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**PURL:** http://resolver.sub.uni-goettingen.de/purl?PPN101433392X_0036

**LOG Id:** LOG_0101
**LOG Titel:** Crustal structure of the western United States from seismic-refraction measurements in comparison with Central European results
**LOG Typ:** article

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*Zeitschrift für Geophysik, 1970, Band 36, Seite 477—500. Physica-Verlag, Würzburg*

# Crustal Structure of the Western United States from Seismic-Refraction Measurements in Comparison with Central European Results[1])

By C. PRODEHL, Karlsruhe[2])

Eingegangen am 6. März 1970

*Summary:* In 1961—1963, a network of 64 seismic-refraction profiles was recorded by the U.S. Geological Survey in the western United States, west of longitude 109° W. By the re-interpretation with the aid of record sections, a basic travel time diagram could be derived, similar to that found for central Europe. Besides the first arrivals on profiles in the Snake River Plain, the northern Basin and Range province, and the Middle Rocky Mountains two dominant phases in secondary arrivals are correlated, whereas the profiles in other areas show only one dominant phase in secondary arrivals. Under the southern Cascade Mountains and the Snake River Plain the top of material with velocities of 6.5—7.0 km/s is found at depths of 7 to 17 km. Velocity inversions within the upper 20 kilometers of the earth's crust are indicated under the southern Cascade Mountains, the Middle Rocky Mountains, and partly under the Basin and Range province. Beneath the northern part of the Basin and Range province and the Middle Rocky Mountains, an intermediate transition zone between upper and lower crust can be well determined. The resulting velocities at the base of the crust and in the uppermost part of the upper mantle lie between 7.3 and 7.9 km/s for most parts of the western United States except for southern California and the Middle Rocky Mountains (≥ 8.0 km/s). The base of the crust dips from 30—36 km under the Basin and Range province toward the adjacent Sierra Nevada (42 km), Snake River Plain (44 km), Middle Rocky Mountains (45 km), and Colorado Plateaus (43 km). The crust is relatively thin under the Mojave desert (28 km) and the Coast Ranges of central California (24—26 km), but shows 37 km thickness under the Transverse Range in southern California.

*Zusammenfassung:* In den Jahren 1961—1963 legte der U.S. Geological Survey in den westlichen Vereinigten Staaten (westlich des Längengrades 109° W) ein refraktionsseismisches Profilnetz mit 64 Profilen an, die größtenteils mit Schuß und Gegenschuß beobachtet wurden. Für sämtliche Profile wurden Seismogramm-Montagen hergestellt. Bei der Reinterpretation dieser Profile wurde eine charakteristische Anordnung von Laufzeitkurven gefunden, die den Ergebnissen in Mitteleuropa ähnelt. Außer den Ersteinsätzen lassen sich in späteren Einsätzen bei den Profilen in der Snake River Plain, der nördlichen Basin and Range province und den mittleren Rocky Mountains zwei dominierende Phasen korrelieren, während bei den Profilen in anderen tektonischen Einheiten im wesentlichen nur eine dominierende Phase in späteren

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[1]) Contribution No. 124 within the research program "Determination of Crustal Structure in Central Europe" of the Deutsche Forschungsgemeinschaft (German Research Association). Contribution No. 53, Geophysical Institute, University of Karlsruhe.

[2]) Dr. CLAUS PRODEHL, Geophysikalisches Institut der Universität Fridericiana, 75 Karlsruhe, Hertzstr. 16, Germany.

Einsätzen sichtbar ist. Unter den südlichen Cascade Mountains und der Snake River Plain wird die Oberfläche von Material mit P-Wellen-Geschwindigkeiten zwischen 6,5 und 7,0 km/s in einer Tiefe von 7 bis 17 km angetroffen. Geschwindigkeitsinversionen innerhalb der oberen 20 Kilometer der Erdkruste müssen unter den südlichen Cascade Mountains, den mittleren Rocky Mountains und Teilen der Basin and Range province angenommen werden. Unter der nördlichen Basin and Range province und den mittleren Rocky Mountains ist eine Übergangszone zwischen oberer und unterer Kruste gut ausgebildet. Für die meisten Gebiete der westlichen Vereinigten Staaten ergeben sich an der Basis der Erdkruste und im obersten Erdmantel Geschwindigkeiten zwischen 7,3 und 7,9 km/s, lediglich in Südkalifornien und in den mittleren Rocky Mountains wurden höhere Geschwindigkeiten (≥ 8,0 km/s) gefunden. Die Basis der Erdkruste taucht von 30—36 km in der Basin and Range province unter die umliegenden Gebiete: Sierra Nevada (42 km), Snake River Plain (44 km), mittlere Rocky Mountains (45 km) und Colorado Plateaus (43 km). Unter der Mojave-Wüste beträgt die Mächtigkeit der Kruste etwa 28 km, unter den Transverse Ranges in Südkalifornien bis zu 37 km und unter den Coast Ranges von Mittelkalifornien 24—26 km.

## Introduction

During the last 12 years, in many countries of the world detailed investigations of the earth's crust and upper mantle by explosion seismology have been carried out. Summaries of most of the results in central Europe and North America were published for example by PAKISER and STEINHART [1964], JAMES and STEINHART [1966], MORELLI et al. [1967], CLOSS [1969], and HEALY and WARREN [1969]. The results presented show that the structure of the crust and upper mantle varies from area to area. However, the results also show a rather heterogeneous character, depending on different authors and different methods used for the interpretation of the data. To eliminate heterogeneity of the models caused by heterogeneity in the methods of interpretation, CHOUDHURY et al. [1967] and GIESE [1968] have compiled most of the data for the Alps and for western Germany and presented uniform models.

Based on the same method [GIESE 1966] used by CHOUDHURY et al. [1967] and GIESE [1966, 1968] the author has re-interpreted a detailed seismic- refraction survey in the western United States, performed by the U.S. Geological Survey from 1961 to 1963. Most of the field work was done as a part of the VELA UNIFORM Project of the Advanced Research Projects Agency, U.S. Department of Defense, under ARPA Order No. 193. A network of 64 profiles, mostly reversed and recorded to distances of 300—400 km, was observed in Nevada, California, Utah, and adjacent areas.

Chemical explosions in drill-holes, lakes or the Pacific Ocean served as energy sources, the charges ranging in size from less than 0.5 to 10 tons. Additionally several underground explosions of nuclear devices at N.T.S. (Nevada Test Site) were recorded. At each recording-site, six vertical-component seismometers were placed at 0.5 km intervals to form 2.5 km spreads in line with the direction of the profile as far as terrain permitted. Technical details concerning instruments and field work have been described by WARRICK et al. [1961] and JACKSON et al. [1963].

Most of the data including some earlier measurements have been published by various authors: Diment et al. [1961], Eaton [1963, 1966], Eaton et al. [1964], Gibbs and Roller [1966], Healy [1963], Hill and Pakiser [1966, 1967], Johnson [1965], Pakiser and Hill [1963], Roller [1964, 1965], Roller and Healy [1963], Ryall and Stuart [1963], and Willden [1965] and summarized for example by Pakiser [1963], Stuart et al. [1964], and Warren [1968a, b].

## Geologic setting

Fig. 1 and Table 1 show the location of shotpoints and profiles and the physical division of the area of investigation after Fenneman and Johnson [1964].

