REGIONAL GEOPHYSICS OF THE BASIN AND RANGE PROVINCE

×10021

George A. Thompson
Department of Geophysics, Stanford University, Stanford, California 94305

Dennis B. Burke
U.S. Geological Survey, Menlo Park, California 94025

> *Of late years the most important contributions have come from the Physicists, and in their scales have been weighed the old theories of Geologists.*
>
> G. K. Gilbert (1874)

INTRODUCTION AND GEOLOGIC SETTING

Nearly one hundred years ago, Gilbert (23, 24) and other geologic pioneers introduced the idea that much of the seeming jumble of mountains and valleys in western North America was the result of far different processes than fold mountain systems such as the Appalachians or Alps. After a century of geologic and geophysical investigations in the region, it is now generally accepted that the physiography of the Basin and Range province (Figure 1) is one of sculptured and partially buried fault-bounded blocks that have been produced by the extension of the region during late Cenozoic time. Crustal blocks composed of complexly deformed, diverse pre-Cenozoic rocks and relatively undeformed, predominantly nonmarine volcanic rocks of early and middle Cenozoic age have been variously uplifted, tilted, and dropped along numerous normal faults throughout a broad region from Mexico to Canada—from as far west as California and Oregon to as far east as western Texas (e.g. Cook, 13; Gilluly, 27; Thompson, 76).

The distribution of late Cenozoic normal faults in the western United States is shown on Figure 2 (note that the regional extent of faulting is somewhat larger than the Basin and Range physiographic province of Figure 1). The recent seismicity (Figure 3) shows that small earthquakes are widespread in what Atwater (5) called a wide soft zone accommodating oblique divergence between the Pacific and North American plates. The net effect of fault movements within this region is a crustal extension oriented roughly WNW–ESE. The actual motion on individual faults is quite variable, however, and appears to be controlled by the orientation of faults with respect to this principal extension (Thompson & Burke, 78). In the northern portion of the region—across Nevada and western

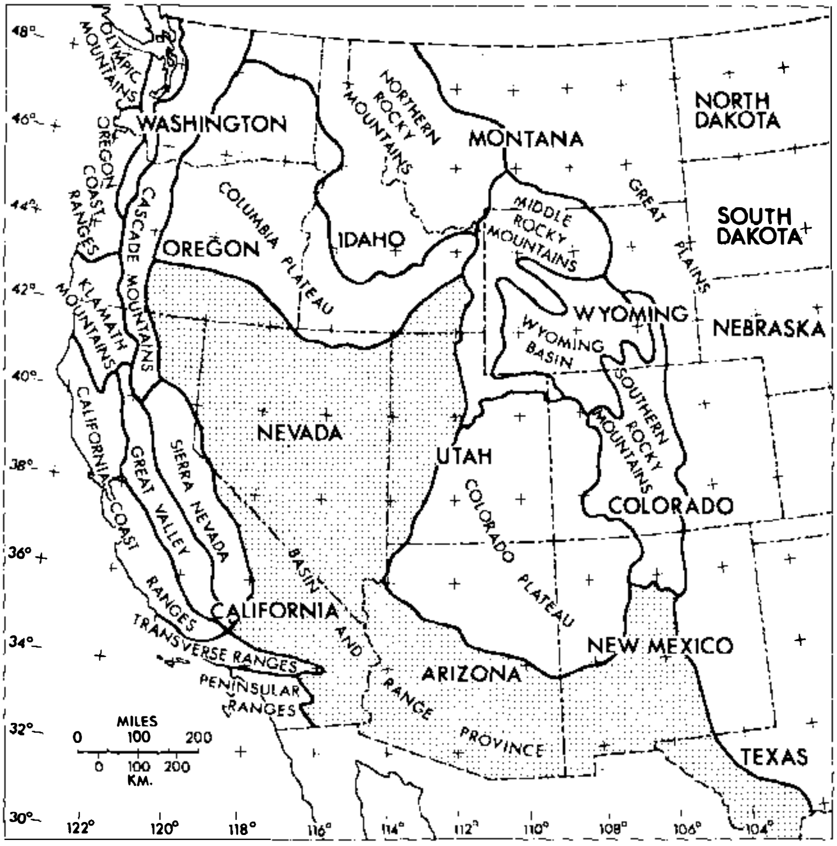


Figure 1 Physiographic provinces of the western United States (Fenneman, 21).

Utah—the domain of faulting is neatly confined between the Sierra Nevada of California and the Wasatch Mountains of north-central Utah. The relatively unfaulted Colorado Plateau separates the central portion from a zone of faulting in the Rio Grande trough in New Mexico and west Texas. Relative motion between the unextended and rather enigmatic mass of the plateau and the encircling faulted terrain is presumably accommodated by a component of right-lateral strike-slip along the southern plateau border. Faulted terrain extends southwards without interruption into Mexico and the Gulf of California. Faulting seems to die out to the north, and the manner in which relative motions are accommodated along the northern boundary remains a troublesome problem.

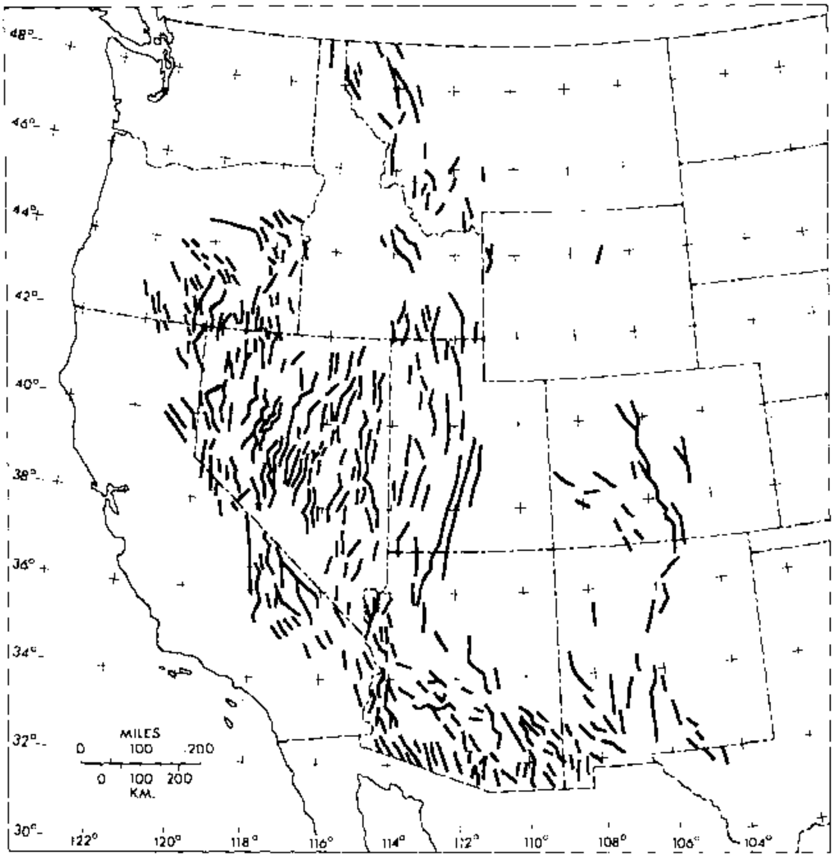


Figure 2 Predominantly normal (Basin and Range) faults of late Cenozoic age in the western United States (modified from Gilluly, 26).

Although the Basin and Range province is in many ways a unique physiographic and geologic entity, increasingly precise and reliable geophysical studies, together with advances in tectonic theory, highlight similarities between the province and other regions of past or present crustal extension. It has a high heat flow and widespread volcanism like other regions of active normal faulting, such as the Rift Valleys of Africa, the Lake Baikal depression of the USSR, the Rhine graben of Europe, the marginal basins of the western Pacific Ocean, and the worldwide system of oceanic ridges and rises. Along with the Sierra Nevada and Colorado Plateau, it forms a wide elevated region averaging 1–2 km above sea level and thus may resemble the elevated, thermally expanded oceanic ridges (Sclater &

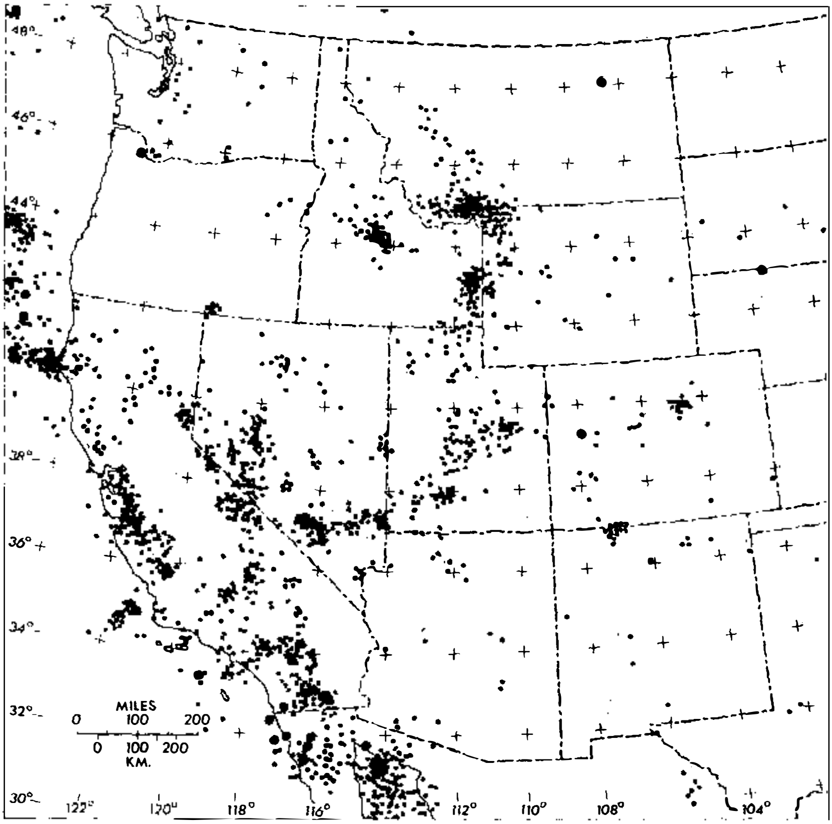


Figure 3 Earthquake epicenters in western North America for the period 1961–1970. Small dots represent earthquakes of magnitude about 3 to 5, large dots greater than 5. National Oceanographic and Atmospheric Administration epicenters replotted by J. C. Lahr and P. R. Stevenson of the US Geological Survey (personal communication, 1973).

