UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 20

CONTINENTAL CRUST*

By

L. C. PAKISER**

DENVER, COLORADO

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-20
June 15, 1964

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 20

CONTINENTAL CRUST*

By

L. C. PAKISER**

This paper has been submitted for inclusion in the "Encyclopedia of Earth Sciences," to be edited by Prof. Rhodes W. Fairbridge of Columbia University and published by Reinhold Publishing Corporation.

Sincerely,

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-64.
** U. S. Geological Survey, Denver, Colorado.

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L. C. Pakiser**

Abstract. The structure of the earth's crust (the outer shell of the earth above the M-discontinuity) has been intensively studied in many places by use of geophysical methods. The velocity of seismic compressional waves in the crust and in the upper mantle varies from place to place in the conterminous United States. The average crust is thick in the eastern two-thirds of the United States, in which the crustal and upper-mantle velocities tend to be high. The average crust is thinner in the western one-third of the United States, in which these velocities tend to be low. The concept of eastern and western superprovinces can be used to classify these differences. Crustal and upper-mantle densities probably vary directly with compressional-wave velocity, leading to the conclusion that isostasy is accomplished by the variation in densities of crustal and upper-mantle rocks as well as in crustal thickness, and that there is no single, generally valid isostatic model. The nature of the M-discontinuity is still speculative.

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

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Introduction. The term "crust" was originally based on the concept of a solid crust resting on a molten interior. However, the crust of the earth is now usually defined as the outer shell of the earth above the discontinuity in seismic velocity discovered by Mohorovicic (1910). The crust constitutes only 1.5 per cent of the volume and 1 per cent of the mass of the earth, but its surface area is large. The crust completely encloses the mantle and the core of the earth, and thus it prevents man's direct observation of them. Some samples of the mantle are brought up by volcanic eruptions, but it is usually impossible to determine their place of origin. For these reasons, we have largely depended on geophysical methods to study the earth's interior, but deep drilling may soon penetrate the earth's crust and bring up samples of the mantle.

The Mohorovicic (M) discontinuity is a global seismic boundary below which, in the upper mantle, the velocity of seismic compressional waves is about 8 km/sec, and above which, in the deep crust, the

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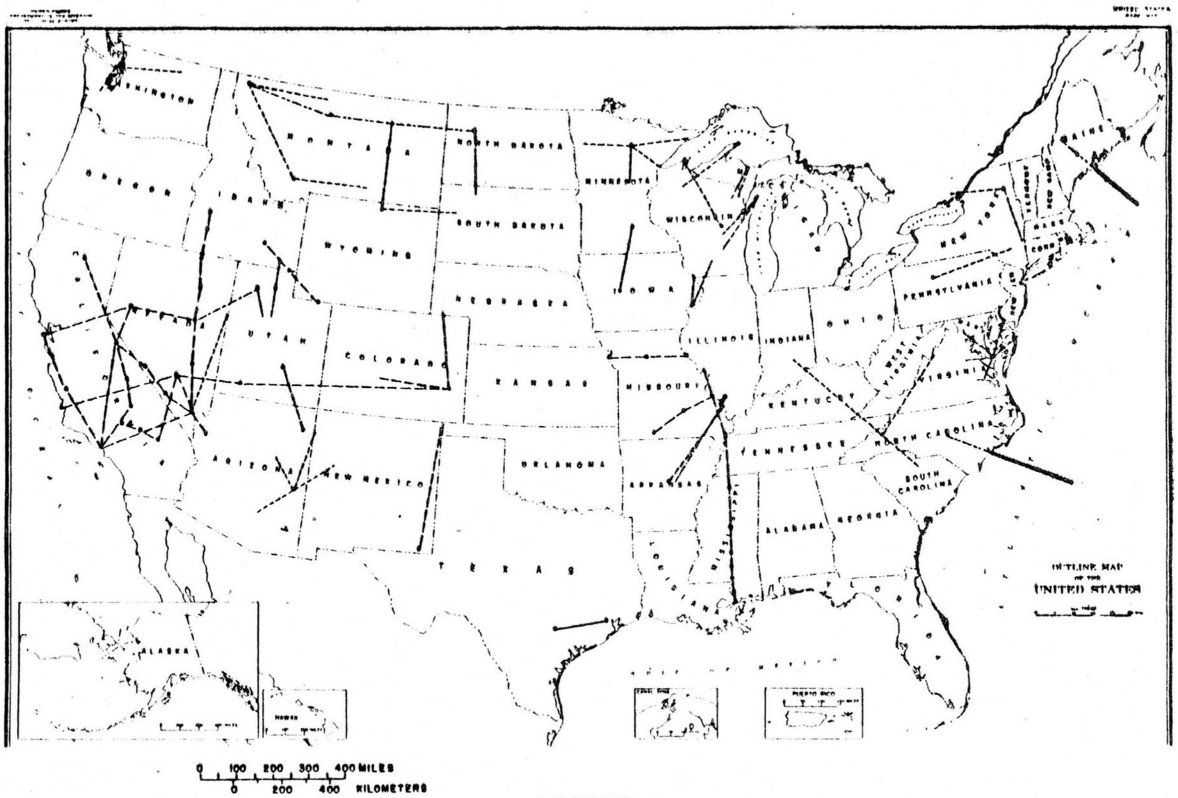
velocity is significantly smaller. The depth to the M-discontinuity under continents ranges from less than 20 to perhaps 70 km, and averages about 40 km. In general, depth to the M-discontinuity varies directly with increasing altitude of the earth's surface above sea level (the crust tends to be thick under high mountains), but recent research has demonstrated that this generalization is not everywhere valid. The depth to the M-discontinuity under oceans is only a few kilometers in most places. The mantle rocks below the M-discontinuity are also more dense (3.3 g per cm^3 or more) than the crustal rocks above. The composition of the upper-mantle rocks is still speculative.