Table 1: Shotpoints.

| No. | Shotpoint | Coordinates | | Altitude (meters) |
|---|---|---|---|---|
| | | latitude | longitude | |
| 1 | San Francisco | 37° 36.08′ | 122° 41.55′ | Sea level |
| 2 | Camp Roberts | 35° 47.38′ | 120° 49.98′ | 208 |
| 3 | San Luis Obispo | 35° 07.60′ | 120° 47.10′ | Sea level |
| 4 | Santa Monica Bay | 34° 00.06′ | 118° 33.28′ | Sea level |
| 5 | Shasta Lake | 40° 46.17′ | 122° 13.92′ | 314 |
| 6 | Mono Lake | 37° 59.00′ | 119° 07.60′ | 1950 |
| 7 | Independence | 36° 44.79′ | 118° 15.72′ | 1655 |
| 8 | China Lake | 35° 47.00′ | 117° 44.96′ | 677 |
| 9 | Fallon | 39° 31.43′ | 118° 52.48′ | 1220 |
| 10 | Shoal | 39° 12.02′ | 118° 22.82′ | 1740 |
| 11 | Boise | 43° 34.70′ | 115° 58.95′ | 931 |
| 12 | Strike Reservoir | 42° 55.29′ | 115° 53.70′ | 748 |
| 13 | Mountain City | 41° 50.24′ | 115° 53.70′ | 1683 |
| 14 | Elko | 40° 46.23′ | 115° 40.97′ | 1625 |
| 15 | Eureka | 39° 30.82′ | 115° 39.00′ | 1806 |
| 16 | Delta | 39° 40.55′ | 112° 35.55′ | 1150 |
| 17 | Lida Junction | 37° 20.96′ | 117° 29.54′ | 1658 |
| 18 | Lathrop Wells | 36° 37.18′ | 116° 13.76′ | 951 |
| 19 | Nevada Test Site (NTS) | 37° 07′ * | 116° 02′ * | 1400* |
| 20 | Hiko | 37° 54.20′ | 115° 13.80′ | 1538 |
| 21 | Navajo Lake | 37° 32.53′ | 112° 47.55′ | 2912 |
| 22 | Lake Mead | 36° 05.28′ | 114° 47.96′ | 369 |
| 23 | Mojave | 35° 03.02′ | 118° 00.33′ | 786 |
| 24 | Barstow | 34° 58.34′ | 117° 04.23′ | 755 |
| 25 | Ludlow | 34° 49.36′ | 116° 11.02′ | 396 |
| 26 | Kingman | 35° 19.36′ | 114° 03.92′ | 1180 |
| 27 | American Falls Reservoir | 42° 50.14′ | 112° 48.66′ | 1360 |
| 28 | Bear Lake | 41° 56.35′ | 111° 17.10′ | 1820 |
| 29 | Flaming Gorge Reservoir | 40° 56.77′ | 109° 38.43′ | 1730 |
| 30 | Hanksville | 38° 21.99′ | 110° 55.64′ | 1430 |
| 31 | Chinle | 35° 55.64′ | 109° 34.44′ | 1830 |

* Approximate center of location of the NTS shots used in this report.

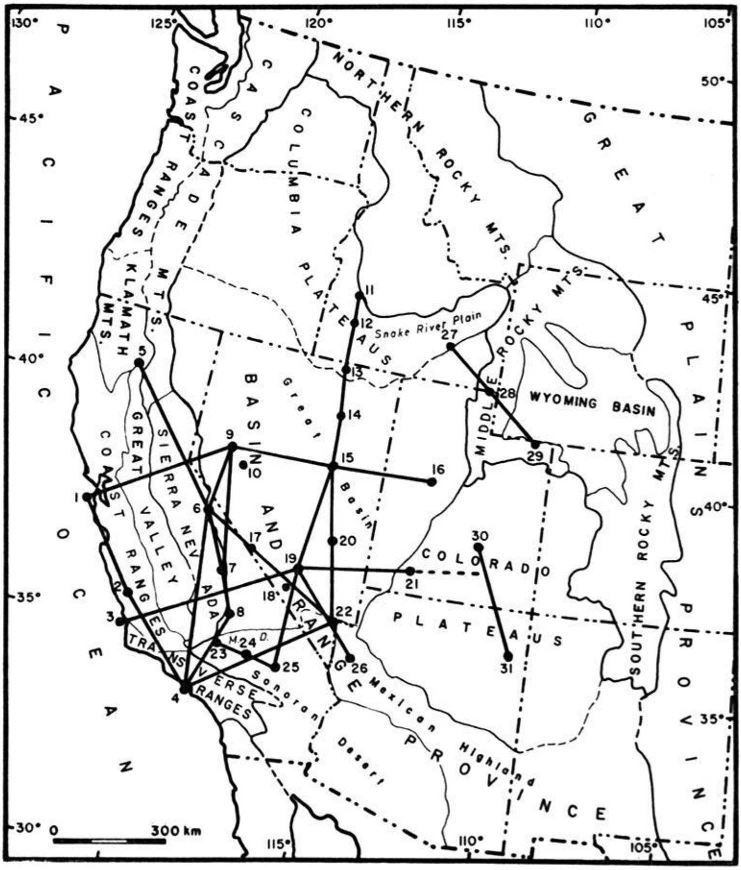


Fig. 1: Physical divisions of the western United States after FENNEMAN and JOHNSON [1946] and location of seismic refraction profiles.

M.D. Mojave Desert

Shotpoints

1 San Francisco,
2 Camp Roberts,
3 San Luis Obispo,
4 Santa Monica Bay,
5 Shasta Lake,
6 Mono Lake,
7 Independence,
8 China Lake,
9 Fallon,
10 Shoal,
11 Boise,
12 Strike Reservoir,
13 Mountain City,
14 Elko,
15 Eureka,
16 Delta,
17 Lida Junction,
18 Lathrop Wells,
19 Nevada Test Site (NTS),
20 Hiko,
21 Navajo Lake,
22 Lake Mead,
23 Mojave,
24 Barstow,
25 Ludlow,
26 Kingman,
27 American Falls Res.,
28 Bear Lake,
29 Flaming Gorge Res.,
30 Hanksville,
31 Chinle.

The westernmost profiles were recorded in the Coast Ranges of California, a part of an active mobile orogenic belt in which sedimentation, deformation, volcanism, and plutonism have been intimately associated since the mid-Mesozoic [CROWELL 1968]. The Coast Ranges are separated from the Sierra Nevada by the Great Valley of central California, a great depression with the structure of a complex synclinorium floored with alluvial deposits [KING 1959].

The Sierra Nevada to the east is mainly composed of plutonic rocks of the Sierra Nevada batholith of Mesozoic age and is a huge block formed by westward tilting and profound late Cenozoic faulting on the east [BATEMAN et al. 1963, BATEMAN and WAHRHAFTIG 1966, PAKISER et al. 1964]. Here some profiles were recorded parallel to the geologic structures, one profile reaching into the Cascade Mountains in the north, a volcanic mountain range built by eruptions of basaltic to rhyolitic lava during Pliocene, Pleistocene, and recent time [MACDONALD 1966]. Other profiles cross the geologic structures of Coast Ranges, Great Valley, and Sierra Nevada, and reach into the Basin and Range province on the east.

The main part of the seismic investigation was concentrated on the Great Basin of the Basin and Range province in Nevada and western Utah. The obvious Cenozoic structures of the Basin and Range province are block faults due to crustal extension. The present north-trending ranges were formed mostly since the early Miocene and stand 500—1200 m above the alluvial floors of flanking basins [HAMILTON and MYERS 1966, 1968]. According to HAMILTON and MYERS, the total extension of the whole province across the wide northern part has been between 50 and 300 km. One seismic-refraction line extends from the Basin and Range province into the Snake River Plain in the north, a part of the Columbia Plateaus. According to HAMILTON and MYERS, the Snake River Plain is a lava-filled tension rift formed in the lee of the northwestward-drifting plate of the Idaho batholith.

