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TRANSCONTINENTAL GEOPHYSICAL SURVEY (35°–39° N)

SEISMIC REFRACTION PROFILES OF THE CRUST AND UPPER MANTLE FROM 87° TO 100° W LONGITUDE

By
David H. Warren

MISCELLANEOUS GEOLOGIC INVESTIGATIONS
MAP I-534-D

A CONTRIBUTION TO THE UPPER MANTLE PROJECT

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INTRODUCTION

Determinations of continental crustal structure by seismic-refraction surveys are summarized on the accompanying maps at a scale of 1:1,000,000. This is an interim compilation prepared in cooperation with the Advanced Research Projects Agency. It covers the United States between latitude 35°N and 39°N (the area of the Transcontinental Geophysical Survey) and does not extend into the adjacent ocean basins.

Several recent publications summarize seismic studies of the crust of the continental United States. Hamilton and Pakiser (1965) utilized seismic data in making a cross section along the 37th parallel on a horizontal scale of 1:2,500,000. Review articles include those by Healy and Warren (in press), James and Steinhart (1966), Pakiser and Zietz (1965), and Pakiser and Steinhart (1964). A comprehensive analysis and compilation is given by Steinhart and Meyer (1961); and a recent compilation is given by McConnell and others (1966).

Sources of data for this compilation are listed in the section entitled Data References. Interpretations from unpublished sources are preliminary, and profiles that have been shot but not interpreted are shown to indicate the extent of coverage.

METHOD OF COMPILATION

The selection of data has been subjective. Where a newer, more detailed refraction survey has been available, older work in the same area has not been included. Surveys generally have not been included unless they penetrated to the Mohorovicic discontinuity, designated on the profiles by the letter M.

Many surveys of this compilation show the major features of the "normal" continental crust. At the top of the crust is a veneer of varying thickness of sedimentary, volcanic, and metamorphic rocks (in many places too thin to show on the scale used) in which the velocity is usually less than 5.5 km/sec. The upper part of the earth's crust is presumably granitic in composition, and shows a remarkably uniform velocity of 5.9-6.1 km/sec.

The lower part of the earth's crust, called the "intermediate" layer, probably is of more mafic composition. It is less well delineated, and apparently is not uniform in either velocity or thickness. Available evidence indicates a velocity range for the lower crust from about 6.5 km/sec. to as high as 7.4 km/sec. near the bottom of the crust in some places. The transition to lower crust may be either abrupt or gradual. In the western U.S. a number of surveys have found a relatively sharp transition that has been called the Conrad discontinuity. In the eastern U.S., little evidence for a sharp discontinuity has been found. Some of the published sources include an alternate interpretation showing a single-layered crust. Where this was done the two-(or more) layer interpretation is given here. This was done to provide a more uniform comparison of data from many sources, and because it provides a better approximation of the true velocity distribution. Thus, although a discontinuity within the crust has been indicated from one end of the continent to the other, a sharp boundary is not necessarily implied.

An abrupt increase in velocity does occur at the M discontinuity, marking the transition to the upper mantle. Beneath the discontinuity, the velocity in the upper mantle varies from 7.8 to 8.4 km/sec. The differences in this velocity, between large areas of the U.S., seem to be significant.

The data are shown in a manner that results from standard assumptions in the interpretation of refraction surveys, which are: (1) sharp boundaries between layers, (2) layers of constant velocity, and (3) increasing velocity with depth. Because these conditions may in reality not be met, the refraction results give only an approximation to the velocity structure of the earth's crust. (For a brief discussion of the limitations of the refraction method, see Steinhart and others, 1962; a more exhaustive discussion is given by Steinhart and Meyer, 1961.) The accuracy depends upon the coverage obtained and, to some extent, upon the judgment involved in the interpretation. In spite of this subjective factor, one may assess the accuracy of the results by investigating how much the interpretation can be changed without violating the traveltime data. Based upon the author's experience along these lines, a high quality survey can result in depth measurements good to 10 percent, and velocity measurements accurate to ± 0.1 km/sec.

Results are shown as perspective fence diagrams extending between shotpoints, named for nearby towns, and all velocity and depth values are also listed in the accompanying table. Each line is composed of data from one to several shotpoints, with one vertical plane between any two shotpoints. Layer boundaries generally are shown as solid lines; dashed lines are used where the interpretation is less certain. In most cases depths are plotted in a southerly direction, at a scale of 1 km = 1 mm, the same as the horizontal scale. For profiles running nearly north-south, depths are plotted in an easterly direction. Altitude above sea level is plotted for each profile, exaggerated 5 to 1, on a scale of 1 km = 5 mm.

