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THE AGE OF BASIN-RANGE FAULTING IN ARIZONA

by

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Abstract

Basin-range faulting is defined to include all normal faults within the Basin and Range province or in adjacent areas that are not obviously related to local structures and that belong to the most recent tectonic episode in the province, which is roughly Cenozoic in age. Such a definition is preferable to one that includes only those faults that bound present ranges because it avoids the limitation of erosion rates in determination of the age of initiation of the faulting. A review of the literature on basin-range faulting in Arizona indicates that the faulting began during late Mesozoic—early Tertiary time, not during the late Tertiary as has often been suggested. This age for initiation of basin-range faulting conflicts with several plate tectonic models for the origin of these structures. Regional extension in Arizona may have occurred behind an active subduction zone during the early Cenozoic, similar to a model proposed by Scholz and others (1971) for the Great Basin, or because of a change from dip-slip to strike-slip subduction at the latitude of Arizona during the early Cenozoic. Continued basin-range faulting into the late Cenozoic may have been due to action of a mantle diapir or to withdrawal of vertical support due to extensive Tertiary and Quaternary volcanism.

Introduction

As shown on Figure 1, a large portion of Arizona lies in the physiographic Basin and Range province. Extensive study in the province has produced the generally accepted conclusions that the topographic ranges and basins are also structural features, that these structures are generally characterized by Cenozoic normal faulting, and that the normal faulting is due to regional extension. However, as will be discussed in the next section, the actual definition of basin-range structure is not clear.

Atwater (1970) presented a time framework for the Cenozoic history of the western United States using magnetic anomalies in the northeastern Pacific Ocean. Her hypothesis was that a Cenozoic trench had existed off the western coast of North America and that subduction was active south of the Mendocino fracture zone until at least 29 m.y. ago. Several authors then published theories on the origin of the Basin and Range province based on Atwater's time framework and on plate tectonic concepts. McKee (1971) and Scholz, Barazangi, and Sbar (1971) dealt only with the Great Basin portion of the province. Christiansen and Lipman (1972) and Lipman, Prostka, and Christiansen (1972) presented continental evidence for Atwater's model based on information from throughout that portion of the province that lies in the United States.

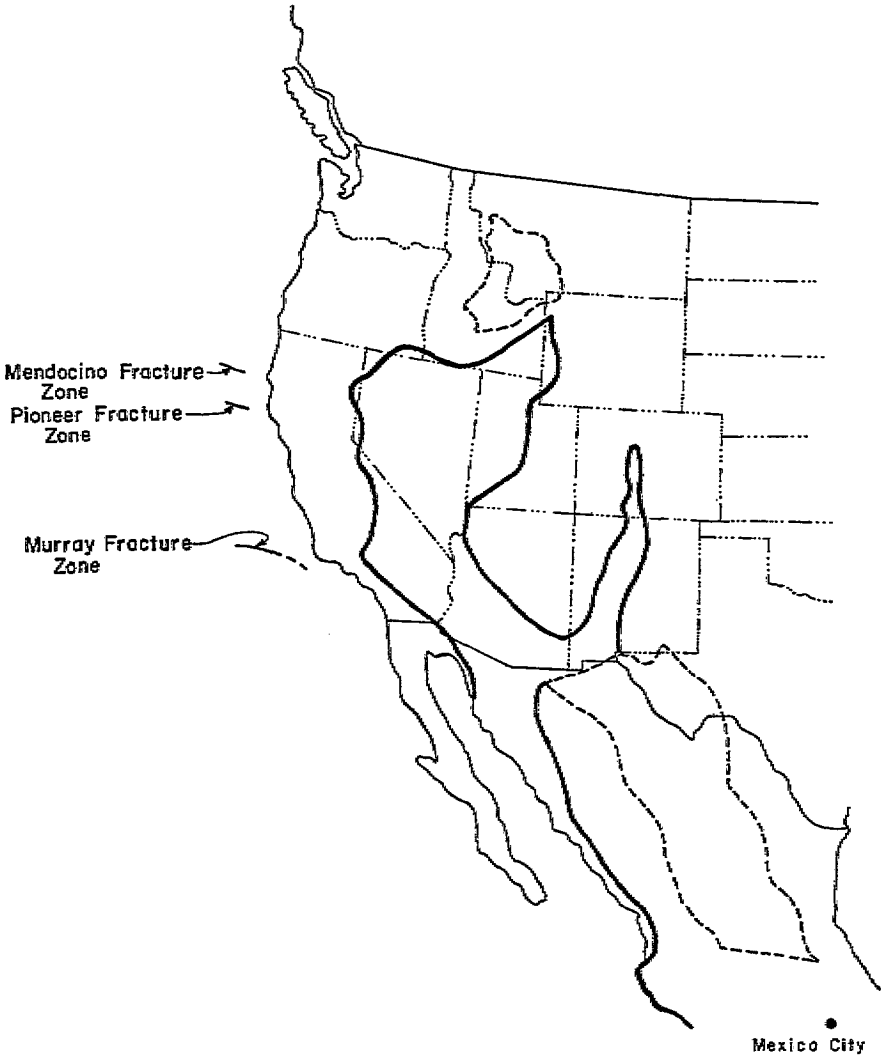

Figure 1. Basin and Range province in the western United States and Mexico. Modified from Hamilton and Myers (1966), Kellum (1944), and Raisz (1964). Solid line outlines Basin and Range province; dashed line outlines additional areas of basin-range structure.

This paper presents results from a survey of the literature on the age of basin-range faulting in Arizona. Undoubtedly, some references have been overlooked. Others describe basin-range faults but do not give specific ages for the faults. In addition, such a study is biased by lack of agreement on the definition of basin-range faults and by absence of pertinent rocks in many areas. Fault ages based on the relation of faults to undated volcanics must be considered tentative pending radiometric dating of the volcanic rocks. However, this study was undertaken to see if published ages of basin-range faulting agree with theoretical ages based on plate tectonic models for the origin of these structures.

Definition of Basin-Range Faulting

Southern and western Arizona is included in the Basin and Range province as described by Fenneman (1931), i.e., a physiographic province, topographically distinguished by isolated, roughly parallel, mountain ranges separated by desert basins. There are two notable physiographic differences between the Arizona and Utah-Nevada portions of the province. Whereas the mountains of Utah and Nevada, with the exception of western Nevada near the Walker Lane and Las Vegas Shear Zone, trend north to north-northeast, many of the mountains of Arizona have a northwest trend (Fig. 2). Also, the mountains of Arizona have a much more varied trend than those of Nevada and Utah.

