UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 16

VARIATIONS IN REGIONAL TRAVELTIMES*

by

J. H. Healy**

DENVER, COLORADO

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-16
January 30, 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 16

VARIATIONS IN REGIONAL TRAVELTIMES*

by

J. H. Healy**

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-63.
** U. S. Geological Survey, Denver, Colorado.

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ABSTRACT

Precise epicentral location of a seismic event is made difficult by variations in regional traveltimes. A discussion is presented on delays to be expected in the various segments of a generalized travel path of seismic waves.

Traveltime variations caused by changes in crustal structure and velocity introduce a major part of the uncertainty in traveltime at both the seismic source and receiver. Consideration of geologic factors that tend to be related to crustal thickness and mantle velocity may permit an estimate of the amount of delay introduced at the source. Delay at the seismic receiving stations can be determined and corrected for by a study of crustal thickness and a calibration of the velocity structure under the stations.

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INTRODUCTION

The precise location of a seismic event requires detailed knowledge of the regional traveltimes between the event and the recording locations. The determination of these regional traveltimes is one of the major problems facing a seismic-detection system.

Early seismologists were impressed by the apparent symmetry of the earth as revealed by seismic waves from earthquakes. Jeffreys and Gutenberg independently developed traveltime tables which predict arrival times from distant sources with deviations that are usually less than 2 sec. Recently, seismic waves from large explosions have revealed systematic variations in regional traveltimes. For example, the GNOME explosion produced traveltime residuals of about -4 sec at 2000 km to the east and traveltime residuals of +2 to +7 sec at 2000 km to the west of the shot site. Traveltime variations of this magnitude prevent the determination of accurate locations of seismic events. When accurate locations are needed, some way to correct for traveltime anomalies must be found.

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A major effort is being made to locate and map regions of anomalous traveltimes. Many areas in seismology are contributing to these studies. These include direct measurement of traveltimes from nuclear and high-explosive sources, the measurement and analysis of body-wave phases on earthquake seismograms, and worldwide studies of surface-wave dispersion.

Much work remains to be done before we can adequately define the variations in regional traveltimes, but we are now able to make an estimate of the magnitude of these variations and an estimate of the relative importance of the different segments of the propagation path.

VARIATIONS IN TRAVELTIME

To discuss the subject of traveltime variations in an orderly way, a typical generalized travel path has been divided into segments (Fig. 1) as follows:

1. Near-surface low-velocity rocks.
2. Upper crust of granitic to dioritic composition.
3. Lower crust of gabbroic composition.
4. Mantle.
    a. Upper mantle.
    b. Deep mantle.

The zone of near-surface low-velocity rocks represents the shortest segment of the travel path, but contributes a significant proportion of the traveltime variation. An estimate of the relative

