COCORP profiles from the Montana plains: The Archean cratonic crust and a lower crustal anomaly beneath the Williston basin

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ABSTRACT

New COCORP deep seismic reflection profiles from the Montana plains between the Rocky Mountains and the Williston basin image the crystalline continental basement of the Archean Wyoming cratonic province on a regional scale. The crust is, in general, reflective throughout its entire thickness. West of the Williston basin, the crust-mantle boundary is at the base of the reflective zone and is not marked by the presence of any distinctive reflections. The lowermost crust beneath the Williston basin is, in contrast, characterized by a prominent, laterally extensive zone of relatively high-amplitude reflections. If, as the spatial correlation suggests, the anomalously reflective lower crustal zone is causally related to the subsidence of the basin, then the data place constraints in addition to those of the sedimentary record on physical models for the evolution of the Williston basin.

INTRODUCTION

COCORP has recently acquired a series of six deep seismic reflection profiles totaling 425 km and extending from the Rocky Mountain front in north-central Montana into the Williston basin in northeastern Montana (Fig. 1). The common depth point (CDP) data were collected by using a Vibroseis energy source. Acquisition and processing procedures generally followed those outlined by Brown (1985). The profiles are the newest and easternmost part of a transect that began in western Washington. The area of northern Montana between the Rocky Mountain front and the North Dakota state line lies within the Archean Wyoming province, an area where basement rocks formed before 2 Ga and which has remained essentially stable at least since the Middle Proterozoic (Peterman, 1981). Phanerozoic disturbances of the region are limited to gentle regional uplift and subsidence of the Sweetgrass arch and the Williston basin, respectively, and to localized Cenozoic magmatism, most notably in the Bearpaw and Little Rocky mountains. This preliminary report summarizes the results of the survey, with emphasis on a lower crustal reflection anomaly that is spatially correlated with the Williston basin and may be related to the basin's origin.

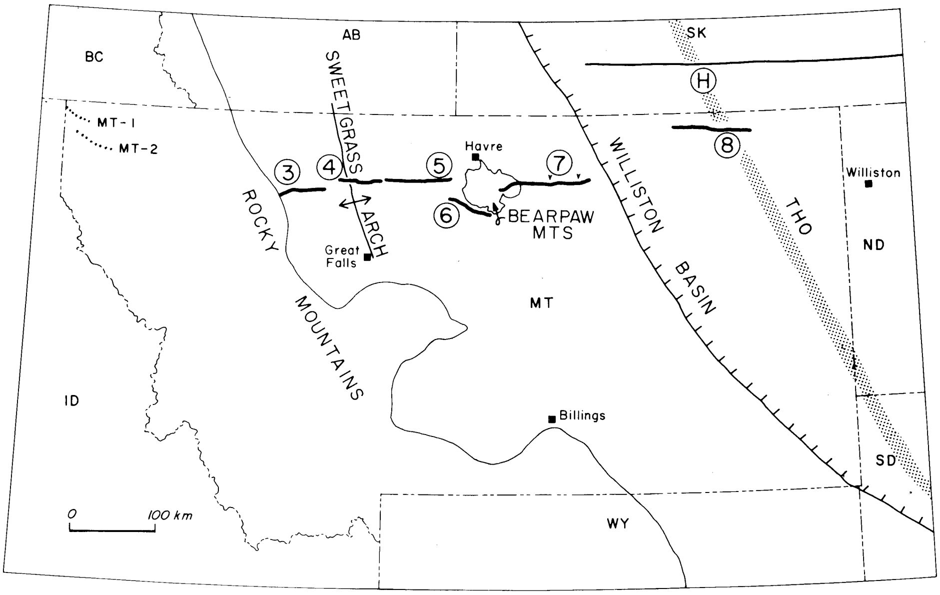

Figure 1. Location of COCORP Montana lines 3–8, east edge of Rocky Mountains, Bearpaw Mountains Tertiary volcanic field, west edge of Williston basin, east edge of Archean Wyoming province. Arrows on line 7 indicate location of excerpt shown in Figure 3. H is location of refraction survey.

REFLECTION CHARACTER OF THE ARCHEAN CRUST WEST OF THE WILLISTON BASIN

The Montana plains survey includes Montana lines 3 through 8 (Fig. 1); lines 3 through 7 are west of the Williston basin, and line 8 is within the western part of the basin. Lines 1 and 2, in the Rocky Mountain thrust belt, are part of an earlier survey described by Potter et al. (1986). All of the profiles are presented as unmigrated line drawings in Figure 2. An excerpt from the eastern part of line 7 (Fig. 3) is representative of the data west of the Williston basin.

