Crustal Structure from Pacific Basin to Central Nevada

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Abstract. Seismic refraction, gravity, and phase velocity data are generally consistent with an interpretation of crust and upper mantle structure from the Pacific basin across the edge of the continent, the Coast Ranges, the Great Valley of California, the Sierra Nevada, and part of the Basin and Range province. The derived structure consists of a thin oceanic crust beneath the Pacific basin, thickening at the continental slope to a little more than 20 km under the Coast Ranges and Great Valley, and thickening further under the Sierra Nevada and Basin and Range province. The ocean basin is underlain by a normal high-velocity mantle, but the entire continental area is underlain by an anomalous upper mantle whose velocity and density are about 3% less than normal. The anomalous mantle extends to a depth of about 50 km and its lower boundary may be gradational. The crust under the Sierran highland region (Sierra Nevada and western Basin Ranges) is thicker than that in the area to the east; this 'root' of the highland is not limited to the Sierra Nevada proper. The root and the voluminous plutonic rocks constitute the core of the Cordilleran eugeosyncline. The root derived from a simple gravity model is about 32 km deep and, from seismic refraction data, more than 40 km deep. To reconcile the two a denser root is required, and it is suggested that this represents a residue of partial melting to form the plutonic rocks. The anomalous upper mantle, which is probably composed of plagioclase peridotite derived by a phase change from garnet peridotite or pyroxene peridotite, can explain no more than about 1 km of the Cenozoic uplift in the region. To explain greater uplift by this means requires renewal of the anomalous mantle, possibly by differentiation into basalt and peridotite followed by convective overturn to bring fresh garnet peridotite to the upper mantle. An anomalous upper mantle characterizes many regions of recent tectonic activity. Superimposed upon the regional gravity anomalies are anomalies caused by large anomalous masses in the upper part of the crust: (1) a negative anomaly of about 50 mgal caused by sedimentary rocks of the Great Valley, (2) positive anomalies associated with the 'greenstone belt' beneath the Great Valley and the western Sierra Nevada, (3) negative anomalies due to granitic batholiths, and (4) a negative anomaly suggesting thick sedimentary rocks on the continental slope. The positive gravity and magnetic anomaly of the greenstone belt is comparable with anomalies marking the mafic belts of other geosynclines.

INTRODUCTION

Many different kinds of geophysical data bear on the problem of crustal structure in the western part of the United States. These data come from gravity measurements, travel times of seismic body waves, dispersion of surface waves, aeromagnetic measurements, well logs, density determinations, and, of course, geologic studies of surface rocks. Our aim in this paper is to synthesize existing information and combine it with data obtained specifically during the course of this study to obtain the crustal structure along a section from the Pacific basin to central Nevada.

Although it is obvious that the different kinds of data that bear on the crustal structure in an area should supplement each other, it is not at all obvious how, in practice, the different lines of evidence can be combined into a single solution.

Thus, if seismic refraction and gravity measurements are made in the same area for the purpose of determining crustal structure, how can the seismic and gravity results be compared? Or, if measurements are made of the dispersion of surface waves, how can they be

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related to gravity and seismic refraction data? *Press* [1957] reports a thinner than normal crust in the San Francisco Bay area and ascribes it to thinning of the continental crust near the transition to the oceanic crust. Does this agree with the gravity evidence, and how can we explain the fact that other coastal areas (say, the east coast of the United States) do not have a thinner than normal crust? *Byerly* [1938*a*], *Gutenberg* [1943], and many other authors have cited evidence of a root of the Sierra Nevada from observations of a relative delay of P_n waves from earthquakes in California, at stations east of the Sierra Nevada. Is this quantitatively substantiated by gravity evidence? Can we instead explain the delay of P_n waves merely by a thickening of the crust regionally under the Sierra Nevada and under the region to the east of it? Is the gravity high west of the Sierra Nevada merely a relative high emphasized by the negative effects of the Great Valley sediments on the west and the roots of the Sierra on the east, as *Ivanhoe* [1957] maintained, or is the high caused by a body of gabbro deep in the crust as *Woollard* [1943] suggested? If the crust is thin in the Basin and Range province, as the pioneering studies of *Tatel and Tuve* [1955] first indicated, how does this affect the 'roots of mountains' theory? How is this area isostatically compensated? There is evidence both from explosion and earthquake seismology that the upper mantle underlying the western United States has systematically lower longitudinal wave velocities. What effect does this have on the interpretations of gravity data? In some parts of the area under study, notably the Great Valley of California, detailed data are available about the thicknesses and densities of sediments. Are the gravity anomalies compatible with observations of surface geology and density, and can any inference be made from the gravity measurements about the depth of, say, the granitic batholiths of the Sierra Nevada? Can the results of aeromagnetic measurements made over the Great Valley and the western Sierra Nevada be tied to the gravity measurements there? What is the nature of the transition of the oceanic crust to the continental crust?

We have obviously not been able to answer all these questions, but we have tried to present a unified solution with these questions in mind.

Structural Provinces

The section chosen for study extends from the Pacific basin to central Nevada in a direction normal to the regional geologic structures (Figure 1). It 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. Some of the more important characteristics of these provinces are summarized here.

The floor of the Pacific Ocean 500 km southwest of San Francisco lies 4.8 km below sea level. It shallows very gradually to a depth of 3.7 km at the base of the continental rise 130 km from San Francisco and from there rises with comparatively steep slopes to the shallow continental shelf within a distance of 80 km. The shelf itself is about 50 km wide, and its outer edge is marked by a group of small rocky islands, the Farallons, composed of biotite quartz diorite. At the base of the continental slope two small seamounts have yielded basalt in dredge hauls, and on the continental slope Miocene shale and chert were dredged from outcropping ledges west of the Farallon Islands down to a depth of 2.3 km [*Hanna*, 1952; *Chesterman*, 1952]. The gravity data, as will be seen, indicate that these sedimentary rocks are thick. The continental shelf between the islands and the coast is probably also underlain by thick Cenozoic rocks, for such rocks strike obliquely from the coastline toward the shelf.

The California Coast Ranges consist of several subparallel ranges confined to a belt about 100 km wide. They rise abruptly from the sea on the west and border the Great Valley on the east. Most of the ridges are only about 1 km high; they are interrupted by San Francisco Bay, so that they appear unusually small along our section. Cenozoic sedimentary deposits of the Coast Ranges (Figure 2), including some as young as Pleistocene, are strongly deformed. Beneath the Cenozoic rocks lie two contrasting types of basement, separated by the San Andreas fault and its branches, which cross our section on the west side of San Francisco. On the seaward side of the fault zone, Cretaceous granitic rocks and older schist, quartzite, and limestone compose the basement, whereas on the east side the eugeosynclinal Franciscan for-

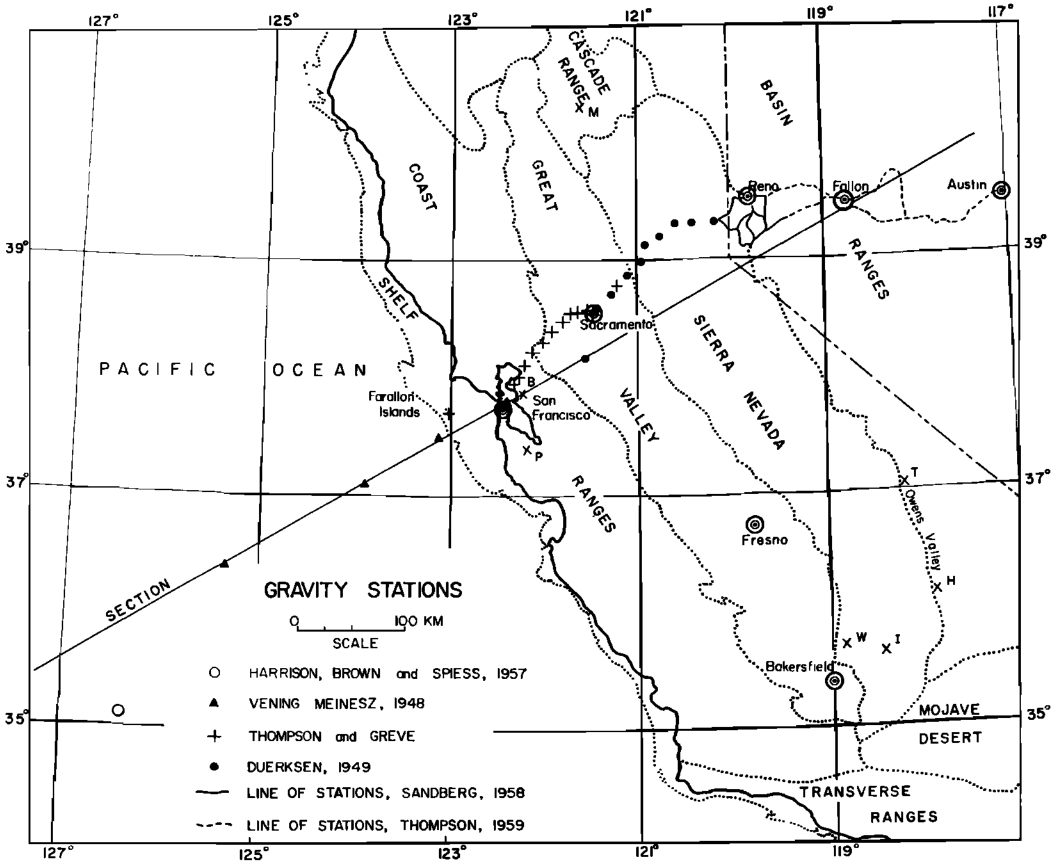

Fig. 1. Structural provinces, gravity stations, and location of section. Letters identify seismic observatories: B, Berkeley; P, Palo Alto; M, Mineral; W, Woody; I, Isabella; T, Tinemaha; H, Haiwee.

mation of Cretaceous and Jurassic age forms the basement. With regard to gravity data, the two basements show little contrast and hence are not distinguished on the generalized geologic map (Figure 2).

The Great Valley, comprising the Sacramento and San Joaquin valleys in central California, is a broad alluvial-floored depression lying near sea level. Structurally it is a synclinorium containing several kilometers of Cenozoic and Cretaceous deposits (Figure 3), which to the west are partly uplifted and exposed in the Coast Ranges. The axis of greatest thickness is closer to the west side of the valley, and from the axis eastward the rocks thin gradually and lie unconformably on the surface of the west-tilted Sierran block. The Cretaceous sedimentary rocks differ from those farther west in the Coast Ranges in that they are less deformed and better sorted and have appreciable porosity and consequently lower density than the eugeosynclinal rocks of the Franciscan formation, a fact of significance in the gravity interpretation.

The Sierra Nevada consists primarily of a great block tilted about 2° westward. Throughout much of its length, the range is sharply bounded on the east by an escarpment caused by normal faulting and warping; 100 km to the west the tilted block descends gradually beneath the Great Valley sediments. It is important to remember that the present Sierra Nevada block is only a fragment, shaped in Cenozoic time, of a more extensive earlier eugeosynclinal and granitic terrane.

