# THE RIFT SYSTEM OF THE WESTERN UNITED STATES

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## Abstract

The rift system of the western United States was first recognized by G.K. Gilbert in 1875. It was later realized that the normal-fault complex was much more extensive than the Great Basin. Unless one wishes to lump together all of the tectonically active region, it seems reasonable to define the rift system as that part of the Cenozoic fault system characterized by lateral spreading or tensional strain.

The following conclusions may be drawn:

1. In some areas, especially near the margins of the rift system, there is an overlap in types of deformation, i.e. the normal faults have a strike-slip component, or (as in west Texas) broad anticlinal uplifts occur with the normal faults.
2. Present seismic activity does not coincide with the rift zone.
3. The region of anomalously thin crust and anomalous upper mantle correlates roughly but not exactly with the rift system.
4. Volcanism and heat flow show the closest correlation with the rift system, but more heat flow measurements are needed. Magnetic anomalies, which may also be thermally dependent, show promise and need further investigation.
5. Individual rifts may be underlain by igneous intrusions at a depth of 10 km or less.
6. Volume changes at the moment of large earthquakes are consistent at least qualitatively with elastic rebound theory.

## EXTENT AND CHARACTERISTICS

Although he did not call it that, the rift system of the western United States was first recognized by G.K. Gilbert during the early geological exploration of the west (Gilbert, 1875). Gilbert found strong evidence that the Cenozoic mountains and basins of the internally draining Great Basin were not formed by folding as had been thought, but were created instead by intricate block faulting. It was later realized that the region of normal faulting extends far beyond the limits of the Great Basin, and the larger region is commonly referred to as the Basin and Range Structural Province. It is the normal-fault complex of this region that I refer to as the rift system.

Stated another way, unless we wish to lump together all of the tectonically active region, it seems reasonable to define the rift system as that part of the Cenozoic fault system characterized by lateral spreading, i.e. extension or tensional strain. This does not mean that a component of strike-slip faulting may not be present also, but simply that the component of extension is essential. Defined in this way, the rift system is similar to the Iceland, the Oslo and the Rhine grabens, and to the African rifts, but it is dissimilar to the San Andreas fault system, which is characterized by past and present compression superimposed on strike-slip faulting. Gilbert himself confused the problem of the origin of the Basin Ranges. Perhaps influenced by the tectonic theories of his day, notably the shrinking earth hypothesis, he supposed that the normal faulting results from deep seated compression. However, extension is demonstrated clearly by geodetic measurements of strain increments at the time of large earthquakes along the rift system (Thompson, 1959, p. 224-226).

Figure 1 shows the extent of normal faulting - the rift system of the western United States - as compiled by Gilluly (1963, p. 158). The great faults forming the east escarpment of the Sierra Nevada are prominent. An active zone of large earthquakes in western Nevada converges southward with the Sierra Nevada faults. To the east, the faults near the west side of the Colorado Plateau are also active (Cook, 1966). Northward, the rift system narrows markedly and joins the Rocky Mountain Trench. Southward it diverges and includes a very broad region in Mexico.

It is noteworthy that there are some strike-slip movements in this region of predominant normal faulting. The Las Vegas shear zone in southern Nevada shows evidence of right-lateral strike-slip displacement (Longwell, 1950). The Owens Valley faulting in 1872 had a right lateral component although it was predominantly dip-slip (Bateman, 1961). The Dixie Valley-Fairview Peak earthquake of 1954 also had a right lateral component along part of the fault trace. The amount of strike-slip in these examples is small in comparison with the San Andreas system, and the strike-slip movements accompany extension in all the examples of recent faulting, whereas in the San Andreas system compression of Coast Range anticlines accompanies the present right-lateral shearing movement (Burford, 1965).

Figure 2 shows the epicentres of earthquakes between 1937 and 1957 as compiled by Woollard (1958, p. 1138). The two lines enclose the rift system shown on the preceding slide. The rift system cannot be defined by seismicity because the coastal region, where strike-slip faulting and compressional folding predominate, is obviously more active today.

