UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 8

STRUCTURE OF THE CRUST AND UPPER MANTLE IN THE WESTERN UNITED STATES*

By

L. C. Pakiser**

DENVER, COLORADO

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-8
January 28, 1963

Dr. Charles C. Bates
Chief, VELA UNIFORM Branch
Advanced Research Projects Agency
Department of Defense
Pentagon
Washington 25, D. C.

Dear Dr. Bates:

Transmitted herewith are 10 copies of:

TECHNICAL LETTER NUMBER 8

STRUCTURE OF THE CRUST AND UPPER MANTLE IN

THE WESTERN UNITED STATES*

By

L. C. Pakiser**

We intend to submit this report for publication in a scientific journal.

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-62.

** U. S. Geological Survey, Denver, Colorado.

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Abstract. Seismic waves generated by underground nuclear and chemical explosions have been recorded in a network of nearly 2,000 stations in the western conterminous United States as a part of the VELA UNIFORM program. The network extends from eastern Colorado to the California coastline and from central Idaho to the border of the United States and Mexico.

The speed of compressional waves in the upper-mantle rocks ranges from 7.7 km/sec in the southern part of the Basin and Range province to 8.2 km/sec in the Great Plains province. In general, the speed of compressional waves in the upper-mantle rocks tends to be nearly the same over large areas within individual geologic provinces.

Measured crustal thickness ranges from less than 20 km in the Central Valley of California to 50 km in the Great Plains province. Changes in crustal thickness across provincial boundaries are not controlled by regional altitude above sea level unless the properties

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** U. S. Geological Survey, Denver, Colorado.

of the upper mantle are the same across those boundaries. The crust tends to be thick in regions where the speed of compressional waves in the upper-mantle rocks (and presumably the density) is high, and tends to be relatively thin where the speed of compressional waves in the upper-mantle rocks (and density) is lower. Within the Basin and Range province, crustal thickness seems to vary directly with regional altitude above sea level. Evidence that a layer of intermediate compressional-wave speed exists in the lower part of the crust has been accumulated from seismic waves that have traveled least-time paths, as well as secondary arrivals (particularly reflections).

On a scale that includes many geologic provinces, isostatic compensation is related largely to variations in the density of the upper-mantle rocks. Within geologic provinces or adjacent provinces, isostatic compensation may be related to variations in the thickness of crustal layers. Regions of thick crust and dense upper mantle have been relatively stable in Cenozoic time. Regions of thinner crust and low-density upper mantle have had a Cenozoic history of intense diastrophism and silicic volcanism.

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By

L. C. Pakiser**

Introduction. The individual papers in the following pages represent the preliminary results of a field program of long-range seismic-refraction recording that began in April 1960 and is still in progress. This paper is intended as an introduction, summary, and review of these papers. It is not intended as a comprehensive review of the related literature, but the work of others bearing closely on our results is cited in this paper and throughout the symposium that follows. The work is sponsored by the Advanced Research Projects Agency (ARPA) of the U. S. Department of Defense as a part of the VELA UNIFORM program. In less than 2 years a network of profiles of about 1,500 recordings of seismic waves generated by chemical explosions in drilled holes and bodies of water has been extended from eastern Colorado to the California coastline and from central Idaho to southern California (Fig. 1). Most of these profiles have been reversed, and some have included intermediate shotpoints. In addition to the network of profiles from chemical explosions,

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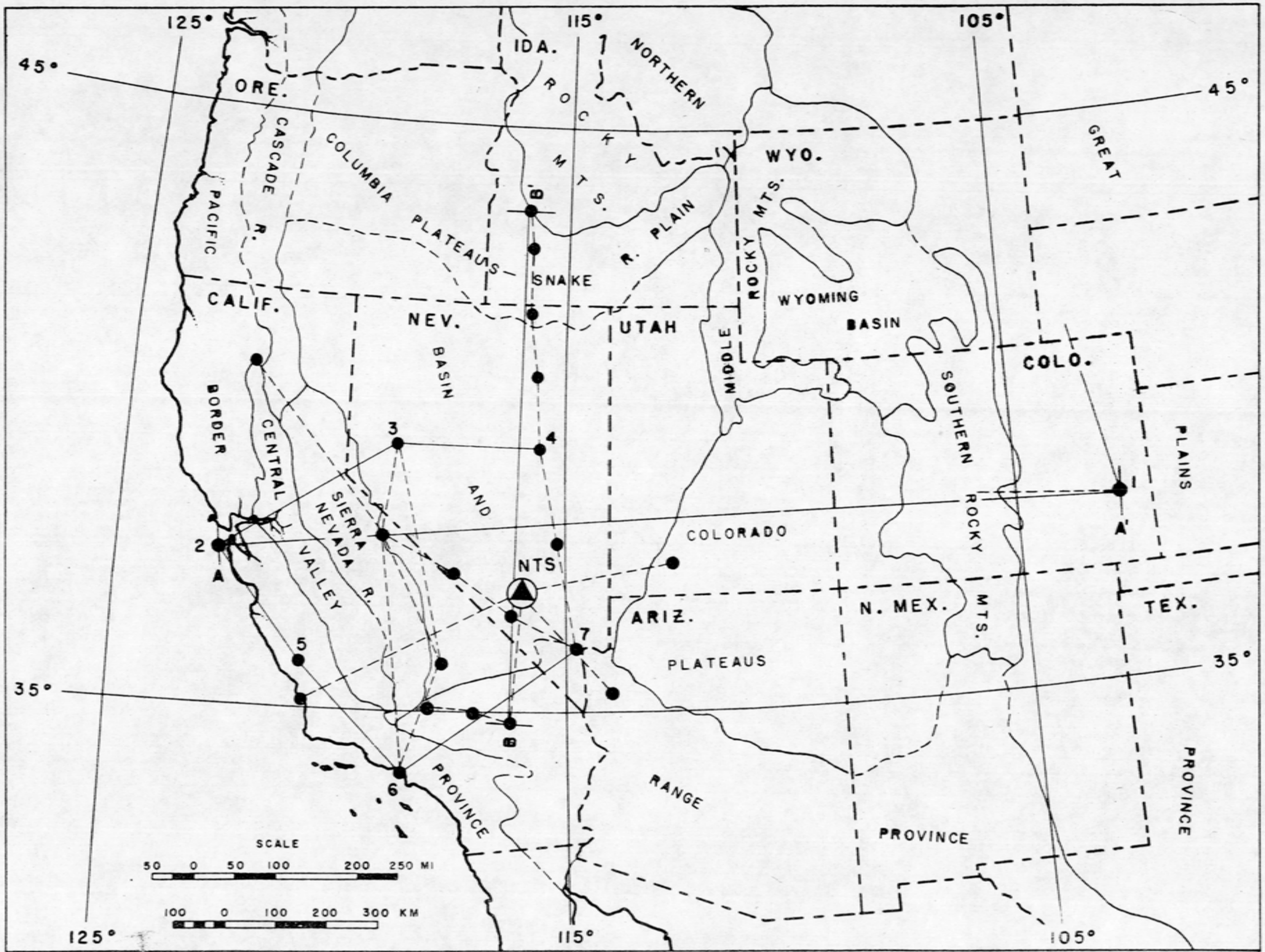