The original structure extended eastward and westward. Beneath a thin and fragmentary

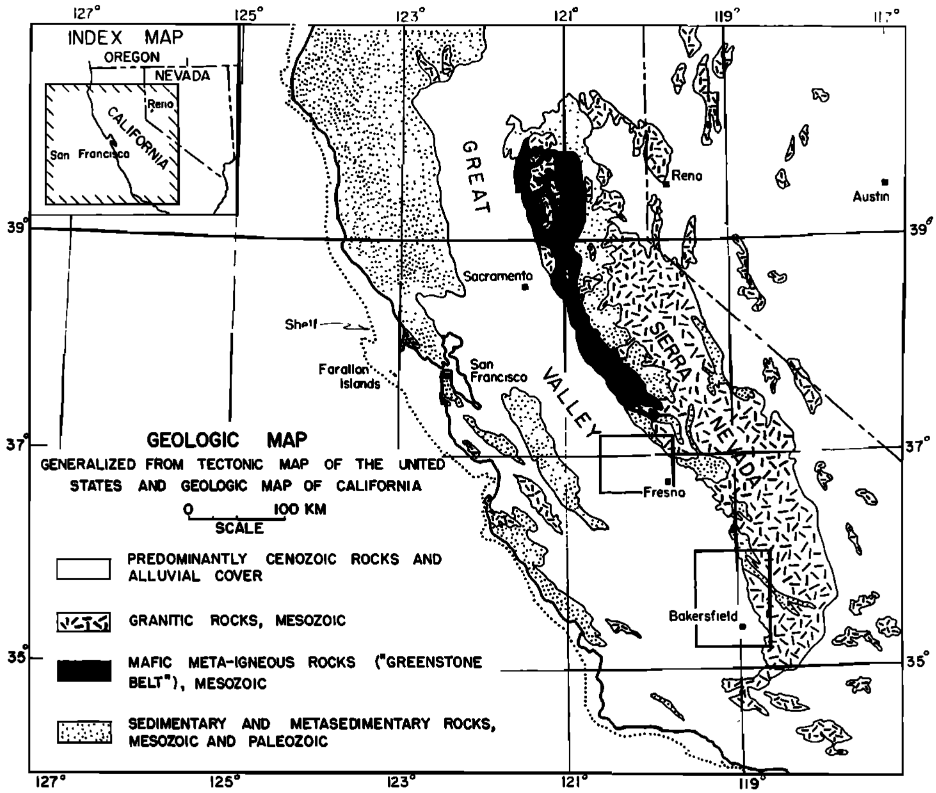

Fig. 2. Generalized geologic map. Rectangles at Fresno and Bakersfield show locations of Figures 5 and 6, respectively.

cover of Cenozoic volcanic debris, the major Sierran rocks of importance in a regional geophysical study are the following. (1) Metamorphosed sedimentary rocks comprise abundant slate and schist of Mesozoic and Paleozoic age. (2) Metamorphosed intermediate to mafic volcanic rocks, mainly of Mesozoic age, are interstratified with the sedimentary rocks. With their associated intrusions they are often loosely but conveniently referred to as greenstones, but they include rocks ranging in metamorphic grade from greenschist to amphibolite. The greenstones are concentrated in a belt partly exposed in the western Sierra Nevada and partly concealed beneath younger sediments of the Great Valley (Figure 2). (3) Granodiorite and other quartz-bearing plutonic rocks, which we shall call granitic rocks, were emplaced in many separate intrusions during Jurassic and Cretaceous time. Taken together, the metamorphosed sediments and lavas are a typical eugeosynclinal assemblage, an assemblage with a considerably broader extent than the present mountain range. The central part of the eugeosynclinal accumulation has been most extensively invaded by batholiths.

The Basin and Range province extends eastward from the Sierra Nevada to the Colorado plateau; our section extends across its western part. The ranges commonly reach altitudes of 3 or 4 km, and the intervening basins generally stand 1½ to 2 km above sea level. From the Sierra Nevada the crests of the ranges and the floors of the basins descend gradually eastward to Carson Sink and Dixie Valley, and from there rise toward the Ruby Range beyond the eastern limit of the section. Cenozoic volcanic and sedimentary rocks are thicker and more extensive than in the Sierra Nevada. Beneath them lies the continuation of Mesozoic and Paleozoic rocks of the Sierra; exposed granitic rocks become gradually less abundant to the east. The transition from eugeosynclinal to miogeosynclinal rocks lies near the eastern end of

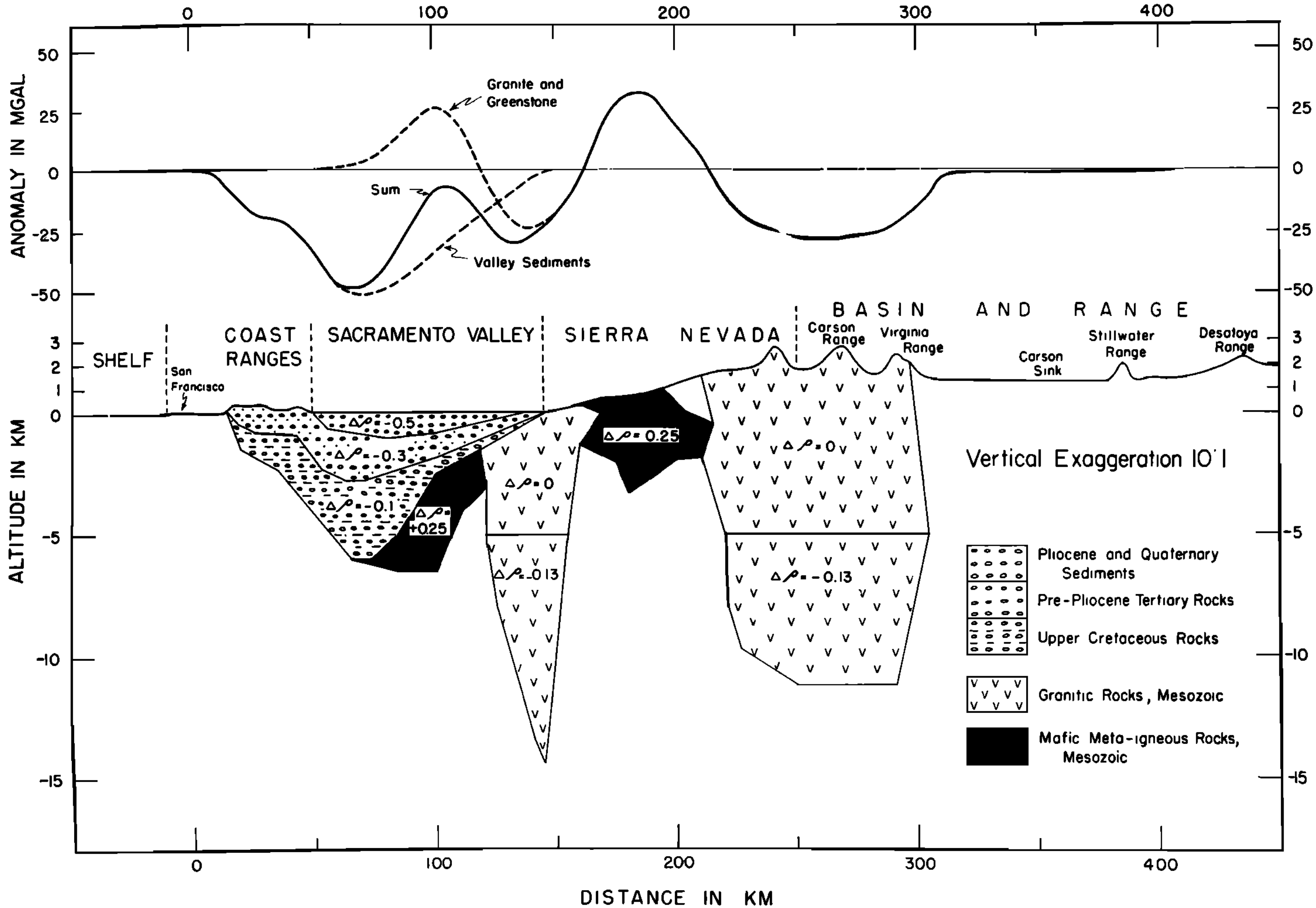

Fig. 3. Local gravity anomalies associated with sedimentary, granitic, and mafic meta-igneous rocks. Computed effect of bodies with indicated density contrasts is shown by curves at top.

TABLE 1. Gravity Data

Station*	Distance on Profile, km	Bouguer Anomaly,† mgal	Remarks
H77	−447	303	Sea stations
V100	−305	277	Sea stations
V99	−152	217	Sea stations
V98	−72	15	Sea stations
V97	0	12	Sea stations
D1034	84	−45	Pendulum stations
D1035	118	−46	Pendulum stations
D1036	136	−72	Pendulum stations
D1037	156	−71	Pendulum stations
D1038	175	−59	Pendulum stations
D1039	185	−62	Pendulum stations
D1040	201	−93	Pendulum stations
D1041	218	−124	Pendulum stations
D1042	232	−158	Pendulum stations
D1043	250	−184	Pendulum stations
TG1	−50	42	Big Farallon Island
TG3	16	3	
TG4	22	−25	
TG6	33	−5	
TG7	45	−21	
TG8	58	−22	
TG9	70	−46	
TG10	83	−50	
TG11	93	−36	
TG12	100	−26	
TG13	110	−32	
TG14	113	−41	
TG16	146	−92	
TS	260	−190	Regional value from detailed survey
TS	275	−194	Regional value from detailed survey
TS	288	−184	Regional value from detailed survey
TS	300	−174	Regional value from detailed survey
T	325	−157	Regional value from detailed survey
T	350	−153	Regional value from detailed survey
T	375	−154	Regional value from detailed survey
T	400	−167	Regional value from detailed survey
T	425	−178	Regional value from detailed survey
T	450	−195	Regional value from detailed survey
T	475	−208	Regional value from detailed survey
T	500	−215	Regional value from detailed survey

* Letter preceding station number indicates source of data: H, *Harrison et al.* [1957]; V, *Vening Meinesz* [1948]; D, *Duerksen* [1949]; TG, Thompson and Greve, unpublished; TS, *Thompson and Sandberg* [1958]; T, *Thompson* [1959].

† The Bouguer anomalies include terrain corrections in steep or mountainous areas.

the section. Like the Sierra Nevada, the Basin and Range province was subjected to structural deformation over a long span of time, but the present high elevation of both provinces, and the Colorado plateau as well, is a product of late Cenozoic uplift. The Basin and Range province is distinguished by intricate block faulting and internal disruption which occurred during uplift.

Geophysical Data

Gravity data. The gravity data and their sources are listed in Table 1. To check the validity of these values and their applicability to regional interpretations we examined unpublished maps of local areas, some kindly supplied by petroleum companies and some contained in Ph.D. theses. In addition we made detailed computations on another long gravity profile, parallel to the one discussed here but 350 km to the southeast. The seaward end of this supplementary profile, crossing the coast north of Point Conception, is from measurements by *Harrison et al.* [1957] and the landward part, passing north of Bakersfield, is from *Ivanhoe* [1957]. It became evident from this exploratory work that a single profile could represent the regional structure very well and moreover that two-dimensional computations could be applied to the problem.

The values in Table 1 are reduced to standard Bouguer anomalies, 2.67 g/cm³ being used for the density of all material above sea level. Departures from this density in the region above sea level are included in the interpretation, rather than in the reduction, since the actual densities are never perfectly known. This procedure offers the great advantage of cleanly separating the analytical reduction from the interpretation. In water areas the differential density between 2.67 and the density of sea water, 1.03, was used in the reductions. Terrain reductions are included in the Bouguer anomalies in steep or mountainous areas where the reductions exceed 1 or 2 mgal.

East of the Sierra Nevada, in the Basin and Range province, we compiled regional gravity values instead of individual measurements. In this region local anomaly relief associated with low-density sediments in basins amounts to as much as several tens of milligals. Because these local anomalies have already been interpreted in some detail and the results published, we chose regional values from the ranges, thus effectively eliminating the sedimentary fill of the basins. A similar situation arises in the California Coast Ranges, where local anomaly relief of at least 20 mgal is produced by Cenozoic sedimentary rocks. Here we plotted individual measurements but ignored the small-scale local relief in the interpretation. Local anomaly relief, which does not materially affect the analysis of crustal structure, is better reserved for study on gravity maps at an enlarged scale.

The plotted Bouguer gravity values (Figure 4) show two first-order features, the continental slope gradient and the western Sierra gradient. The gravity relief across these steep gradients amounts, respectively, to more than 200 mgal and more than 100 mgal, and reflects major changes in the crust-mantle system, connected with major changes in altitude of the solid earth. Several large anomalies of second-order magnitude are superimposed on the first-order features. The second-order anomalies are (1) a strong negative anomaly over the continental slope, (2) a large negative anomaly over the entire Great Valley and extending westward into the Coast Ranges, (3) two positive anomalies, one over the eastern part of the Great Valley and one over the western Sierra greenstone belt, (4) separating the two positive anomalies, a negative anomaly over the Rocklin batholith at the east side of the Great Valley, and (5) a negative anomaly associated with the Sierran highland region comprising the Sierra Nevada proper and the western Basin Ranges.