The maps and table show depths relative to a sea level datum. Most of the surveys do not adequately measure the near-surface layering. A detailed presentation of near-surface velocity structure is beyond the scope of this compilation. The surficial layer thicknesses given in the table are based in some cases on assumed velocities. Where the surficial velocity is given in the table, it is a measured not an assumed value. The surficial layer is plotted on the maps where thick enough to show below sea level datum. Commonly, the topmost layer given is the upper crustal layer. If the crust has been approximated by more than two layers, the additional layer is shown in the central column of the table. In some cases the additional layer is part of the upper crust, and in others should be included in the lower crust. All depth and thickness values in the table have been rounded off to the nearest kilometer. The values apply to shotpoint locations.

Most of the velocity determinations are given to the nearest tenth km/sec. Any velocity measurement given on the map applies for the entire line in which it appears, unless a different velocity is given at another portion of the line, in which case a shotpoint location marks the change in measured velocity. Velocities given are reversed true values unless only one shotpoint was used. There is some redundancy in the table for the deeper layers on surveys consisting of multiple shotpoints along the line. In such cases all of the velocity values do not necessarily represent individual measurements. Determinations of the lower crust in many places are not based upon first refracted arrivals, but partially upon reflections or later refracted arrivals. Where the velocity has been merely assumed, it is given in parentheses in the table but is not shown on the maps.

The portion of a layer actually traversed by a seismic ray begins at some distance from a shotpoint; this is 40 km or more for M. The profiles have all been plotted as if the layer interfaces extend back to the shotpoint. This affords a comparison of different results measured from the same shotpoint. Comparisons can also be readily made where different lines cross. Some of the discrepancies that occur may be due to limitations of the refraction method, but in a number of cases marked structural changes occur in different directions from the same shotpoint (e.g., the San Francisco and Mono Lake results in California). The disagreement among a number of lines which terminate at the Nevada Test Site (NTS) suggests that there may be structural complications which none of the individual surveys have resolved.

EDITING OF DATA

Some of the interpretations have been altered from their published forms, usually to include an intermediate layer where none was reported. Each instance of alteration is described here and referred to by the number in Data References.

Nevada Test Site (NTS) to Kingman, Arizona. References 1 and 14 are reports of two unreversed profiles each with recording sites that are not far from a line connecting NTS and Kingman. The coverage is such that the combined surveys do not quite make a reversed profile, but the two are here treated as a unit. An intermediate layer was not found in either direction. A reinterpretation was made for this compilation assuming the presence of a "masked" intermediate layer of velocity 7.0 km/sec at the shallowest depth consistent with the fact that first arrivals from the layer were not observed. The reinterpretation increased the depth to M by 2–3 km. A portion of the line from Kingman bends more to the north near Las Vegas. On this unreversed portion the depth to M was deduced to increase abruptly. A constant depth to the top of the intermediate layer was assumed.

Nevada Test Site to Ludlow, California. In reference 4, recordings of events fired at the Nevada Test Site (NTS) are reversed by a line of recordings from the Ludlow shotpoint. First and secondary arrivals from Ludlow delineate a 6.8 km/sec velocity. In the published interpretation, the assumed depth of 14 km to the top of the intermediate layer at NTS is not supported because intermediate layer first arrivals were not observed from NTS. The assumption of a masked layer of apparent velocity 6.9 km/sec results in a minimum depth of 18 km at NTS, which is given here. The depths to M change by 1 km or less. In reference 4, the depth to M was deduced to continue to decrease to the south from unreversed arrivals from NTS. The depth to the intermediate layer has been assumed to be constant to the south.

Coast of California. Reference 2 shows a reinterpretation of the San Francisco to Camp Roberts portion of the survey originally described in reference 7 and interpreted in terms of a single crustal layer. No first arrivals were observed that indicate an intermediate layer. However, some secondary arrivals were found which could be explained in this way, and in reference 6 possible velocity structure within the crust was described in some detail. For the present compilation the two-layer interpretation of reference 2 was used, and the Camp Roberts to Santa Monica portion of the survey was recomputed to include the shallowest possible depth to the intermediate layer, in a manner similar to that used to edit the NTS to Kingman results.

