THE REFLECTION MOHO ALONG THE COCORP NORTHWEST U.S. TRANSECT

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Abstract. Marked variations in the seismic reflection character of the continental Moho occur on the COCORP deep seismic reflection transect of the northwestern U.S. These variations correlate with the four major tectonic provinces crossed by the transect, the extended Cordilleran interior, the Rocky Mountain thrust belt, the Precambrian craton, and the western Williston basin. Variations in Moho structure and reflectivity observed along this transect provide an important constraint on processes and structures at the base of the crust. The prominent reflectivity beneath both the Cordilleran interior and Williston basin edge suggests that magmatic underplating may have played an important role in the development of the Moho in both regions.

Introduction

The COCORP (Consortium for Continental Reflection Profiling) Northwest U.S. transect crosses the accreted terranes of northern Washington, the region of documented Eocene extension and exposed core complexes of the Cordilleran interior, the Rocky Mountain thrust belt, the Precambrian Wyoming craton, the Tertiary Bearpaw alkaline intrusive complex, and the intracratonic Williston basin [Potter et al., 1986; Yoos et al., in press; Latham et al., 1988] (Figure 1). This transect thus provides the opportunity to investigate a range of reflection characteristics of the Moho in several different, but contiguous, geologic provinces. To date, characterizations of Moho variability have been generally qualitative in nature and have often focused on one particular 'type' of observed reflection pattern.

The Mohorovicic discontinuity was originally recognized as an abrupt change in seismic P-wave velocities as obtained from earthquake data. Modern seismic refraction and wide-angle reflection observations variously suggest sharp, gradational, or layered transitions at the boundary between crust and mantle [e.g., Hale and Thompson, 1982; Braile and Chiang, 1986; Mooney and Brocher, 1987]. In recent years, near-vertical incidence seismic reflection surveys have reaffirmed that the Moho represents a major boundary within the earth, and yet suggest considerable lateral variability [e.g., Hale and Thompson, 1982; Oliver, 1982]. Although this lateral variability has long been recognized [e.g., Steinhart and Meyer, 1961], clear and detailed images of the structural variation have remained elusive.

Coincident or adjacent reflection and refraction/wide-angle reflection profiles in locations around the world show a general correspondence in depth of refraction-defined Moho and reflection-defined Moho [e.g., Mooney and Brocher, 1987]. However, differences in techniques and uncertainties in resolution make it prudent to maintain the separate entities of reflection Moho and refraction Moho, especially when only limited data of any type are available for a region, as is the case here. For this study, previously interpreted velocity-depth models from refraction surveys in the northwestern U.S. and southwestern Canada were converted to two-way travel time and compared with the reflection data. It should be noted, however, that these comparisons use data of varying ages and distances from the reflection transect.

Two criteria are commonly used to identify deep reflections as images of the Moho. First, the reflections typically mark a prominent boundary between an overlying reflective zone (crust) and an underlying non-reflective zone (upper mantle). Second, the travel times to the reflection Moho are in general agreement with available refraction results collected coincident with or near the deep seismic reflection data. In this paper, we show that Moho reflections generally agree in travel time with features that were previously suggested by available refraction data. In some regions, however, the reflection data simply show the dying-out of a reflective zone (crust) at travel times consistent with the depth to the base of the crust.

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Continental Lithosphere: Deep Seismic Reflections
Geodynamics 22
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Data Acquisition and Processing

A total of 1050 km of seismic reflection data was collected to form a transect across the northwestern U.S. (Figure 1). These data were collected using the Vibroseis technique, and were carried out over local roads using 4 or 5 vibrators in line with a station interval of ~100.6 m (330 ft) and off-end or asymmetric split geophone spreads with a maximum far-offset of approximately 10 km and a nearest group offset of 3 to 5 vibrator stations. Acquisition parameters were occasionally varied along the transect.

Data processing for this study consisted of a standard series of steps (see Zhu and Brown, 1987 for review of typical processing of similar data). Some variations in the processing sequences were dictated by variations in the data quality of the individual seismic lines; in some cases, additional processing steps were applied, typically before deconvolution. For example, data with low-frequency noise (WA 7; ID 2; MT 1,2) benefited from a low-cut bandpass filter (14-32 Hz). A frequency-wavenumber filter [Yilmaz, 1987] was applied to several of the lines (MT 1, 8) in order to remove low apparent-velocity noise, improving the quality of the shallow data. Editing of noisy traces improved the signal-to-noise ratio of data collected in areas of high traffic noise. Lateral variations in relative amplitude on the field data were removed by a combination of noise-spike removal and inter-trace amplitude balancing. The data were processed with a common datum of 1 km above sea level, and are displayed with an automatic gain correction and coherency filter applied, and no vertical exaggeration at a conversion velocity of 6 km/s. Although this paper shows only unmigrated data, migrations of larger portions of the transect have been presented in Potter et al. [1986], Sanford et al. [1988], and Yoos et al. [in press].