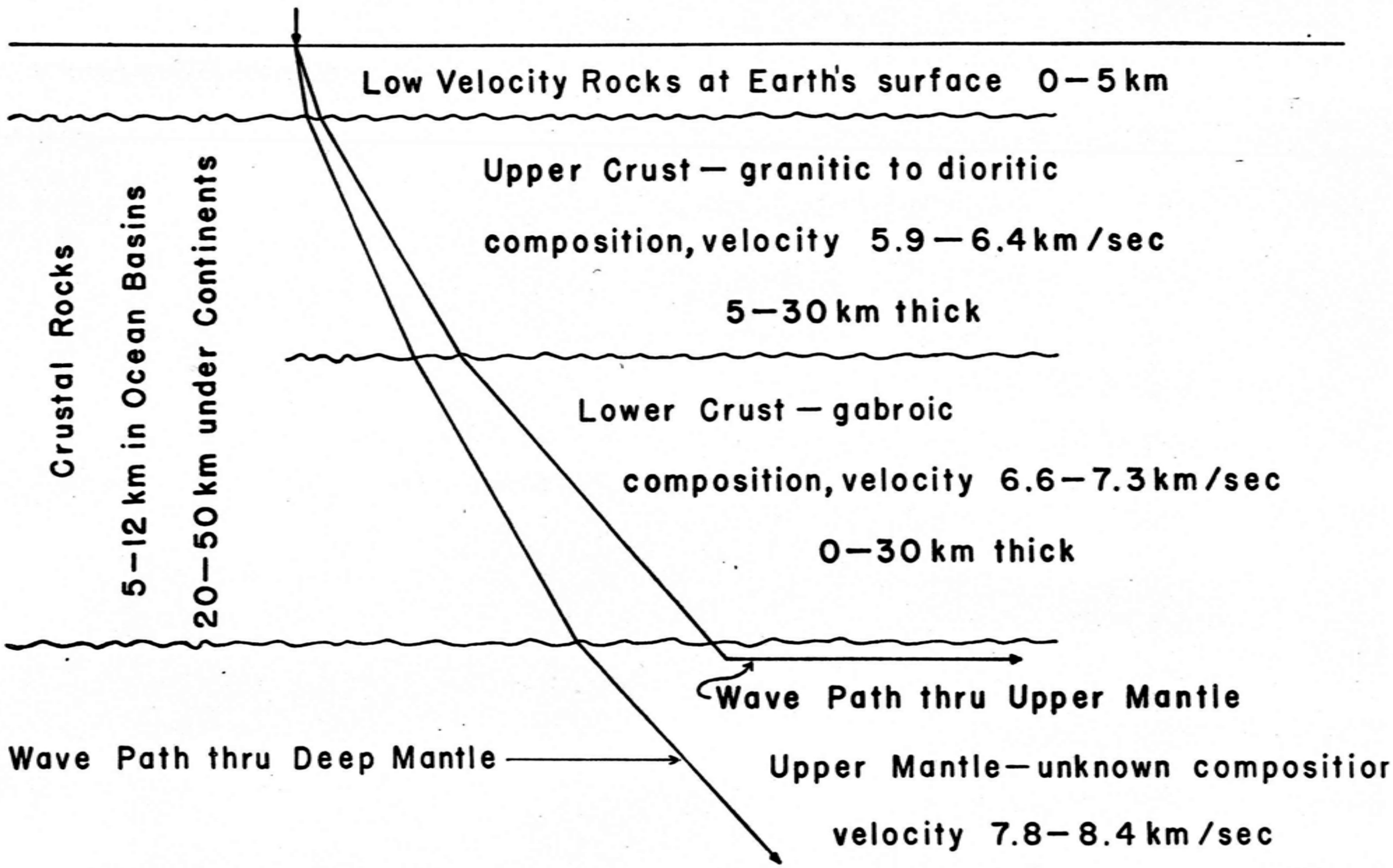

Figure 1.--Schematic diagram of the travel path of seismic waves.

importance of various segments of the travel path can be made from measured seismic traveltimes. Table 1 is a summary of a number of seismic-refraction profiles recorded by the U. S. Geological Survey in the western United States.

The times of first arrivals on each profile can usually be approximated by a few straight lines whose equations are presented in the table in the form:

$$\text{Traveltime} = \text{Zero intercept time in sec} + \frac{\text{distance in km}}{\text{apparent velocity in km/sec}} \qquad (1)$$

The time spent by a seismic wave in each layer can be estimated from the zero intercept time because the time of the refracted arrival for flat layers is given by:

$$T = \sum_{i=1}^{N-1} \frac{2h_i \sqrt{1 - \left(\frac{V_i}{V_N}\right)^2}}{V_i} + \frac{X}{V_N} \qquad (2)$$

where V_i = Velocity of ith layer

V_N = Velocity of refracting layer

h_i = Thickness of ith layer at the shotpoint

By comparison with (1), we can see that $\sum_{i=1}^{N-1} \frac{2h_i \sqrt{1 - \left(\frac{V_1}{V_N}\right)^2}}{V_i}$

is a measure of the time spent in the layers above the refracting horizon.

Table 1.-- Time-distance data in terms of intercept times and apparent velocities
Δ = distance in km

Profile	P_g	Intermediate	P_n
Santa Monica, Calif., to Lake Mead, Nev.	$1.7 + \Delta/6.3$	Not as first arrival	$7.1 + \Delta/7.8$
Lake Mead, Nev., to Santa Monica, Calif.	$0.6 + \Delta/6.1$		$5.5 + \Delta/7.8$
Santa Monica, Calif., to Fallon, Nev.	$1.9 + \Delta/6.1$		$7.1 + \Delta/7.9$
Mono Lake, Calif., to Santa Monica, Calif.	$1.0 + \Delta/6.1$	$2.8 + \Delta/6.3$ (?)	- - - - -
Mono Lake, Calif., to Fallon, Nev.	$1.4 + \Delta/6.1$		
Fallon, Nev., to Mono Lake, Calif.	$1.6 + \Delta/6.1$	$3.5 + \Delta/6.6$	$7.6 + \Delta/7.9$
Fallon, Nev., to San Francisco, Calif.	$1.4 + \Delta/6.2$	$3.9 + \Delta/6.7$ (?)	
San Francisco, Calif., to Fallon, Nev.	$-0.2 + \Delta/5.4$		$4.5 + \Delta/7.9$ (?)
Fallon, Nev., to Eureka, Nev.	$1.7 + \Delta/6.1$	$3.3 + \Delta/6.6$	$5.6 + \Delta/7.6$
Eureka, Nev., to Fallon, Nev.	$0.7 + \Delta/6.0$	$3.6 + \Delta/6.6$	$7.2 + \Delta/8.1$
Santa Monica, Calif., to Fallon, Nev.	$2.0 + \Delta/6.1$		$6.4 + \Delta/7.6$
China Lake, Calif., to Santa Monica, Calif.	$1.4 + \Delta/6.3$		
China Lake, Calif., to Fallon, Nev.	$1.4 + \Delta/5.9$		
Fallon, Nev., to Santa Monica, Calif. (east of Sierra)	$1.4 + \Delta/6.1$		$8.0 + \Delta/8.0$