Figure 1.-- Locations of seismic-refraction profiles recorded from chemical explosions. Solid lines are profiles included in this symposium; dashed lines are not included. Numbered shotpoints are: (1) Nee Granda Res., near Lamar, Colo., (2) San Francisco, Calif., (3) Fallon, Nev., (4) Eureka, Nev., (5) Camp Roberts, Calif., (6) Santa Monica Bay, Calif., (7) Lake Mead, Ariz. and Nev. Profile A-A' extends from San Francisco to Lamar; Profile B-B' extends from Ludlow, Calif., to Boise, Ida.

seismic waves generated by underground nuclear explosions at the Nevada Test Site (NTS) and near Carlsbad, New Mexico (Stewart and Pakiser, 1962), have been recorded at about 300 places in many azimuths and at distances ranging from a few to more than 1,100 km from the source (Fig. 2).

From these observations it has been possible to deduce variations in the thickness and layering of the crust and the seismic properties of the upper-mantle rocks in a broad area that includes parts of 10 geologic and physiographic provinces. None of the classic concepts of crustal structure and isostatic compensation are fully supported by these observations, nor are any of them wholly contradicted. Each province seems to have its own characteristic crustal and upper-mantle properties, some of which are shared with other provinces and some of which are strikingly different.

Two of the papers of this symposium (Jackson, Stewart, and Pakiser, 1963; Pakiser and Hill, 1963) are essentially progress reports on the preliminary results of continuing studies; the remaining papers (Eaton, 1963; Healy, 1963; Roller and Healy, 1963; Ryall and Stuart, 1963) are final reports. The entire symposium represents a progress report to our colleagues in the earth sciences on the largest program of seismic-refraction exploration of a continental crust that has yet been undertaken in the Western World.

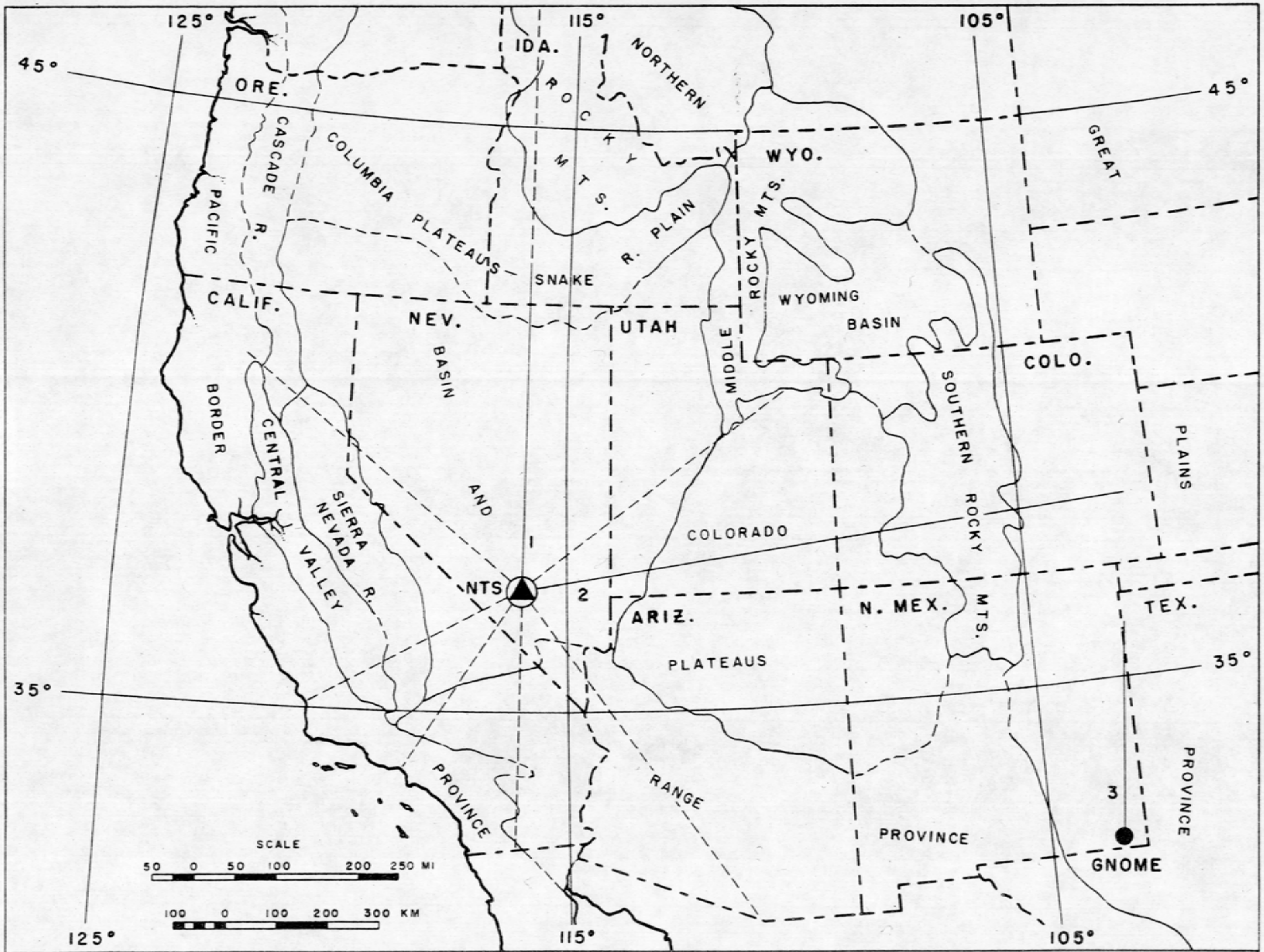

Figure 2.-- General locations of profiles recorded from underground nuclear explosions at the Nevada Test Site (NTS) and near Carlsbad, N.M. (GNOME). Solid lines (NTS to Snake River Plain, NTS to eastern Colo., and GNOME to northeastern N.M.) are included in this symposium or were previously published (Stewart and Pakiser, 1962); dashed lines are not included.