On the east, the Basin and Range province is bordered by the Colorado Plateaus, a region of large plateaus, escarpments, and canyons, the plateaus reaching heights of 3000—3600 m [KING 1959], and by the Middle Rocky Mountains which comprise ranges of deformed miogeosynclinal rocks on the west and a set of rather simple uplifts and basins on the east [KING 1959]. Both in the Colorado Plateaus and in the Middle Rocky Mountains, a seismic-refraction line with two or three shotpoints was recorded in 1963.

## Analysis of seismic-refraction profiles

The examination of the record sections prepared for each profile to be re-interpreted shows that on nearly all profiles similar phases can be correlated and that the corresponding traveltime curves show a typical arrangement which is very similar to that found by GIESE [1966] and GIESE et al. [1967] for central Europe. Figs. 2 to 7 present the record sections of several profiles recorded in different tectonic units:

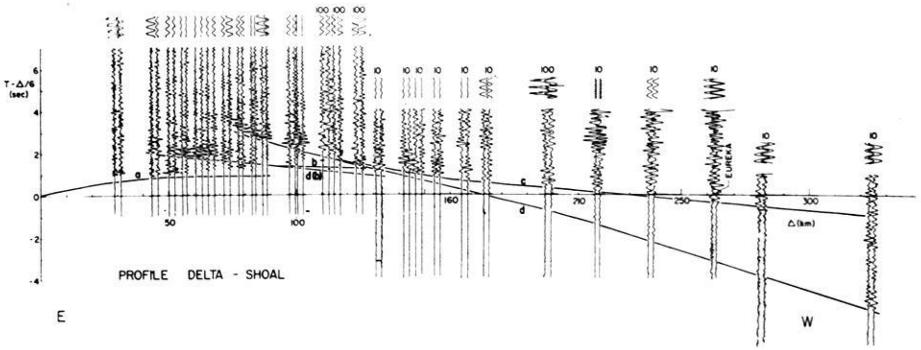


Fig. 2: Record section of the profile Delta (16)—Shoal (10). Calibration on top of each trace in microvolts. The numbers behind the shotpoints refer to Fig. 1.

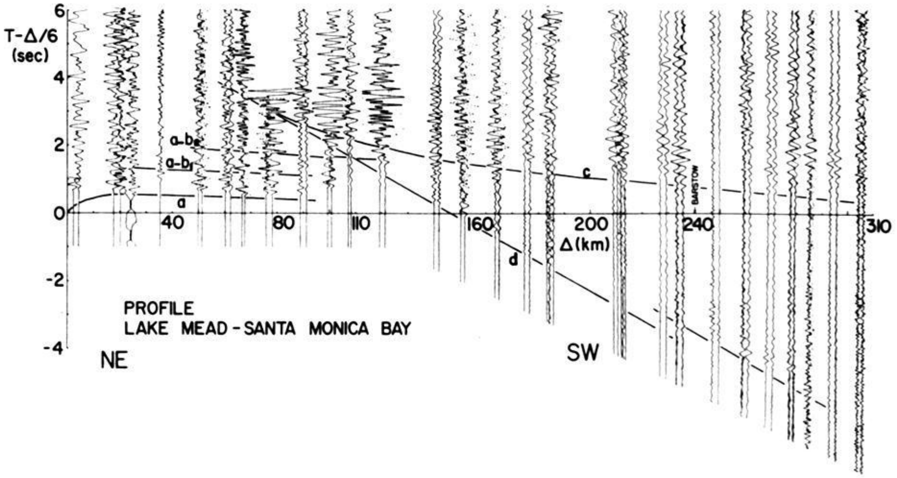


Fig. 3: Record section of the profile Lake Mead (22)—Santa Monica Bay (4).

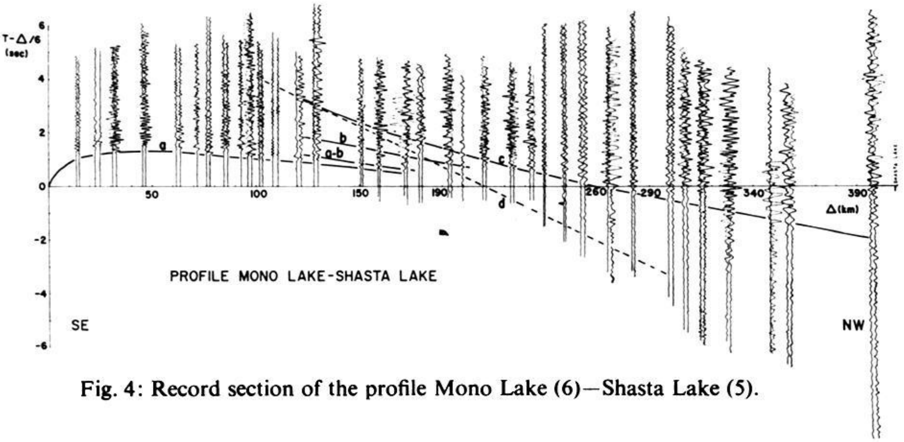


Fig. 4: Record section of the profile Mono Lake (6)—Shasta Lake (5).

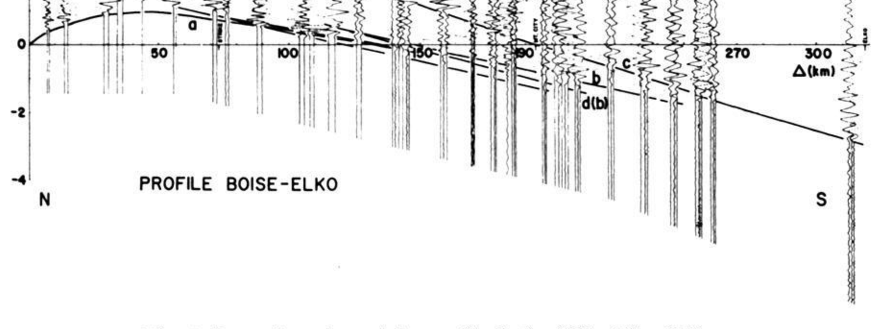


Fig. 5: Record section of the profile Boise (11)—Elko (14).

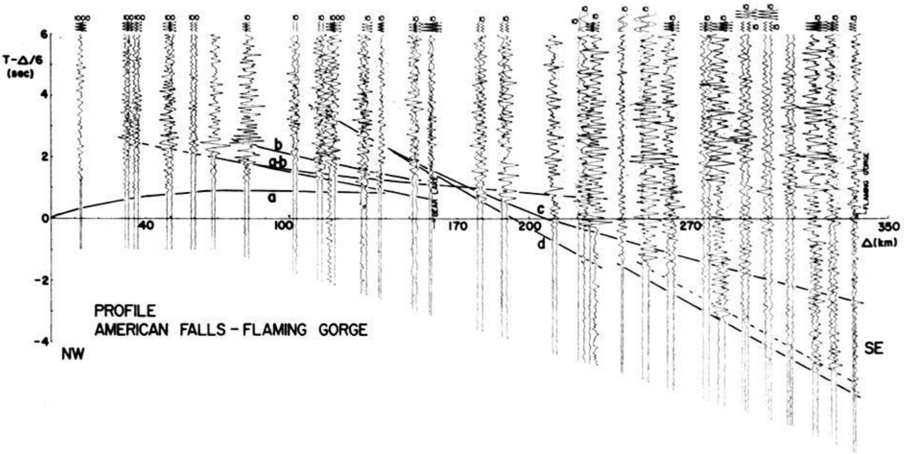


Fig. 6: Record section of the profile American Falls Reservoir (27)—Flaming Gorge Reservoir (29).