Methods of study. Essentially all geology is directed toward study of the composition and structure of the earth's crust, but study of the crust as an entity and of its relations to the upper mantle is usually accomplished by geophysical methods. The most important of these methods are the seismic-refraction, surface-wave, and gravity methods. Interpretation of seismic-refraction recordings of compressional waves provided most of the results described in this article. Russian, Western European, and Canadian geophysicists have conducted excellent and extensive seismic-refraction studies of the structure of continents, but I will describe mainly the continental crust of the conterminous United States because I have been directly involved in the study of it.

The results in the United States presented in the following sections were taken from numerous sources, which are cited by Steinhart and Meyer (1961), Pakiser (1963), and Pakiser and Steinhart (in press). Results in the European Alps were discussed in a memoir edited by Closs and Labrouste (1963). Results in the U.S.S.R. were discussed in a collection of papers edited by Zverev, Mikhota, Pomerantseva, and Margot'yeva (1962).

Crustal models. Seismic studies of crustal structure have been made in many parts of the United States (Figure 1). Representative crustal models from four provinces--(1) Basin and Range, (2) Snake River Plain, (3) Great Plains, and (4) Coastal Plain--have been selected to illustrate the continental crust of the conterminous United States (Figure 2).

1. The Basin and Range province lies near the center of the Intermountain Plateaus (Figure 3); it includes all of Nevada and parts of adjacent states (Figure 1). The province is characterized by fault-block mountains and valleys that were formed by Cenozoic diastrophism and accompanying volcanism. Altitudes above sea level average about 2 km. Surprisingly, the crust is thin in this mountainous province, typically about 35 km; the crust is divided into two fairly distinct layers, and the velocity of seismic compressional waves in the upper mantle is less than 8 km/sec.



EXPLANATION

Shot Point

Profile recorded prior to 1960 and tabulated in Steinhart and Meyer (1961)

Profile recorded by U.S. Geological Survey (Diment, Stewart, and Roller, 1961; Eaton, 1963; Healy, 1963; Jackson, Stewart, and Pakiser, 1963; Pakiser, 1963; Pakiser and Hill, 1963; Roller and Healy, 1963; Roller, 1964; Ryall and Stuart, 1963; Stewart and Pakiser, 1962; Stuart and others, 1964)

Profile recorded by Berg and others (1960)

Profile recorded in cooperative program of Carnegie Institution of Washington, Pennsylvania State University, Princeton University University of Michigan, University of Wisconsin, and Woods Hole Oceanographic Institution from 1960 to 1963 (Asada and others, 1961; Meyer and others, 1962; Steinhart and others, 1962a, 1962b)

Profile recorded by University of Wisconsin (Cohen and Meyer, 1963; McCamy and Meyer, 1963)

Profile recorded by Cram (1961)

Figure 1.--Locations of crustal seismic-refraction profiles in the conterminous United States (from Pakiser and Steinhart, in press).

