Geology of the Crust and Mantle, Western United States

Geophysical data reveal a thin crust and anomalous upper mantle characteristic of active regions.

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Even today young school children sometimes learn that the earth's surface relief—its continents and plateaus and mountain ranges—came into being when the outer skin of the earth wrinkled as it cooled and contracted soon after the formation of the globe. This appealing analogy with a shriveled apple is wrong on many counts, but especially as to the time of formation of surface relief, for mountain ranges are rapidly *destroyed* by erosion (in the scale of geologic time), and their origin is a dynamic problem of the present as well as the past. High mountains exist today only where earth movements are active now or have been in the recent geologic past. The mountains of California and Nevada are part of an unusually active belt surrounding the Pacific Ocean, a belt in which most of the total earthquake energy of the earth is released.

The causes and mechanisms of diastrophism—mountain building—are far from fully understood. The movements originate in the crust and mantle of the earth. "Crust" comes from the early misconception that solid rock is underlain by molten lava, but the crust is now defined as the complex outer layer of rocks, generally 20 to 50 kilometers thick in the continents, in which longitudinal elastic waves from explosions and earthquakes travel at a velocity of less than about 7.2 kilometers per second. Below the crust and, usually separated from it by a discontinuity in velocity (the Mohorovičić discontinuity) is the earth's upper mantle; it is composed of rocks which are denser, have a higher longitudinal wave velocity (generally 7.8 to 8.2 km/sec), probably contain a larger percentage of iron and magnesium silicates, and are probably more like stony meteorites than the rocks of the crust. The mantle extends halfway to the center of the earth, where it overlies a core assumed to be metallic; the outer part of the core is believed to be liquid because it does not transmit transverse elastic waves. That the rocks of the crust and mantle are completely solid, except for small pockets of magma, is shown by their ability to transmit transverse elastic waves. However, many lines of evidence, including extensive laboratory experiments, show that rocks become progressively less brittle, more ductile, and more subject to creeping flow with increasing depth. The change in rheological properties is gradual and appears to be independent of the contrast in seismic velocities at the Mohorovičić discontinuity.

The energy of earthquakes and volcanoes is of internal origin. Heat flows out of the interior of the earth and is radiated off into space at the rate of 10^{28} ergs per year (*1*). The energy of earthquakes is only 10^{25} ergs per year, and that of volcanism only 10^{26} ergs per year. Although these figures have a considerable range of uncertainty, they indicate that thermal energy sources are probably adequate to account for the more spectacular phenomena. The internal heat comes largely from radioactive decay of uranium, thorium, and potassium in rocks. Energy from gravitational compaction of the earth and from changes in rotation may be added to radiogenic energy, but the latter appears to be adequate by itself. Some continental crustal rocks, in fact, contain a surfeit of radioactive heat sources, indicating that such rocks cannot extend to depths of more than about 30 kilometers. The chief uncertainty is in the content of radioactive elements in the mantle, which must be estimated from measurements on what are thought to be samples of the mantle carried to the surface in volcanoes or in the exposed former roots of mountain belts. The radioactivity of stony meteorites, which possibly resemble primitive mantle material, provides another clue. But the critical experiment—direct sampling of the mantle by drilling to the Mohorovičić discontinuity—has not yet been performed.

If we accept the view that internal heat is adequate as an energy source we must then ask the interesting question, What kind of heat engine, or engines, in the crust-mantle system produces diastrophism? One plausible mechanism is that of creeping thermal convection currents in the plastic mantle. Another is expansion and contraction of rocks by changes in mineral phase at critical conditions of pressure and temperature. For example, the reaction

$$\underset{\text{Garnet}}{CaMg_2Al_2Si_3O_{12}} \rightarrow \underset{\text{Plagioclase}}{CaAl_2Si_2O_8} + \underset{\text{Olivine}}{Mg_2SiO_4}$$

is accompanied by a volume increase of more than 10 percent. But also, why are some regions so much more active tectonically than other regions? Despite much research and speculation, these are questions about which little is known. Progress toward answering them will depend partly on geophysical exploration of the crust-mantle system in various regions. In this article we report progress in one region, along a section crossing the continental margin in California.

Structural Provinces

The section chosen for study crosses the continental slope and shelf, the California Coast Ranges, the Great Valley, the Sierra Nevada, and the western part of the Basin and Range province (Fig. 1). At the profound boundary between ocean basin and continent, the floor of the ocean rises from a depth of 3.7 kilometers to the shallow continental shelf in a distance of only 80 kilometers. The foot of the slope west of San Francisco is marked by two small seamounts of basalt, the characteristic volcanic rock of the ocean basins. At the top of the slope

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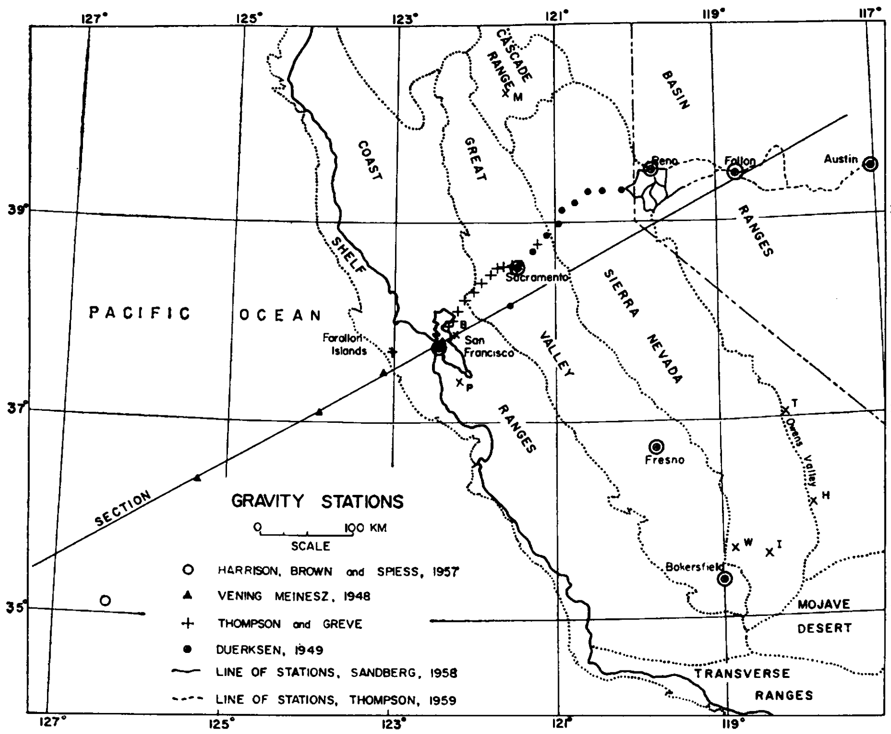


Fig. 1. Location of the section studied, relative to structural provinces. Details of the gravity data are given elsewhere (*18*). The letters identify seismic observatories: *B*, Berkeley; *P*, Palo Alto; *M*, Mineral; *W*, Woody; *I*, Isabella; *T*, Tinemaha; *H*, Haiwee.

(the outer edge of the continental shelf) the Farallon Islands jut out of the sea; they are composed of granitic rock, characteristic of continents. A major mystery of the continental slope is that it cuts discordantly across major structures of the Coast Ranges, which trend obliquely into the edge of the continent.

