(?) Sandstone.

The Kaibab and Toroweap are among the most easily recognizable stratigraphic units because of their distinctive topographic expression. The Toroweap and Kaibab each contain a carbonate sequence 200–300 feet thick composed of distinctive gray limestone with abundant lenses and layers of dark-weathering chert. These resistant carbonate units are separated by about 100 feet of relatively nonresistant sandstone, shale, and gypsum in the upper part of the Toroweap. Differential erosion results in a characteristic double cliff or, in areas of steep tilting, a double ridge.

### MESOZOIC ROCKS

Mesozoic rocks totaling about 4,100 feet in thickness are well exposed in the north-central part of the mapped area. The Mesozoic section is represented by three widespread formations — in ascending order, the Moenkopi and Chinle Formations of Triassic age and the Aztec Sandstone of Jurassic(?) age. The Aztec Sandstone is overlain by undated sedimentary rocks, the lower part of which may be Cretaceous in age. (See later description of Gale Hills Formation.)

The Moenkopi Formation is well exposed on the southeast flank of Pinto Ridge and in the Pinto Valley. The Moenkopi there is about 1,700 feet thick and comprises, in ascending order, rocks equivalent to the following members recognized in southwestern Utah by Gregory (1948, 1952): Timpoweap, lower red, Virgin Limestone, middle red, Shnabkaib, and upper red. As noted by McKee (1954) the various red members are in many respects lithologically similar. The Virgin Limestone Member, the most distinctive unit in the Moenkopi, consists of light-gray to yellowish-gray thin- to medium-bedded marine limestone and silty limestone that is much more resistant to erosion than the subjacent and superjacent red-bed units. The easily distinguished Virgin aids greatly in deciphering fold structures and fault offsets in the structurally complex area along the north-central margin of the mapped area.

The Chinle Formation consists mostly of red and brown mudstone, siltstone, and sandstone interstratified with gypsum. Except for the conglomerate of its Shinarump Member, which commonly forms a low discontinuous ridge at the base of the formation, the Chinle is weakly resistant and is poorly exposed along drainages in predominantly alluviated areas of low topography. Longwell, Pampeyan, Bowyer, and Roberts (1965, p. 40) reported a measured thickness of 905 feet for the Chinle at the head of Boulder Wash in Pinto Valley (pl. 1).

The Aztec Sandstone, very well exposed in a major ridge that parallels the Hamblin Bay fault, is a very distinctive quartz sandstone with uniform brick-red color and magnificent very thick crossbedding. At least 1,500 feet of Aztec is exposed near Sandstone Spring.

### TERTIARY ROCKS

The mapped area lies across the boundary between a broad northern area where Tertiary sedimentary rocks were deposited in local basins developed on Mesozoic and Paleozoic sedimentary rocks and a broad southern area where Tertiary rocks of predominantly igneous origin were intruded into and erupted onto Precambrian crystalline rocks (Longwell and others, 1965; Longwell, 1963; Anderson and others, 1972). Potassium-argon age data from the northern and southern areas indicate that much of the sedimentary sequence is contemporaneous with the igneous sequence and that most of the rocks are of Miocene and early Pliocene age (Anderson and others, 1972). In both areas these strata are overlain by sedimentary and volcanic rocks of the Muddy Creek Formation of Pliocene age. Following mapping by Longwell, Pampeyan, Bowyer, and Roberts, (1965) the pre-Muddy Creek sedimentary rocks in the northern part of the area are shown as the Gale Hills Formation (pl. 1). In the southern part of the area the pre-Muddy Creek rocks are mapped as rocks of the Hamblin-Cleopatra volcano and as unassigned volcanic and intrusive rocks.

#### GALE HILLS FORMATION

The Gale Hills Formation rests with either apparent conformity or low-angle unconformity on rocks ranging from the Kaibab Limestone to the Aztec Sandstone. The basal beds of the Gale Hills are conglomerate composed of angular to rounded sand- to boulder-size detritus derived from pre-Tertiary sedimentary rocks. The conglomerate, 50–100 feet thick, is very resistant to erosion owing to a tough carbonate cement, and it is generally well exposed in conspicuous brown to reddish-brown cliffs, such as those at the crest of Razorback Ridge and along the Hamblin Bay fault. In the latter exposures the conglomerate is overlain by about 200 feet of interbedded red, gray, and brown calcareous sandstone, siltstone, and arenaceous limestone that grades upward by decreasing amounts of clastic material into 200–300 feet of pale-yellow, light-gray, and white nonmarine limestone that is overlain by an unknown thickness of bedded white gypsum. Although the upper part has been removed by faults in many places, this clastic-carbonate-evaporite sequence shows remarkable stratigraphic continuity along the 9-mile extent of the ridge that parallels the Hamblin Bay fault. It is very similar to the lower part of the Thumb Formation of Cretaceous (?) age in the Rainbow Gardens area southeast of Frenchman Mountain (Longwell and others, 1965; Anderson and others, 1972). Whereas the basal beds of the Gale Hills consist of conglomerate throughout the mapped area, the overlying beds of the lower part of the formation show abrupt lateral stratigraphic variations from fault block to fault block along the northwest margin of the area (pl. 1). West of the Echo Hills, for example, the basal conglomerate is overlain directly by limestone beds several hundred feet thick. On the north flank of the Echo Hills, the conglomerate-sandstone-siltstone beds are overlain by a thick succession of bedded gypsum with only minor thin beds of interstratified carbonate in a transition zone 10–20 feet thick between the clastic and evaporite sequences.

The upper part of the Gale Hills Formation in the mapped area is a very complex assemblage of weakly resistant strata that consist mostly of light-red to grayish-pink sandstone and siltstone interstratified with beds of white gypsum, light-brown pebble to boulder conglomerate, and light-gray to very light gray bedded tuff and tuffaceous sandstone. Some clastic beds are slightly to strongly calcareous, and the unit contains sparse nonmarine limestone. These weakly resistant strata are generally found in topographically low areas such as north of Echo Bay, Bitter Spring Valley, and west and northwest of Hamblin Mountain. Although these areas are largely covered by alluvium, the Gale Hills strata dip at moderate to steep angles, and excellent partial sections are exposed along washes that bevel the beds. The upper part of the Gale Hills Formation is at least 3,000 feet thick in each of the three areas mentioned.

The lower part of the Gale Hills Formation has not been dated, as it has yielded no fossils and contains no volcanic materials. For the same reasons, no dating has been done on the lower part of the Thumb Formation with which the lower part of the Gale Hills may correlate. These rocks could be Cretaceous in age. Most of the rock in the upper part of the Gale Hills is correlative with either the Miocene Horse Spring Formation or the Tertiary upper part of the Thumb Formation (Anderson and others, 1972). Although faults complicate most stratigraphic sections, the upper and lower parts of the Gale Hills appear to be conformable, thus, perhaps, favoring a Tertiary age for the lower part of the formation in the mapped area.

### ROCKS OF THE HAMBLIN-CLEOPATRA VOLCANO

In late Miocene time an andesitic stratovolcano formed in what is now the northern extremity of the Black Mountains north of Lake Mead. The volcano has been disrupted into three principal parts by lateral displacements on a system of northeast-trending strike-slip and oblique-slip faults. From west to east, these parts are, for convenience, herein termed the Hamblin Mountain, middle, and Cleopatra Wash parts. Stratigraphic studies were made to determine whether the volcanic and sedimentary rocks in the disrupted parts of the volcano are correlative. To aid in this determination, petrographic studies were made of 30 thin sections of rocks collected mainly from the widely separated Hamblin Mountain and Cleopatra Wash parts.

The exposed parts of the Hamblin-Cleopatra volcano consists of about 2,500–3,000 feet of lavas and breccias that rest on perhaps as much as 700 feet of clastic sedimentary rocks and interstratified basaltic lavas. This sedimentary and volcanic sequence is cut by a magnificent system of coeval radial dikes and several irregular intrusive masses (pl. 1).

