Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of Basin and Range faulting

JOHN M. PROFFETT, JR. *Anaconda Company, 1849 West North Temple, Salt Lake City, Utah 84116*

ABSTRACT

In the Yerington district, western Nevada, pre-Tertiary rocks are overlain by an Oligocene ignimbrite sequence and Miocene andesites. Basin and Range normal faulting began in Miocene time, as andesitic volcanism died out (17 to 18 m.y. ago), and has continued to the present. The faults dip east and are curved, concave upward, with net displacements in a nearly east-west direction. Movement on the curved faults has resulted in steep westward tilting of the Miocene andesites and of all older rocks. Alluvium and 8- to 11-m.y.-old basalt flows deposited during the period of faulting are tilted gently west. The oldest faults, which dipped steeply east when they were active, are now inactive and dip gently eastward as a result of westward tilting on other faults. Younger faults dip more steeply east, and the youngest faults, those responsible for present Basin and Range topography, are the steepest. More than 100 percent of east-west extension has taken place across the district because of normal faulting. The rate of extension was most rapid between 17 and 11 m.y. ago and was slower after 11 m.y. ago. The extension is deep seated rather than thin skinned and apparently involves thinning of the crust. Several theories of origin for Basin and Range structure can be rejected because of the field data at Yerington, and the theory that Basin and Range structure was caused by a continental spreading axis best fits the data. Basin and Range spreading seems to have been most active between the projections of the Mendocino and Murray fractures. It may have first started south of the Great Basin, when these fractures were farther south relative to the continent and when the oceanic spreading axis that had been between these fractures was interacting with the continent.

INTRODUCTION

Geologic mapping in the Yerington district, Nevada (Figs. 1, 2), has revealed strongly developed late Cenozoic structure, which includes gently, moderately, and steeply east-dipping normal faults and moderate to steep westward tilting of the rocks. The gently and moderately dipping faults were steep when they were active (Proffett, 1971a) and are not to be confused with large landslide or gravity-slide type faults related to high topographic relief, that have been described in some parts of the Basin and Range province (see, for example, Longwell, 1951; Drewes, 1959, 1963, p. 48–52, and references cited there; Mackin, 1960, p. 119–122; Kurie, 1966, p. 869). The steeply dipping normal faults of the Yerington district control the present Basin and Range topography of the region, and the older moderately and gently dipping normal faults were Basin and Range faults in the past. Description and interpretation of the complex history and geometry of Basin and Range structure at Yerington has been made possible through detailed surface mapping and abundant subsurface information. It is necessary to understand the complex Basin and Range structure in the Yerington region in order to understand the pre-Tertiary geology and ore deposits, which will be discussed in other papers.

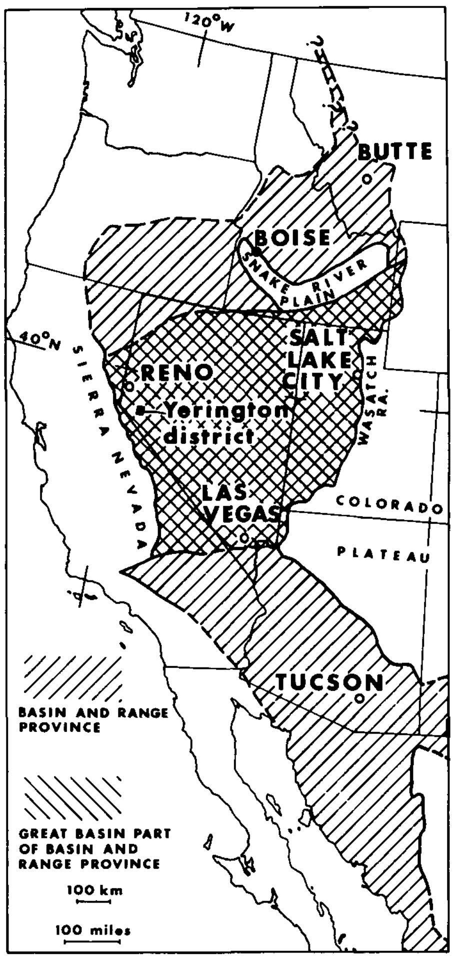

Figure 1. Map of part of western North America, showing Basin and Range province, Great Basin part of province, and Yerington district.

Most of the time I worked in the Yerington district (June to September 1966, January 1967 to February 1971) was spent mapping the geology of approximately 200 km^2, (75 mi^2) at a scale of 1 in. = 1,000 ft, logging cores and cuttings from more than 30,000 m (100,000 ft) of drilling, and compiling and interpreting these data.

GEOLOGIC SETTING

The oldest rocks of the Yerington district are metamorphosed volcanic and sedimentary rocks of Triassic and Early Jurassic age. The other pre-Tertiary rocks of the district include intrusive and volcanic rocks of Jurassic and possibly Cretaceous age. A prominent widespread unconformity was developed in the pre-Tertiary rocks by Cretaceous(?) and early Tertiary erosion. The oldest rock units that overlie the unconformity consist of conglomerate, sedimentary breccia, and minor basalt, all of probable early Tertiary age (Fig. 3). These untis are overlain by a sequence of widespread silicic ignimbrite sheets as much as 1,400 m (4,500 ft) thick of Oligocene[1] age (Fig. 3;

[1]In this paper a date of 22.5 m.y. B.P. is used for the Oligocene-Miocene boundary (Turner, 1970; Bandy and Ingle, 1970). Because dates of 5.0 to 13.0 m.y. B.P. have been determined by various workers for the controversial Miocene-Pliocene boundary (Harland and others, 1964; Evernden and others, 1964; Bandy and Ingle, 1970; Kulp, 1961), rocks that fall into this age range are referred to here by their radiometric age.

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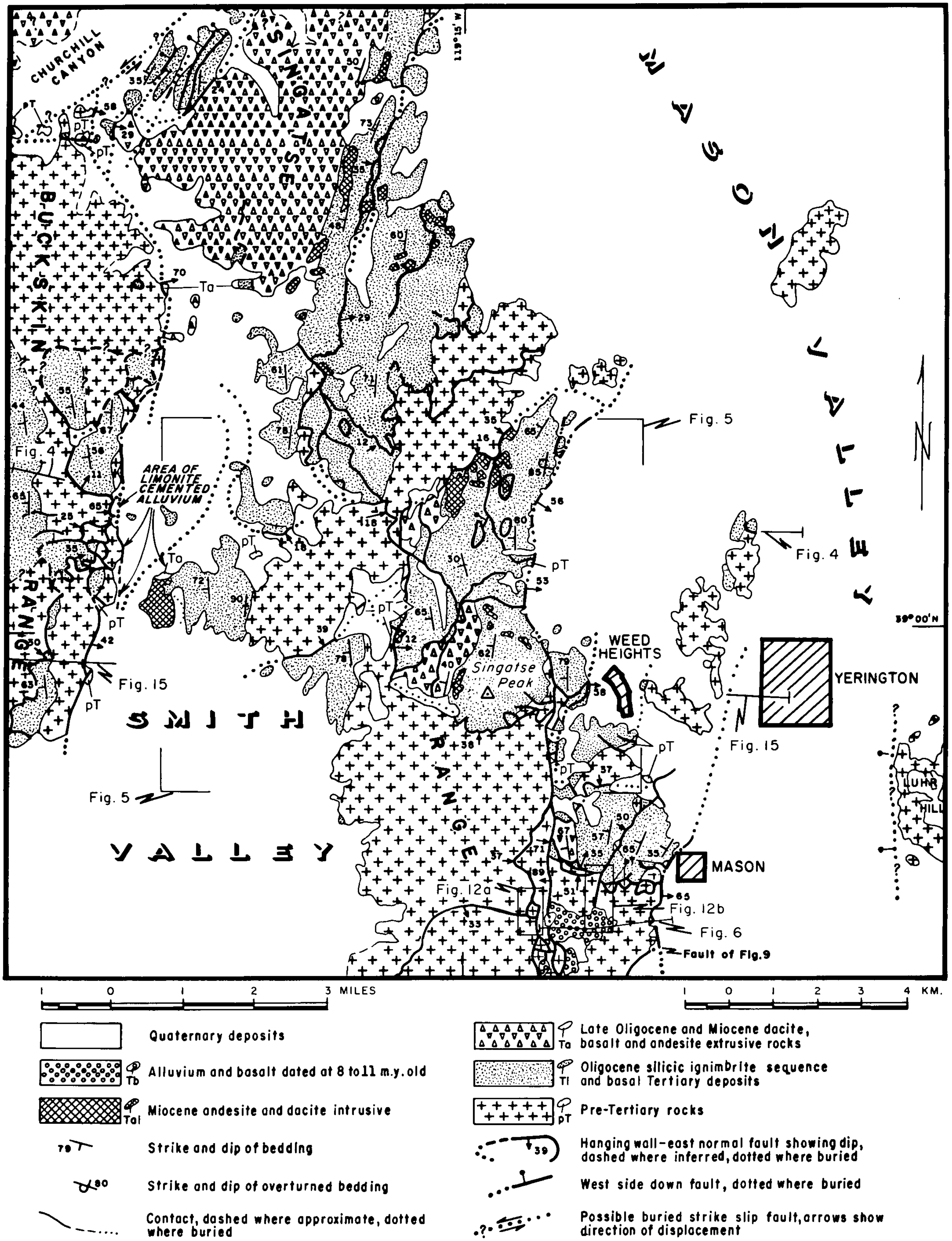


Figure 2. Generalized geologic map of Yerington district, Nevada, showing major Cenozoic features.

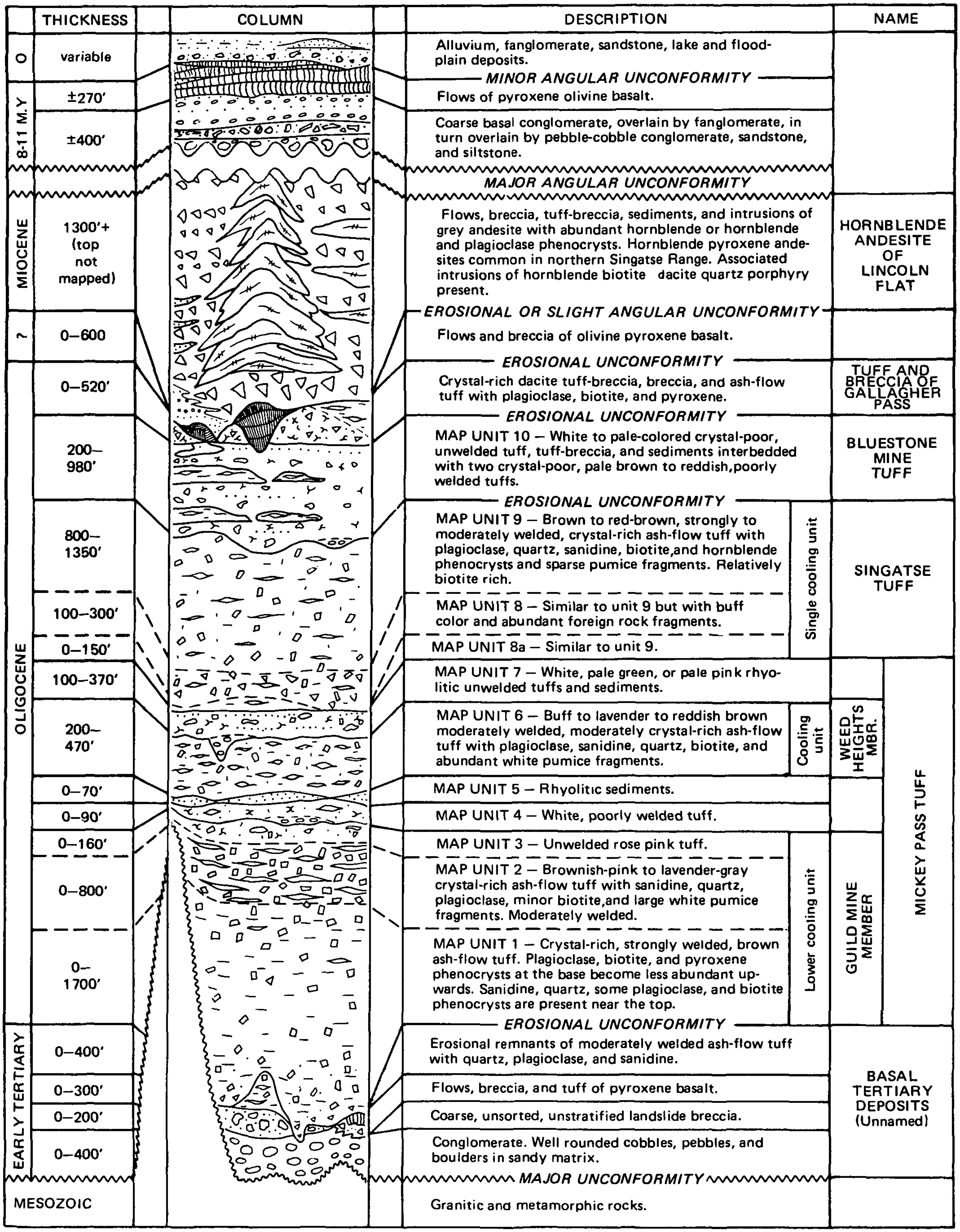


Figure 3. Stratigraphic section of Cenozoic rocks of Yerington district, Nevada, after Proffett and Proffett (1976) (courtesy of Nevada Bureau of Mines and Geology).