Seismic refraction data. Evidence has accumulated in the last few years that the crust and upper mantle in the western United States have a different structure from what had hitherto been considered normal continental structure, that is, a crust approximately 35 km thick with velocities ranging from about 6.0 to 7.2 km/sec, overlying a mantle having a velocity of 8.0 to 8.2 km/sec. The earliest indication of this difference was reported by *Tatel and Tuve* [1955], who found a thickness of 29 km in the Basin and Range province. This was confirmed by *Berg et al.* [1960], who also measured a low velocity in the upper mantle (7.6 km/sec). *Press* [1960] and *Diment et al.* [1961] essentially confirmed these findings for another part of the Basin and Range region, although Press assigned the low-velocity material (7.6 km/sec) to the crust, which therefore had to be thick. The intensive work of the U. S. Geological Survey, begun in 1961 and summarized by *Pakiser* [1963], greatly extended earlier findings.

Evidence for a low-velocity mantle comes from many sources, including those already mentioned. *Jeffreys* [1962] showed that the velocity of P_n determined from three earthquakes in California was systematically lower than the value of P_n from European earthquakes. *Herrin and Taggart* [1962] and *Stuart et al.* [1964] mapped interval P_n velocities in different parts of the United States. Their results, which include the seismic refraction work of the U. S. Geological Survey, demonstrate

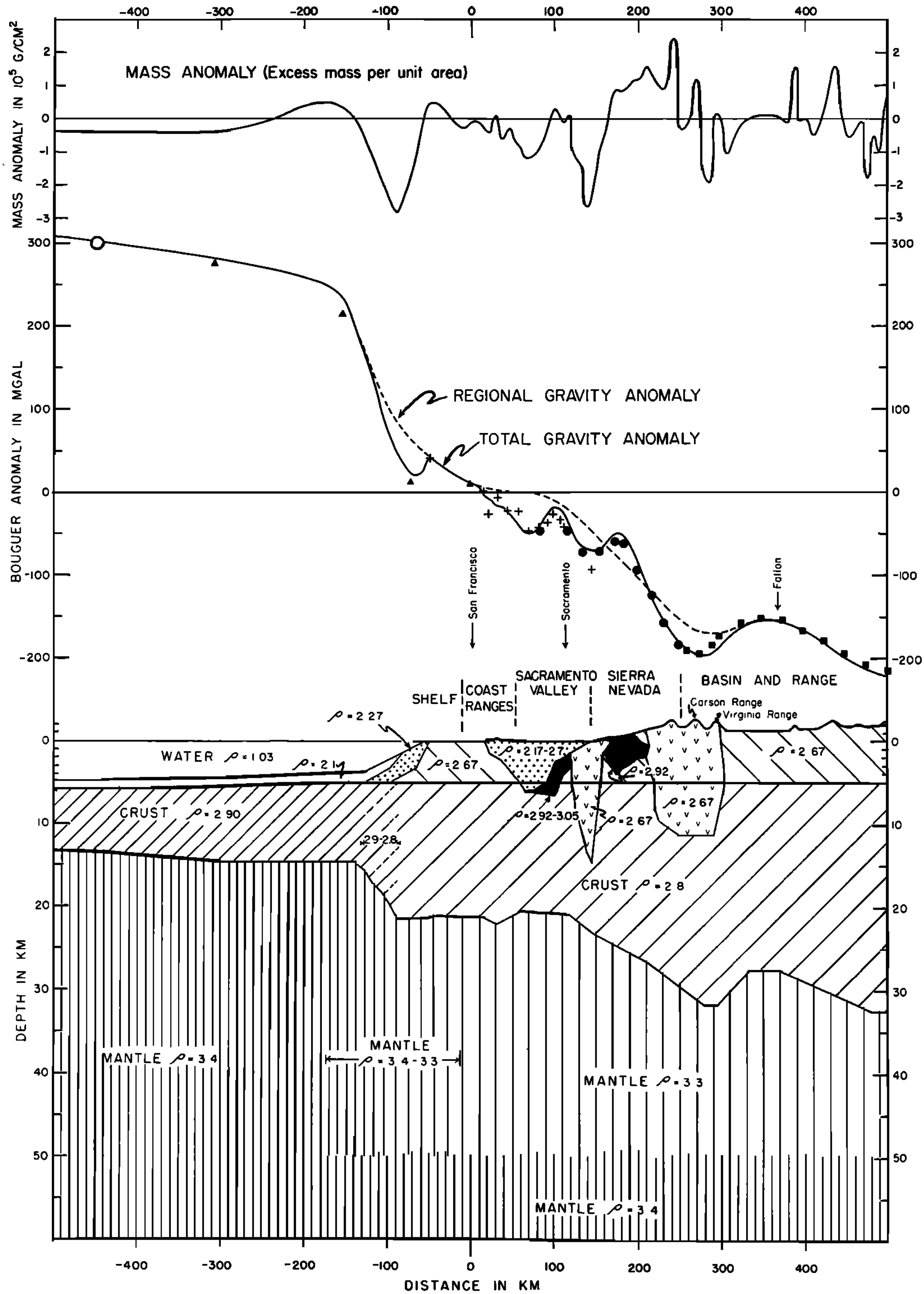

Fig. 4. *Bottom:* section of crust and upper mantle, vertically exaggerated 10:1. Dotted patterns represent sedimentary rocks; checks, granitic rocks; shading, greenstone. *Center:* gravity anomaly computed from section, compared with observed points. *Top:* mass anomaly computed from section.

TABLE 2. Seismic Refraction Data

Location	Depth to M, km	Velocity below M, km/sec	Source
Pacific basin, 500 km southwest of San Francisco	11	8.3	*Vacquier* [1962]
San Francisco area	23	8.0	*Healy* [1963]
Coast Ranges and Great Valley	20	7.9	*Eaton* [1963]
Sierra Nevada	>40	?	*Eaton* [1963]
Basin and Range, Carson Sink	22	7.8–7.9	*Eaton* [1963]
Basin and Range, eastern Nevada	32	7.8	*Eaton* [1963]
Basin and Range, eastern Nevada–western Utah	25	7.6	*Berg et al.* [1960]

clearly that P_n velocities west of the Rocky Mountains are systematically lower than those to the east. Of special interest to the present study are the results of *Healy* [1963] and *Eaton* [1963]. These are summarized with some earlier refraction results in Table 2.

Phase velocities. 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 in favorable circumstances may be highly critical. The most important observations relative to the present study cover the San Francisco Bay area [*Evernden,* 1954; *Press,* 1957], the Sierra region [*Press,* 1956], and the Basin and Range area [*Ewing and Press,* 1959]. These observations are shown in Figure 9.

Magnetic data. Anomalies in the total intensity of the earth's magnetic field or its vertical component are particularly useful in close comparison with gravity anomalies as an aid to identifying the anomalous material or structure. Serpentine, for example, is highly magnetic but of low density, whereas mafic igneous rocks such as basalt are typically both magnetic and dense. Sedimentary rocks and silicic igneous and metamorphic rocks vary widely in density but are not usually very magnetic.

Sources of data in the region of immediate interest include (1) a long aeromagnetic profile 60 km northwest of and nearly parallel with our section [*Balsley,* 1953], particularly useful in the Great Valley and in the western Sierra Nevada; (2) a total-intensity aeromagnetic map of part of the Great Valley, extending north and south of the profile [*Grantz and Zietz,* 1960]; (3) an oil company vertical intensity magnetic map of the region farther south in the valley, studied by *Bayoumi* [1961]; and (4) a vertical intensity magnetic profile through Bakersfield in the southern part of the valley [*Woollard,* 1943]. Sources (3) and (4) are important because they cover areas of extensive drilling into the basement rocks of the Great Valley and hence give us a basis for interpreting the anomalies along our section farther north. Bayoumi determined the magnetic susceptibilities and densities of numerous core samples.

Method of Interpretation

The principal boundaries to speculation about the crust and upper mantle are set by gravity and seismic information. These two lines of investigation complement each other in a remarkable, but sometimes poorly appreciated, manner; gravity presents uniquely the sum effect of all the parts of a structure, whereas refraction seismology records some of the parts in nice detail but omits others. The rapidly advancing field of surface-wave seismology adds another kind of boundary to possible interpretations, and magnetic data are helpful when available. Very few other kinds of geophysical quantities, such as heat flow, have yet been measured in the area of immediate interest.

In the present paper we derive a crustal cross section in which the densities and dimensions are such that the gravity anomaly computed from the section matches the observed Bouguer anomaly. For this purpose it is convenient to separate the observed anomaly into a local and a regional anomaly. The local anomaly is then ascribed to relatively shallow anomalous masses, and the regional anomaly is explained in terms of variations in crustal thickness and changes in the density of the upper mantle. This separation into local and regional anomalies is, of course, not unique, and we shall consider alternative explanations for some portions of the gravity anomaly profile. Several bases have been used in order to associate local anomalies with shallow crustal bodies. The approximate density and thickness of the Great Valley sediments were known and the corresponding anomaly was computed. The sedimentary body on the continental slope was not known but was inferred from the fact that the gradient of the Bouguer anomaly at the continental edge is too steep to be explained by changes in crustal thickness or in mantle composition alone. The correlation between positive local anomalies and the greenstone bodies, as well as between negative local anomalies and the granite bodies, which is treated more fully in a later section, was considered established and was used in the separation of local and regional anomalies. It is the usual practice in small-scale studies to ignore the cause of the regional anomalies and in large-scale regional studies to average out the local anomalies. In our study we have, on the contrary, considered both scales of anomaly; this imposes considerable limitation on possible structures and leads to more credible solutions of the problem.

In studying regional structures from gravity data it is important to note that gravity data alone cannot be used to establish the structure. Gravity data (1) provide a check on structure deduced by geological inference or seismic refraction with respect to the total mass in columns to a fixed depth; (2) give indications, from a study of the gradients, of a maximum depth to which lateral density variations can take place; (3) permit the extrapolation and interpolation of seismically deduced structures to unknown areas; and (4) serve to determine the position of a discontinuity if the shallower structure is known and only one deeper density discontinuity is unknown.

In our problem we attempt to determine a reasonable regional structure mainly on the basis of seismic results and then consider the variations of the depth of the base of the crust to explain the remaining regional gravity anomaly. The seismic results cited earlier indicate that the crustal thickness in the coastal area is not much greater than 20 km. This contrasts with a coastal crustal thickness of about 35 km [*Katz,* 1955] in the eastern United States. The thickness of approximately 32 km in the Basin and Range province (elevation about 2 km) appears incompatible with the thickness of the crust under the east coast, within the Airy system of isostasy, but it compares more favorably with the crustal thickness under the west coast. Since there is no evidence of any remarkable differences in crustal density, the only way to reconcile the difference in crustal thicknesses east and west of the Rocky Mountains is to assume that the upper mantle has a different density in the two areas. This is directly supported by the evidence of low seismic longitudinal velocity in the upper mantle, cited earlier.