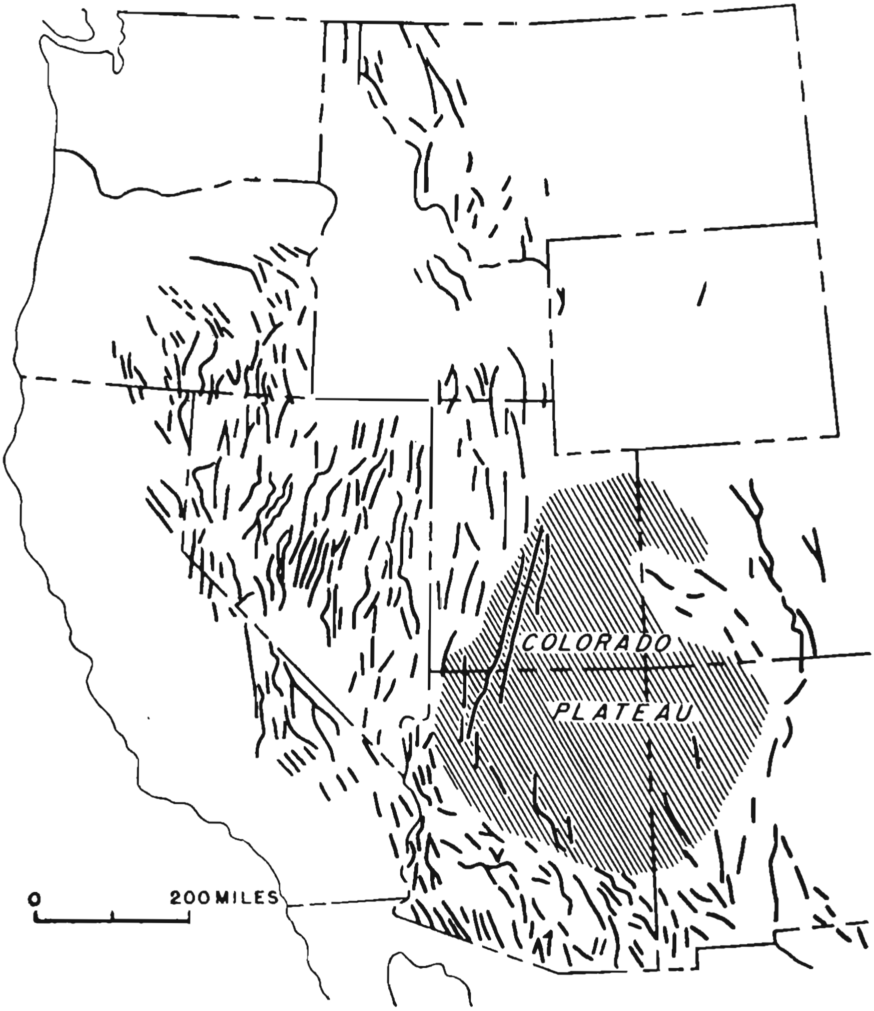


Figure 1. Cenozoic normal faults of western United States, from Gilluly (1963). The extent of normal faulting best defines the rift system.