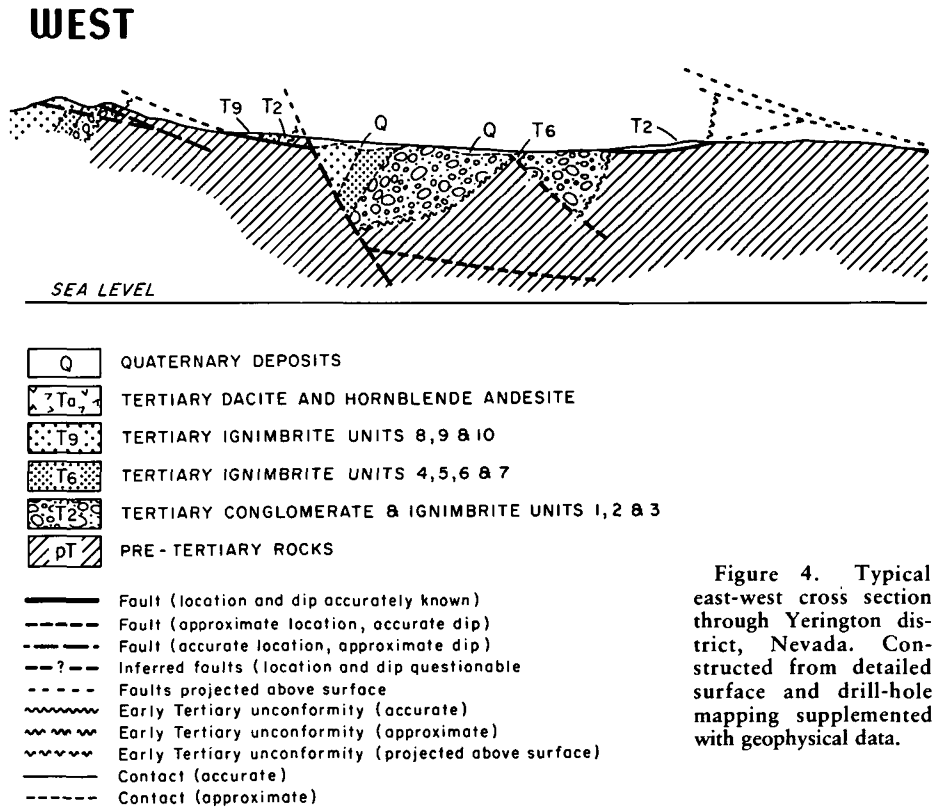


Figure 4. Typical east-west cross section through Yerington district, Nevada. Constructed from detailed surface and drill-hole mapping supplemented with geophysical data.

Table 1). This sequence contains three major ignimbrite cooling units, several thin ignimbrites, and thin interbeds of rhyolitic sedimentary rocks and tuff. For mapping purposes, the sequences has been divided into 10 units, which are fairly uniform and continuous throughout and beyond the district. Individual mapping units are distinctive enough to be identifiable, even in drill holes and isolated outcrops. This has helped immeasurably in working out the geometry of late Cenozoic structure. The 10 map units have been grouped into three formations (Fig. 3; Proffett and Proffett, 1976) that can be identified well beyond the district, but to facilitate detailed description of the structure, the numbered units will be used in most of the following discussion and illustrations. The ignimbrite sequence is disconformably overlain by the late Oligocene tuff and breccia of Gallagher Pass, a dacite unit about 150 m (500 ft) thick, which consists of ignimbrites and volcanic breccia (Fig. 3; Table 1). The dacite is disconformably overlain by a basalt unit of local extent and by several hundred to a few thousand metres of Miocene hornblende and hornblende pyroxene andesite breccia and flows (Fig. 3; Table 1). Miocene intrusive rocks identical petrographically and in age (Table 1) to the Miocene andesite represent feeders and vents. Intrusive bodies of biotite-hornblende dacite, similar in age (Table 1), petrography, and distribution to the Miocene andesites, are also present. The Miocene andesites and all older rocks are now tilted moderately to steeply westward and are cut by many large east-dipping normal faults.

The oldest known rocks that postdate formation of hornblende andesite in the district are a few hundred metres of alluvium, overlain by several flows of basalt dated as 8 to 11 m. y. old (Fig. 3; Table 1). These deposits are tilted gently westward and postdate most normal faults but predate some. The alluvium is similar to that in present basins, but its position on ridges in the Singatse Range attests to changing locations of basins and ranges during the development of Basin and Range structure.

A large gap in the stratigraphic record between the Miocene andesite and the 8- to 11-m.y.-old alluvium corresponds in age to much of the Basin and Range faulting. It is possible that thick sections of upper Miocene and Pliocene sedimentary rocks that occur in surrounding areas such as Aldrich Station (50 km south of Yerington), southeastern Smith Valley, and southeastern Mason Valley (Axelrod, 1956; Moore, 1969; Gilbert and Reynolds, 1973) may fill this gap. Some of these sedimentary rocks may have filled basins that were formed by the earlier Basin and Range faults.

The youngest rocks in the district are Quaternary sedimentary deposits in the present basins (Figs. 2, 3). The oldest of these is a limonite-cemented fanglomerate of probably early or middle Pleistocene age. Upper Pleistocene sedimentary rocks include beach deposits formed during two high stands of Artesia Lake (Wellington Lake) and Lake Lahontan (Morrison and Frye, 1965) and fanglomerate deposited in the time between the high stands of the lakes. Deposits of Holocene age include fanglomerate, dune sand, and the floodplain alluvium of the Walker River. The oldest of the Quaternary units are tilted a few degrees to the west and are offset a few tens to a few hundred metres on steep range-front faults. The youngest Quaternary units are tilted only very slightly westward and are offset only locally 1 m or so on a few range-front faults.

LATE CENOZOIC STRUCTURE

Tilting

Smith (1904) first recognized that Tertiary rocks of the Yerington region are tilted conspicuously westward in contrast to equivalent rocks in the Sierra Nevada. Significant westward tilting in the Yerington district was also recognized by Knopf (1918) and Wilson (1963). With few exceptions, the rocks of the Yerington district are tilted westward (Figs. 2, 4, 5). Dips in the Oligocene ignimbrites are commonly very steep westward and vertical or even overturned steeply to the east. Moderate to gentle westward dips also occur in the ignimbrites, but they are caused by drag along east-dipping normal faults rather than by a lesser amount of tilting. Because of the influence of drag upon some of the westward dips, the steepest dips within a block are considered to be the best index of the total tilting. Thus, most of the blocks of the district have been tilted westward 75° to 90° or more. The lower Tertiary unconformity and the pre-Tertiary rocks have also been tilted steeply westward.

There are no angular unconformities in the stratigraphic section between the base of the lower Tertiary conglomerate and the base of the Miocene andesite (Fig. 3). Within the Miocene andesite formation, and locally at its base, minor angular unconformities appear to separate individual units, the overlying units being tilted slightly less steeply westward than the underlying units. Thus, tilting began during deposition of the Miocene andesite sequence; but, since even the youngest part of the sequence is moderately to steeply tilted, most of the tilting must have taken place after its eruption. The 8- to 11-m.y.-old basalt and underlying alluvium dip 6° to 25° westward (Fig. 6). Therefore, most of the tilting took place before deposition of these units, but a significant amount followed. The uppermost of the 8- to 11-m.y.-old basalt flows dips only about 5° or 6° west-

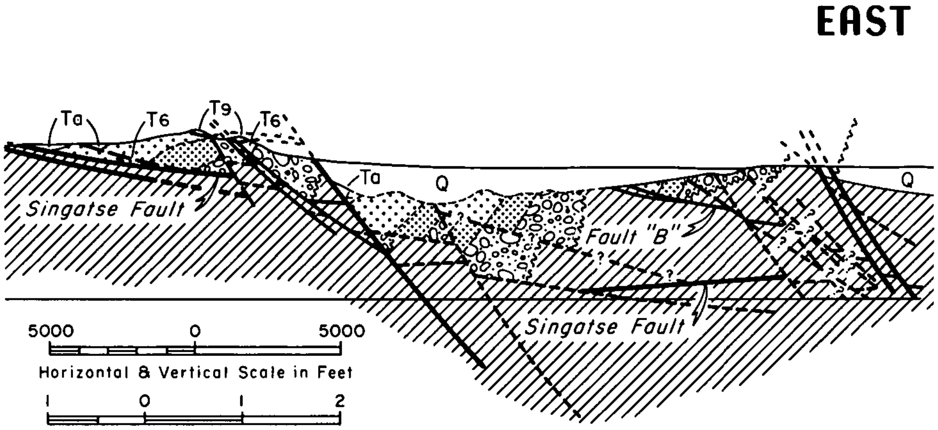


Figure 4. (*Continued*).

ward, indicating that a few more degrees of tilting had taken place by the time of its deposition (Fig. 6). Locally as much as 8° of westward tilting has taken place since deposition of the lower or middle Pleistocene(?) limonite-cemented fanglomerate. Alluvium of late Pleistocene and younger age is generally not measurably tilted, except locally adjacent to the most recently active faults (Fig. 6). However, the Walker River flows on the extreme west side of its broad, latest Pleistocene to Holocene flood plain through most of Mason Valley, apparently owing to slight westward tilting of the flood plain. The floor of Smith Valley (Fig. 2) likewise appears to be tilted slightly westward. Furthermore, many of the mountain ranges in the area have steep east flanks due to eroding fault scarps, and gently sloping west flanks, apparently due to westward tilting. Thus, westward tilting has continued until very recent times and may still be continuing.

Normal Faults

Attitudes of Faults

The rocks of the Yerington district are cut by numerous upper Cenozoic eastward-dipping normal faults. Gently and steeply east-dipping faults were recognized in the district as early as 1914 by Reno Sales (unpub.), and several steeply and moderately east-dipping faults were mapped by Knopf (1918).

During this study, the attitudes of faults in the Yerington district have been measured in natural exposures, artificial cuts and pits, drill holes, and mine workings and have been inferred from expression of fault outcrops on topography. Some faults have very gently easterly dips, some have moderate easterly dips, and some have steep easterly dips (Fig. 4). A few very steep eastward-dipping normal faults locally dip steeply westward, making them steep reverse faults at these localities (Fig. 6). The east-side-down west-dipping reverse fault in the McConnell mine (Knopf, 1918, Fig. 4), may be part of such a fault. Some gently east-dipping normal faults are so nearly horizontal that they locally dip gently westward, at which point they become apparent reverse or thrust faults (for example, the Singatse fault near the east end of Fig. 4).

Shape of Fault Planes

Many of the faults of the district are trough shaped; the axes of the troughs trend roughly east-west, and the concave side of the trough faces up or eastward (see Fig. 5, fault "C" and Singatse fault, and Fig. 7, b). The faults also flatten with depth or to the east (Figs. 4 and 7, a). Thus, many of the faults are spoon shaped, with the bowl of the spoon facing up and to the east. Surface exposures and drill-hole intersections of two major gently east-dipping faults (Singatse fault and fault "B" of Fig. 4; Fig. 7, a) show that they flatten eastward, or with depth, by about 0.3° to 0.7°/100 m (1° to 2°/1,000 ft).

Normal faults are known to flatten with depth in a few other areas. The Hurricane fault is nearly vertical on the rim of the Grand Canyon and flattens about 1.3° to 2°/100 m (4° to 6°/1,000 ft) of depth to a dip of about 60° west at the bottom (Hamblin, 1965). Other normal faults in the area appear to have similar curvatures. West-

TABLE 1. K-Ar AGES OF CENOZOIC ROCKS FROM YERINGTON DISTRICT, NEVADA

Rock unit*	Sample no.	Mineral	Age (m.y.)
Uppermost and least tilted gently dipping basalt flow	583	Whole rock	8.2 ± 1.2
Uppermost of more tilted gently dipping basalt flows (McConnell Canyon)	584	Whole rock	8.6 ± 1.3
Lowermost gently dipping basalt flow (McConnell Canyon)	431	Whole rock	10.6 ± 1.0
Andesite of Lincoln Flat			
Porphyritic hornblende biotite dacite intrusion, related to hornblende andesite sequence	664	Hornblende	18.7 ± 2.5
	664	Plagioclase	18.5 ± 2.7
Porphyritic hornblende andesite dike; cuts and intrudes one of oldest Basin and Range normal faults in district	602	Hornblende	18.5 ± 2.5
	602	Plagioclase	18.9 ± 2.8
Hornblende andesite flow	665	Hornblende	17.7 ± 2.4
Porphyritic hornblende andesite breccia	671	Hornblende	18.7 ± 1.9
	671	Plagioclase	17.0 ± 2.5
Tuff and breccia of Gallagher Pass pumice block	662	Biotite	24.1 ± 0.9
	662	Plagioclase	23.6 ± 2.0
Singatse tuff	S-29	Biotite	27.2 ± 1.1
	S-29	Hornblende	31.7 ± 1.8
Mickey Pass tuff			
Weed Heights Member (map unit 6)	661	Biotite	27.8 ± 1.0
	661	Sanidine	26.1 ± 0.9
Guild Mine Member (map unit 1)	267	Biotite	27.1 ± 0.9
	675	Biotite	28.0 ± 1.0
	675	Plagioclase	25.1 ± 1.8

Note: Age of determinations by Geochron Laboratories, Inc.
* In order of stratigraphic position, youngest at top.