The upper crust is about 20 km thick or a little more, and compressional waves travel in it at velocities ranging from 5.8 to 6.4 km/sec; its average composition probably approximates that of diorite or granodiorite. The lower crust is about 10 km thick or a little more, and compressional waves travel in it at velocities ranging from 6.6 to 7.0 km/sec; its composition probably approximates that of gabbro. Densities of the crustal layers and the upper mantle can only be inferred from the velocities, but they are probably about 2.8 g per cm^3 for the upper crust, 3.0 g per cm^3 for the lower crust, and 3.3 g per cm^3 for the upper mantle. These are approximate averages of values determined in laboratory studies (Birch, 1961).

Values for crustal thickness and upper-mantle velocity in Japan as obtained by Japan's Research Group for Explosion Seismology (see Steinhart and Meyer, 1961, p. 32-37) are similar to those in the Basin and Range province. Japan has also been subjected to widespread Cenozoic diastrophism and volcanism.

2. The Snake River Plain lies in southern Idaho just north of the Basin and Range province (Figure 1). It is the eastward projecting arm of the Columbia Plateaus province, which forms the northern part of the Intermountain Plateaus (Figure 3). The Snake River Plain is a surface of low relief and is largely covered by flood basalt flows of Cenozoic age. The plain is about 1-1/2 km above sea level. Velocities and densities in the crustal layers and upper mantle are similar to those of the Basin and Range province, but the upper crust thins to