The Coast Ranges are a young and active mountain belt, as shown by frequent earthquakes, tilted shorelines, and deformed rocks of Pliocene and Pleistocene age. The famous San Andreas fault, which extends longitudinally through the Coast Ranges, cuts these rocks and the underlying consolidated rocks of the basement. Miles of horizontal sliding along this vertical break and its branches have brought granitic and metamorphic rocks on the west side against marine sedimentary-volcanic (eugeosynclinal) rocks of the Mesozoic Franciscan Formation on the east side. The Franciscan rocks, although too deformed for accurate measurement, are probably more than 15 kilometers thick (*2*); they may have been deposited directly on a thin oceanic crust. Farther east, at about the same time, marine shelf or slope sediments were accumulating in the area of the Great Valley (*3*). They evidently mark the approximate edge of the continent in late Mesozoic time.

In contrast with the intricately folded and faulted Coast Ranges, the Sierra Nevada consists primarily of a great block tilted about 2 degrees westward. Throughout much of its length the range is sharply bounded on the east by a magnificent escarpment caused by normal faulting and warping (Fig. 2), which are still active. It is important to remember that the Sierra Nevada block is only a fragment, shaped in Cenozoic time, of a more extensive earlier eugeosynclinal and granitic terrane. Sediments accumulating in the Paleozoic and Mesozoic Cordilleran eugeosyncline were possibly initially laid down on a thin oceanic crust, while miogeosynclinal sediments accumulated in eastern Nevada and in Utah. Thus the evidence suggests a westward growth of the continent from central Nevada to the Great Valley and finally to its present position.

The enormous volume of granitic rocks in the Sierran highland region (Sierra Nevada and western Basin Ranges) was emplaced in Cretaceous and Jurassic times (*4*). Paleozoic and Mesozoic strata on opposite sides of the highland dip steeply into the granitic core (*4*); they seem to represent a great crustal downfold, in the trough of which plutonic rocks were generated by metamorphism and melting of sedimentary rocks. Can this be the upper part of a "root" of thickened crustal rocks that supports the entire Sierran highland region in isostatic (buoyant) balance? Recent geophysical evidence supports this interpretation in preference to the theory of a narrower root beneath the Sierra Nevada.

Fig. 2. Sierran escarpment, looking west across Owens Valley and Owens Lake. The escarpment is the uplifted and eroded edge of a broad westward-tilted block, which is separated from the valley block in the foreground by a normal fault. [Courtesy of Roland von Huene]

Two types of Sierran rocks produce large anomalies in the gravitational field: the granitic rocks, which have a density (average, about 2.67 g/cm^3) lower than the crustal average, and metamorphosed volcanic rocks (interstratified with eugeosynclinal sediments), which have a high density (average, about 2.92 g/cm^3). These volcanic and other associated igneous rocks constitute the "greenstone belt" of the western Sierra (Fig. 3); concealed beneath younger sediments, the belt extends west of Sacramento and south through Fresno and Bakersfield.

Like the Sierra Nevada, the Basin Ranges resulted from Cenozoic block faulting and warping, which are still in progress. In the Basin and Range province the breaking up of the crust was intricate, and in its details this implies a considerable lateral extension of the region. Uplift of the whole area seems to have taken place during the same period as the breaking up and jostling of individual blocks.

Geophysical Data

Observations of longitudinal seismic waves, measurements of gravity, and studies of dispersion of seismic surface waves all bear directly on the problem of crust and mantle structure. Magnetic and heat-flow measurements, a wealth of geologic studies, and a variety of experimental data on rocks provide additional information. While it is obvious that the different kinds of data should supplement each other, it is not obvious how, in practice, one can decipher a single solution from the different lines of evidence; in fact, published interpretations from one field of study often conflict with those from another. Gravity and seismic observations set the principal boundaries to speculation about the regional structure of the crust and upper mantle. These two lines of investigation complement each other in a remarkable, but sometimes poorly appreciated, manner: gravity data record uniquely the sum effect of all the parts of a structure, whereas refraction seismology records some of the parts in detail but generally omits others. The approach we take is to start with well-determined portions of the seismic refraction structure, add to and modify them to fit the gravity data, and test the results against surface wave dispersion. The product is still incomplete or incorrect unless it is in accord with the other lines of evidence. Although the interpretation presented here is in approximate accord with the various lines of evidence, it is admittedly crude and subject to much future modification as better evidence is obtained.

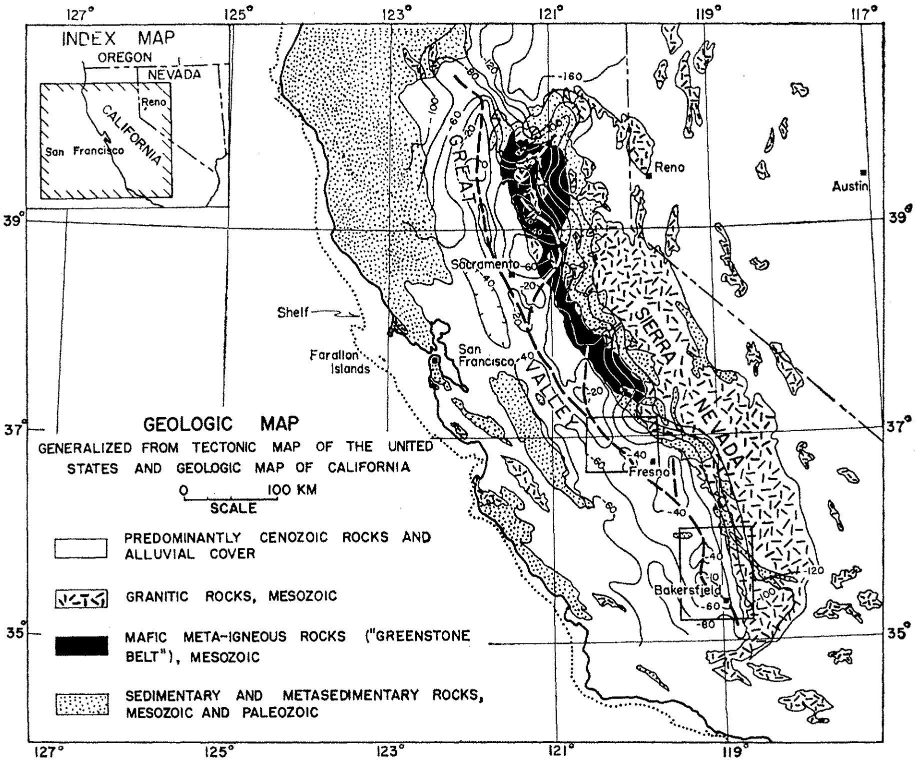


Fig. 3. Generalized geological map. Contours of Bouguer gravity anomaly are shown in the Great Valley and western Sierra Nevada. [These contours are reproduced from *International Gravity Measurements* (*17*) with the permission of the Society of Exploration Geophysicists and G. P. Woollard.] The heavy dashed line marks the axis of the gravity maximum. Rectangles at Fresno and Bakersfield outline areas of extensive drilling to basement (*18*).