Reflection Moho Variations

Cordilleran Interior--A single Moho reflection

Moho reflections beneath the extended Cordilleran interior are notable for their nearly constant travel time and apparent continuity throughout the extended zone. Strong, subhorizontal reflections occurring at 10.5-11.2 s on the seismic profiles are prominent along portions of this segment of the transect, with individual reflections laterally continuous for up to 30 km. The Moho reflections are strongest on Washington lines 1, 2, 5 and 8, and Idaho line 1, but are also evident on Washington line 3. On the stacked sections, Moho reflections characteristically are 2-3 cycle events having a duration of 0.1-0.3 s, and locally dipping or horizontal events occur immediately overlying them. Overlying dipping reflections are most clearly seen on Washington lines 5 and 8, and Idaho line 1 [Potter et al., 1986; Sanford et al., 1988]. In general, the reflection Moho appears sub-horizontal throughout the extended Cordilleran region, over a distance of approximately 250 km. Apparent gaps in the reflection Moho, in the form of vertical blank panels, can be related to surface conditions [Prussen, 1989].

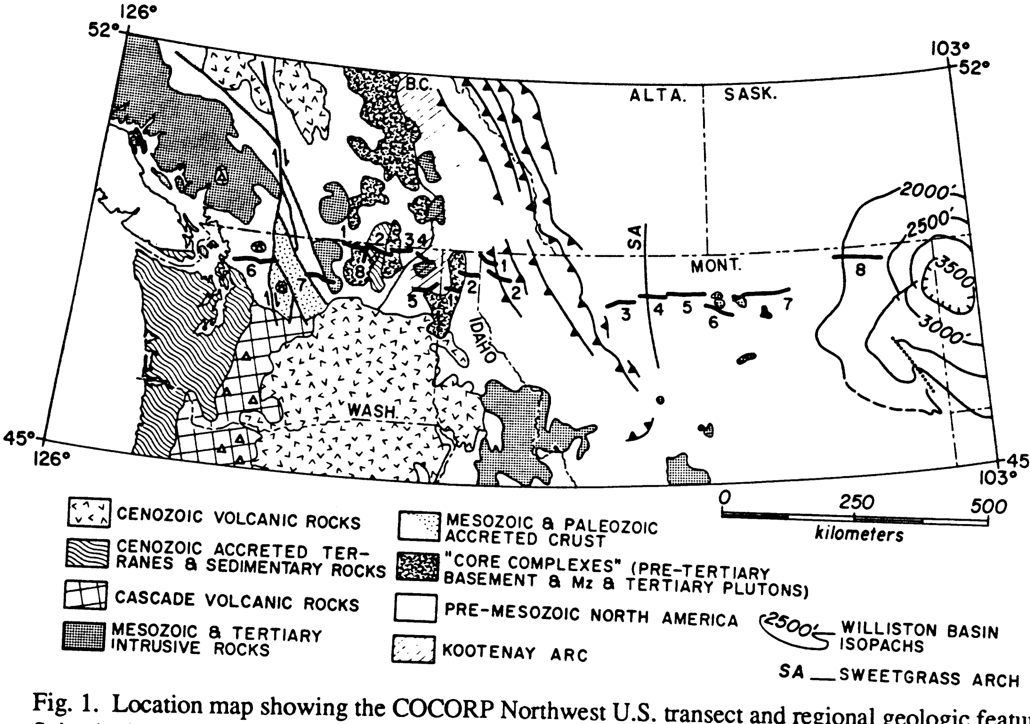

Fig. 1. Location map showing the COCORP Northwest U.S. transect and regional geologic features. Seismic lines are shown with heavy lines and numerals.

Previous estimates of the depth to Moho within the Cordilleran interior in northern Washington and southern British Columbia range between 30 and 35 km [Hill, 1972; Rohay, 1982]. Figure 2 compares Washington line 8 with the velocity-depth model of Hill [1972] from an unreversed refraction profile about 35 km east of the seismic reflection line. The refraction results suggest two possible models for the crust. The strong reflection Moho seen on the COCORP lines closely corresponds with the refraction model which yields a Moho two-way travel time of 11.0 s. Similar Moho reflections appear on some of the data collected by the Canadian Lithoprobe group about 100 km north of the COCORP lines [Cook et al., 1988; Varsek et al., 1989], and on a deep reflection line collected within the Omineca crystalline belt about 350 km north of the COCORP data [Mair and Lyons, 1976].