Acknowledgments. It is a pleasure to acknowledge the assistance of a number of geophysical institutions and individual geophysicists who assisted us in getting this program underway, and who offered helpful ideas on the conduct of this program at many stages.

Professor Frank Press, Director of the Seismological Laboratory, California Institute of Technology, was our consultant and advisor in the early stages of this program. He offered many useful ideas on seismic instrumentation, field procedures, and the general scope of our program. The nature of our program as it exists today and as presented in this symposium reflects to a large extent ideas and concepts which were developed in discussions with Professor Press.

Drs. M. A. Tuve and L. T. Aldrich of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, offered many useful ideas on the development of our instrumentation and field program. Dr. Tuve freely made available to us DTM designs, circuit diagrams, information on instrument characteristics, and other information of importance in the development of our own seismic system.

Dr. W. M. Wells of Stanford Research Institute also offered a number of valuable ideas on the development of seismic instrumentation, particularly in the integration of reel-to-reel magnetic-tape recording into our seismic system.

Professors G. P. Woollard and R. P. Meyer and Dr. J. S. Steinhart were particularly helpful in offering suggestions on seismic-refraction instrumentation and on radio-communications and timing equipment developed by the University of Wisconsin and used in the University's

field program. Professor Woollard was also very helpful in making arrangements for one of our seismic-recording crews (using conventional equipment) to join the operations of the University of Wisconsin in Montana during the summer of 1960. Many useful ideas on field procedures were obtained from Professor Meyer, who directed the operations in Montana. (Dr. Steinhart is now with the Carnegie Institution of Washington.)

Dr. E. A. Eckhardt advised us on contract specifications for field work.

Drs. C. C. Bates and J. W. Berg of ARPA participated actively in the planning of this program of crustal studies, and supported our work in many ways. Their participation was always constructive and friendly and a source of gratification to the Geological Survey. (Dr. Berg is now at Oregon State University.)

The instruments used in these studies were developed by Dresser Electronics, SIE Division, according to strict performance specifications of the Geological Survey. Field work was done with the assistance of United ElectroDynamics, Inc., and the affiliated United Geophysical Corporation. Permitting of shotpoints in California and Nevada was done with the assistance of the U. S. Army Corps of Engineers.

Without the assistance of these institutions and geophysicists, our program of crustal studies could not have been launched so rapidly and smoothly.

Terminology. Various proposals have been made in recent years to revise or replace the traditional terminology of seismology. In general, these proposals consist of using subscripts for velocities that identify seismic waves according to the number or velocity of the deepest layer to which these waves have penetrated. No rigid standards of terminology have been enforced in the papers of this symposium, but we have resisted the temptation to present a new terminology or to endorse any of the recent proposals for a new terminology. We feel that new systems of nomenclature more often than not fail to eliminate the confusion of the past, and in many instances they add new confusion. The traditional terms P_g and P_n describe seismic waves with essentially unique properties, and we use them without apology. The terms P* and $\overline{P}$ are less precise in meaning but, if a statement concerning them is made, we feel that they continue to be useful in the literature of geophysics.

In general, these terms are used with the following meanings:

P_g represents a compressional wave that has penetrated through the sedimentary veneer of the earth and travels as a critically-refracted wave in the upper layer of the crust at a speed of about 6.0 km/sec.

P* represents a compressional wave that has penetrated through the upper layer of the crust and travels as a critically-refracted wave in a deeper layer of the crust at speeds ranging from 6.5 to about 7.0 km/sec.

P_n represents a compressional wave that has penetrated through the crust and travels as a critically-refracted wave in the upper-mantle rocks at speeds ranging from 7.7 to about 8.2 km/sec.

$\overline{P}$ represents a guided wave that travels in the upper layers of the crust with a speed near that of P_g (See Ryall and Stuart, 1963, for a discussion of this wave).

Reflections from the Mohorovicic discontinuity and the upper surface of an intermediate layer are designated P_MP and P_IP respectively.

The speeds given above are only examples, and are not intended as restrictive definitions. We have not, however, used P_g to describe any seismic wave that travels with a speed of 6.5 km/sec or more, nor P_n to describe any seismic wave that travels with a speed of less than 7.5 km/sec.

Speed of P_n. The speed of compressional waves in the upper-mantle rocks ranges from 7.7 km/sec in the southern part of the Basin and Range province (Pakiser and Hill, 1963) to 8.2 km/sec in the Great Plains province (Stewart and Pakiser, 1962).

Over most of the Basin and Range province, the speed of P_n is in the range 7.8 to 7.9 km/sec (Eaton, 1963; Pakiser and Hill, 1963; Roller and Healy, 1963; Ryall and Stuart, 1963). Along the California coastline, the speed of P_n ranges from 8.0 to 8.2 km/sec (Healy, 1963), and in the Sierra Nevada the speed of P_n is probably near 7.9 km/sec (Eaton, 1963). The best estimate of the speed of P_n in the Colorado Plateaus is 8.0 km/sec (Ryall and Stuart, 1963). Transitions in the speed of P_n across provincial boundaries, e.g., from the Basin and Range province to the Colorado Plateaus (Ryall and Stuart, 1963), commonly take place in fairly narrow zones.

In general, variations in the speed of P_n from our observations are similar to those observed by Herrin and Taggart (1962), but less extreme. Part of the variations they observed may be related to variations in the thickness of the crust or the speed of compressional waves in near-surface materials. Earlier Ryall (1962), and still earlier Byerly (1956) observed significant variations in the speed of P_n in the western United States. Press (1960), Berg and others (1960), and Diment, Stewart, and Roller (1961) have also observed compressional-wave speeds in the range 7.6 to 7.8 km/sec in the Basin and Range province (see Pakiser and Hill, 1963, for discussion).