In the last few years, seismic refraction evidence has accumulated which indicates that the crust and upper mantle in the western United States have a structure different from what had been hitherto considered normal continental structure. Instead of a crust

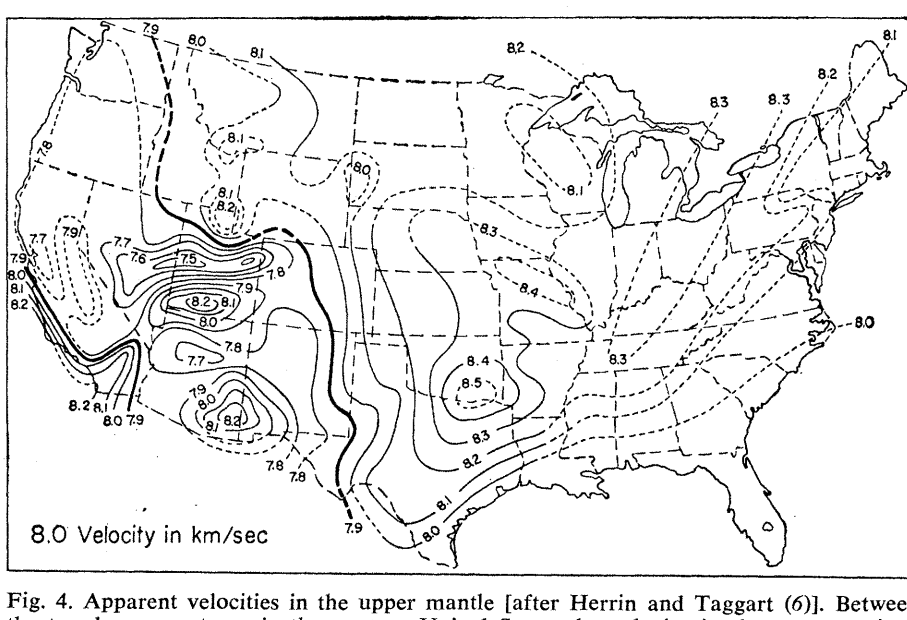
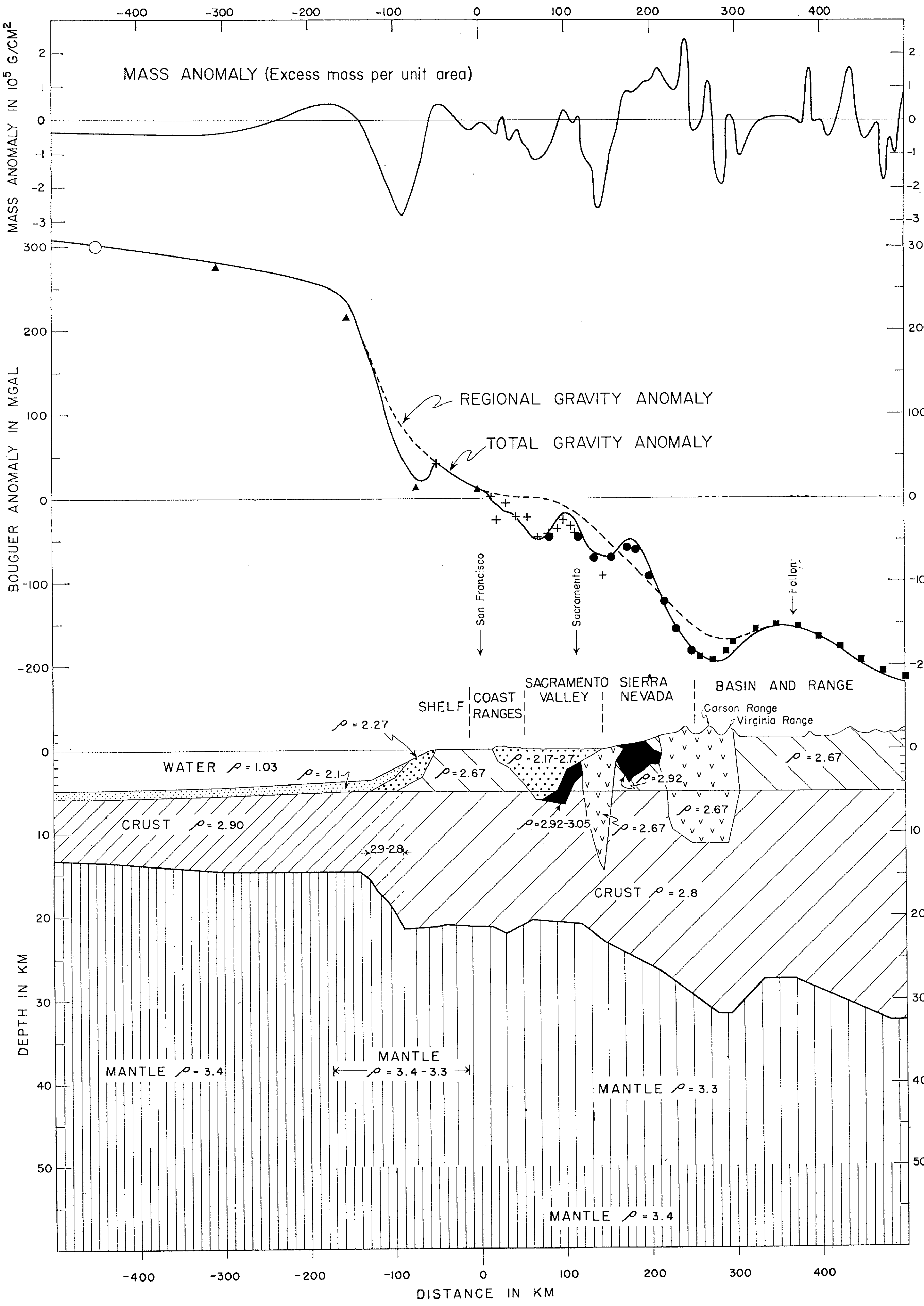


Fig. 4. Apparent velocities in the upper mantle [after Herrin and Taggart (*6*)]. Between the two heavy contours in the western United States the velocity is almost everywhere 7.9 kilometers per second, or less.


MASS ANOMALY (Excess mass per unit area)
MASS ANOMALY IN 10^5 G/CM^2
BOUGUER ANOMALY IN MGAL
REGIONAL GRAVITY ANOMALY
TOTAL GRAVITY ANOMALY
San Francisco
Sacramento
Fallon
SHELF
COAST RANGES
SACRAMENTO VALLEY
SIERRA NEVADA
BASIN AND RANGE
Carson Range
Virginia Range
WATER ρ = 1.03
ρ = 2.27
ρ = 2.1
ρ = 2.67
ρ = 2.17-2.7
ρ = 2.92
ρ = 2.92-3.05
CRUST ρ = 2.90
2.9-2.8
CRUST ρ = 2.8
MANTLE ρ = 3.4
MANTLE ρ = 3.4-3.3
MANTLE ρ = 3.3
DEPTH IN KM
DISTANCE IN KM

approximately 35 kilometers thick with seismic velocities from about 6.0 to 7.2 kilometers per second, overlying a mantle of velocity 8.0 to 8.2 kilometers per second, a crust approximately two-thirds the normal thickness has been found overlying a mantle of anomalously low velocity (*5*). As this "anomalous upper mantle" has properties between those of the normal crust and the normal mantle, it has sometimes been assigned alternatively to the crust; this assignment leads to a confusion in terms, but in the area under study the properties are clearly closer to those of the mantle. A regional study of the anomalous upper mantle was made by Herrin and Taggart (*6*), who utilized travel times both from explosions and from earthquakes (Fig. 4). Seismic refraction work by Pakiser and his co-workers has firmly established the broad picture of a thin crust and anomalous mantle in the western United States and has added many critical details (*7*); of special interest to the study under discussion are the results of Healy (*8*) and Eaton (*9*). Table 1 summarizes these and earlier refraction results for areas near the section chosen for study. It is necessary to keep in mind some limitations of crustal refraction work: (i) structures are averaged over horizontal distances of tens of kilometers, and (ii) a slow increase or decrease in velocity with depth is generally not detectable and may lead to errors in the calculated depth.