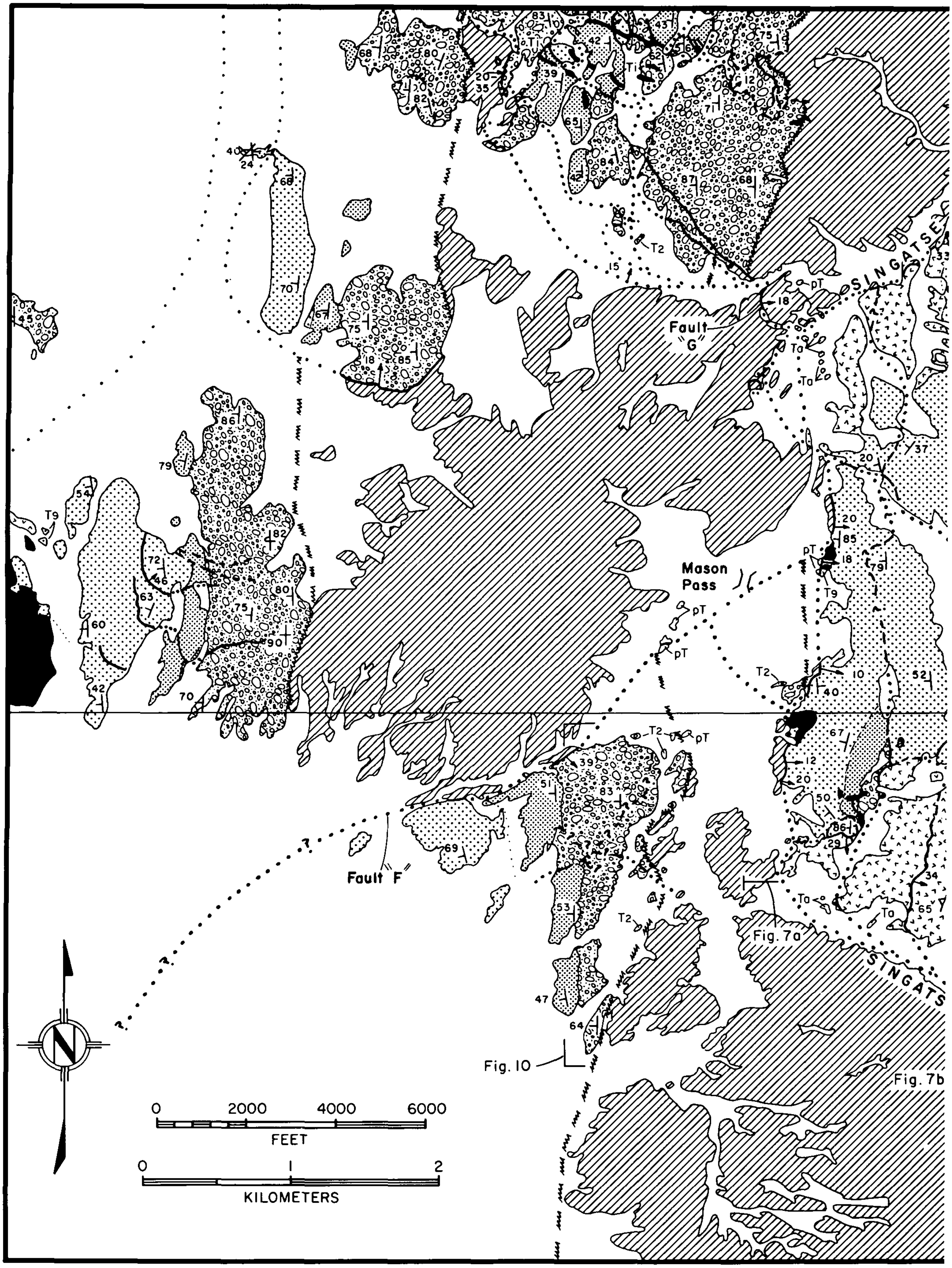


Figure 5. Generalized geologic map of part of Yerington district, Nevada.

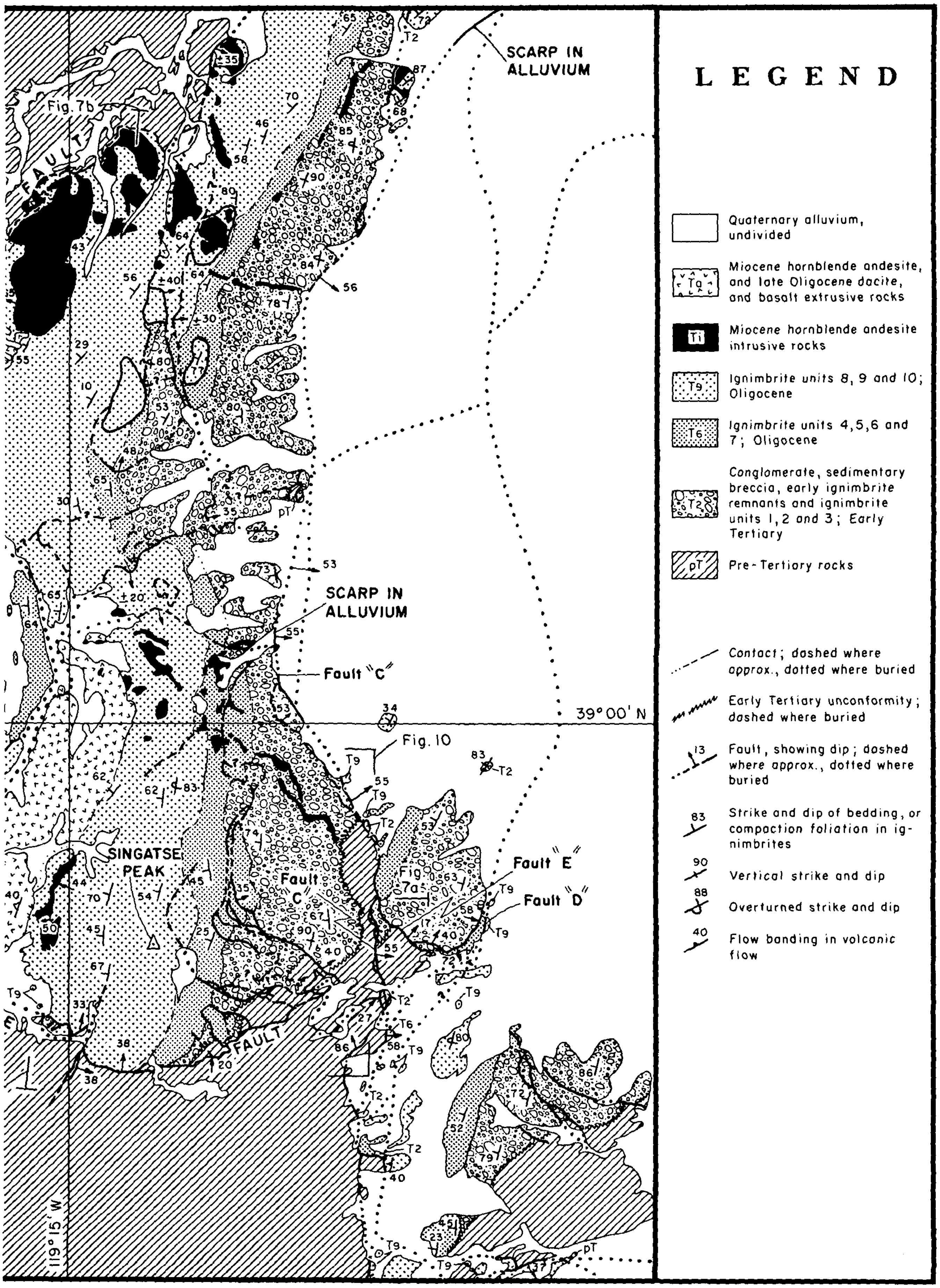


Figure 5. (*Continued*).

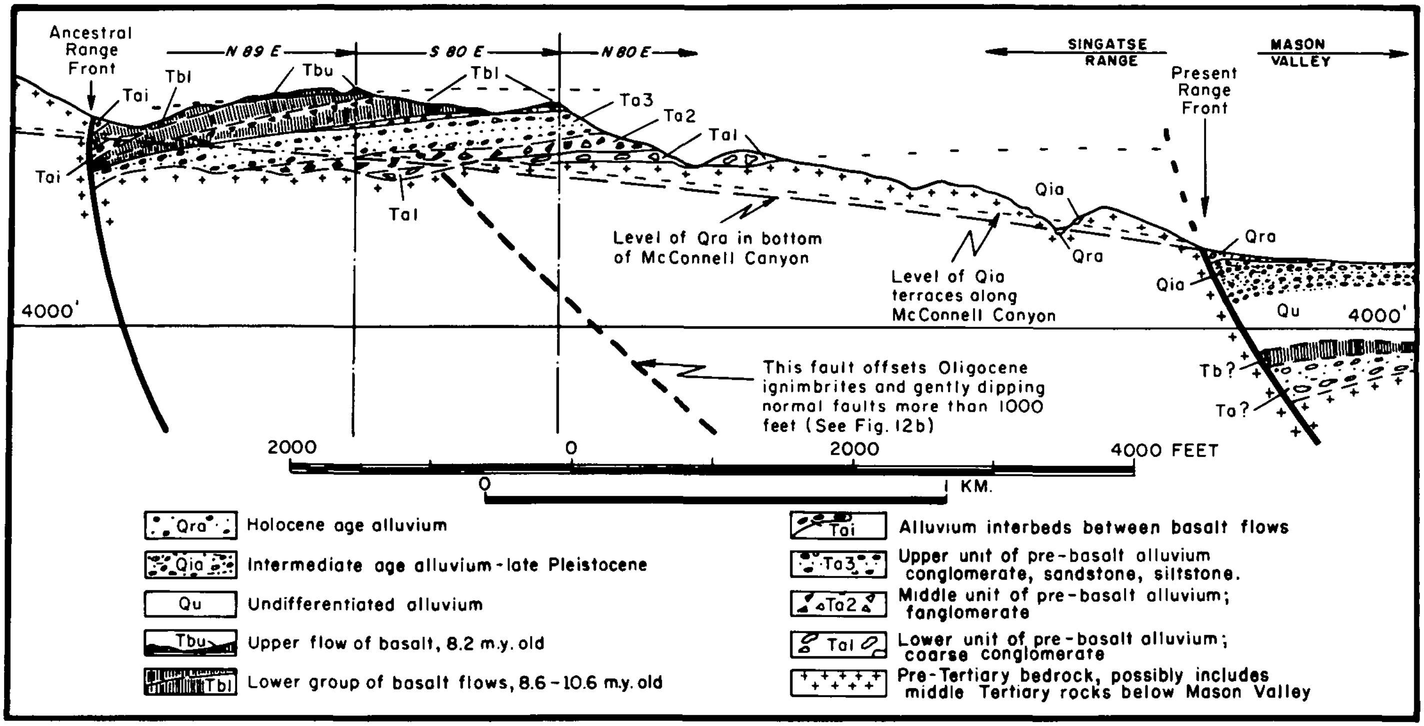


Figure 6. East-west cross section showing 8- to 11-m.y.-old basalt and alluvium and Quaternary deposits about 1.2 km (0.75 mi) south of Mason.

dipping normal faults north of Las Vegas flatten with depth by about 0.7° to 1.3°/100 m (2° to 4°/1,000 ft; Longwell, 1954, p. 112).

The 0.3° to 0.7°/100 m curvatures at Yerington were measured on parts of faults that were about 3,000 to 4,500 km (10,000 to 15,000 ft) deep (see section below) at the time of faulting, and the curvatures are slightly greater on the westward or updip parts of the faults. This suggests that the rate of flattening with depth may decrease with increasing depth (Fig. 8). The high curvature of the Hurricane fault lends some support to this; locally preserved intrafaulting deposits (Hamblin, 1965) suggest that the present exposures of the Hurricane fault were shallow at the time of faulting.

The zigzag patterns of some range fronts in the Yerington region, such as the west side of the Pine Nut Range or the southern Singatse Range, are mainly due to intersecting trough-shaped faults, sharp bends in the faults (Fig. 9), and the en echelon arrangement of some groups of normal faults. The average strike of most faults along the range fronts is north to north-northeast, and locally north-northwest.