Sedimentary rocks are exposed beneath the main volcanic pile northeast of Saddle Mountain, at the southwest end of Pinto Valley, and in a horse northwest of Hamblin Mountain (pl. 1). At the southwest end of Pinto Valley, a highly faulted and steeply tilted section of sedimentary rocks is well exposed. The section consists from base to top of about 150 feet of red siltstone, sandstone, and pebble conglomerate; about 250 feet of pale-yellowish-orange, light-brown, and light-gray tuffaceous sandstone and siltstone interbedded with minor pebble and cobble conglomerate and basaltic lava; and about 300 feet of reddish-brown to grayish-purple sandy to conglomeratic volcaniclastic rocks composed of basaltic detritus and interstratified with basaltic lava. These volcaniclastic upper beds seemingly correlate with a sequence of similar dark volcaniclastic rocks 5 miles to the east in the middle part of the volcano, where the beds are intruded by numerous dikes. Sedimentary rocks were not found in the Cleopatra Wash part of the volcano, possibly because that part of the volcano is not sufficiently denuded. The clastic, volcaniclastic, and extrusive rocks beneath the main volcanic pile differ from the Gale Hills Formation, which is dominantly nonvolcanic. Their stratigraphic relationship to the Gale Hills is not known.

Most of the Hamblin-Cleopatra volcano consists of lava and autoclastic volcanic breccia. Pyroclastic and tuffaceous sedimentary rocks are conspicuously absent. Thick deposits of volcanic breccia that lack lava cores are especially common in the lower part of the volcano. Lavas are common in the upper part, but many have well developed and locally thick autoclastic breccia envelopes. Epiclastic volcanic breccias (mudflow breccias) characterized by clay- and sand-rich matrices occur at several horizons in the upper half of the volcanic pile. These breccias lack all but the most incipient of bedding features and probably resulted from downslope mass movement of unstable unconsolidated materials that were deposited on the upper slopes of the volcanic cone. These epiclastic breccias are distinctly lighter in color than the lavas and autoclastic breccias, and they are useful as marker beds. One particular autoclastic breccia that is well exposed beneath the capping dark lavas and flow breccias west of Cleopatra Wash is very similar in lithology, thickness, and stratigraphic position to a probable correlative breccia west of Hamblin Mountain. This correlation is strengthened by the occurrence in the uppermost strata of the volcano of a distinctive flow breccia in which very large dark-gray to black fragments are set in a gray or light-brown to yellowish-brown matrix. The flow breccia is found in all three parts of the volcano, and its correlation on the basis of general appearance was firmly established during numerous low-altitude flights conducted in conjunction with an Apollo 17 training mission in January 1972.

The lavas and breccias consist of mafic to intermediate rocks that lack intratelluric quartz and alkali feldspar. Augite andesite, augite-hypersthene andesite, augite-olivine andesite, and augite-hypersthene-olivine andesite are most common. Some of these rocks contain sparse amounts of hornblende and (or) biotite. In some of the volcanic rocks, olivine phenocrysts or pseudomorphs after olivine predominate over pyroxene, and these rocks are probably basalts or basaltic andesites. Lavas in which phenocrysts of hornblende plus biotite predominate over pyroxene were found at only two localities: (1) at the top of the volcanic pile in the middle part of the volcano, and (2) on the north flank of Hamblin Mountain near the top of that volcanic pile. Although the two lavas are very similar in mineral content, the phenocrysts in the rock on Hamblin Mountain are about four times the size of those in the rock from the middle part of the volcano. Thus, the two lavas are probably not exact equivalents even though their similar and somewhat unusual mineralogy and stratigraphic position suggest coevality.

The intensity of alteration generally increases downward in the volcanic piles in each part of the disrupted volcano; many of the rocks low in the section are propylites. Because of this alteration, stratigraphically high flows in each part of the volcano offer the best opportunity for direct correlation supported by petrographic data. As determined from petrographic studies of such strata, the northeast flank of Hamblin Mountain and the area south of Echo Bay contain some lavas that are virtually identical. Two-pyroxene andesites with or without olivine, hornblende, and biotite predominate in both areas. Nevertheless, these studies, perhaps because they were not sufficiently detailed, failed to provide strong evidence for direct correlation of flow sequences.

Each part of the volcano contains parts of a once-continuous and coherent system of radial dikes that intruded the core of the volcano. The dikes range in thickness from a few inches to 70 feet, and the larger ones are shown on the geologic map (pl. 1). The smaller ones are generally basalt; the larger ones, dacite or andesite. They have chilled margins against one another and against the volcanic country rock and are generally massive to faintly foliated. An upward change from dense to vesicular texture was noted in one dike south of Cleopatra Wash. In the northern part of Cleopatra Wash, northeast of Saddle Mountain, and near Sandy Cove, the dikes form as much as 80 percent of the volume of igneous rock. These are also the most highly altered parts of the volcano, and distinguishing volcanic rock from intrusive rock is very difficult. Accordingly, northeast of Saddle Mountain and near Sandy Cove the contacts shown between the volcanic-dike complex and the larger intrusive masses are only approximately located because the dike swarms there pass gradationally into the larger masses by decrease in abundance of volcanic rock. The larger intrusive masses are composed mostly of hornblende-pyroxene-biotite dacite. Hornblende- and biotite-rich rocks are more common in the intrusive than extrusive parts of the volcano, and they were not found in the lower part of the volcanic pile. They therefore apparently represent a youthful phase of the magmatism.

### UNASSIGNED VOLCANIC AND INTRUSIVE ROCKS

Volcanic and intrusive rocks that are not part of the Hamblin-Cleopatra volcano are found in the south-central mapped area and in a small area north of Hamblin Mountain. The best exposures of the volcanic rocks are in the Saddle Mountain area; there, more than 500 feet (base not exposed) of grayish-red-purple to dusky-brown phenocryst-poor basaltic andesite lava and flow breccia is overlain by as much as 500 feet of yellowish-gray to pale-greenish-yellow zeolitized bedded tuff which is overlain by at least 300 feet of gray to brownish-gray rhyodacite lava.

The volcanic rocks on Canyon Point are highly altered andesite(?). Their contact with the underlying intrusive is very diffuse and is located very approximately (pl. 1). The large intrusive in that area is a highly complex composite mass that forms the northern part of the Wilson Ridge pluton which, in turn, probably connects with other epizonal intrusives to form an intrusive mass of batholithic proportions in the area south of Lake Mead (Anderson, 1969, 1971a). Within the mapped area the intrusive consists of many tens, perhaps hundreds, of separate dikelike masses of varied composition ranging from rhyolite to basalt and from porphyritic granite to porphyritic diorite. It was only studied in brief reconnaissance. The structural form lines on the geologic map mark the traces of contacts between different intrusives or fault contacts between rocks of contrasting color (and presumably lithology) as observed on very high quality aerial photographs. Fault displacements probably preceded, accompanied, and followed emplacement of the mass, which is pervasively fractured and, locally, highly sheared and brecciated. Contacts with younger rocks are both intrusive and fault contacts.

The volcanic and intrusive rocks north of Hamblin Mountain include rhyodacite lava in the western fault block and hornblende-biotite dacite and pyroxene andesite in the eastern fault blocks (pl. 1). They are not presumed to have been either coextensive or coeval with the other unassigned volcanic rocks.

Exclusion of the unassigned volcanic rocks from the rocks of the Hamblin-Cleopatra volcano is based on the fact that bedded tuffs and rhyodacite lavas are not found in the Hamblin-Cleopatra pile. That pile is highly unusual and distinctive in the narrowness of its compositional range. (See description of contemporaneous Mount Davis Volcanics south of

Lake Mead, Anderson, 1971a). Exclusion of the large unassigned intrusive mass from the Hamblin-Cleopatra volcano is based on its lithologic and structural continuity with the Wilson Ridge pluton and on its broader range of lithologies, especially in the high-silica direction, than the intrusive rocks associated with the volcano.

### MUDDY CREEK FORMATION

North of the Hamblin Bay fault the Muddy Creek Formation consists of typical basin fill that was deposited across tilted and beveled older strata, mostly of the Gale Hills Formation. Most of the rock is coarse fanglomerate with associated weakly cemented siltstones and sandstones.

South of the Hamblin Bay fault, a wide variety of rocks are included in the Muddy Creek Formation. The Muddy Creek in that area was mapped by Longwell, Pampeyan, Bowyer, and Roberts (1965, pl. 1). To their Muddy Creek I have added a thick prism of fanglomeratelike volcaniclastic rock that occurs between the Cleopatra Wash and middle parts of the volcano. The prism includes sparse white tuffaceous sedimentary rocks. The prism of sedimentary rock was deposited on the middle part of the volcano and was faulted against the Cleopatra Wash part, probably during the disruption of the volcano. The broad area of Muddy Creek between Boathouse and Cleopatra Coves consists of fanglomerate, light-colored lacustrine clastic and evaporite beds including some dark-colored manganiferous sandstone, and intercalated dark basalt lavas and breccias (fig. 2). These strata were deposited on the southeast flank of the Hamblin-Cleopatra volcano.