Although the basins and ranges of the province are now known to be structurally controlled, the actual definition of basin-range structure is not clear. Gilbert (1928) defined basin-range structure as the fault block structure of the present ranges in the Great Basin. However, with this definition, the age of basin-range structure is limited by rates of erosion, because once the range is eroded, the faults can no longer be called basin-range faults. Mackin (1960b) suggests the definition of basin-range structure be broadened to apply to Cenozoic block faulting without regard for the relationships of the faulting to present topographic form. He comments (1960b, p. 106-107): "If commonly held rates of erosion are accepted as true, there can be no topographic evidence of early Tertiary deformation—perhaps this point lies behind the idea that Great Basin block faulting occurred chiefly during the late Tertiary." Mackin's (1960b) broadened definition of basin-range structure as Cenozoic block faulting is generally the definition that will be used in this paper.

Because much of the Cenozoic faulting described in the literature is not specifically called basin-range faulting, three criteria are used to determine whether particular examples are considered basin-range faults for this report: location, type of fault, and relation to other structures. For this report, basin-range faulting is defined as including all normal faults of late Mesozoic through Cenozoic age that are found within the physiographic Basin and Range province or in adjacent areas and that are not obviously related to local structures, such as intrusive domes. This definition is not restricted to range-front faults. Faults described as high-angle faults with dip-slip displacement are considered to be basin-range faults with the same limitations just described for normal faults; high-angle faults known to have reverse dip-slip histories have been excluded. High-angle faults with both dip-slip and strike-slip displacement or whose displacement is not known are considered basin-range faults with the understanding that conclusions based on such faults are less reliable than those based on normal faults. The amount of fault displacement is not considered critical in determining whether a particular fault is of basin-range type.

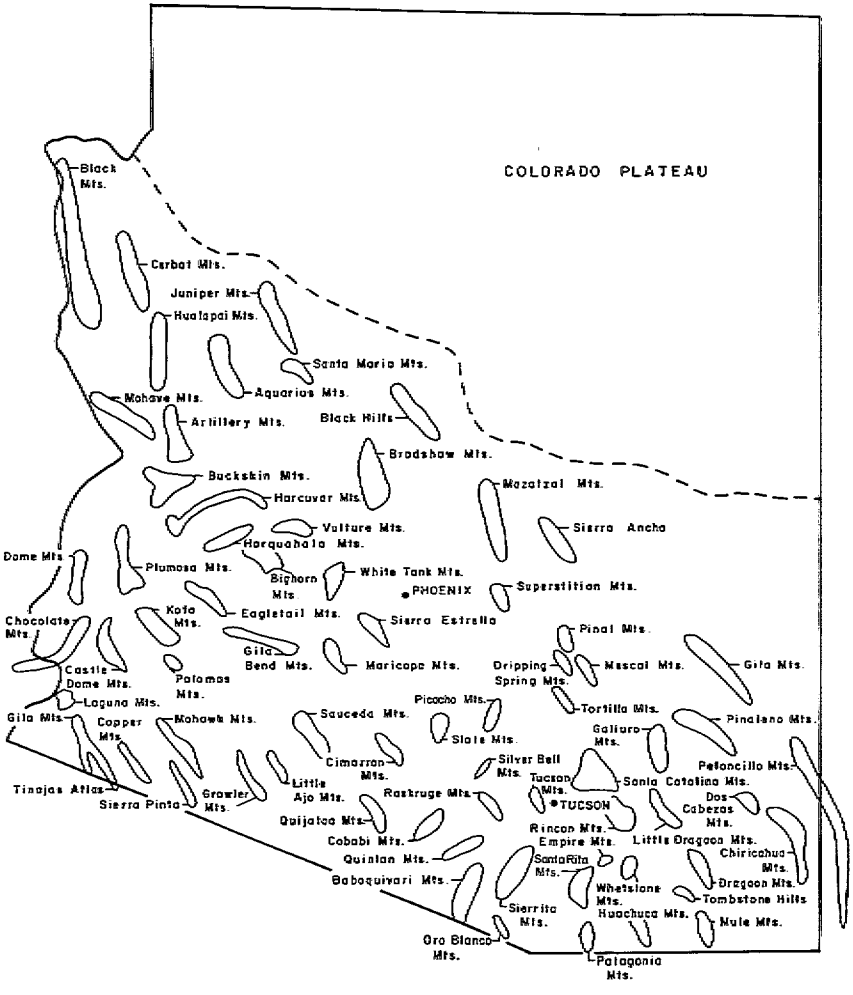

Figure 2. Index map of selected localities in Arizona.

Age of Basin–Range Faulting in Arizona

The following paragraphs summarize published information on the age of basin-range faulting in Arizona. Faulting of late Mesozoic-early Tertiary and middle Tertiary age is described in some detail because that faulting has been least emphasized in the literature on basin-range structure. Late Tertiary and Quaternary faulting is tabulated in Table 1. The data in each section are roughly given in geographical order, beginning with the northwestern part of the state, then the southwest, then the southern and southeastern, and finally the area east of Phoenix and just south of the Colorado Plateau. Numbers in parentheses in the text refer to fault localities on the corresponding index maps.

Where ages are given in the literature in millions of years, the Geological Society (London) Phanerozoic time-scale 1964 (Harland, Smith, and Wilcock, 1964) has been used to assign the dates to Cenozoic epochs. In this paper the Paleocene (65-53 m.y.) and Eocene (53-37 m.y.) are included in the early Tertiary, Oligocene (37-26 m.y.) and early Miocene (26-c. 18 m.y.) in the middle Tertiary, and middle to late Miocene (c. 18-c. 7 m.y.) and Pliocene (c. 7-1.5 m.y.) in the late Tertiary. Laramide, as used here, refers to the Late Cretaceous–early Tertiary time span falling roughly between 70 and 50 m.y.B.P.