Density of the upper mantle. Variations in the density of the upper-mantle rocks can only be inferred from variations in the speed of P_n. The total variation in the speed of P_n (7.7 to 8.2 km/sec) in the area studied is 6 percent. This corresponds to a 6-percent variation in density, from 3.25 to 3.45 g per cm^3, according to the velocity-density relations of Nafe and Drake (Talwani, Sutton, and Worzel, 1959). However, from the work of Birch (1961a) it can be shown that the observed variation in the speed of P_n can be accounted for by a variation of a few percent in the mean atomic weight of the upper-mantle rocks with no change in density. Similarly, anisotropy of velocity measured for dunite (Birch, 1961a) could account for the observed variations of the speed of P_n if the orientation of crystals varies in the upper-mantle rocks. Nevertheless, the requirement of regional isostatic equilibrium, to be discussed in a later section, seems to require some direct relation between the speed of P_n and the density of the upper-mantle rocks.

The velocity-density relations of Nafe and Drake (Talwani, Sutton, and Worzel, 1959) will be adopted in the discussion that follows, but the uncertainties discussed above, and at greater length by Birch (1961a, 1961b), make it necessary to avoid any implications of exactness in determination of upper-mantle densities from the speed of P_n.

Variations in crustal thickness. Crustal thickness has been determined from an extensive network of reversed seismic-refraction profiles that cover most of California and Nevada and parts of Arizona, Idaho, and Utah, and from two unreversed profiles in Colorado (Fig. 1). In addition, an extensive network of profiles radiating outward from NTS has been used to provide additional information on crustal thickness (Fig. 2). Analyses of traveltimes from 8 of these profiles (shown in solid lines on Figs. 1 and 2) have been included in this symposium or earlier publications (Stewart and Pakiser, 1962), but preliminary results from the remaining profiles (shown in dashed lines on Figs. 1 and 2) have been used freely in this summary paper.

Crustal thickness along the California coastline, if a layer of intermediate compressional-wave speed is not present in the lower crust (Fig. 3), is in general about 23 km (Healy, 1963; Eaton, 1963). In the vicinity of Los Angeles, however, where the structure of the crust is influenced by the high mountains of the Coast and Transverse Ranges, crustal thickness may be 30 km or more (Healy, 1963; Roller and Healy, 1963).

The crust thins eastward to less than 20 km under the Central Valley of California, and farther east thickens to more than 40 km under the Sierra Nevada Range (Eaton, 1963).

Crustal thickness in the Basin and Range province (Fig. 3) is generally in the range 25 to 35 km (Pakiser and Hill, 1963; Roller and Healy, 1963), but it may increase to about 40 km near the western boundary with the Sierra Nevada (Eaton, 1963), the eastern boundary with the Colorado Plateaus (Ryall and Stuart, 1963), and the northern boundary with the Snake River Plain (Fig. 4). Variations in crustal thickness in the Basin and Range province seem to be closely related to regional altitude above sea level. The crust tends to be thicker under the high ranges in the vicinity of Eureka and Elko, Nevada (Pakiser and Hill, 1963), and thinner under regions of lower average altitude, such as Fallon, Nevada (Eaton, 1963), Kingman, Arizona (Pakiser and Hill, 1963), and the Mojave Desert (Roller and Healy, 1963). Preliminary results from the profiles not included in this symposium support this generalization. Depths to seismic discontinuities