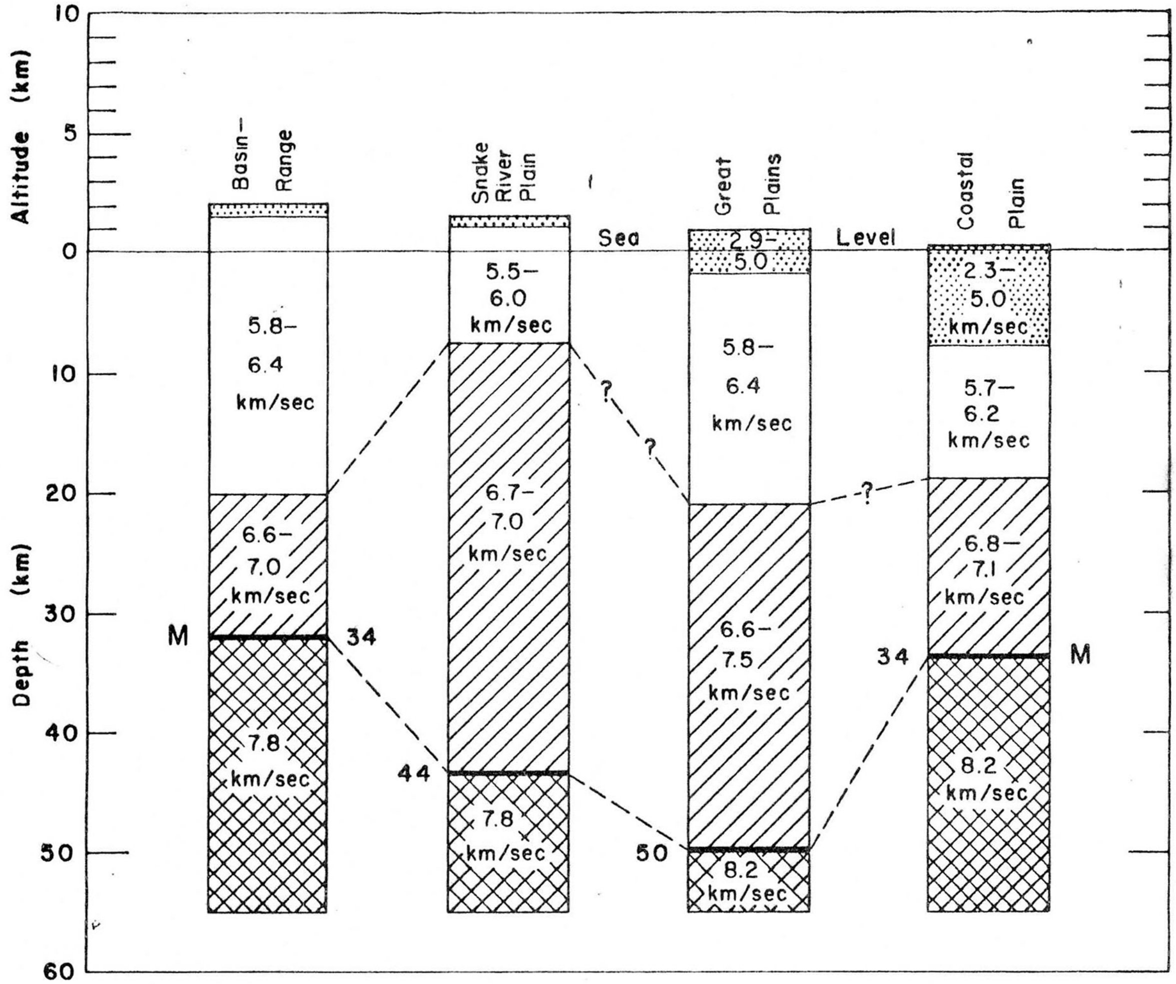


Figure 2.--Generalized crustal models in four provinces of the United States showing approximate distribution of compressional-wave velocity with depth.

less than 10 km under the Snake River Plain, and the lower crust thickens to about 35 km (Figure 2). The total crustal thickness--about 45 km--is about 10 km greater than that of the Basin and Range province to the south, although the surface in the Snake River Plain is lower than that of the high Basin Ranges. The Ivrea region, Italy, along the eastern border of the Alps seems to have crustal structure similar to that of the Snake River Plain.

3. The broad, flat Great Plains province extends from Mexico into Canada (Figure 1) in the western part of the Interior Plains (Figure 3). It includes parts of Texas, New Mexico, Oklahoma, Colorado, Kansas, Nebraska, Wyoming, South Dakota, North Dakota, and Montana. The rocks therein have been little deformed and the province has been relatively free of volcanism in Cenozoic time, but many areas where sediments were deposited at or near sea level in the early Cenozoic have since been elevated to about 1 km.

Seismic work in the Great Plains province provides less convincing evidence for separation of the crust into distinct layers than seismic work in the Basin and Range province and the Snake River Plain. The velocity of compressional waves in the crust can be represented by a continuous increase of velocity with depth which is only crudely layerlike. Therefore, the line separating the rocks of the upper crust from those of the lower crust (Figure 2) should not be taken as necessarily a discontinuity, but rather as a line above which the compressional-wave velocity is less than about 6.5 km/sec and below which the velocity is greater than about 6.5 km/sec. The average properties of the rocks above this line are probably those of diorite or granodiorite, and below this line the average properties are probably those of gabbro. Secondary seismic phases on many profiles suggest the existence of material with a compressional-wave velocity of about 7.5 km/sec in the lowest part of the crust. Depth to the M-discontinuity in the Great Plains province is about 50 km. The velocity of compressional waves in the upper mantle is greater than 8 km/sec, and the mantle rocks are more dense under the Great Plains than under the Basin Ranges and Snake River Plain. Many regions of the U.S.S.R. (e.g., the Russian and Siberian Platforms) have crustal and upper-mantle properties similar to those of the Great Plains.

4. The Coastal Plain province extends eastward from the Gulf Coastal Plain of Texas and Louisiana to Florida, and then northeastward along the Atlantic coastline to New York (Figures 1 and 3). Topographic relief is slight, and altitudes generally are less than 100 m above sea level. The crustal and upper-mantle velocities are similar to those of the Great Plains, except that the upper several kilometers of the crust consists of rocks of compressional-wave velocities in the range 2.3 to 5.0 km/sec (Figure 2); these are largely sedimentary deposits of marine origin. Crustal thickness in the Coastal Plain averages about 35 km. The crust in the West Siberian Lowlands of the U.S.S.R. resembles that in much of the Coastal Plain.