Late Mesozoic–Early Tertiary (Fig. 3)

In the Cerbat Mountains of northwestern Arizona (1), northwest-trending fault veins and dikes with steep dips suggest there was Laramide tension in a northeast-southwest direction in this area (Eidel, Frost, and Clippinger, 1968). The Laramide age for this tension is indicated by quartz latite dikes which occupy the northwest faults and fractures and by mineralization in the northwest fault-fissures; both the dikes and mineralization are presumably related to a 72 m.y. old intrusion in the Wallapai district (Eidel and others, 1968). The northwest-striking veins also have postmineral movement. Dings (1951) says that the northwest faults are high-angle oblique faults and that they cut Precambrian structures but are filled by Late Cretaceous dikes and veins (1). To the northeast on the Kaibab Plateau(2), Strahler (1948) says that the north-striking West Kaibab faults formed during Late Cretaceous–early Tertiary time. He assumes they are the same age as the East Kaibab monocline which affects rocks as young as Late Cretaceous but is unconformably overlain by the Eocene Wasatch Formation.

In the Artillery Mountains (3), the early Eocene(?) Artillery Formation was deposited in a northwest-trending valley that may have been of basin-range type, although it could have been related to thrusting (Lasky and Webber, 1949). Evidence cited by Lasky and Webber as favoring the former interpretation is that breccia beds lie close to the basin margins as do pre-Artillery Formation faults. The early Eocene(?) age for the Artillery Formation is based on the age of fossil palm roots and *Chara* fruits found in the unit, which suggested to them that the formation was Wasatchian (Wasatchian could be upper Paleocene to lower Eocene according to Funnell, 1964). In addition, at Artillery Peak, one normal fault that is older than Miocene(?) lavas affects the Artillery Formation.

In the Bagdad area (4), the north-striking Mountain Spring normal fault cuts Precambrian granite but is cut by Upper Cretaceous quartz monzonite (Livingston, Mauger, and Damon, 1968) and Laramide dikes (Anderson, Scholz, and Strobell, 1955). In addition, the north-striking Hillside normal fault cuts Precambrian granite, seems to be cut by the Upper Cretaceous quartz monzonite, and contains mineralization related to the quartz monzonite intrusion (Anderson and others, 1955).

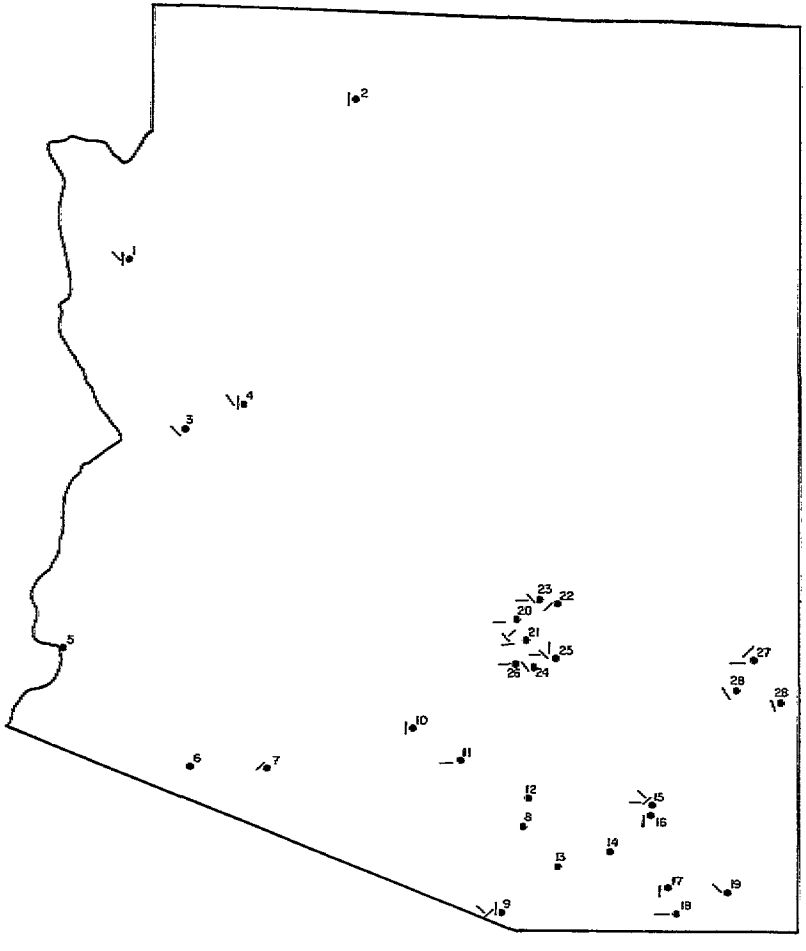

Figure 3. Localities of late Mesozoic—early Tertiary basin-range faulting. Lines show generalized fault directions to the nearest 45 degrees. Numbers correspond to references in text.

In the Laguna and Chocolate Mountains (5) of southwestern Arizona, there were several episodes of faulting and tilting during early and middle Tertiary time, according to Olmsted (1968). To the southeast in the Cabeza Prieta Game Range (6), normal faulting may have formed the mountains in Late Cretaceous—early Cenozoic time (Simmons, 1966).

There appears to be good evidence for early or middle Tertiary normal faulting in the Little Ajo Mountains (7) (Gilluly, 1937, 1946; Dixon, 1966). The north-northeast-striking Gibson normal fault cuts the upper Tertiary Cornelia Quartz Monzonite but does not disturb the middle (?) Tertiary Locomotive Fanglomerate which overlies the fault.

Schmitt (1959) says that some normal faulting in southern Arizona (8) followed granitic intrusion and thrusting but preceded ore mineralization. Thus, this faulting is probably early Tertiary in age. In the Oro Blanco Mountains (9) of southern Arizona, north-northeast-, northeast-, and northwest-striking normal faults probably had early Tertiary movement. The north-northeast faults offset all pre-Tertiary rocks, including the Cretaceous(?) Ruby diorite, but are older than the Tertiary Sidewinder quartz monzonite (Knight, 1970). The northeast faults are younger than initial movement on the north-northeast faults but significantly displace rocks no younger than the Cretaceous(?) Ruby diorite (Knight, 1970). The northwest faults are younger than the others but had at least some movement before emplacement of the Tertiary quartz monzonite (Knight, 1970). These ages are supported by crosscutting relationships on Knight's cross sections. Knight says that the northwest normal faults are most important and that there are mineralized faults of all three trends. He concludes that basin-range structure is Late Cretaceous—early Tertiary in age and had only minor mid-Tertiary adjustments.

There may have been early Tertiary north-northeast normal faulting near the southern Slate Mountains (10) west of Tucson. A normal fault bounds Cretaceous andesite on the east, but a cross section by Harper and Reynolds (1969) shows that the normal fault is offset by an "overthrust" that involves Upper Cretaceous quartz diorite (67 m.y.; Johnston, 1972).