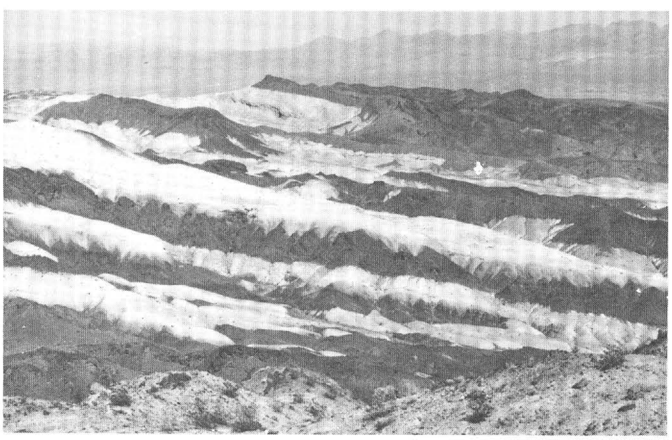

FIGURE 2. — Southeast-dipping strata of the Muddy Creek Formation consisting of alternating beds of evaporites, siltstone, and sandstone (light) and basalt and fanglomerate (dark) northeast of Boathouse Cove. These strata are not shown separately on the geologic map (pl. 1).

Similar, but more structurally disturbed, rocks occur in the Saddle Mountain area to the west. The Muddy Creek rocks in both areas were mapped in detail and briefly described by McKelvey, Wiese, and Johnson (1949) as part of an appraisal of manganese potential. These investigators made detailed stratigraphic divisions and mapped some small structures that are not shown on the geologic map (pl. 1).

## STRUCTURE

The most important structures in the mapped area are faults. Though of widely differing types and diverse trends, most were probably formed during a single period of deformation in late Tertiary time. The effects of this deformation so dominate the structural patterns in the area that little is known of the earlier structural history except what can be inferred from stratigraphic relationships.

The earliest record of orogenic activity is the widespread uniform conglomerate at the base of the Gale Hills Formation. This conglomerate is part of a prevolcanism clastic-carbonate-evaporite sequence, parts of which strongly resemble the Willow Tank Formation of Late Cretaceous age and the lower part of the Thumb Formation of Cretaceous (?) age. If these correlations are correct, the lithologic assemblage, thickness, and stratigraphic continuity of these beds indicate that the area was a broad shallow basin, possibly a closed one, in Cretaceous time. Only very mild deformation could have occurred prior to deposition of the conglomerate, which rests disconformably or with low-angle unconformity on older rocks. Pre-Tertiary rocks in the area lack structures that could be related to the compressional tectonics of the Sevier orogeny of Cretaceous age. Therefore, if the lower strata of the Gale Hills are Cretaceous in age, they must have been deposited in the foreland region of the Sevier orogeny (Armstrong, 1968) and probably reflect deposition of materials derived from orogenic activity some distance to the north or west in the orogenic belt. The alternative possibility is, of course, that the lower part of the Gale Hills is Tertiary.

The clastic and evaporite beds of the upper part of the Gale Hills Formation rest with apparent conformity on the lower part of the Gale Hills and therefore seem to record continuous basinal deposition to late Tertiary time.[1] Lateral and vertical

[1] The Overton Fanglomerate and overlying Horse Spring Formation in the Muddy Mountains (Longwell and others, 1965, p. 44) and the lower and upper parts of the Thumb Formation in the Frenchman Mountain area (Anderson and others, 1972) seem to record similar continuous basinal deposition extending into the late Tertiary. The late Tertiary age is based on potassium-argon age values for rocks in the upper part of the Thumb Formation and in the Horse Spring Formation (Anderson and others, 1972).

gradations from coarse clastics through fine clastics to carbonate or evaporite beds, evident at several localities, suggest that by Miocene time the broad early basin had been divided into smaller local basins and that deformation was active at their margins.

Volcanic ash is common in the upper part of the Gale Hills Formation, but lava is sparse to absent. Although volcanism was generally not occurring in the basins themselves, it was active nearby. Contemporaneous nearby volcanism, mostly yielding intermediate-composition material, is known to have occurred in a broad belt extending south from Lake Mead (Longwell, 1963; Anderson, 1971a; Anderson and others, 1972). This volcanism was accompanied and followed by intense faulting and epizonal plutonism. The Hamblin-Cleopatra volcano formed in late Miocene time at the northern boundary of this broad area of volcanism. Its construction to a height of more than 3,000 feet and a breadth of about 8 miles was probably rapid. The late-stage eruptions were accompanied by extensive emplacement of dikes and irregular intrusive masses. When the volcanism subsided (about 12 m.y. ago), the volcano was probably slightly elongated northeast and contained intrusive masses with a similar preferred orientation. The volcano probably developed along a preexisting northeast-trending fault or fault zone.

Volcanism and sedimentation in the area were followed by a period of intense deformation which disrupted the volcano and the sedimentary basins. Even though precise correlations of individual flows have not been made between the three major parts of the disrupted volcano, lithologic and stratigraphic similarities between strata at Hamblin Mountain and at Cleopatra Wash leave little doubt that those two volcanic piles were once one and have since been separated by about 12 miles on the Hamblin Bay fault. The following discussion considers first the Hamblin Bay fault and then structures to the south and north of it.

### HAMBLIN BAY FAULT

The Hamblin Bay fault is a steeply dipping zone of brecciated and, locally, very highly sheared rock ranging in width from a few feet to several hundred feet. Where the fault cuts sedimentary rock, the bedding surfaces are commonly dragged parallel to the fault surface, and much of the slippage probably occurred along the bedding surfaces. Slickensides on slip surfaces typically have a rake of 20°, indicating oblique slip. In the fault zone, gypsum is common, as are exotic blocks and breccias of Precambrian crystalline rocks.

As well as obviously truncating and offsetting the Hamblin-Cleopatra volcano, the Hamblin Bay fault truncates other major and minor structural elements in the area, the most conspicuous being the northern part of the Black Mountains structural block (fig. 8). North-trending dikes, faults, and foliation characterize the uplifted Black Mountains block for at least 10 miles south of Boulder Canyon (my unpublished mapping). From there, these north-trending features can be traced north across Boulder Canyon into the mapped area (pl. 1), where they bend sharply to the west into the Hamblin Bay fault, which truncates the structural block. Toward the fault, the intrusive and metamorphic rocks of the uplifted block become increasingly brecciated and sheared. North of the Hamblin Bay fault, north-trending normal faults that cut the volcanic pile at Hamblin Mountain bend eastward into the Hamblin Bay fault. Together the two drag features form a sigmoidal bend suggestive of left-lateral displacement. Abrupt truncation of such major structural features as the Black Mountains block, together with drag of its internal structures, clearly indicates major strike-slip displacement.

Excellent examples of truncation of smaller fold and fault structures by the Hamblin Bay fault are south of the Echo Hills (pl. 1). Steep faults with hundreds of feet of displacement in sedimentary strata there terminate southward at the Hamblin Bay fault. Asymmetric steep folds (probably early drag features) are also truncated by the fault.

Projections of the Hamblin Bay fault to the northeast and southwest are highly speculative owing to its concealment by Quaternary alluvium and the waters of Lake Mead. To the northeast the Hamblin Bay fault seems either to merge with or to be truncated by a more easterly trending fault system that bounds Bitter Spring Valley on the south. To the southwest the fault trace bends southward near Sandy Cove and may connect beyond the mapped area with splays designated the Fortification and Mead Slope faults by Longwell (1963).