The sources and locations of gravity measurements, which are made with pendulums or sensitive spring balances, are shown in Fig. 1. Adjustments are made in the raw measurements to eliminate the effects of varying altitude and of topographic masses, and a normal value of gravity for the latitude of measurement is subtracted. The resulting Bouguer gravity anomaly (named for a pioneering French geodesist) reveals variations in density and total mass below the land surface. The anomaly is plotted in profile across the middle of Fig. 5 [in units of a milligal—an acceleration of a thousandth of a centimeter per second squared, or about a millionth of the gravitational field of the earth]. Other data, for areas to the north and south, show that this profile is representative and therefore that two-dimensional computation can be used in its interpretation. The most remarkable feature of the profile is one that is characteristic of oceans and continents: the anomaly is positive by about 300 milligals over the ocean, close to zero over the land areas near sea level, and negative by about 200 milligals over the higher land. If the rocks underlying these areas were of uniform density, the anomaly would be uniformly zero. The observed pattern thus demands the conclusion that the average density of rocks differs beneath oceans and continents. When analyzed quantitatively it demonstrates also that, despite the differences in density, the total mass per unit area is very nearly the same beneath oceans and continents; that is, the continents and ocean basins are in isostatic equilibrium (as shown by the mass anomaly at the top of Fig. 5). From the steep slope of the gravity anomaly it can be shown that the main density differences extend to depths of only tens of kilometers, for the slope decreases as the depth of sources increases.

Fig. 5 (left). (Bottom area) Section of crust and upper mantle; vertical exaggeration, 10 : 1. (Dot pattern) Sedimentary rocks; (check marks) granitic rocks; (black) greenstone. (Middle area) Gravity anomaly computed from section, compared to observed points. (Top area) Mass anomaly computed from section.

To correlate seismic and gravity data a relation is needed between compressional wave velocity and density. Birch (*10*) demonstrated that compressional wave velocity is determined by two principal variables, density and mean atomic weight. For rock compositions similar to those of common surface rocks we need not consider mean atomic weight and can therefore relate the velocities and densities approximately by the Nafe-Drake empirical curve (*11*).

Rayleigh-wave phase velocities afford an independent means of testing interpretations of crust-mantle structure. Because in a general way the short-period waves in a train of dispersed waves are sensitive to the shallow structure and the longer waves are sensitive to the deeper structure, the phase velocity data, under favorable circumstances, may be highly critical. Observations are available for the San Francisco Bay area (*12*), the Sierra region (*13*), and the Basin and Range region (*14*). These observations are plotted in Fig. 6 and are discussed in connection with the regional structure. A serious problem of interpretation arises because phase velocities are influenced not only by longitudinal wave velocities and densities of layers but also, and more strongly, by transverse wave velocities. As transverse wave velocities have not often been measured in seismic refraction work it is necessary to assume a simple relation (fixed by Poisson's ratio) between longitudinal and transverse wave velocities. We assume a Poisson's ratio of 0.278, an average value based upon several measurements in crustal layers (*15*).

Anomalies in the intensity of the earth's magnetic field also yield information on rocks of the crust and shallow parts of the mantle. The narrow breadth and steep gradients of most anomalies indicate that they do not originate deep in the mantle (*16*). This fact is interpreted to mean that the mantle is too viscous to produce magnetic fields dynamically and, below a depth of about 30 or 40 kilometers, too hot for minerals to retain their ferromagnetic properties (the Curie temperature of pure magnetite is 578°C). Magnetic anomalies on the land (detailed magnetic data have been published for only a small part of the world's land area) are sometimes directly correlatable with data for exposed rock bodies and with gravity observations. Thus the more mafic igneous and metamorphic rocks, such as those in the greenstone belt, are both denser and more magnetic than most rocks; hydrated ultramafic rock (serpentinite) in the greenstone belt is highly magnetic but of low density. The magnetic data of most direct importance to our study are data for the Great Valley, where a large positive magnetic anomaly extends the length of the valley, covering approximately the same area as a large positive gravity anomaly.

Heat-flow measurements made in recent years have demonstrated that the *average* outward flow through ocean bottoms is about the same as the average outward flow through the surface of continents, despite the fact that crustal rocks of the continents have a much larger content of heat-producing radioactive elements. This surprising discovery shows clearly that more heat is coming from the oceanic mantle than from the continental mantle. Interpreted straightforwardly and without regard to sharp local anomalies, the observations suggest that the total radioactivity per unit area is the same under continents and under oceans;

hence, continents are mainly a product of vertical segregation of matter (*1*). Little is yet known of regional and local variations in heat flow in Western North America. Consequently, in using this promising tool for interpreting crust-mantle structure we are at present limited to a rough comparison of oceanic and continental structure.

Interpretation of Local Gravity Anomalies

The variations in the gravity profile shown in the middle portion of Fig. 5 can be divided into local anomalies with breadths of tens of kilometers and regional anomalies with breadths greater than 100 kilometers. Still smaller anomalies of third-order breadth and magnitude have been eliminated from the curves by smoothing. As the local anomalies are of shallow origin, it is convenient to interpret them first.

A negative anomaly amounting to about −50 milligals span the Sacramento Valley and part of the Coast Ranges. Knowledge of the densities and depths of sedimentary rocks in that area, based on drill-hole measurements, allows us to compute the gravitational effect and compare the result with observations (Fig. 7).

The two positive anomalies in the Sacramento Valley and western Sierra Nevada (Fig. 5) are part of a gravity maximum extending the entire length of the Great Valley, a distance of 700 kilometers (*17*). An important key to interpreting them is the association of the eastern anomaly with the greenstone belt of the western Sierra Nevada. The rocks of the greenstone belt are a metamorphosed assemblage characteristic of eugeosynclines: abundant dense volcanic rocks interstratified with marine sedimentary rocks and intruded by lesser amounts of gabbro and serpentine. The average density of the volcanic rock is 2.92 grams per cubic centimeter, and the sizes that bodies of that density would have to be to account for the observed gravity anomalies are shown in Fig. 7. South of the line of section the two anomalies merge and the greenstones are concealed by younger sediments of the Great Valley (Fig. 3), but near Fresno and near Bakersfield many drill holes penetrate the younger sediments and bottom in greenstone near the axis of the gravity anomaly (*18, 19*). A positive magnetic anomaly (*20*) generally follows the axis of the gravity anomaly.

The origin of the gravity and magnetic anomalies has been a persistent problem for a long time, and one or the other of them has been attributed to a gabbro intrusion (*21*), to an isostatic effect of the Sierra Nevada (*22*), to ultramafic rock below the basement surface (*23*), and to rocks in the lower part of the earth's crust, possibly related to rocks of the upper mantle (*24*). But the probable association of the anomalies with the greenstone belt is now evident (*18, 25*). The volcanic belts of other ancient geosynclines can probably be recognized, even where they are deeply concealed, by their gravity and magnetic anomalies. The "midcontinent gravity high"—a remarkable feature on a gravity map of the United States—and a corresponding magnetic high are caused by Precambrian volcanic and intrusive rocks (*26*). Similar associations with positive anomalies are known on the Canadian Shield and elsewhere.

