GEOPHYSICAL RESEARCH LETTERS, VOL. 11, NO. 4, PAGES 299-302, APRIL 1984

CRUSTAL STRUCTURE OF SOUTHWESTERN MONTANA AND EAST-CENTRAL IDAHO: RESULTS OF A REVERSED SEISMIC REFRACTION LINE

Steven D. Sheriff

Earthquake Research Laboratory, University of Montana

Michael C. Stickney

Earthquake Studies Office, Montana College of Mineral Science and Technology

Abstract. On October 20, 1982, we collected seismic refraction data on a 250 km line segment between Butte, Montana and Challis, Idaho. These data are from two open pit mine blasts; one at Anaconda Minerals Companys' southeast Berkely pit and the other at Cyprus Mines Corporations' Thompson creek mine. Eight of our ten recorders wrote clear records of both blasts with measured travel times accurate to +/-0.2 seconds. We supplemented these data with data from permanent stations in the Butte area. The Pg (crustal) velocity is 5.8 km/s to the southwest and 6.0 km/s to the northeast. The Pn (mantle) velocity is 7.9 km/s to the northeast and 8.1 km/s to the southwest; total travel-times are equal. The S-wave velocity in the crust is about 3.5 km/s. The symmetry of the travel-time results, with their intersection within one kilometer of the midpoint between the pit blasts, strongly suggests the refraction line overlies a horizontal Moho or parallels the strike line of a dipping Moho surface. These data indicate the crust in southwestern Montana and east-central Idaho is approximately 33 km thick. Contrasting tectonic processes, compression and thickening during the Laramide orogeny with extension and thinning since the Paleocene, resulted in a crust with slightly less than normal thickness.

Introduction

Three geologic provinces characterize the northern Rocky Mountains of the United States: 1) the Idaho Batholith, 2) the Laramide fold and thrust belt and, 3) the Tertiary sedimentary basins of southwestern Montana and east-central Idaho (Figure 1). Recent literature and symposia concerning these provinces [e.g. Hyndman, 1983; Lageson and Couples, 1982; Tucker, 1981; Hobbs, 1983] attest to the current interest in regional geologic studies. Yet, knowledge of crustal structure of the northern Rockies is limited. However, Kleinkopf [1983], Stickney and Sheriff [1983], Carlson and Sheriff [1983] and Braile et al. [1982] recently contributed new ideas along with regional gravity, magnetic and seismic data that complement Smiths' [1978] discussion of regional crustal structure.

The Mohorovicic discontinuity (Moho), which is generally accepted as the base of the crust, was precisely defined by Mohorovicic [1909]. Determining the thickness of the crust is the first step in determining an accurate crustal and orogenic model. A review of seismic refraction studies shows that the term Moho is now generally used for an abrupt, deep-crustal P-wave velocity increase from about 6.5 km/s to approximately 8 km/s. However, recent seismic reflection profiling of the lower crust shows that many areas are underlain by packages of near horizontal reflectors that may represent mixtures of crust and mantle rock [e.g. Oliver et al., 1983]. Thus, based on new seismic reflection studies of the crust, the Moho is now recognized as a much more complex structural feature than initially assumed. Yet, in the northern Rocky Mountains, even the depth to the Moho is poorly known.

At the time of Smiths' [1978] compilation, very little published data were available to constrain estimations of depth to the mantle beneath southwestern Montana and east-central Idaho; few new data pertaining to this problem have been collected. Because of this lack of data in a critical area of the western Cordillera, we are in the process of determining a more accurate crustal model for the Rocky Mountains of Idaho and Montana. A new seismic refraction line allows us to put some limits on the depth to the Moho between Butte, Montana and Challis, Idaho.

Seismic Refraction Procedures and Results

We deployed ten portable Sprengnether MEQ-800 seismographs along a 250 kilometer line segment between Butte, Montana, and a position 30 kilometers southwest of Challis, Idaho (Figure 1). These smoked-paper recorders were placed at 25 kilometer intervals along the refraction line and within 5 kilometers of the line. On October 20, 1982, we recorded two open pit mine blasts; one from Anaconda Minerals Company's southeast Berkely pit and the other from Cyprus Mines Corporations' Thompson Creek mine (Figure 1). Eight of our ten recorders wrote clear records of both blasts. The seismograms were recorded at a rate of 60 mm/min. Time corrections between Coordinated Universal Time and each instrument clock were determined by recording three minutes of WWV radio signal at the beginning and end of each seismogram. We supplemented the data from the portable recorders with data from two permanent stations that one of us (MCS) operates in the