### STRUCTURES SOUTH OF HAMBLIN BAY FAULT

The Boulder Wash fault is the northern extremity of the range-front fault system that bounds the northern part of the Black Mountains block on the east. Structurally, the small triangular area between the Boulder Wash fault and Saddle Mountain is part of the downdropped Detrital Valley block (fig. 8; pl. 1), a major Basin and Range type block-faulted valley that borders the Black Mountains block on the east and extends south from Lake Mead for about 40 miles. These structural designations conflict with the topographic designation of the Black Mountains as a feature which extends northeastward to Echo Bay. South of the mapped area the Boulder

Wash fault of the Black Mountains trends north (fig. 8), but as it crosses Lake Mead it bends westward as though it had been dragged and ultimately truncated by left-lateral movement on the Hamblin Bay fault and related fractures. Anderson, Longwell, Armstrong, and Marvin (1972) concluded that approximately 6,000 feet of vertical displacement occurred between the uplifted core of the northern Black Mountains block and the downdropped block to the west that contains the Colorado River valley (fig. 8). A similar magnitude of contemporaneous vertical displacement is reasonable for the Detrital Valley block, represented in the mapped area by displacement on the Boulder Wash fault (pl. 1). Most of these vertical displacements occurred between 12 and 10.6 m.y. ago, roughly synchronous with displacement on the Hamblin Bay fault (Anderson and others, 1972). Therefore, the area south of the Hamblin Bay fault should provide an opportunity to assess the relationships, if any, where large-scale normal and strike-slip faults intersect.

The northern, Cleopatra Wash part of the Hamblin-Cleopatra volcano is separated from the middle part by a fault that places the thick prism of coarse epiclastic rocks of the Muddy Creek Formation against the lavas and breccias of the Cleopatra Wash part. The fault is best interpreted as an oblique-slip fault with about 3 miles of left-lateral displacement and an unknown but appreciable amount of normal displacement. The coarse clastics probably accumulated on the downthrown side while the fault was active. The fault does not project to the southwest as a simple oblique-slip fault. In that direction part of the movement seems to be taken up in a strongly asymmetric east-trending syncline, the steep south limb of which shows evidence of left-lateral drag. The eastern part of the syncline is beautifully developed in evaporite beds of the Muddy Creek Formation. Part of the movement also seems to be taken up by large displacements on a system of closely spaced north-trending normal faults that have dips averaging about 30° W. (pl. 1). A possible mechanism for translation of oblique-slip displacement into large-scale extension on normal faults is shown in figure 3. This mechanism seems highly reasonable in terms of the synchronous strike-slip and normal faulting in the area. I attribute the structural complexity of the entire area between the Boulder Wash fault and the Cleopatra Wash part of the volcano to a complex interplay between large-scale strike-slip and normal displacements. A simplistic view of this interplay is as follows: As southwesterly translation of the northern area occurred along such faults as the Hamblin Bay fault, major simultaneous extension to the south caused a splay from the main strike-slip system to project into the extended area as a more northerly trending oblique-slip fault. At the point of separation, movement on the splay was almost entirely strike-slip. It became progressively more oblique-slip as it penetrated into the area of extension and ultimately became transformed (with some complications due to folding) into predominantly extensional strain.

Steeply east-dipping strata in the South Virgin Mountains appear to be offset about 7 miles left-laterally by the Gold Butte fault (fig. 8). This fault does not project into the Black Mountains along its strike to the southwest as suggested by Longwell (fig. 8). Much of the lateral displacement on the Gold Butte fault is probably translated into extensional strain beneath Detrital Valley. Similarly, it is quite possible that much of the movement on the Hamblin Bay fault and related faults is translated into the well-known large-magnitude extensional strain that dominates the structural pattern along the Colorado River valley south of Hoover Dam (Anderson, 1971a).

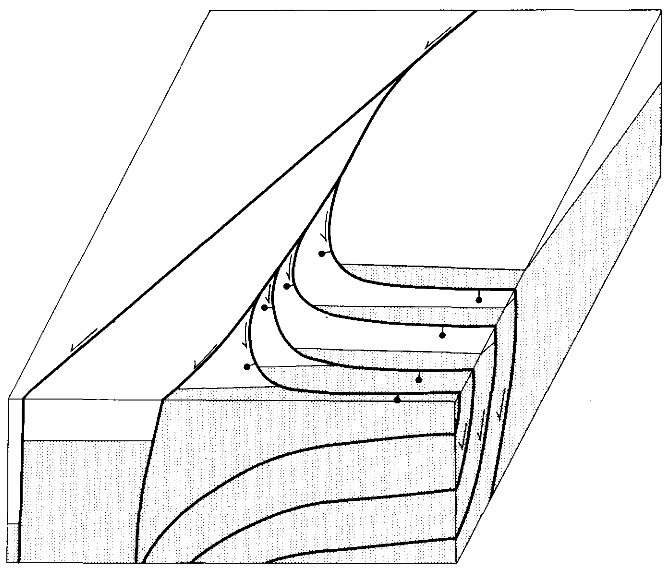

FIGURE 3. — Block diagram illustrating the distribution of fault surfaces at the intersection of a strike-slip system with an area undergoing extension. Some of the strike-slip displacement is transformed into extension on normal faults (bar and ball on downthrown side). Displacement on the strike-slip system decreases toward the viewer.

### STRUCTURES NORTH OF HAMBLIN BAY FAULT

The area of pre-Tertiary rocks in the north-central mapped area consists of three main structural blocks—the Echo Hills block, the Pinto Ridge block that includes Pinto Valley and the ridge to the southeast parallel to the Hamblin Bay fault, and the

Razorback Ridge block that includes the ridge of Permian carbonate rock to the northwest of Razorback Ridge (fig. 8; pl. 1). All three structural blocks are cut and bounded by large faults. The following paragraphs describe first the structures within the area of pre-Tertiary rocks, then the boundary structures, and, finally, structures in adjoining terrain.

Longwell, Pampeyan, Bowyer, and Roberts (1965) showed Pinto and Razorback Ridges separated by a northeast-trending normal fault that is offset in several places by more northerly trending normal faults. Their mapping in that area implies relatively simple Basin and Range type southeast-tilted fault blocks. My more detailed field studies indicate a more complex structural configuration that includes large-scale displacements on northeast-trending left-lateral faults and associated folding and normal faulting. Because the stress conditions implied by my interpretation are so different from those implied in the earlier interpretation, the structures will be described in some detail.

A complex fault zone 7 miles long separates Pinto Ridge from Razorback Ridge. The zone consists of several faults that form a braided pattern. Stratal dips in the fault zone are generally reversed from the prevailing southeast dips in the area. Near the large faults, bedding surfaces tend to dip steeply and lie parallel to fracture surfaces. As a result of shearing and stretching, stratigraphic thicknesses are generally strongly attentuated in zones tens to hundreds of feet wide near the faults. Left-lateral offset of the basal contact of the Gale Hills Formation is indicated in the northeastern part of the fault zone (pl. 1). There, strong evidence indicates that left-lateral displacement on the fault system was responsible for truncation of the carbonate strata in Pinto Ridge. As the resistant strata of the ridge and the overlying Mesozoic rocks are traced northeastward along strike, their dips steepen and their strikes turn northward into the fault zone. The resulting structure resembles a truncated steep to vertically plunging drag fold at the northeast extremity of the ridge. Blocks and breccias of the truncated strata are found to the southwest where they are smeared along the fault. The drag fold and the displaced blocks indicate left-lateral shear.

Careful study of bedding attitudes on Pinto Ridge shows that as the ridge is crossed from the southeast, stratal strike trends change from parallel to the ridge to more northerly, and the dips decrease. Locally the strikes swing through about 90°; they are normal to the ridge trend near the boundary fault. Obviously the ridge is not a simple strike ridge produced by tilting on normal faults. The ridge is, indeed, cut by numerous north-trending normal faults (only a few are shown on the geologic map, pl. 1). Displacements on these faults increase significantly northward where the faults appear to merge with the northeast-trending fault that bounds the ridge. The changes in bedding attitudes are closely related to the increased displacements; both structures are interpreted as drag features that developed in the relatively competent carbonate rocks southeast of the major fault. The major fault is an oblique-slip structure with left-lateral and down-to-north displacement. Northwest of the major fault, asymmetric folds that generally have low axial plunges are recognizable where competent marker beds are available for stratigraphic control (pl. 1). In distribution and arrangement, the small asymmetric folds and the normal faults in the Pinto Ridge–Razorback area resemble larger structures of similar origin that occur along the Clarence and other strike-slip faults in New Zealand (fig. 4; Bishop, 1968, figs. 2–5). A close genetic relation is indicated between the main strike-slip system and these subsidiary structures.