Fault Gouge

The normal faults are marked by zones of gouge that consist of broken, crushed, and finely ground rock material and which change in character with depth. In the parts of large faults that were shallow at the time of faulting, gouge is commonly several centimetres to a few metres thick and consists of abundant sheared slickensided plastic clay and sheared breccia containing rolled pebble- and cobble-sized rock fragments. Zones of breccia and broken rock several metres thick may lie on either or both sides. Along parts of the same faults that were deep at the time of faulting, the gouge is commonly only a few centimetres thick and consists mainly of clay that is brittle and in-

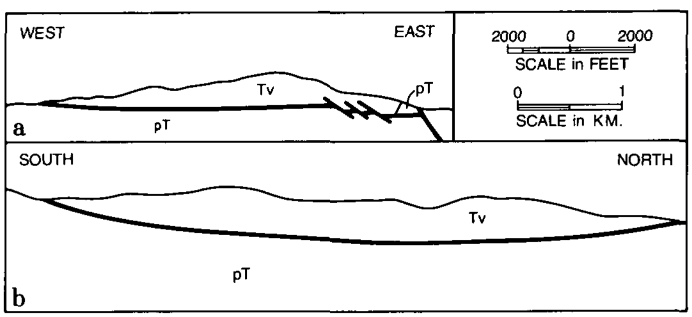


Figure 7. East-west section (a) and north-south section (b) across Singatse fault (see Fig. 5), showing Tertiary volcanic rocks (TV) and pre-Tertiary rocks (pT).

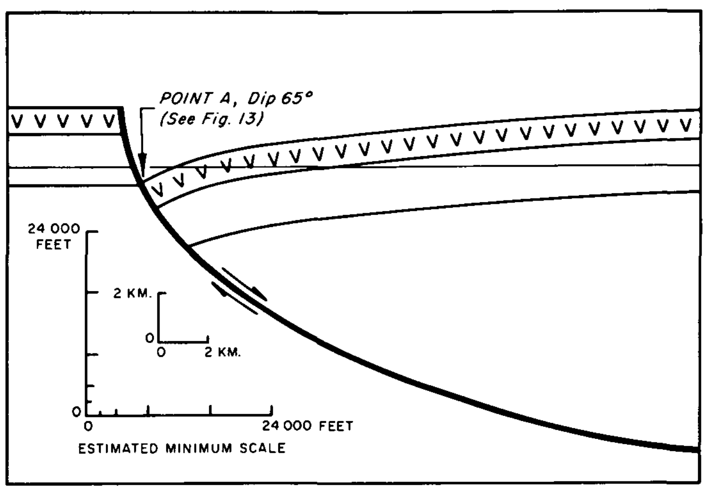


Figure 8. Cross section showing idealized fault of type found at Yerington, showing decrease in dip, inferred decrease in concave-upward curvature with increasing depth, and increase in tilting of hanging-wall rocks toward fault. Scale is estimated from available data as discussed in text, but depth shown at which fault becomes flat is probably a minimum.

durated rather than plastic. There is little or no brecciation of the adjacent rock, but a crude foliation may result from shearing. Some faults have a tendency to split into two or more strands upward, or to the west.

Direction of Displacement

Several lines of evidence show that the net direction of displacement on many, and perhaps all, of the east-dipping Cenozoic normal faults in the Yerington district was largely dip slip, or hanging-wall eastward and that there is no significant north-south component of displacement.

Slickensides. Slickensides indicate direction of at least some displacement along faults. The average trend of the several slickensides found on the many layers of a fault gouge would most reliably indicate direction of total displacement. Slickensides trends for gently, moderately, and steeply east-dipping normal faults in the Yerington district vary 20° to 40° within single exposures, but the estimated average of several trends from single exposures is east to east-southeast.

Troughlike Form. Displacement parallel to the axes of trough-shaped faults would be much easier than across the axes. The troughs resemble giant mullions. The east-trending trough axes of many faults in the district suggest east-west movement. This means that the trough-shaped faults should be dip slip only near the center of the troughs, where the strike is due north, but they should be oblique slip or even strike slip along the sides.

Bends in Fault Planes. Sharp bends in fault planes are comparable to large mullions, whose axes should be parallel to fault displacement. Most axes of such bends of fault planes mapped in the district trend approximately east (Figs. 5, 9), indicating displacement in this direction. An unusual trend of S65° to 70°E was found on one bend on the fault of Figure 9, which is one of the youngest faults in the district.

Pinch-out of Beds. The net direction of displacement of a fault can be measured by the offset of linear features cut by the fault. The pinch-out lines of beds provide such linear features. For example, the lower Tertiary conglomerate and ignimbrite unit 1 pinch out against a lower Tertiary hill of pre-Tertiary rocks in the hanging wall and footwall of the Singatse fault (Fig. 10). The pinch-out of the conglomerate in the hanging-wall block of the Singatse fault lies about S85°E from the pinch-out of the conglomerate in the footwall (Fig. 10, points A and A′), and the pinch-out of ignimbrite unit 1 in the hanging wall lies about N89°E from the pinch-out of unit 1 in the footwall (Fig. 10, points B and B′).

The weathered and broken nature of the pre-Tertiary rocks exposed for a distance of 900 m (3,000 ft) along the lower Tertiary hill indicates that this hill could not have been unusually steep — certainly not more than about 35°. The apparent slope of the lower Tertiary hill (angle of pinch-out) in present outcrop as shown in Figure 10 is 25°. Geometry requires, therefore, that the average orientation of the lines that represent the pinch-outs cannot be close to parallel to the strike of the tilted beds (Figs. 11a, 11b). This limits the possible error in estimating the net direction of displacement on the Singatse fault from the offset of the pinch-outs. The possible error is further minimized because of the gentle dip of the fault, as illustrated in Figure 11c. The net displacement direction of the Singatse fault can be confidently placed between S80°E and N85°E and probably between S85°E and due east, or hanging wall relative to footwall.

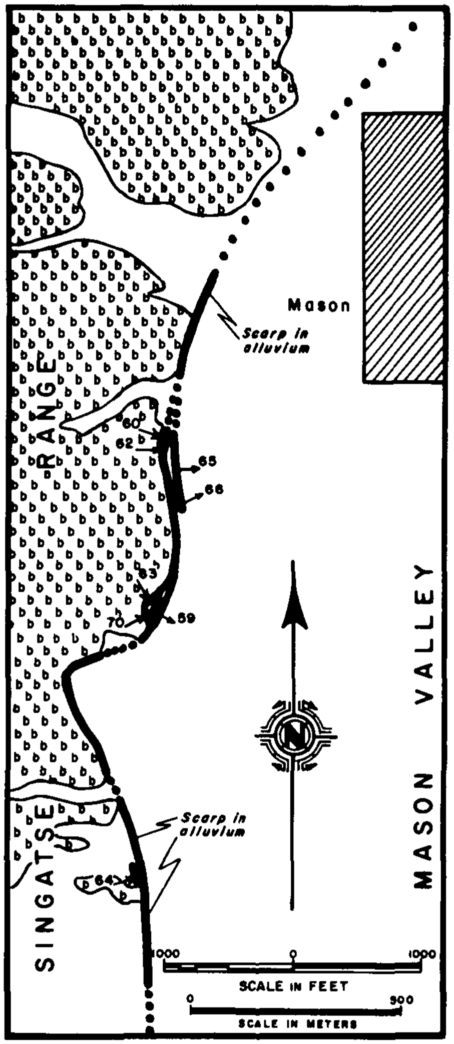


Figure 9. Outcrop map of range-front fault southwest of Mason (see Fig. 2 for location) that has been active in Holocene time. Blank area is Quaternary alluvium, "b" pattern is bed rock.

Changes in strike of the early Tertiary surface in unexposed parts of the hanging-wall block could add possible error. However, this is not considered likely because of the uniformity of strike over the long exposed distance of the lower Tertiary hill over variable present topography and because of similarity of strike in exposures of the lower Tertiary surface on both sides of the fault and in other nearby fault blocks not shown in Figure 10.

Other faults for which Tertiary conglomerate and volcanic units pinch out in both hanging-wall and footwall blocks, such as faults C, D, and E of Figure 5, are steeper; hence, the possible error is greater in calculating net direction of displacement by this method (between N60°E and S40°E, for hanging wall relative to footwall).

Correlation of Basement Rocks. Correlation of features in pre-Tertiary rocks across several faults in the district has yielded displacement direction between S80°E and due east. The most useful features, which cannot be shown on the simplified maps here, are dike swarms, contacts of plutons, distinctive types of metamorphism, and distinctive zones of mineralization and alteration. For example, the nor th edge of a pre-Tertiary dike swarm, which lies a little north of A and A' shown in Figure 10, has been offset approximately S83° to 85°E by the Singatse fault.

Amount of Displacement. The largest net displacement measured in the district is 4,000 m (13,000 ft) on the gently dipping Singatse fault (Fig. 10). Several other gently to moderately dipping faults have displacements of between 600 and 2,500 m (2,000 and 8,000 ft; Fig. 4). The largest displacement measured on a steeply east-dipping normal fault is about 1,200 m (4,000 ft), and several steeply dipping faults have 150 to 1,200 m (500 to 4,000 ft) of displacement. Numerous faults have less than 150 m (500 ft) of displacement.

Age of Normal Faults

No normal faulting in the Yerington district is known to predate the lowest part of the Miocene andesite. For any individual fault, all units below and including the lowest part of the Miocene andesite are offset by the same amount. In the north part of the district, a porphyritic hornblende andesite dike, identical petrographically, chemically, and in age (Table 1) to Miocene andesite extrusive breccia dated to 17 to 19 m.y. old (Table 1), cuts across and intrudes along the fault plane of a gently dipping normal fault (Fig. 5, north edge, just west of center). Therefore, this fault predated at least part of the hornblende andesite breccia. Other dikes of hornblende andesite, identical to hornblende andesite flows dated at 17 to 19 m.y. old (Table 1), are

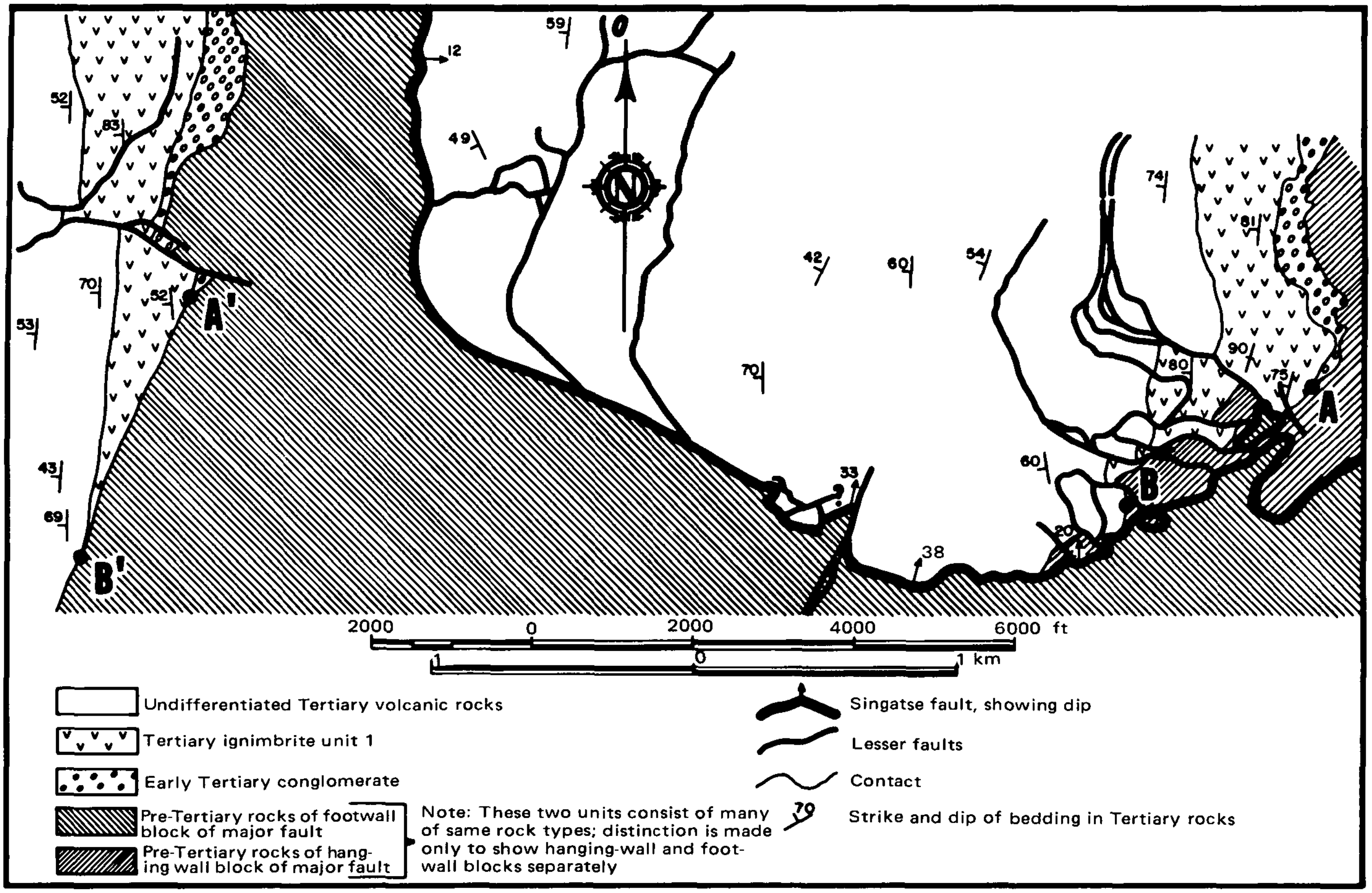


Figure 10. Singatse fault, showing offset units that pinch out in its hanging wall and footwall.

found, in diamond drill holes, to intrude the fault planes of some major gently dipping normal faults, such as fault "B" of Figure 4 and the Singatse fault. The margins of the dikes are partly converted to fault gouge, and the hornblende andesite flows are offset a few thousand metres by the faults. These faults were therefore initiated before the end of hornblende andesite igneous activity, but most of their displacement occurred afterward. Most other faults of the district, which are as steep as or steeper than the faults that are intruded by dikes, entirely postdate the Miocene hornblende andesite. It is evident that normal faulting began during the later phases of hornblende andesite igneous activity, about 17 to 18 m.y. ago, but that most normal faulting followed.