Francheteau, 65). Also like some of these other regions, it has a thin crust and low mantle velocity.

Can regional geophysical data for the Basin and Range province, combined with interpretations of its geologic history, lead toward a better understanding of the tectonic processes that have controlled its development? To what extent have earlier geologic events in the region preordained the pattern of faulting that we now see in western North America? What constraints must be heeded in tectonic models of the region, and what aspects of the province allow these models to be compared with other portions of the global system of ever-changing lithosphere plates? We believe this last consideration to be of great importance, although it can only be touched on lightly here, because much understanding of the province derives from analogy with other regions of crustal extension. The currently most promising models relate Basin and Range structure to an earlier subducting plate at the western margin of North America, and they incorporate close physical comparisons with the marginal basins of the western Pacific.

REGIONAL CRUST AND MANTLE STRUCTURE

Crustal Thickness: Seismic Refraction

Seismic waves from explosions have provided the most reliable and detailed information on crustal thickness and indicate that the region of distinctive Basin and Range structures corresponds quite closely with a region of thin continental crust (Pakiser, 52; Prodehl, 55). Prior to the work of Tatel & Tuve (74) it was generally assumed that the crust would be thicker under this elevated region than in continental regions near sea level, a relationship that has been found in other mountain regions. It was thought that lateral variations of velocity and density in the mantle were unimportant, or at least inconvenient in seismic interpretation, and that isostatic compensation was accomplished mainly by variations in crustal thickness.

Tatel and Tuve found that the crust in northwestern Utah is an anomalously thin 29 km. Verification came from Berg et al (6), Diment et al (16), and Press (54), although these authors initially used a different definition of the crust. They found abnormally low *P*-wave velocities of 7.6 to 7.8 km/sec at shallow depth for what we have now come to identify as P_n, the wave traveling in the uppermost mantle below the *M* discontinuity.

Extensive explosion studies carried out by the US Geological Survey established the basic picture as we know it today. David H. Warren, of the USGS (personal communication, 1973) has compiled and interpreted these and other data into a contour map of crustal thickness (Figure 4). The contours are based on data of varying quality and on varying interpretation of velocity structures within the crust; nonetheless they represent a good first approximation. Almost the whole region from the Rocky Mountains westward has a thin but variable crust, roughly two thirds the thickness found in stable regions of comparable elevations. The eastern border of the Basin and Range province is marked by a fairly sharp gradient at the 35 km contour to a thicker crust under the Colorado Plateau. Southeast of the Colorado Plateau there is some indication of thinning beneath the Rio Grande trough of New Mexico and west Texas.

The crust is thicker beneath the Sierra Nevada to the west of the province [although this conclusion has been called into question by Carder (10)]. It is interesting to point out that in detail the thick crust of the Sierran region (Figure 5) extends into the Basin and Range province to the east of the Sierra Nevada. The eastward extent of thick crust does not correspond with the eastern border of the Mesozoic Sierra Nevada batholith (Figure 6), however; although a correlation of the low velocity zone with the border of the batholith is not ruled out.

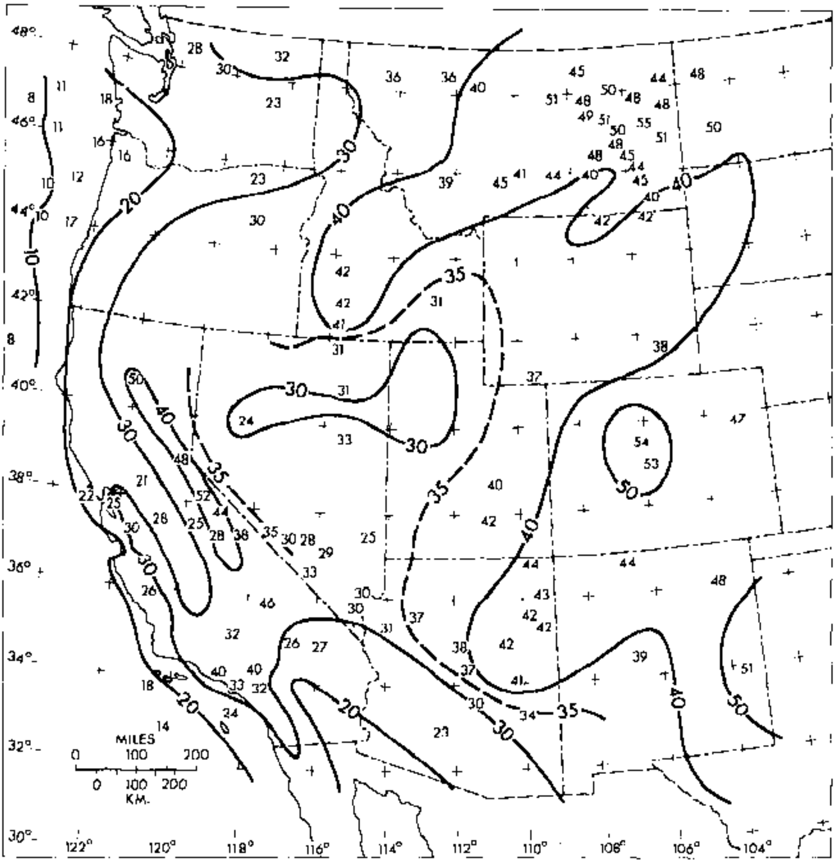


Figure 4 Contour map of crustal thickness (in kilometers) based on seismic refraction studies. Small numbers indicate individual thickness determinations. Compiled by David H. Warren from the following sources: 1, 4, 7, 11, 16, 19, 20, 22, 30, 34–39, 44, 55, 57–59, 62, 66, 67, 70, 72, 73, 82–85.

Upper Mantle Velocity and Implications From Gravity

When it was found that the crust is abnormally thin beneath the Basin and Range province and adjacent regions it was also discovered that P_n is anomalous. Its velocity of 7.7 to 7.9 km/sec is significantly less than the normal velocity of about 8.2 km/sec observed in stable regions (Pakiser, 52; Herrin & Taggart, 33; see Figure 7). Most of the Basin and Range province is characterized by the lowest P_n velocities, less than 7.8 km/sec.

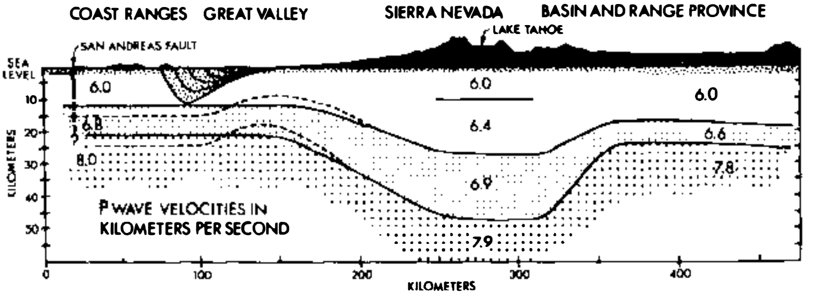


Figure 5 Crust and upper mantle structure in a section across central California and west-central Nevada as deduced from seismic-refraction studies. An alternative model beneath the Coast Ranges and Great Valley is shown by dashed lines; topography greatly vertically exaggerated (from Eaton, 20).

Gravity data supply a fundamental constraint on the amount of mass per unit area underlying any region. This information is particularly valuable because seismic refraction measurements do not by themselves allow interpretations of the thickness of the anomalous upper mantle of low P_n velocity. Gravity interpretation utilizes: 1. crustal thicknesses from seismic refraction, 2. crustal densities estimated from seismic velocities and geology, and 3. upper mantle densities estimated from P_n velocities. The gravity data then yield estimates of the thickness of anomalous mantle relative to stable regions (Thompson & Talwani, 79). The required thickness of low-density, low-velocity anomalous upper mantle is at least 20 km over much of the region.

In comparison with stable continental regions near sea level, most of the isostatic support for the high Basin-Range and adjacent regions is in the anomalous upper mantle. This material must surely be a key element in any tectonic model.

Isostatic gravity anomalies in the United States (Figure 8) show that most of the region from the west coast to the eastern limit of the Basin and Range province is deficient in mass, with an average anomaly of perhaps around -10 mgal. In this respect the region is similar to marginal basins of the western Pacific, which also tend to be isostatically negative.

The Lake Bonneville Experiment

A natural experiment in gravitational unloading of the Basin-Range crust occurred as pluvial Lake Bonneville, of late Pleistocene age, dried up, leaving the Great Salt Lake as its principal remnant. Prominent shorelines around the edge and on former islands mark the successively lower levels of Lake Bonneville. These shorelines are domed up toward the center as much as 64 m as a result of the unloading (Gilbert, 25; Crittenden, 14).