Table 1.-- Time-distance data in terms of intercept times and apparent velocities (continued)
Δ = distance in km

Profile	P_g	Intermediate	P_n
San Francisco, Calif., to Camp Roberts, Calif.	$1.6 + \Delta/6.1$ (?)		$5.7 + \Delta/8.05$
Camp Roberts, Calif., to Santa Monica, Calif.	$1.3 + \Delta/6.1$		$6.2 + \Delta/8.0$
Camp Roberts, Calif., to San Francisco, Calif.	$1.5 + \Delta/6.1$		$5.7 + \Delta/7.9$ (?)
Santa Monica, Calif., to Camp Roberts, Calif.	$1.6 + \Delta/6.1$ (?)		$7.8 + \Delta/8.45$
Eureka, Nev., to Mountain City, Nev.	$0.3 + \Delta/5.9$		$5.5 + \Delta/7.9$
Mountain City, Nev., to Eureka, Nev.	$0.2 + \Delta/5.9$		$6.9 + \Delta/7.9$
Elko, Nev., to Mountain City, Nev.	$0.8 + \Delta/5.9$	$3.5 + \Delta/6.85$	No velocity higher than 6.85 recorded as first breaks.
Mono Lake, Calif., to Lake Shasta, Calif.	$1.7 + \Delta/6.25$		$8.3 + \Delta/7.8$
Lake Shasta, Calif., to Mono Lake, Calif.	$1.0 + \Delta/6.5$		$8.0 + \Delta/7.9$
Kingman, Ariz., to NTS	$0.4 + \Delta/6.0$		$5.9 + \Delta/7.6$
Mono Lake, Calif., to Lake Mead, Nev.	$1.3 + \Delta/6.05$		$7.4 + \Delta/7.8$
Lake Mead Nev., to Mono Lake, Calif.	$1.2 + \Delta/6.3$		$7.4 + \Delta/7.95$
Ludlow, Calif., to NTS	$1.0 + \Delta/6.3$		$5.7 + \Delta/7.8$
Ludlow, Calif., to Mojave, Calif.	$1.4 + \Delta/6.15$		$6.9 + \Delta/8.25$
Mojave, Calif., to Ludlow, Calif.	$0.7 + \Delta/6.0$		$5.6 + \Delta/7.7$

Table 1.-- Time-distance data in terms of intercept times and apparent velocities (continued)

Δ = distance in km

Profile	P_g	Intermediate	P_n
Barstow, Calif., to Ludlow, Calif.	$0.5 + \Delta/5.7$	Higher velocity recorded but not enough points to establish a velocity.	
Navajo Lake, Utah, to NTS	$1.3 + \Delta/6.1$	No higher velocity determined due to weak arrivals.	
Lake Mead, Nev., to Eureka, Nev.	$0.6 + \Delta/6.2$		$7.1 + \Delta/7.9$
Eureka, Nev., to Lake Mead, Nev.	$0.7 + \Delta/6.2$	$4.7 + \Delta/7.2$ (Determined from only 3 points)	$7.7 + \Delta/7.9$
Mono Lake, Calif., to China Lake, Calif.	$1.5 + \Delta/6.1$	No higher velocity recorded.	
China Lake, Calif., to Mono Lake, Calif.	$1.1 + \Delta/6.1$	Do.	
Mountain City, Nev., to Boise, Idaho	$0.1 + \Delta/5.4$	$2.6 + \Delta/6.8$	
Boise, Idaho, to Mountain City, Nev.	$0.0 + \Delta/5.0$	$2.1 + \Delta/6.7$	
(The following profiles are from intermediate shotpoints and the profiles were not intended to be long enough to record arrivals other than P_g.)			
Elko, Nev., to Eureka, Nev.	$0.9 + \Delta/6.0$		
Lathrop Wells, Nev., to Lake Mead, Nev.	$0.8 + \Delta/6.0$		
Lathrop Wells, Nev., to Mono Lake, Calif.	$1.4 + \Delta/6.2$		
Lida, Nev., to Mono Lake, Calif.	Not sufficient number of points to verify velocity.		