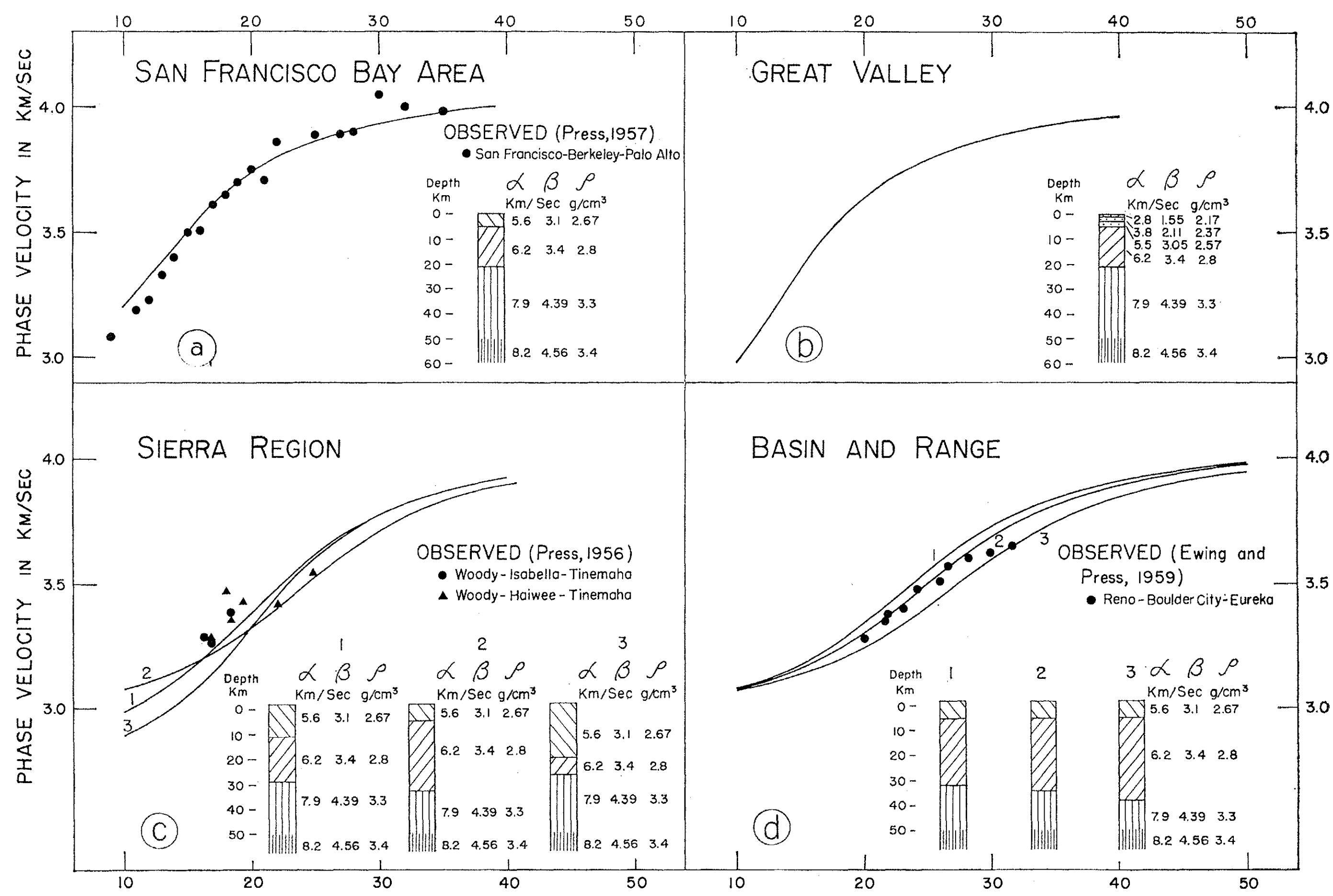


Fig. 6. Computed and observed Rayleigh-wave dispersion curves. For station locations, see Fig. 1.

In the Sierran highland region granitic batholiths and a probable thickened crust or "root" beneath the high topography are both associated with a large gravity minimum. Gravity minima associated with granitic rocks are common in other regions and lend support to the theory that batholiths are emplaced by buoyant rise of hot material of low density. But how much of the Sierran anomaly is a "local" effect of the granitic rocks and how much of it is a "regional" effect of the thickened crust? The extremes for possible interpretations were calculated by Thompson and Talwani (*18*); an intermediate case, in which part of the anomaly is attributed to granitic rocks, is shown in Figs. 5 and 7.

The local negative anomaly at the continental slope is taken as evidence of thick sedimentary rocks of low density. This is an interesting area for more detailed study.

In general, basement rocks of the upper crust have not been explored seismically, so gravity measurements and in some places magnetic measurements supply the main geophysical clues to their structure. Seismic exploration of the crystalline rocks of the upper crust, especially where surface geologic control is good, should be rewarding.

Regional Structure and "Sierran Root"

Knowledge of the regional crust-mantle structure comes from seismic and gravity data. A model in agreement with both kinds of data can be constructed in the following way. The thickness of the crust and the presence of an upper mantle of anomalously low velocity are well determined by refraction measurements near the coast (*8, 9*) (Table 1). From surface measurements and from the empirical velocity–density relation noted earlier, densities can be assigned. Comparison of the gravity data with data for a "standard section" (*27*) fixes the lower boundary of the anomalous upper mantle (seismically indeterminate) at a depth of approximately 50 kilometers. We may next let the lower boundary of the crust vary in depth along the section to satisfy the gravity measurements at all points. The section at the bottom of Fig. 5 represents the resulting model; the results of direct computation of the gravitational effect of the model are represented by the solid line above the section, and observed points are plotted for comparison. When subsequent geophysical information requires an adjustment of this

Table 1. Seismic refraction data.

Location	Depth to Mohorovičić discontinuity (km)	Velocity below Mohorovičić discontinuity (km/sec)	Reference
Pacific Basin, 500 km SW of San Francisco	11	8.3	(*41*)
San Francisco Area	23	8.0	(*8*)
Coast Ranges and Great Valley	20	7.9	(*9*)
Sierra Nevada	>40	?	(*9*)
Basin and Range, Carson Sink	22	7.8–7.9	(*9*)
Basin and Range, Eastern Nevada	32	7.8	(*9*)
Basin and Range, Eastern Nevada-Western Utah	25	7.6	(*5*)