Rocky Mountain Thrust Belt--non-reflective Moho

COCORP seismic data from northwestern Montana in the Rocky Mountain fold and thrust belt (ID 2, MT 1-2) show a highly reflective upper crust down to a travel time of 7.0-8.0 s. These reflections define structures within the thrust belt, and the discontinuous, prominent reflection sequence that marks the base of this reflective zone has been interpreted as the basal décollement of the thrust belt [Yoos et al., in press]. Below this sequence, the seismic section is notable for its nearly complete lack of reflections (Figure 3). Regional refraction data over the Rocky Mountain thrust belt have been interpreted to indicate an eastward increase in depth to Moho [Hales and Nation, 1973; Cumming et al., 1979]. The velocity-depth model of Hales and Nation [1973] gives a depth to Moho of 37.5 km, near the Montana/Idaho border, which converts to a travel time of 12.3 s.

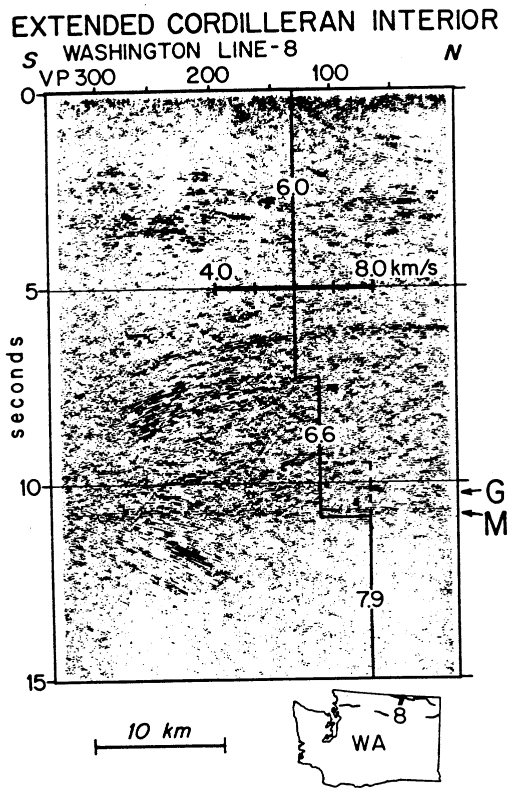

Fig. 2. Unmigrated, coherency-filtered seismic section of Washington line 8, a north-south oriented line within the extended Cordilleran interior, shown with a comparison of the refraction results of Hill [1972]. The 'M' indicates the reflection Moho, and 'G' is the overlying reflection discussed by Sanford et al. [1988]. The prominent reflection below 'M' becomes a dipping lower crustal reflection upon migration.

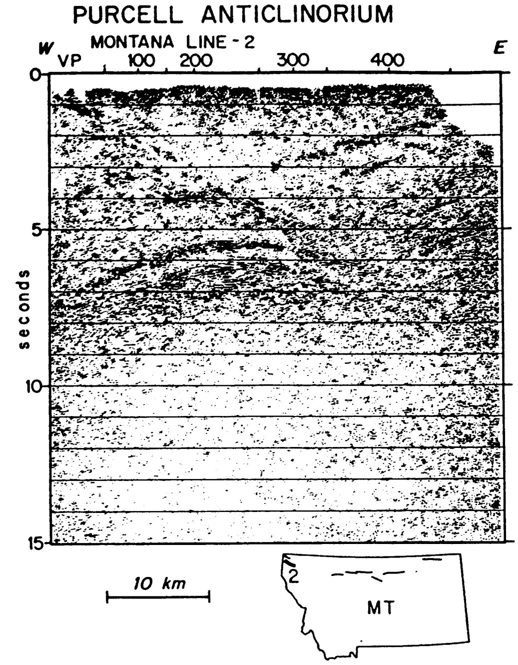

Fig. 3. Unmigrated, coherency-filtered section of Montana line 2. The crust beneath the western Rocky Mountain thrust belt shows highly reflective crust down to travel times of 7-8 seconds, with almost no coherent lineups below that time.

The absence of reflections below 7.0-8.0 s might be the result of energy lost while penetrating the thick, highly reflective fold-thrust belt [Yoos et al., in press] in the upper crust [e.g., Waters, 1981]. It is not clear whether the lack of lower crustal reflections beneath the thrust belt is a signature of geologic differences we would expect between the thrust belt and metamorphic hinterland, or whether it is simply an artifact of complex raypaths.

Montana Plains (Craton)--Moho defined by a downward cessation of crustal reflections

On the Montana plains data over the craton (MT 3-7), east of the edge of the Rocky Mountain thrust belt, reflections beneath the base of the sedimentary section (at 1.0-2.0 s) extend downward to between 14 and16 s. Short, discontinuous, subhorizontal reflections and occasional diffractions occur throughout the crust. The Moho beneath the craton appears to be defined by a decrease in the density of reflections, although locally, interpreted Moho reflections are noted (Figure 4).