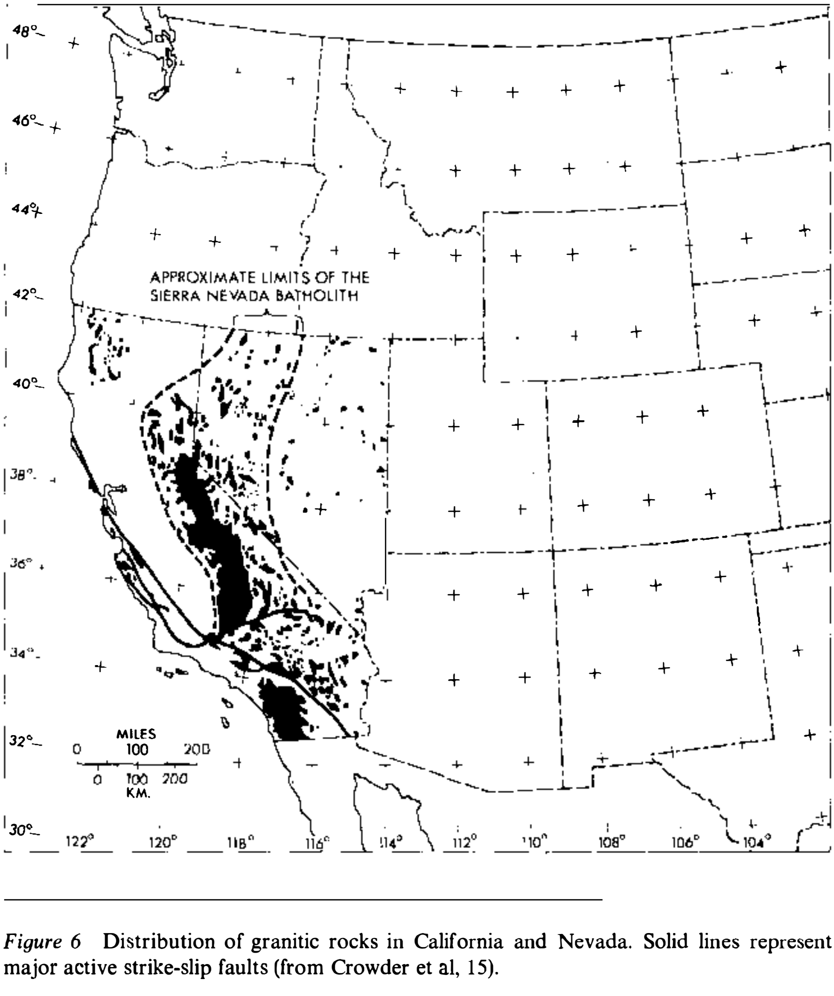


Figure 6 Distribution of granitic rocks in California and Nevada. Solid lines represent major active strike-slip faults (from Crowder et al, 15).

Using data from this natural experiment and a simple model of an elastic lithosphere floating on a fluid asthenosphere, Walcott (81) has computed the apparent flexural rigidity of the lithosphere and compared it with that of other regions subjected to various kinds of loading and unloading. Walcott's results, as shown in Table 1, illustrate that the flexural rigidity of the Basin and Range lithosphere is unusually low. He suggests that the anomaly may be explained by a "very thin lithosphere, only about 20 km thick, with hot, lower crustal material" acting as part of the asthenosphere. In contrast, the flexural rigidity of stable continental and oceanic regions suggests lithosphere thicknesses of 110 km and

Table 1 Apparent flexural rigidity of the lithosphere (from Walcott, 81)

Data	Region	Apparent flexural rigidity, Newton meters	Characteristic time, years
Lake Bonneville	Basin and Range province	5×10^{22}	10^4
Caribou Mountains	Stable continental platform	3×10^{23}	5×10^6
Interior Plains	Stable continental platform	4×10^{23}	5×10^6
Boothia uplift	Stable continental platform	7×10^{22}	5×10^8
Lake Algonquin	Stable continental platform	6×10^{24}	10^3
Lake Agassiz	Stable continental platform	9×10^{24}	10^3
Hawaiian archipelago	Oceanic lithosphere	2×10^{23}	10^7
Island arcs	Oceanic lithosphere	2×10^{23}	10^7

75 km or more, respectively. The low P_n velocity and high heat flow (discussed in a later section) are consistent with Walcott's interpretation.

Anomalous Mantle and the Low-Velocity Zone

Several studies have indicated that the Basin-Range region has an unusually well-developed upper mantle low-velocity zone (LVZ) for both P- and S-waves. The relationship is not always clear between the accentuated LVZ (as defined by waves refracted at deeper levels in the mantle) and the anomalous upper mantle (as defined by low P_n velocity). In a study applicable to the central part of the Basin and Range province in Nevada and western Utah, Archambeau and associates (2) derived a model (Figure 9) in which the M discontinuity is at a depth of 28 km and the P_n velocity just below it is 7.7 km/sec. This low velocity remains nearly constant to a depth of 130 km, where it undergoes a rapid transition to 8.3 km/sec. Thus the LVZ is about 100 km thick; it begins at the top of the mantle and coincides with the anomalous upper mantle.

In comparison, the same investigators derived three models applicable to regions northeast and east of the Basin and Range province, including the Colorado Plateau (Figure 9). These models have in common a "lid" of higher velocity material (P_n about 8.0 km/sec) above the LVZ, which is only about half as thick as in the Basin-Range model.

In the foregoing discussion a single model has been assumed to represent the Colorado Plateau, and this assumption seems reasonable because of the geological uniformity of the Plateau. However, within the limited resolution of the data, P_n velocities (Figure 7) appear to vary markedly over the Plateau and would not allow a single upper mantle model. This seeming conflict invites further research.

Helmberger (31) developed a new technique for studying regional variations of the LVZ. The method makes use of the nearly constant velocity of the PL wave in the crustal wave guide and the regional variation in the velocity of long-period P-waves. Results are mapped on Figure 10 (York & Helmberger, 87) as observed time differences minus the time difference predicted from a model LVZ roughly

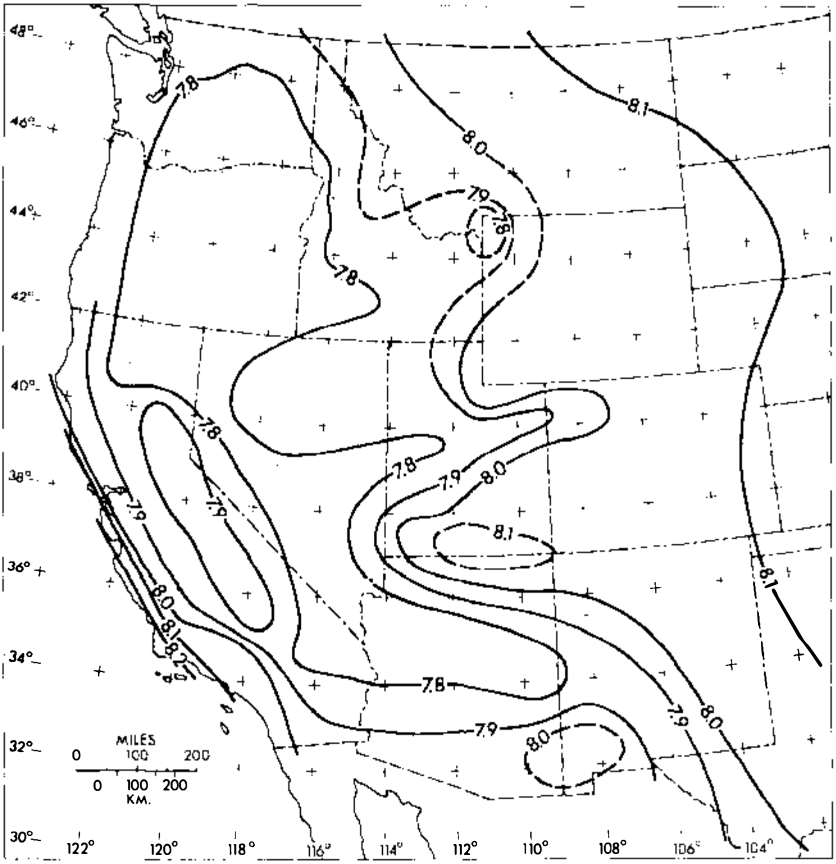


Figure 7 Contour map of P_n (upper mantle) velocities (in kilometers per second) (from Herrin, 32).

comparable to the Colorado Plateau model of Figure 9. Progressively more negative Δt values (delays of the long-period *P*-wave relative to the model) represent progressively thicker LVZ or lower upper mantle velocity. Positive values represent thinner or higher velocity LVZ relative to the model. Two main zones of thick LVZ within the −3 sec contour trend northward through eastern Nevada and western Utah and northeastward into the Rio Grande trough in New Mexico. These zones join to the southwest and continue across southern California and northern Mexico toward the continental borderland off southern California (generally considered to have Basin-Range structure) and the Gulf of California. The Colorado Plateau is strikingly outlined by the zero contour, which is expected because the reference model resembles the Colorado Plateau mantle.

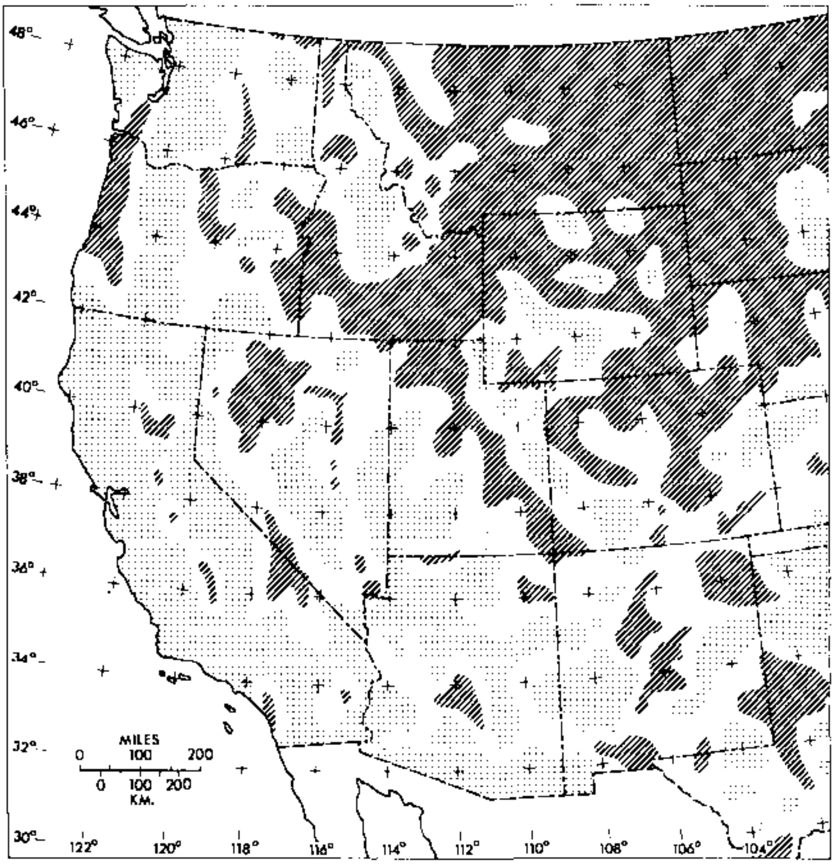


Figure 8 Regional isostatic gravity anomaly (based on Airy-Heiskanen concept with standard column 30 km). Line pattern, greater than +10 mgal; stippled pattern more negative than −10 mgal (from Woollard, 86).