The Echo Hills block consists of steeply tilted and highly faulted rocks that strike mostly northwest. A major shear zone truncates the northwest-trending strata and bounds the block on the south against the Pinto Ridge block. To the east this shear zone is highly complex, and Mesozoic and Cenozoic rocks are intensely deformed along at least three parallel faults. This complex shear zone truncates a steeply plunging drag structure formed in the basal beds of the Gale Hills Formation that form the long ridge parallel to the Hamblin Bay fault. This drag structure is much like the one at the northeast end of Pinto Ridge, a similarity that suggests large left-lateral displacement of the Echo Hills block relative to the Pinto Ridge block. Major splays of this left-lateral shear zone veer into the Echo Hills block where the steeply tilted strata are cut by several low-angle normal faults of large displacement. The relationship between the normal and strike-slip faults is not clear, but because these two systems are closely related elsewhere in the mapped area, a genetic tie is inferred for the Echo Hills block.

Although there is probably a significant component of normal displacement on the fault zone between the Pinto Ridge and Razorback Ridge blocks, I interpret the stratal repetition of these blocks as resulting primarily from oblique-slip with dominant left-lateral displacement. The fault is, therefore, analogous to the one that passes west of the Cleopatra Wash part of the Hamblin-Cleopatra volcano (p. 9). Large left-lateral displacement is inferred between the Echo Hills and Pinto Ridge blocks. That interpretation is supported by stratigraphic relationships in the lower part of the Gale Hills Formation. In the Pinto Ridge block the Gale Hills rests on the Jurassic(?) Aztec Sandstone with remarkable lateral stratigraphic continuity. In the complex Echo Hills block, however, the Gale Hills Formation is different lithologically and rests on older rocks including Permian carbonate strata. The abrupt lithologic contrasts are consistent with juxtaposition of the two blocks by large lateral displacements. A similar, though less convincing, argument can be based on stratigraphic contrasts between the Pinto Ridge and Razorback Ridge blocks, which contain

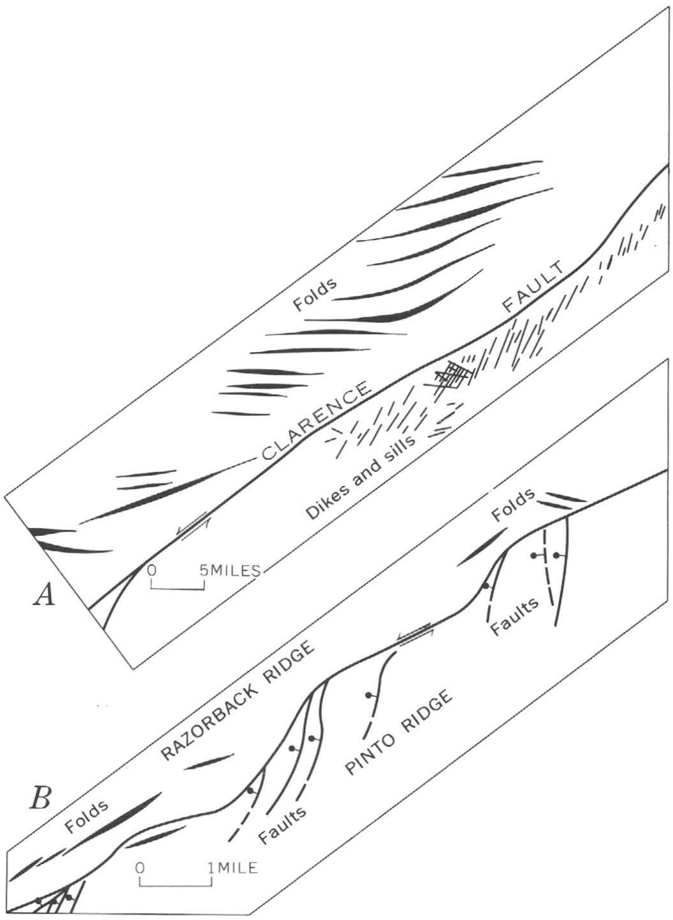


FIGURE 4.—Generalized sketch maps showing comparison between selected fold and tension structures associated with strike-slip faults. *A*, Fold and intrusive trends associated with the Clarence fault, Marlborough area, New Zealand (Bishop, 1968). For purposes of comparison, sketch is drawn as mirror image of actual map. *B*, Fold and fault trends along strike-slip fault between Razorback and Pinto Ridges. Only one of several strike-slip faults that form a braided pattern is shown. Bar and ball on downthrown side of subsidiary normal faults. Note scale difference between *A* and *B*.

the basal Gale Hills beds resting on different rocks in each of the blocks (pl. 1).

The north-central area of pre-Tertiary rocks is bounded on the north against Bitter Spring Valley by a major fault system that was interpreted as a normal fault by Longwell, Pampeyan, Bowyer, and Roberts (1965). My studies indicate a remarkable lack of structural continuity across this fault zone from Echo Bay southwest for 18 miles to Callville Bay. As an example, the homoclinally east-dipping Gale Hills strata in eastern Bitter Spring Valley terminate southward against the Echo Hills block in a left-lateral drag structure characterized by steeply north-dipping strata (pl. 1). Although most of Bitter Spring Valley to the southwest is outside the mapped area, unpublished reconnaissance mapping and photogeologic studies there reveal abrupt terminations in drag structures of major folds located north of the western part of the mapped area. The vertical to steep northwest dips of the Gale Hills strata along the fault zone (pl. 1) are part of these drag structures. Fault and fold structures along the adjoining part of the Razorback Ridge block are very similar to those described for the Pinto Ridge block, indicating similarly large amounts of left-lateral slip between the Razorback Ridge block and the terrain to the north.

The southwest boundary of the area of pre-Tertiary rock is marked by one of the most perplexing fault structures in the area. The fault is well exposed in many places; it is generally steep, and its trace is unusually sinuous. A 1-mile-long segment of the fault trace at the southwest end of Pinto Valley is buried beneath the hanging wall of a low-angle reverse fault. To the east it appears either to merge with or to be truncated by the Hamblin Bay fault. At the southwest end of Pinto Ridge there is major apparent left-lateral drag of fault planes that cut Triassic beds. Resistant sandstone beds of the Moenkopi Formation show thousands of feet of apparent drag along the fault, but whether the drag is right-lateral or left-lateral is not obvious. The fault splits in that area, and the two splays seem to embrace a large mass composed mostly of unassigned volcanic and intrusive rocks. The dogleg trace of the northern splay is difficult to reconcile with strike-slip displacement. However, the fault there separates areas of contrasting lithology and structural pattern, truncates numerous important structural elements, including the major strike-slip fault zone between Pinto and Razorback Ridges, and contains scattered blocks and breccias of Precambrian rock—all features suggestive of large lateral displacement. Perhaps some of the bending of the fault occurred after major strike-slip displacement. Much of the movement may be taken up by the largely buried southern splay that bounds Hamblin Mountain on the north. West of where the two splays rejoin, the fault zone is complicated by fold structures (fig. 5) and exotic horses of Precambrian rapakivi granite and younger rocks.

Other important structures north of the Hamblin Bay fault are located at Echo Bay and Callville Bay. In both areas large faults are associated with broad zones of steeply dipping and folded strata of the Gale Hills Formation. At Echo Bay the tilting is probably associated with a major, largely buried zone of strike-slip displacement. At Callville Bay the zone of tilting is bounded by a normal fault; there, the young almost-undeformed lavas of the Hamblin-Cleopatra volcano may have been downfaulted against Gale Hills strata that were highly deformed by earlier fault displacements.

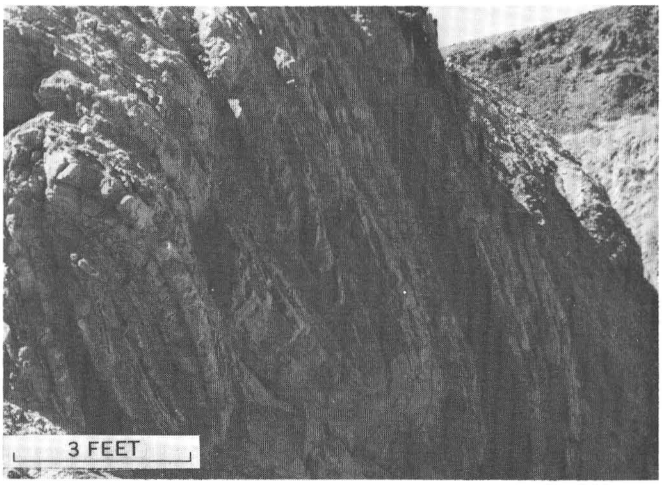


FIGURE 5. — Isoclinal folds developed in sandstone and siltstone of the Gale Hills Formation along northeast-trending fault zone west of Hamblin Mountain (pl. 1). Fold axes plunge about 35° SW., away from viewer.