Except for variations in the thickness of sedimentary deposits, and possible variations in the velocities in the deep crust, the crust and upper mantle in much of the two-thirds of the United States east of the Rocky Mountains have roughly uniform properties. They are also similar to a large area of the U.S.S.R., and probably other continental areas that have not been studied as thoroughly. A notable exception is the complex crustal structure (in some ways similar to that in the Snake River Plain) associated with the Mid-Continent Gravity High. This feature extends from Minnesota to Kansas along a buried trough filled by Precambrian Keweenawan lava flows. Complexities in crustal structure associated with regional geologic features (e.g., the Appalachian Mountains) undoubtedly will be revealed in future detailed seismic work east of the Rocky Mountains. The presence of large masses of dense rock at shallow depths in the Appalachian Highlands has been established by gravity studies.

Crustal structure in and west of the Rocky Mountains is complex and cannot be described according to "average" characteristics. The Columbia Plateaus and adjacent areas probably differ from the remainder of the Intermountain Plateaus because of the presence of a thick gabbroic layer that probably extends from depths of 10 km or less to the M-discontinuity.

Description of a continent. Interpretation of the broad but discontinuous network of long-range seismic-refraction profiles (Figure 1) has advanced knowledge of the crust and upper mantle to the stage at which generalized contours of crustal thickness, mean crustal velocity, and upper-mantle velocity can be drawn (Figure 3). Crustal thickness and mean crustal velocity interpreted from seismic traveltimes are mutually dependent, so that modification of one requires modification of the other. These qualifications notwithstanding, regional variations in crustal thickness and mean crustal velocity such as those shown on Figure 3 are required by the seismic data. These crustal parameters in areas where seismic-refraction observations have been made are probably within about 10 per cent of the contour values.

The map of crustal thickness, mean crustal velocity, and upper-mantle velocity supports the following generalizations:

1. Crustal thickness at sea level is not constant. It ranges from about 20 km in California to more than 30 km along the Coastal Plain.

2. Crustal thickness is not simply related to altitude above sea level in the continental interior. In much of the high region of the Intermountain Plateaus, and particularly in the Basin and Range province, the crust is less than 40 km thick, and in some mountainous regions the crust is thinner than it is at sea level in the Coastal Plain.

3. Mean crustal velocity varies by at least 10 per cent. It tends to be high where the crust is relatively thick and low where the crust is relatively thin.