In other important investigations Robinson & Kovach (56) studied upper mantle *S*-waves in the Basin and Range province, and Herrin (32) compared the Basin and Range upper mantle with that of a stable region, the Canadian Shield. Using direct measurements of the travel time gradient, Robinson and Kovach found a thin lid zone (9 km) of shear velocity 4.5 km/sec at the top of the mantle, overlying a low velocity zone with a minimum velocity at 100 km. Herrin's comparative model for the Canadian Shield contains no LVZ for *P*-waves and only a weak one for *S*-waves. The comparison is important because it emphasizes a degree of similarity between the Basin and Range and Colorado Plateau mantles relative to the stable region.

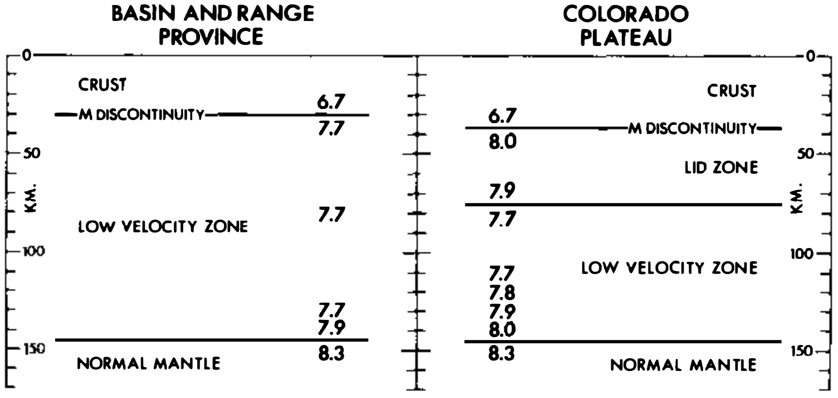


Figure 9 Generalized comparison of crust and upper mantle structure in the Basin and Range province and Colorado Plateau. *P*-wave velocities are in kilometers per second (adapted from Archambeau et al, 2).

RATE AND DIRECTION OF SPREADING

Seismological Evidence

Recent studies of focal mechanisms of many small earthquakes highlight a strikingly consistent direction of ongoing Basin and Range extension. Although recent earthquakes have been concentrated near the eastern and western borders of the province and in a belt across southern Utah and Nevada, evidence of older faulting indicates that they are a reasonable sample of this longer but much more widespread tectonic activity.

Focal solutions compiled by Scholz et al (64) show predominantly normal faulting, with the extension direction ranging approximately from east-west to northwest-southeast. The few examples of strike-slip motion are also consistent with this extension direction.

Only a few of the larger historical earthquakes were accompanied by surface ruptures large enough for the amount of offset to be directly observed, and these larger shocks (Figure 11) probably account for most of the total deformation. The main north-south zone of historical faulting in Nevada and adjacent California is nearly continuous. Horizontal extension across the faults ranges from a few centimeters to a few meters (Thompson, 75) and is greatest near the north and south ends of the zone. This wide range in extension, plus the existence of unfaulted gaps, shows that the 100-yr historical period is too short for measuring a meaningful rate of extension.

Dixie Valley, a Type Basin

Near the northern end of the zone of historical faulting, at the site of the 1954 faulting in Dixie Valley (Figure 12), two measures of long-term displacement have

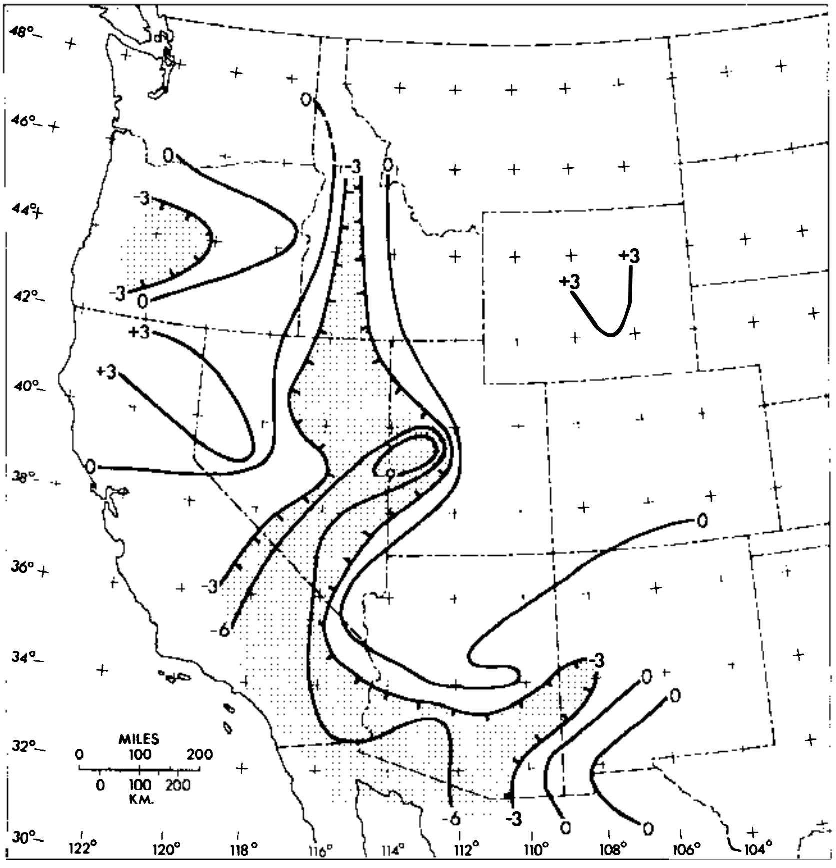


Figure 10 Relative development of upper mantle LVZ (low velocity zone), expressed as contours of time difference in seconds with respect to a model LVZ similar to that of Colorado Plateau. Stipple pattern accentuates region of pronounced (thicker or lower velocity) LVZ (from York & Helmberger, 87).

been investigated (Thompson & Burke, 78): 1. Displacements of the shoreline of a late Pleistocene lake supply a measure of extension during the last 12,000 years (Figure 13), and 2. fault displacements determined from geophysical exploration of the valley give the total amount of extension for late Cenozoic time, at least 5 km in 15 m.y. The average spreading rates are 1 mm/yr for the short interval and at least 0.4 mm/yr for the total displacement. The spreading direction we obtained from large slickenside grooves on fault planes is approximately N55°W–S55°E,

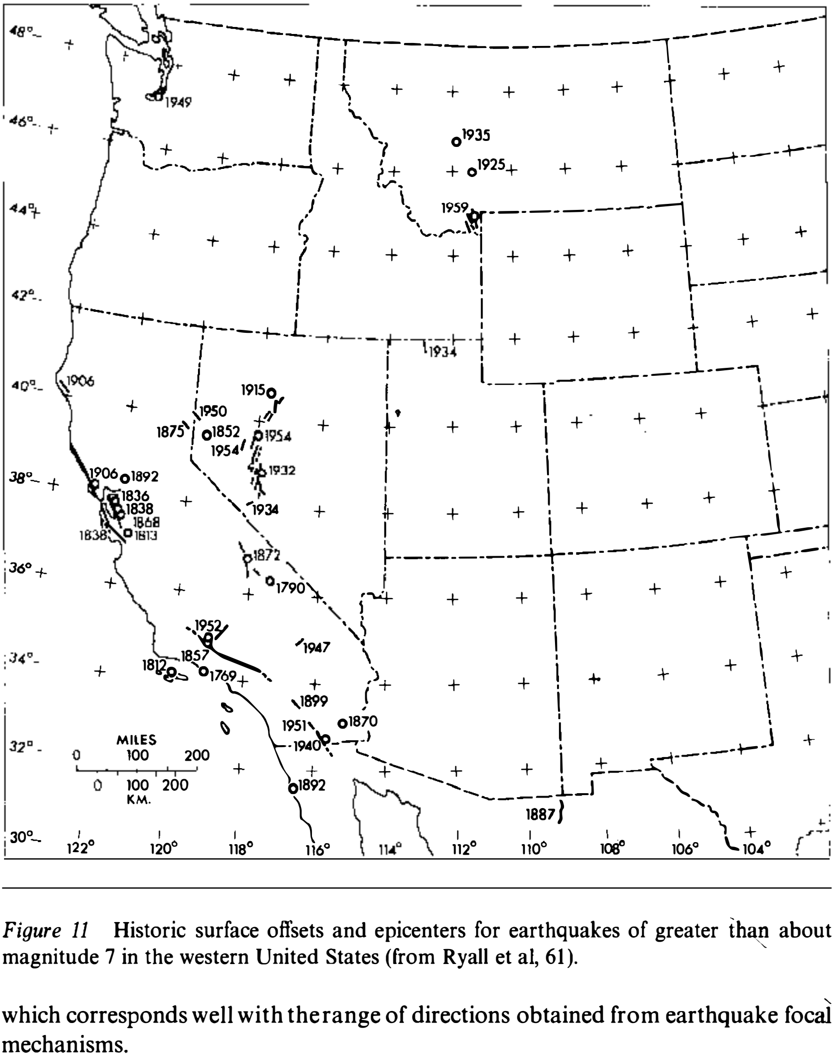
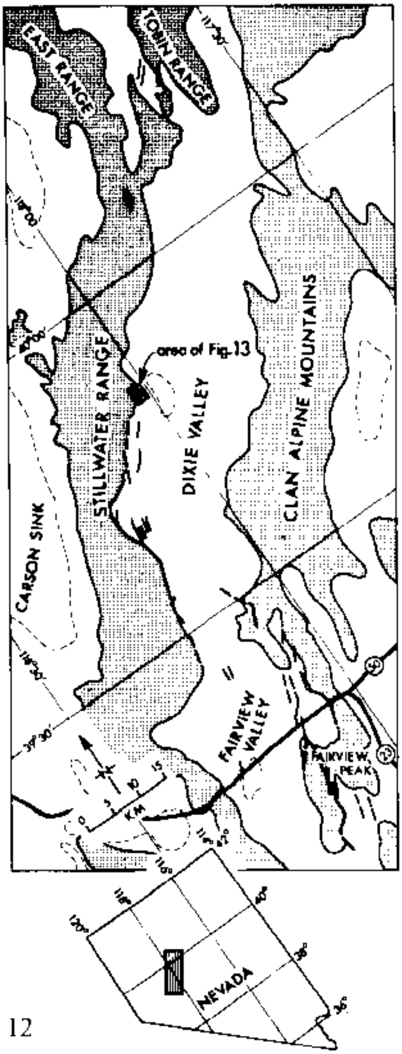