Paper number 4L0156.
0094-8276/84/004L-0156$03.00

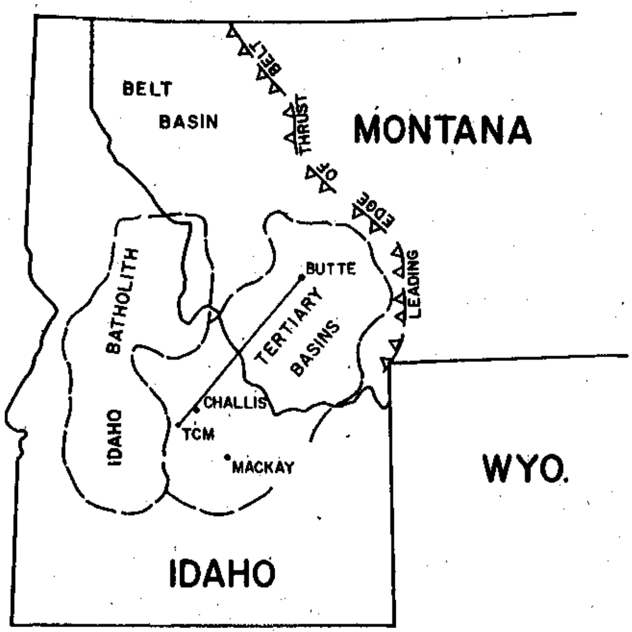

Fig. 1. Index map showing general geology and geography, location of our reversed seismic refraction line and mine blasts. TCM is Cyprus Mines Corporations' Thompson Creek mine; Anaconda Minerals' S.E. Berkely pit is in Butte. Portable seismographs were placed at 25 km intervals along the refraction line.

Butte area. We used two instruments, one within 300 meters of each blast, to record blast origin times. Table 1 lists measured P and S wave travel times which are accurate to +/- 0.2 seconds; we did not make elevation corrections. In Table 1, and in our discussion of these data, we use the following standard notations: Pg is a compressional wave traveling through the upper crust directly between the source and receiver and, Pn is a critically refracted wave traveling along the boundary between the crust and mantle (Moho). We use the same subscripts for S waves.

Figure 2 presents the data from our reversed seismic refraction line on a standard graph of travel time plotted against distance from the seismic source. The Pg (crustal) velocity is 5.8 km/s to the southwest and 6.0 km/s to the northeast. The Pn (mantle) velocity also shows some directional dependence; to the northeast it is 7.9 km/s and to the southwest it is 8.1 km/s. However, these differences are probably not significant at our level of precision. The S-wave velocity in the crust is about 3.5 km/s. The observations that the total travel-times for P waves are equal in each direction and that travel-time curves cross at the center of the plot (Figure 2) further suggest that our data are of high quality. Significantly, the Pg lines do not go exactly through their respective origins. The Pg intercept time on the Butte end is 0.38 seconds and that on the Thompson Creek end is 0.58 seconds. These discrepancies may be due to one or more factors such as a low-velocity weathered layer, local velocity variations near sources and/or receivers, or elevation differences between the source and nearest receivers.

Interpretation

The symmetry of the travel-time results from our reversed-refraction line (Figure 2) strongly suggests the refraction line overlies a horizontal Moho or, by chance, parallels the strike line of a dipping Moho surface. If the crust thickens parallel to the refraction line (Figure 1), the observed Pn velocities would be significantly different: the apparent up-dip velocity would be greater than the true velocity; conversely the apparent down-dip velocity would be less than the true velocity. However, the difference in Pn velocities (Figure 2) is not statistically significant nor is the midpoint shifted a consequential amount. Thus, within the precision of our data, the Moho surface does not dip northeast toward Butte or southwest toward Challis.

Our seismic recording sites, with an average spacing of 25 kilometers, are widely separated (Figure 1). Although several of our seismograms have some distinct phases other than Pg, Pn and, Sg, the spacing of our seismograph stations li-

TABLE 1. Travel Times of Various Phases at Sites with Successful Recordings.

				Butte Blast (SE Berkely pit) 46.01°N, 112.48°W				Thompson Ck Mine Blast 44.31°N, 114.55°W			
Station	Lat	Long	Elev	Distance	Pn	Pg	Sg	Distance	Pn	Pg	Sg
EPM	46.10	112.38	1973	13.1		2.6		262.1	40.4	45.0	75.2
LRM	45.82	112.45	1820	20.4		3.9		235.7	37.2	40.5	68.8
1	45.83	112.64	2067	22.8		4.3	7.7	226.5	36.0	39.1	65.1
2	45.68	112.85	1982	46.6		8.4		202.8	32.8	33.4	58.4
3	45.53	113.07	2195	70.4	16.7	12.5	21.1	178.7	29.9	30.4	51.6
4	45.35	113.24	2445	93.9	19.3	16.7	27.1	155.3	27.1	27.4	46.8
6	45.07	113.60	1860	136.0	24.5	23.6	41.1	113.1	21.6	19.9	33.7
8	44.77	113.96	1750	179.4	30.0	31.2	52.2	69.7		12.5	21.3
9	44.63	114.19	1518	203.6	32.9	35.3	59.8	45.5		8.5	
10	44.45	114.35	2140	226.7	35.8	38.8	66.0	22.5		4.4	7.6