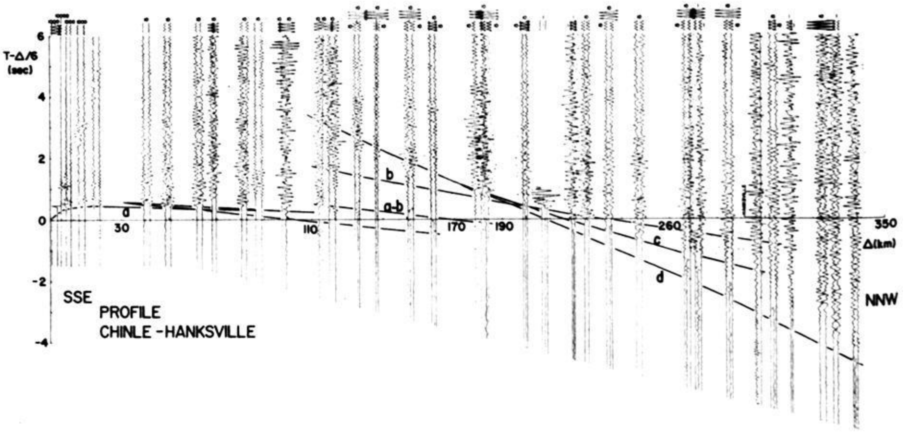


Fig. 7: Record section of the profile Chinle (31)—Hanksville (30).

The profile Delta-Shoal (Fig. 2) was recorded in the northern part, the profile Lake Mead-Santa Monica Bay (Fig. 3) in the southern part of the Basin and Range province.

The profile Mono Lake-Shasta Lake (Fig. 4) was recorded parallel to the geologic structures of the Sierra Nevada, Fig. 5 (Boise-Elko) presents a profile recorded mainly within the Snake River Plain, and finally profiles through the Middle Rocky Mountains (Fig. 6: American Falls Reservoir-Flaming Gorge Reservoir) and the Colorado Plateaus (Fig. 7: Chinle-Hanksville) are shown.

The first arrivals generally align on two traveltime curves: $a(P_g)$, correlated with the basement, and $d(P_n)$, correlated with the upper mantle. Except for the profiles in the Snake River Plain basement velocities of 5.9—6.3 km/s are found based on curve *a*. On the profiles in the Snake River Plain (Fig. 5), however, as well as on the profile Shasta Lake-Mono Lake the northernmost part of which crosses the southern Cascade Mountains, velocities of 6.6—7.0 km/s result at relatively small distances from the shotpoint.

Depending on crustal thickness, phase *d* can be correlated beginning from a distance of 130—200 km. At distances greater than 250 km very often the amplitudes of the corresponding arrivals increase. In some cases, these arrivals are delayed with respect to the phases well recognizable up to 200 km distance (Fig. 3 and 6). This delay may be due to the influence of sedimentary layers beneath the corresponding stations, but more often the first arrivals seem to disappear with increasing distance which may be explained by the structure of the upper mantle. On the profiles in the Snake River Plain (Fig. 5) phase *d* was not recorded, also on some profiles in the Sierra Nevada (Fig. 4) phase *d* was not or only weakly recorded. The measured apparent velocities vary between 7.3 and 8.25 km/s. Details will be discussed below.

Characterized by large amplitudes, a dominant phase *c* can be correlated in later arrivals between 70 and 240 km or even greater distances from the shotpoint. The corresponding apparent velocity decreases with increasing distance from about 7.2—8.0 km/s to 6.2—7.0 km/s, and the traveltime curve *d* is tangent to curve *c* at the end closest to the shotpoint. This phase *c* is interpreted as a reflected phase from the Mohorovičić (M) discontinuity, named $P_{\mathrm{M}}P$, by most authors [see for example Healy and Warren 1969, Pakiser and Steinhart 1964]. This phase was best recorded in the Basin and Range province and the Snake River Plain (Fig. 2, 3, and 5), yet can be well recognized on most profiles in other areas of the western United States as shown in Fig. 4, 6, and 7. It can be correlated on most profiles in central Europe also [Giese 1966]. However, Giese has shown that the explanation as a reflected wave is not in agreement with the exact curvature of curve *c* in most cases for central Europe. Rather phase *c* originates in a more or less thick transition zone between crust and upper mantle.

In some areas of the western United States, a well-defined phase *b* is observed between 50 and 150 km distance from the shotpoint. Like phase *c*, this phase *b* is interpreted as reflected phase by most authors, named $P_{\mathrm{I}}P$, i.e. reflected from an intermediate layer. Though very well observed on profiles in the northern Basin and

Range province (Fig. 2), the Snake River Plain (Fig. 5), or the Middle Rocky Mountains (Fig. 6), this phase is very weak or even absent on other profiles as for example in the southern Basin and Range province (Fig. 3). Also in central Europe, the nature of a corresponding traveltime curve $b$ usually is not clear and unique [GIESE 1968]. When phase $b$ is very well developed, often an additional phase $d(b)$ can be observed, usually in first arrivals, the traveltime curve of which is tangent to curve $b$ (Fig. 2 and Fig. 5).

## Basic data

Before determining velocity-depth relations, CHOUDHURY et al. [1967] and GIESE [1968] have presented some parameters for the Alps and western Germany which give objective information on the general features of any structure. Such data are: the cross-over distance $\Delta d$ between the traveltime curve $d(P_n)$ and the distance axis in the reduced traveltime diagram, the "critical" distance $\Delta_c$ which is defined here as the distance at which curve $d$ is tangent to curve $c$, the corresponding "critical" reduced time $\bar{T}_c$, and the $P_n$ velocity resulting from curves $d$ of reversed profiles. Having found a similar arrangement of traveltime curves in the western United States as found for central Europe, it is reasonable to look for similar typical parameters on the profiles in the western United States and to draw corresponding contour maps.

Figs. 8 and 9 show contour maps of the parameters $\Delta_d$ and $\Delta_c$. The corresponding values were plotted at half their distance. In addition to the profiles re-interpreted, some additional data were available for the parameter $\Delta_d$: a seismic-refraction survey in the Coast Ranges of central California, carried out in 1967 [STEWART 1968, 1969], a survey in central Arizona of 1964 [WARREN 1969] and the $P_n$ traveltime curve published by BERG et al. [1960] for the eastern Basin and Range province. In the contour map (Fig. 8), the corresponding shotpoints are marked by open quadrangles. The contour maps of $\Delta_c$ and $\Delta_d$ represent in a first approximation the variation of the total crustal thickness. Minima result for the Pacific coast of central California, central Nevada, and southeastern California, maxima are obtained for the Sierra Nevada, the Snake River Plain, the Middle Rocky Mountains, and the Colorado Plateaus. A comparison with the corresponding maps by CHOUDHURY et al. [1967] and GIESE [1968] for the Alps and western Germany shows that the maximum values of $\Delta_d \geq 200$ km and $\Delta_c = 120-140$ km in the western United States are comparable with the results found for the Alps while the minimum values of $\Delta_d = 120-140$ km and $\Delta_c = 60-80$ km in the western United States are comparable with areas in western Germany outside of the Alps.