In the Silver Bell Mountains (11), horsts and grabens were formed by west-southwest-striking faults that cut Cretaceous(?) rocks and lower Tertiary volcanics (Richard and Courtright, 1966), but the faults were partly obliterated by lower Tertiary intrusions. Kinnison (1959) says it is probable that some normal faulting in the southern Tucson Mountains (12) formed shortly after Laramide folding and that some high-angle faults formed during extrusion of the Cat Mountain Rhyolite (Late Cretaceous). Bikerman and Damon (1966) describe the Tucson Mountains as a typical north-northwest-trending, basin and range type mountain range, having a high scarp on the west and a dip slope on the east. Their east-west cross section through the southern Tucson Mountains (12) shows conformable eastward dips on rocks radiometrically dated as Late Cretaceous and Paleocene. These units are overlain by upper Oligocene to Miocene volcanic rocks which are shown as lying unconformably, with no dip, on the older rocks (Bikerman and Damon, 1966). This suggests the tilting was early or middle Tertiary. Their cross section through the northern Tucson Mountains shows Cretaceous(?) and Oligocene to lower Miocene volcanics dipping conformably eastward, which implies a younger age for tilting there.

Drewes and Finnell (1968) say that normal faulting in the Santa Rita and Empire Mountains (13) took place along with thrusting and tear faulting in Late Cretaceous and early Tertiary time. Tyrrell (1964) concludes, without giving evidence, that Early Cretaceous block faulting occurred in the Whetstone Mountains (14). Much of the normal faulting

in the Little Dragoon Mountains (15) may have been Late Cretaceous or early Tertiary in age. Most of the faults contain ore that is probably related to the lower Eocene (50 m.y.; Ridge, 1972) Texas Canyon stock, and the north-northeast- and east-striking faults contain quartz, which was faulted and then followed by deposition of more quartz (Cooper and Huff, 1951). Late Cretaceous—early Tertiary block faulting took place in the Dragoon quadrangle (16) where the north-striking Tungsten King normal fault cuts thrust plates but is, in turn, cut by aplites that are spatially associated with and are probably genetically related to the Eocene (Ridge, 1972) Texas Canyon stock (Cooper and Silver, 1964).

The Tombstone Hills and Mule Mountains (17) have numerous examples of Late Cretaceous—early Tertiary normal faults. The Ajax Hill normal fault cuts Lower Cretaceous sediments but has frozen contacts with a Cretaceous intrusion (Jones, 1966). Two other normal faults are cut by a 63 m.y. intrusion (Creasey and Kistler, 1962). At Bisbee (18), the west-northwest to west-striking Dividend normal fault cuts Paleozoic beds but provided the uplifted block that was eroded to form a Lower Cretaceous conglomerate (Rove, 1942). In addition, the Paleozoic sediments on the south side of the Dividend fault were block faulted prior to thrust faulting (Rove, 1942); the thrusting is probably Laramide in age. Minor Late Cretaceous—early Tertiary movement on the Dividend fault displaced Cretaceous sediments (Bryant and Metz, 1966). Coates and Cushman (1955) say that the mountains bordering Douglas Basin (19) were uplifted along northwest-striking fault zones during the early Cenozoic.

At the Superior district near the Superstition Mountains (20), some normal and oblique faulting of east-west trend may be early Tertiary in age. The movement is post-Pennsylvanian, but some faults are mineralized, whereas others were the channels for intrusion of Laramide quartz monzonite porphyry (Short and others, 1943). At the Magma mine (21) in the Superior district, Hammer and Peterson (1968) indicate there was early normal faulting of late(?) Mesozoic to middle Tertiary age. East- to northeast-striking normal faults cut Pennsylvanian sediments but were intruded by Laramide dikes. In addition, Hammer and Peterson say that northwest-trending block faulting and eastward tilting probably preceded Laramide intrusion. They also say that north- to northwest-striking faults probably began to form during Laramide intrusion and before deposition of the lower Oligocene (Banks and others, 1972) Whitetail Fanglomerate.

Late Cretaceous—early Tertiary normal faulting is reported from the Globe-Miami district (22, 23). Northwest- and northeast-striking faults cut Laramide intrusions but were then intruded by diabase before being mineralized (Peterson, 1952a, 1962; Peterson, Gilbert, and Quick, 1951). The diabase is also Laramide in age because it intrudes the Paleocene (62, 64 m.y.; Livingston and others, 1968) Lost Gulch Quartz Monzonite but is, in turn, intruded by granite porphyry that is probably a late stage of the Paleocene (58, 60 m.y.; Livingston and others, 1968) Schultze Granite. Peterson (1962) also says that the present attitude of the sedimentary beds (dipping southwest) may be partly the result of block faulting before the intrusion of the diabase, as is suggested by the alinement of the blocks, but undoubtedly considerable displacement occurred as a result of the injection of such a great volume of diabase magma.

At the Ray deposit (24), high-angle normal faulting followed Cretaceous-Paleocene plutonism and developed basins in which the lower Oligocene Whitetail Conglomerate was deposited (Banks and others, 1972). These basins, as well as early late Tertiary ones, lie at an angle to the present topographic features (Banks and others, 1972). Metz and

Rose (1966) say that subsidence along normal faults at the Ray deposit (24) followed early Tertiary intrusion but preceded mineralization.

In the Dripping Spring Mountains (25), north-northwest-striking normal faults may be Late Cretaceous—early Tertiary in age (Kiersch, 1949, 1952). Some are pre-ore but may have closely preceded Laramide granitic intrusion. Other north-south faults are post-dike but pre-ore. The northern Tortilla Mountains (26) were affected by high-angle, east-west normal faulting in early or middle Tertiary time. According to Schmidt (1971b), these faults cut Precambrian and Laramide rocks but do not affect mid-Tertiary conglomerates.

Movement on Late Cretaceous or early Tertiary northeast- or east-striking step faults caused a progressive southward lowering of fault blocks in the Morenci district (27) (Moolick and Durek, 1966). According to Langton (1972), andesite flows, flow breccias, and agglomerates filled northwest-trending grabens approximately 15 to 35 miles southwest and southeast of Morenci (28). He says these rocks correlate with other Upper Cretaceous volcanics in southern Arizona and are genetically related to Upper Cretaceous—lower Tertiary igneous rocks in the Morenci district.

Middle Tertiary (Fig. 4)

Several authors claim basin-range faulting began in Arizona during the middle Tertiary. Wilson and Moore (1959) say normal faulting ranges in age from middle and late Tertiary to Pleistocene. Cooley and Davidson (1964) and Hayes (1969) give similar ages.