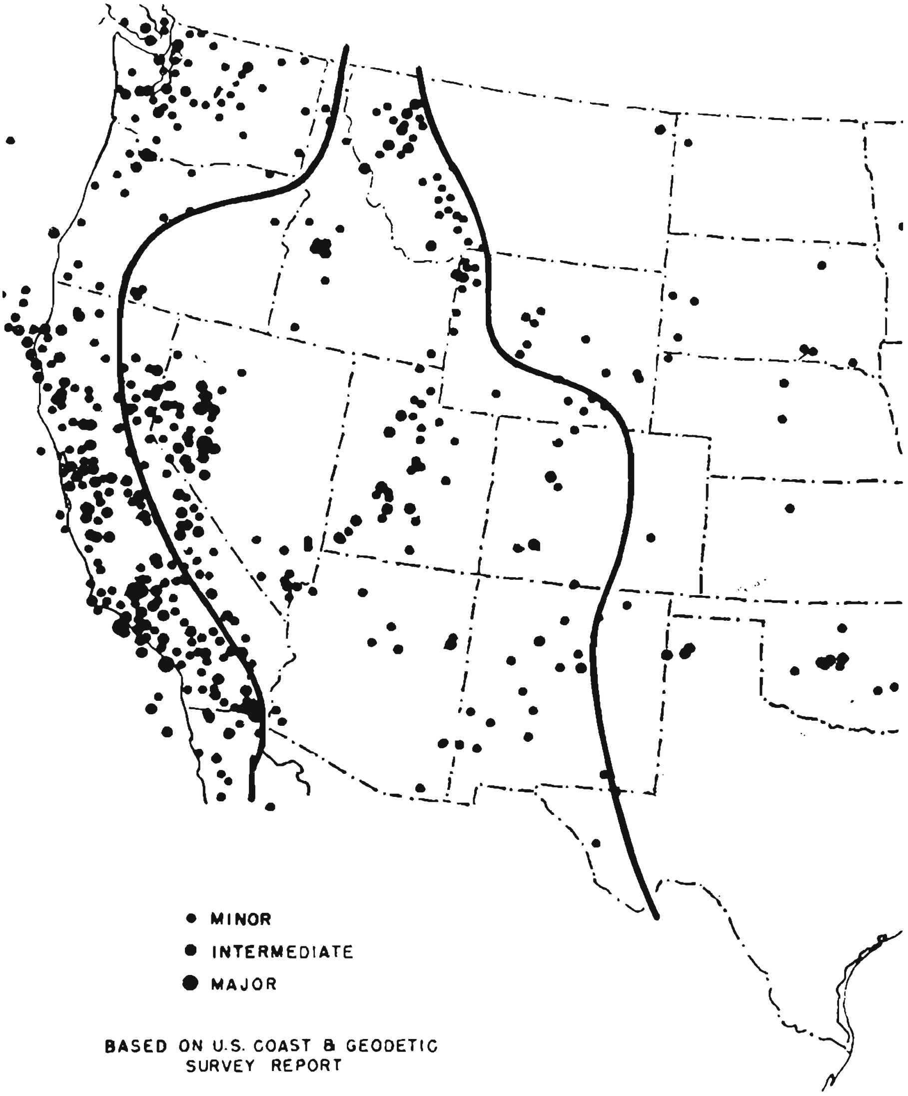


Figure 2. Earthquake epicenters, 1937 to 1957, from Woollard (1958). The two lines are approximate boundaries of the rift system shown in Figure 1. Part of the rift system appears seismically inactive.

Within the rift system some areas of intense normal faulting in the past are comparatively inactive today: e.g. southeastern Oregon, eastern Nevada, southern Arizona, and westernmost Texas. On the other hand, the Sierra Nevada front, the western border of the Colorado Plateau in Utah, and the Dixie Valley zone in western Nevada are highly active.

How does this fit into the oceanic rift system? Menard (1961, p. 53) suggests that the East Pacific Rise continues into the highland region of western North America. Ever since Ewing and Heezen (1956) first suggested that the rifts may be continuous on a world-wide scale, oceanographers have usually drawn the rift or its main branch through the Gulf of California and along the San Andreas fault. However, it seems more reasonable to include western Mexico with the Gulf of California in the rift zone, together with the whole broad zone of normal faulting to the north.

The Gulf should be included because of the evidence of lateral spreading concurrent with strike-slip faulting there (Hamilton, 1961). The continental borderland off southern California may also be a branch of the rift system, but it is not clear whether that area has undergone extension.

## CRUST AND MANTLE

Several unusual properties of the crust and mantle are more or less closely associated with the rift zone of western United States.

First, the upper mantle velocity is anomalously low, and the crust is anomalously thin. Pakiser and Steinhart (1964, p. 137) have summarized the upper mantle velocities for the region. They show that the entire western area of the rift zone (the shaded area in their diagram) has a $P_n$ velocity less than 8.0 km/sec. Neither the eastern nor the western boundary of this low velocity region corresponds exactly with the boundaries of the rift zone, but the geneneral correspondence with the broader highland region – the rise – is striking. The central part of the zone close to the rifts has the lowest velocity. A crustal section across the western side of the rise, computed by Thompson and Talwani (1964), shows that the area is isostatically balanced, but the crust is anomalously thin, and the upper mantle is anomalous in velocity and density. These anomalies extend over the whole of the seismically active area at this latitude and do not stop at the boundary of the rift zone along the eastern front of the Sierra Nevada. The thin crust and anomalous mantle correlate with the rise rather than the rift zone.