Regional refraction data from the north-central Montana plains, on the craton, have been interpreted in terms of a variety of velocity-depth models [Meyer et al., 1961; Asada and Aldrich, 1966]. The models from this older data set yield two-way travel times to the Moho that vary between 12.5 and 18.2 s. Although comparison using these data sets is tenuous because of the variation in the refraction models, the Moho travel times calculated from the refraction models show general agreement with the observed cessation of crustal reflections on the COCORP data.

Williston Basin--Moho at base of reflection/ diffraction band

Deep reflections beneath the western Williston basin are unique along the transect. On Montana line 8, a 1.0-1.5 s wide band of strong reflections and diffractions is observed between 12.5 and 14.0 s. Individual events are laterally continuous for up to 6 km. This band appears to be up to 1.0 s shallower at the eastern end of the line, occurring at 11.2-12.7 s from VPs 670-800. Some of the events within this band are interpreted as diffractions on the basis of their agreement with calculated diffraction curves, and also collapse when migrated. Figure 5 compares Montana line 8 with recent refraction data collected by COCRUST from the Williston basin in southern Alberta. The velocity-depth model was taken from an east-west trending line approximately 100 km north of Montana line 8. The reflection / diffraction band on Montana line 8 generally corresponds with the position of the high-velocity zone (>7.0 km/s) modeled at the base of the crust on the refraction data [Morel-à-l'Huissier et al., 1987].

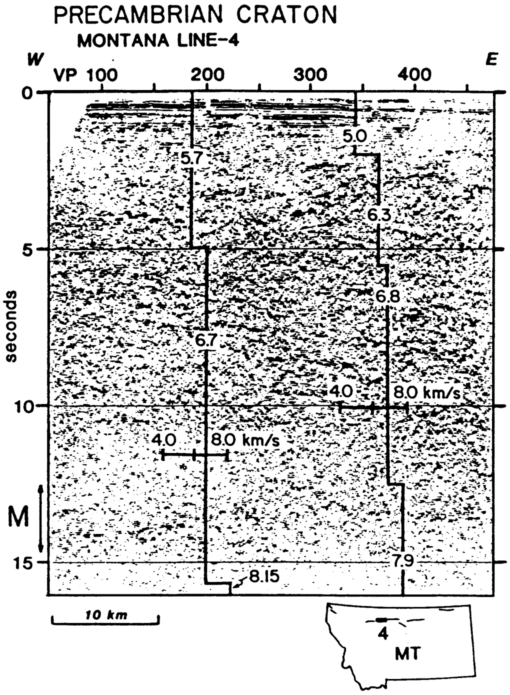

Fig. 4. Unmigrated, coherency-filtered section of Montana line 4 compared with the refraction results of Meyer et al. [1961]. The refraction results show general agreement with the cessation of reflections on Montana line 4. 'M' shows the location of possible Moho reflections.

The anomalously high concentration of diffractions indicates sharply defined (with respect to the signal wavelength) discontinuities at the base of the crust in this region. The refraction results, combined with the diffractions on the reflection data, suggest a band of high-velocity discrete bodies in the lowermost crust.

Discussion

Implications for Reflection Moho Development

The distinct differences in character of the reflection Moho beneath the Cordilleran interior and the Williston basin are a fundamental feature of the crust along this transect. The observed variations can be compared to provide insights into processes and structures at the crust-mantle transition.

The geometry of Moho reflections in the Cordillera suggests a simple boundary for the base of the crust and may imply a relatively sharp discontinuity 0.4-1.1 km thick (for a conversion velocity of 7.0 km/s). On the other hand, elsewhere in the Cordilleran interior, a thicker and perhaps more transitional zone is sugggested. Other workers have suggested that the Moho may be a transition zone several kilometers thick, inferred from both surface geologic relations and geophysical information [Meissner, 1973; Hale and Thompson, 1982; Braile and Chiang, 1986]. Although the determination of a soling or truncation relation is difficult, the termination of dipping reflections at the the reflection Moho, in particular on Washington line 5 and Idaho line 1, suggests an abrupt, non-transitional boundary that has developed via an active process within the upper mantle. Similar, sharply-defined Moho reflections observed in southern British Columbia [Mair and Lyons, 1976; Varsek et al., 1989] may suggest that the deep crust here has undergone similar processes.