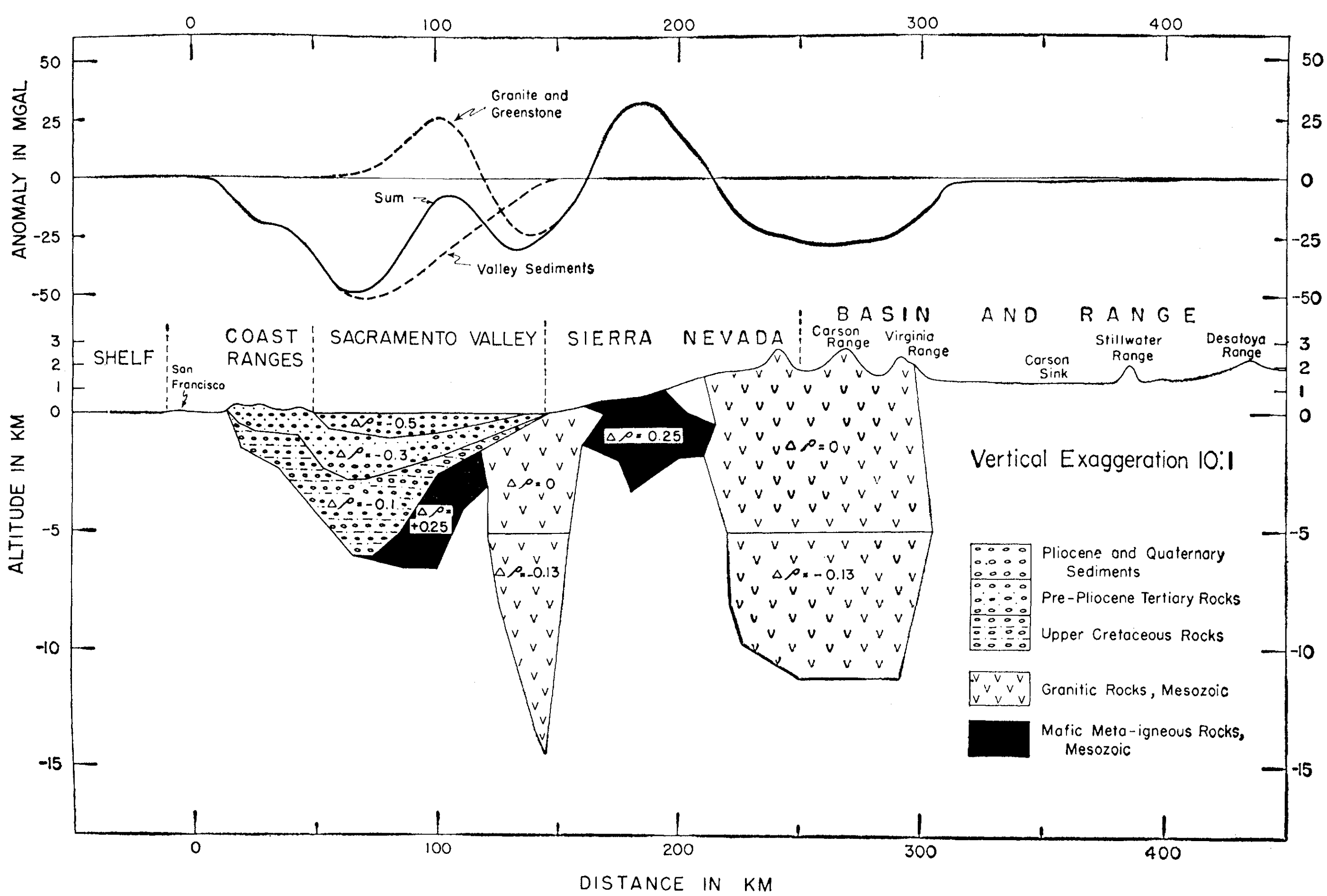


Fig. 7. Local gravity anomalies associated with sedimentary, granitic, and mafic meta-igneous rocks. Computed effect of bodies composed of rocks of the density contrasts indicated is shown by curves at top.

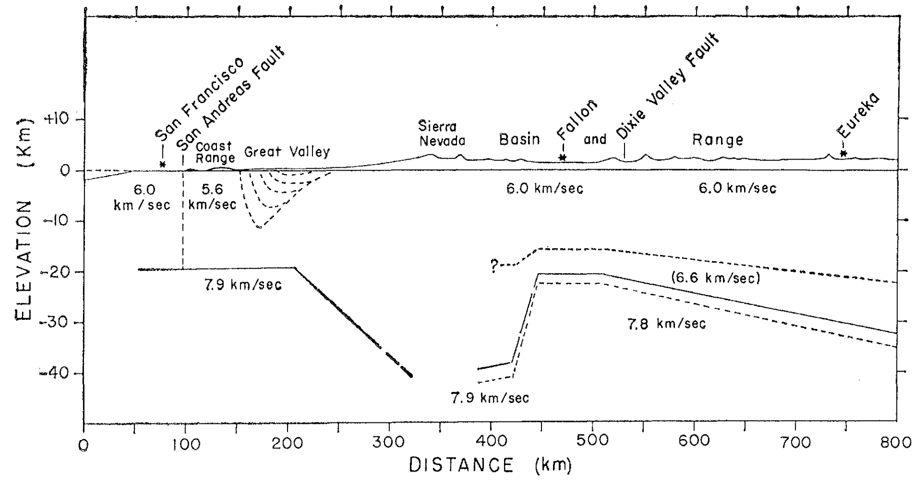


Fig. 8. Seismic section from San Francisco to Eureka, Nevada; vertical exaggeration, 5:1 [after Eaton (*9*)]. The dashed lines show Eaton's alternative two-layer interpretation of the crust.

model, complementary changes will have to be made such that the gravity data are still satisfied. For example, if the crust in some area proves to be thicker than it is shown to be in the model, an added mass in the crust or upper mantle will be required.

It is of interest to examine variations in total mass per unit area at points along the section. This quantity is plotted at the top of Fig. 5. Fluctuations about the average value are small and narrow in breadth and, as mentioned before, show the close approach of the whole section to isostatic balance.

The thickened crust shown in the Sierran region of the model raises a special question—the "root" problem. As mentioned earlier, an unknown part of the anomaly in the Sierran region is attributable to the granitic rocks. Hence the root may be smaller or larger than that shown in the model, within limits (*18*). Much seismic evidence on the root has been obtained since Byerly first reported delays in earthquake waves (*28*), and, in detail, much of the evidence is conflicting. In almost all studies, with the exception of Eaton's (*9*), it was concluded that a root was localized under the Sierra Nevada proper, a conclusion that conflicts with the gravity data and is also puzzling in view of the late geologic origin of the Sierra Nevada block. It seems much more probable to us that a crustal root underlies the entire Sierran highland region and is genetically associated with the core of the Cordilleran eugeosyncline, now occupied by plutonic rocks.

It is interesting to compare Fig. 8, Eaton's seismic refraction section (*9*), with Fig. 5. The following three points are noteworthy.

Starting near the west end of Eaton's section, the velocity contrast shown on opposite sides of the San Andreas fault is not reflected in a contrast of measured densities, nor in the gravity anomaly. Possibly the particulate nature of the largely sedimentary Franciscan rocks on the east side causes the low velocity without affecting the density much; certainly the rocks are practically nonporous. However, a reasonable alternative explanation is available from Birch's demonstration that, in rocks of the same density, velocity varies inversely with mean atomic weight (*10*). The Franciscan rocks on the east side contain much mafic volcanic material; they probably contain more iron, and therefore have higher mean atomic weight, than the granitic and metamorphic rocks on the west side of the fault.

Second, Eaton shows a much thicker crust (> 40 km) in the Sierran highland region than is consistent with the gravity model. Moreover, it would be extremely difficult to satisfy the gravity data by adding an assumed variation in the mantle to the seismic section. If further seismic work shows that the crust is in fact as much as 40 kilometers thick, a good possibility for reconciling the data is available: the crust may be abnormally dense, say 3.0 grams per cubic centimeter, directly under the batholiths. If the plutonic rocks, which are of low density, were formed by either partial melting or fractional crystallization it is indeed likely that dense residual material underlies them.

Third, in the Basin and Range province the depths to the base of the crust, as determined seismically, are about 5 kilometers less than those of Fig. 5. Eaton suggested that the seismic indications of a thin crust at Fallon might be explained alternatively by the presence of high-velocity material in the crust near Fallon. Variations in the anomalous upper mantle could also reconcile the gravity data with a thinner crust. The upper-mantle velocities given by Eaton are almost constant across the section, whereas those given by Herrin and Taggart (Fig. 4) have a considerable variation in the same region and are notably low near the eastern end of the section of our study. This variation is in the right direction for reconciliation of the gravity data with a thinner crust. Because the apparent velocities are affected by inclination of the Mohorovičić discontinuity, however, and also by variations within the crust, further seismic work is needed to resolve this velocity question.