Table 1.-- Time-distance data in terms of intercept times and apparent velocities (continued)
Δ = distance in km

Profile	P_g	Intermediate	P_n
Barstow, Calif., to Mojave, Calif.	$0.5 + \Delta/6.0$		
Hiko, Nev., to Lake Mead, Nev.	$0.3 + \Delta/5.6$		
Hiko, Nev., to Eureka, Nev.	$0.6 + \Delta/5.6$		
Independence, Calif., to Mono Lake, Calif.	$0.8 + \Delta/6.0$		
Independence, Calif., to China Lake, Calif.	$0.6 + \Delta/5.9$		
C. J. Strike Reservoir, Idaho, to Mountain City, Nev.	$1.6 + \Delta/5.9$		
C. J. Strike Reservoir, Idaho, to Boise, Idaho	$1.3 + \Delta/5.6$		

Examination of the intercept times for the P_g arrival in Table 1, shows that the intercept times vary from -0.2 to +1.7 sec for a total range of variation of 1.9 sec. The average of all the intercept times is 1.0 sec, and the mean variation is 0.48 sec.

To estimate the time spent by a seismic wave in the deeper crustal layers, it is necessary to make a correction for the layers above. This could be done for all the crustal layers that give prominent refraction arrivals, but the data from intermediate layers are usually inadequate. Therefore we will consider the total time spent in the crust between the near-surface low-velocity rocks and the Mohorovičić discontinuity.

A reasonable estimate of traveltimes through the crust can be made without a detailed knowledge of crustal velocities, but it should be noted that detailed knowledge of the velocity structure in the crustal rocks is needed to understand the amplitude and arrival times of certain important secondary events.

To estimate traveltime in the crust, we use the intercept times of the P_n arrivals and correct them for the time spent in the near-surface low-velocity rocks. An exact correction would require knowledge of the velocity and structure in the near-surface materials at the source and at all detectors. This information is not available. An approximate correction can be made by taking the corresponding intercept time for P_g and assuming that this intercept time would apply over the length of the profile. This traveltime for P_g can then be converted to an equivalent traveltime for P_n by reference to the graph (Fig. 2), which gives a relation