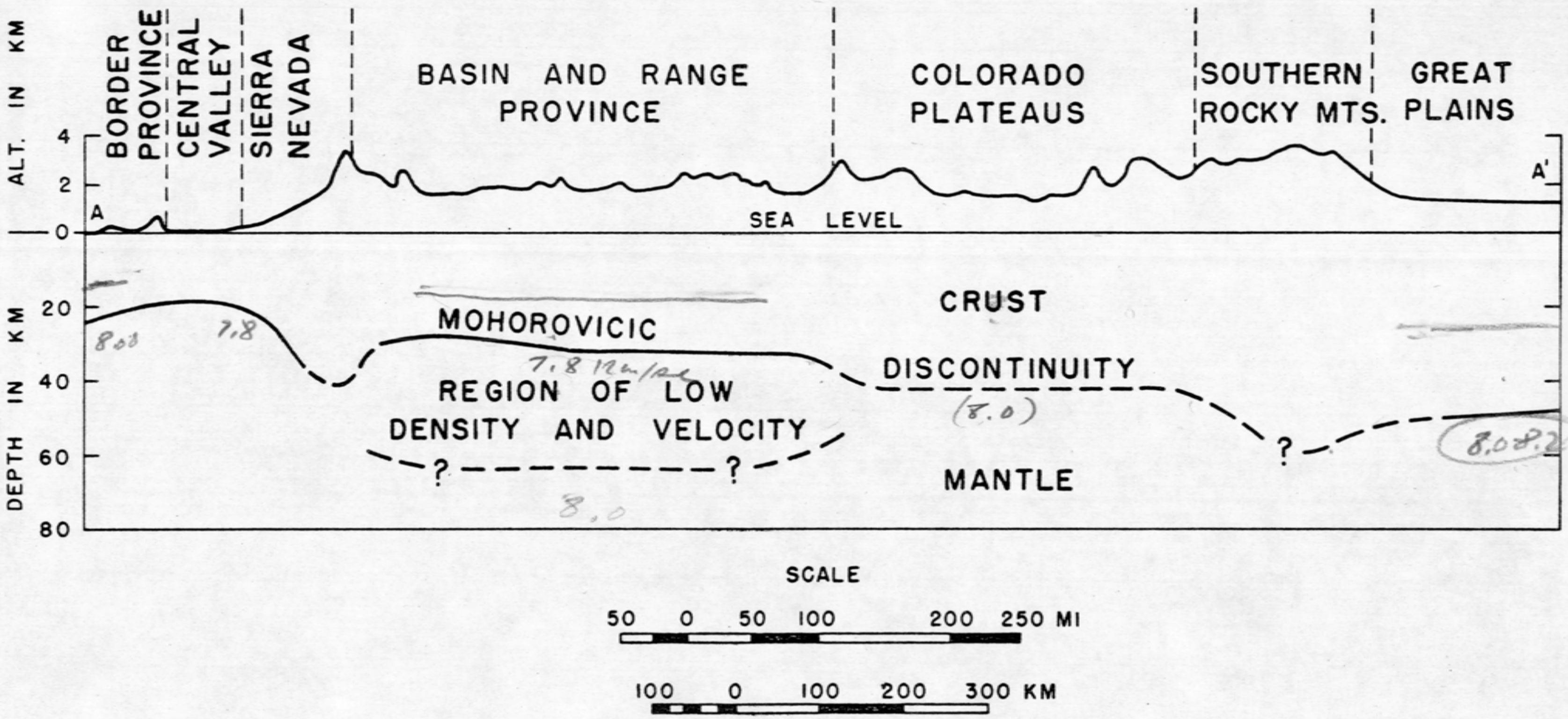

Figure 3.-- Variations in crustal thickness from San Francisco, Calif. (A), to Lamar, Colo. (A').

in the Basin and Range province determined by other workers (Berg and others, 1960; Diment, Stewart, and Roller, 1961; Press, 1960; Tatel and Tuve, 1955) in close agreement with our results have been previously reported (see Pakiser and Hill, 1963, for discussion).

We have made no seismic observations in which both source and recording locations are wholly within the Colorado Plateaus. However, Ryall and Stuart (1963) have interpreted the low apparent velocity of P_n east of NTS to indicate crustal thickening toward the boundary of the Basin and Range province and the Colorado Plateaus (Fig. 3). Based on this interpretation, and computations from a phase provisionally identified as SPS (Ryall and Stuart, 1963), crustal thickness in the Colorado Plateaus is slightly more than 40 km.

The crustal thickening to about 60 km under the southern Rocky Mountains (Fig. 3) has only been inferred, mainly from the unreversed profile extending westward from near Lamar, Colorado, to Salida, Colorado (Fig. 1), which failed to show evidence of P_n as a first arrival.

Crustal thickness in the Great Plains province has been determined to be about 50 km from an unreversed profile extending north from Lamar to near Sidney, Nebraska (Jackson, Stewart, and Pakiser, 1963), and from recordings in eastern New Mexico of seismic waves generated by the GNOME explosion (Stewart and Pakiser, 1962).

From south to north, crustal thickness increases gradually from about 28 km in an area of low altitude in the Mojave Desert (B in Fig. 4) to about 34 km in the higher region to the north,

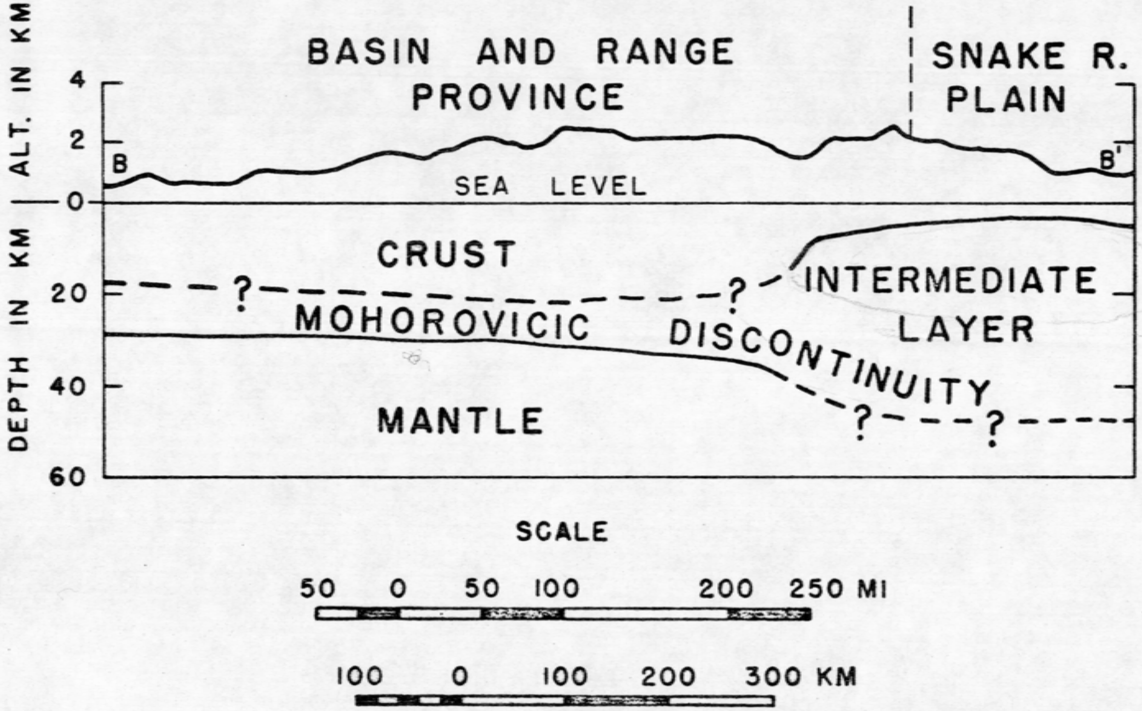

Figure 4.-- Variations in crustal thickness and an intermediate crustal layer from Ludlow, Calif. (B), to Boise, Ida. (B').

assuming the presence of an intermediate crustal layer (Pakiser and Hill, 1963). North of Elko, a layer of intermediate velocity was mapped from first arrivals having a speed of 6.7 km/sec (D. P. Hill, written communication). This layer rises to within a few km of the surface near the center of the Snake River Plain (Fig. 4). The increase upward in the thickness of this intermediate layer seems to be abrupt. If this layer continues downward to the Mohorovicic discontinuity, delays in the traveltimes of P_n from seismic waves generated by nuclear explosions at NTS require that the crust thicken to at least 47 km in the Snake River Plain (Fig. 4). If the density of the 6.7 km/sec layer is about 2.9 to 3.0 g per cm^3, considerations of isostatic equilibrium would require at least that much crustal thickening under the Snake River Plain (D. P. Hill, written communication). Evidence for the intermediate crustal layer will be discussed in the next section.