Several large gently to moderately dipping normal faults are covered by, but do not offset, deposits of 8- to 11-m.y.-old basalt and alluvium. The steepest normal fault known to predate this basalt and alluvium dips 45° to 50° east (Figs. 6 and 12, b), and this fault postdates many less steeply dipping faults. This basalt and alluvium are cut only by a few steeply dipping normal faults (Fig. 6). Thus, most normal faulting had taken place before deposition of the 8- to 11-m.y.-old basalt and alluvium, but some faulting has taken place since then, all on steeper faults.

Early or middle Pleistocene(?) limonite-cemented fanglomerate in the western part of the district (Fig. 2) postdates most normal faulting in that area, as it lies across three fault blocks that are separated by faults having several hundred metres of displacement. However, it appears to be offset about 75 m (250 ft) by the Buckskin range-front fault (Fig. 2). Late Pleistocene fanglomerate is offset a few metres to a few tens of metres by some steep east-dipping faults along the east side of the Singatse Range. The range-front fault southwest of Mason (Figs. 2, 9) offsets Holocene fanglomerate 1 m or so. Only fanglomerate of channels that have been active during historic flash floods are unaffected by this fault. Many range-front faults in the surrounding region have been active during Holocene time.

If the potassium-argon age determinations listed in Table 1 are correct, then faulting and tilting in the Yerington district started about 17 to 18 m.y. ago and was at least two-thirds complete by 8 to 11 m.y. ago but has continued with significant intensity through Pleistocene and Holocene time.[2]

Relationship between Dip and Age of Normal Faults

Relationships between east-dipping normal faults and rock units, discussed above, show that the oldest faults are the most gently dipping, that faults of intermediate age dip moderately, and that the youngest faults dip most steeply. In almost all cases where two faults intersect, the more steeply dipping of the two cuts the most gently dipping. This is true whether or not the dips of the two faults differ greatly (Figs. 4, 5, 12a, 12b; see also Knopf, 1918, Pl. 3). The only exceptions to this occur where north- or south-dipping faults are offset by faults that

[2] These age determinations, along with revisions of the radiometric time scale, thus make obsolete a previous statement (Proffett, 1971a) that "faulting began between the late Miocene and middle Pliocene and has probably proceeded at approximately the same rate to the present."

dip eastward by a lesser amount. In this case the south- or north-dipping fault may represent the north or south side of a trough-shaped fault, which has a more gentle eastward overall dip (Fig. 12b, and fault "F" of Fig. 5)

Relationship between Normal Faulting and Tilting

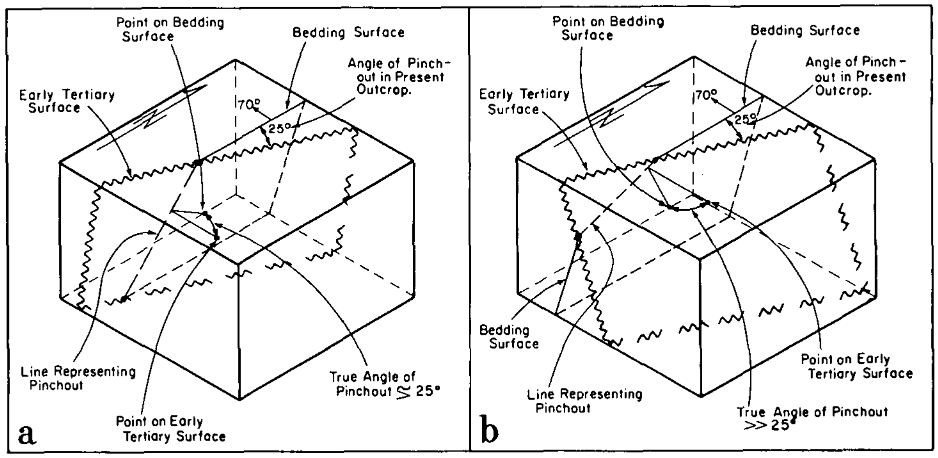
The coincidence in time of westward tilting and of faulting along east-dipping normal faults suggests that the two are related, and the curvature of the fault planes offers an explanation of this relationship. Displacement along curved, concave-upward, east-dipping normal faults may be accompanied by westward tilting of the hanging-wall block. The steep westward dips of each block of Miocene andesite and older rocks in the Yerington district are the result of accumulated tilt resulting from displacement along several large faults west of the block.

The gentle westward tilt of the 8- to 11-m.y.-old basalt and alluvium is due to displacement on only the ancestral range-front fault, and the amount of tilting increases toward the plane of this fault (Fig. 6). Increased westward tilting toward the fault plane can also be observed in Holocene or upper Pleistocene fanglomerate in the hanging wall of present range-front faults (Fig. 6). Similar observations have been made in the western part of the Colorado Plateau by Hamblin (1965). These observations indicate that the curvatures of the faults are greatest near the surface and decrease with depth, as shown in Figure 8 and as suggested by independent evidence discussed earlier.

Original Orientation of Normal Faults

Since the most gently east-dipping faults are the oldest, they must owe at least part of their unusual flatness to westward tilting produced by movement along more recently active normal faults (Figs. 8, 13). It can, in fact, be shown that many gently dipping faults dipped steeply east when they were active, just as the recently active faults do now. Some of these gently dipping faults, as discussed previously, are intruded by dikes of 17- to 19-m.y.-old hornblende andesite, the extrusive equivalents of which are now tilted moderately to steeply west. Since the average dip of these faults is now 0° to 10° east and the hornblende andesite extrusives dip 40° to 60° west, the faults must have dipped 40° to 70° east at the time the dikes were intruded. It was shown in the section on Age of Normal Faults that the dikes were intruded when the faults were active. By virtue of predating all or part of the activity of the faults intruded by the dikes, several other gently dipping faults, such as fault "F" in Figure 5, can be shown to have dipped steeply east when they were active.

For the same reason that the amount of westward tilt increases toward the fault planes, tilting of a fault due to displacement along another curved fault in the footwall block would tend to decrease the amount of curvature of the first fault (Fig. 13).



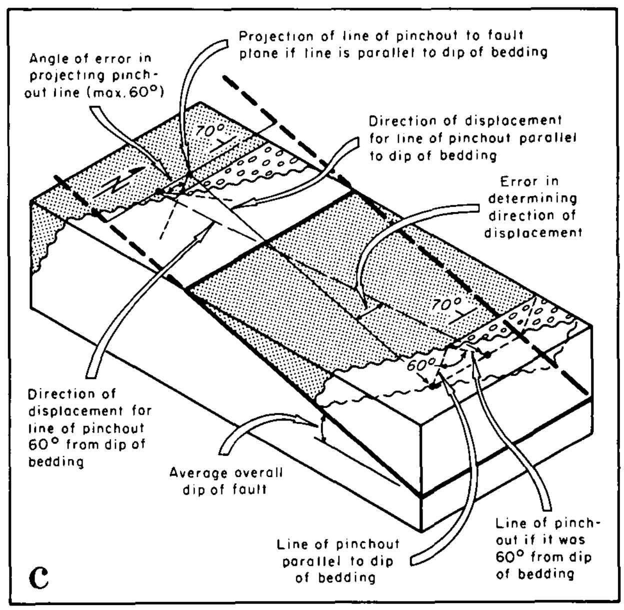


Figure 11. a, Block diagram of pinch-outs of Figure 10. Average strike of early Tertiary surface, strike and dip of bedding, and angle of pinch-out in present outcrop (about 25°) are known (variations in present topography, not shown in Fig. 10, have been taken into account). Slope of early Tertiary hill (= true angle of pinch-out) could not have been greater than about 35°, so true angle of pinch-out is equal to or slightly (as much as 10°) greater than angle of pinch-out in present outcrop. Therefore, average dip of early Tertiary surface must be such that line representing pinch-out is perpendicular to strike of bedding or diverges from perpendicular to strike by a certain limited angle. If true angle of pinch-out was as high as 35° (not likely), then variance of line of pinch-out from perpendicular to strike could have been as much as 60° if pinch-out line plunged north or 40° if it plunged south. Even such an unlikely high variance from perpendicular-to-strike results in a small error in calculating direction of displacement (Fig. 11c). b, If line representing pinch-out was nearly parallel to strike of bedding, as in example illustrated, then slope of early Tertiary hill (= true angle of pinch-out) would have to be unreasonably high. c, Diagram shows that for gently dipping faults, error in calculating net displacement direction from an offset pinch-out line is much smaller than error in estimating orientation of line of pinch-out. Average overall dip of Singatse fault is only about 3° (exaggerated in diagram), which would result in maximum possible error of about 5° (exaggerated) in determining displacement direction for Singatse fault.

Depth of Flattening of Normal Faults

The Singatse fault, where exposed in drill holes in a position that was 8 to 10 km (5 to 6 mi) deep at the time of faulting (east end of Fig. 4) still makes an angle of 40° to 50° with the westward-tilted Miocene andesites. This provides a minimum scale for Figures 8 and 13 and suggests that the depth at which the Singatse fault became horizontal when it was active was *at least*

13 to 16 km (8 to 10 mi). Similar evidence is found for other faults.

The gently dipping normal faults that can be seen today were not originally the flat lower parts of downward-flattening faults but were the moderately to steeply dipping upper parts. The late Cenozoic structure in the Yerington district is not a thin-skinned tectonic phenomena, and the flat faults are not detachment structures.

Antithetic Faults

In the Yerington mine, detailed mapping by W. W. Atkinson revealed several small steeply northeast-dipping reverse faults. If these faults have been tilted westward since the time they were active, then they could originally have been antithetic normal faults, as shown in Figure 14.

A possible east-dipping reverse fault, shown in Figure 4 (east of center), appears, in plan, to be cut by a gently east-dipping normal fault, which is cut by a moderately east-dipping normal fault, which is cut by a steeply east-dipping normal fault. The reverse fault could therefore be old enough to have been tilted considerably westward since it was active and may have originally been an antithetic west-dipping normal fault. Some very steep west-dipping normal faults with as much as a few hundred metres of offset have been mapped by B. Proffett near the northwest corner of the area shown in Figure 2. These appear to be older than some gently east-dipping normal faults and may have been moderately west-dipping antithetic normal faults when they were active. No other unequivocal antithetic normal faults are recognized in the district, although at the west edge of Luhr Hill, southeast of Yerington (Fig. 2), a west-dipping normal fault may be inferred because of the steep north-trending west edge of the hill.

It is apparent that in the Yerington district, the antithetic set of west-dipping normal faults is greatly subordinate to east-dipping normal faults.

Extension by Normal Faulting and Tilting

East-west cross sections through the Yerington district show clearly that much extension has occurred because of late Cenozoic normal faulting and tilting. The direction of this extension was the same as the average direction of net displacement of the normal faults, or approximately east-west. A typical east-west cross section (Fig. 4) shows that a prefaulting east-west distance of 7.3 km (24,000 ft) has been extended to a present east-west distance of 17.3 km (56,800 ft), as measured along pre–late Cenozoic surfaces, such as horizons in the Oligocene ignimbrite section. The cross section in Figure 15 shows about the same amount of extension. Thus, more than 100 percent of east-west extension has taken place (Proffett, 1971a). The average rate of east-west extension across the Yerington district, which has an east-west dimension of 16 to 19 km (10 to 12 mi), since normal faulting began 17 to 18 m.y. ago, has been about 0.06 to 0.07 cm/yr. The rate was 0.12 cm/yr or greater early during the period of faulting and 0.02 cm/yr or less during the past 11 m.y.