TEXT REFERENCES

Hamilton, Warren, and Pakiser, L. C., 1965, Geologic and crustal cross section of the United States along the 37th parallel: U.S. Geol. Survey, Misc. Geol. Inv. Map I-448.

Healy, J. H., and Warren, D. H., Continental crust and upper mantle in North America as deduced from explosion seismology, *in* Am. Geophys. Union Mon. 13, (in press).

James, D. E., and Steinhart, J. S., 1966, Structure beneath continents: a critical review of explosion studies 1960-1965, *in* The earth beneath the continents: Am. Geophys. Union Mon. 10, p. 293-333.

McConnell, R. K., Jr., Gupta, R. N., and Wilson, J. T., 1966, Compilation of deep crustal refraction profiles: Rev. Geophysics, v. 4, p. 41-100.

Pakiser, L. C., and Zietz, Isidore, 1965, Transcontinental crustal and upper-mantle structure: Rev. Geophysics, v. 3, p. 505-520.

Pakiser, L. C., and Steinhart, J. S., 1964, Explosion seismology in the western hemisphere, *in* Research in geophysics, v. 2. Solid earth and interface phenomena Cambridge, Mass., Mass. Inst. Technology Press, p. 123-147.

Steinhart, J. S., Green, R., Asada, T., Rodriguez, B. A., Aldrich, L. T., and Tuve, M. A., 1962, Seismic studies: Carnegie Inst. Washington Year Book 61, 1961-62, p. 221-234.

Steinhart, J. S., and Meyer, R. P., 1961, Explosion studies of continental structure: Carnegie Inst. Washington Pub. 622, 409 p.

DATA REFERENCES

The circled numbers at ends of profile lines on the maps correspond to the numbers in this list.

1. Diment, W. H., Stewart, S. W., and Roller, J. C., 1961, Crustal structure from the Nevada Test Site to Kingman, Arizona from seismic and gravity observations: Jour. Geophys. Research, v. 66, p. 201-214.
2. Eaton, J. P., 1966, Crustal structure in northern and central California from seismic evidence *in* Geology of northern California: California Div. Mines and Geology Bull. 190, p. 419-426.
3. Eaton, J. P., 1963, Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic-refraction measurements: Jour. Geophys. Research, v. 68, p. 5789-5806.
4. Gibbs, J. F., and Roller, J. C., 1966, Crustal structure determined by seismic-refraction measurements between the Nevada Test Site and Ludlow, California: U.S. Geol. Survey Prof. Paper 550-D, p. 125-131.
5. Hales, A. L., Helsley, C. E., Dowling, J. J., and Nation, J. B., 1967, The east coast onshore offshore experiment I. The first arrival phases: U.S. Air Force Office Sci. Research Pub. 67-0852.
6. Hart, P. J., 1954, Variation of velocity near the Mohorovicic discontinuity under Maryland and northeastern Virginia: Ph. D. Thesis, Harvard Univ.
7. Healy, J. H., 1963, Crustal structure along the coast of California from seismic-refraction measurements: Jour. Geophys. Research, v. 68, p. 5777-5787.
8. Hill, D. P., and Pakiser, L. C., 1966, Crustal structure between the Nevada Test Site and Boise, Idaho from seismic-refraction measurements, *in* The earth beneath the continents: Am. Geophys. Union Mon. 10, p. 391-420.
9. Jackson, W. H., Stewart, S. W., and Pakiser, L. C., 1963, Crustal structure in eastern Colorado from seismic-refraction measurements: Jour. Geophys. Research, v. 68, p. 5767-5776.
10. Johnson, L. R., 1965, Crustal structure between Lake Mead, Nevada, and Mono Lake, California: Jour. Geophys. Research, v. 70, p. 2863-2872.
11. McCamy, K., and Meyer, R. P., 1966, Crustal results of fixed multiple shots in the Mississippi Embayment, *in* The earth beneath the continents: Am. Geophys. Union Mon. 10, p. 370-381.
12. Qualls, B. R., 1965, Crustal study of Oklahoma: Master's Thesis, Univ. Tulsa.
13. Roller, J. C., 1965, Crustal structure in the eastern Colorado Plateaus province from seismic-refraction measurements: Seismol. Soc. America Bull., v. 55, p. 107-119.
14. Roller, J. C., 1964, Crustal structure in the vicinity of Las Vegas, Nevada, from seismic and gravity observations: U.S. Geol. Survey Prof. Paper 475-D, p. 108-111.
15. Roller, J. C., and Healy, J. H., 1963, Seismic-refraction measurements of crustal structure between Santa Monica Bay and Lake Mead: Jour. Geophys. Research, v. 68, p. 5837-5849.
16. Ryall, Alan, and Stuart, D. J., 1963, Travel times and amplitudes from nuclear explosions, Nevada Test Site to Ordway, Colorado: Jour. Geophys. Research, v. 68, p. 5821-5835.
17. Stewart, S. W., 1968, Crustal structure in Missouri by seismic-refraction methods, Seismol. Soc. America Bull., v. 58, p. 291-323.
18. Stewart, S. W., and Pakiser, L. C., 1962, Crustal structure in eastern New Mexico interpreted from the Gnome explosion: Seismol. Soc. America Bull., v. 52, p. 1017-1030.
19. U.S. Geological Survey, Preliminary and unpublished interpretations of crustal refraction surveying by John C. Roller, Roger D. Borcherdt, and Cecelia Borcherdt.
20. Warren, D. H., Roller, J. C., and Jackson, W. H., 1965, A seismic-refraction survey in the vicinity of the Tonto Forest Seismological Observatory, Arizona [abs.]: Am. Geophys. Union Trans., v. 46, p. 155.