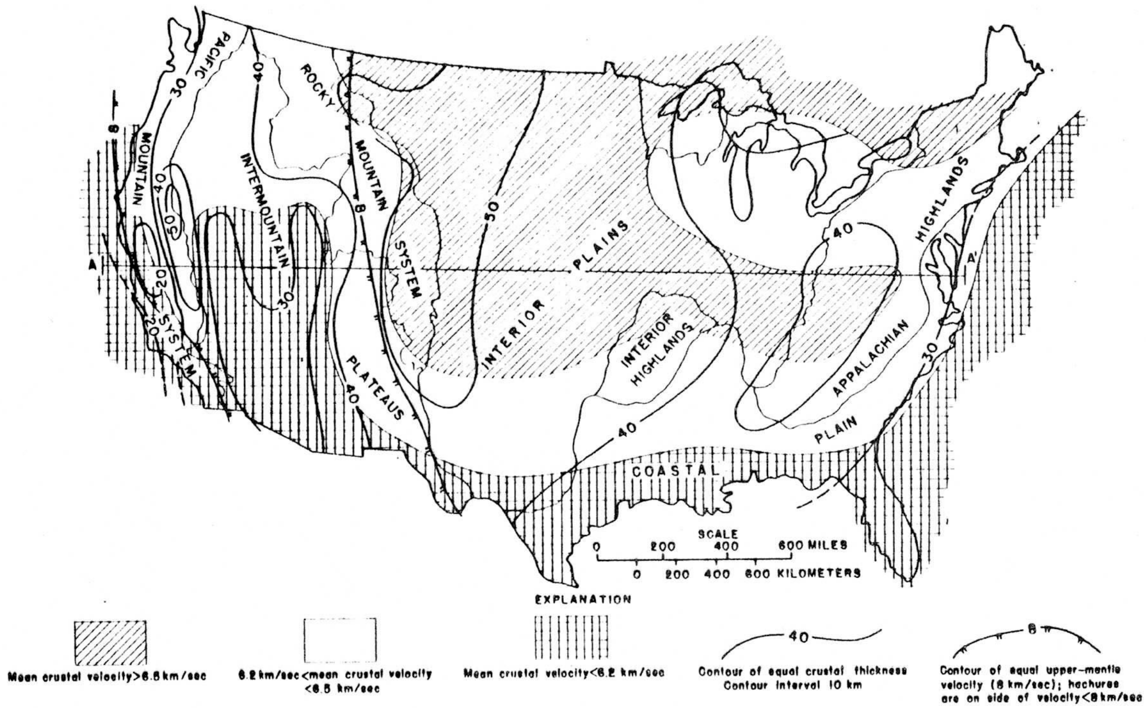


Figure 3.--Variations in crustal thickness, mean crustal velocity, and upper-mantle velocity in the conterminous United States (adapted from Stuart and others, 1964, and Pakiser and Steinhart, in press).

4. Upper-mantle velocity varies by at least 6 per cent. It also tends to be high where the crust is relatively thick and low where the crust is relatively thin.

East of the Rocky Mountains, the average crust is thick and the mean crustal and upper-mantle velocities are high. This broad area can be visualized as an eastern superprovince in which crustal and upper-mantle properties are generally uniform. West of the Rocky Mountains, the average crust is thin and the mean crustal and upper-mantle velocities are low. This broad area can be visualized as a western superprovince of complex crustal structure and uniform upper-mantle properties. Mean Crustal velocity is also low in the Coastal Plain because of the thick sedimentary section. The average crust is thickest in the Great Plains province, and thinnest near and east of the California coastline.

The continent can also be visualized in cross section (Profile A-A', Figures 3 and 4). The crust is slightly more than 20 km thick near the California coastline, and it thins to less than 20 km just east of the coastline. The crust thickens to more than 50 km under the high Sierra Nevada Mountains on the extreme east of the Pacific Mountain System, and thins farther east to about 35 km under the Basin and Range province. The crust thickens to about 40 km under the Colorado Plateaus, west of the Rocky Mountain System, and to about 50 km or more near the boundary between the Rocky Mountains and the Great Plains. The crust gradually thins farther east to