Thus it is seen that, in general, changes in crustal thickness across provincial boundaries have little direct relation to altitude above sea level unless the speed of P_n is constant across those boundaries. The crust tends to be thick in regions where the velocity of compressional waves in the upper-mantle rocks is greater than 8.0 km/sec, and relatively thin in regions where the velocity of compressional waves in the upper-mantle rocks is less than 8.0 km/sec. This implies that the speed of P_n in the Snake River Plain is greater than 8.0 km/sec, but measurements to substantiate this implication are not available at present. Within regions of uniform compressional-wave velocity in the upper-mantle rocks, such as the Basin and Range province and perhaps others, crustal thickness seems to vary directly with regional altitude above sea level.

Intermediate crustal layers. Direct evidence for a crustal layer of intermediate compressional-wave speed was found from first arrivals in eastern Colorado (Jackson, Stewart, and Pakiser, 1963) and in eastern New Mexico (Stewart and Pakiser, 1962). The structure of the traveltime curves displaying these first arrivals is not such that it can be unequivocally concluded that the boundary between an intermediate layer and the upper layer of the crust is a sharp one. Some increase downward in the compressional-wave speeds of the crust is required by these observations, however.

On the reversed profiles from chemical explosions north of Elko, Nevada, and extending to Boise, Idaho (Fig. 1), an intermediate layer of velocity 6.7 km/sec was detected by first arrivals over long ranges of distance (D. P. Hill, written communication). In fact, P_n was not observed as first arrivals on these profiles, except possibly at the most distant recording locations. P_n was observed in this area on recordings of seismic waves generated by underground-nuclear explosions at NTS, however. Indications of first-arriving energy from an intermediate layer were observed elsewhere in the Basin and Range province, but over such short ranges of distance that their identity is in doubt.

Eaton (1963) and Roller and Healy (1963) have observed what seem to be reflections from an intermediate layer and from the

Mohorovicic discontinuity, and these would require the presence of an intermediate layer. The analysis of Ryall and Stuart (1963) of the phase $\bar{P}$ calls for an intermediate layer in the Basin and Range province with a compressional-wave speed of 6.5 km/sec or slightly more.

Although much of the evidence for an intermediate layer is indirect, it seems likely that such a layer is present in the lower part of the crust over much and perhaps all of the area included in this symposium.

Implications concerning isostatic compensation. Isostatic compensation on a regional scale is accepted by most geophysicists. Two ideas concerning density variations in the upper part of the earth, those of Airy and Pratt, have been put forward and modified in various ways to explain isostasy. Airy isostasy calls upon variations in the thickness of a low-density layer near the surface (commonly visualized as the crust) to maintain a condition of isostatic equilibrium; Pratt isostasy calls upon variations in the density of the upper layers of the earth. Neither of these ideas can exclusively explain the observations of the previous sections.

On a scale that includes many geologic provinces, a large part of isostatic compensation is obviously achieved by variations in the density of the upper-mantle rocks (Fig. 5). The regions requiring upper-mantle rocks of high density are the regions in which the speed of compressional waves in those rocks is greater than 8.0 km/sec,

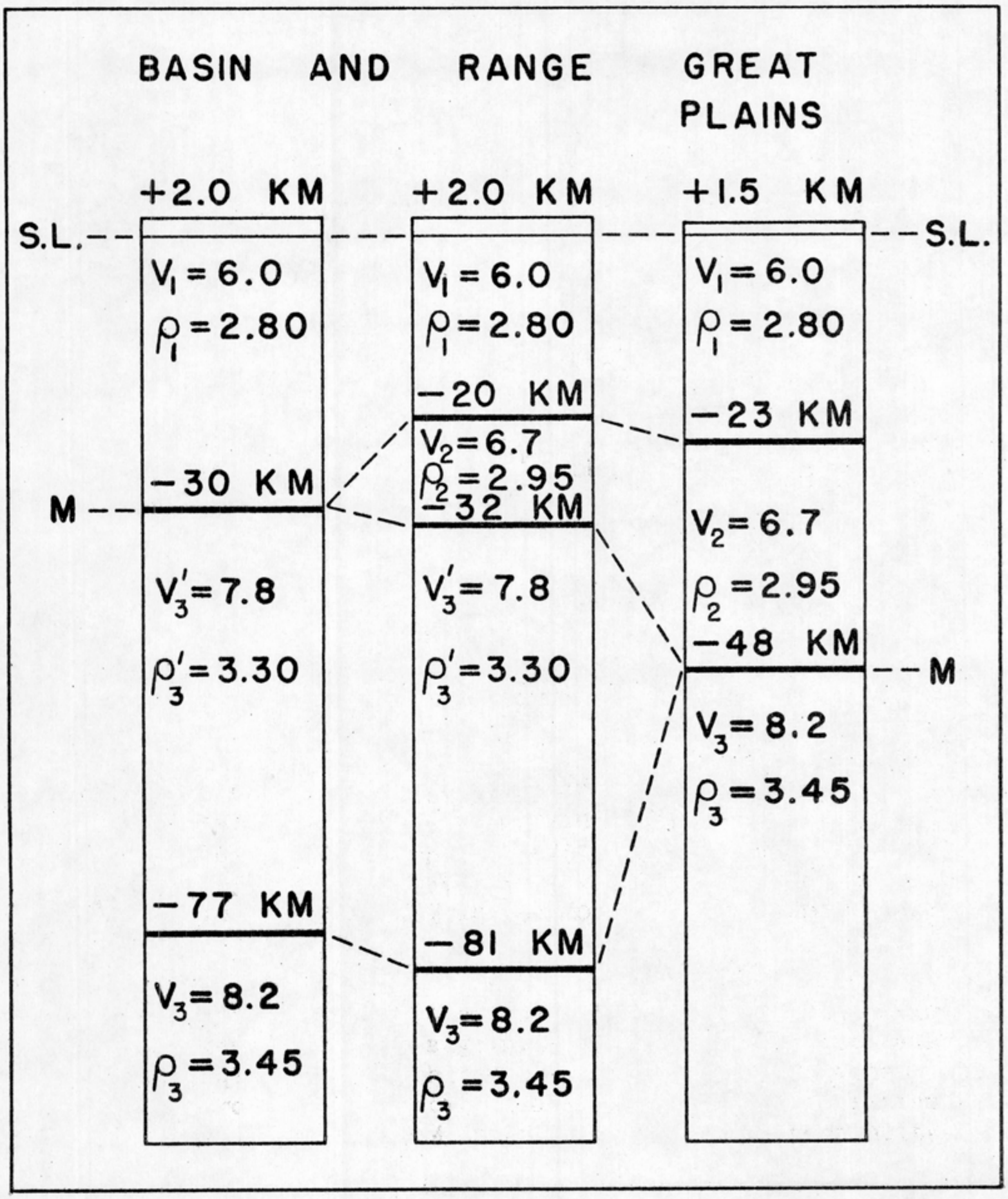

Figure 5.-- Alternate models of the crust and upper mantle in the Basin and Range province that are in isostatic equilibrium with the crust of the Great Plains province. Velocities are in km/sec and densities in g per cm^3. M is the Mohorovicic discontinuity.