## AGE AND MAGNITUDE OF STRIKE-SLIP DISPLACEMENTS

An andesite lava stratigraphically high in the Hamblin-Cleopatra volcano gave a potassium-argon age value of 12.7 m.y. (Anderson and others, 1972). This indicated age predates about 12 miles of left-lateral displacement on the Hamblin Bay fault and related faults. Some rocks of the overlying Muddy Creek Formation were deposited during and deformed by these fault displacements. A basalt lava from Callville Mesa 3 miles west of the mapped area gave a potassium-argon age value of 11.1 m.y. (Anderson and others, 1972). That basalt is very mildly faulted and rests unconformably on tilted and beveled upper Tertiary strata. It is assigned to the Fortification Basalt Member of the Muddy Creek Formation and probably postdates most of the area's strike-slip faulting. On the basis of these ages, about 12 miles of left-lateral slip occurred on the Hamblin Bay fault system between 12.7 and 11.1 m.y. ago.

The data are equivocal, but strike-slip faulting apparently both preceded and followed displacement on the Hamblin Bay fault. As an indication of earlier displacements, the major left-lateral fault between Pinto and Razorback Ridges is offset by the perplexing fault that forms the southwest boundary of the area of pre-Tertiary rocks. The latter fault seemingly is offset by the Hamblin Bay fault. Also, a palinspastic map of the Hamblin-Cleopatra volcano indicates that the volcano is elongated parallel to the fault trend, as are intrusive masses which penetrate the volcano. These preferred orientations suggest a prevolcanic zone of weakness. As an indication of later lateral displacements, the major fault zone that bounds Bitter Spring Valley on the south appears to truncate the Hamblin Bay fault. Even though the full age range of strike-slip displacements in the area is not known, such displacement was probably a short episode in the late Cenozoic, coinciding, as was mentioned, with uplift of the Black Mountains block to the south.

The cumulative magnitude of slip on the broad left-lateral fault zone is appreciably greater than the 12 miles on the Hamblin Bay fault, but the true value is not known from geologic relationships in the mapped area. A speculative, but reasonable, estimate of 35–40 miles can be made from data on adjacent areas.

As noted in "Introduction and Acknowledgments," Precambrian crystalline rocks and Tertiary volcanic rocks are widely exposed south and southeast of a line that passes through the mapped area (fig. 1). A very distinctive rapakivi granite of Precambrian age is extensively exposed in the South Virgin Mountains (fig. 8; Volborth, 1962). Large landslide blocks and breccias composed of similar rapakivi granite occur near Frenchman Mountain (fig. 8). No source area for these materials now exists in the vicinity of Frenchman Mountain: Precambrian rocks are not exposed to the north, and to the south, rapakivi granite has not been identified in the McCullough Mountains–River Mountains–Colorado River–Black Mountains areas (fig. 8). Potassium-argon data indicate a late Tertiary age for the upper part of the Thumb Formation in which the slide masses and breccias are contained (Anderson and others, 1972). Thus, they are roughly contemporaneous with the volcanism and major strike-slip tectonism in the region. Longwell (1971) recently suggested that these granite slide masses had a northerly source and, further, that the source area has been shifted about 30 miles eastward by right-lateral displacement on the Las Vegas shear zone and its inferred southeasterly extension (fig. 8). According to this interpretation the southeastward extension of the Las Vegas shear zone either is concealed beneath the Tertiary volcanic and sedimentary rocks that I have mapped (Longwell, 1971) or is offset by displacements on left-lateral faults related to those I have mapped in the area shown on plate 1. The first possibility is wholly untenable in the light of recent geologic mapping which shows that the volcanic and sedimentary rocks are intricately and intensely involved in the strike-slip displacements on the northeast-trending fault system. The second possibility is equally untenable because the northeast-trending left-lateral fault would have to pass through the Black Mountains structural block along Boulder Canyon (fig. 8), but remarkable structural continuity from south to north across the block precludes any large lateral displacements. Instead, the source of the granite slide masses was probably to the south; if so, the Frenchman Mountain block was probably shifted about 35–40 miles west-southwest by left-lateral displacement on the system of northeast-trending faults that passes through the mapped area (fig. 8). The common occurrence of horses and breccias of rapakivi granite along the mapped faults strongly supports this interpretation. These granites are only found along the southern faults that displace blocks against the crystalline-volcanic terrain, just as would be expected in such a structural interpretation.

The occurrence of boulder trains of rapakivi granite in strata equivalent to the Thumb Formation south of the Muddy Mountains is easy to explain by assuming a southern source but precludes a fault solution such as that suggested by Longwell (fig. 8).

From stratigraphic evidence Longwell, Pampeyan, Bowyer, and Roberts (1965, p. 43) concluded—and I agree—that thick wedges of coarse conglomerate contained in the upper part of the Thumb Formation in the southeastern part of the Frenchman Mountain block came from the south. As for the rapakivi granites, no source rocks now exist to the south which could have furnished the coarse clastic materials. The conglomerates consist of Paleozoic and Mesozoic sedimentary rocks that could not have been totally removed by erosion from the terrain to the south because many of the Tertiary volcanic rocks which rest on the Precambrian crystalline rocks there are older than the conglomerates (Anderson and others, 1972). The coarse clastic wedges thus provide evidence of large left-lateral shift corroborative with the evidence supplied by the slide masses of rapakivi granite.

Less convincing evidence of large lateral displacement is found in the stratigraphy of the Permian red beds and overlying Coconino(?) Sandstone in the mapped area. That stratigraphy has a closely similar counterpart in the northern part of Lime Ridge in the South Virgin Mountains about 25 miles to the northeast. An essential factor in this suggested correlation is the anomalously excessive thickness of the Coconino(?) in the mapped area. In the South Virgin Mountains, Bitter Ridge is a northeast-trending structural element situated athwart the northerly projection of Lime Ridge (Longwell and others, 1965, pl. 1). The position and trend of Bitter Ridge may reflect left-lateral drag on the inferred fault on which the Lime Ridge stratigraphic sequence is truncated and offset. If these interpretations are valid, 25 miles of slip would have occurred north of the Hamblin Bay fault in addition to the the 12 miles of displacement on the Hamblin Bay fault.

## RELATIONSHIPS BETWEEN STRIKE-SLIP AND NORMAL FAULTS

The close temporal relationship between normal and strike-slip fault systems in the southern Great Basin as outlined recently by Anderson, Longwell, Armstrong, and Marvin (1972) was determined from an appraisal of available potassium-argon age values. On a provincewide basis the close association between these two fault systems was discussed by Shawe (1965) and Hamilton and Myers (1966). In an appraisal of the structural geology of a 30-mile-wide belt of highly deformed Tertiary and Precambrian rocks extending south from Lake Mead (Anderson, 1971a), I concluded that strike-slip and oblique-slip faults in that area are genetically related to normal faults which range in dip from steep to low angles. In that area the strike-slip faults trend at a high angle to the strike of both the strata and the normal faults. The strike-slip faults are interpreted as structures which compensate for varying amounts or rates of extensional strain within or between highly distended lobate or plate-like structural units that have moved several miles over or past one another. These fault relationships are shown schematically in figure 6. Strike-slip and normal faults so related are common in a broad region around the mapped area. The Prospector fault described by Longwell (1945) in the Desert Range and other transcurrent faults in that area can be interpreted as oblique-slip and strike-slip faults. They bound plates of Paleozoic strata that have been shifted westward on low-angle normal faults. In the South Virgin Mountains, Morgan (1968, p. 58, 59) considered it likely that some of the north- and northeast-trending high-angle normal faults are genetically related to the Gold Butte and Lime Ridge strike-slip faults. I concur with this interpretation and add that the large displacements on low-angle normal faults there are also related to the strike-slip faulting. My mapping (unpublished) in the Frenchman Mountain block and in the River Mountains east and southeast of Las Vegas has revealed outstanding examples of close genetic ties between late Cenozoic normal and strike-slip faulting. Similar relationships have been recognized in the Pahranagat Lakes area of Lincoln County, Nev., by G. L. Dixon (oral commun., 1971).