The east-west extension must have been compensated for by vertical crustal thinning (Fig. 15). Geophysical data indicate that the crust beneath west-central Nevada is in fact unusually thin, between 24 and 27 km (15 and 17 mi) in most areas (Eaton, 1963; Pakiser, 1963). Nearby areas that have not undergone Basin and Range fault-

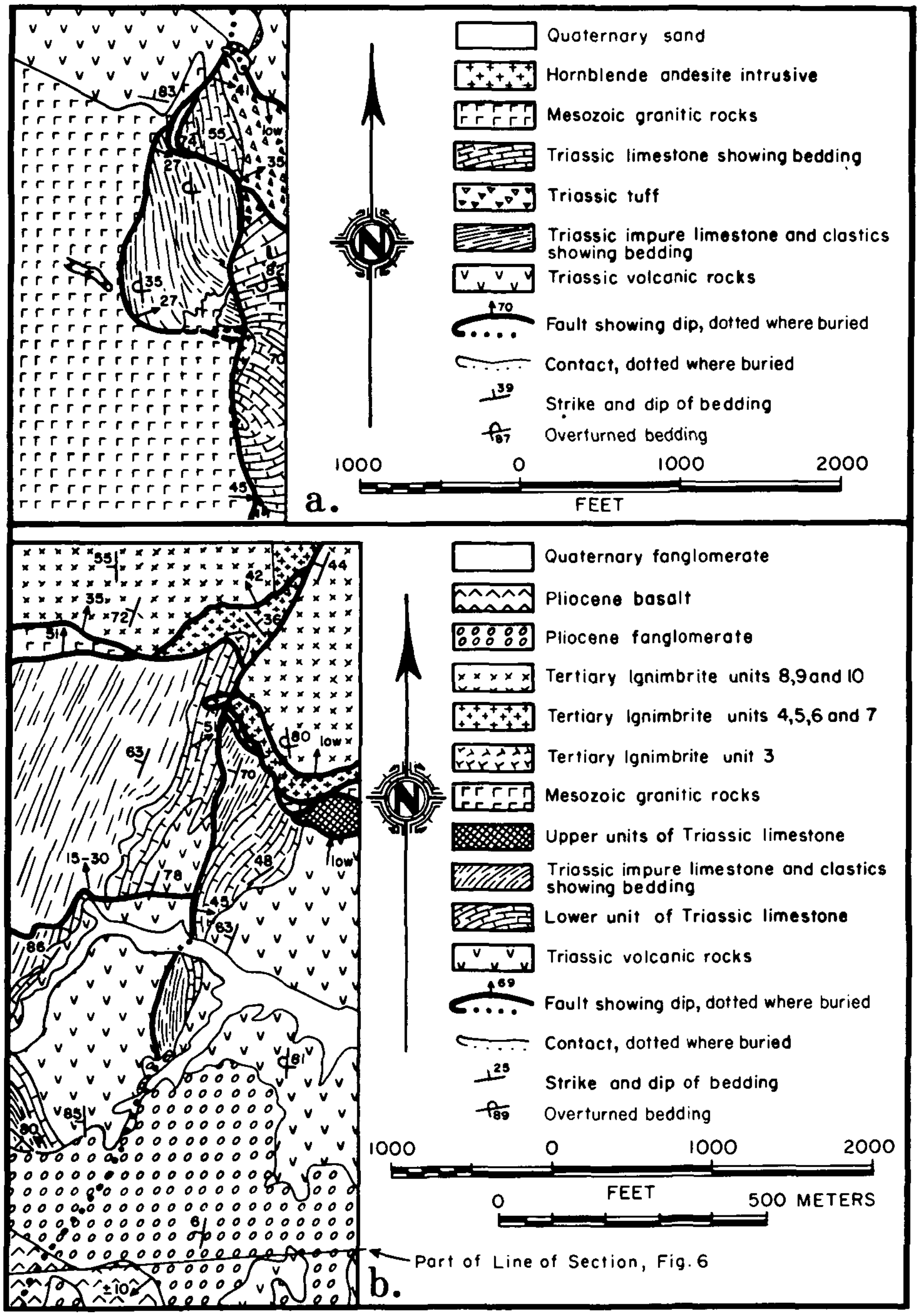


Figure 12. a, Moderately east-dipping normal fault cut by slightly steeper one. b, South flanks of gently dipping trough-shaped faults cut by moderately east-dipping fault (see Fig. 2 for locations).

ing have thicker crust (Eaton, 1963, Pakiser, 1963; Hamilton and Pakiser, 1965), ranging from 40 to 44 km (25 to 27 mi) beneath the Colorado Plateau to as much as 56 km (35 mi) beneath the Sierra Nevada. If the Yerington district had a crust of comparable thickness before Basin and Range faulting, then the amount of thinning required to explain the present thickness agrees favorably with the amount of east-west extension reported here (for example, crustal thinning from 48 to 24 km would accommodate 100 percent of east-west extension).

Evidence discussed in the section Depth of Flattening of Normal Faults suggests that at least the upper 13 to 16 km (8 to 10 mi) of the crust, and possibly even the entire thickness of the crust and perhaps part of the lithosphere below, are involved in this east-west extension and crustal thinning through Basin and Range faulting.

Reconstruction of Faulting Sequence

Faulting began about 17 to 18 m.y. ago in the Yerington district upon steeply east-dipping normal faults, which must have displaced the land surface when they were active, resulting in Basin and Range topography (Figs. 15b, 15c, 15d). Because of the curved, concave-upward nature of the fault planes, faulting was accompanied by rotation of the hanging-wall block, resulting in westward tilting of the rocks and flattening of previously formed fault planes. As faulting progressed, new steeply east-dipping normal faults were formed to take the place of the older faults, as the older faults were rotated to gently dipping orientations (Figs. 15d, 15e). The present orientation of the gently and moderately dipping faults of the district (Figs. 2, 5) is such that before rotation, their original strikes would have been approximately north-south and locally northwest or northeast. These earlier normal faults must have therefore controlled a topography of basins and ranges of approximately north-south average trend, much as the present Basin and Range faults do. Such topography was probably present throughout the past 17 to 18 m.y., but the location of the different basins and ranges has probably changed several times. Basins may have been present at one period where ranges stood at an earlier period, and vice versa (Figs. 15b–15f).

The geometry of faulting and crustal thinning would be expected to have resulted in a general lowering of elevation, but the region now stands at a high elevation, and there is evidence (for example Axelrod, 1956) that the elevation has increased since middle Tertiary time. Apparently, an uplifting force has been acting on the region while faulting was taking place.

Except for broad overall uplift, Basin and Range faulting in the Yerington district has been essentially a horizontal tectonic phenomenon rather than a vertical tectonic phenomenon. Only the near-surface manifestations involve strong vertical relative movements (see Figs. 8, 13).

ORIGIN OF BASIN AND RANGE STRUCTURE IN YERINGTON DISTRICT

Several theories of origin for Basin and Range structure, such as simple collapse of a rising arch (LeConte, 1889), collapse due to magma withdrawal (Mackin, 1960, p. 128–129), or expansion in the roof of a magma chamber or chambers (Willis, 1934; Thompson, 1959; 1966), can be rejected because of evidence found in the Yerington district for the Basin and Range structure there (see Proffett, 1972, for further discussion).

The east-west direction of extension for most of the Yerington district Basin and Range faulting precludes origin as part of a broad northwest-trending right-lateral megashear system, which has been envisioned as the origin of Basin and Range structure by Carey (1958), Deutsch (1960), Wise (1963), and Hamilton and Myers (1966) and presented in terms of plate tectonics by Atwater (1970). Such a strike-slip–related origin would require northwest-southeast or obliques slip displacement for the Basin and Range faults.

Basin and Range structure in the Yerington district and surrounding region does not in general follow pre-existing structural grain as has been suggested for Basin and Range structure by others (Shawe, 1965). The dominant structural grain in the Yerington district before faulting began trended N45°W to east-west, but the average strike of most Basin and Range faults is nearly north-south. Similar relationships can be found in many other parts of the Great Basin (see Proffett, 1972, for further discussion).

Basin and Range structure at Yerington must be explained by a theory that invokes large deep-seated horizontal extension of the crust in an east-west direction. Spreading axes, along which the sea floors are being created and are spreading from, are the best known features that involve such large horizontal extension (Menard, 1960; Hess, 1962; Dietz, 1961; Vine, 1966). "Interarc basins," areas of sea floor behind some island arcs, have also been interpreted to have originated as spreading axes with large horizontal extension (Karig, 1970), although the evidence is less convincing. Basin and Range structure at Yerington can best be explained by a hypothesis involving a continental equivalent of a spreading axis in the Great Basin (Proffett, 1971a). Menard (1960) first suggested such a hypothesis, observing that the East Pacific Rise, along which spreading axes are now known to occur, appears to continue northward into the continent from the Gulf of California, where it may have caused some of the seemingly anomalous features of the Basin and Range province. A

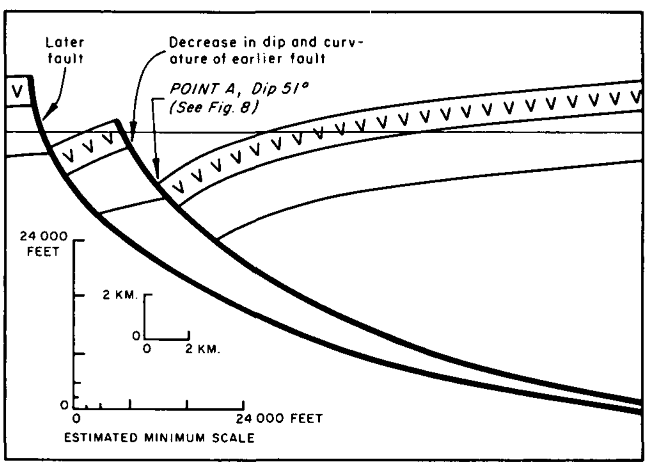


Figure 13. Tilting and reduction of dip and curvature of early normal fault (fault of Fig. 8) by tilting due to displacement on later normal fault. Note that vertical displacement as well as tilting are due to hanging-wall block adjusting in shape to fill a potential void resulting from horizontal extension between hanging wall and footwall. Hanging wall could have adjusted to its new shape by development of antithetic faults instead of tilting, as has clearly been shown by Hamblin (1965), but in Yerington district tilting was dominant.

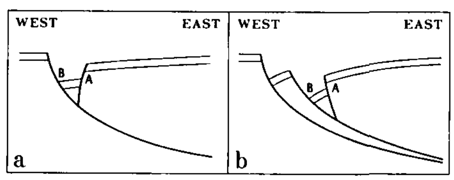
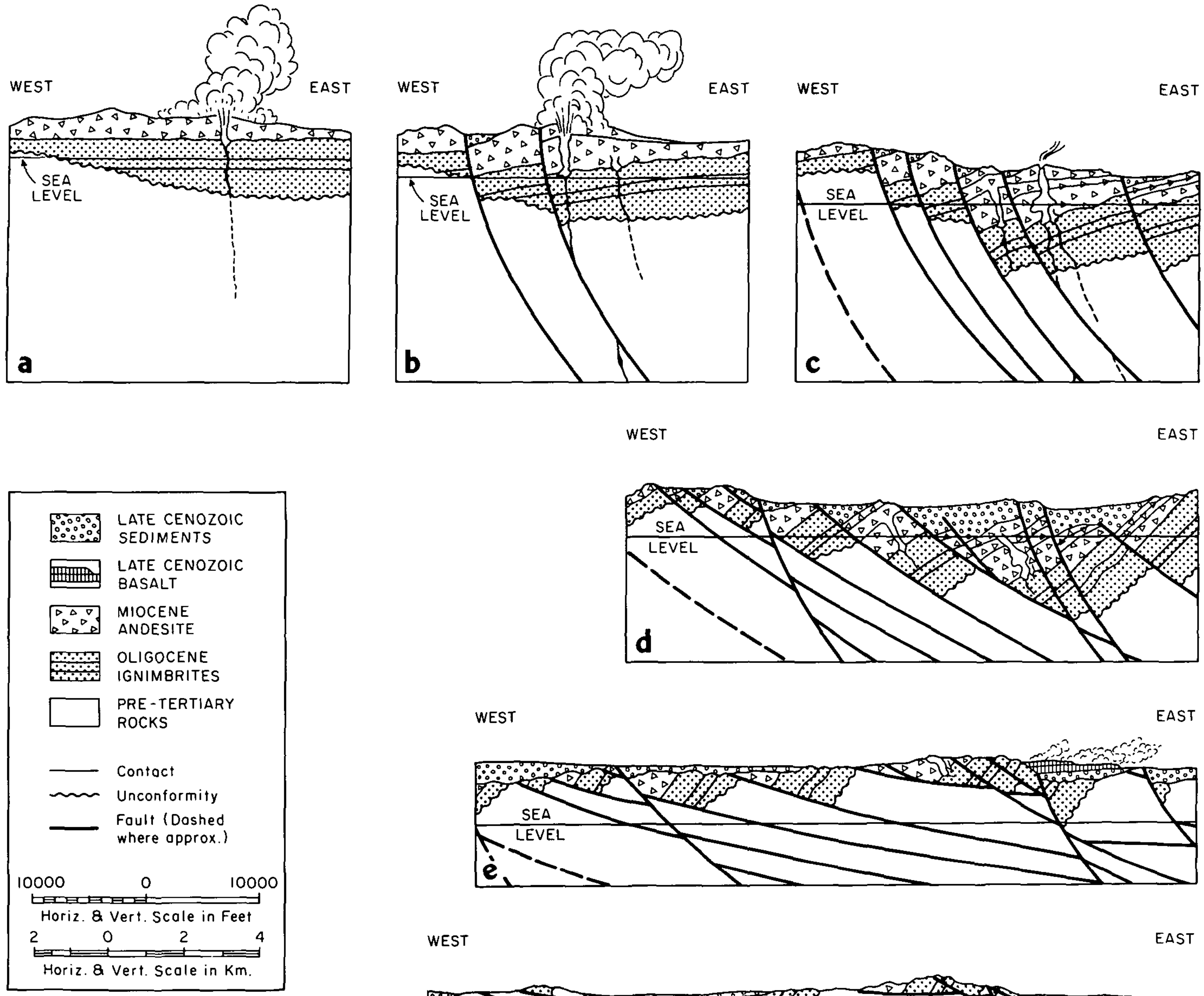


Figure 14. Diagrammatic cross section showing antithetic normal fault A at time a, changed to reverse fault at later time b due to westward tilting on east-dipping normal fault. Note that antithetic fault A developed in place of westward tilting in hanging wall block of fault B.