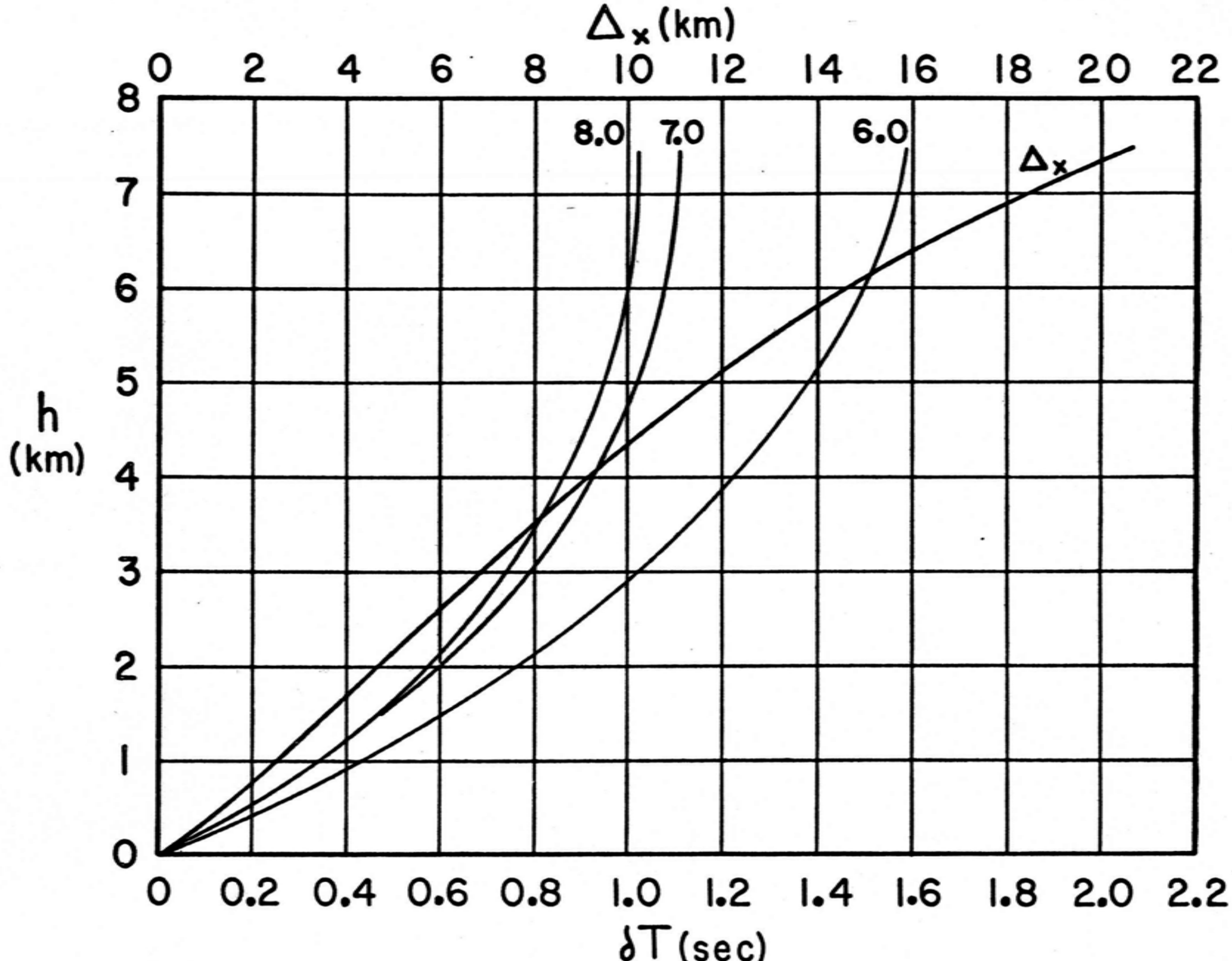

Figure 2.--Traveltime delays in sediments. Near-surface delays, δT, for waves with apparent velocities of 6.0 km/sec (P_g), 7.0 km/sec (P*), and 8.0 km/sec (P_n) emerging through a sedimentary basin of depth h and velocity 1.9 + 0.55 Z km/sec overlying a crust of velocity 6.0 km/sec are plotted as a function of h. Z is depth in km. Δ_x, the distance at which P_g emerges ahead of the wave refracted through the sediments, is also plotted as a function of h. In the basin, the P_g traveltime line intercept is twice the P_g delay.

between P_g, P*, and P_n traveltimes in the near-surface low-velocity rocks. The relation was derived using an average velocity-depth function for near-surface rocks (Eaton, 1963).

This correction was made for all the profiles with P_n intercept times in Table 1, but the correction is not included in the tabulated values. The results from 25 profiles show intercept times ranging between 4.4 sec and 7.2 sec, or a maximum variation of 2.8 sec. The mean of the 25 traveltimes is 5.86 sec, and the mean deviation is 0.83 sec.

These results are strictly applicable only to a crust that can be described by a series of layers with plane boundaries, but they are approximately applicable to more complicated structures, in which the intercept times equal the sum of the delay times for the crust at the source and at the receiving station.

Two situations are considered for the travel path through the mantle: 1) where the distance from source to receiver is somewhat less than 1000 km and the path is through the upper mantle, and 2) where the distance is somewhat greater than 1000 km and the travel path is through the deep mantle.

Wave speeds in the upper mantle have been measured at numerous places in the United States (Fig. 3). Wave-speed variations between 7.8 and 8.2 km/sec are common, and larger variations are possible. The time variation depends on the distance traveled and is about 6 sec/1000 km for speed differences of 0.4 km/sec.

Traveltime variations along the travel path in the deep mantle appear to be small, usually less than 2 sec. However, waves traveling