To eliminate the traveltime delays caused by sedimentary layers the "critical" reduced time $\bar{T}_c$ was corrected by the corresponding reduced traveltime $\bar{T}_{a,c}$ of curve $a(P_g)$ at the "critical" distance $\Delta_c$. The resulting time difference $\bar{T}_c - \bar{T}_{a,c}$ was plotted at half the "critical" distance $\Delta_c/2$ (Fig. 10). High values indicate that the medium of propagation contains material with relatively low $P$ wave velocities. They are found

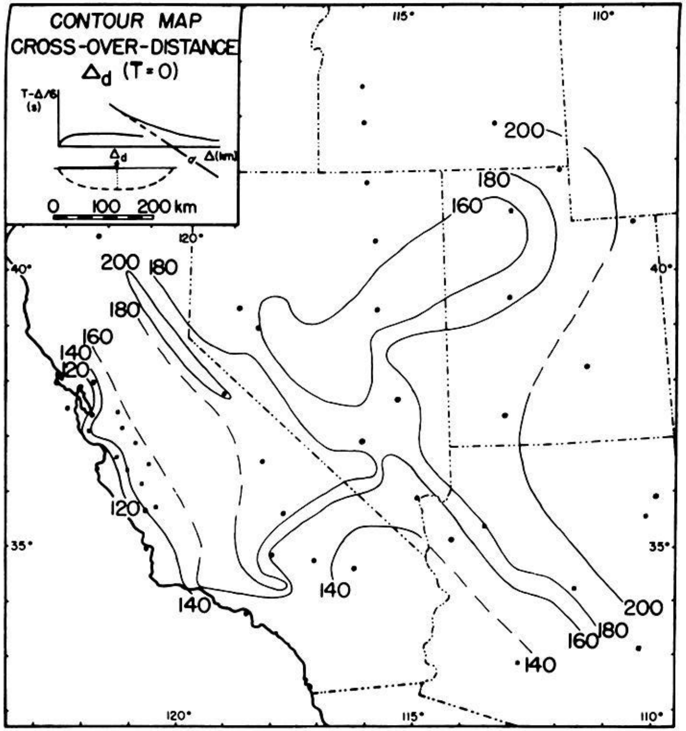


Fig. 8: Contour map of the cross-over distance $\Delta_d$ between $P_n$ (curve $d$) and $v = 6$ km/s ($\Delta$-axis).

Full circles: Shotpoints according to Fig. 1 and Table 1.

Open squares: Shotpoints of other seismic refraction surveys, the $P_n$ traveltime curves of which are used.

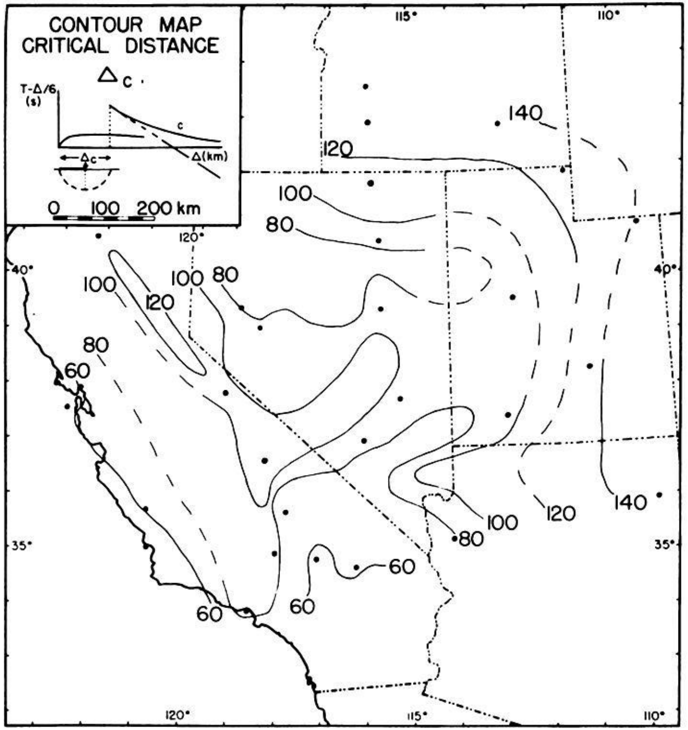


Fig. 9: Contour map of the "critical" distance $\Delta_c$.

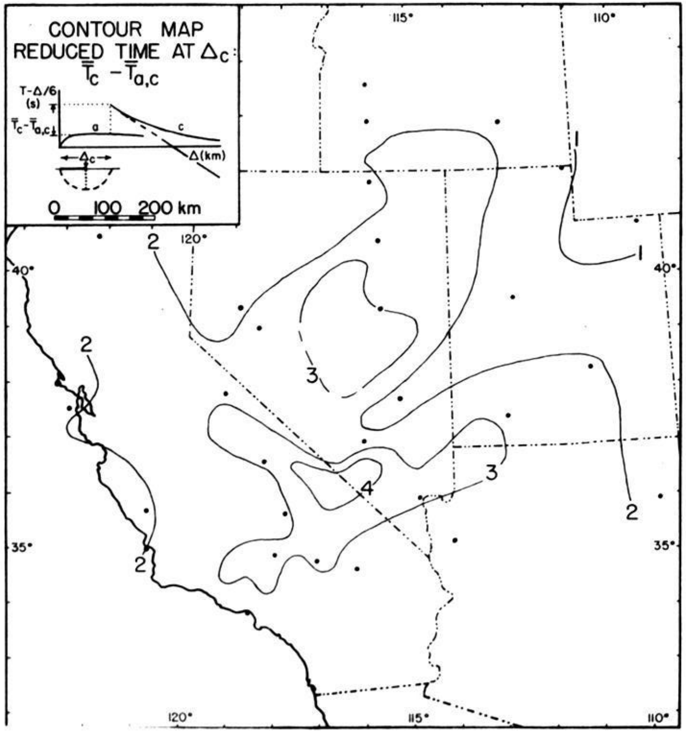


Fig. 10: Contour map of the reduced traveltime $\overline{T}_c - \overline{T}_{a,c}$.

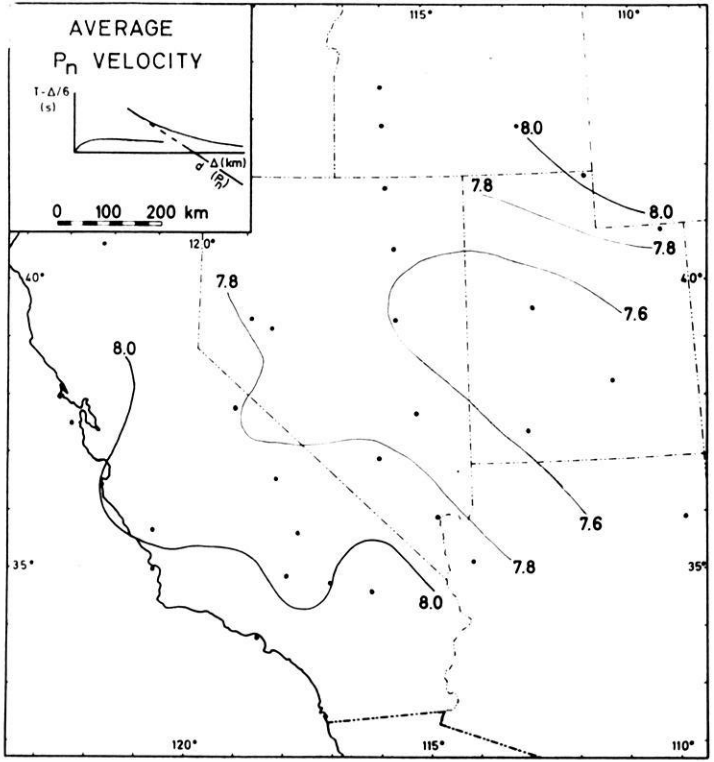


Fig. 11: Contour map of the average $P_n$ velocity based on curve *d*.