In our simplified regional crustal picture we assume an anomalous upper mantle (density 3.3 g/cm^3) under the continental area separated by a sharp boundary at a depth of 50 km from the normal mantle (density 3.4 g/cm^3). The boundary has been assumed to be a sharp one merely for ease of computation. It might well be a gradational one. The depth of this boundary is not determined at all from seismic data. Assuming the crustal densities discussed in the next paragraph, we obtained the depth of this boundary by 'balancing' this section against an adopted standard section (based upon the work of *Talwani et al.* [1959*b*], who utilized a section 32 km thick and of density 2.87 g/cm^3 overlying a mantle of density 3.4 g/cm^3). Our standard section, in which the densities of all layers below the uppermost are rounded to the first decimal, can be represented by 5 km of material of density 2.67 g/cm^3 and 25 km of material of density 2.9 g/cm^3, overlying a mantle of density 3.4 g/cm^3. Since it is only the total mass that is important, any other section having the same mass down to a given depth in the mantle is equivalent. It should be borne in mind that if the density contrast between the normal and the anomalous mantle is changed, this boundary shifts accordingly. If the contrast is 0.15 g/cm^3 instead of 0.1 g/cm^3, the boundary moves up to 40 km. If the contrast is 0.075 g/cm^3, it moves down to 60 km. We have satisfied ourselves, however, that a large part (probably exceeding 90%) of the compensation of the continent with regard to the ocean must be above a depth of 60 km (indicating the approach of a limit to the depth of anomalous mantle), for otherwise it is impossible to match the slope of the Bouguer anomaly at the continental edge. Furthermore, if 7.9 km/sec and 8.2 km/sec are accepted as the anomalous and normal mantle velocities and if density changes are assumed proportional to velocity changes (constant mean atomic weight), the density contrast should be about 0.1 g/cm^3 and hence the depth of the anomalous mantle about 50 km. We assume that the upper mantle has a density of 3.4 g/cm^3 under the Pacific area and grades laterally from 3.4 to 3.3 g/cm^3 under the continental margin. It is possible that the gradational change is associated with the San Andreas fault, which in our section is close to the continental margin.

The crustal density was chosen in the following manner: The density of the top 5 km, which indirectly is used in the Bouguer anomaly reduction in the ocean areas and which is very important in considering the shallow anomalous bodies, was chosen to be 2.67 g/cm^3. This value, originally established by averaging many samples of crystalline rocks, has been generally used for reducing Bouguer anomalies. Subsequent sampling by numerous investigators in mountain regions of the world has shown that 2.67 is a reasonably good average for silicic plutonic rocks, gneisses, and schists. It is obvious from their geologic structure that such rocks commonly extend far below sea level; on the other hand, it is equally clear from geophysical data that the average density of the whole crust is much greater. We chose a density of 2.8 g/cm^3 for the remainder of the crust, principally to make the derived sections match the seismic results but also to represent simply the vertical gradient of density in the crust. We realize that the actual crust must be much more complicated; in particular we have avoided an intermediate layer. Any such complexities will leave our main conclusions little altered; as more information becomes available, intermediate layers can be introduced in the model and accommodated by correspondingly altering the lower boundary of the crust. The density of 2.9 g/cm^3 was adopted for the oceanic crust, which is generally thought to be more dense than the continental crust. Since detailed gravity results for the vicinity of the San Andreas fault indicate no systematic density difference in crustal rocks on the two sides, we assume that the gradation of density from 2.8 to 2.9 g/cm^3 takes place under the continental slope.

For determining the variations of crustal thickness from gravity data it is necessary, in addition to adopting crustal and mantle densities, to fix the crustal thickness at one point. Along our section the best seismically determined thickness appears to be the value for the San Francisco Bay area [*Healy*, 1963; *Eaton*, 1963], where we adopted a value of 21 km. The thickness of the crust at other points along the profile is then obtained by matching the computed gravity anomalies to the observed ones.

The final calculations of gravitational attraction were made on a digital computer (IBM 1620) using the method of *Talwani et al.* [1959*a*]. Two-dimensionality and a flat earth were assumed.

We have also computed Rayleigh wave phase velocity versus dispersion for some of the gravitationally derived structure sections and compared them with experimental data. The phase velocity depends on the density and on the additional parameters of longitudinal-wave velocity α and transverse-wave velocity β. To calculate the phase velocity, we assumed the densities and longitudinal velocities to be related according to the Nafe-Drake empirical curve [*Talwani et al.*, 1959*b*]. Since transverse-wave velocities have not often been measured in seismic refraction work, it is necessary to assume a simple relation between longitudinal-wave and transverse-wave velocities. This we have done by adopting a Poisson's ratio of 0.278, an average value based upon several measurements in crustal layers [*Ewing and Ewing*, 1959]. Determinations of crustal structure from phase velocity data, especially in a limited range of periods, are nonunique, and the possibility of variations of relations between the wave velocities and density, as well as variations in Poisson's ratio, may lead to further problems. The present calculations have been made with the idea that if a structure fits gravity and seismic refraction data, and, with a reasonable assumption of a Poisson's ratio, also fits phase velocity data, the agreement tends to increase the reliability of the structure determination.

We are well aware of the uncertainties in our results because of the simplifications and the assumptions stated above. We are equally aware of the uncertainties inherent in interpretations of different kinds of geophysical data independently. We believe that, despite the simplifications and assumptions, crustal models that are derived from different kinds of data are inherently more useful than those for which a large amount of available information is ignored.

Results

Great Valley. Petroleum production and exploration in the Sacramento and San Joaquin valleys provides a wealth of subsurface information on the thick sedimentary rocks and considerable data on the underlying basement rocks. Although in density the Franciscan rocks differ little from the 'normal upper crust,' 2.67 g/cm^3, low-density sedimentary rocks of upper Cretaceous and Cenozoic age make a major contribution to the gravity anomaly. To compute the effect of these low-density sedimentary rocks, we smoothed and generalized *Taliaferro*'s [1951] section of the Great Valley and *Lawson*'s [1914] section in the Coast Ranges and approximated the whole with straight-line segments. Figure 3 shows the result. Three divisions of the low-density sedimentary rocks—Pliocene and Quaternary, pre-Pliocene Tertiary, and upper Cretaceous deposits—are sufficient for a general gravity computation. The densities of these divisions are estimated from data summarized in Table 3, and the density contrasts with normal upper crust of density 2.67 g/cm^3 are given in Figure 3. It must be emphasized that the figure does now show the *complete* sedimentary section but only the part of it having significantly lower density than 2.67 g/cm^3. The gravitational effect of the Great Valley sediments is approximately -50 mgal, as shown in Figure 3, and this amount agrees well with

TABLE 3. Measured Densities

Rocks	Location	No. of Samples	Density, g/cm^3 Range	Density, g/cm^3 Average
Pliocene and Quaternary sediments	Great Valley	Many*	1.7–2.5	2.2
Pre-Pliocene Tertiary rocks	Great Valley	Many*	2.2–2.6	2.4
Upper Cretaceous rocks	Great Valley	Many*	2.4–2.7	2.6
Franciscan rocks	San Francisco area			
Graywacke†		10	2.62–2.69	2.67
Shale		3	2.64–2.67	2.66
Chert		3	2.61–2.69	2.66
Submarine basalt		12	2.88–2.99	2.95
Serpentine		4	2.21–2.42	2.32
Granitic rocks‡	Rocklin, E. side Great Valley	3	2.63–2.65	2.64
	Western Sierra	5	2.63–2.77	2.70
	Farallon Island	3	2.61–2.63	2.62
	Western Basin Ranges§	5	2.62–2.66	2.64
Mafic meta-igneous rocks	Western Sierra Nevada	7	2.88–3.07	2.93
Gabbro	Western Sierra Nevada	3	2.94–2.99	2.97
Metavolcanic rocks‖	San Joaquin Valley	43	2.75–3.14	2.92
Metasedimentary rocks	Western Sierra Nevada			
Paleozoic schist		3	2.59–2.63	2.61
Mesozoic slate		3	2.72–2.75	2.74

* Basic data from oil companies.
† Predominant rock type in Franciscan formation.
‡ Granitic rocks vary systematically in density with mineral composition [*Bateman et al.*, 1963]. This variation within and between intrusions is beyond the scope of the present paper.
§ From *Thompson and Sandberg* [1958].
‖ From *Bayoumi* [1961].

the local negative anomaly that is apparent in the data of Figure 4.

Greenstone problem. One of the major features on gravity maps of California is a belt of positive anomalies extending the entire length of the Great Valley; it is superimposed on the broader negative anomaly associated with the valley sediments. The belt is represented in our section (Figure 4) by two positive anomalies; the eastern one is clearly associated with the western Sierra greenstone belt.

Johnston [1940] noted the positive anomaly in the western Sierra and attributed it to a gabbro intrusion. *Woollard* [1943] studied the positive anomaly far to the south, near Bakersfield, suggested that it was an extension of that noted by Johnston, and computed the size of the gabbro body that would be required to produce the anomaly. *Balsley* [1953] presented an aeromagnetic profile which shows a broad high corresponding with the Great Valley gravity high, a low where the Rocklin granite projects beneath valley sediments and in the Sierran foothills, highs on greenstone, lows on metasedimentary rocks, and sharp highs of about 1000 γ over the narrow serpentine bodies. *Ivanhoe* [1957] published a generalized map of the belt of gravity anomalies and claimed that they represented merely a relative maximum between the negative anomaly associated with the valley sediments and the negative anomaly associated with isostatic compensation for the Sierra Nevada. *Thompson and Talwani* [1959] concluded that the positive anomaly belt was directly associated with the greenstone belt, partly exposed and partly concealed beneath Great Valley sediments. *Grantz and Zietz* [1960] presented a magnetic map of the Great Valley, showing a positive anomaly along the same belt as the gravity anomaly. They suggested igneous rock masses at a depth of 8 to 16 km but noted that sharper, superimposed anomalies indicate a shallower depth, approximately the depth to basement. *Irwin and Bath* [1962] proposed that the Great Valley magnetic anomaly is caused by ultramafic rock below the basement surface, near the maximum depth suggested by Grantz and Zietz. They explain the sharper superimposed anomalies by smaller bodies of ultramafic rock at the top of the basement. *Oliver and Mabey* [1963] suggest that the magnetic anomaly, and hence the gravity anomaly, originates in rocks related to the earth's upper mantle.

The exposed rocks of the greenstone belt are principally mafic to intermediate submarine volcanics but include small bodies of gabbro and diabase and narrow belts of serpentine. Gabbro alone is too scarce to explain the gravity anomaly, as Johnston supposed. The serpentine has a low density, as well as a relatively small volume, and is not pertinent to the discussion of gravity on a regional scale. The volcanic rocks are interstratified with metasedimentary rocks; the belt shown on the geologic map (Figure 2) simply records crudely the extent of terrain where greenstone is most abundant. The correspondence of the eastern of the two positive gravity anomalies with this belt first became clear to us with the help of Lorin D. Clark (personal communication, 1959). Density measurements of the greenstone (Table 3) support the correlation. As we know only the surface boundary of the greenstone, the bottom of the anomalous mass must be determined from the local gravity anomaly, which has an amplitude of about 30 mgal. The result of assuming a density contrast of 0.25 g/cm^3 is shown in Figure 3. The shape of this body can be varied somewhat, but its cross-sectional area for the given gravity anomaly and density contrast is fixed. We might assume that the average density contrast of the body is smaller owing to sedimentary rocks interstratified with the volcanics. If it is only half of 0.25 g/cm^3, the depth of the body is very nearly twice as great.