Table of Seismic Refraction Data at Shot Points

Reference No.	Shot Point Name		Latitude	Longitude	Surficial v	Surficial d	Surficial h	Upper Crust v	Upper Crust d	Upper Crust h	Addtl. Layer v	Addtl. Layer d	Addtl. Layer h	Lower Crust v	Lower Crust d	Lower Crust h	Upper Mantle v	Upper Mantle d
					Layering Velocity v (km/sec), Depth d (km), and Thickness h (km)													
6	Patuxent River	△+	38°22′	76°30′				6.2	0	22				6.6–7.0	22	8	8.0	30
5	ECOOE 303	△ *	37°46′	75°16′	2.1	0	2	5.8	2	8				6.3	10	16	8.0	26
5	ECOOE 316	△ *	37°26′	74°31′	2.1	0	2	5.8	2	8				6.3	10	16	8.0	26
19	ECOOE 126	△ *	34°03′	76°07′				6.0	0	24				6.7	24	13	8.1	37
19	ECOOE 132	△ *	34°28′	77°14′				6.0	0	24				6.7	24	13	8.1	37
19	Burgaw	*	34°32′	77°43′					0	21					21	14		35
								6.0–6.1						6.7			8.1	
19	Troy	*	35°24′	80°02′					0	20					20	14		34
								6.1						6.7			8.1	
19	Erwin	*	36°09′	82°20′					-1	31					30	3		33
								6.1						6.7			8.1	
19	Burnside	*	36°55′	84°25′					0	(6)					(6)	28		34
19	Dahlonega-Gainesville	+*	34°28′	83°52′					-1	12					11	34		45
								6.1						6.6			8.0	
19	Chattanooga	*	35°13′	85°06′					0	9					9	40		49
								6.1						6.6			8.0	
19	Smithville	*	36°02′	85°52′					0	11					11	34		45
								6.1						6.6			8.0	
19	Campbell	*	36°37′	87°38′					0	15					15	25		40
19	Burnside	*	36°54′	84°34′					0	6					6	28		34
								6.1						6.7			8.0	
19	Crossville	*	36°05′	84°55′					0	6					6	33		39
								6.1						6.7			8.0	
19	Tullahoma	*	35°25′	86°04′					0	15					15	29		44
								6.1						6.7			8.0	
19	Moulton	*	34°22′	87°11′					0	17					17	34		51
11	Cape Girardeau	+	37°32′	89°28′		0	1		1	6		7	22		29	16		45
					4.7			6.2			6.5			7.4			8.1	
11	Little Rock	+	34°46′	92°18′		0	6		6	5		11	21		32	14		46
17	Ste. Genevieve		38°00′	90°03′		0	1		0	4		4	21		25	19		44
					5.0			6.0			6.3			6.9			8.0	
17	Gladden		37°30′	91°21′		0	1		1	9		10						
					5.0			6.0			6.1			7.3			8.1	
17	Hercules		36°42′	92°54′		0	1		1	8		9	22		31	12		43
17	Hannibal		39°34′	91°11′		0	1		1	5		6	12		18	20		38
					5.0			6.1			6.2			6.6			8.0	
17	Swan Lake		39°36′	93°12′		0	1		1	4		5	17		22			
					5.0			6.1			6.2			6.7			8.0	
17	St. Joseph		39°37′	95°03′		0	2		2	10		12	12		24	18		42
12	Chelsea		36°30′	95°29′					0	14		14	16		30	21		51
								5.9_5			6.6_5			7.2			8.3	
12	Manitou		34°32′	98°53′					0	14		14	16		30	21		51
9	Nee Granda	△	38°18′	102°45′	4.8–5.2	-1	2	5.8	1	10	6.1	11	15	6.7	26	20	8.0	46
18	Gnome	△	32°16′	103°52′	4.9	-1	4	6.1	3	15	6.7	18	12	7.1	30	20	8.2	50