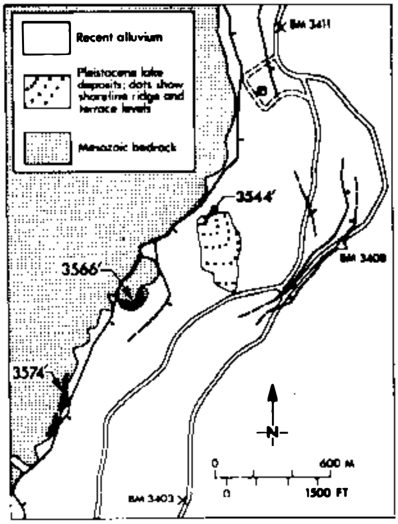
Figure 11 Historic surface offsets and epicenters for earthquakes of greater than about magnitude 7 in the western United States (from Ryall et al, 61).

which corresponds well with the range of directions obtained from earthquake focal mechanisms.

Dixie Valley is the only basin for which this much data is available. A simple extrapolation to 20 major basins across this part of the province suggests a total Basin-Range spreading of about 100 km (10% increase in crustal area) and a spreading rate of 8 mm/yr. On somewhat different assumptions, Gilluly (28) estimated that the areal expansion ranges from 4% to 12% over most of the province. Stewart (71) estimated 50 to 100 km (5% to 10%) of extension on the basis of a careful analysis of all available data. Hamilton & Myers (29) suggest that the extension may be as great as 300 km (30%). More subsurface data on many basins is needed to improve these estimates.



12



13

Figure 13 (*above*) Map of offset lake shorelines in west-central Dixie Valley. The relative vertical spacing of beach ridges around the valley demonstrates that the highest beach ridge preserved in this area (3544 ft) marks—like the tufa cemented terrace deposits on bedrock—the highest lake stand. The age of the high shoreline is 12,000 years (from Thompson & Burke, 78).

Figure 12 (*left*) Dixie Valley region. Fault scarps formed or reactivated in 1903, 1915, and 1954 are shown (from Thompson & Burke, 78).

Locus and Time of Basin-Range Faulting

The present seismicity (Figure 3) is a misleading guide to even the geologically youngest faulting. Fault scarps of Quaternary age are widespread and bear little relation to the seismicity. Slemmons (69) has documented this fact for Nevada with maps of faults in three age groups covering roughly the last 100,000 years. The locus of faulting appears to have shifted randomly over the whole breadth of the province rather than having been confined to the area of recent seismic activity.

Although older normal faults are known (Burke & McKee, 9), the main onset of block faulting is marked by the widespread disruption of drainage and formation of local sedimentary basins about middle or late Miocene time. The lower Miocene ash-flow sheets which cover broad areas were deposited on surfaces of low tectonic relief (McKee, 46; Noble, 50). The inception of Basin-Range faulting over at least Nevada and adjacent California is dated at 15 to 17 m.y. (see Noble, 50, for references). It must be emphasized that after faulting began it was probably sporadic in any one area. On physiographic evidence, some areas appear to have been inactive for a long time (for example, parts of Arizona, New Mexico, and west Texas), while activity continued to the present in other areas.

THE PATTERN OF RUPTURE

Basin-Range faults are often described in a general way as high-angle normal faults striking north to northeast, but the impression conveyed by that description is highly misleading. Individual faults tend to be extremely crooked in map plan and the fault pattern is more nearly rhomboid or even rectilinear. Some mountain ranges are bounded by en echelon faults that strike diagonal to the range (eastern front of Sierra Nevada for example). Considerable warping and tilting of the blocks accompany the faulting, particularly near the ends of elongate basins.

Nowhere is the fault pattern better exhibited than in the late Cenozoic basalt flows of south-central Oregon (Figure 14), but similar patterns are common from Nevada (Figures 12 and 13) to Texas. Moreover, the roughly rhomboid map pattern of faulting is characteristic of other regions of present or past crustal extension, such as the African Rifts, the Rhine graben, the Oslo graben, and the Triassic basins of eastern North America.

No well-founded explanation for the complex rupture pattern is known. Alternative hypotheses include changes in the stress system with time, influence of older structures, and anisotropy in mechanical properties of the crust. Another possibility is that the pattern is roughly analogous to the near-orthogonal pattern formed by oceanic ridges and transform faults, a pattern which has been explained as offering minimum resistance to plate separation (Lachenbruch & Thompson, 42). Oldenburg & Brune (51) dramatically reproduced the near-orthogonal oceanic pattern in a laboratory model with a thin crust of wax forming on molten wax, and Duffield (18) observed similar patterns forming on the solidified crust of a convecting lava lake.

The simple application of the minimum resistance theory to the Basin and Range province would suggest a series of northeast-trending grabens (normal to the spreading direction) and northwest-trending transform faults. The actual mechanics are more complex, and the faults commonly are hybrid, having components of

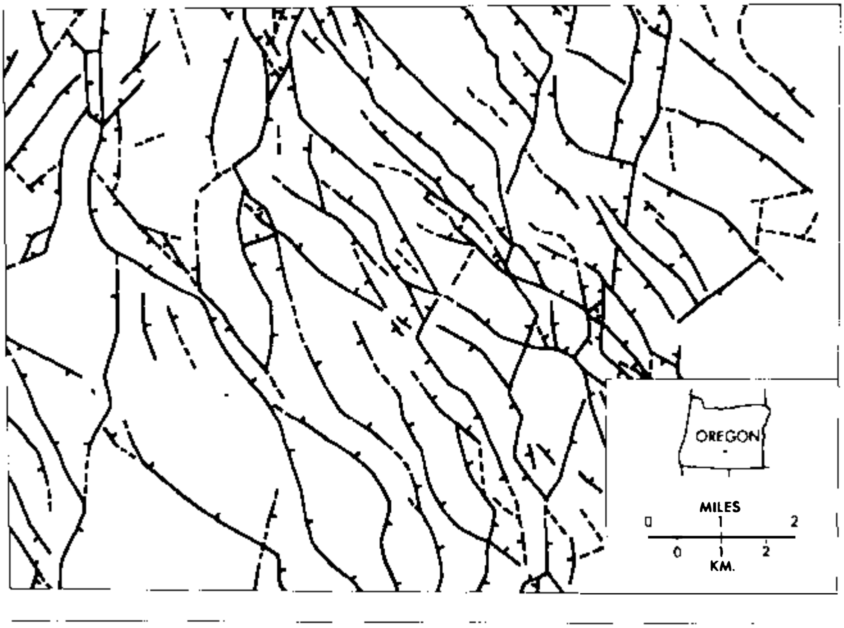


Figure 14 Rhomboid pattern of rupture expressed by late Cenozoic normal faults in south-central Oregon. Barbs on downthrown side of faults; faults dashed where inferred (from southeast portion of plate 3 of Donath, 17).

both dip- and strike-slip. The pattern is not simple and the question of the rupture pattern is far from resolved.

In addition to the problem of the pattern of faulting, the question of whether the normal faults systematically flatten with depth has been much debated, in part because such changes would imply greater regional extension. The seismic focal mechanisms lend no support to the notion of major decreases in dip, however, and serious geometric problems would ensue at the ends of basins if such decreases did occur. Therefore the low dipping to subhorizontal normal faults that have been observed in surface exposures and mine workings seem best ascribed to gravitational sliding and tilting in response to deeper primary faulting. The problem has been explored by Stewart (71) and Moore (48). Armstrong (3) interprets low-angle faults in eastern Nevada as gravitational sliding features of late Cenozoic age.