Gardner (1942, 1952) says that the earliest movement on the Hurricane fault (1), which lies partly in northwestern Arizona, is post-Eocene but pre-Miocene(?). The fault cuts the Eocene Wasatch Formation, but the two sides of the fault were eroded before being covered by Miocene(?) lavas.

Olmsted (1968) says that the Laguna and Chocolate Mountains (2) of southwestern Arizona began to assume their present outline soon after deposition of mid-Tertiary volcanics and that structural activity continued on a reduced scale into late Tertiary time. To the east, in the Little Ajo Mountains (3), the west-northwest-trending Little Ajo Mountain normal fault appears to be largely middle Tertiary in age (Gilluly, 1937, 1946). The fault displaces the middle(?) Tertiary Ajo Volcanics. It also apparently largely preceded deposition of the middle(?) Tertiary Sneed Andesite because the underlying middle(?) Tertiary Locomotive Fanglomerate seems to have been tilted along the fault prior to the Sneed eruptions. The Locomotive Fanglomerate has been assigned a middle(?) Tertiary age because it rests unconformably on the Cornelia Quartz Monzonite (62 m.y.; Livingston and others, 1968) but is overlain by the Ajo Volcanics which probably belong to the middle Tertiary episode of volcanism in Arizona.

As described in the previous section, Bikerman and Damon (1966) imply that some tilting in the Tucson Mountains (4) is early or middle Tertiary in age. However, in another reference (Damon and Bikerman, 1964), they say that extensive block faulting in the Tucson Mountains is post-late Oligocene in age because an andesite unit of that age has been steeply tilted. Middle Miocene volcanics are only gently tilted, indicating block faulting continued into Miocene time.

Near the Rincon Mountains (5), northwest-striking vertical faults may be late middle Tertiary in age. Middle Miocene(?) andesite

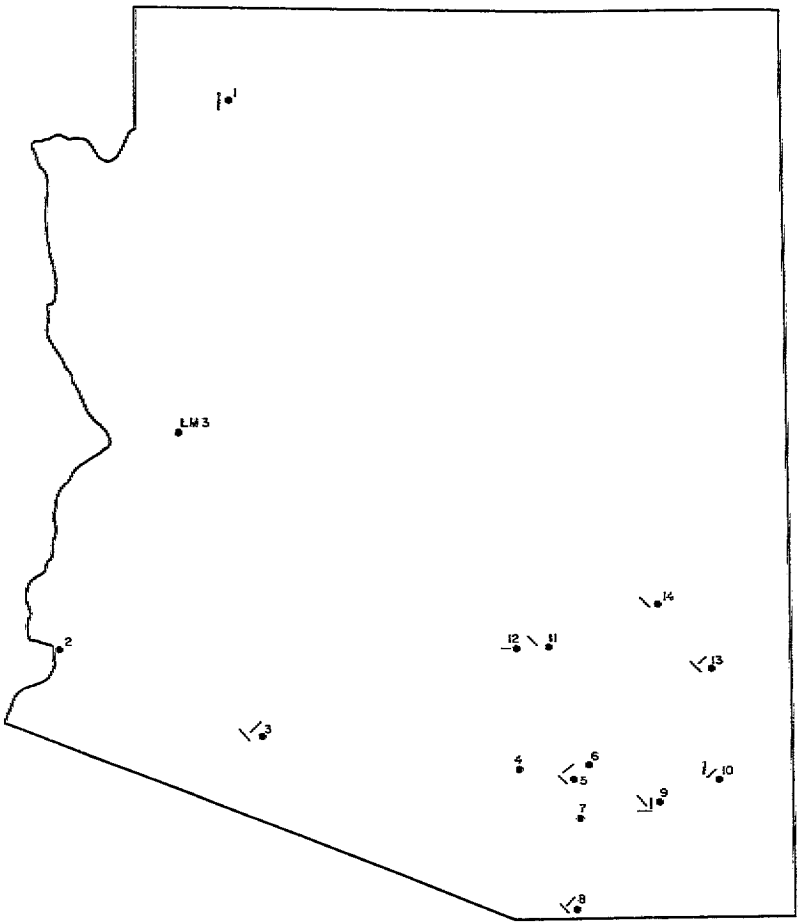

Figure 4. Localities of middle Tertiary basin-range faulting. Lines show generalized fault directions to the nearest 45 degrees. Numbers correspond to references in the text.

was intruded along the faults, and according to McColly (1961), the faults must be close to mid-Miocene in age. Northeast-striking faults probably uplifted the Rincon Mountains block in middle Tertiary time. McColly (1961) says the uplift followed Cretaceous metamorphism but preceded deposition of the middle Miocene Pantano Formation. Potassium-argon dates on metamorphic rocks of the Catalina-Rincon blocks fall between 20 and 30 m.y. (Mauger and others, 1968), indicating the metamorphism was middle Tertiary, not Cretaceous.

Mauger and others (1968) cite another paper (Damon, Erickson, and Livingston, 1963) in which it was suggested that the mid-Tertiary metamorphic ages of the Catalina-Rincon block (6) were due to "refrigeration after block faulting." Uplift of the block was probably in progress by early Miocene time and had stopped by late Miocene or early Pliocene time, based on the fact that late Oligocene to early Miocene sedimentary rocks have steep dips away from the gneissic terrain, whereas late Miocene to Pliocene rocks are essentially flat lying (Damon and others, 1963, in Mauger and others, 1968).

At Cienega Gap (7) between the Rincon and Empire Mountains, Brennan (1957, 1958, 1962) says basin-range structure began to form during early Miocene time. He bases this on the types of sediments in the Pantano Formation, i.e., boulder conglomerate to mudstone, and on its 13,762-foot thickness, which suggests the presence of highlands and basins. To the south in the Patagonia Mountains (8), Baker (1962) claims there may have been northwest and northeast high-angle faulting during middle Tertiary time before late middle Tertiary(?) intrusive activity.

In the Dragoon quadrangle (9), northwest-, north-, and east-striking normal faults are mid-Tertiary to Quaternary in age. They cut middle(?) Tertiary Galiuro volcanics, but many do not cut alluvium (Cooper and Silver, 1964; Cooper, 1959). In the Dos Cabezas Range (10), north- to northeast-striking faults have related rhyolite dikes and sills which are Oligocene in age (Erickson, 1968).