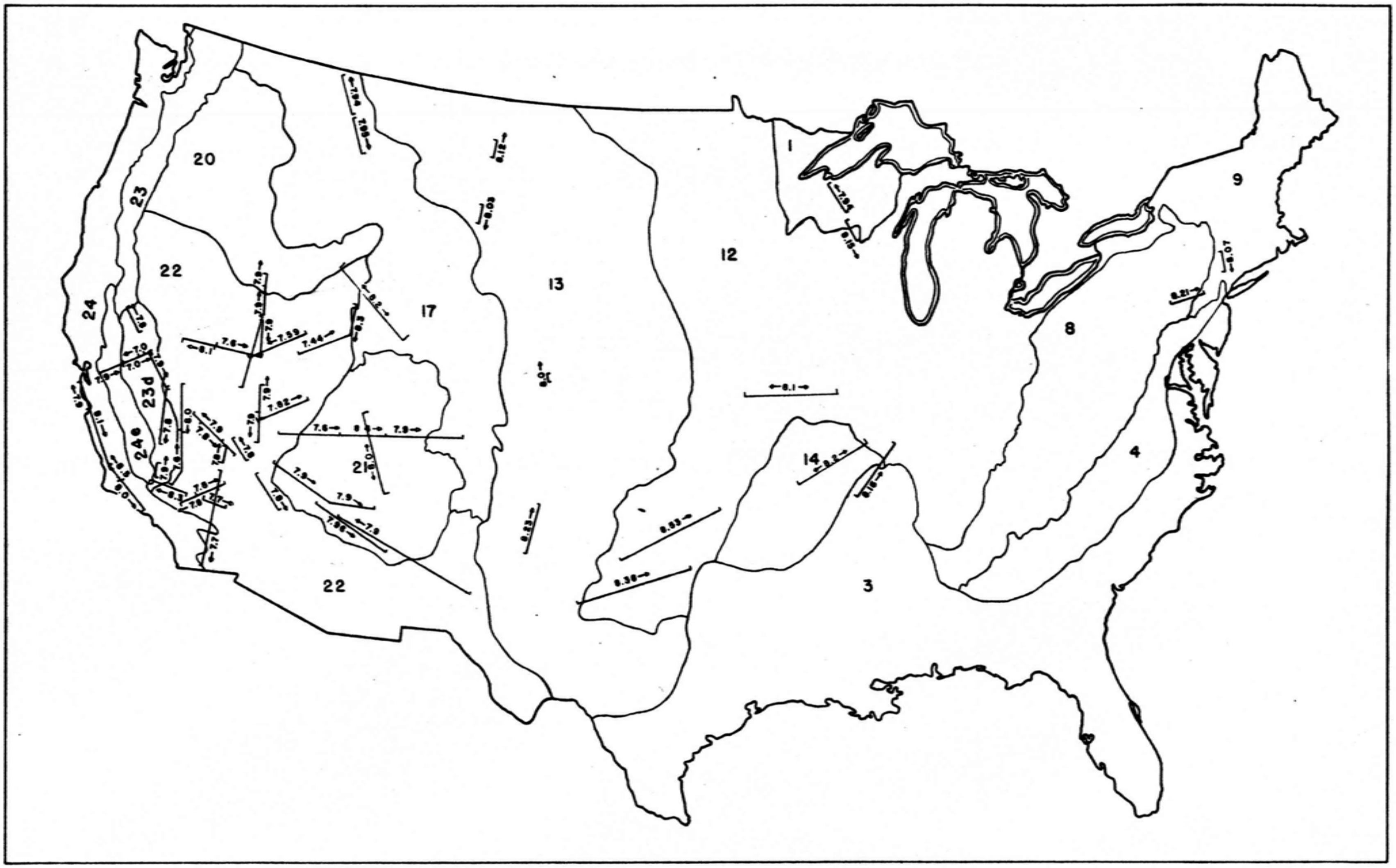

Figure 3.-- See facing page for caption.

Figure 3.--Map of the United States showing geologic provinces after Fenneman's Physical Divisions of the United States (1946). The location of seismic profiles and the apparent velocities of P_n arrivals are indicated. Some very recent work is not plotted, and the reader is referred to Steinhart and Meyer (1961) for a complete compilation of data reported prior to 1960.

1. Superior Upland - Southern part of the Canadian Shield, a central stable region.

3. Coastal Plain.

4, 8, 9. Appalachian Highlands - An ancient mountain system similar to the Ural Mountains in the Soviet Union.

12. Central Lowland - A relatively stable area since Precambrian time; possibly similar to the Russian Platform.

13. Great Plains - Similar to the central lowlands, but at a higher general elevation.

14. Interior Highlands.

17. Rocky Mountain System - A major Cenozoic mountain chain.

20. Columbia Plateaus - An area composed of volcanic rocks, primarily basalts.

21. Colorado plateaus - A relatively stable region since the Precambrian.

22. Basin and Range province - Extensive volcanism and block faulting during Cenozoic time. A region with relatively thin crust and low-mantle velocities.

23, 23d. Cascade-Sierra Mountains - A major Cenozoic mountain chain.

24, 24e. Pacific Border province - Late Cenozoic deformation forming coastal mountain ranges and major basins.

through the deep mantle have higher apparent velocities at the surface than waves traveling in the upper mantle, so a given variation in traveltime will result in a larger error in location. In the extreme case, where source and receiver are on opposite sides of the earth, the apparent velocity becomes very large and an uncertainty in distance of thousands of kilometers may result. Because there are few controlled experiments where both the time and position of the source are known, a precise estimate of deep-mantle traveltime variations cannot be made.

The calibration of regional traveltimes. It can be seen from Table 2 that traveltime variations in the near-surface rocks represent an appreciable fraction of the total possible traveltime variation. These times, of course, are made up of two parts; the part which occurs at the source, if the source is on the surface, and the part which occurs at each receiver. The time delay at the source cannot be estimated; however, relatively simple measurements can be made to correct for uncertainties introduced into the traveltimes in this layer at the recording positions.

Traveltime variations caused by variations in crustal structure and velocity introduce a major fraction of the uncertainty in traveltimes. These times are introduced both by the path through the crust at the source and by the path up through the crust at each receiver. Consideration of geologic factors that tend to be related to crustal thickness may permit an estimate of the amount of delay introduced at the source by crustal thickness variations.

Table 2.-- Summary of traveltime variations

Portion of travel path	Average traveltime	Reasonable limits of variation	Mean Variation
Near surface layer	1.0 seconds	-0.2 to +1.7 sec	0.48 sec
Crustal rocks - near surface layer	5.86 seconds	4.4 to 7.2 sec	0.83 sec
Upper mantle	Distance/8.0	$\frac{Dist}{7.7} - \frac{Dist}{8.3}$	3 sec/1000 km*
Deep mantle	- - - -		(1 to 2) sec⁺

* Estimated (mean variation shows strong regional bias).

⁺ Estimated from earthquake data.