In the examples given in the preceding paragraph, the principal direction of movement of hanging-wall blocks is generally westward or southwestward. Where a transcurrent fault forms the north boundary of a distended or displaced structural block, the slip is right-lateral; at the south boundary it is left-lateral (fig. 6). The size of the blocks and the magnitude of their displacement range from a few tens of feet to several miles. The normal and strike-slip faults are first-order extensional strain features that form a thin-skinned tectonic system in the brittle upper crust. These fault mechanics differ sharply from those deduced by Shawe (1965) in his analysis of historical faults and ancient fault patterns in the Western United States. He concluded that conjugate systems of deep-seated strike-slip faults constituted a fundamental control of Basin and Range structure.

Though normal faulting and strike-slip faulting are known to have occurred synchronously and to have been closely related physically in the mapped area, the patterns are more diverse, and, by inference, the mechanics are more complex than in the areas just cited. An interpretation of the relationships in the south-central mapped area is given in figure 3. Some normal faults in the north-central part of the mapped area—on Pinto Ridge, for example—are second-order fractures related to drag on the strike-slip faults; others may predate strike-slip displacements, as suggested by drag-and-offset relationships; and still others, as in the Echo Hills, may be related in the manner suggested in figure 6.

According to Gilluly (1970, p. 54), the crust is locally so weak, and both the crust and the mantle are so heterogeneous, that yielding must be highly irregular. Stewart (1971, p. 1039) postulated a considerable variety of movement in the plastically deforming layer beneath the brittle upper crust to account for local complexity of Basin and Range structure. As evidence of the inhomogeneity of stress fields to which the crust has responded, Gilluly (1970, p. 54, 55) cited several examples of diverse types of simultaneous deformation that occurred close to one another in the Western United States. The synchronous interplay of vertical and horizontal tectonics at the northern boundary of the Black Mountains is an excellent additional example of strong local inhomogeneity of stress.

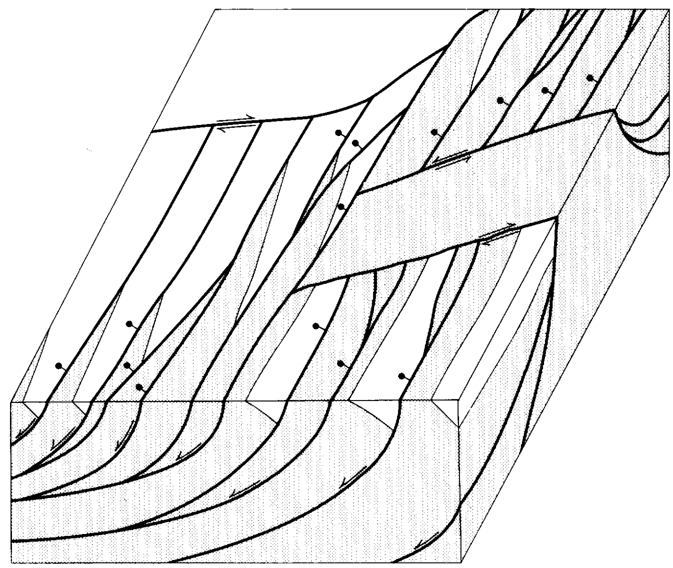

FIGURE 6. — Block diagram illustrating the role of strike-slip faults in areas of unevenly distributed extension. In the diagram they bound areas of extension against areas of no extension, but in many actual field examples they develop in areas of varying amounts or rates of extension. Bar and ball on downthrown side of normal faults.

## REGIONAL SETTING AND IMPLICATIONS

The mapped area occupies a critical position in the tectonic configuration of the southern Great Basin. It lies across an important northeast-trending structural boundary along which thick sedimentary sequences belonging to the Paleozoic, Mesozoic, and Cenozoic Eras terminate southward against a broad structurally elevated area where Precambrian basement rocks are overlain by Cenozoic volcanic rocks (Anderson and others, 1972). The part of this boundary that crosses the mapped area is a broad northeast-trending fault zone with perhaps 40 miles of left-lateral displacement. The mapped area also lies athwart the southwesterly projection of the Sevier orogenic belt and the southeasterly projection of the Las Vegas shear zone (figs. 7, 8), but I see no evidence in the area for either of these major structural elements. Not only are the compressional structures of the Sevier belt absent in the mapped area, but they are not found to the west in the Frenchman Mountain block. A major splay of the Las Vegas shear zone with at least 25 miles of right-lateral separation passes north of Frenchman Mountain (Longwell, 1960; Longwell and others, 1965). To produce truncation of the structures in the Sevier orogenic belt (fig. 7), the Las Vegas shear zone must project eastward from Frenchman Mountain and pass south of the Muddy Mountains. The Sevier belt is inferred to be offset to the Spring Mountains by as much as 45 miles of displacement on the Las Vegas shear zone (Longwell, 1960; Armstrong, 1968; Fleck, 1970).

Although the location of the trace of the Las Vegas shear zone is a major unknown, general structural relationships seemingly dictate that the rocks between that fault zone and the Hamblin Bay fault and related faults have been shifted many miles westward relative to the rocks to the north and south of those structures. Between the two large strike-slip structures the rocks resemble those of the Sevier foreland belt (Armstrong, 1968) that here has been shifted westward some 40 miles. These rocks not only occupy an exotic structural position but also form an unusual structural pattern of northeast-trending fault ridges of which the north-central mapped area is a part. Viewed from great distance and extremely high altitude on infrared photography (near-space X–15 high-speed flight, Weaver, 1969), this pattern resembles linear flowage ridges in a glacier, the leading lobe of which is Frenchman Mountain. Explanations of the large horizontal transport of such a narrow belt of rock (less than 10 miles wide in places) by classical fault mechanics acting within a rigid crust seem very inadequate. As Gilluly noted (1970) in commenting on crustal deformation in the Western United States, tectonic activity of a region must be connected with crust-mantle interaction, and deformation of any crustal segment must surely depend on the directly underlying mantle. The crust is deformed passively under drag of subcrustal motion of the mantle (Gilluly, 1970, p. 68). Dickinson (1966) interpreted fault and fold patterns along the San Andreas fault in the Castle Mountain Range, Calif., as having formed in a passive surficial plate that was deformed as it rode coupled to a moving undermass. The area north of Lake Mead is structurally similar to the Castle Mountain Range area. Subcrustal mantle flow seems to be the only plausible driving force that could have produced the large-scale horizontal shift of the Frenchman Mountain block and its trail of faulted ridges.

If, as I have suggested, most of the normal faulting in the Lake Mead area is related in either a first-order or a second-order sense to strike-slip displacements, and if, in turn, all the late Cenozoic displacements are a surficial crustal response to subcrustal motion of the mantle, then it should be instructive to assess the relation between this deformation and the most fundamental structural boundary of Cenozoic age in the region—the boundary between the Colorado Plateau and the Basin and Range (fig. 7).

Stewart (1971), as others before him, related Basin and Range structure to the fragmentation of the brittle upper crust over a plastically extending substratum. Armstrong (1968) likened the plastic extension phenomenon to the stretching of taffy, and Gilluly (1972) referred to it as metamorphic flowage. The crust in the Great Basin is notably thin (Pakiser and Zietz, 1965). Apparently one result of the stretching was the thinning during Cenozoic

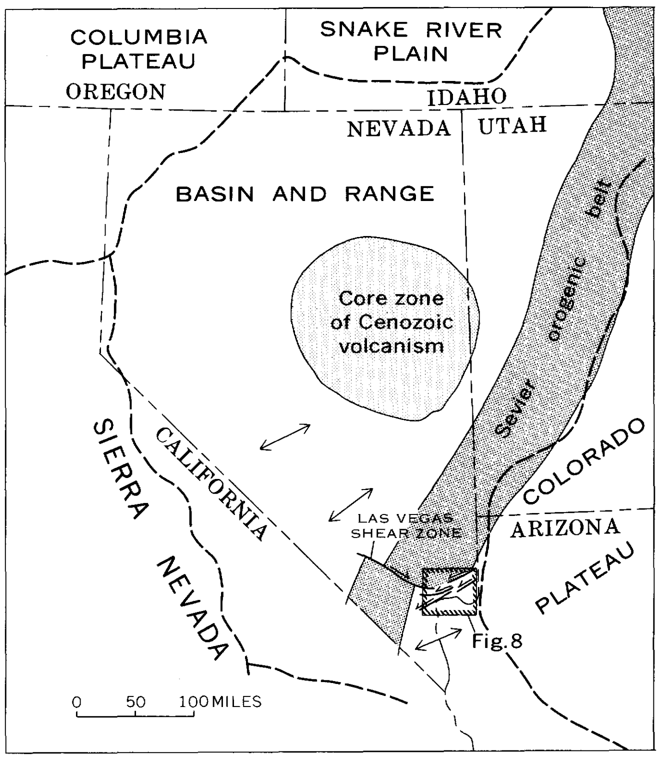


FIGURE 7. — Tectonic index map showing position of the Lake Mead area (hachured, fig. 8) relative to some major structural features. Compressional tectonics characterized by large-magnitude eastward overthrusting occurred in the Sevier orogenic belt during most of the Cretaceous. Large-volume silicic volcanism occurred in the core zone in east-central Nevada from 30 to 40 m.y. ago and subsequently spread outward. Double-headed arrows indicate direction of late Cenozoic extension in some areas where large-magnitude displacements occurred on low-angle normal faults.