For the construction of the contour lines, for reversed profiles an average value was used, for profiles where the $P_n$ velocity increases with increasing distance the lowest well-defined value was used.

in central Nevada and across southern Nevada including adjacent parts of California. On the corresponding map for western Germany [Giese 1968], similar high values of 3—4 seconds occur in southeastern Bavaria and adjacent parts of Tyrol. Times of 1—2 seconds in other areas of the western United States are comparable with the values found for the main part of western Germany.

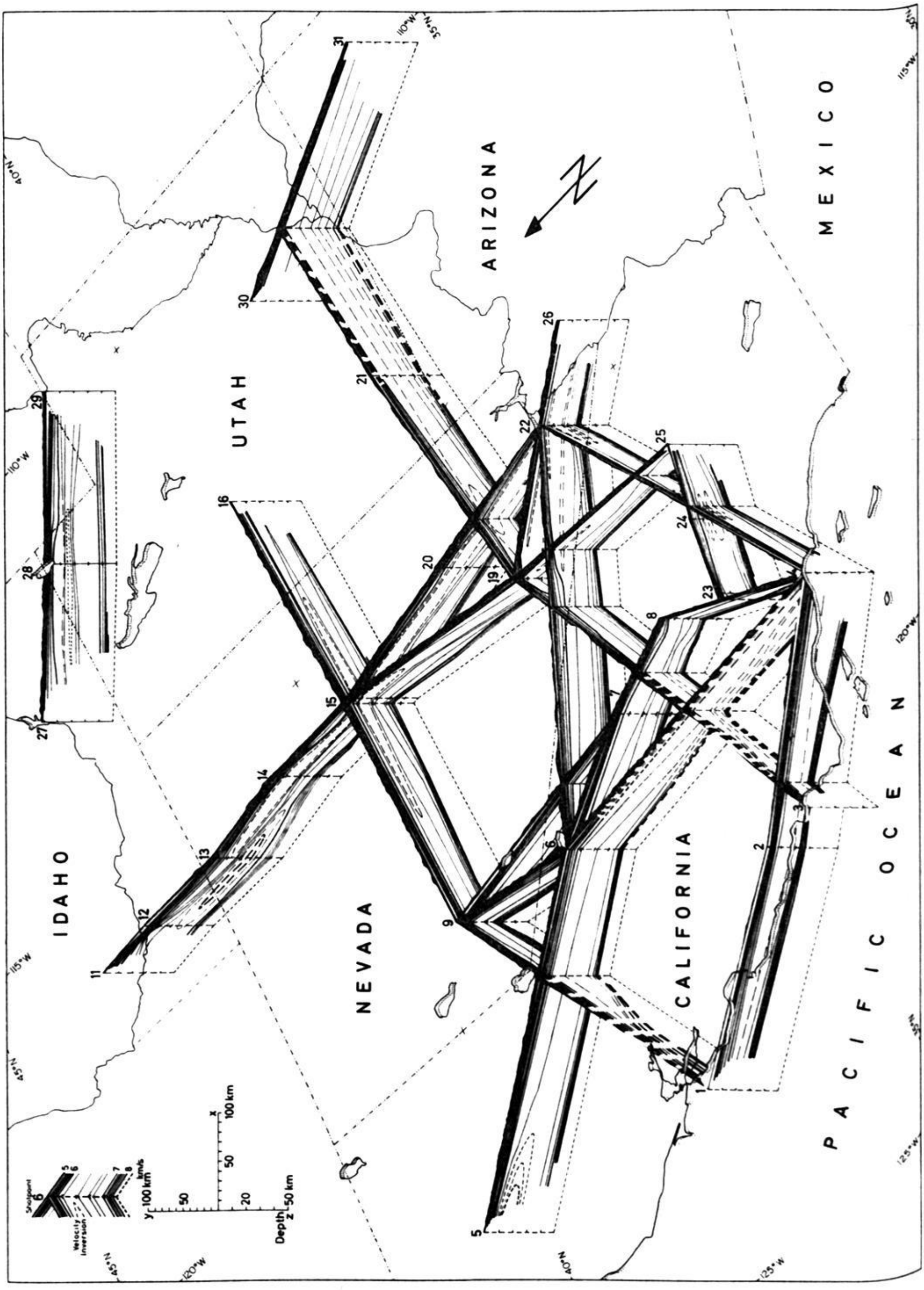
The contour map of the average $P_n$ velocity (Fig. 11) is based on curve *d*. The velocity gradient in the upper mantle is very small as indicated by the fact, that curve *d* is a nearly straight line in most cases. The resulting velocity values are strongly influenced by horizontal velocity gradients. To obtain approximately true velocities, therefore, an average value was used for reversed profiles, and plotted at the middle of the corresponding two shotpoints. While, with the exception of two areas in the central part of western Germany, the $P_n$velocity found in central Europe is equal to or greater than 8.0 km/s as shown by Giese (1968) by the corresponding contour map for western Germany and stated by various authors [Fuchs et al. 1963, German Research Group 1964, Prodehl 1965, Fuchs and Landisman 1966, Giese 1966, Meissner 1967, Ansorge 1968, Closs 1969], the $P_n$ velocities found for the western United States are generally less than 8.0 km/s varying between 7.6 and 7.9 km/s. Only beneath the Coast Ranges of California, southern California, and the Middle Rocky Mountains, $P_n$ velocities of 8 km/s and higher are obtained. Except for the Mojave desert in southern California this result is in general agreement with former investigations [Pakiser 1963, Pakiser and Steinhart 1964, Stuart et al. 1964, Pakiser and Zietz 1965].

## Crustal structure

Giese [1963, 1966] has used succesfully the Herglotz-Wiechert method for the determination of velocity-depth functions in cases where $t(\Delta)$ is a continuous function. On nearly all profiles in central Europe as well as on most profiles in the western United States, however, the traveltime curves cannot be combined to a continuous system with cusps (triplications) corresponding to depths where the velocity-gradient is very strong. Besides indirect methods [Fuchs and Landisman 1966, Mueller and Landisman 1966], velocity-depth functions can also be found directly with the aid of an approximation method developed by Giese [1966].

The crustal models presented in this paper are based on Giese's method. The results of the velocity-depth determinations were used to construct 15 crustal cross sections through the area of investigation showing lines of equal velocity. All cross sections were combined to a fence diagram (Fig. 12). Because of the wide spacing of the shotpoints, the crustal cross sections cannot give detailed changes in horizontal direction, but only an approximate picture of changes in crustal structure.

Under the Snake River Plain and under the southern Cascade Mountains the velocity increases within a small depth range to 6.6—7.0 km/s. It is possible that upper crustal material is lacking here as indicated by basaltic volcanic surface material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21
22
23
24
25
26
27
28
29
30
31
Shotpoint
6
Velocity
Inversion
km/s
5
6
7
8
y
100 km
50
x
100 km
50
Depth
z
50 km
20
40°N
45°N
35°N
30°N
110°W
115°W
120°W
125°W

[Pakiser and Hill 1963, Pakiser 1964, Hamilton and Myers 1966, 1968]. Under the Snake River Plain curves *a*, *b*, and *d*(*b*) (Fig. 5) result from velocity increases within probable basaltic material. Under the southern Cascade Mountains beneath a zone of strong velocity increase between 0 and 7 km, a velocity inversion from 6.6 to 6.0 km/s is found between 8 and 17 km depth corresponding to a local gravity low within a more extended gravity high [Pakiser 1964].