Subhorizontal reflections in the top 1 s two-way traveltime (TWTT) of the sections are from Paleozoic and Mesozoic sedimentary strata. Although the reflections are generally flat and continuous, some disruption can be observed in places. The sedimentary section is gently warped over the Sweetgrass arch, the crest of which is located near the west end of line 4, and the Bearpaw Mountains magmatism is responsible for the slight disruption of the sedimentary section seen on the western part of line 6. On the western part of line 7, which is located within the Bearpaw Mountains, uplift due to intrusions and subsequent erosion have thinned the sedimentary section (Hearn, 1976) to such an extent that almost no reflections from the section are observed. Subhorizontal lineups between 1 and 2 s TWTT, most conspicuous in the western one-third of line 3 and in the eastern one-third of line 5, may be multiple reflections from the sedimentary section. It is also possible that the subhorizontal events on line 3 might be reflections from stratified Precambrian rocks; the stacking velocities do not eliminate either possibility.

Reflections from the Precambrian basement west of the Williston basin begin between 1 and 2 s TWTT and die out at about 15 s. In most places, the basement is reflective throughout its entire thickness. Zones where coherent reflections are absent are often, although not always, the results of technical problems rather than geologic variability. The apparently nonreflective vertical panels on line 3, for example, correlate with areas of higher cultural noise and therefore reflect a local degradation of the seismic signal. The reduced number of coherent reflections on the western part of line 7 is apparently due to complex near-surface structures caused by the early Tertiary Bearpaw Mountains magmatism. The origin of the blank zone on line 5 just below the reflections from the Phanerozoic sedimentary section is not as clear; source-generated noise (e.g., multiples, refractions) is present and could be interfering with reflections, but it is also possible that the upper part of the basement could be acoustically transparent in that area.

Although individual reflections are generally subhorizontal, short, and discontinuous, some zones of reflections are continuous over long distances. A prominent dipping zone of reflections and diffractions is evident between 5 and 10 s on line 4. Dipping reflections are also present on line 3 and in parts of line 7. The source of the mid-crustal dipping zone of reflections on line 4 is not known, but the zone's location under the Sweetgrass arch suggests that the reflections could be related to the origin of the arch. The prominent west-dipping events on line 6 do not correlate with any dipping features that have been identified at the surface or in the shallow subsurface (Hearn, 1976). The very linear nature, both on shot records and on the stacked section, and the apparent velocities (between 5 and 6 km/s) of the events suggest that they may be refractions reflected from the numerous steep-walled intrusions in the area.

Across all the profiles west of the Williston basin, reflections die out fairly abruptly at about 15 s TWTT. Data from several refraction surveys, summarized by Allenby and Schnetzler (1983), give an average crustal thickness in north-central Montana of approximately 48 km, a depth that corresponds to between 15 and 16 s TWTT on a reflection profile, given a reasonable average crustal P-wave velocity of slightly more than 6 km/s. In this area, therefore, as has been observed in other cratonic areas (Allmendinger et al., 1987), the Moho depth determined from refraction data corresponds approximately to the depth at which crustal reflections die out.

Although the reflectivity of the Archean basement is complex in detail, some generalizations can be made that permit comparison with other areas. The upper crust in the Montana plains is reflective in most places, in contrast to the relatively transparent upper crust that is sometimes observed in cratonic areas (e.g., Kansas; Brown et al., 1983). The base of the reflective zone is relatively abrupt and occurs approximately at the depth of the Moho. The dying out of reflections at Moho depths is consistent with observations made elsewhere on the craton (Allmendinger et al., 1987; Brown et al., 1983), but it is distinct from the lower crustal laminated zones and prominent Moho reflections seen in areas where tectonic extension and/or magmatism have occurred (e.g., the Great Basin: Klemperer et al., 1986; the Cordilleran hinterland: Potter et al., 1986; Great Britain: Matthews and Cheadle, 1986).