At each receiving station it is possible to make measurements that would lead to corrections for variations in crustal thickness. The measurements are considerably more elaborate than the measurements necessary to correct for the few kilometers of near-surface material, but they could be made in a relatively simple matter in accessible territory.

These corrections for traveltimes through the crust and through the low-velocity material at the surface should remove a large part of the uncertainty in traveltimes, but, the most-serious possible cause of error still remains. It arises in the situation where waves are recorded through the upper mantle in areas which display a regional bias in traveltimes. There are two possibilities for correcting deviations in traveltimes resulting from regional variations in mantle velocities. One is by direct measurements of mantle velocities in the region of interest. This might be done by large calibration shots, by direct measurement with crustal-refraction profiles, or by studies of traveltimes of earthquakes between seismograph stations in the region.

A second possibility, the possibility of a geological basis for calibration arises from the fact that work in the United States seems to show a relationship between the properties of the mantle and surficial geologic features. Although at present this relationship is hypothetical, it may prove to be a useful supplement to other means of calibration. Figure 3 shows the locations of some crustal refraction profiles in the U. S., with the apparent velocities of mantle arrivals. A tentative conclusion that may be drawn from the map is that regions which have had stable crusts since Precambrian and perhaps more recent times tend to have higher mantle velocities, and regions that have been active in Cenozoic and perhaps older times tend to have lower mantle velocities. Further evidence of the relationship between surface geologic features and crustal structure is found in the major changes in crustal structure or mantle velocities at or near boundaries between previously recognized geologic provinces. Most prominent of these features is at the ocean-to-continent boundary which is a zone of unusually profound change in crustal structure. In the United States, changes in crustal structure have been found along the eastern margin of the Sierra Nevada, at the boundary between the Snake River Plain and Basin and Range province, at the boundary between the Great Plains and the Rocky Mountains, at the boundary between the Basin and Range province and the Colorado Plateaus, and across the San Andreas fault. It is difficult to tell whether these changes occur precisely at the previously recognized geologic boundary, but it seems that in the cases mentioned the changes in the structure of the crust and in the mantle velocity occur within 20 to 30 km of the geologic boundary.

To illustrate how a comparison of crustal structure in the United States might be used to estimate possible crustal structure in the Soviet Union, a map of the Soviet Union was divided into geologic provinces according to Nalivkin (1960). Locations of some Soviet crustal refraction profiles have been plotted on the map (Fig. 4).