Under the Basin and Range province, within the upper crust a slight velocity inversion from 6.1—6.3 to 6.0—6.1 km/s is found. Especilally under its southern part relatively low *P* wave velocities of 6.0 km/s are found within the upper 20 km and seem to exist even below that depth near Lake Mead and N.T.S. Also under the southernmost part of the Sierra Nevada, near China Lake, low-velocity material (6.1 km/s) reaches to depths of about 20 km. Under the Middle Rocky Mountains the existence of a zone with velocity inversion within the upper crust, from 6.4 to 5.8 km/s, is indicated at a depth of about 17 km. Under the Colorado Plateaus, the main part of the Sierra Nevada, and the Coast Ranges of California, however, a velocity inversion is not evident within the crust.

From the existence of a well-defined traveltime curve *b* in some areas (Figs. 2 and 6) a well-defined intermediate transition zone within the crust is derived where the velocity increases from 6.4—6.6 to 7.0 km/s within the small depth range of a few kilometers. Such a zone is found under the Middle Rocky Mountains and the northern part of the Basin and Range province. Moving in the Basin and Range province from north to south, the intermediate transition zone disappears. There are no or only weak indications for a distinct division of the crust in an upper and a lower part beneath the southern part of the Basin and Range province. Under the Sierra Nevada, the Coast Ranges of California, and the Colorado Plateaus, an intermediate transition zone is not clearly developed, rather the velocity increases more or less uniformly from 6.1—6.2 km/s in the uppermost crust to 6.7—6.8 km/s at the top of the crust-mantle transition.

The base of the crust is generally a transition zone, the thickness of which varies between 2 and about 10 km and in which the velocity increases gradually from 6.6 to 7.0 km/s to about 7.8 km/s. This zone is relatively thin under the Coast Ranges of California, the Basin and Range province, and the Snake River Plain, but increases in thickness under the Sierra Nevada, the Middle Rocky Mountains, and the Colorado Plateaus.

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Fig. 12: Fence diagram of the western United States showing crustal structure by lines of equal velocity (contour interval 0.2 km/s). The diagram is viewed from an angle of 45° from the Pacific Ocean toward the northeast, approximately parallel to the line from Los Angeles to Salt Lake City. The depth $z$ is exaggerated 2:1 *versus* the horizontal direction $y$ (SW to NE). The scale of surface elevation corresponds to the scale of $z$. Velocity lines less than 5 km/s are not shown. Dashed lines indicate uncertain results. The depth scales under the shotpoints are divided into 10 km intervals. The shotpoints are numbered according to Fig. 1 and Table 1.

Strongly increasing velocity in combination with an increasing velocity gradient within the crust-mantle transition zone suggests to define the depth of the strongest velocity gradient as the base of the crust and to draw a corresponding contour map for the depth of strongest velocity gradient $z(\Delta_c)$ (Fig. 13). With an average thickness of 32—34 km, the crust is thinner under the Basin and Range province than under the surrounding Sierra Nevada in the west, the Snake River Plain in the north, the Middle Rocky Mountains in the northeast, and the Colorado Plateaus in the east where crustal thickness reaches more than 40 km. This result was already suggested by the contour maps for $\Delta_a$ and $\Delta_c$ (Figs. 8 and 9). Beneath the Basin and Range province minima in crustal thickness are found near Fallon, Nevada (29 km), near Delta, Utah (29 km), and between Kingman, Arizona, and Ludlow, California (28 km). The minimum near Delta, Utah, may correspond to an interpretation of **Berg** et al. [1960] who found the top of a layer with 7.59 km/s at 25 km depth beneath northwestern Utah.

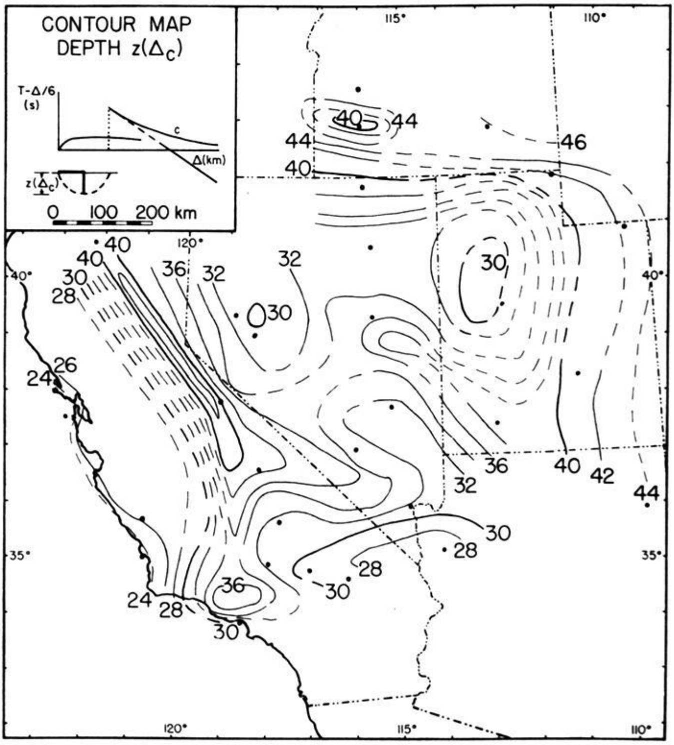

Fig. 13: Contour map of total crustal thickness. The contour lines show the depth of the strongest velocity gradient in the transition zone between crust and mantle: $z(\Delta_c)$. The values are plotted at half "critical" distance from the corresponding shotpoint.

The thick crust under the Sierra Nevada is not confined to its morphologic boundary in the east at Owens Valley but reaches far to the east in its central part concordant with the geologic observation that the Sierra Nevada batholith south of Mono Lake extends eastward from Owens Valley into the Death Valley region [BATEMEN et al. 1963] and "is broken into numerous large and small basin-and-range blocks" [HAMILTON and MYERS 1967]. To the south the crustal thickness decreases to 33 km near China Lake.

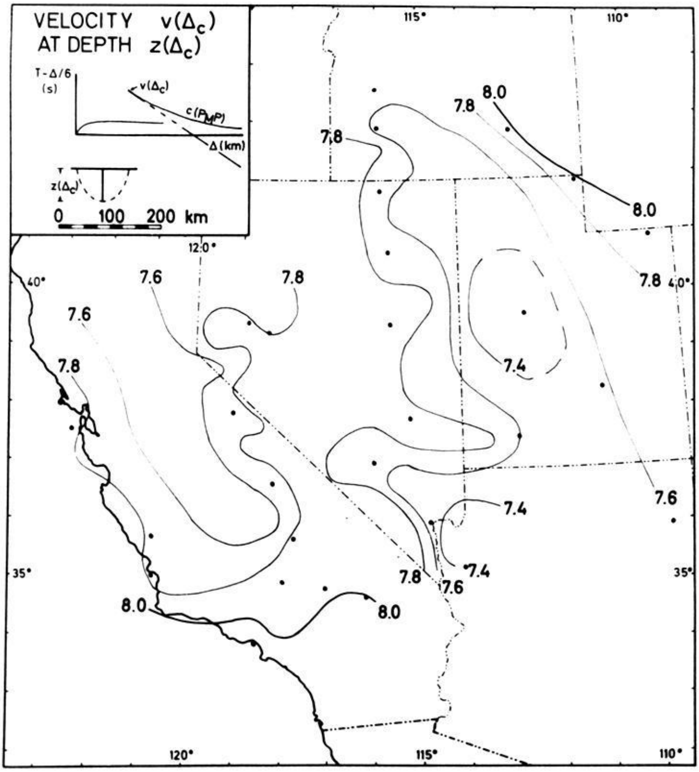

Fig. 14: Contour map of the velocity $v(\Delta_c)$ at the depth of strongest velocity gradient $z(\Delta_c)$ in the crust-mantle transition zone. The values are plotted at half the "critical" distance from the corresponding shotpoint.