The other positive gravity anomaly, which is in the Sacramento Valley, is similar in amplitude and breadth to the first. From subsurface exploration it is clear that the anomaly cannot be attributed to the Great Valley sedimentary rocks or to relief of the basement surface. An associated magnetic anomaly [*Grantz and Zietz*, 1960] confirms this conclusion. We regard a belt of greenstone similar to that in the Sierra Nevada as by far the most likely explanation [*Thompson and Talwani*, 1959]. A regional gravity map [*Woollard*, 1963] in fact shows that the two belts are only branches of a single larger belt extending the length of the Great Valley. The evidence for our interpretation includes data from many holes drilled into the basement farther south in the Great Valley. Figure 5 shows the basement rocks in drilled

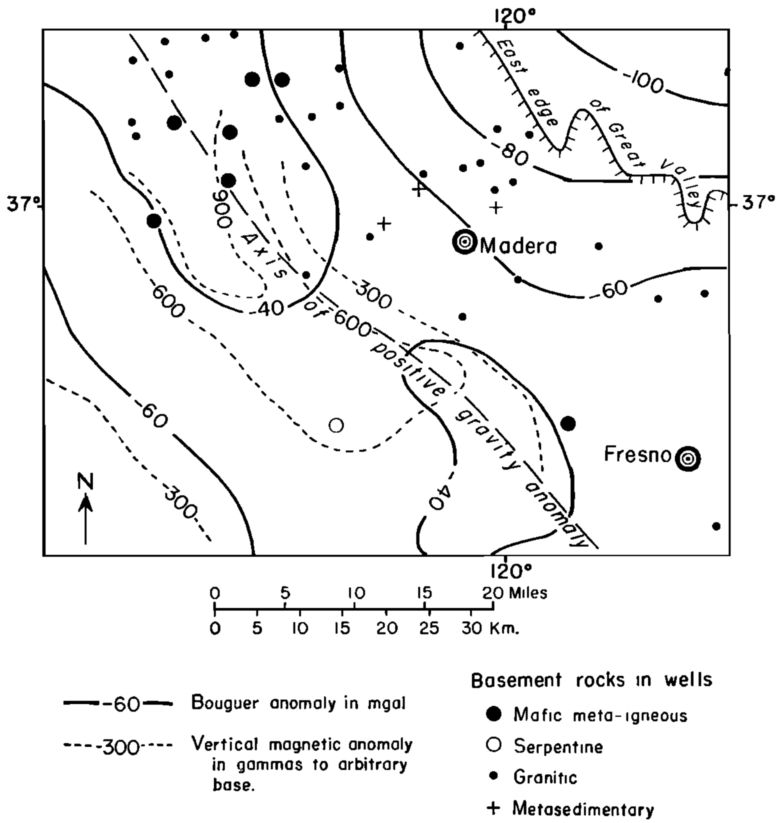

Fig. 5. Association of positive magnetic and gravity anomalies with mafic basement rocks of Great Valley near Fresno. After *Bayoumi* [1961].

holes relative to the positive gravity and magnetic anomalies. A close correspondence of the anomalies with a concealed greenstone belt is apparent. *Bayoumi* [1961] was able to explain the anomalies quantitatively on the basis of measured density and magnetic susceptibility data. Still farther south, near Bakersfield, the available drilling records (Figure 6) again show a close correspondence between the gravity anomaly and the greenstone belt. The quantity of greenstone of density contrast 0.25 g/cm^3 required to produce the gravity anomaly in our section is shown in Figure 3. As indicated previously for the Sierran greenstone, the cross-sectional shape of the body is not uniquely determined. For a given gravity anomaly the cross-sectional area, on the other hand, can be varied only if the density is also changed.

Comparable gravity, and possibly magnetic, anomalies also mark the belts of mafic igneous rocks in other ancient geosynclines. In Minnesota and Wisconsin a linear positive gravity anomaly of about 50 mgal, part of the mid-continent gravity high, is caused by Precambrian mafic volcanic and intrusive rocks [*Craddock et al.*, 1963]. *Zietz and Griscom* [1963] report a corresponding magnetic anomaly. For the Appalachians *Griscom* [1962] reports a strong linear positive gravity anomaly associated with mafic rocks. In the Precambrian shield of Canada there are large belts of positive anomaly associated with mafic belts [*Innes*, 1960; *Thompson and Garland*, 1957]. Our unpublished measurements across the greenstones of the Franciscan eugeosyncline in California reveal associated positive anomalies. These few examples serve to indicate that belts of positive gravity anomaly associated with mafic rocks are major and characteristic features of many ancient geosynclines.

Western granitic body. At the east side of the Great Valley a granitic body, which is quar-

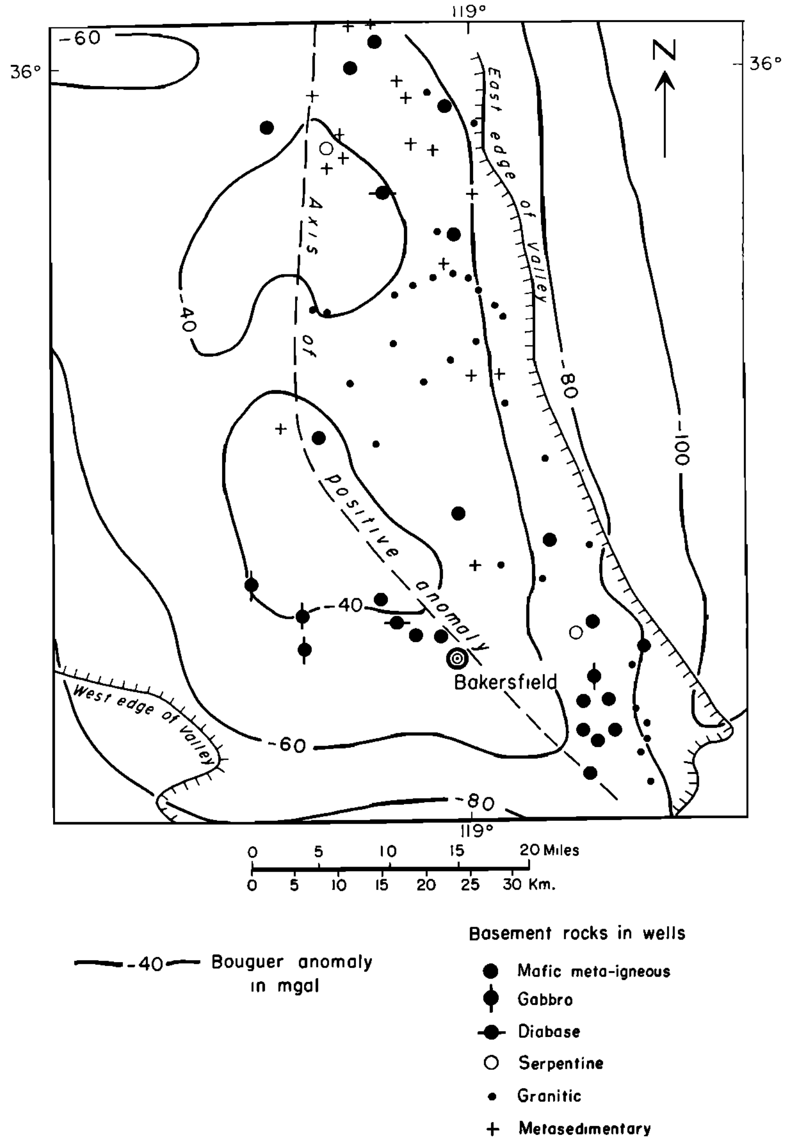

Fig. 6. Association of positive gravity anomaly with mafic basement rocks of Great Valley near Bakersfield. Gravity data from *Woollard* [1963]; rock data from *May and Hewitt* [1948].

ried at the town of Rocklin, has an associated local negative gravity anomaly of about 30 mgal. Here the separation of the negative anomaly from the two adjacent positive anomalies discussed above is somewhat arbitrary. A value considerably more or less than 30 mgal might be chosen with a complementary change in the adjacent positive anomalies and therefore in the inferred size of the greenstone bodies. The density of the granitic body is about 2.64 g/cm^3 (Table 3), which is close to the assigned density of the normal upper crust, 2.67 g/cm^3. Stated in another way, there is little density contrast with the metasedimentary schists and slates. The most likely explanation for the large anomaly, then, is that most of it originates at greater depth, where the density contrast is greater. The granitic body, which is assumed to have a fairly uniform density, extends downward into crustal material that increases in density with depth. With the density contrasts given in Figure 3, the body would extend downward about 15 km, but this formal solution should not be taken too seriously. The additional small, though appreciable, contrast of the measured density (2.64 g/cm^3) with normal upper crust, if included in the computation, would enlarge the computed negative anomaly by 5 to 10 mgal and result in an improved fit with the observations.

Sierran batholiths. Granitic rocks in enormous volume compose the principal basement rock in the Sierra Nevada and also in the western Basin Ranges. Only by virtue of deep erosion and consequent extensive exposure can these rocks be said to characterize the Sierra Nevada more than the area to the east. East of the Virginia Range, however, metamorphic basement rocks predominate over granitic rocks, so that general limits of the regional extent of plutonic intrusions can be drawn. The cross section (Figure 3) shows these limits at the basement surface, and Figure 4 shows that a broad gravity low is roughly coextensive with the granitic rocks. There is a strong probability that this gravity low is caused at least partly by the plutonic rocks [*Thompson and Sandberg*, 1958] and not simply by a 'Sierran root.' *Bateman et al.* [1963] demonstrated that the density of granitic rocks farther south in the Sierra Nevada varies from about 2.6 to 2.8 g/cm^3 and averages close to 2.67. There is an eastward decrease of about 0.08 g/cm^3 in average density, but the local variations of density within individual zoned plutons is usually even greater. *Oliver et al.* [1961] utilized the eastward decrease of density and an arbitrarily simple form and uniform depth of granitic bodies to arrive at a structure consistent with the gravity data. Since the depth of the granitic rocks and their density distribution throughout are unknown, we examined a range of possibilities.

The gravitational effect of a body of intermediate depth is shown in Figure 3. The density contrast with normal upper crust to a depth of 5 km below sea level is assumed to be negligible, as in the preceding analysis of the small western granitic body. Geologically, this approximates the fact that the average densities of the metasedimentary and granitic rocks as measured at the surface do not differ significantly, and only the more mafic metamorphic and igneous rocks, such as those in the greenstone belt, are considerably more dense. In the denser crust at greater depth the granitic rock is assumed to have a negative density contrast of 0.13 g/cm^3.

Figures 4, 7, and 8 illustrate respectively the body of intermediate size and the extremes of a very small body and a body of maximum size.

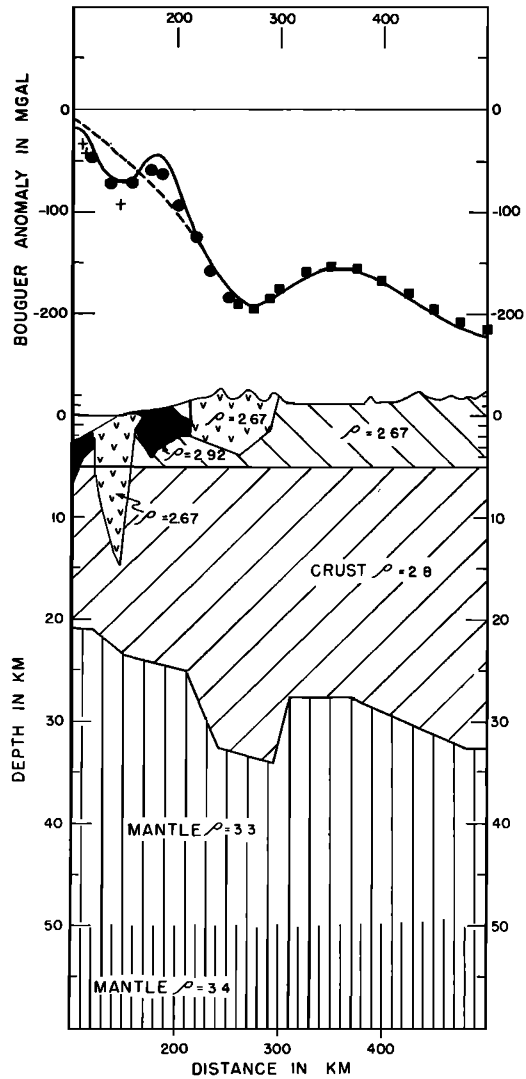

Fig. 7. *Bottom:* alternative section with deep root for Sierran highland region; patterns same as in Figure 4. *Top:* regional (dashed) and total gravity anomaly computed from section, compared with observed points.