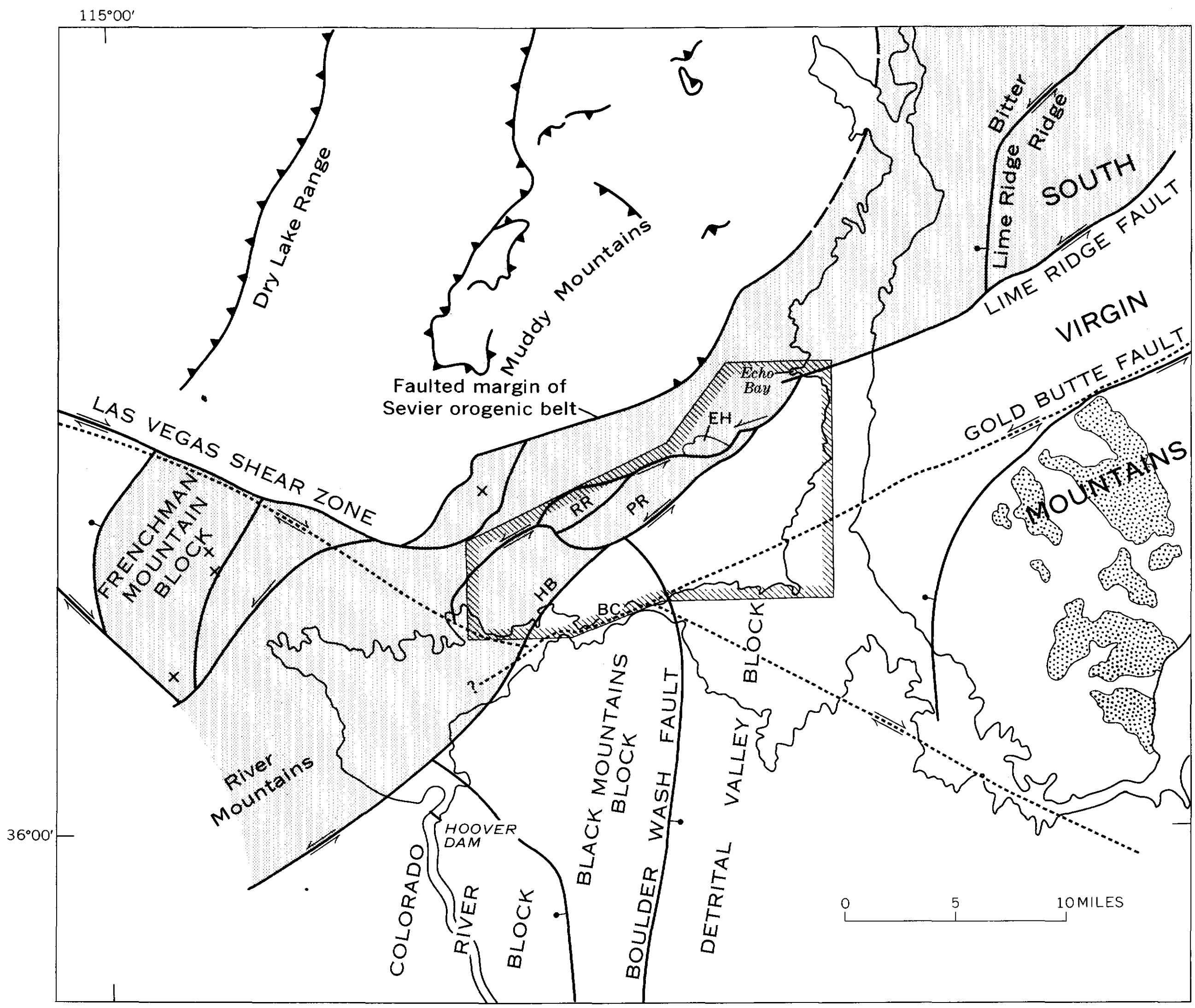


FIGURE 8. — Highly generalized tectonic map showing position of mapped area (hachured) relative to traces of major strike-slip faults. Faults postulated by Longwell (1971; written commun., 1971) shown by dotted lines; faults postulated by Anderson (this paper) shown by solid lines. Selected normal faults (bar and ball on downthrown side) and thrust faults (sawteeth on upper plate) are also shown. Bedrock exposures of rapakivi granite in the South Virgin Mountains are stippled. The locations of landslide masses and boulder trains of rapakivi granite included in the Thumb Formation and equivalent strata are marked by crosses. Shaded area is dominated by normal and left-lateral strike-slip faults along which rocks have been displaced to the southwest and west relative to the areas to the northwest and southeast. HB, Hamblin Bay fault; BC, Boulder Canyon; RR, Razorback Ridge block; PR, Pinto Ridge block; EH, Echo Hills block.

time of a crust that had been much thicker as the result of compressional tectonics during Mesozoic time. Thinning could not have occurred by surficial erosion and deposition of the eroded materials elsewhere. The stretching-and-thinning mechanism implies slow lateral movement of mass in the plastic zone which probably includes the lower crust and part of the upper mantle. Volcanism also developed during the period of crustal stretching and thinning. Armstrong, Ekren, McKee, and Noble (1969) showed that the locus of silicic volcanism in the Great Basin shifted progressively outward from a core zone in east-central Nevada toward the margins of the Great Basin. Scholz, Barazangi, and Sbar (1971) related the outward spreading of volcanism in the Great Basin to a rising diapiric plume of mantle material that was trapped beneath a strong sialic crust and flattened and spread laterally as new material was added to it from below. Lateral mass movements at depth must have progressed outward in the same manner as the volcanism, and where obstacles were encountered, such as the Colorado Plateau, the plastic material may have tended to flow around them. The Colorado Plateau is inferred to have lacked a plastic zone (Armstrong, 1968), although in southwestern Utah Hamblin (1963) and Hintze (1963) recognized a broad transition zone of common block faulting between the relatively fault-free Colorado Plateau and the highly faulted Basin and Range, possibly also indicating a transition zone at depth in the plastic zone. A zone of increased lateral velocity, which would be expected along the boundary of an obstacle like the Colorado Plateau, may explain the perplexing large-scale westerly shift of the Frenchman Mountain block and its trail of faulted ridges. Perhaps these elements were carried southwestward and westward on a fast-moving current of mantle and possibly lower crustal material that was banked against and deflected around the Colorado Plateau.

The foregoing interpretation is highly speculative, partly because of the numerous uncertainties concerning the Las Vegas shear zone and partly because of unknown offset relationships, if any, between the terrain north of the Las Vegas shear zone and the Precambrian basement terrain south of Lake Mead. At present, only the relative displacement of the block that lies between these two terrains is known. Also needed is information on the nature of structural interaction between the northwest- and northeast-trending strike-slip systems.

If, for purposes of discussion, the Las Vegas shear zone is ignored, an alternative interpretation of the regional significance of the northeast-trending left-lateral system is possible. Some strike-slip and oblique-slip faults in the Great Basin compensate for differing amounts or rates of extensional strain in the adjoining blocks that are separated by the transcurrent structure. The Hamblin Bay fault and related left-lateral faults in the mapped area may compensate for contrasting amounts of extensional strain as the Basin and Range structural province broadens northward around the Colorado Plateau (fig. 7). As such, the sense of displacement and tectonic significance is analogous to that suggested for the Garlock fault by Hamilton and Myers (1966, p. 533). If direction and rate of strain were at all constant over broad areas of the Great Basin during the late Cenozoic, clearly zones of compensation like that suggested for the Hamblin Bay fault must exist where the breadth of the deformed crust changes markedly.

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