Rayleigh-wave dispersion curves calculated for various parts of the section of Fig. 5 are presented in Fig. 6, along with available observed points. In the San Francisco Bay area, Press obtained a crustal thickness of 30 kilometers from the data of Evernden (*12*), but the data also agree well with a model in which a thin crust of 21 kilometers overlies an anomalous upper mantle (Fig. 6*a*). For the Great Valley (Fig. 6*b*) no observational data are as yet available. For the Sierran region three curves have been calculated; curve 1 in Fig. 6*c* corresponds to a root of intermediate size similar to that in the section of our study. Curves 2 and 3 represent large and minimum roots. Although the scatter and the short range of periods in the data which apply to the southern Sierra Nevada (*13*) make comparison difficult, the shapes of the curves suggest that curve 2 (deep root) may provide the best fit; the fit could be improved by increasing the velocities in the crust. For the Basin and Range province the computed curve 2 in Fig. 6*d* refers to the eastern end of the section and is consistent with observations over the broader region (*14*). Curve 1 corresponds to a slightly thinner crust and curve 3, to a thicker crust. In general the phase velocity data are in agreement with the section shown in Fig. 5, but more detailed observations covering smaller areas are needed.

It seems evident that a better knowledge of the internal structure of the lower crust and upper mantle is critically important to understanding of the regional structure and its bearing on diastrophism. Carefully designed seismic experiments in which both refraction and reflection techniques are used, coupled with phase velocity and gravity studies, are needed.

Tectonic Evolution

An objective of geophysical investigations of the crust and mantle is greater understanding of the mechanisms of structural evolution. If continents have grown laterally during geologic time, how was the crust thickened? What are the significance and origin of the anomalous upper mantle in relation to broad uplifts of the land? For the region under study the evidence favors a westward growth of the continent, as mentioned in the discussion of structural provinces. This growth was, of course, complex in detail. Offshore volcanic and structural ridges occasionally rose above the sea, and larger land masses may also have stood offshore, much as the peninsula of Lower California now stands off the Mexican shore.

The crustal thickening necessary to convert oceanic to continental crust may have taken place primarily through the addition of sediments and volcanics to an essentially oceanic crust, as shown in Fig. 9. A large but undetermined lateral compressive deformation further added to the vertical dimension. In the Sierran highland region the strata of the Cordilleran eugeosyncline dip steeply into the plutonic core (*4*); they may be regarded as the flanks of a great crustal downfold whose trough is obliterated by the granitic batholiths (*29*). Presumably the batholiths resulted from metamorphism and melting of the sedimentary rocks at depth, a process that also welded and consolidated the thickened crust.

Accepting the possibility of crustal thickening by deposition, we still must look to the mantle for the ultimate origin of sediments and volcanics in such enormous volumes, for otherwise the continental crust in source areas would be rapidly depleted. Material of basaltic, and perhaps intermediate, composition derived from the mantle is fractionated in the sedimentary processes of weathering, erosion, and deposition, and among the products are more silicic rocks. Metamorphism and partial melting may complete the conversion of mantle-derived material to sialic crust.

The cause of the broad uplift of the Sierra Nevada and Basin-Range regions is a critical problem in the later (Cenozoic) history of the region. Cenozoic block faulting of the basins and ranges demonstrates a deformation in the sense of lateral extension. This tends to reduce the average thickness

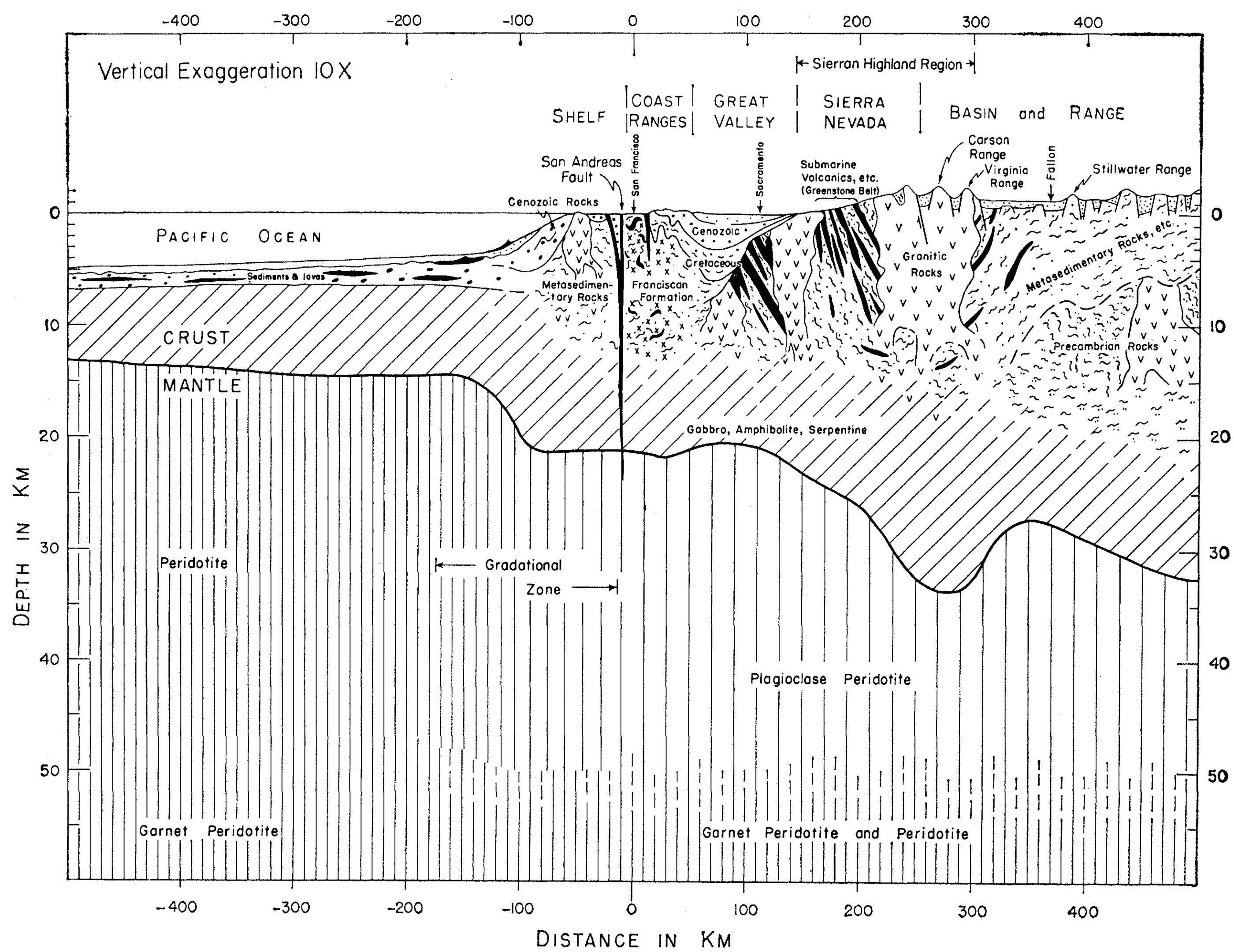


Fig. 9. Geologic section of the crust and upper mantle, as interpreted from present evidence. The rock identities suggested in the upper mantle and lower crust are speculative.

of the crust and hence to reduce the surface altitude. Regional uplift took place despite the extension and thus appears to result from changes in the upper mantle rather than in the crust. A conversion of normal to anomalous mantle would be accompanied by a volume expansion of 3 to 4 percent, as suggested by the velocity difference. The 25 kilometers or so of anomalous mantle would therefore represent an expansion and uplift of only about 1 kilometer, whereas the actual Cenozoic uplift in many places exceeds 2 kilometers. We suggest, instead of a single cycle of expansion, a more complex process that involves expansion, differentiation of the anomalous mantle into crust and mantle fractions, and a renewed supply of primitive mantle material from below.