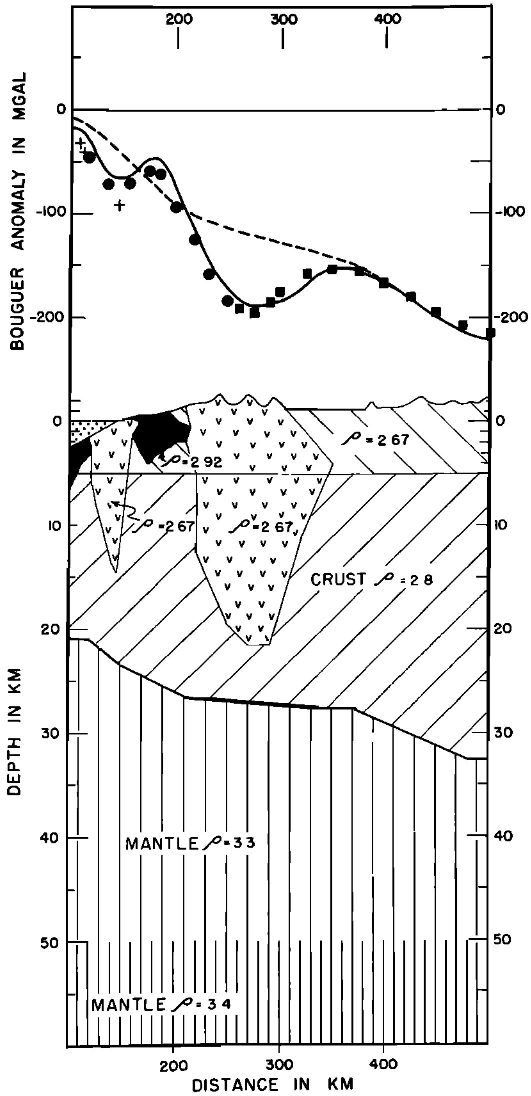

Fig. 8. *Bottom:* Alternative section with no root for Sierran highland region; patterns same as in Figure 4. *Top:* regional (dashed) and total gravity anomaly computed from section, compared with observed points.

We discuss these further in the section on the Sierran root.

Sedimentary deposits on the continental slope. Figure 4 shows the local negative anomaly (about 40 mgal) in the vicinity of the continental slope. When we first analyzed the gravity in this area we did not have the station on Farallon Island at the outer edge of the continental shelf. Even without this station the steep gradient could not be explained simply by the steep dip of the lower boundary of the crust, and we postulated thick sedimentary rocks at the continental slope and rise [*Thompson and Talwani,* 1959]. The possibility remained that the steep gravity gradient could be explained by an abrupt gradation of density from the oceanic to the continental crust. Subsequently we measured the gravity anomaly on Big Farallon, which is an outcrop of granitic rock, and we also learned of dredge hauls of Tertiary sedimentary rocks from the continental slope west of the Farallon Islands.

On the basis of an assumed density contrast of -0.4 g/cm^3, the sedimentary rocks have a thickness of about 3 km, as shown in Figure 4. More detailed measurements in this area could yield interesting information and might result in considerable modification of this preliminary interpretation.

Ocean basin. The water at the west end of the profile is about 4.8 km deep, and the 13-km depth to the base of the crust is slightly greater than the seismically determined depth of 11 km [*Vacquier,* 1962]. The gravity calculations have been made on the assumption of a flat earth. The correction for curvature can be of appreciable magnitude, but it varies slowly. It is estimated that if the derived crustal thickness were modified with a correction for curvature, the principal difference from the present section would be a decrease in the thickness in the ocean area by perhaps 1 or 2 km. This would improve the agreement between the present section and the seismically deduced value.

Coastal area and Great Valley. From a thickness at the coast of 21 km, chosen on the basis of seismic refraction data, the crust thins eastward slightly under the Great Valley. There is no evidence of a sufficient crustal thinning under the valley to compensate the low-density sediments isostatically, but it is interesting that the greenstone in this region provides a partial compensation for the sediments, wholly within the crust. Also, the greenstone should cause seismic refraction anomalies, which might be erroneously interpreted as indicating a thinner crust. The slight bulge we have indicated at the base of the crust under the Coast Ranges may not exist, for the gravitational effect of this bulge is hardly noticeable at the surface; hence the implied compensation of the Coast Ranges cannot be proved. The crustal thickness under the Great Valley agrees approximately with the seismic thickness reported by *Eaton* [1963].

The crustal thickness obtained by *Press* [1957] from a study of the velocity of Rayleigh waves in the San Francisco area is worth comparing with the thicknesses cited above. Press obtained a thickness of 30 km on the assumption that the crust and upper mantle seismic velocities were typical of continental areas. (Actually the measurements were referred to a 35-km crust for Africa as a standard.) His data [from *Evernden,* 1954] are shown in Figure 9*a*. We computed a dispersion curve for the indicated structure, using a digital computer program written by *Dorman* [1962]. As stated earlier, the transverse wave velocities were chosen by an assumption of a Poisson's ratio of 0.278, and the longitudinal wave velocities and densities were related by the Nafe-Drake curve. The fit of the computed curve to the data points is good (Figure 9*a*); thus we can say that the phase velocity data are not in disagreement with a thin crust of 21 km under the coastal area, overlying a mantle with a zone of lower than normal velocity which extends down to 50 km. The thin crust cannot be related to proximity of the ocean as Press suggested, but rather must be considered normal continental thickness for areas overlying an altered mantle. We conclude that the thickness does not change substantially eastward for about 200 km or until the Sierra Nevada is approached.

A phase velocity curve is also computed for the Great Valley (Figure 9*b*). No observational data are now available for comparison.

Sierran highland area—'Root of the Sierra Nevada.' Byerly [1938*a, b;* 1939] demonstrated that P_n waves arriving at Tinemaha and Haiwee from near earthquakes with epicenters to the west and northwest were systematically delayed with respect to arrivals at Fresno (Figure 1). Arrivals from other azimuths were not delayed. Byerly attributed this delay to a deep granitic root for the Sierra Nevada, as proposed earlier by *Lawson* [1936] on isostatic grounds. Since Byerly's earlier findings, many geophysical data have been obtained which generally support the idea of a root. One important point is that if a root is associated with high topography and large negative Bouguer anomalies, it must underlie the entire Sierran highland area, that is, the Sierra Nevada plus the western ranges of the Basin and Range province. Thus Tinemaha and Haiwee (their position is roughly comparable to the valley west of the Carson Range in the profile shown in Figure 4) would not be in the 'lee' of the root, as Byerly suggested, but on top of it.

The latest seismic information on the nature of the Sierran root comes from the work of *Eaton* [1963]. From seismic refraction work across the Sierran highland area and along the eastern flank of the Sierra Nevada, he estimated that the crust is more than 40 km thick. Eaton (personal communication, 1964) reinforces this estimate from profiles shot longitudinally along the crest of the Sierra Nevada.

In the present paper we present three interpretations of the gravity data over the Sierran highland area (Figures 4, 7, and 8). These interpretations are all within the framework of the simplified model that we have considered, and they result from different choices of the regional and residual anomalies. In case 3 (Figure 8) the 'extra low' in the Bouguer anomaly has been considered a local anomaly and attributed to a large thickening of the granite batholiths. In case 2 (Figure 7) the entire negative anomaly has been considered a regional anomaly and attributed to a thicker crust. Case 1 is an intermediate case (Figure 4); part of the anomaly is ascribed to the granite batholiths and part of the anomaly to a thickened crust. These computations illustrate how the same gravity data may admit a range of geologically reasonable interpretations. In case 2 the mantle is raised on either side of the root. Also, the presence of the greenstone body on the west helps to explain the steep gradient of the Bouguer anomaly. Even somewhat steeper gradients than those in our section can be accommodated. This implies that the root could possibly be even deeper than that shown in Figure 7. On the other hand, it cannot be indefinitely deep; if it were, the calculated anomalies would be impossible to match with the observed Bouguer gradients on either side.

The root of the Sierran highland area as determined by Eaton is at least 6 km deeper than that in case 2. The conflict with the gravity model becomes even greater when we consider that case 2 is an extreme possibility (within our model) and that the granite batholiths proba-

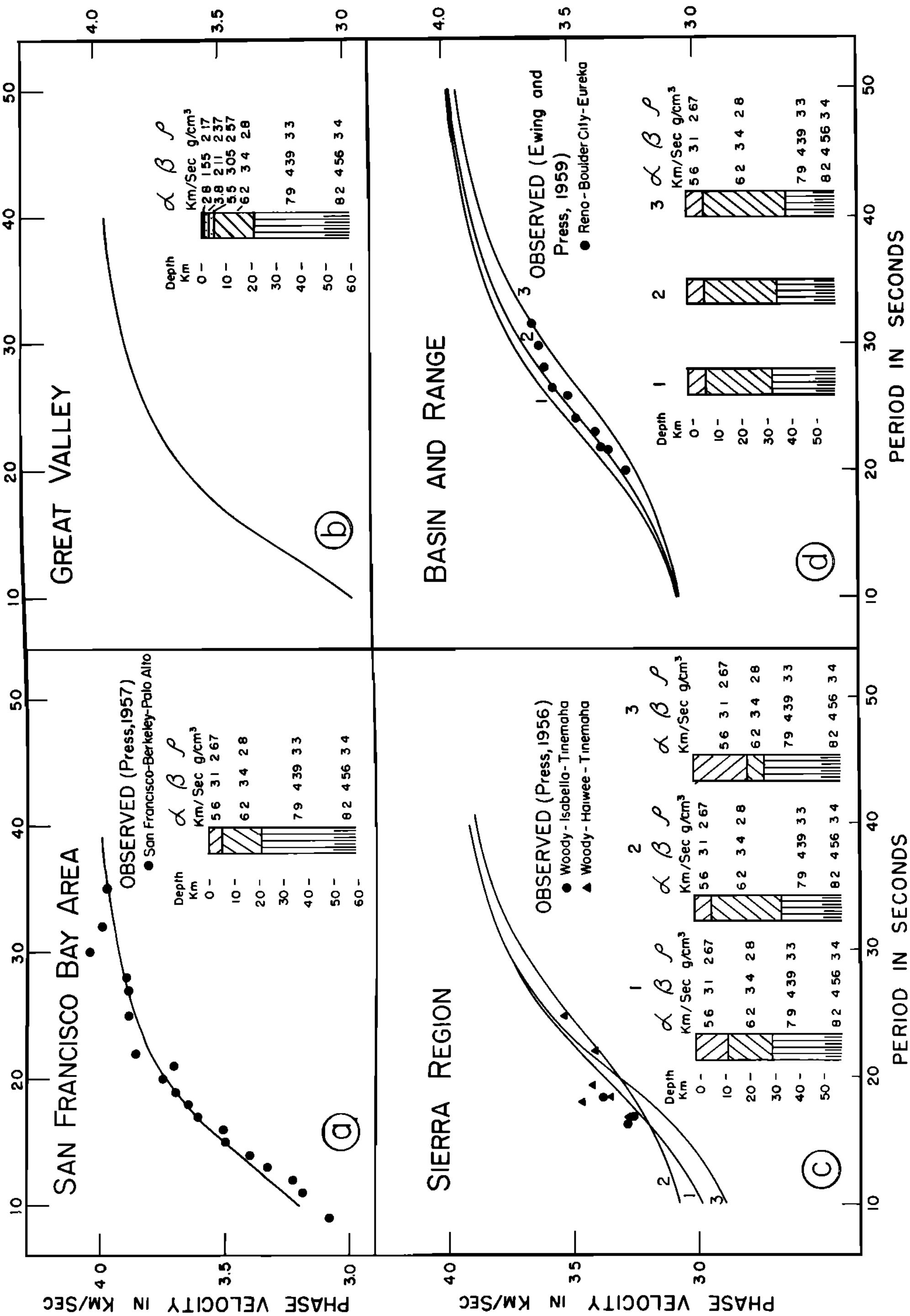

Fig. 9. Computed and observed Rayleigh wave dispersion curves.

bly contribute to the negative anomaly. If we accept Eaton's interpretation, we evidently need to modify some of the assumptions used in the gravity calculations. As the gravity data do not permit much modification of the total masses involved, two main possibilities emerge. Either the lower part of the crust is unusually dense, in which case it can be shown that more lower crust is required to produce the same mass deficiency, or else there is extra mass in the upper mantle beneath the Sierran highland region. The latter possibility is the less attractive because even if the anomalous upper mantle were completely absent beneath the highland there would still not be sufficient mass without a change in the crust also. On the other hand, the possibility of a denser lower crust accords with the geologically likely condition of a much larger than normal density (say 3.0 g/cm^3) in the part of the crust directly under the batholiths. If the batholiths which are lighter than normal, were formed by partial melting and differentiation within the crust, it is quite likely that the remaining rocks below them in the crust are heavier than normal.