A second attribute of the rift zone is volcanism. The tectonic map of the United States shows this very well, and the world-wide association of rifts with volcanism is widely accepted. The relationship is far from exact, however. Some areas of normal faulting are free of volcanics at the surface, and some volcanic areas have few normal faults.

Because of the regional Cenozoic volcanism, we expect the heat flow to be high, and recent measurements are bearing out the expectation (Lee and Uyeda, 1965). The high heat flow seems to be restricted to a narrower region than the anomalous mantle, but the details are not yet clear.

Magnetic anomalies within the rift zone differ from those elsewhere (Zietz, 1965). Broad anomalies that may have their sources in the lower crust or within the mantle are conspicuously absent. Zietz tentatively explains this observation in terms of a silicic crust and a hot upper mantle.

## MODEL FOR A BASIN-RANGE RIFT

It is of interest to inquire into the subsurface structure and origin of a graben. Figure 4 shows diagrammatically a rift of fairly typical dimensions in the Basin Ranges. To take a specific example, it represents Dixie Valley, Nevada, reasonably well (Meister, 1965; Thompson, 1959). That valley widened 5 feet in the 1954 earthquake and one side sank 7 feet. The accumulated lateral spreading of this valley in all the earthquakes of the last 10 to 15 million years amounts to about 3 km. The geometry of faulting clearly requires sizable extension. A second notable fact is that the faults, which dip about 60°, converge at a depth of only about 10 km. Plastic flow of the rocks below this depth could account for regional spreading but could not readily account for localized dilation below the graben. A satisfactory explanation may be that an igneous intrusion or zone of intrusions dilates the lower crust beneath the graben, a suggestion which I published in 1959 (Thompson, 1959, p.222), but for which there is still no definite evidence. Numerous hot springs hint that the active valleys are thermally anomalous, and detailed heat flow studies might be especially enlightening. No magnetic anomalies diagnostic of a concealed intrusion have been found (Smith, 1965; Meister, 1965), but the volcanic rocks in this region are silicic, so that we should perhaps not expect a magnetic anomaly.

Turning again to the regional picture, if deep-seated plastic or convectional spreading is taking place on a broad scale, as suggested by the bottom arrows in Figure 3, it may be complementary to regional compressional deformation in the coastal region to the west, near the San Andreas fault zone (Thompson, 1960, p. 65).

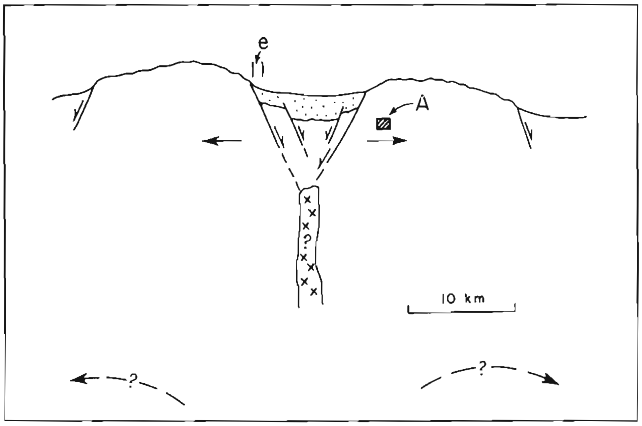
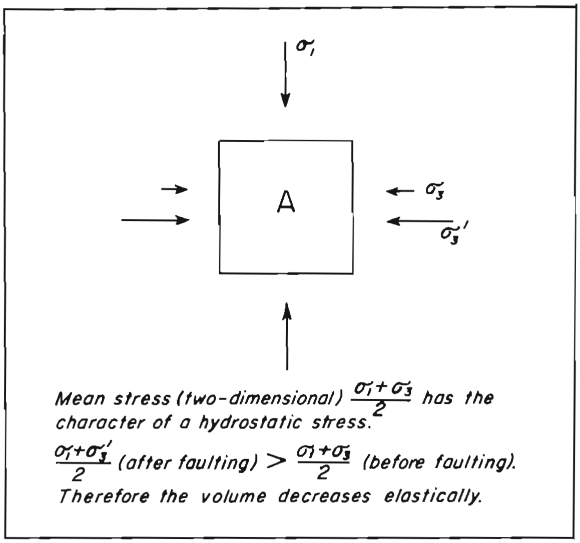