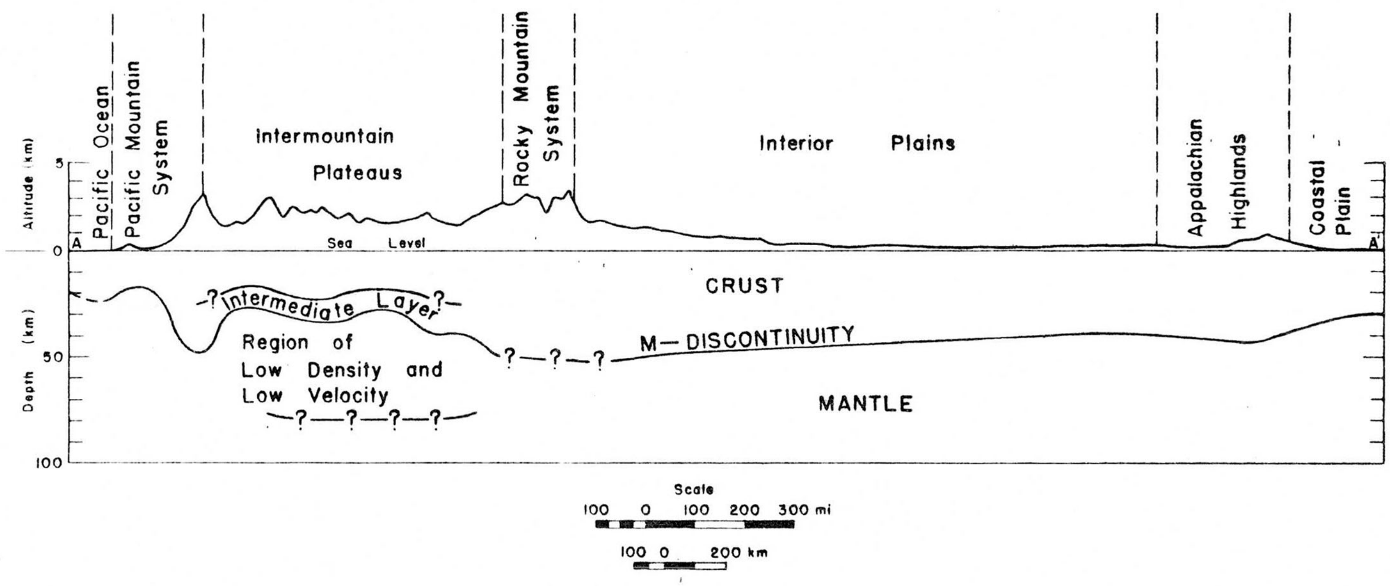


Figure 4.--Crustal and upper-mantle structure along Profile A-A'.

about 30 km at the Atlantic coastline, but probably thickens slightly under the Appalachian Highlands.

Distinct crustal layering is fairly well established in the Intermountain Plateaus, but elsewhere the presence or absence of such layering is controversial. I favor the opinion that the crust, below the near-surface veneer of sedimentary deposits, is composed of two main layers or zones -- an upper crust approximating diorite or granodiorite in composition, and a lower crust approximating gabbro -- but there are probably compositional as well as velocity and density gradients within these layers or zones. The controversy between a layerlike and a continuously varying crust may, therefore, be merely one of emphasis.

Isostasy and roots of mountains. The average crustal thickness in the superprovince west of the Rocky Mountains is clearly less than the average crustal thickness in the superprovince east of the Rocky Mountains, although the average surface altitude above sea level is higher to the west (Figure 4). Both of these areas are regionally in isostatic equilibrium (i.e., the average weight of a column of rock of the same area down to some level of compensation is constant).[1/]

[1/]There are two classical models for isostatic equilibrium: Airy isostasy and Pratt isostasy. In the Airy model, topographic variations are compensated by variations in the thickness of the crust; this is the roots-of-mountains or floating-iceberg concept. In the Pratt model, topographic variations are compensated by variations in the density of the crust.

The density of the upper mantle below the Intermountain Plateaus is less than it is farther east. The density of the upper mantle in the Intermountain Plateaus corresponding to a compressional-wave velocity of 7.8 km/sec would be about 3.30 g per cm^3; the density of the upper mantle in the Great Plains corresponding to a compressional-wave velocity of 8.2 km/sec would be about 3.45 g per cm^3. The region of low density under the Intermountain Plateaus extends to a depth of about 80 km if the above are the actual densities of the upper mantle and if the region is in isostatic equilibrium with the Great Plains. The "roots" of the high Intermountain Plateaus, taken as a unit, are therefore in the mantle and not in the crust, as assumed in Airy isostasy, and the depth of compensation is probably about 80 to 100 km.

Some individual mountain ranges or narrow systems of ranges have Airy crustal roots, and others do not. The crust beneath the Sierra Nevada thickens to more than 50 km compared with about 35 km in the Basin and Range province to the east, whereas the crust in the Rocky Mountains is as thin as or thinner than the crust in the Great Plains province farther east. The European Alps also have crustal roots. Some volcanic mountain ranges such as the southern Cascade Range are isostatically compensated by low-density material in the upper part of the crust.

In summary, isostasy may be accomplished by several factors as follows:

1. Variations in the density of the rocks of the upper mantle.

2. Variations in the mean density of the crust related to variations in the thickness of major crustal layers or zones.

3. Variations in the mean density of the crust related to variations in the thickness of low-density deposits in the upper part of the crust.