HEAT FLOW AND CRUSTAL TEMPERATURE

Regional Variation of Heat Flow

A region of anomalously high heat flow comprises the entire Basin and Range province and extends across the Columbia Plateau and part of the Rocky Mountain province (Figure 15). Heat flow values greater than 2 HFU [heat flow

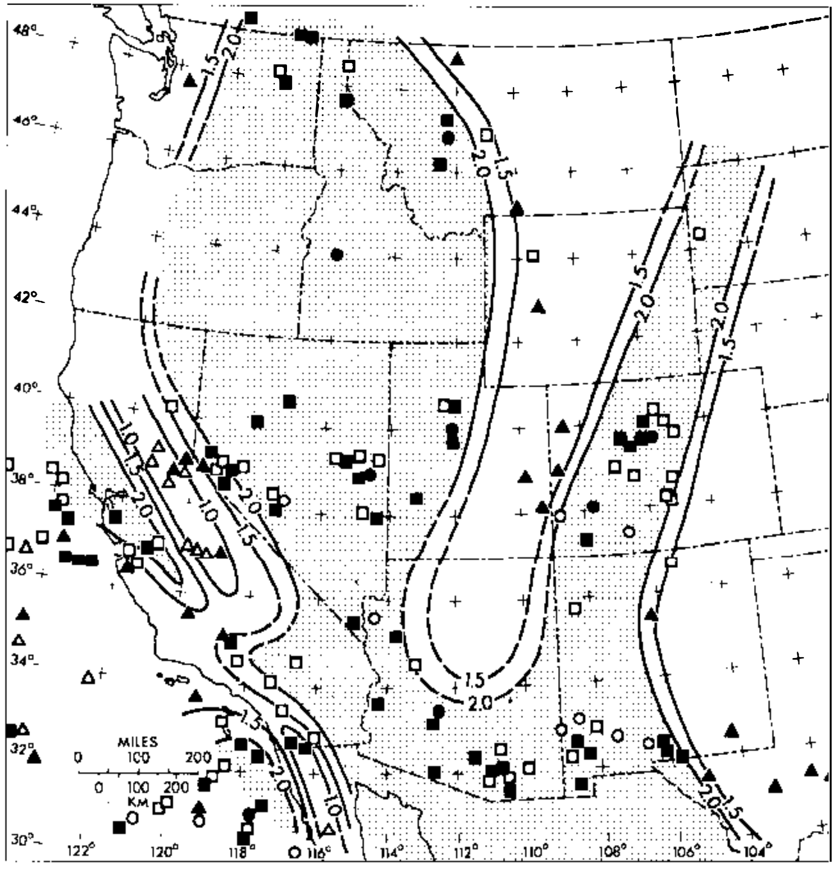


Figure 15 Contour map of heat flow. Contours in Heat Flow Units (μcal cm^{-2} sec^{-1}); dashed where extended on the basis of meager data. Data points shown as open triangles are measured heat flows in the range 0 to 0.99; solid triangles, 1.0 to 1.49; open squares, 1.5 to 1.99; solid squares, 2.0 to 2.49; open circles, 2.5 to 2.99; solid circles, 3.0 and larger (from Roy et al, 60).

units (HFU), μcal cm^{-2} sec^{-1}] characterize this broad region, in contrast to normal average values of about 1.5 HFU.

Although the Colorado Plateau is at least partly an area of normal heat flow, the distribution of measurements is inadequate to explore its boundaries with the Basin and Range province. The boundary with the Sierra Nevada appears to be surprisingly sharp.

Another compilation of the regional heat flow, by Sass and associates (63),

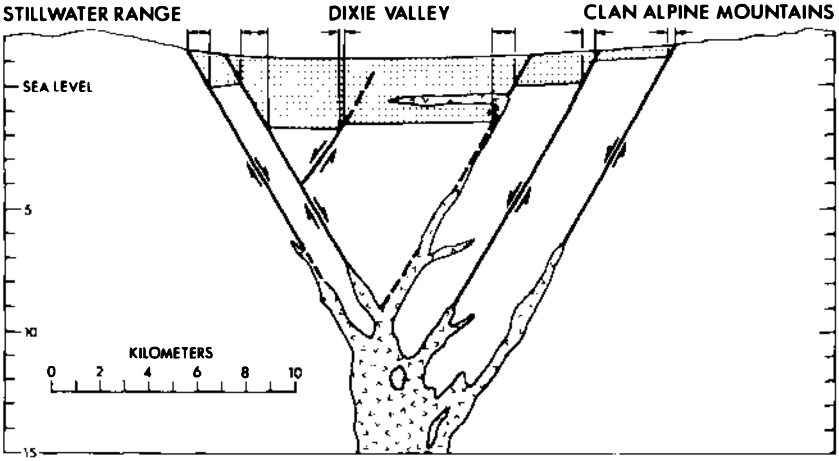


Figure 16 Cross section of Dixie Valley, Nevada. The subsurface structure to the depth of the sedimentary fill (stippled) is based on geophysical exploration. Dike at depth is hypothesized to accommodate surface extension, as shown by arrows (based on Burke, 8; Thompson, 76).

although more conservatively contoured, contains important additional details. One cluster of consistently high values (mostly above 3 HFU), the "Battle Mountain high" in northern Nevada, is interpreted as a transient effect of fairly recent crustal intrusion. To the south in Nevada, a cluster of values less than 1.5 HFU, the "Eureka low," is thought to be the result of unusual deep circulation of ground water. These examples emphasize the importance of nonconductive heat transfer. We point out that spreading of the grabens may be accompanied by intrusion of dikes at depths of a few kilometers (Thompson, 76), and these intrusions may be important in the heat transfer (Figure 16). The Battle Mountain high is on the projection of the active zone of spreading (historic fault breaks) at its north end (Figure 11).

The thermal transition to the Sierra Nevada may occur within a lateral distance of only 10 or 20 km (Sass et al, 63). If this proves to be the case, it will require shallow heat sources and will strengthen the hypothesis of intrusions beneath the grabens. Furthermore, present evidence suggests that the heat flow boundary with the Sierra Nevada follows in detail the irregular boundary of the normal faulting and not the generalized physiographic or topographic boundary.

Heat Production and the Linear Heat Flow Relation

A surprising and remarkably simple relationship has been found between heat flow and the heat production of surface rocks in plutonic areas; that is, within areas such as the Sierra Nevada and Basin and Range province, the heat flow varies linearly with the radioactive heat production at the surface (Roy et al, 60). This relationship is best explained by an exponential decrease of heat production with depth in the crust, combined with an additional flow of heat from the mantle (Lachenbruch, 41). The flow from the mantle—called the reduced heat flow—amounts to 1.4 ± 0.2 HFU in the Basin and Range province, compared to 0.8 ± 0.1 HFU in the United States east of the Rocky Mountains and only 0.4 HFU in the Sierra Nevada (Roy et al, 60).

Crustal temperature profiles for the three heat-flow provinces have been calculated by Lachenbruch (41), based on the exponential model. Temperatures at a depth of 30 km in the Basin and Range province range from 700–1000°C (depending on surface heat flow or heat production), as compared to 400–600°C in eastern United States. Temperatures in the Basin-Range crust may thus reach the melting range for granite, and temperatures in the upper mantle may reach melting for basalt. These high temperatures, combined with widespread late Cenozoic volcanism, form a basis for the generally accepted hypothesis that partial melting is responsible for the thin lithosphere and for the shallow, accentuated low velocity zone (asthenosphere) of the Basin and Range province.

The conductive model will need to be modified if much heat is carried into the crust by intrusions beneath spreading centers, as we have suggested (Figure 16).

Hot-spots and Mantle Plumes?

The Yellowstone volcanic region in northwestern Wyoming may represent a hot-spot above an upwelling convective plume in the mantle (Morgan, 49). According to Morgan's theory the North American lithosphere as a whole is moving west-southwest with respect to the mantle. The trail of the persistent Yellowstone hot-spot across its mantle plume would be marked by the older volcanics west-southwest of Yellowstone (in the Snake River part of the Columbia Plateau province). Other possible hot-spots have been suggested within the Basin and Range province.

A significant point about the theory should be kept in mind regarding the origin of the fault-block structures. If the Yellowstone plume is a driving mechanism for the structures and the lithosphere is moving westward across it, the locus of Basin-Range tectonic activity should be migrating eastward; and we know of no strong evidence for an eastward march of tectonic activity. Westward movement of the lithosphere at a rate on the order of 1 cm/yr would have produced a movement of 150 km in the 15 m.y. since the inception of Basin-Range faulting.

MAGNETIC AND ELECTRICAL ANOMALIES

Anomalies in the regional magnetic field and in electrical conductivity generally support other evidence of a hot upper mantle in the Basin and Range province, but the resolution of lateral variations has so far been very limited.

Zietz (88) showed that from the Sierra Nevada to the Rocky Mountains, magnetic anomalies are subdued in amplitude, and that long-wavelength anomalies are absent. This fact suggests that the lower crust and mantle may be above the Curie temperature (578° for magnetite). Surprisingly, the magnetic field over the Colorado Plateau does not appear to differ significantly from that over the Basin and Range province, in contrast to results from other kinds of studies.

Porath & Gough (53) explored variations in mantle electrical conductivity from the eastern and southern Basin and Range province to the Great Plains by measuring geomagnetic fluctuations. The anomalies are well represented by variations in depth to a half-space of conductivity 0.2 $(\text{ohm m})^{-1}$. The top of this conductor is inferred to correspond approximately with the 1500° isotherm. Depths to the surface of the conductor are 190 km under the Basin and Range province and 350 km under the Colorado Plateau, with a ridge of depth 120 km at the boundary. The depth under the Rio Grande trough is 120 km, that under the southern Rocky Mountains is 150 km, and that under the Great Plains is 350 km. Although such models are naturally not unique, they strengthen the interpretations of regional heat-flow variations and add another dimension to the unusual properties of the Basin and Range province.

PETROLOGIC RELATIONS

Three important relationships among the rocks deserve special emphasis:

1. Prior to Basin and Range faulting, lower and middle Cenozoic volcanoes erupted largely intermediate-composition rocks that become more alkalic toward the continental interior (Lipman et al, 43). This pattern is similar to volcanics now being erupted around the Pacific margin in association with convergent plate margins.

2. A major change to fundamentally basaltic volcanism (including bimodal mafic-silicic associations) took place during late Cenozoic time at about the inception of Basin-Range faulting (Christiansen & Lipman, 12). The transition to this new volcanism began in the southeastern part of the region and moved northwestward. The time of transition may be correlated with the initial intersection of the East Pacific Rise with the continental-margin trench system, an intersection which Atwater (5) also interprets as having progressed northwestward.