Latitudes are °N; longitudes are °W; source to receiver distances are in kilometers; elevations are in meters; travel times are in seconds.

mits the detail of any model we may generate. The data are best suited to developing a simple model of crust over mantle with a depth to Moho of about 32 kilometers near Challis, Idaho. The southwest to northeast segment indicates a depth to the Moho of about 34 kilometers near Butte, Montana. The similarity of these two values is expected from the symmetry of Figure 2 and implies that the crustal thickness in the area of southwestern Montana and east-central Idaho is approximately 33 kilometers. This interpretation is not unique because different velocity-depth functions for the crust can give first arrivals on the same line segments. Thus, ours is a rough approximation of crustal structure. Nonetheless, it is important because it suggests a much thinner crust than the 40 to 45 kilometers indicated by Smith [1978] or the 60 to 70 kilometers suggested by Ballard [1980]. It is also thinner than the determination of 48 kilometers by Braile et al. [1982] for an area 125 kilometers southeast of Challis, Idaho. The crust may actually be thinner than our data suggest because low-velocity layers are common in continental crust. Moreover, Hales and Nation [1973] suggest a low-velocity layer exists in the Northern Rocky Mountains. Such a layer causes a delay in Pn travel-time that results in an overestimation of crustal thickness.

It is suprising to find less than normal thickness crust in a region where others have predicted a much thicker than normal crust. We could explain the anomaly by constructing a model that would allow thicker crust and make the determination from our data inaccurate. Such a model would have one or more zones of rapid velocity increase in the crust. If the thickness of such a layer is small or, if it has a small velocity contrast with the rocks beneath it, then the layer is not represented by first arrivals on a travel-time versus distance plot like Figure 2. Such zones cause an underestimate of depth to the source of first arrivals. If this is the case in our study area then, the crust is thicker than 33 kilometers. Both high and low-velocity zones are common structural components of continental crust. The occurrence of both features would cancel some of the error in a model based on seismic refraction data. Although we could shuffle low-velocity layers and slabs of high-velocity material into our model to make our result fit any prediction, we prefer to use the simplest interpretation.

The crust in southwestern Montana and east-central Idaho is about 33 km thick. Such a thin crust, in a terrane shortened and tectonically thickened during the late Cretaceous through Paleocene Laramide orogeny, points to extension. Indeed, Eocene through present history of this region is characterized by crustal extension and thinning. Most of the Tertiary basins of this part of the northern Rockies have been evolving for at least 40 million years [Peterson, 1983]; Garmezy and Sutter [1983] show that normal faulting along the Bitterroot basin began at least 45 million years ago. Our refraction line crosses the southern Big Hole basin which contains a minimum of 5000 meters of Cenozoic fill. Nearby, the Madison basin contains up to 4500 meters of Tertiary and recent sedimentary rocks which have been accumulating since the late Eocene. The

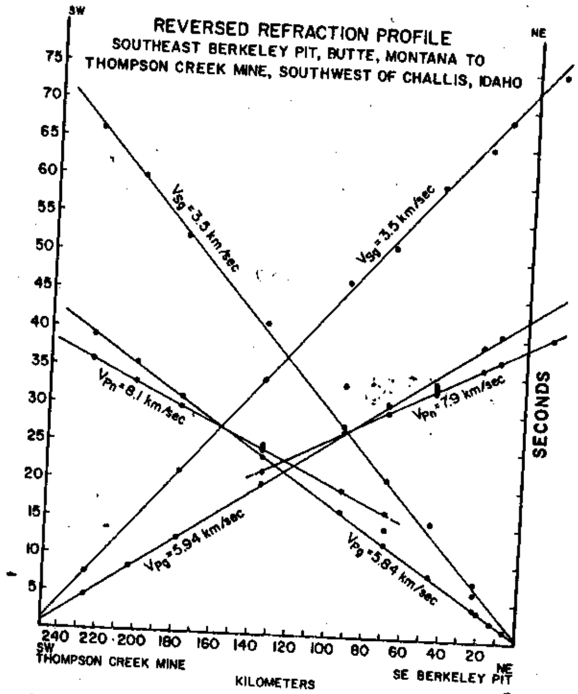

Fig. 2. Standard representation of seismic refraction results on a plot of time versus distance.

evidence is similar for other Tertiary basins of the region. Obviously, crustal extension and thinning was an important structural process during the formation of these basins and, it continues today. Southwest Montana and east-central Idaho lie within the very active intermountain seismic zone and the allied Idaho seismic belt [Smith, 1978]. The number of existing fault-plane solutions is limited for this region but those available show that normal faulting is the dominant focal mechanism [Smith and Lindh, 1978; Qamar and Hawley, 1979; Stickney, 1978]. Normal faulting with this duration and current frequency, combined with the thick sections of Tertiary rock in the basins, implies that large-scale, post-Paleocene crustal thinning has balanced the older, Laramide crustal thickening. The product of these competing tectonic events is a crust that has slightly less than normal thickness.