13	Chinle		35°56′	109°34′	3.0	-2	1		-1	25					24	17		41
								6.2						6.8			7.8	
13	Hanksville		38°22′	110°56′	3.0	-2	2		0	26					26	12		38
20	Sunrise		35°34′	109°48′		-2	4		2	24					26	14		40
					(4.7)			6.2						(6.8_5)			7.8_5	
20	Winslow		35°01′	110°38′		-2	2		0	28					28	12		40
					(4.7)			6.2						(6.8_5)			7.8_5	
20	Strawberry		34°22′	111°26′		-2	3		1	25					26	10		36
20	Carrizo		34°02′	110°18′					-1	4		3	21		24	16		40
								5.9			6.1			(6.8)			7.8_5	
20	Strawberry		34°22′	111°26′	2.9	-2	0		-1	3		2	22		24	11		35
								5.8			6.1			(7.0)			7.8_5	
20	Cottonwood		34°46′	111°59′					-1	3		2	22		24	13		37
								5.9			6.1			(7.0)			7.8_5	
20	Blue Mountain		35°33′	113°20′					-1	8		7	19		26	9		35
14	Kingman		35°19′	114°04′		-1	3		2	18					20	10		30
					5.2			6.1_5						(7.0)			7.8	
1	Nevada Test Site	+	37°10′	116°05′		-2	2		0	19					19	10		29
16	Nevada Test Site	△+	37°10′	116°05′				6.0	0	20				6.7	20	4	7.9	24
8	Eureka		39°36′	115°40′					-1	20					19	14		33
								6.0						6.7			7.9	
8	Nevada Test Site	+	37°10′	116°05′					-1	20					19	10		29
4	Nevada Test Site	+	37°10′	116°05′					0	18					18	14		32
								6.1						6.8			7.9	
4	Ludlow		34°50′	116°11′					1	13					14	13		27
10	Lake Mead		36°06′	114°48′	2.8	0	1		0	24					24	7		31
								6.1_5						7.1			7.8	
10	Lathrop Wells		36°37′	116°14′					1	24					25	8		33
								6.1_5						7.1			7.8	
10	Lida Junction		37°21′	117°30′					1	24					25	9		34
								6.1_5						7.1			7.8	
10	Mono Lake		37°59′	119°08′	2.1, 4.0	-2	2		0	31					31	13		44
15	Lake Mead	°	36°06′	114°48′					1	19					20	8		28
								6.1						7.0			7.8	
15	Santa Monica Bay	°	34°00′	118°33′					3	24					27	7		34
3	Eureka		39°36′	115°40′					-1	23					22	12		34
								6.0						6.6			7.8	
2,3	Fallon		39°32′	118°52′					1	16					17	7		24
2	San Francisco	△	37°36′	122°42′				6.0,5.6	2	10				6.8	12	9	8.0	21
2	China Lake		35°47′	117°44′					1	12		13	8		21	25		46
								6.0			6.4			6.9			7.9	
2	Mono Lake		37°59′	119°08′					1	10		11	17		28	24		52
7	Santa Monica Bay		34°00′	118°33′					2	17					19	21		40
								6.1						(7.0)			8.2	
2,7	Camp Roberts		35°47′	120°50′					1	14					15	9		24
								6.0						6.8			8.0	
2,7	San Francisco		37°36′	122°42′					1	14					15	9		24

* Preliminary interpretations.

\+ Average location used.

° Depths and thicknesses are average values near the end of the profile-not at shot point.

△ Velocity measurements are unreversed.