3. The composition of the crust and upper mantle as it existed beneath the Colorado Plateau prior to Basin-Range faulting has been ingeniously reconstructed from crystalline rock fragments in a breccia-filled diatreme, which is about 30 m.y. old (McGetchin & Silver, 45). The crust contained about 31% intermediate and acidic igneous rocks, 66% basic metaigneous rocks, and 3% eclogite. The upper mantle to a depth of about 100 km contained about 75% peridotite and pyroxenite and 25% eclogite. It is especially interesting that the mantle 30 m.y. ago contained this much eclogite, because eclogite is capable of converting into gabbro with a volume expansion of about 10% in response to a rise in temperature or decrease in pressure.

Eclogite may be a key to an understanding of late Cenozoic uplift of the broad region that includes the Sierra Nevada, Basin and Range province, and Colorado Plateau. The expansion of eclogite in only 60 km of mantle could produce an uplift of 1.5 km (60 × 25% × 10%). The former eclogite may now be represented by gabbro dispersed in the mantle low velocity zone, or by crustal additions of basic metaigneous rock, or by basaltic volcanics.

SYNTHESIS AND TECTONIC MODEL

The regional geophysical data put many useful constraints on speculations about the fundamental tectonic processes of the Basin and Range province. Among these data the heat flow is central; the volcanism, thin crust, low mantle velocity, accentuated low velocity zone, generally high elevation, subdued magnetic anomalies, high electrical conductivity, and great breadth of the seismically active zone can logically be associated with high temperatures and high heat flow.

The gravity data—coupled with the estimated extension—supply an interesting constraint that does not seem to have been widely recognized (Thompson, 77). If a 30 km crustal plate were simply attenuated by a horizontal extension of 10%, a negative isostatic anomaly of more than 300 mgal would be produced. If the attenuated plate were only 10 km thick the anomaly would still be 100 mgal. Because the regional isostatic anomalies average no more than about 10 mgal, the gravity emphatically indicates that the circuits of mass flow must be closed. Near-surface crustal spreading is almost perfectly matched by lateral backflow in the mantle.

If we imagine a vertical fence surrounding the Basin and Range province and extending through the crust and mantle, the integrated flux of mass through the fence must be zero, despite the outward flow by extension in the upper crust. We now need to find out how the deep lateral inflow takes place. Is the lateral flow in the low velocity zone? Is it a deeper mantle flow associated with narrow upwelling convective plumes, analogous to a thunderhead in the atmosphere? Is the flow related to former subduction of an oceanic lithospheric plate at the continental margin? At present these questions lead rather quickly into speculation.

The regional geophysical characteristics, geologic history, and petrology rather strongly suggest a link with plate-tectonic interactions at the western edge of the continent going back to early Cenozoic time. Analogies with spreading marginal basins of the western Pacific are especially promising (Karig, 40; Matsuda & Uyeda, 47; Scholz et al, 64; Sleep & Toksöz, 68; Thompson, 77; Uyeda & Miyashiro, 80).

The general idea is that in a broad belt on the continental side of an arc-trench system, a descending lithospheric plate either generates magma along its upper surface or creates a convecting subcell by viscous drag. The rising magma or convection current helps to move the arc away from the continent, creating a spreading marginal basin. The situation is somewhat different along the central coast of North America in that subduction ceased when a spreading ridge reached the trench in middle Cenozoic time. But because the descending young lithosphere would still be very hot when the ridge reached the trench, and because conductive heat transfer is very slow, it is easy to imagine that the thermal effects of a past subduction process are still being felt in the Basin and Range province.

ACKNOWLEDGMENTS

We thank David Warren for allowing us to use his unpublished map of crustal thickness[1]; John Lahr and Peter Stevenson for their map of earthquake epicenters; and Kimberly Bailey, James Baxter, Robert Daniel, Allan Lindh, Dohn K. Riley, Don C. Riley, and Donald Steeples for stimulating discussions in a seminar which ranged widely over many of the topics discussed here.

Literature Cited

1. Aldrich, L. T. et al 1960. The earth's crust. *Carnegie Inst. Washington Yearb.* 1959–1960: 202–8
2. Archambeau, C. B., Flinn, E. A., Lambert, D. G. 1969. Fine structure of the upper mantle. *J. Geophys. Res.* 74: 5825–65
3. Armstrong, R. L. 1972. Low-angle (denudation) faults, hinterland of the Sevier orogenic belt, eastern Nevada and western Utah. *Geol. Soc. Am. Bull.* 83: 1729–54
4. Asada, T. et al 1961. See Ref. 1, 1960–1961: 244–50
5. Atwater, T. 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *Geol. Soc. Am. Bull.* 81: 3513–36
6. Berg, J. W., Cook, K. L., Narans, H. D., Dolan, W. M. 1960. Seismic investigation of crustal structure in the eastern part of the Basin and Range province. *Seismol. Soc. Am. Bull.* 50: 511–36
7. Berg, J. W. et al 1966. Crustal refraction profile, Oregon Coast Range. *Seismol. Soc. Am. Bull.* 56: 1357–62
8. Burke, D. B. 1967. Aerial photograph survey of Dixie Valley, Nevada. In *Geophysical study of Basin-Range structure, Dixie Valley region, Nevada.* US Air Force Cambridge Res. Lab. Spec. Rep., 66-848
9. Burke, D. B., McKee, E. H. 1973. Mid-Cenozoic volcano-tectonic features in central Nevada. *Geol. Soc. Am. Abstr. with Programs* 5: 18
10. Carder, D. S. 1973. Trans-California seismic profile, Death Valley to Monterey Bay. *Seismol. Soc. Am. Bull.* 63: 571–86
11. Carder, D. S., Qamar, A., McEvilly, T. V. 1970. Trans-California seismic profile, Pahute Mesa to San Francisco Bay. *Seismol. Soc. Am. Bull.* 60: 1829–46
12. Christiansen, R. L., Lipman, P. W. 1972. Cenozoic volcanism and plate-tectonic evolution of the western United States. II Late Cenozoic. *Phil. Trans. Roy. Soc. London Ser. A* 271: 249–84
13. Cook, K. L. 1969. Active rift system in the Basin and Range province. *Tectonophysics* 8: 469–511
14. Crittenden, M. D. Jr. 1963. Effective viscosity of the earth derived from isostatic loading of Pleistocene Lake Bonneville. *J. Geophys. Res.* 68: 5517–30
15. Crowder, D. F., McKee, E. H., Ross, D. C., Krauskopf, K. B. 1973. Granitic rocks of the White Mountains area, California-Nevada: age and regional significance. *Geol. Soc. Am. Bull.* 84: 285–96
16. Diment, W. H., Stewart, S. W., Roller, J. C. 1961. Crustal structure from the Nevada Test Site to Kingman, Arizona, from seismic and gravity observations. *J. Geophys. Res.* 66: 201–14
17. Donath, F. A. 1962. Analysis of Basin-Range structure, south-central Oregon. *Geol. Soc. Am. Bull.* 73: 1–16
18. Duffield, W. A. 1972. A naturally occurring model of global plate tectonics. *J. Geophys. Res.* 77: 2543–55
19. Eaton, J. P. 1963. Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic-refraction measurements. *J. Geophys. Res.* 68: 5789–5806
20. Eaton, J. P. 1966. Crustal structure in northern and central California from seismic evidence. In Geology of northern California, ed. E. H. Bailey. *Calif. Div. Mines Geol. Bull., 190,* 419–26
21. Fenneman, N. M. 1946. Physical divisions of the United States. *US Geol. Surv. Map* (1:7,000,000 scale)
22. Gibbs, J. F., Roller, J. C. 1966. Crustal structure determined by seismic-refraction measurements between the Nevada Test Site and Ludlow, Cali-

---

[1] Warren, D. H., Healy, J. H. Structure of the crust in the conterminous United States. *Tectonophysics*. In press.