Nature of Anomalous Mantle

In exploring the hypothesis of mantle expansion we may imagine that the anomalous upper mantle is composed of partly serpentinized (hydrated) peridotite, as Hess proposes (*30*), or of plagioclase peridotite, as Ringwood proposes (*31*). There are serious objections to other suggested possibilities, such as a layer of glass.

The serpentine hypothesis presents several difficulties, including the fact that a fortuitous degree of partial serpentinization would be required to explain the velocities (*18*).

The plagioclase peridotite hypothesis is consistent with available data, and an upper mantle of plagioclase peridotite would constitute an interesting heat engine capable of elevating or depressing the land (*32*). Seismic data require that the normal upper mantle be composed of peridotite, of eclogite, or of mixtures of the two, such as garnet peridotite (*33*). If the primitive undifferentiated mantle is assumed to have been composed of eclogite and peridotite in a ratio of 1 part to 4 (*31*), seismic requirements of the anomalous upper mantle can also be satisfied. The eclogite fraction of a garnet peridotite is convertible into basalt under suitable conditions of pressure and temperature (*34*), so that

$$\text{Garnet peridotite} \rightleftharpoons \text{plagioclase peridotite}$$

with mineral changes like the reaction given in the first section of this article. The phase boundary would be 30 to 55 kilometers deep, under estimated normal conditions of temperature and pressure in the earth, and deeper under conditions of high heat flow (*35*). We suggest that the lower boundary of the anomalous upper mantle at a depth of about 50 kilometers is a gradational phase boundary between plagioclase peridotite and garnet peridotite of the normal mantle (Fig. 9).

The mantle compositions suggested in Fig. 9 are based partly upon geothermal data which indicate that the average radioactivity per unit area is the same under continents and oceans (*1*). Peridotite, required as a component to explain the seismic velocities in the oceanic upper mantle where garnet peridotite is not stable, has a radioactivity too low to explain oceanic heat flow (*36*), and it is therefore suggested that garnet peridotite underlies the peridotite. Conversely, too much garnet peridotite under the continents would result in a heat flow too high to be in agreement with observations of heat flow. The flaw in carrying such arguments very far at present is that the average quantities and especially the ranges in amounts of radioactive elements contained in these rocks is poorly known.

We noted earlier that the tectonic history seems to require renewal of the anomalous upper mantle, and we offered the proposition that the anomalous upper mantle may differentiate into a crustal fraction (basalt, amphibolite) and a normal mantle fraction (peridotite). A local upwelling or turnover in the mantle, or alternatively, a regional convection current might supply fresh garnet peridotite to the top of the mantle, where it would expand to form a new layer of anomalous mantle. Evidence of large movements, presumably involving the mantle, is exhibited in the tens of kilometers of horizontal displacement along the San Andreas fault, but the existence of large convection cells is still an open question. It is logical to ask if a local turnover in the mantle might originate in a low-velocity zone of the upper mantle, either in the world-encircling transverse wave channel (at a depth of more than 100 kilometers in continental regions and at somewhat shallower depths in oceanic areas) or in a compressional wave channel, for which there is evidence in tectonically active regions (*37*). Some lavas probably originate at depths comparable with the depths of the low-velocity regions (*34, 38*), and this strongly implies that an inversion of density as well as of velocity takes place at least locally. A layer of partly melted or partly vitreous garnet peridotite would tend to rise buoyantly in a manner analogous to the rise of salt domes from a salt layer. The anomalous upper mantle could thus be replenished.

On the other hand, if the anomalous upper mantle is composed of partly serpentinized peridotite instead of plagioclase peridotite we must assume that further serpentinization would convert the anomalous mantle into crustal material. If this is true, serpentinite should be a major constituent of the lower crust, despite the fact that rocks of basaltic composition are far more abundant at the surface. The question is a critically interesting one for further investigation by geophysical exploration and drilling.

One interpretation of the anomalous upper mantle, suggested by several authors, is that it may be identical with, or a part of, the compressional-wave low-velocity zone. The gravity data allow this interpretation, with certain restrictions. For example, a laterally uniform zone that is merely shallower in the regions underlain by anomalous mantle is not consistent with the gravity data. One of the most interesting suggestions consistent with the gravity data is that the compressional-wave low-velocity zone is restricted to tectonically active regions and is identical with the anomalous upper mantle found in these same regions (*37*).

Conclusions and Summary

Seismic refraction, gravity, phase velocity, and magnetic data, coupled with the geologic record, are all approximately satisfied by the structure shown in Fig. 9. A 20-kilometer crust under the Coast Ranges and Great Valley thickens to more than 30 kilometers under the Sierra Nevada and parts of the Basin and Range province; this whole area is underlain by an anomalous upper mantle with a velocity and density about 3 percent less than normal. It is not likely that the anomalous mantle extends much deeper than 50 kilometers, and the lower boundary may be gradational.

The thicker crust or "root" under the Sierran highland region (Sierra Nevada and western Basin Ranges) is not limited to the Sierra Nevada proper. The root and the voluminous plutonic rocks originated in the Mesozoic era, and they constitute the now consolidated core of the Cordilleran eugeosyncline. But it must not be supposed that the root has persisted unchanged. The great mountain-building uplifts in the Cenozoic era must have been accompanied by large changes in the root and adjacent mantle.

A zone of positive gravity and magnetic anomalies extending the length of the Great Valley is associated with mafic rocks of the western Sierra greenstone belt, an element of the Cordilleran eugeosyncline. Belts of mafic-to-intermediate lavas, accompanied by mafic and ultramafic intrusions, are marked by similar anomalies in other ancient geosynclines.

An anomalous upper mantle of plagioclase peridotite, an expanded phase of the normal mantle, could explain about 1 kilometer of the uplift that took place over much of the region in Cenozoic time. To explain all of the Cenozoic uplift in the Sierra Nevada and Basin Ranges by this means would require the hypothesis of a separation of the anomalous mantle into crust and normal mantle fractions, followed by a renewal of the anomalous mantle through the action of regional convection currents or local overturning in the upper mantle. The low-velocity zones for compressional and transverse waves in the upper mantle may be related to this problem.

Whatever its origin and composition, an anomalous upper mantle characterizes many regions of present or recent tectonic activity, such as Japan and the Mid-Atlantic Ridge (*39*). The anomalous mantle of western North America might form a continuous belt to the south, with anomalous mantle beneath the crest of the East Pacific Rise (*40*). The anomalous upper mantle may thus be an essential part of the heat engine driving the tectonic activity of these regions.

The Basin and Range region was broken into blocks and laterally extended during the Cenozoic uplift, so that some blocks lagged behind, or sank. Some of the intricate disruption of the upper crust may be related to shallow Cenozoic volcanism. The relatively large and rigid Sierra Nevada block may have been tilted westward during Basin-Range deformation because of the high density of greenstones on the west side and the lower density of granitic rocks to the east.

Man's environment, in the longer view of geologic time, is strongly influenced by mountain-building processes originating in the earth's crust and mantle. In the scale of a few lifetimes, climate, sea level, and the shape of the land are appreciably altered. How this comes about, and whether man can hope to influence the processes, are challenging, unsolved problems. But enough has now been learned about the crust and mantle to suggest precisely what questions must be answered and what critical experiments performed.

Note added in proof: Osborne (*42*) has directed our attention to the possibility that the granitic rocks and also the andesites and dacites were formed by fractional crystallization of basaltic magma under conditions of high oxygen pressure. This possibility in no way conflicts with the geophysical data. In fact, such direct additions to the silicic upper crust from the mantle or lower crust would simplify the perplexing problem of how the crust is replenished in areas of great erosion.

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