Whatever structure finally evolves from more detailed seismic data, it must satisfy the gravity data by a direct computation. The important restrictions that gravity data impose on this problem are that the Bouguer gradients be satisfied and that the total gravitational attraction not conflict with the total mass in a standard section elsewhere.

Phase velocity data from the southern Sierra Nevada [*Press*, 1956] are plotted in Figure 9*c* and are compared with theoretical curves computed for the structures corresponding to cases 1, 2, and 3 for the Sierran highland region. The scatter of the data, as well as the short range of periods in the data, makes comparison difficult; nevertheless, the shapes of the curves suggest that case 2 (deep root) may be the best case, and the fit might be improved by increasing the velocities in the crust.

Basin and Range province. The depths determined to the base of the crust from Carson Sink eastward correspond only roughly with those determined seismically by Eaton, since his depths are about 5 km smaller. He suggested that the indications of an unusually thin crust under Fallon, Nevada, might be due to the presence of a high-velocity intrusive body under the shot point at Fallon. Alternatively, and perhaps more likely, the gravity data can be reconciled with a thinner crust if the anomalous upper mantle has a lower density (and velocity), and/or a greater thickness, than elsewhere. A higher mantle temperature would tend to produce a thicker anomalous upper mantle in our interpretation.

Phase velocity data are available (Figure 9*d*) for the Reno–Boulder City–Eureka tripartite net [*Ewing and Press*, 1959]. This covers a large area, the southern part of which has a somewhat lower average elevation than that along our profile and the western part of which overlaps the Sierran highland region. The computed curve 2 in Figure 9*d* refers to the section at the eastern end of the profile.

Curve 1 corresponds to a slightly thinner crust, and curve 3 to a somewhat thicker crust. The other parameters are not altered. Agreement of data points with curve 2 lends support to the structure derived for the Basin and Range province.

Mass anomaly. A mass anomaly is useful to indicate directly the excesses or deficiencies of mass in the derived section. The mass in columns of unit area and a fixed depth, below which lateral inhomogeneities are assumed to be absent, is calculated along the profile. A constant, equivalent to the mass of the standard column used in the gravity computations, is subtracted from the preceding quantity to obtain the mass anomaly.

The mass anomaly gives directly the state of isostatic balance along the profile of the deduced section. It suffers from the same ambiguities as the deduction of the structure section. If the best estimate of actual structure is made in the structure section, the mass anomaly must also represent the best possible estimate of the isostatic equilibrium.

The mass anomaly profile as derived in the present paper has two defects. Two-dimensionality is assumed and the effect of earth curvature is neglected. It is estimated that if proper allowance were made for curvature the mass anomaly would become close to zero in the Pacific basin and the changes elsewhere would be small. The lack of a perfect fit between the computed and observed Bouguer anomalies has also been ignored in computing the mass anomaly.

A convenient unit for expressing the mass anomaly is 10^5 g/cm^2. A gravity anomaly of 41.9 mgal corresponds roughly to 1 mass anomaly unit. (A flat layer of infinite extent 1 km thick and with a density difference of 1 g/cm^3 will give rise to a mass anomaly of 1 unit.)

The most prominent mass anomaly along the entire profile is about −3 units on the continental slope (Figure 4). Isostatic anomalies computed by Vening Meinesz at his station on the slope (at −74 km along the profile) range from −47 to −79 mgal. If the deduced structure section is correct, the negative zone extends over the entire slope and reaches a minimum about halfway down the slope (at −87 km along the profile).

Over the Coast Ranges the mass anomaly is nearly zero, implying isostatic compensation, and over the Great Valley the largest anomaly is −1 unit, implying a lack of complete compensation for the sediments. There is another minimum (−2.5 units) at 140 km. This anomaly is correlated with the Rocklin granite.

The mass anomaly is positive over the eastern greenstone body and fluctuates widely over the Sierran highland region, but it retains an average positive value. The fluctuations correspond to the ridges and valleys. One could assume local roots for each hill or ridge, as is done tacitly in the computation of isostatic anomalies. This would eliminate the fluctuations of the mass anomaly. But since the gravitational effect of these local roots would be nearly zero at the surface, we preferred not to show any such hypothetical roots.

The mass anomaly becomes less positive over the Sierran highland region for case 2, in which the root is much deeper, and becomes more positive for case 3, in which the compensation is very shallow. If we consider the gravity anomalies we can see the corresponding situation—the free air anomalies (which correspond to a zero depth of compensation) are positive while the Pratt-Hayford anomalies (for a large depth of compensation) are negative.

Farther eastward over the Basin and Range province the mass anomaly is nearly zero.

Tectonic evolution and the anomalous upper mantle. A promising objective of geophysical investigations of the crust and mantle is a reconstruction of the history and causes of the structural evolution. Processes that affect crustal thickness include erosion and deposition; extension, compression, and plutonic activity within the crust; and addition (and perhaps subtraction) of crustal material derived from the mantle. Theories of origin of the anomalous upper mantle are highly speculative, but a process involving mineral phase changes that are sensitive to pressure-temperature conditions appears most promising.

Starting with the question of crustal thickness, we note the spatial coincidence of the Sierran highland area with the core of the Paleozoic and Mesozoic Cordilleran eugeosyncline. The Cordilleran miogeosyncline lay to the east, in eastern Nevada and western Utah, and we may suppose that the edge of the continent, as defined by the top of the continental slope, once stood near central Nevada. The center of eugeosynclinal deposition had shifted westward by Cretaceous time, when sediments of the Franciscan formation were accumulating in the Coast Range area and shelf or slope sediments were accumulting in the area of the present Great Valley. Evidently the continent had grown toward the west.

Beneath the deposits of the Cordilleran and Franciscan eugeosynclines sialic basement rocks are generally unknown. Those on the seaward side of the San Andreas fault, which cuts off the west side of the Franciscan eugeosyncline, are thought to have been displaced laterally for a great distance. It is reasonable to suppose that both of these great accumulations were laid down on an essentially oceanic crust. If this is so, the crust may have increased in thickness primarily by the addition of sediments on top. A large but undetermined lateral compression further added to the thickness. Paleozoic and Mesozoic strata on opposite sides of the Sierra Nevada dip steeply into the plutonic core [*Bateman et al.*, 1963], and *King* [1959] regards them as the flanks of a great crustal downfold whose trough is obliterated by the granitic batholiths.

Lateral sedimentary additions to the continental crust cannot be explained without facing the consequences of crustal destruction by erosion elsewhere. The continents can hardly have grown simply by erosional thinning of the crust and lateral accretion of the erosion products, as *Gilluly* [1963] has shown dramatically that to fill the Rocky Mountain geosyncline would require a volume equal to a 500-meter slice from the entire United States. If we accept the idea of continental growth, material must certainly have been added to the crust from the mantle. Presumably, the added material is mainly basaltic in composition, becoming more silicic by sedimentary processes in successive cycles of erosion and deposition. Metamorphism, plutonic activity, and igneous differentiation complement the sedimentary processes, particularly in the production of the large volume of quartz that now resides in sandstone.

The anomalous upper mantle may well hold the key to the Cenozoic tectonic history of this region. Without the anomalous mantle, much of the area would have too thin a crust to stand in equilibrium above sea level. We may imagine that the anomalous mantle is composed of partly serpentinized peridotite [*Hess*, 1955] or of plagioclase peridotite [*Ringwood*, 1962]. We do not think that partly serpentinized peridotite is a good possibility because (1) at a depth of 50 km the anomalous mantle is probably hotter than 500°C, the temperature which is considered to limit the formation of serpentine; (2) the limited range of velocity would require a surprisingly fortuitous degree of partial serpentinization; (3) the volume increase accompanying serpentinization is about equal to the added volume of water; deeper in the mantle where the water is assumed to have been driven out of the rocks there should be a complementary loss of volume; and (4) the chemical composition of serpentine is not a satisfactory source for the volcanic additions to the crust.

The mineral phase changes in the reversible reaction

$$\underset{\text{eclogite}}{\text{garnet} + \text{pyroxene A}} \rightleftharpoons \underset{\text{basalt}}{\text{plagioclase} + \text{pyroxene B}}$$

have been studied by numerous investigators; the basic pressure-temperature relations are summarized by *Yoder and Tilley* [1962]. *Thompson* [1960] suggested the probable importance of this reaction in the Basin and Range province on the basis of the tectonic history and the then-known crustal structure. *Ringwood* [1962] suggested that the primitive, undifferentiated mantle has a composition corresponding to about 1 part of eclogite and 4 parts of peridotite. At appropriate depths in the mantle this rock would be a garnet peridotite or possibly a pyroxene peridotite [*Green and Ringwood*, 1963] and would be convertible at the phase boundary according to the reaction

$$\underset{\text{garnet peridotite}}{\text{garnet} + \text{olivine} + \text{pyroxenes}} \rightleftharpoons \underset{\text{plagioclase peridotite}}{\text{plagioclase} + \text{olivine} + \text{pyroxenes}}$$

With the assumed proportions, 1 part of eclogite or basalt to 4 parts of peridotite, the low-pressure phase, plagioclase peridotite, has an expected velocity in the range 7.8 to 7.9 km/sec and density in the range 3.2 to 3.3 g/cm^3. The high-pressure phase has the high velocity 8.2 and high density 3.3 to 3.4. Plagioclase peridotite supplies an attractive explanation of the anomalous mantle. We suggest that the base of the crust in the continental part of the region under study is a boundary between material of basaltic composition in the lower crust and plagioclase peridotite in the anomalous upper mantle. The lower boundary of the anomalous upper mantle represents a gradational phase boundary between plagioclase peridotite and garnet peridotite (or pyroxene peridotite) of the normal mantle. Yoder and Tilley indicate that the gradational zone may be several kilometers thick; the temperature curves of *Birch* [1955] for low and high thermal gradients in continental areas indicate that the center of the zone could be 40 to 50 km deep in regions of normal heat flow and, of course, deeper in regions of high heat flow. This depth is in reasonable agreement with our section.

Phase change in the anomalous upper mantle may seem to offer an attractive hypothesis for explaining uplift or depression of the land surface, but the maximum expansion represented by 25 km of such a material is only about 1 km, whereas the actual Cenozoic uplift in many places exceeds 2 km. We suggest, instead of a single cycle of expansion, a more complex process that involves differentiation of the anomalous mantle and a renewed supply of primitive mantle material from below. The plagioclase peridotite may differentiate by partial melting to form basalt, which is added to the crust, and residual peridotite, which becomes part of the normal mantle. A local upwelling or turnover in the mantle, or alternatively a regional convection current, may supply fresh garnet peridotite to the top of the mantle, where it would expand to form a new layer of anomalous mantle. Indirect evidence of large-scale mantle movements is apparent in the horizontal displacements along major faults such as the San Andreas fault. The hypothesis of expansion, differentiation, and a renewed supply of primitive mantle material from below has the advantage of explaining broad plateau uplifts and also of accounting for accretion to the base of the continental crust; the accretion seems necessary to balance the losses by erosion and lateral continental growth.

Conclusions

Seismic refraction, gravity, and phase velocity data agree on a structure consisting of a 20-km crust under the Coast Range and Great Valley areas, thickening under the Sierra Nevada and Basin and Range province. This whole area is underlain by an anomalous upper mantle with a velocity and density about 3% less than normal. To a first approximation the anomalous mantle can be considered a uniform layer having a density 0.1 g/cm^3 less than normal mantle, and in this model the anomalous mantle extends to a depth of 50 km. Actually, the lower boundary is probably gradational.