In contrast to the Cordilleran interior, beneath the western Williston basin on Montana line 8, a 1.0-1.5 s band of reflections and diffractions occurs with the reflection Moho defined as the base of this zone. For a velocity of 7.0 km/s, the thickness of this zone would be 3.5-5.3 km. The refraction results, when viewed with the diffractions observed on the reflection data, suggest a band of discrete high-velocity bodies in the lowermost crust. These data thus suggest addition of material, perhaps as discontinuous sills, to the base

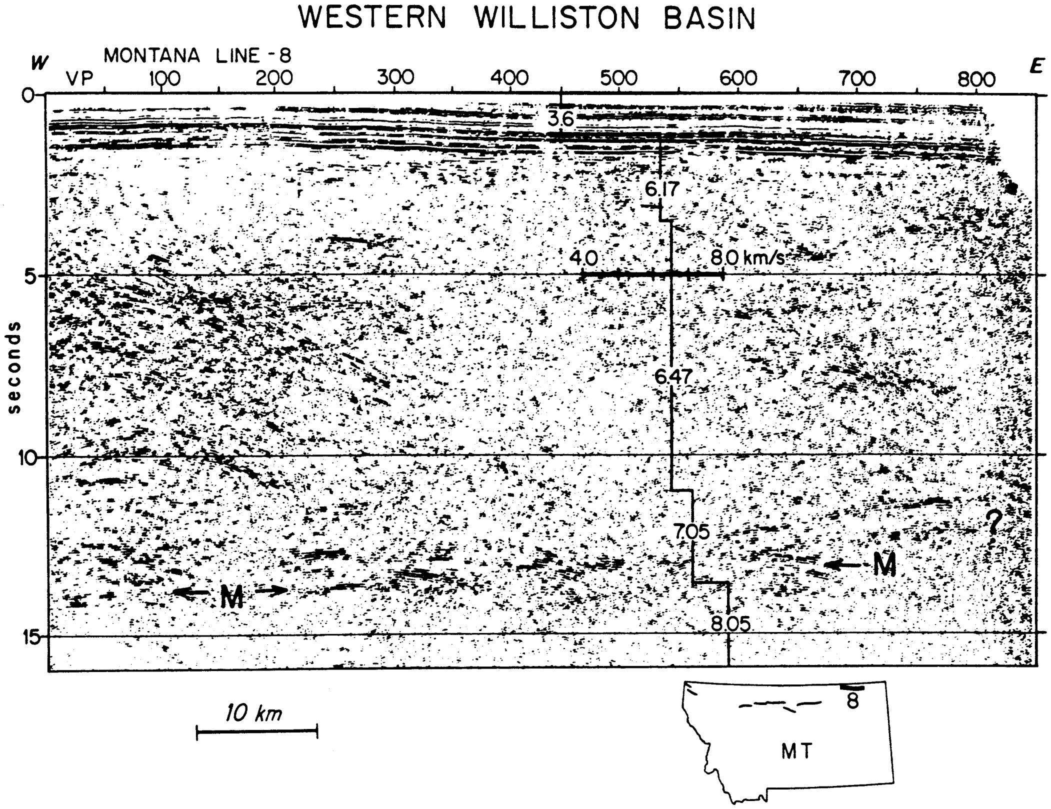

Fig. 5. Unmigrated, coherency-filtered section of Montana line 8, on the western edge of the Williston basin, compared with the refraction results from line H of Morel-à-l'Huissier et al. [1987]. 'M' indicates the reflection Moho at the base of this band.

of the crust. Furlong and Fountain [1986] suggested that mantle-derived crustal material can add more than 10 km to the thickness of the crust, via underplating of mafic magma, although exact thicknesses and resulting seismic velocities are dependent on the compositions and thermal histories of the material. Mafic magma intruding the base of the crust as sills might change the overall composition of the layer enough to modify the seismic velocity observed on refraction data, and cause the discontinuities observed on the reflection data. Other regions have lower crustal zones which may be analogous to the high-velocity layer below the Williston basin. U. S. Geological Survey seismic refraction data from the central Columbia Plateau show an anomalous, high-velocity 'pillow' (7.5 km/s) at the base of the crust beneath a thick sediment-filled graben; this high-velocity layer is similar in shape and velocity to those observed in several other continental rifts such as the Mississippi Embayment, the East African Rift, and the Salton Trough [Catchings and Mooney, 1988].

Studies of the subsidence history of the Williston basin have postulated the existence of subcrustal loads to explain the existence of the basin. Fowler and Nisbet [1985] postulate that the essentially steady, non-exponential subsidence of the basin can be explained by the presence of a mafic subcrustal body undergoing transformation to eclogite, and calculate that a sill-like layer of gabbro less than 5 km thick, with a diameter of 400 km, would be needed. This model would be consistent with the results observed from the refraction and reflection data, in that a broad region intruded by material of gabbroic composition could explain the observed velocity contrast, and the high-amplitude and complexity of the lower crustal reflections. Alternatively, the tectonic emplacement of a mafic crustal slab during mid-Proterozoic plate convergence in the region could also explain the anomalous layer [Fowler and Nisbet, 1985; Green et al., 1985].