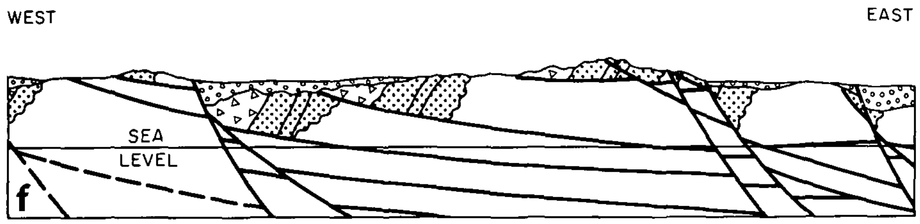


Figure 15. Cenozoic geologic history of Yerington district, Nevada, shown on east-west cross section. Various stages have been reconstructed by sequentially unfaulting and untilting present cross section (f). Sea level estimated for diagrams a through e. a, Late Oligocene through early Miocene; deposition of ignimbrite sequence followed by beginning of deposition of hornblende andesite, 18 to 19 m.y. ago. b, Early Miocene, 17 to 18 m.y. ago; continued eruption of andesite and beginning of Basin and Range faulting and tilting. c, Early Miocene, 17 m.y. ago; end of andesite volcanism and continued Basin and Range faulting with erosion of up-faulted blocks. d, Early and middle Miocene, 11 to 17 m.y. ago; continued faulting, tilting, erosion of ranges, and deposition of sediments in basins. Early faults rotated to such a flat dip that they are no longer in favorable orientation for continued faulting. New steeper faults form to take their place. e, Eight to 11 m.y. ago; all early faults tilted to gentle dips and inactive, but faulting and tilting continues on newly formed steep faults; erosion of ranges and deposition of sediments and locally basalt in basins. f, Present time; continued faulting and tilting along steep range-front faults, erosion of ranges and deposition in basins.

hypothesis that involves some type of spreading axis can also explain the high heat flow (Roy and Blackwell, 1966), low upper-mantle seismic velocity (Pakiser, 1963), general uplift, and basaltic volcanism in the Basin and Range province.

POSSIBLE MECHANICAL MODEL FOR BASIN AND RANGE FAULTING AT YERINGTON

A possible model for faulting, worked out mathematically by Prandtl (1924; see also Varnes, 1962) has been modified to fit the geologic conditions of Basin and Range faulting in the Yerington district (see Proffett, 1972, for more detailed discussion). This model suggests an east-west extending, vertically thinning cell of faulting, coupled to westward-moving material at its base (Fig. 16). The cell of faulting could be the upper brittle rocks of the lithosphere, and the westward-moving material at depth could be moving or stretching by laminar flow.

Large extension would cause relatively closely spaced faults of large displacement, resulting in the style of structure at Yerington. Lesser extension would result in the more commonly observed style of Basin and Range structure, with gentle tilting of hanging-wall rocks toward mainly steep, widely spaced fault planes. Because of the gentler tilting, faults would not be rotated to gently dipping inactive orientations.

Horst and graben versus tilted-block models of Basin and Range faulting are not necessarily fundamentally different as was implied by Stewart (1971). Both types of basins and ranges can be explained as different responses of hanging-wall blocks to motion along similar curved, downward-flattening normal faults (compare Fig. 8 and 14a). This was clearly pointed out by Hamblin (1965).

Yerington style, simple gently tilted block style, and horst and graben style Basin and Range structure may all result as differing degrees and styles of response to east-west horizontally directed regional extensive stress, according to a model such as that of Figure 16.

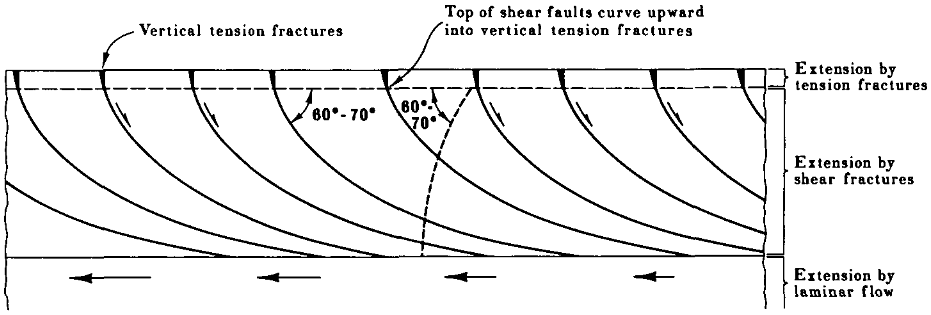


Figure 16. Possible mechanical model for Basin and Range faulting in Yerington district, shown on east-west cross section looking north. Depth of suggested change from tension to shear failure is not determined, but observational data suggest it is not deep. Walls of upper tension-fracture part of structure probably collapse, resulting in what appears to be near-vertical normal or reverse fault (as westernmost fault in Fig. 6). Deep-seated antithetic faults (dashed fault) are suppressed, perhaps because potential voids would result at base of cell. However, shallow antithetic faults could form in hanging wall of east-dipping normal faults instead of tilting (Fig. 14).

COMPARISONS WITH OTHER AREAS OF BASIN AND RANGE STRUCTURE

The combination of strongly developed Basin and Range faulting and tilting of the style found at Yerington has apparently not yet been adequately described and interpreted elsewhere. Therefore, limited reconnaissance and extensive review of published and unpublished work was undertaken to assess the possible importance of this style of structure in the Basin and Range province, and to help in evaluating different models and timing of an origin related to a spreading axis. Space does not permit discussion of individual areas here, but it was found that structure approaching the Yerington style, although not always as well developed, may be present in some other areas of the Great Basin (for example, Fig. 17a, locs. 1 through 8, 10, 30, and 31), and in southern Arizona and the Mojave Desert (for example, Fig. 17a, locs. 15 through 21). It should be noted that this is only a possible interpretation, which, although consistent with mapping in the references cited in the caption to Figure 17a (in some cases supplemented by unpublished work), is not generally the interpretation of the authors cited.

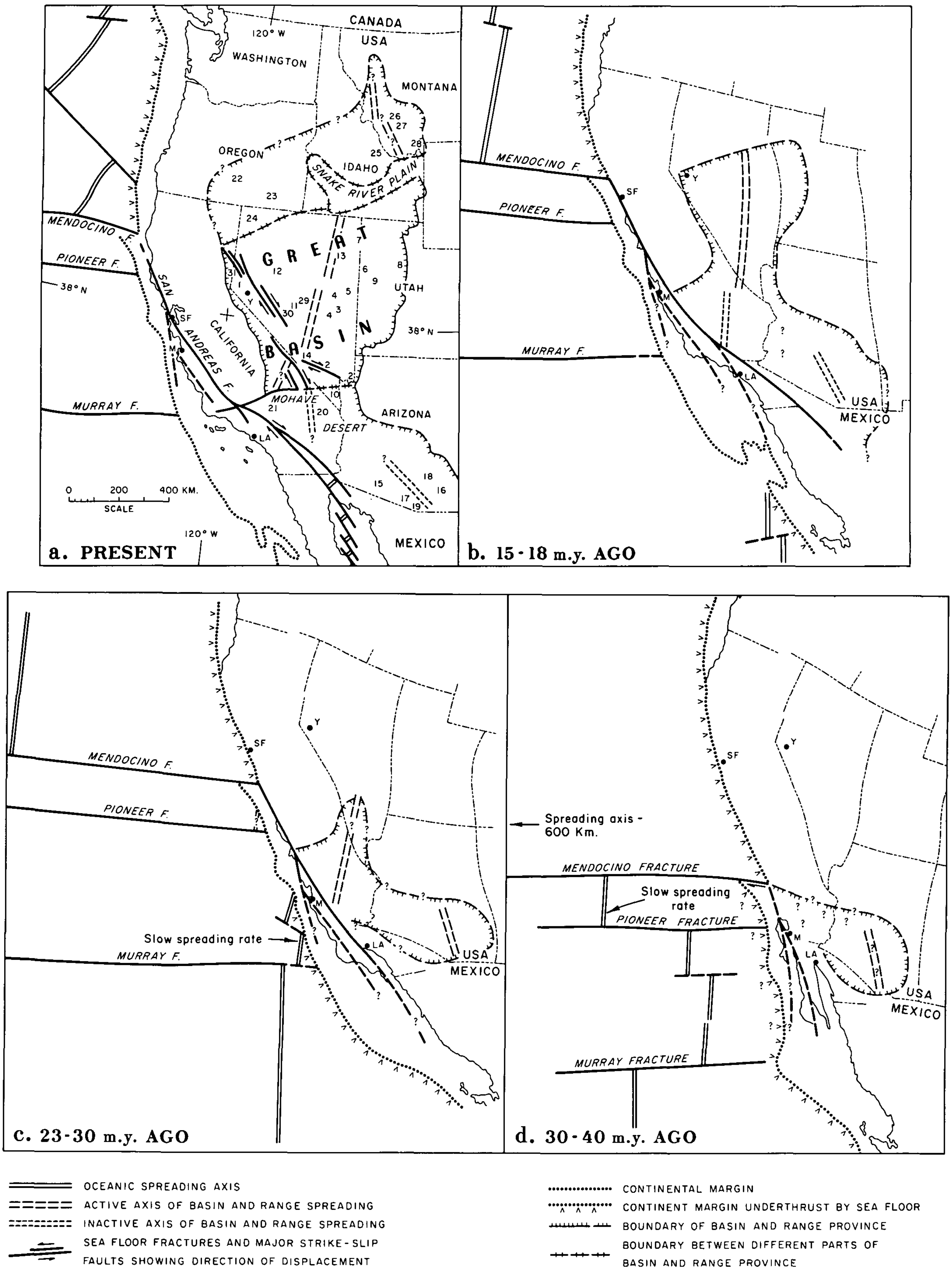
Within the Great Basin, patches of structure that approaches the Yerington style, implying large extension, seem to be distributed within a larger area of less developed tilted-block structure and locally horst and grabben structure (local areas of strike-slip–dominated structure will be discussed later). The patch that includes the Yerington district measures about 100 km (65 mi) east-west by about 50 km (30 to 35 mi) north-south. The patches of possible Yerington style structure occur mainly in the eastern and western parts of the Great Basin. Westward tilting and east-dipping normal faults are dominant in the western part of the Great Basin, and eastward tilting and west-dipping normal faults seem to be dominant in the eastern part.

In the central part of the Great Basin, most of the major Basin and Range normal faults dip steeply, either east or west, and are widely spaced compared to those in the Yerington district (see, for example, Fig. 17a, locs. 11 through 14 and 29, and unpublished reconnaissance in several localities). Tilting is gentle, predominantly eastward in areas of mainly west-dipping faults, and westward in areas of east-dipping faults. In some areas, antithetic faults have resulted in gently tilted or untilted horst and graben structures (Stewart, 1971). The amount of east-west extension that has taken place is estimated at 10 to 15 percent (Proffett, 1972; Thompson and Burke, 1973).

All this suggests a crudely symmetrical aspect for much of the Basin and Range structure in the Great Basin (Fig. 18), locally with moderate to large extension on east-dipping faults in the west and on west-dipping faults in the east and less extension in the center (Proffett, 1971a). Symmetry is also reflected in regional topography (Proffett, 1972), distribution of Pleistocene lakes (Feth, 1961), seismicity (Woollard, 1958), and crustal thickness (Fig. 18). Geophysical data indicate that the crust of the Great Basin is anomalously thin (Berg and others, 1960; Eaton, 1963; Pakiser, 1963; Hamilton and Pakiser, 1965; Hill and Pakiser, 1967). Assuming that the crust was originally comparable in thickness to that surrounding the Great Basin, the amount of thinning agrees fairly well with reasonable estimates for extension in different parts of the Great Basin: 35 to 100 percent in the western and eastern parts and 10 to 15 percent in the central part. An overall average extension of 30 to 35 percent, or 160 to 180 km, across the entire Great Basin does not seem unreasonably. Based on the faulting model of Figure 16, the suggested symmetry may indicate material moving westward in the western part of the Great Basin and eastward in the eastern part, with an axis of spreading in the central part (Figs. 17a, 17b, 18).