In the Dripping Spring Mountains (11), Kiersch (1949, 1952) says northwest-striking normal faults are middle to late Tertiary in age. They displace orebodies and dikes but preceded deposition of the undisturbed Gila Conglomerate and accelerated oxidation of certain exposed orebodies. In the northern Tortilla Mountains (12), Schmidt (1971a) says that deposition of the mid-Tertiary sediments followed in response to the rising Tortilla Mountain block and that this uplift caused gravity sliding into a Miocene lake. Schmidt claims tilting of the block was completed before the Pliocene-Pleistocene Gila Conglomerate was deposited.

Uplift along the northwest-striking Butte normal fault in the Gila Mountains (13) caused oxidation of the Safford deposit, but then middle or early Tertiary volcanics were extruded, pinching out along the east flank of the range (Robinson and Cook, 1966). Possible middle to late Tertiary block faults cut middle(?) Tertiary volcanics but not Pliocene basalt and Gila Conglomerate on the San Carlos Indian Reservation (14) (Bromfield and Shride, 1956).

Late Tertiary–Quaternary (Fig. 5)

Table 1 lists published occurrences of late Tertiary and Quaternary basin-range faulting in Arizona. Such faults are described from all areas of the state that lie within the Basin and Range province. In most cases the faults are well dated because they cut alluvium, basin fill, or late Tertiary volcanic rocks. However, the state geologic map shows very few range-front faults.

Table 1. Late Tertiary and Quaternary basin-range faulting

Locality Number (Fig. 5)	Area	Age	Evidence	Reference
1	Virgin Mountains	Quaternary	Faulted alluvium	Seager, 1970
1	Virgin Mountains	Late Tertiary	None	Seager, 1966
2	Virgin and Beaverdam Mountains	Late Tertiary-Quaternary	None	Moore, 1967
3	Lake Mead area	Late Tertiary	Dips of Pliocene sediments	McKelvey and others, 1949
4	Between Hoover and Davis Dams	Late Tertiary	Volcanic relations and interbedded debris	Longwell, 1963
5	Gerbat Mountains	Late Tertiary-Quaternary	Followed Tertiary volcanism	Thomas, 1949, 1953
6	Aubrey Valley	Late Tertiary	Relation of faults to Pliocene gravels and volcanics	Blissenbach, 1952
7	Uinkaret Plateau	Late Tertiary-Quaternary	Citations. Relation to Quaternary lava	Koons, 1943, 1945
8	Whitmore area	Late Tertiary-Quaternary	Hurricane fault cuts alluvium and late Tertiary-Quaternary basalt	Sorauf, 1963
9	Hurricane fault	Late Tertiary-Quaternary	Cuts late Tertiary and Quaternary flows	Gardner, 1941, 1952; Hamblin, 1965
10	Hualpai Reservation	Late Tertiary-Quaternary	None	Koons, 1964

Table 1. Late Tertiary and Quaternary basin-range faulting--Continued

Locality Number (Fig. 5)	Area	Age	Evidence	Reference
11	Oak Creek Canyon	Late Tertiary	Pliocene basalt cut by normal faults	Finnell, 1962; Eastwood and Murray, 1972
12	Prescott and Paulden quadrangles	Late Tertiary-Quaternary	Post-basin fill faulting	Krieger, 1952, 1965
13,14	Jerome area	Late Tertiary-Quaternary	Cut late Tertiary and Quaternary sediments	Anderson and Creasey, 1958; Lehner, 1958, 1962
15	Black Hills	Late Tertiary-Quaternary	Cut Pliocene(?) lava and late Tertiary rocks	Canney and others, 1967; Creasey, 1952
16	Bagdad	Late Tertiary-Quaternary	Cut late Tertiary basalt and conglomerate	Anderson and others, 1955
17	Artillery Mountains	Late Tertiary-Quaternary	Basin-fill deposits; faults cut Quaternary(?) basalt	Kumke and others, 1957; Lasky and Webber, 1949
18	Little Ajo Mountains	Late Tertiary	Younger than mid-Tertiary(?) volcanics but no topographic expression	Gilluly, 1937, 1946
19	Papago Reservation	Late(?) Tertiary	Cut late(?) Tertiary rocks but not late(?) Tertiary unconformity	Heindl, 1960
20	Vekol Mountains	Late Tertiary-Quaternary	None	Carpenter, 1948
21	Tucson Basin	Late Tertiary	Cut late(?) Tertiary sediments but the blocks are eroded	Pashley, 1966

Table 1. Late Tertiary and Quaternary basin-range faulting--Continued

Locality Number (Fig. 5)	Area	Age	Evidence	Reference
22	Rincon Mountains	Pliocene(?)	Caused Pantano beds to be stripped from raised blocks	McColly, 1961
23	Agua Verde Hills	Late Tertiary	Uplifted Pantano Formation	Kerns, 1958
24	Empire Mountains	Late Tertiary-Quaternary	None	Schafroth, 1966
25	Patagonia Mountains	Pliocene(?)	Followed mid-Tertiary(?) mineralization and preceded Pleistocene gravel	Baker, 1962
26	Whetstone Mountains	Late Cenozoic	None	Tyrrell, 1964
27	West-central Cochise County	Late Tertiary-Quaternary	Some faults are younger than Gila Conglomerate but faults are obscure	Gilluly, 1956
28	Dragoon quadrangle	Late Tertiary-Quaternary	Followed mid(?)-Tertiary volcanism but preceded alluvium	Cooper, 1959
29	Tombstone Hills	Late Tertiary-Quaternary	Displace valley fill	Butler and others, 1938
30	Mule Mountains	Pliocene	None	Bryant and Metz, 1966
31	Douglas Basin	Late Tertiary-Quaternary	Displace Tertiary volcanics	Coates and Cushman, 1955
32	Courtland-Gleeson	Late Tertiary-Quaternary	Cut rhyolite, ore, and thrusts	Wilson, 1927; McRae, 1965, 1966