Unlike the data beneath both the Cordilleran interior and the Williston basin, the reflection data from the Montana craton show only sparse reflections at approximate Moho travel times, as estimated from the refraction data. Similar reflection character is observed on other data sets over stable intracratonic areas having undergone little or no extension, such as the Colorado Plateau and the Minnesota Precambrian Shield [Meissner, 1986; Gibbs, 1986; Lundy, 1988]. Geochemical analyses of the sparse Eocene volcanics in the Montana craton indicate mantle derivation and little crustal contamination [O'Brien et al., in press]. This interpretation is also supported by the absence of voluminous Cenozoic volcanics as seen in the Cordilleran interior.

Numerous explanations of general Moho reflectivity have been given in the literature: some have included metasedimentary packages, cumulate igneous layering, lenses of partial mantle melt, or a detachment or decoupling horizon [e.g., Meissner, 1973; Hale and Thompson, 1982; Matte and Hirn, 1988]. Seismic reflectivity modeling suggests that the high amplitude of some lower crustal and Moho reflections might not be caused by simple velocity contrasts, but can be explained as the result of constructive interference [Braile and Chiang, 1986; Hurich and Smithson, 1987]. A material explanation for high-amplitude reflections could be provided by voluminous early Cenozoic magmatism in the region [e.g., Armstrong, 1988] which might be manifested as discrete sills or widespread intrusive zones at the base of the crust. In the same sense, the prominent reflection Moho beneath the extended Cordilleran interior can also be related to Cenozoic magmatism and extension in the region [Potter et al., 1986]. Wilshire [1990] presents a model for evolution of the crust-mantle boundary in the southwestern Basin and Range which suggests that extension affects both the upper mantle and lower crust, and is temporally overlapped by multiple magmatic episodes. This may be directly analogous to the northwest Cordillera. Eocene extension in the northwest Cordillera is recognized from structural and geochronological evidence [for review, Parrish et al., 1988], and is superimposed on deeply penetrating Mesozoic thrusts [Monger et al., 1986; Brown et al., 1986; Price et al., 1985]. For the Williston basin, no analogous surface geologic evidence supporting major extension or rifting exists; however, the geophysical data are consistent with somewhat thinner crust, relative to the craton, beneath the basin.

Implications for a Younger Moho

Two opposing styles of Moho reflections have been observed on deep seismic reflection data worldwide. Regions where the data show crustal structures that crosscut and offset the Moho, or simply show an offset, suggest the early development of the reflection Moho as a 'rigid' non-dynamic boundary [Matthews and Cheadle, 1985; Hauser et al., 1987]. Other data suggest that dipping crustal structures are terminated at the Moho, where they are either truncated by the Moho or approach the Moho asymptotically, possibly acting as a décollement surface [Nelson et al., 1985; Matte and Hirn, 1988]. In some regions where deep seismic data suggest that the Moho is horizontally superimposed over earlier crustal structure, surface geologic relations show that a period of large-scale extension post-dates an older compressional episode [Allmendinger et al., 1987]. The inference that can be made for this last case is that, just as crustal extension was the most recent major tectonic episode in these regions, the Moho formed last as a dynamic boundary. On the other hand, basin analysis of data from the Valencia trough [Watts et al., 1990] suggests that the reflective lower crustal layer in the Iberian crust was formed before mid-Tertiary extension, and was thus unrelated to the last tectonic episode in the area. The possibility that a more widespread extensional event, such as that associated with the Tethys, caused the highly reflective lower crust of Iberia cannot be ruled out [Watts et al.,1990].

Evidence from both the Cordilleran interior and western Williston basin suggests the importance of magmatism in the development of the reflection Moho. Whereas the reflection Moho beneath both regions may be interpreted solely as the result of magmatism, the sub-horizontal nature of the reflection Moho and reflective lower crust in the Cordilleran interior may have also developed in association with significant (~30%) crustal extension in the region [Parrish et al., 1988]. In contrast, the reflection Moho beneath the western Williston basin may have developed through intrusion associated with an incipient rifting event in the absence of significant crustal extension.

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References

Allmendinger, R. W., K. D. Nelson, C. J. Potter, M. Barazangi, L. D. Brown, and J. E. Oliver, Deep seismic reflection characteristics of the continental crust, *Geology, 15*, 304-310, 1987.

Armstrong, R. L., Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, in Processes in Continental Lithospheric Deformation, edited by S. P. Clark, B. C. Burchfiel, and J. Suppe, *Spec Pap. Geol. Soc. Am. 218*, 55-91, 1988.

Asada, T., and L. T. Aldrich, Seismic observations of explosions in Montana, in *The Earth beneath the continents, Geophys Monogr. Ser., 10*, edited by J. Steinhart and T. Smith, pp. 244-250, AGU, Washington, D.C., 1966.