Information on the direction of net slip of Basin and Range faults is lacking in most areas, but where it is available, it usually shows that the direction of fault displacement, and therefore extension, was within 10° to 20° of east-west, as at Yerington. However, on a few faults, mainly some of those with relatively young displacement (see, for example, Thompson and Burke, 1973; Wright and others, 1974), the direction was northwest-southeast.

Basin and Range faulting began during late Oligocene to middle Miocene time in various parts of the Great Basin (see reference for Fig. 17a, locs. 1, 4, 11, 12, 14, 29; and this paper). The limited data suggest the possibility of increasing age in this time span, in a south or southeast direction. There is no evidence that Basin and Range faulting started later in the central Great Basin than in the eastern or western parts. The lower extension in the central part is



CANADA
USA
120° W
WASHINGTON
MONTANA
OREGON
IDAHO
SNAKE RIVER PLAIN
GREAT BASIN
UTAH
38° N
CALIFORNIA
SAN ANDREAS F.
MENDOCINO F.
PIONEER F.
MURRAY F.
SF
M
Y
LA
MOHAVE DESERT
ARIZONA
MEXICO
0 200 400 KM.
SCALE
a. PRESENT
b. 15-18 m.y. AGO
c. 23-30 m.y. AGO
Slow spreading rate
d. 30-40 m.y. AGO
Spreading axis - 600 Km.
MENDOCINO FRACTURE
PIONEER FRACTURE
MURRAY FRACTURE
OCEANIC SPREADING AXIS
ACTIVE AXIS OF BASIN AND RANGE SPREADING
INACTIVE AXIS OF BASIN AND RANGE SPREADING
SEA FLOOR FRACTURES AND MAJOR STRIKE-SLIP FAULTS SHOWING DIRECTION OF DISPLACEMENT
CONTINENTAL MARGIN
CONTINENT MARGIN UNDERTHRUST BY SEA FLOOR
BOUNDARY OF BASIN AND RANGE PROVINCE
BOUNDARY BETWEEN DIFFERENT PARTS OF BASIN AND RANGE PROVINCE

Figure 17. Generalized tectonic map of western North America and adjacent sea floor, showing possible evolution. Axes of Basin and Range spreading should not be thought of as narrowly defined features with exact locations like oceanic spreading axes, but simply as approximate axes of crude symmetry of broad zones of spreading. Strike-slip faulting sequence in California adapted from Suppe (1970), Huffman (1972), and Silver (1974). Axis of Basin and Range spreading in Montana adapted in part from Pardee (1950). SF = San Francisco; M = Monterey; LA = Los Angeles; Y = Yerington. Numbers in part a show locations referred to in text: 1, Comstock district (Becker, 1882; Coats, 1938; Thompson, 1956; Thompson and White, 1964; Bonham, 1969). 2, North and east of Las Vegas (Longwell, 1936, 1945; Longwell and others, 1965). 3, Egan Range–Cave Valley (Kellogg, 1964). 4, Grant, White Pine, and Horse Ranges (Moores and others, 1968). 5, Schell Creek Range (Drewes, 1960, 1964; Kellogg, 1964). 6, Gold Hill district (Nolan, 1935). 7, Pilot Range (Hague, 1877). 8, Wasatch fault–Oquirrh Range area (Gilbert, 1928; Gilluly, 1932; Hunt and others, 1953; James and others, 1961; Smith, 1961; Morrison, 1965). 9, Thomas Range (Staatz and Osterwald, 1959). 10, South of Las Vegas (Longwell, 1963; Anderson, 1971). 11, Central Nevada (Emmons, 1870; Meinzer, 1917; Kleinhampl and Ziony, 1967; Steward, 1971). 12, Stillwater Range and Dixie Valley (Page, 1965; Thompson and Burke, 1973). 13, East Humboldt and Ruby Ranges (Sharp, 1939). 14, Nevada Test Site (Hansen and others, 1963; Christiansen and others, 1965; Ekren and others, 1968). 15, Ajo district (Gilluly, 1946). 16, Dragoon area (Cooper and Silver, 1964). 17, Baboquivari Mountains (Heindl and Fair, 1965). 18, San Manuel district (Creasey, 1965; Lowell, 1968). 19, Oro Blanco district (Knight, 1970). 20, Providencia Mountains (Hazzard, 1954). 21, Western Mojave Desert (Noble, 1954; Dibblee, 1960, 1963, 1967). 22, Lake County (Donath, 1962). 23, Steens Mountain (Williams and Compton, 1953). 24, Northwest Nevada (Noble and others, 1970). 25, East-central Idaho (Dort and Knoll, 1973). 26, Butte district (Meyer and others, 1968). 27, Tobacco Root Mountains (Kuenzi and Fields, 1971). 28, Madison Range (Fraser and others, 1964). 29, Little Fish Lake Valley (Ekren and others, 1974). 30, Western Big Smokey Valley (unpub. reconnaissance). 31, Northwest of Reno (unpub. reconnaissance).

apparently the result of a slower average extension rate rather than younger, less developed structure. This is supported by the higher seismicity in the eastern and western Great Basin than in the central Great Basin (Woollard, 1958). On the other hand, there is no evidence that formation of Basin and Range structure began earlier in the central part of the Great Basin and expanded outward (Armstrong and others, 1969; Scholz and others, 1971).

If the estimates made here for total extension in the Great Basin are approximately correct, then the average rate of extension since the beginning of Basin and Range faulting has been nearly 1 cm/yr. If most of the extension took place early in the period of faulting as it did at Yerington, then the rate may have been 2 cm/yr or greater during this early period.

EVOLUTION OF BASIN AND RANGE FAULTING

The northern limit of large late Cenozoic east-west Basin and Range extension in the Great Basin corresponds approximately to an eastward projection of the Mendocino fracture (ignoring here what appears to be relatively little developed, very young extension north of the Great Basin; Fig. 17a, locs. 22 through 28). The position and orientation of the axis of Great Basin spreading, relative to sea-floor features (Fig. 17a), correspond closely to the spreading axis of the East Pacific Rise segment that has been "missing" from between the Mendocino and Murray fractures since its collision with the continent (Atwater, 1970). We know that when formation of Basin and Range structure began 17 to 18 m.y. ago at Yerington, the Great Basin was 250 or 300 km farther north relative to sea-floor features (Fig. 17b) because this is the amount of right-lateral displacement that has taken place since that time on the San Andreas fault (Huffman, 1972). Limited data suggest that at this time little or no significant Basin and Range faulting had begun very far north of the Yerington district and that the area of the most active Basin and Range spreading was between the projections of the Mendocino and Murray fractures (Fig. 17b).

It is thought that the sea-floor spreading axis between the Mendocino and Murray fractures collided with the North American continent 23 to 30 m.y. ago (Atwater, 1970; modified by revised time scale of Tarling and Mitchell, 1976). The relative north-south positions of North America and the Pacific plate are unknown for this time, except that we know that about 300 km of displacement on the San Andreas fault took place between Cretaceous and early Miocene time (Suppe, 1970; Huffman, 1972). Figure 17c is drawn by assuming that the northern limit of active Basin and Range faulting was in southern Nevada (some normal faulting is thought to have started there about 26.5 m.y. ago, according to Ekren and others, 1968) and that this coincided approximately with the eastward projection of the Mendocino fracture.

Limited data suggest that Basin and Range faulting involving large horizontal extension as at Yerington may have taken place in some areas of Arizona (Fig. 17a, locs. 15 through 19) and the Mojave Desert (Fig. 17a, locs. 20 and 21) in middle and possibly early Cenozoic time. Such structure appears to be crudely symmetrical around the possible axes shown in Figure 17, but it is no longer active (and is not to be confused with later steep north-trending normal faults in much of Arizona or northwest-trending strike-slip faults in the Mojave Desert and southwest Arizona). The middle Cenozoic Basin and Range structure may have been active during the time that Arizona and the Mojave Desert were just inland from the colliding segment of the East Pacific Rise (Fig. 17c), and some may have been active even earlier (Fig. 17d).

Alternative processes by which spreading may have been transferred from the sea floor to the Basin and Range province may be considered. Formation of Basin and Range structure may have begun before the East Pacific Rise collided with the continent, owing to compensation for a slowdown in the spreading rate of offshore segments of the spreading axis (Fig. 17d). A slowdown in spreading rate just before and during collision of the East Pacific Rise and the continent (Atwater, 1970) might have been compensated for by the Basin and Range faulting shown in Figure 17c. Alternatively, if the Pacific and American plates had relative motions away from each other, Basin and Range faulting may have started in parts of Arizona and the Mojave Desert after the spreading axis collided with the continent (Fig. 17c) to compensate for this

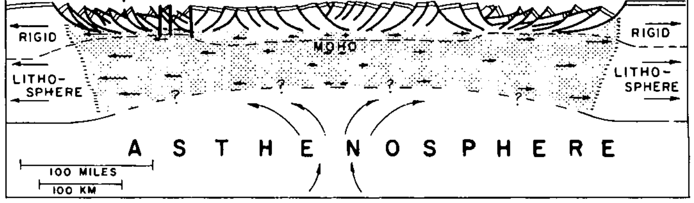


Figure 18. East-west cross section of Great Basin, diagrammatically showing crude symmetry of Basin and Range faulting and possible flowage of material at depth. For simplicity, antithetic faults are not shown, but they could be present in place of at least part of tilting in some areas. Large extension in which antithetic faulting rather than tilting was dominant would not result in the steep tilting and flattened normal faults shown diagrammatically in eastern and western Great Basin and might be difficult to document. Such structure could well be buried by younger rocks, large areas of which are common in eastern and western Great Basin.

relative motion. However, if plate spreading is driven by convection, then the driving mechanism could have simply been transferred from sea floor to continent. Interarc basins (Karig, 1970) have also been proposed as a mechanism by which Basin and Range spreading began (Scholz and others, 1971). However, known interarc basins are located mainly behind west-dipping underthrust zones (Moore, 1973) whereas the underthrust zone along the coast of western North America dipped east. Further, the Basin and Range extension in the Great Basin was not part of a trench–volcanic arc system as interarc basins are thought to be, but took place mainly between the Mendocino and Murray fractures, where the trench-arc system had been destroyed.

By whatever mechanism Basin and Range spreading began, its locus probably moved into the Great Basin from the south, as the North American continent moved south relative to sea-floor features of the Pacific plate (Fig. 17; Proffett, 1971b). There is no evidence that it migrated into the Great Basin from the west, as would be expected if Basin and Range structure in the Great Basin was the result of the continent overriding the East Pacific Rise from the east, as suggested by McKee (1971). Heat-flow evidence supports this contention (Blackwell and Roy, 1971).

The most rapid east-west spreading took place in the Yerington district shortly after the locus of spreading arrived there (Fig. 17b). The rate of east-west spreading has been much slower in the past 10 or 12 m.y. During this time, strike-slip faults, especially northwest-striking right-lateral faults (see for example, Nielsen, 1965; Wright and Troxel, 1970), and oblique-slip faults with northwest-southeast displacement (see, for example, Thompson and Burke, 1973; Wright and others, 1974) have become locally significant. Timing of the change from rapid to slower east-west spreading in the Yerington district and local faulting with an important right-lateral component in the Great Basin correspond to a change from slow to rapid displacement on the San Andreas fault (Huffman, 1972). These changes may be related to changes in the direction of sea-floor spreading that took place at approximately the same time (Menard and Atwater, 1968). This change in the nature of faulting in parts of the Great Basin shows that studies of recent faulting, earthquakes, and microearthquakes, although useful, may not discern the true nature and origin of older Basin and Range structure. The plate tectonic interpretation of the Basin and Range province proposed by Atwater (1970) may explain the more recent strike- and oblique-slip–related faulting in parts of the Great Basin, although, as discussed earlier, it cannot explain most of Basin and Range structure.

The great width of the zone of Basin and Range faulting in the western United States contrasts with the narrow rift zones in some other continental areas where spreading axes have become active, such as the Red Sea and the Gulf of California. The nature of the underlying crust may be the cause of the differences. The continental crust of the Red Sea area consists of a complex of Mesozoic granitic and metamorphic rocks. Most of the Great Basin is underlain by less metamorphosed volcanic and sedimentary rocks, with less abundant granitic plutons and local thin Precambrian crust. Significantly, the Great Basin margins are close to where the crust changes to a thicker Precambrian crust to the east and a thicker Mesozoic granitic-metamorphic crust to the west.

Fyfe and Leonardos (1973) proposed that successful continental rifts might develop only in areas of refractory crusts that have undergone previous orogeny and magma formation. According to this hypothesis, if a spreading axis became active in crust that had not undergone previous large-scale magma generation, such as much of the Great Basin, the high heat flow from the spreading axis would cause a large melt fraction to build up. Lowering of viscosity and slowdown of rifting would result. This might help explain the apparent slowdown of spreading in the Great Basin. It might also explain why areas of largest extension have been near the western and probably the eastern margins of the Great Basin, where the crust may have been more refractory (because of abundant Mesozoic batholiths in the west and probably thicker Precambrian crust in the east) than in other parts.

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