fornia. *US Geol. Surv. Prof. Pap. 550-D,* D125–31

23. Gilbert, G. K. 1874. *US Geogr. Geol. Surv. W. 100th Meridian Progr. Rep.*
24. Gilbert, G. K. 1875. *US Geogr. Geol. Surv. W. 100th Meridian,* Rep. 3
25. Gilbert, G. K. 1890. Lake Bonneville. *US Geol. Surv. Monogr. 1,* 438 pp.
26. Gilluly, J. 1963. The tectonic evolution of the western United States. *Quart. J. Geol. Soc. London* 119:133–74
27. Gilluly, J. 1970. Crustal deformation in the western United States. In *The Megatectonics of Continents and Oceans,* ed. H. Johnson, B. L. Smith, 47–73. New Jersey: Rutgers Univ. Press
28. Gilluly, J. 1972. Tectonics involved in the evolution of mountain ranges. In *The Nature of the Solid Earth,* ed. E. Robertson, 406–39. New York: McGraw. 677 pp.
29. Hamilton, W., Myers, W. B. 1966. Cenozoic tectonics of the western United States. *Rev. Geophys.* 4:509–49
30. Healy, J. H. 1963. Crustal structure along the coast of California from seismic-refraction measurements. *J. Geophys. Res.* 68:5777–87
31. Helmberger, D. V. 1972. Long period body wave propagation from 4° to 13°. *Seismol. Soc. Am. Bull.* 62:325–41
32. Herrin, E. 1972. A comparative study of upper mantle models: Canadian Shield and Basin and Range province. See Ref. 28, 216–34
33. Herrin, E., Taggart, J. 1962. Regional variations in *Pn* velocity and their effect on the location of epicenters. *Seismol. Soc. Am. Bull.* 52:1037–46
34. Hill, D. P. 1963. Gravity and crustal structure in the western Snake River Plain, Idaho. *J. Geophys. Res.* 68:5807–19
35. Hill, D. P., Pakiser, L. C. 1966. Crustal structure between the Nevada Test Site and Boise, Idaho, from seismic-refraction measurements. In the earth beneath the continents, ed. J. S. Steinhart, T. J. Smith. *Geophys. Monogr. 10,* Am. Geophys. Union, Washington DC, 391–419
36. Jackson, W. H., Pakiser, L. C. 1965. Seismic study of crustal structure in the southern Rocky Mountains. In Geological Survey Research 1965. *US Geol. Surv. Prof. Pap. 525-D,* D85–92
37. Jackson, W. H., Stewart, S. W., Pakiser, L. C. 1963. Crustal structure in eastern Colorado from seismic-refraction measurements. *J. Geophys. Res.* 68:5767–76
38. Johnson, L. R. 1965. Crustal structure between Lake Mead, Nevada, and Mono Lake, California. *J. Geophys. Res.* 70:2863–72
39. Johnson, S. H., Couch, R. W. 1970. Crustal structure in the North Cascade Mountains of Washington and British Columbia from seismic refraction measurements. *Seismol. Soc. Am. Bull.* 60:1259–69
40. Karig, D. E. 1971. Origin and development of marginal basins in the western Pacific. *J. Geophys. Res.* 71:2542–61
41. Lachenbruch, A. H. 1970. Crustal temperature and heat production: implications of the linear heat-flow relation. *J. Geophys. Res.* 75:3291–3300
42. Lachenbruch, A. H., Thompson, G. A. 1972. Oceanic ridges and transform faults: their intersection angles and resistance to plate motion. *Earth Planet. Sci. Lett.* 15:116–22
43. Lipman, P. W., Prostka, H. J., Christiansen, R. L. 1972. Cenozoic volcanism and plate-tectonic evolution of the western United States. I. Early and middle Cenozoic. *Phil. Trans. Roy. Soc. London Ser. A* 271:217–48
44. McCamy, K., Meyer, R. P. 1964. A correlation method of apparent velocity measurement. *J. Geophys. Res.* 69:691–99
45. McGetchin, T. R., Silver, L. T. 1972. A crustal-upper mantle model for the Colorado Plateau based on observations of crystalline rock fragments in the Moses Rock dike. *J. Geophys. Res.* 77:7022–37
46. McKee, E. H. 1971. Tertiary igneous chronology of the Great Basin of western United States—implications for tectonic models. *Geol. Soc. Am. Bull.* 82:3497–3502
47. Matsuda, T., Uyeda, S. 1971. On the Pacific-type orogeny and its model—extension of the paired belts concept and possible origin of marginal seas. *Tectonophysics* 11:5–27
48. Moore, J. G. 1960. Curvature of normal faults in the Basin and Range province of the western United States. In Geological Survey Research, 1960. *US Geol. Surv. Prof. Pap. 400-B.* B409–11
49. Morgan, W. J. 1972. Deep mantle convection plumes and plate motions. *Am. Assoc. Petrol. Geol. Bull.* 56:203–13
50. Noble, D. C. 1972. Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, western United States. *Earth Planet. Sci. Lett.* 17:142–50
51. Oldenburg, D. W., Brune, J. N. 1972. Ridge transform fault spreading in freezing wax. *Science* 178:301–4
52. Pakiser, L. C. 1963. Structure of the crust

and upper mantle in the western United States. *J. Geophys. Res.* 68:5747–56

53. Porath, H., Gough, D. I. 1971. Mantle conductive structures in the western United States from magnetometer array studies. *Geophys. J. Roy. Astron. Soc.* 22:261–75
54. Press, F. 1960. Crustal structures in the California-Nevada region. *J. Geophys. Res.* 65:1809–14
55. Prodehl, C. 1970. Crustal structure of the western United States from seismic-refraction measurements in comparison with central European results. *Z. Geophys.* 36:477–500
56. Robinson, R., Kovach, R. L. 1972. Shear wave velocities in the earth's mantle. *Phys. Earth Planet. Interiors* 5:30–44
57. Roller, J. C. 1964. Crustal structure in the vicinity of Las Vegas, Nevada, from seismic and gravity observations. *US Geol. Surv. Prof. Pap. 475-D.* D108–11
58. Roller, J. C. 1965. Crustal structure in the eastern Colorado Plateaus province from seismic-refraction measurements. *Seismol. Soc. Am. Bull.* 55:107–19
59. Roller, J. C., Healy, J. H. 1963. Seismic-refraction measurements of crustal structure between Santa Monica Bay and Lake Mead. *J. Geophys. Res.* 68:5837–48
60. Roy, R. F., Blackwell, D. D., Decker, E. R. 1972. Continental heat flow. In *The Nature of the Solid Earth*, ed. E. Robertson, 506–43. New York: McGraw. 677 pp.
61. Ryall, A., Slemmons, D. B., Gedney, L. D. 1966. Seismicity, tectonism, and surface faulting in the western United States during historic time. *Seismol. Soc. Am. Bull.* 56:1105–36
62. Ryall, A., Stuart, D. J. 1963. Travel times and amplitudes from nuclear explosions, Nevada Test Site to Ordway, Colorado. *J. Geophys. Res.* 68:5821–35
63. Sass, J. H., Lachenbruch, A. H., Monroe, R. J., Greene, G. W., Moses, T. H. Jr. 1971. Heat flow in the western United States. *J. Geophys. Res.* 76:6376–6413
64. Scholz, C. H., Barazangi, M., Sbar, M. L. 1971. Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin. *Geol. Soc. Am. Bull.* 82:2979–90
65. Sclater, J. G., Francheteau, T. 1970. The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth. *Geophys. J. Roy. Astron. Soc.* 20:509–42
66. Shor, G. G. Jr. 1955. Deep reflections from southern California blasts. *Trans. Am. Geophys. Union* 36:133–138
67. Shor, G. G., Raitt, R. W. 1958. Seismic studies in the southern California continental borderland. In *Tomo 2 Geof. Aplicada: Int. Geol. Congr. 20th., Mexico, D. F., 1956 (Trabajos), Sect. 9*, 243–59
68. Sleep, N. H., Toksöz, M. N. 1971. Evolution of marginal basins. *Nature* 233:548–50
69. Slemmons, D. B. 1967. Pliocene and Quarternary crustal movements of the Basin and Range province, USA. *J. Geosci. Osaka City Univ.* 10:91–103
70. Steinhart, J. S., Meyer, R. P. 1961. Explosion studies of continental structure. Univ. of Wisconsin, 1956–1959. *Carnegie Inst. Wash. Publ. 622.* 409 pp.
71. Stewart, J. H. 1971. Basin and Range structure: a system of horsts and grabens produced by deep-seated extension. *Geol. Soc. Am. Bull.* 82:1019–44
72. Stewart, S. W. 1968. Preliminary comparison of seismic travel times and inferred crustal structure adjacent to the San Andreas fault in the Diablo and Gabilan Ranges of central California. In *Proc. Conf. Geol. Prob. San Andreas Fault System*, ed. W. R. Dickinson, A. Grantz, 218–30. Stanford, California: Stanford Univ.
73. Stewart, S. W., Pakiser, L. C. 1962. Crustal structure in eastern New Mexico interpreted from the GNOME explosion. *Seismol. Soc. Am. Bull.* 52:1017–30
74. Tatel, H. E., Tuve, M. A. 1955. Seismic exploration of a continental crust. *Geol. Soc. Am. Spec. Pap.* 62:35–50
75. Thompson, G. A. 1959. Gravity measurements between Hazen and Austin, Nevada, a study of Basin-Range structure. *J. Geophys. Res.* 64:217–30
76. Thompson, G. A. 1966. The rift system of the western United States. In The world rift system, ed. T. N. Irvine. *Geol. Surv. Can. Dep. Mines Tech. Surv. Pap.* 66-14:280–90
77. Thompson, G. A. 1971. Cenozoic Basin Range tectonism in relation to deep structure. *Geol. Soc. Am. Abstr.* 3(2): 209. 1972 *Proc. Int. Geol. Congr., 24th Sect.* 3:84–90
78. Thompson, G. A., Burke, D. B. 1973. Rate and direction of spreading in Dixie Valley, Basin and Range province, Nevada. *Geol. Soc. Am. Bull.* 84:627–32
79. Thompson, G. A., Talwani, M. 1964. Crustal structure from Pacific basin to central Nevada. *J. Geophys. Res.* 68:4813–37

80. Uyeda, S., Miyashiro, A. Plate tectonics and Japanese Islands. Unpublished
81. Walcott, R. I. 1970. Flexural rigidity, thickness and viscosity of the lithosphere. *J. Geophys. Res.* 75:3941–54
82. Warren, D. H. 1969. A seismic-refraction survey of crustal structure in central Arizona. *Geol. Soc. Am. Bull.* 80:257–82
83. Warren, D. H., Healy, J. H., Bohn, J., Marshall, P. A. 1973. Crustal structure under LASA from seismic refraction measurements. *J. Geophys. Res.* 78:8721–34
84. Warren, D. H., Jackson, W. H. 1968. Surface seismic measurements of the project GASBUGGY explosion at intermediate distance ranges. *US Geol. Surv. Open File Rep.* 45 pp.
85. Willden, R. 1965. Seismic-refraction measurements of crustal structure between American Falls Reservoir, Idaho, and Flaming Gorge Reservoir, Utah, *US Geol. Surv. Prof. Pap. 525-C.* C44–50
86. Woollard, G. P. 1972. Regional variations in gravity. See Ref. 28, 463–505
87. York, J. E., Helmberger, D. V. 1973. Low-velocity zone variations in the southwestern United States. *J. Geophys. Res.* 78:1883–86
88. Zietz, I. 1969. Aeromagnetic investigations of the earth's crust in the United States. In The Earth's Crust and Upper Mantle, ed. P. J. Hart, 404-15, *Am. Geophys. Union Monogr. 13.* 735 pp.

CONTENTS