Braile, L. W., and C. S. Chiang, The continental Mohorovicic discontinuity: results from near-vertical and wide-angle seismic reflection studies, in *Reflection seismology: A global perspective, Geodyn. Ser., 13*, edited by M. Barazangi and L. Brown, pp. 257-272, AGU, Washington. D.C., 1986.

Brown, R. L., J. M. Journeay, L. S. Lane, D. C. Murphy, and C. J. Rees, Obduction, backfolding and piggyback thrusting in the metamorphic hinterland of the southeastern Canadian Cordillera, *J. Struct. Geol., 8*, 255-268, 1986.

Catchings, R. D., and W. D. Mooney, Crustal structure of the Columbia Plateau: Evidence for continental rifting, *J. Geophys. Res., 93*, 459-474, 1988.

Cook, F. A., A. G. Green, P. S. Simony, R. A. Price, R. R. Parrish, B. Milkereit, P. L. Gordy, R. L. Brown, K. C. Coflin, and C. Patenaude, Lithoprobe seismic reflection structure of the southeastern Canadian Cordillera: Initial results, *Tectonics, 7*, 157-180, 1988.

Cumming, W. B., R. M. Clowes, and R. M. Ellis, Crustal structure from a seismic refraction profile across southern British Columbia, *Can. J. Earth Sci., 16*, 1024-1040, 1979.

Fowler, C. M. R., and E. G. Nisbet, The subsidence of the Williston basin, *Can. J. Earth Sci., 22*, 408-415, 1985.

Furlong, K. P., and D. M. Fountain, Continental crustal underplating: thermal consideratons and seismic-petrologic consequences, *J. Geophys. Res., 91*, 8285-8294, 1986.

Gibbs, A. K., Seismic reflection profiles of Precambrian crust: a qualitative assessment, in *Reflection seismology: The continental crust, Geodyn. Ser., 14*, edited by M. Barazangi and L. Brown, pp. 95-106, AGU, Washington, D.C., 1986.

Green, A. J., Z. Hajnal, and W. Weber, An evolutionary model of the western Churchill province and western margin of the Superior province in Canada and the north-central United States, *Tectonophysics, 116*, 281-322, 1985.

Hale, L. D., and G. A. Thompson, The seismic reflection character of the continental Mohorovicic discontinuity, *J. Geophys. Res., 87*, 4625-4635, 1982.

Hales, A. L., and J. B. Nation, A seismic refraction survey in the northern Rocky Mountains: more evidence for an intermediate crustal layer, *Geophys. J. R. astr. Soc., 35*, 381-399, 1973.

Hauser, E. C., J. Gephart, T. Latham, J. E. Oliver, S. Kaufman, L. D. Brown, and I. Lucchitta, COCORP Arizona transect: Strong crustal reflections and offset Moho beneath the transition zone, *Geology, 15*, 1103-1106, 1987.

Hill, D. P., Crustal and upper mantle structure of the Columbia Plateau from long-range seismic refraction measurements, *Geol. Soc. Am. Bull., 83*, 1639-1648, 1972.

Hurich, C.A., and S. B. Smithson, Compositional variation and the origin of deep crustal reflections, *Earth Planet. Sci. Lett., 85*, 239-242, 1987.

Latham, T., J. Best, T. Chaimov, A. Barnes, J. Oliver, L. Brown, and S. Kaufman, COCORP profiles from the Montana plains: The Archean cratonic crust and a lower crustal anomaly beneath the Williston Basin, *Geology, 16*, 1073-1076, 1988.

Lundy, J., Deep crust of the Colorado Plateau: The COCORP reflection surveys, M. S. thesis, 67 pp., Cornell University, Ithaca, New York, 1988.

Mair, J. A., and J. A. Lyons, Seismic reflection techniques for crustal structure studies, *Geophysics, 41*, 1272-1290, 1976.

Matte, P., and A. Hirn, Seismic signature and tectonic cross section of the Variscan crust in western France, *Tectonics, 7*, 141-155, 1988.

Matthews, D. H., and M. J. Cheadle, Deep reflections from the Caledonides and Variscides west of Britain and comparison with the Himalayas, in *Reflection seismology: A global perspective, Geodyn. Ser., 13*, edited by M. Barazangi and L. Brown, pp. 5-19, AGU, Washington. D.C., 1986.

Meissner, K. R., The "Moho" as a transition zone, *Geophysical Surveys, 1*, 195-216, 1973.

Meissner, R., *The Continental Crust: A Geophysical Approach*, 426 pp., Academic Press, Inc., New York, 1986.

Meyer, R. P., J. S. Steinhart, and W. E. Bonini, Montana, 1959, in *Explosion studies of crustal structure*, edited by Steinhart, J. S., and R. P. Meyer, Carnegie Institute of Washington Publications, 622, 305-343, 1961.