Figure 3. Sketch section of a graben in the Basin and Range province. Commonly the faults are unequally developed and the floor is tilted. The underlying dyke is hypothetical. Note the convergence of faults at depths about equal to the breadth of the graben. "e" is the horizontal extension on one fault; "A" is a small region shown in Figure 4.



*Mean stress (two-dimensional)* $\frac{\sigma_1+\sigma_3}{2}$ *has the character of a hydrostatic stress.*

$\frac{\sigma_1+\sigma_3'}{2}$ *(after faulting)* $>$ $\frac{\sigma_1+\sigma_3}{2}$ *(before faulting).*

*Therefore the volume decreases elastically.*

Figure 4. Stresses before and after an earthquake. The vertical principal stress, maintained by the gravitational load, remains constant but the horizontal principal stress (taking compression positive) increases. An elastic decrease in volume therefore allows the graben to drop during an earthquake.

## ELASTIC REBOUND

If the detailed model has any validity, it should also account for the sudden subsidence of a graben block at the moment of an earthquake and the accompanying sudden lateral extension. In the example of the Dixie Valley earthquake of 1954, the elevation of the mountain blocks changed hardly at all, whereas the valley dropped as much as 7 feet. This asymmetry between the movement of the mountain and valley blocks demonstrates a serious inadequacy of present dislocation and strain theory, which neglects gravity and also assumes a perfectly uniform half space (Press, 1965). The horizontal strain jump at the time of the 1954 earthquake died off with distance from the fault, so that points distant, say 50 km, from the fault on either side moved little or not at all with respect to each other (Whitten, 1957). The observed relations can be understood if we assume the shallow crust was slowly distended elastically in the years preceding the earthquake. At the time of the earthquake these accumulated stresses were suddenly relaxed.

Consider the stresses in a small region "A", shown in Figure 4. The vertical principal stress, maintained by the gravitational load, remains constant during faulting. The horizontal principal stress, taking compression as positive, diminishes during strain accumulation up to the point of rupture. At rupture, the horizontal principal stress suddenly increases. The volume of "A" abruptly decreases, mainly in a horizontal direction, because of the abrupt increase in the mean stress. It is this abrupt elastic volume decrease in the adjacent mountain blocks that can permit the valley block to subside suddenly during an earthquake. At the surface a considerable volume disappears too quickly for it to be explained by plastic flow or movements of magma at depth. A check on this reasoning is available from the recent Alaskan earthquake, for a strike-slip or thrust movement should be accompanied by a decrease in the mean stress and a consequent increase in volume. The Alaskan data are in accord with this expectation; the volume of uplift appears to be roughly twice the volume of subsidence (Plafker, 1965), making a large net increase of volume.

## CONCLUSIONS

1. The rift system of western United States is most logically defined by the Cenozoic normal faulting, which characterizes the region of lateral extension.

2. In some areas, especially near the margins of the rift system, there is an overlap in types of deformation, i.e. the normal faults have a

strike-slip component, or (as in west Texas) broad anticlinal uplifts occur with the normal faults.

3. Present seismic activity does not coincide with the rift zone.

4. The region of anomalously thin crust and anomalous upper mantle correlates better with the rise than with the rift system.

5. Volcanism and heat flow may show the closest correlation with the rift system, but more heat flow measurements are needed. Magnetic anomalies, which may also be thermally dependent, show promise and need further investigation.

6. Individual rifts may be underlain by igneous intrusions at a depth of 10 km or less.

7. Volume changes at the moment of large earthquakes are consistent at least qualitatively with elastic rebound theory.

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