Table 1. Late Tertiary and Quaternary basin-range faulting--Continued

Locality Number (Fig. 5)	Area	Age	Evidence	Reference
33	Pedregosa and Swisshelm Mountains	Late Tertiary	None	Epis, 1959
34	Dos Cabezas and Chiricahua Mountains	Pliocene	Cut volcanics but there are no scarps	Sabins, 1957
35	Peloncillo Mountains	Late Tertiary-Quaternary	Cut late Tertiary latite	Gillerman, 1958
36	White Mountains	Late Tertiary	Cut late Tertiary basalt but not Quaternary rocks	Finnell and others, 1967
37	Tonto Basin	Pliocene-Quaternary	Cut Pliocene rocks	Lance and others, 1962
38	Superstition Mountains	Miocene	Citation	Hammer and Peterson, 1962
38	Superstition Mountains	Late Tertiary	Forms fault contact between mid-Tertiary dacite and late Tertiary conglomerate	Short and others, 1943
39,40	Globe-Miami area	Late Tertiary-Quaternary	Followed Gila Conglomerate and dacite eruption	Peterson, 1952, 1962; Peterson and others, 1951; Reed and Simmons, 1962; Rubly, 1938
41	Ray deposit	Late Tertiary	Followed Miocene tuff and preceded younger Miocene tuff	Banks and others, 1972
42	Magma mine	Late Tertiary-Quaternary	Followed Miocene dacite; Gila Conglomerate deposited in local basins	Hammer and Peterson, 1968

Table 1. Late Tertiary and Quaternary basin-range faulting--Continued

Locality Number (Fig. 5)	Area	Age	Evidence	Reference
43	Dripping Spring Mountains	Late Tertiary-Quaternary	Cut Gila Conglomerate	Kiersch, 1949, 1952
44	Mescal Mountains	Late Tertiary-Quaternary	Cut Gila Conglomerate	Willden, 1964
45	Tortilla Mountains	Late Tertiary-Quaternary	Cut middle Tertiary sediments and Gila Conglomerate	Schmidt, 1971b
46	Mammoth area	Late Tertiary-Quaternary	Cut Gila Conglomerate and other late Tertiary sediments	Creasey, 1965, 1967; Heindl, 1963; Thomas, 1966; Peterson, 1938
47	Galiuro Mountains	Late Tertiary-Quaternary	Cut Gila Conglomerate	Kuhn, 1941
48	Gila River and San Simon Creek areas	Late Tertiary	Gila Conglomerate undisturbed but faults may have formed Pliocene lake basin	Knetchel, 1938
49	Gila Mountains	Late(?) Tertiary	Displaces Tertiary(?) basalt	Robinson and Cook, 1966
50	Morenci district	Late Tertiary	Cut Gila Conglomerate and ore	Moolick and Durek, 1966; Langton, 1972
51	San Carlos Reservation	Late Tertiary-Quaternary	Cut Pliocene lake beds	Bromfield and Shride, 1956
52	Blue Range Primitive Area	Late Tertiary-Quaternary	Cut Miocene volcanics and some cut Gila Conglomerate	Ratte and others, 1969

Table 1. Late Tertiary and Quaternary basin-range faulting--Continued

Locality Number (Fig. 5)	Area	Age	Evidence	Reference
53	North-central Arizona	Late Tertiary-Quaternary	Citation	Sabels, 1962
54	Sycamore Canyon	Late Tertiary-Quaternary	Offset late Tertiary basalt	Huff and others, 1966

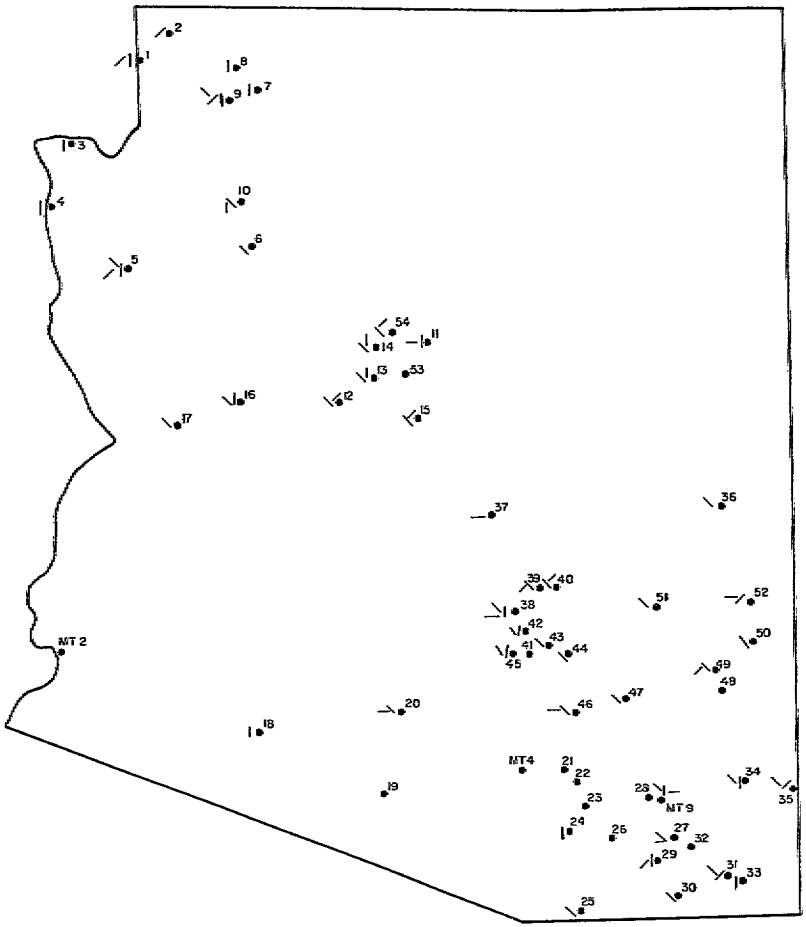

Figure 5. Localities of late Tertiary—Quaternary basin-range faulting. Lines show generalized fault directions to the nearest 45 degrees. Numbers correspond to references in text.

Discussion of the Age of Basin–Range Faulting

The determination of basin-range fault ages is severely limited by the original distribution of sediments and by the effects of erosion. Late Tertiary and Quaternary faults are often well dated because they cut young sediments. However, over half of the Arizona portion of the Basin and Range province is covered by late Tertiary or Quaternary sediments, which means that many older faults may lie buried by basin fill. Moreover, most Arizona ranges do not have complete Mesozoic and Tertiary sections, which makes it difficult to pinpoint the age of initiation of basin-range faulting.