4. Variations in total crustal thickness.

Airy isostasy seems to be valid in broad regions in which the mean crustal and upper-mantle densities are uniform, and Pratt isostasy seems to be valid in broad regions in which these densities vary laterally. In general, isostasy is complex and is achieved by some combination of the variations given above. There is no single, generally valid isostatic model.

<u>Nature of the M-discontinuity</u>. The nature of the M-discontinuity is still a topic for speculation. A qualitative comparison of the depths to this interface in the Basin and Range and the Great Plains provinces indicates that the discontinuity does not represent the basalt-eclogite phase transformation.[2/] If the M-discontinuity in the Great Plains is at the pressure of the basalt-eclogite phase transformation for a given temperature, eclogite could not exist stably at any lower pressure (depth) at the same or any higher temperature. But mantle material does exist at a much shallower depth in the Basin and Range province (about 35 km) than in the Great

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[2/] Eclogite is the high-pressure chemical equivalent of basalt.

Plains province (about 50 km), and the heat flow is probably higher in the Basin and Range province. This condition suggests that the upper mantle is composed of a rock like peridotite, perhaps a mixture of basalt and peridotite, and that the M-discontinuity separates materials of different chemical composition.

If future research substantiates the existence in the deep crust of material having compressional-wave velocity near 7.5 km/sec, this finding would suggest the existence of a rock unlike the average basalt, for which experimentally determined velocities are usually lower. This material might be a mixture of crustal basalt and mantle peridotite, or alternatively basalt that has been partly or wholly transformed to eclogite. If the latter material, the upper mantle in the Great Plains (and other areas where its velocity is high) would be a mixture of peridotite and subordinate eclogite, and the upper mantle in the Intermountain Plateaus (and other areas where its velocity is low) would be a mixture of peridotite and subordinate basalt. The basalt-eclogite phase transformation surface or zone would then be within the crust where the crust is thick and pressures in the lower crust are high, and within the mantle where the crust is thin and pressures in the lower crust are low.

Partial serpentinization of mantle peridotite, temperature effects (including partial melting), or regional variations in the chemical composition of the mantle could also explain the observed and inferred variations in velocity and density.

Conclusions. The main generalization that can be drawn from this review of the crustal and upper-mantle structure of the continental crust is that the United States is divided by the Rocky Mountain System into two crustal and upper-mantle superprovinces.

The western superprovince includes the Pacific Mountain System, the Intermountain Plateaus, and the Rocky Mountain System. It has the following properties: (1) the velocity of compressional waves in the upper-mantle rocks is low, (2) the mean-crustal velocity is low, (3) the crust is generally thin, and (4) the crust seems generally to be divided into two fairly distinct layers by a boundary or velocity transition zone. There are, of course, important regional variations in the thickness of crustal layers within the western superprovince, but the upper mantle seems to be fairly uniform.

The eastern superprovince includes the Interior Plains, the Interior Highlands, the Appalachian Highlands, and the Coastal Plain. It has the following properties: (1) the velocity of compressional waves in the upper-mantle rocks is high, (2) the mean-crustal velocity is high, (3) the crust is generally thick, and (4) evidence for separation of the crust into distinct layers is generally less convincing than in the west. Below the veneer of sedimentary rocks the velocity of compressional waves in the crust may increase continuously with depth to the M-discontinuity. As in the western superprovince, there are important regional variations in the thickness of the crust, and the degree of uniformity of the upper mantle is still a matter for debate and further experimentation.

Laboratory measurements of density and seismic velocity, gravity measurements, and considerations of isostasy indicate that crustal and upper-mantle densities vary directly with velocity, so the western superprovince is characterized by low crustal and upper-mantle densities and the eastern superprovince by relatively high densities.

The western superprovince has been subjected to widespread late Mesozoic and Cenozoic diastrophism, plutonism, and volcanism, whereas the eastern superprovince has been relatively stable and quiescent during the past 100 million years or so. The crust and upper mantle in the western superprovince can be thought of as youthful -- still in the process of evolution. The crust and upper mantle in the eastern superprovince can be thought of as mature. The low-density crust of the west is now receiving mafic material from the mantle whereas the high-density crust of the east has already been extensively intruded with material from the mantle.

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