and the regions requiring upper-mantle rocks of lower density are the regions in which the speed of compressional waves in those rocks is less than 8.0 km/sec. This is in accord with the velocity-density relations of Nafe and Drake (Talwani, Sutton, and Worzel, 1959) and Birch (1961a, 1961b).

Within the Basin and Range province, isostatic compensation is achieved in large part by variations in the thickness of the crust. This broad area of uniform upper-mantle compressional-wave speed and density can probably be extended westward to include the Sierra Nevada and, perhaps, the entire region west of the Colorado Plateaus and south of the Columbia Plateaus-Snake River Plain region. Higher P_n speeds are observed along the California coastline, however (Healy, 1963). Within this region, Airy isostasy involving crustal thickness variations at least qualitatively explains our observations on structure of the crust and upper mantle.

Isostatic compensation across the boundary of the Basin and Range province and the Snake River Plain is seemingly achieved at least in part by variations in the thickness of an intermediate crustal layer (Fig. 4).

It is therefore clear that no single model can specify the mechanism of isostatic compensation. In the western United States three factors are involved: (1) variations in overall crustal thickness, (2) variations in the thickness of an intermediate crustal layer, requiring variations in the average density of the crust, and (3) variations in the density of the upper mantle.

It has been popular to visualize the crust as an iceberg whose hidden "roots" extend downward into an ocean of uniform density to depths proportional to the height of the iceberg above the surface of the ocean. It would be nearer the truth to visualize the geologic provinces as individual icebergs with different internal density layering and floating in an ocean of varying density. An upper mantle of high density extends eastward from the Rocky Mountains into the interior of the continent, and there the average crust is thick. An upper mantle of lower density extends westward from the Colorado Plateaus and southward from the Snake River Plain to the continental margin, and there the average crust is thin. The Colorado Plateaus and the Snake River Plain perhaps represent a transition zone from the dense upper mantle of the interior of the continent to the less dense upper mantle of the Western Cordillera.

An attempt has been made to determine the depth to which the material of compressional-wave speed 7.8 km/sec extends into the mantle (Fig. 5). To do this, the average crust in the Great Plains province as determined in eastern Colorado (Jackson, Stewart, and Pakiser, 1963) and eastern New Mexico (Stewart and Pakiser, 1962) was adopted as the standard. Two alternate models of the Basin and Range crust, one with an intermediate crustal layer and one without, were compared with the Great Plains crust. Densities for the crustal layers and the high- and low-density versions of the upper mantle were taken from the velocity-density curve of Nafe and Drake (Talwani, Sutton, and Worzel, 1959). To maintain isostatic equilibrium from the Great Plains to the Basin and Range province, it is necessary that the material of compressional-wave velocity 7.8 km/sec and density 3.30 g per cm^3 extend to a depth of about 80 km into the standard mantle of compressional-wave velocity 8.2 km/sec and density 3.45 g per cm^3 (Fig. 5).

This computation is very sensitive to small differences in the density of the upper-mantle rocks, but it should be reliable by a factor of 2 or better. Of course, a continuous variation of mantle velocity and density may be more reasonable than the model used in the computation above (Fig. 5).

Implications concerning gravity studies. Regional isostatic compensation can be accepted as established, so no information can be obtained on regional variations in crustal structure from gravity studies that cannot be inferred directly from regional variations in altitude above sea level. This is true because the regional free-air gravity anomaly tends toward zero and the regional Bouguer gravity anomaly is directly proportional to the regional altitude above sea level, with a change of sign. The meaning of the term "regional" here is critical. It can be taken to imply an area of which the horizontal dimensions are much larger than crustal thickness, or an area within which only local departures from isostatic equilibrium are permissible.

The main geophysical (as opposed to geodetic) value of gravity surveying is in studies of non-topographic local departures from isostatic equilibrium: i.e., studies of geologic structures.

Gravity studies should be especially useful in studying those geologic features associated with the changes in crustal and upper-mantle structure in transition zones from one geologic province to another. For such studies, knowledge of the gravity gradient is particularly important. Knowledge of the gravity gradient can be used to place restrictions on possible depths and shapes of the masses that disturb the gravity field. For this reason, gravity stations in areas of critical importance should be placed close together, if possible no more than 2 km apart.

Geologic implications. The rocks of the Great Plains province have not been intensely deformed during Cenozoic time, and the province has been essentially free of Cenozoic silicic volcanism (taken here to be an index of a hot crust). The region may have been elevated vertically by about 1 km, however, since the deposition of the early Tertiary sediments east of the southern Rocky Mountains, and some Quaternary andesites and basalts were erupted in the area east of the Sangre de Cristo Range of southern Colorado and northern New Mexico. The Great Plains province can be classified, therefore, as one that has been relatively stable during Cenozoic time. The crustal and upper-mantle properties of the Great Plains can be classified as follows:

1. The crust is relatively thick (about 50 km).

2. The rocks of the lower part of the crust have speeds appropriate for gabbro (6.7 km/sec or more).

3. The rocks of the upper mantle have compressional-wave speeds in excess of 8.0 km/sec, and relatively high density.

It is postulated that these are typical of the properties of the crust and upper mantle of regions of the continental interior that have been relatively stable during Cenozoic time.

The rocks of the Basin and Range province have been intensely deformed during Cenozoic time, and the province has been subjected to widespread Cenozoic silicic (as well as Basaltic) volcanism. The Basin and Range province can be classified, therefore, as one that has been dynamically active during Cenozoic time. The crustal and upper-mantle properties of the province can be classified as follows:

1. The crust is relatively thin (about 30 km).

2. The rocks of the lower part of the crust probably have speeds appropriate for gabbro, but such material, if it exists, is relatively thin. An exception is the northern part of the Basin and Range province in the transition zone to the Snake River Plain, where a thick intermediate crustal layer is probably present (Fig. 4).