In western Arizona, only the northern Virgin Mountains, Hoover-Davis Dams area, Cerbat Mountains, Bagdad district, Hurricane fault region, Artillery Mountains, Laguna and Chocolate Mountains, and Little Ajo Mountains have published reports of rocks between Triassic and late Tertiary in age as well as dated basin-range faults. Of those localities, six have reported Late Cretaceous or early and middle Tertiary faulting. Southern and eastern Arizona appears to have had much more Late Cretaceous–early Tertiary normal faulting, but there are also more Cretaceous, early Tertiary, and middle Tertiary rocks reported from this area. A combination of lack of published reports on southwestern Arizona and lack of known late Mesozoic through middle Tertiary rocks in much of northwestern Arizona may cause a bias in favor of late Tertiary ages for basin-range faulting in the western part of the state.

From the data presented in the previous section of this paper, it seems that basin-range faulting began as early as late Mesozoic–early Tertiary time in Arizona and continued to late Tertiary and Quaternary time. There do not appear to have been any significant shifts with time in the distribution of basin-range faulting in the state. Late Cretaceous–early Tertiary and late Tertiary–Quaternary faulting is reported from throughout the Basin and Range portion of Arizona. Middle Tertiary faults are not reported from as many localities but are not restricted in distribution. The lack of fault localities in southwestern Arizona (Figs. 3-5) is probably not real but is due to a lack of published geological studies in that area. Armstrong and Suppe (1973) encountered a similar lack of data in southwestern Arizona in their study of radiometric dates on igneous rocks in the Southwest.

Conclusions

A late Mesozoic–early Tertiary age for initiation of basin-range faulting in Arizona conflicts with numerous hypotheses for the origin of the Basin and Range province. Comparison of the age relationships of magnetic anomalies in the eastern Pacific Ocean (Atwater, 1970) and the data of this paper indicates a subducted, but still active, "East Pacific Rise" could not have initiated pre-Miocene extension beneath Arizona to cause basin-range faulting. The presence of offshore magnetic anomalies ranging in age from 20 to 29 m.y. is interpreted by Atwater to mean the East Pacific Rise was still active off the coast of the western United States until at least late Oligocene and possibly into Miocene time. If the rise were still in the Pacific Ocean during Late Cretaceous, early Tertiary, and early middle Tertiary time, it could not have simultaneously caused basin-range extensional faulting in Arizona.

Atwater suggests the Basin and Range province is part of the transform boundary between the North American and Pacific plates and that the province is a zone of northwest-southeast stretching of the crust. According to her model, deformation in the province could not have begun until subduction off western North America had ceased and motion along

the San Andreas transform had begun; she dates basin-range formation as 20 to 5 m.y. old. Christiansen and Lipman (1972) believe normal faulting began in late Oligocene time in southern New Mexico and Arizona and migrated northwestward into the Great Basin and southeastward into Mexico. They agree with Atwater's theory on the origin of the Basin and Range province. A late Mesozoic—early Tertiary age for the beginning of Basin and Range faulting is incompatible with Atwater's and Christiansen and Lipman's theories because the San Andreas transform boundary is, according to Atwater (1970), apparently no older than middle Tertiary.

Scholz and others (1971) present a model for basin-range faulting in the Great Basin that may apply in a general way to Arizona. They believe the Great Basin is an ensialic interarc basin or a continental analog of interarc basins described by Karig (1970, 1971a, 1971b) from several island arc systems in the Pacific Ocean. The oceanic interarc basins, like the Basin and Range province, are characterized by en echelon ridge-trough topography which is apparently the result of normal faulting. Scholz and others (1971) believe that crustal extension in the Great Basin is due to a spreading mantle diapir beneath the crust. According to their model, the diapir rose above the active subduction zone and began to flatten and spread laterally when it contacted the lithosphere. When subduction ceased during late middle Tertiary time, the release of compression allowed more rapid flattening and spreading of the diapir and the beginning of basin-range faulting (Scholz and others, 1971). Perhaps, though, basin-range faulting began when the diapir first began to spread, and the release of compression 25 million years ago only accelerated spreading of the diapir and basin-range faulting.

However, there are several differences between the Arizona and Great Basin portions of the Basin and Range province. Compared with the Great Basin, Arizona has relatively little evidence of recent activity on basin-range faults. The Arizona geologic map (Wilson, Moore, and Cooper, 1969) shows few range-front faults, probably because they have been covered by alluvium. There is also considerably less seismic activity in Arizona than in the Great Basin (Barazangi and Dorman, 1969). Apparently basin-range faulting has died out somewhat sooner in Arizona than in the Great Basin. Furthermore, as has already been pointed out, there is much more variety in the trends of the present mountains and older basin-range faults in Arizona as compared with the rather uniform northward trends in the Great Basin. Using the simple diapir model of Scholz and others (1971), it is difficult to explain the different structural trends of the Arizona and Great Basin portions of the Basin and Range province.

An alternate hypothesis for the origin of basin-range faulting in Arizona is suggested in a paper by Coney (1973). In contrasting the environment of formation of back-arc thrust-fold belts and back-arc spreading belts, Coney (1973) suggests that back-arc extension occurs if the plate on which it develops is nearly stationary, moves parallel to the arc, or moves away from the arc. In contrast, back-arc thrusting occurs if the plate on which thrusting develops is actively driving over the opposing oceanic plate. Unfortunately, information on the Late Cretaceous to middle Tertiary history of the margin of the North American plate west of Arizona is ambiguous. Active subduction off California and Baja California during the Cretaceous is indicated by extensive plutonism of that age parallel to the subduction zone (Armstrong and Suppe, 1973). Plutonism continued into the Eocene in southeastern California and southern Arizona (Armstrong and Suppe, 1973), suggesting subduction was still active into the early Tertiary at that latitude. According to Suppe (1970), early strike-slip motion on the San Andreas fault may have occurred during early Tertiary time. Strike-slip subduction at the latitude of Arizona

may explain initiation of back-arc extension and basin-range faulting in Arizona during Late Cretaceous—early Tertiary time. How this faulting relates temporally and spatially to Late Cretaceous thrust faults of Arizona is not clear. Arizona, particularly southwestern Arizona, and northern Mexico need considerably more study before Cenozoic plate relations can be well understood. Further work should include an attempt to discover the age of initial basin-range faulting in these areas and its temporal and spatial relation to plutonism, volcanism, and thrusting.

Continued faulting into late Tertiary and Quaternary time could have been due to any or all of the following causes:

1. Accelerated flattening of the proposed mantle diapir due to release of compression when subduction stopped (Scholz and others, 1971).

2. Collapse over a regional dome, perhaps related to Scholz's diapir model.

3. Withdrawal of vertical support due to extensive Tertiary and Quaternary volcanism (Mackin, 1960a).

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