Acknowledgments. We wish to extend acknowledgment and thanks to Cyprus Mines Corporation and Anaconda Minerals Company for their excellent cooperation which made this project possible and to the Montana Bureau of Mines and Geology for generously covering field expenses for S.D.S. and fully supporting M.C.S.

References

Ballard, J. H., Gravity and seismic investigation of the crust and upper mantle in southwestern Montana, M.S. thesis, 98 pp., University of Montana, Missoula, 1980.

Braile, L. W., R. B. Smith, J. Ansorge, M. R. Baker, M. A. Sparlin, C. Prodehl, M. M. Schilly, J. H. Healy, S. Mueller and K. H.

Olsen, The Yellowstone-Snake River plain seismic profiling experiment: Crustal structure of the eastern Snake River plain, Jour. Geophys. Res., 87, B4, 2597-2610, 1982.
Carlson, G. L. and S. D. Sheriff, Crustal structure beneath the Sapphire tectonic block and the Idaho batholith of southwestern Montana, Program with abstracts, Pacific Northwest Section of the American Geophysical Union, 8, 1983.
Garmezy, L. and J. F. Sutter, Mylonitization coincident with uplift in an extensional setting, Bitterroot range, Montana-Idaho, Geol. Soc. Amer. Abstracts with Programs, Annual Meeting, 15, #3, 578, 1983.
Hales, A. L. and J. B. Nation, A seismic refraction survey in the Northern Rocky Mountains: More evidence for an intermediate crustal layer, Geophys. Journ. Roy. Ast. Soc., 35, 381-399, 1973.
Hobbs, S. W. (editor), Guide to Field Trips, Belt Symposium II, Dept. of Geology, Univ. of Montana, Missoula, 124 pp., 1983.
Hyndman, D. H., The Idaho batholith and associated plutons, Idaho and western Montana, in: Circum-Pacific Plutonic Terranes, edited by J. A. Roddick Geol. Soc. Amer. memoir 159, 316 pp., 1983.
Kleinkopf, M. D., Gravity and magnetic anomalies of the Belt basin, United States and Canada, in: Program and abstracts, Belt Symposium II, Dept. of Geology., Univ. of Montana, 88 pp., 1983.
Lageson, D. L. and G. D. Couples, A review of the 1982 Penrose conference on Laramide deformation of the Rocky Mountain foreland province, Geol. Soc. Amer. Abstracts with Programs, Annual Meeting, 14, #7, 539, 1982.
Mohorovicic, A., Das bebenvom 8.x.1909, Jb. met. Obs. Zagreb (Agram), 9, 1-63, 1909.
Oliver, J. F., F. Cook and L. Brown, COCORP and the continental crust, Jour. Geophys. Res., 88, B4, 3329-3347, 1983..
Peterson, J. A., General stratigraphy and regional paleostructure of the western Montana overthrust belt, in Montana Geological Society Field Conference and Symposium Guidebook to Southwest Montana, edited by T. E. Tucker, 408 pp., 1981.
Qamar, A., and B. Hawley, Recent earthquake activity near Three Forks basin, Montana, Bull. Seismo. Soc. Amer., 69, 1917-1930, 1979.
Smith, R. B., Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillera, in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R. B. Smith and G. P. Eaton, Geol. Soc. Amer. Memoir 152, pp. 111-144, 1978.
Smith, R. B. and A. G. Lindh, Fault-plane solutions of the western United States: a compilation, in Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R. B. Smith and G. P. Eaton, Geol. Soc. Amer. Memoir 152, pp. 107-110, 1978.
Stickney, M. S., Seismicity and faulting of central western Montana, Northwest Geol., 7, p. 1-9, 1978.
Stickney, M. C. and S. D. Sheriff, A southwest Montana to central eastern Idaho reversed seismic refraction profile, Abstracts with programs, Rocky Mountain and Cordilleran section, Geol. Soc. Amer., 15, #5, p. 317, 1983.
Tucker, T. E., (editor), Montana Geological Society Field Conference and Symposium Guidebook to Southwest Montana, 408 pp., 1981.

S. D. Sheriff, Earthquake Research Laboratory, University of Montana, Missoula, Montana, 59812.

M. C. Stickney, Earthquake Studies Office, Montana College of Mineral Science and Technology, Butte, Montana, 59701.

(Received December 28, 1983;
accepted January 20, 1984)