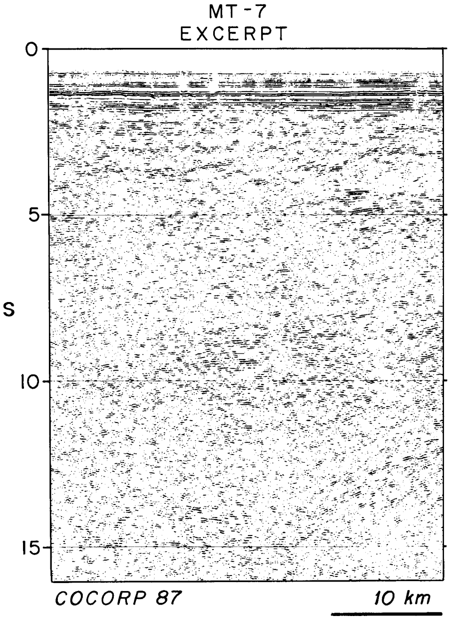

Figure 3. Excerpt from COCORP line 7. Location between Bearpaw Mountains and the Williston basin is shown by arrows in Figure 1. Vertical scale as in Figure 2. Note that there is no distinctive reflective zone in lower crust (13–15 s two-way traveltime).

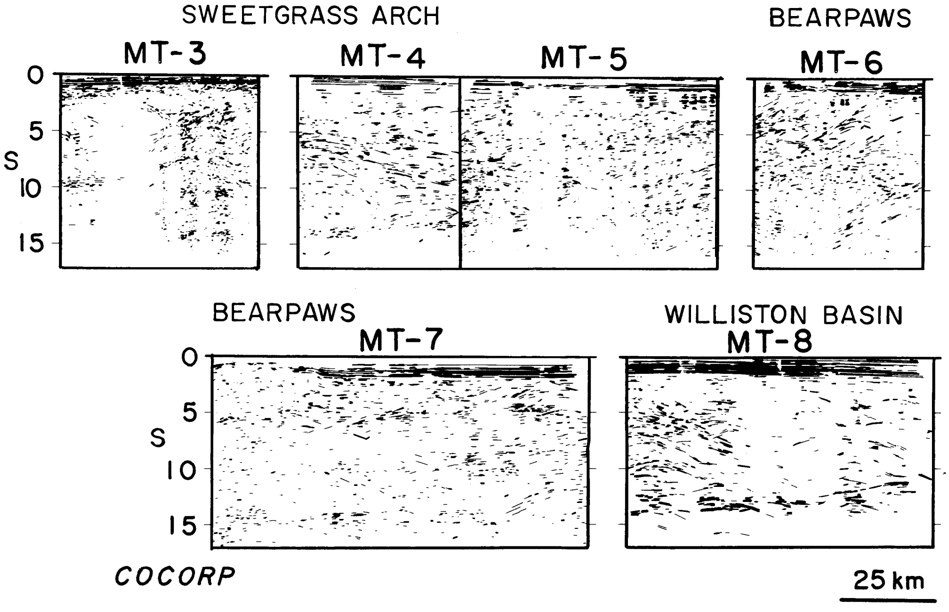

Figure 2. Unmigrated line drawings of COCORP Montana lines 3–8. Vertical scale is two-way traveltime in seconds; 5 s corresponds to about 15 km. Vertical: horizontal is 1:1 for average P-wave velocity of 6 km/s.

STRONG LOWER CRUSTAL REFLECTIONS BENEATH THE WILLISTON BASIN

The Williston basin is an intracratonic sedimentary basin covering parts of North and South Dakota, northeastern Montana, and southern Saskatchewan. The westernmost part of the basin overlies Archean basement of the Wyoming province, and the eastern part overlies Archean rocks of the Superior province. The central part of the basin developed on basement rocks of the Trans-Hudson orogen (Green et al., 1985; Bickford et al., 1986), a Proterozoic metamorphic belt that has been interpreted to be a suture between the two Archean terranes (Lewry, 1981).

Apatite fission-track data (Crowley et al., 1985) show that an episode of uplift and erosion occurred just before the initiation of sedimentation in the Late Cambrian. The subsequent depositional history of the Williston basin has been reviewed by Gerhard et al. (1982). Deposition that began in the Cambrian and throughout the Paleozoic was affected by a series of eustatic transgressions and regressions. From the Ordovician through the Triassic, the Williston basin formed a roughly circular depression with a stationary apparent depocenter (Ahern and Mrkvicka, 1984). During Mesozoic and Cenozoic time, the basin's location in the foreland of the Laramide orogen caused deposition to be dominated increasingly by sediments shed from the Rocky Mountains to the west.