The thinnest crust was found with 24—26 km under the Coast Ranges of central California, similar to a result found by BERG et al. [1966] who obtained a crustal thickness of only 16 km for the Coast Ranges of Oregon.—South of San Luis Obispo the crust thickens and reaches 36—37 km under the Transverse Ranges north of Los Angeles.

The velocity $v(\Delta_c)$ which corresponds to the depth of strongest velocity gradient is mapped in Fig. 14. For some areas significantly lower velocity values result than are shown in the contour map of the $P_n$ velocity (Fig. 11) which are based on curve *d*. These differences may be explained by a further velocity increase below the depth of strongest velocity gradient. This result corresponds to similar differences between velocity in the zone of strongest gradient and $P_n$ velocity mapped by GIESE [1968] for western Germany. For some areas of western Germany the difference amounts to 0.5 km/s or even more.

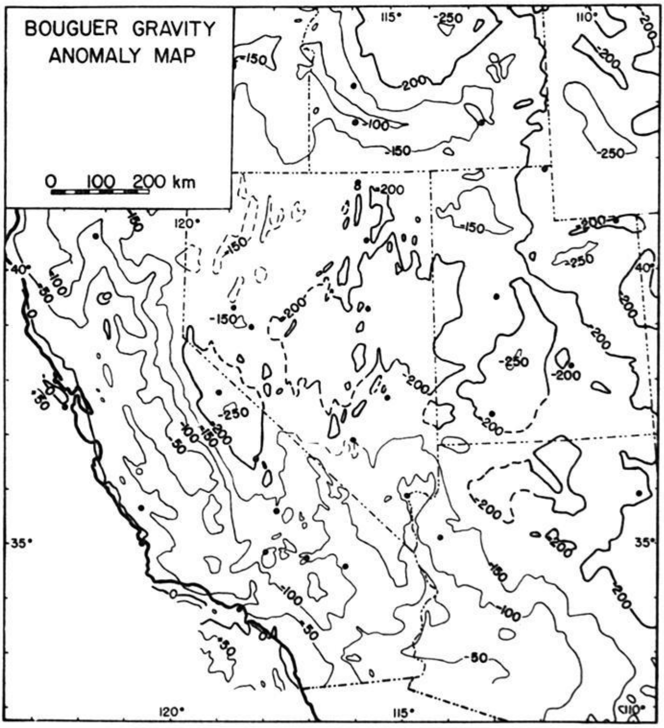

Fig. 15: Bouguer gravity anomaly map of the area of investigation, simplified after the Bouguer gravity anomaly map of the United States [AMERICAN GEOPHYSICAL UNION 1964]. The contour interval is 50 mgal. Full circles mark the position of the shotpoints (Fig. 1 and Table 1).

The comparison between crustal structure and the Bouguer gravity anomalies [AMERICAN GEOPHYSICAL UNION 1964] in Fig. 15 shows general agreement for all areas outside the Basin and Range province. The gravity high under the Coast Ranges of California corresponds to a thin crust, gravity lows under the Colorado Plateaus, the Middle Rocky Mountains, and the Sierra Nevada correspond to a thick crust.

The gravity highs under the Snake River Plain and the southern Cascade Mountains correspond to a mainly basic crust.

This general correlation is evidently not fulfilled for the Basin and Range province. Here low gravity in addition to a thin crust suggests the existence of an anomalous upper mantle which is also indicated by low $P$ wave velocities (Fig. 11 and 14), high heat flow of $\geq 2$ cal/cm$^2$sec [LEE and UYEDA 1965], and velocity-depth determinations for the upper mantle by JOHNSON [1967] and ARCHAMBEAU et al. [1969].

The results presented in this paper show a general agreement with the results summarized by a map of PAKISER and ZIETZ [1965] showing the variations in crustal thickness, mean crustal velocity, and upper-mantle velocity.

Also the interpretations by previous authors which are summarized by WARREN [1968a, b] and HEALY and WARREN [1969] show generally good agreement with the results shown here, with a few exceptions: A thick layer with a velocity of 6.9 km/s in the lower crust of the Sierra Nevada and a resulting total crustal thickness of about 50 km as reported by EATON [1966] could not be confirmed. Also, as discussed in detail above, a well-defined intermediate boundary zone between upper and lower crust could not be found everywhere.

Because of the different tectonic and geologic position of the western United States and of central Europe a comparison of the results obtained for both areas is problematic. Nevertheless, it seems interesting to the author to point out the most obvious similarities and differences of the seismic-refraction data and of the crustal structure derived from those data for both the western United States and central Europe.

The total crustal thickness of the Sierra Nevada and the Middle Rocky Mountains is about the same as found by CHOUDHURY et al. [1967] for the Alps. Also the thickness of the crust-mantle transition zone is within a comparable range. However, the well-defined low-velocity zone under the Alps where the velocity decreases from 6.1—6.2 km/s to about 5.5 km/s is only weakly indicated under the Middle Rocky Mountains and is not evident under the Sierra Nevada. The result that the total crustal thickness as well as the thickness of the crust-mantle transition zone decrease with increasing distance from the Alps is similar to the results found for the environment of the Sierra Nevada. It is questionable, whether the same conclusions can be made for the Middle Rocky Mountains. The structure of the adjacent Colorado Plateaus rather indicates a similar thickness of both the total crust and the transition zone between crust and mantle. Equal crustal thickness of more than 40 km is reported also for the southern Rocky Mountains and the adjacent Great Plains in Colorado [PAKISER 1965]. This result for the Great Plains which belong to the stable platform of the North American continent is significantly greater than found with 30 km for the "normal" crust in central Europe.

The crust under the Apennines between Genoa and Florence is about 25—30 km thick [GIESE et al. 1967, 1968] which agrees with values found for the Coast Ranges of California. Future surveys and interpretations may show whether the crustal and upper mantle structure of the northern Apennines and the adjacent Po Plain in northern Italy can be compared with the crustal and upper mantle structure of the Coast Ranges and the adjacent Great Valley of California.

## Acknowledgements

The present study was enabled by a grant of the Deutsche Forschungsgemeinschaft (German Research Association) in cooperation with the U.S. Geological Survey and a succeeding appointment as a Visiting Scientist at the National Center for Earthquake Research of the U.S. Geological Survey in Menlo Park, California. I am mostly indebted to the staff of the National Center for Earthquake Research, especially to Dr. L. C. PAKISER and Dr. J. H. HEALY for detailed discussion; Dr. J. P. EATON, W. H. JACKSON, J. C. ROLLER, D. J. STUART, and S. W. STEWART for unpublished data, reports, record sections, and computer programs. I am also indebted to Professor P. GIESE, Berlin, for discussion, and to Professors St. MÜLLER, Karlsruhe, and M. LANDISMAN, Dallas, for unpublished record sections of the Mojave-Ludlow profiles. J. ANSORGE, Dr. K. FUCHS, and Dr. G. MÜLLER, Karlsruhe, kindly read the manuscript.

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