3. The rocks of the upper mantle have compressional-wave speeds less than 8.0 km/sec, and relatively low density.

It is postulated that these are typical of the properties of the crust and upper mantle of regions near the continental margin that have been dynamically active during Cenozoic time.

The properties of the crust and upper mantle of the Colorado Plateaus and the Snake River Plain are probably intermediate between those of relatively stable and dynamically-active regions. These intermediate properties may also be the properties of the crust and upper mantle of the Columbia Plateaus. Further research is needed to evaluate this suggestion.

The thickness of the crust under large mountain ranges is probably strongly influenced by crustal thickness in the broad provinces to which they are adjacent. Thus the crustal thickness of the Sierra Nevada is influenced by that of the Basin and Range province, and the crustal thickness of the southern Rocky Mountains is influenced by that of the Great Plains province. Both mountain ranges have Airy roots. In one example these roots extend downward from a relatively thin crust east of the Sierra Nevada and in the other from a relatively thick crust east of the southern Rocky Mountains (Fig. 3).

The properties of the crust and upper mantle of the Pacific Border province are intermediate between those of the Basin and Range province and the Pacific Ocean basin. The crust is relatively thin, except in the vicinity of Los Angeles, where the crustal and upper-mantle properties are influenced by the high Transverse Ranges. The speed of compressional waves in the upper-mantle rocks is near 8.0 km/sec along the California coastline.

Thus there seems to be an intimate relation between geology, especially Cenozoic geologic history, and the properties of the crust and upper mantle. The thin crustal plate extending westward from the Colorado Plateaus and southward from the Snake River Plain may have been evolved more recently in geologic time than the thick crustal plate of the continental interior.

Discussion. We will leave to future speculations (our own as well as others' who may study this symposium) presentation of geodynamic and geochemical theories based on these new findings. A few preliminary remarks seem to be in order, however.

The variations in compressional-wave speeds of 6 percent in the rocks of the upper mantle and the inferred variations in density of 6 percent can possibly be explained in a number of ways: (1) thermal expansion caused by higher heat flow in the regions of low-density upper-mantle material, (2) reversible phase transitions, such as the basalt-eclogite transition, (3) real differences in composition, perhaps involving mixing of crust and mantle materials, (4) serpentinization of olivine in a mantle of dunite or peridotite.

It is difficult to account for temperature differences at the Mohorovicic discontinuity in different places in the western United States of more than a few hundred degrees C, except perhaps for local hot spots. The volumetric thermal expansion from room temperature to 600°C of the common silicates at atmospheric pressure generally averages a little more than 1 percent, and does not exceed 2 percent (Dane, in Birch and others, 1942, p. 32-34). The effect of increasing pressure is to reduce the thermal expansion (Birch, in Birch and others, 1942, p. 48). The variation in density that can be attributed to thermal expansion, therefore, is probably not larger than about 1 percent, so regional variations in heat flow can seemingly account for no more than a fraction of the density variations in the upper-mantle rocks inferred from velocity variations.

However, it must be acknowledged that elevated temperatures may affect velocity more than density. This problem is discussed by Birch (1961b), who points out that the "most serious uncertainty is the effect of temperature ... The investigation of the effect of temperature remains as a future task. It seems likely that this will allow a reconciliation of all of the data with a mantle of nearly uniform mean atomic weight close to that of the average chondrite ..." Although it is unlikely that regional variations in heat flow can account for all of the observed variations in the speed of P_n and the density variations inferred from velocity, thermal expansion may be a significant factor.

Lovering (1958) and others have proposed that the Mohorovicic discontinuity may represent a reversible transition from basalt to its high-pressure modification eclogite. The crust in the Great Plains province would require that the basalt-eclogite phase transition take place at a pressure equivalent to a column of about 50 km of crustal rocks. Eclogite would be unstable at any pressure less than this at the same temperature. However, mantle material exists at a pressure equivalent to a column of only about 30 km of crustal rocks in the Basin and Range province. Further, it can be inferred from the intense Cenozoic deformation and silicic volcanism in the Basin and Range province that the Mohorovicic discontinuity is probably at a higher temperature there than in the Great Plains province. Higher temperatures favor the basalt phase (Lovering, 1958). Therefore, it seems unlikely that the Mohorovicic discontinuity represents the basalt-eclogite phase transition. However, it is possible, as suggested by Broecker (1962), that sudden changes in lithostatic pressure (from rapid loading or unloading) "will result in the replacement of any distinct phase discontinuities with transition zones or the expansion of existing transition zones." Although it is considered unlikely, the low-velocity upper mantle in the Basin and Range province may represent, in part, such a transition zone.

Cook (1962) has explained material of compressional-wave velocity in the range 7.4 to 7.7 km/sec as a mantle-crust mixture. Except for what we interpret as apparent downdip velocities, we have observed no mantle speeds of less than 7.7 km/sec, but this suggestion may explain in part the observed properties of the rocks of the upper mantle in the region we have studied.

Ringwood (1962) has proposed a model for the upper mantle that could account for variations in the speed of compressional waves by variations in the amount of plagioclase present. The presence of relatively large amounts of plagioclase could have the effect of reducing the speed of compressional waves in the rocks of the upper mantle. The model for the upper mantle proposed by Ringwood could account, at least in part, for the low compressional-wave speeds of the upper-mantle rocks in the Basin and Range province.

The presence of significant amounts of serpentine, a material of low density and low compressional-wave speed, in the upper mantle as suggested by Hess (1955) could also account for the properties of the upper mantle in the Basin and Range province. A compressional-wave speed of 7.8 km/sec for the upper-mantle rocks of the Basin and Range province would correspond to about 20 percent of serpentine in a serpentine-olivine aggregate (Birch, 1961a; Hess, 1959).

The three most likely materials making up the upper mantle are peridotite, dunite, and eclogite. Peridotite and dunite have properties similar to those of the upper mantle in the western United States, and both would be stable under the probable pressure-temperature conditions there. Eclogite has appropriate physical properties, but it would probably not be stable under the pressure-temperature conditions of the Basin and Range province.

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