The seismic refraction work indicates a thicker crust under the Sierran highland region (more than 40 km) and a thinner crust under the Basin and Range province (22 km near Fallon) than is required in a simple gravity model. The two kinds of data can be reconciled if the crust beneath the granitic rocks in the Sierran highland region is unusually dense and if the anomalous upper mantle in the Basin and Range province is thicker and/or less dense than elsewhere. If the granitic rocks were formed by partial melting of crustal material, a dense residue below them is to be expected. In the Basin and Range region an anomalous upper mantle that is thicker and less dense than usual could be caused by high mantle temperatures in that volcanic region.

The 'root' beneath the Sierran highland region (Sierra Nevada and western Basin Ranges) is not limited to the Sierra Nevada proper, as has generally been supposed. This root and the voluminous granitic rocks constitute the core of the Cordilleran eugeosyncline.

The anomalous upper mantle, if it represents an alteration of normal mantle, can explain about 1 km of the uplift which took place over much of the region in Cenozoic times. To explain all of the uplift in the Basin Ranges and the much greater uplift in the Sierra Nevada by this means would require some sort of renewal of the anomalous mantle.

An anomalous upper mantle characterizes other regions of present or recent tectonic activity, such as Japan and the mid-Atlantic ridge. The anomalous mantle of western North America possibly extends southward to form a continuous belt with the anomalous mantle beneath the crest of the east Pacific rise [*Menard*, 1960]. An anomalous upper mantle may be an essential part of the heat engine driving the tectonic activity of these regions.

The gravity anomaly near the outer edge of the continental shelf suggests a thick sedimentary body on the continental slope.

The belt of positive gravity anomalies at the Great Valley is associated with mafic rocks of the western Sierra greenstone belt. Comparable belts of mafic lavas accompanied by mafic and ultramafic intrusions are marked by similar anomalies in other ancient geosynclines.

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References

Balsley, J. R., Total-intensity aeromagnetic profile from Denver, Colorado to Point Reyes, Calif., *U. S. Geol. Surv. Open File Rept.*, 1953.

Bateman, P. C., L. D. Clark, N. K. Huber, J.

G. Moore, and C. D. Rinehart, The Sierra Nevada batholith—a synthesis of recent work across the central part, *U. S. Geol. Surv. Profess. Paper 414-D*, 46 pp., 1963.

Bayoumi, A. I., Gravity and magnetic study in the San Joaquin Valley, Ph.D. thesis, Stanford University, 1961.

Berg, J. W., Jr., K. L. Cook, H. D. Narans, Jr., and W. M. Dolan, Seismic investigation of crustal structure in the eastern part of the Basin and Range province, *Bull. Seismol. Soc. Am., 50*, 511–535, 1960.

Birch, F., Physics of the crust, *Geol. Soc. Am. Spec. Paper 62*, 101–117, 1955.

Byerly, P., Comments on 'The Sierra Nevada in the light of isostasy,' by A. C. Lawson, *Bull. Geol. Soc. Am., 48*, 2025–2031, 1938*a*.

Byerly, P., Determination of deep seated crustal structure in California (abstract), *Bull. Geol. Soc. Am., 49*, 1946–1947, 1938*b*.

Byerly, P., Near earthquakes in central California, *Bull. Seismol. Soc. Am., 29*, 427–462, 1939.

Chesterman, C. W., Descriptive petrography of rocks dredged off the coast of central California, *Proc. Calif. Acad. Sci., 27*, 359–374, 1952.

Craddock, C., E. C. Thiel, and B. Gross, A gravity investigation of the Precambrian of southeastern Minnesota and western Wisconsin, *J. Geophys. Res., 68*, 6015–6032, 1963.

Diment, W. H., S. W. Stewart, and J. C. Roller, Crustal structure from the Nevada test site to Kingman, Arizona, from seismic and gravity observations, *J. Geophys. Res., 66*, 201–214, 1961.

Dorman, J., Period equation for waves of Rayleigh type on a layered liquid-solid half space, *Bull. Seismol. Soc. Am., 52*, 389–397, 1962.

Duerksen, J. A., Pendulum gravity data in the United States, *U. S. Coast & Geod. Surv. Spec. Publ. 244*, 218 pp., 1949.

Eaton, J. P., Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic-refraction measurements, *J. Geophys. Res., 68*, 5789–5806, 1963.

Evernden, Jack F., Direction of approach of Rayleigh waves and related problems, 2, *Bull. Seismol. Soc. Am., 44*, 159–184, 1954.

Ewing, J., and M. Ewing, Seismic-refraction measurements in the Atlantic Ocean basins, in the Mediterranean Sea, on the mid-Atlantic ridge, and in the Norwegian Sea, *Bull. Geol. Soc. Am., 70*, 291–317, 1959.

Ewing, M., and F. Press, Determination of crustal structure from phase velocity of Rayleigh waves, 3, The United States, *Bull. Geol. Soc. Am., 70*, 229–244, 1959.

Gilluly, J., The tectonic evolution of the western United States, *Quart. J. Geol. Soc. London, 119*, 133–174, 1963.

Grantz, A., and I. Zietz, Possible significance of broad magnetic highs over belts of moderately deformed sedimentary rocks in Alaska and California, *U. S. Geol. Surv. Profess. Paper 400 B*, B342–B347, 1960.

Green, D. H., and A. E. Ringwood, Mineral assemblages in a model mantle composition, *J. Geophys. Res., 68*, 937–945, 1963.

Griscom, A., Tectonic significance of the Bouguer gravity field of the Applachian system (abstract), Program of Geological Society America meeting in Houston, p. 63A, 1962.

Gutenberg, B., Seismological evidence for roots of mountains, *Bull. Geol. Soc. Am., 54*, 473–498, 1943.

Hanna, G. D., Geology of the continental slope off central California, *Proc. Calif. Acad. Sci., 27*, 325–358, 1952.

Harrison, J. C., G. L. Brown, and F. N. Spiess, Gravity measurements in the northeastern Pacific Ocean, *Trans. Am. Geophys. Union, 38*, 835–840, 1957.

Healy, J. H., Crustal structure along the coast of California from seismic-refraction measurements, *J. Geophys. Res., 68*, 5777–5788, 1963.

Herrin, E., and J. Taggart, Regional variations in P_n velocity and their effect on the location of epicenters, *Bull. Seismol. Soc. Am., 52*, 1037–1046, 1962.

Hess, H. H., Serpentines, orogeny, and epeirogeny, *Geol. Soc. Am. Spec. Paper 62*, 391–407, 1955.

Innes, M. J. S., Gravity and isostasy in northern Ontario and Manitoba, *Publ. Dominion Obs., Ottawa, 21*, 265–338, 1960.

Irwin, W. P., and G. D. Bath, Magnetic anomalies and ultramafic rock in northern California, *U. S. Geol. Surv. Profess. Paper 450-B*, B65–67, 1962.

Ivanhoe, L. F., Jr., A gravity maximum in the Great Valley of California due to the isostatic effect of the Sierra Nevada, *Geophysics, 22*, 62–66, 1957.

Jeffreys, H., Some normal earthquakes, *Geophys. J., 6*, 493–508, 1962.

Johnston, W. D., Jr., Gravity section across the Sierra Nevada, *Bull. Geol. Soc. Am., 51*, 1391–1396, 1940.

Katz, S., Seismic study of crustal structure in Pennsylvania and New York, *Bull. Seismol. Soc. Am., 45*, 303–325, 1955.

King, P. B., *The Evolution of North America*, Princeton University Press, 189 pp., 1959.

Lawson, A. C., *Geologic Atlas of the United States, San Francisco Folio*, U. S. Geological Survey, 1914.

Lawson, A. C., The Sierra Nevada in the light of isostasy, *Bull. Geol. Soc. Am., 47*, 1691–1712, 1936.

May, J. C., and R. L. Hewitt, The basement complex in well samples from Sacramento and San Joaquin valleys, California, *J. Mines Geol., 44*, 129–158, 1948.

Menard, H. W., The east Pacific rise, *Science, 132*, 1737–1746, 1960.

Oliver, H. W., and D. R. Mabey, Anomalous gravity field in east-central California, *Bull. Geol. Soc. Am., 74*, 1293–1298, 1963.

Oliver, H. W., L. C. Pakiser, and M. F. Kane, Gravity anomalies in the central Sierra Nevada,

California, *J. Geophys. Res., 66*, 4265–4271, 1961.
Pakiser, L. C., Structure of the crust and upper mantle in the western United States, *J. Geophys. Res., 68*, 5747–5756, 1963.
Press, F., Determination of crustal structure from phase velocity of Rayleigh waves, 1, Southern California, *Bull. Geol. Soc. Am., 67*, 1647–1658, 1956.
Press, F., Determination of crustal structure from phase velocity of Rayleigh waves, 2, San Francisco Bay region, *Bull. Seismol. Soc. Am., 47*, 87–88, 1957.
Press, F., Crustal structure in the California-Nevada region, *J. Geophys. Res., 65*, 1039–1051, 1960.
Ringwood, A. E., A model for the upper mantle, *J. Geophys. Res., 67*, 857–867, 1962.
Stuart, D. J., J. C. Roller, W. H. Jackson, and G. H. Mangan, Seismic propagation paths, travel times, and crustal structure in the western United States, *Geophysics, 29*, 178–187, 1964.
Taliaferro, N. L., Geology of the San Francisco Bay counties, in *Geological Guidebook of the San Francisco Bay Counties, Calif. Dept. Nat. Resources, Div. Mines, Bull., 154*, 1951.
Talwani, M., J. L. Worzel, and M. Landisman, Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone, *J. Geophys. Res., 64*, 49–59, 1959*a*.
Talwani, M., G. H. Sutton, and J. L. Worzel, Crustal section across the Puerto Rico trench, *J. Geophys. Res., 64*, 1545–1555, 1959*b*.
Tatel, H. E., and M. A. Tuve, Seismic exploration of a continental crust, *Geol. Soc. Am. Spec. Paper 62*, 35–50, 1955.
Thompson, G. A., Gravity measurements between Hazen and Austin, Nevada, *J. Geophys. Res., 64*, 217-239, 1959.
Thompson, G. A., Problem of late Cenozoic structure of the Basin Ranges, *Intern. Geol. Congr., 21st, Copenhagen, 1960*, part 18, 62–68, 1960.
Thompson, G. A., and C. H. Sandberg, Structural significance of gravity surveys in the Virginia City–Mount Rose area, Nevada and California, *Bull. Geol. Soc. Am., 69*, 1269–1282, 1958.
Thompson, G. A., and M. Talwani, Crustal section across California and Sierra Nevada (abstract), *Bull. Geol. Soc. Am., 70*, 1688, 1959.
Thompson, L. G. D., and G. D. Garland, Gravity measurements in Quebec (south of latitude 52°N), *Publ. Dominion Obs., Ottawa, 19*, 111–167, 1957.
Vacquier, V., Magnetic evidence for horizontal displacements in the floor of the Pacific Ocean, in *Continental Drift*, edited by S. K. Runcorn, Academic Press, New York, 1962.
Vening Meinesz, F. A., *Gravity Expeditions at Sea, 1923–1938*, vol. 4, Waltman, Delft, 233 pp., 1948.
Woollard, G. P., Transcontinental gravitational and magnetic profile of North America and the relation to geologic structure, *Bull. Geol. Soc. Am., 54*, 746–790, 1943.
Woollard, G. P., Results of cooperative gravity studies with University of Wisconsin, in *International Gravity Measurements*, by George P. Woollard and John C. Rose, 518 pp., Society of Exploration Geophysicists, Tulsa, Okla., 1963.
Yoder, H. S., Jr., and C. E. Tilley, Origin of basalt magmas: an experimental study of natural and synthetic rock systems, *J. Petrol., 3*, 342–532, 1962.
Zietz, I., and A. Griscom, Geology and aeromagnetic expression of the midcontinent gravity high (abstract), Program of Geological Society of America meeting in New York, p. 184A, 1963.

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