Line 8 is located within the Williston basin, extending from approximately 300 km to approximately 200 km west-northwest of the basin's depocenter. The reflection character of the upper and middle crust along line 8 is much like that seen on profiles to the west (Figs. 2 and 4), but between about 13 and 15 s TWTT, corresponding to a depth of about 39–45 km, strong subhorizontal reflections and diffractions are conspicuous. The reflections in the 13–15 s zone are among the highest amplitude basement reflections on the profile. The individual reflections and diffractions constitute a reflective zone that is continuous across the full length of line 8. The reflective zone is generally subhorizontal, although it is shallower at the eastern end of the profile. Whether the shallower part of the reflective zone is a local perturbation or part of a larger regional trend cannot be determined from the available data.

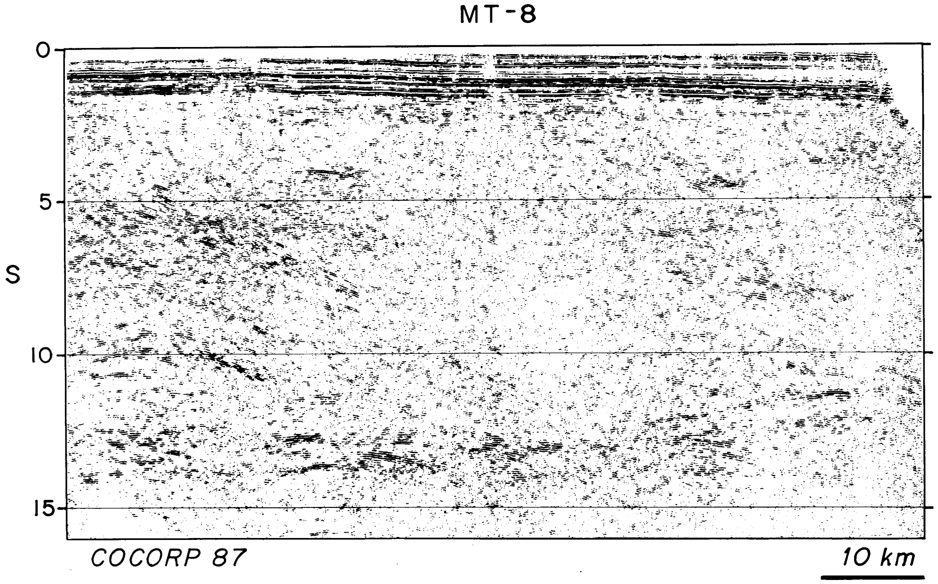

Figure 4. COCORP Montana line 8. Display parameters same as for Figure 3. Line 8 is within Williston basin. Note prominent lower crustal reflective zone between 13 and 15 s two-way traveltime.

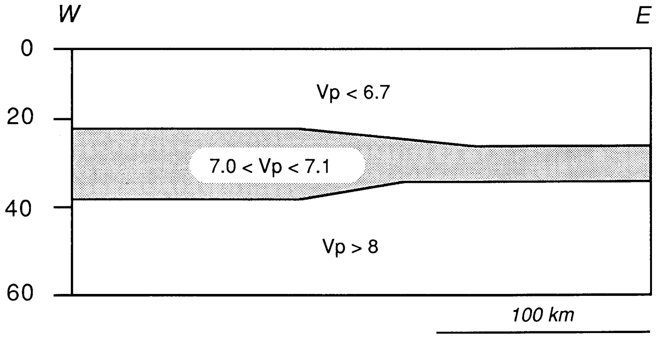

Figure 5. Simplified velocity profile from refraction line H (Morel-à-l'Huissier et al., 1987). See Figure 1 for location. Stipple indicates 7 km/s layer corresponding to lower crustal reflective zone on COCORP Montana line 8.

CORRELATION OF THE LOWER CRUSTAL REFLECTIONS WITH THE WILLISTON BASIN

The zone of strong reflections from the lower crust is in marked contrast to the dying out of reflections observed at comparable traveltimes on profiles west of the basin. If the presence of the lower crustal reflections is related to the formation of the Williston basin and not to older tectonic features, then the anomalous physical properties of the lower crust beneath the basin can provide a key to understanding the origin of the basin.