Monger, J. W. H. (principal compiler), G. J. Woodsworth, R. A. Price, R. M. Clowes, R. P. Riddihough, R. Currie, T. Hoy, V. A. G. Preto, P. S. Simony, P. D. Snavely, and C. J. Yorath, Transect B2, Southern Canadian Cordillera, North American continent-ocean transects, in *Decade of North American Geology Program*, Geological Society of America, Boulder, Colo., 1986.

Mooney, W. D., and T. M. Brocher, Coincident seismic reflection/ refraction studies of the continental lithosphere: A global review, *Reviews of Geophysics, 25*, 723-742, 1987.

Morel-à-l'Huissier, P., A. G. Green, and C. J. Pike, Crustal refraction surveys across the Trans-Hudson orogen/Williston basin of south central Canada, *J. Geophys. Res., 92*, 6403-6420, 1987.

Nelson, K. D., J. H. McBride, J. A. Arnow, J. H. Willemin, J. Huang, L. Zheng, J. E. Oliver, S. Kaufman, and L. D. Brown, New COCORP profiling in the southeastern United States. Part I: Paleozoic suture and Mesozoic rift basin, *Geology, 13*, 714-718, 1985.

O'Brien, H., A. J. Irving, and, I.S. McCallum, Eocene potassic magmatism in the Highwood Mountains, Montana: Petrology, geochemistry and tectonic implications, in Eocene magmatism in the northwestern USA, edited by F. Moye, *Spec. Pap. Geol. Soc. Am.*, in press.

Oliver, J. E., Changes at the crust-mantle boundary, *Nature, 299*, 398-399, 1982.

Parrish, R. R., S. Carr, and D. L. Parkinson, Eocene extensional tectonics and geochronology of the southern Omineca belt, British Columbia and Washington, *Tectonics, 7*, 181-212, 1988.

Potter, C. J., W. E. Sanford, T. R. Yoos, E. I. Prussen, R. W. Keach, J. E. Oliver, S. Kaufman, and L. D. Brown, COCORP deep seismic reflection traverse of the North

American Cordillera, Washington and Idaho: Implications for orogenic evolution, *Tectonics, 5*, 1007-1025, 1986.

Price, R. A., J. W. H. Monger, and J. A. Rodick, Cordilleran cross section; Calgary to Vancouver, in *Field guides to geology and mineral deposits in the southern Canadian Cordillera*, edited by D. J. Templeman-Kluit, pp. 3-1 to 3-85, Geological Society of America, Cordilleran Section, Vancouver, B.C., 1985.

Prussen, E. I., Variations in the seismic reflection character of the Moho along the COCORP Northwest U. S. transect-Washington, Idaho, and Montana, M. S. thesis, 76 pp., Cornell University, Ithaca, New York, 1989.

Rohay, A., Crust and mantle structure of the North Cascades range, Washington, Ph. D. thesis, 163 pp., University of Washington, Seattle, Washington, 1982.

Sanford, W. E., C. J. Potter, and J. E. Oliver, Detailed three-dimensional structure of the deep crust based on COCORP data in the Cordilleran interior, north-central Washingon, *Geol. Soc. Am. Bull., 100*, 60-71, 1988.

Steinhart, J. S., and R. P. Meyer, *Explosion studies of crustal structure*, 409 pp., Carnegie Institute of Washington, 1961.

Varsek, J., F. Cook, R. Clowes, C. Spencer, and E. Kanasewich, Lithoprobe Reflection traverse of southern British Columbia, *Geol. Soc. Am. Abstr. Programs, 21*, 153, 1989.

Waters, K. H., *Reflection Seismology*, 453 pp., John Wiley and Sons, New York, 1981.

Watts, A. B., M. Torne, P. Buhl, A. Mauffret, G. Pascal, and B. Pinet, Evidence for reflectors in the lower continental crust before rifting in the Valencia trough, *Nature, 348*, 631-635, 1990.

Wilshire, H. G., Lithology and evolution of the crust-mantle boundary region in the southwestern Basin and Range, *J. Geophys. Res., 95*, 649-665, 1990.

Yilmaz, Ö., *Seismic Data Processing*, 526 pp., Society of Exploration Geophysicists, Tulsa, 1987.

Yoos, T. R., C. J. Potter, J. L. Thigpen, and L. D. Brown, The Cordilleran foreland thrust belt in northwestern Montana and northern Idaho from COCORP and industry seismic reflection data, *Am. Assoc. Petrol. Geol. Bull.*, in press.

Zhu, T. F., and L. D. Brown, Consortium for Reflection Profiling Michigan surveys: Reprocessing and results, *J. Geophys. Res., 91*, 11,477-11,495, 1986.