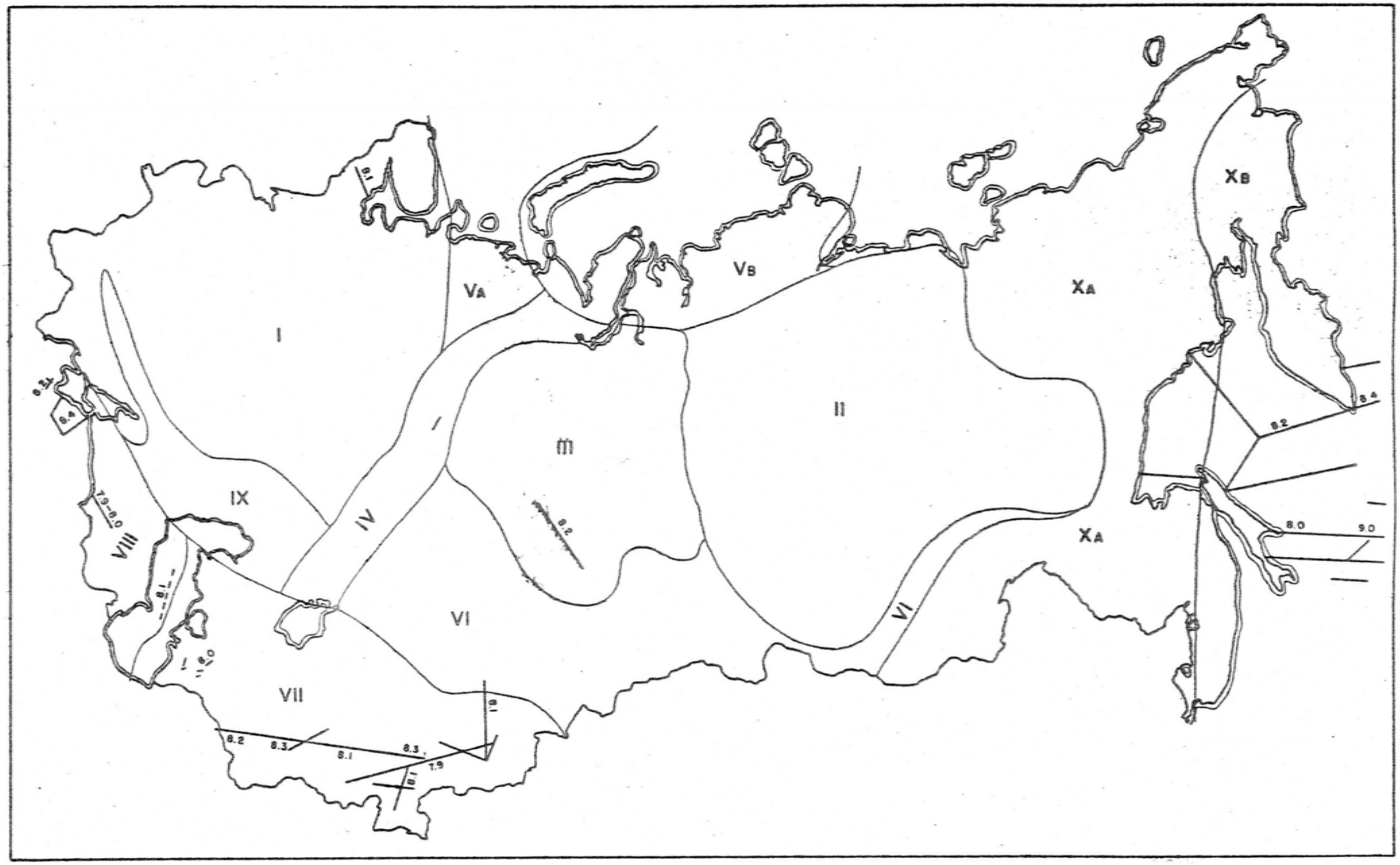

Figure 4.-- See facing page for caption.

Figure 4.--The location of some seismic-refraction profiles in the Soviet Union with reported mantle velocities. The principal geologic provinces of the Soviet Union are from Nalivkin (1960).

I. Russian Platform
II. Siberian Platform
III. West Siberian Lowlands
IV. Ural Mountains
VA. Western Arctic
VB. Timan and adjoining regions
VI. Angara Geosyncline
VII. Central Asia
VIII. Mediterranean Geosyncline
IX. North-Western Border of the Mediterranean Geosyncline
X. Pacific Ocean Geosyncline
XA. Kimmerian Zone
XB. Alpine Zone

Region I in the Soviet Union is the Russian Platform. This is a broad area of Precambrian rocks (that is, rocks more than 500 million years old) overlain by younger, relatively undisturbed Paleozoic sedimentary rocks. Such an area might be compared with much of the central United States.

Region II, the Siberian Platform, an elevated area with exposures of Precambrian rocks, has some similarity to Minnesota and northern Wisconsin.

Region III, the West Siberian Lowlands, is a broad area of comparatively recent downbuckling or sinking, and may be similar to the northern part of the Gulf Coastal Plain in the United States.

Region IV, the Ural Mountains, is an elongated folded mountain range similar in many respects to the Appalachian Mountains.

These comparisons are to a large extent speculations. A proper comparison would require a detailed study of the geologic features of both countries and a consideration of many factors which must be omitted here. The information for such a study is available in the literature, and such comparisons would be relatively simple to derive compared with other difficulties facing an inspection system.

This rather brief and speculative comparison indicates that large areas of the Soviet Union probably have uniform crustal structure and mantle velocities, as indicated by the fact that the crust in these areas appears to have been relatively stable during much of the time since the close of the Precambrian.

Recognition of recently-active tectonic regions will enable us to define areas of difficulty for crustal-structure calibration within the Soviet Union.

RECOMMENDATIONS

1. In the past, too little consideration has been given to the material immediately under each seismic station. It seems likely that a significant improvement in the accuracy of traveltimes can be made by a relatively simple calibration of the velocity structure under a seismic station. Such calibrations should be considered for all major stations.

2. A somewhat larger traveltime uncertainty may be introduced by variations in crustal thickness under seismic stations. This is particularly important in array stations, where variations in crustal structure may limit the effectiveness of an array by distorting the apparent velocities and changing the apparent angle of approach of the seismic energy. Calibration for crustal structure may not be possible at all stations, but certainly the critical stations should be calibrated for the crustal structure under those stations.

3. The variations in seismic velocities in the upper mantle can introduce variations in traveltimes which will, if not corrected, lead to serious errors in the location of seismic events. Direct measurements of upper-mantle velocities are required for accurate locations, but where direct measurements are impossible or are restricted, an estimate of upper-mantle velocities may be possible by studying similar regions

in other parts of the world. It is recommended that measurements of crustal structure and mantle velocities be made in a wide variety of geologic provinces, and that attempts be made to use these data to predict crustal structure and mantle velocities in regions that are inaccessible.

4. The travel paths through the deep mantle seem to have less variation in traveltimes than the travel paths through the upper mantle. However, there are only a limited number of experiments which can be used for a direct estimate of deeper mantle traveltimes, and traveltime variations. Any uncertainty in traveltimes through the deep mantle results in larger errors in location because of the higher apparent velocities of the arrivals. Therefore, it is recommended that attention be given to studies of traveltimes through the deeper mantle.

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