The COCORP data confirm the anomaly's presence between 200 and 300 km from the depocenter of the basin and its absence in the Archean Wyoming province farther to the west. Line 8 is at or near the western edge, inferred from aeromagnetic data (Green et al., 1985), of the area affected by the Early Proterozoic Trans-Hudson orogen. This proximity requires consideration of the possibility that the reflection anomaly is a signature of the Proterozoic orogeny and not of the Paleozoic basin. Future extension of reflection profiles across the full width of the Williston basin will establish whether or not the lower crustal reflective zone crosscuts, and therefore postdates, major Proterozoic terrane boundaries. Seismic refraction data from the Williston basin in southern Manitoba and Saskatchewan (Morel-à-l'Huissier et al., 1987) shed some light on the problem and appear consistent with the hypothesis that the lower crustal reflective zone is associated with the basin. The refraction data show the presence of a high-velocity lower crustal layer 35–45 km deep, bounded above by a velocity discontinuity and below by the Moho (Fig. 5). The 13–15 s TWTT to the reflective zone identified on the COCORP data corresponds to the depth of the top of the high-velocity layer. It can be inferred that the lower crustal reflection anomaly is coincident with the high-velocity layer and that the anomaly extends across much of the basin. The question of the relation between the reflection anomaly and the Williston basin and the Trans-Hudson orogen is not yet fully resolved. Nevertheless, the existing data suggest a correlation with the Paleozoic basin that justifies some speculation about the origin of the basin.

DISCUSSION

In recent years, several physical models for the Paleozoic subsidence of the Williston basin have been proposed. All the models require an increase in the density of the lithosphere in order to cause subsidence, but the models differ in the assumed composition, depth, lateral extent, and mode of emplacement of the excess mass. The models are constrained primarily by their ability to predict quantitatively the depositional history of the basin. If the lower crustal anomaly described above is indeed related to the origin of the basin, then physical models of the origin of the basin must also predict or explain its presence.

Gerhard et al. (1982) suggested that Phanerozoic subsidence of the Williston basin was the result of reactivation of Precambrian basement faults that had formed in an extensional environment resembling a very large pull-apart structure. The model suggests that the crust beneath the basin might exhibit some of the seismic reflection characteristics of crust that has undergone tectonic extension. A reflective zone at the base of the crust is observed in some tectonically extended areas (e.g., Allmendinger et al., 1987; Brown et al., 1985), but the crust beneath the Williston basin is one-third to one-half again as thick as in other areas where extension-related reflective zones have been documented. The great thickness of the crust is difficult to reconcile with a hypothesis based on crustal extension (Hajnal et al., 1984).

Quantitative models developed by Ahern and Mrkvicka (1984) and Ahern and Ditmars (1985) postulated subsidence due to thermal contraction. The results of the cooling-subsidence models show that the hypothetical cooling mass would have to be deep-seated, in the lower lithosphere, in order for subsidence to be as long-lived as observed. The calculations show that substantially elevated temperatures would never be attained in the lower crust or upper mantle. As noted by Ahern and Mrkvicka (1984), thermal subsidence models do not predict the development at depths as shallow as the Moho of an anomaly detectable by seismic reflection profiling.

Fowler and Nisbet (1985) suggested that mafic material could have been introduced into the lower crust or upper mantle, either by magmatic or tectonic processes, during the Proterozoic Hudsonian orogenic event. The Phanerozoic subsidence of the basin would be the result of the transformation of the lower crustal mafic material to eclogite. Consideration of the kinetics of the gabbro-eclogite transition shows that the transition could take place over a period of time appropriate for the subsidence of the Williston basin. Fowler and Nisbet showed that the transition to eclogite of a mafic layer 5 km thick and 400 km in diameter would produce a density anomaly sufficient to cause the observed subsidence. Of the models presented here, the seismic reflection data seem to best support the model of Fowler and Nisbet because of its clear prediction of the existence of a subhorizontal zone of reflections at or near the base of the crust.

It is interesting to compare the results from the Williston basin to deep seismic reflection results from other Paleozoic North American intracratonic basins: the Michigan basin (Zhu and Brown, 1986) and the Illinois basin (Pratt et al., 1988). Strong reflections from the lowermost crust are not observed beneath either of the other two basins. It is possible that the lack of lower crustal reflections beneath the Illinois and Michigan basins is simply the result of limited signal penetration; conversely, it is possible that the nature of the lower crust, and therefore possibly the mechanisms by which each basin formed, varies from basin to basin.

CONCLUSIONS

New COCORP reflection profiles show that the Archean basement of north-central and northeastern Montana is complexly reflective from the base of the subhorizontal Paleozoic and Mesozoic sedimentary cover to the Moho. The upper crust does not appear in general to be acoustically transparent. West of the Williston basin, the base of the crust is characterized by a relatively abrupt decrease in reflectivity; lower crustal laminated zones and prominent Moho reflections are generally absent. In contrast, the lowermost crust beneath the Williston basin is strongly reflective. If the presence of the reflection anomaly is related to the subsidence of the basin, then a new constraint, that the presence of a geophysically anomalous mass in the lower crust must be predicted, is placed on physical models for basin subsidence.

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