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WIDE-ANGLE REFLECTION STUDIES OF THE CRUST AND MOHO BENEATH THE ARCHEAN GNEISS TERRANE OF SOUTHERN MINNESOTA

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Abstract. Densely spaced wide-angle reflection data from oldest Archean crust in southern Minnesota were processed and modeled to place constraints on average crustal structure and the nature of the Moho. A preliminary 1-D extremal inversion of $\tau(p)$ arrivals extracted from vibroseis and quarry blast recordings covering offsets betweeen 70 and 108 km suggests a crustal thickness between 45 and 51 km. Slowness-depth models corresponding to extremal depths have average velocities ranging from 6.5 to 7.0 km/s, with velocities at the base of the crust ranging from 6.8 to 7.5 km/s. Estimates of V_p/V_s based on travel time ratios of P- and S-wave arrivals show an increase from 1.71 ± 0.02 in the near-surface to an average of 1.76 ± 0.03 for the whole crust, which is consistent with an increasingly mafic or plagioclase-rich composition with depth. Although the data are sparse, the occurrence of broad-band P_mP, S_mS, and P_mS/S_mP arrivals at slightly precritical offsets combined with sporadic multicyclic reflections observed in coincident normal-incidence CDP sections suggests that the Moho beneath this terrane is not a simple velocity gradient, but rather a layered zone involving small velocity contrasts.

Introduction

Interpretations of recent seismic reflection profiles over cratons have challenged traditional views regarding the processes involved in the formation and subsequent alteration of Precambrian crust. Although Proterozoic terranes are now covered by several thousand kilometers of normal-incidence reflection profiles, however, coverage of Archean terranes is still rather sparse. In an attempt to better understand crustal features developed during the Archean, the University of Wyoming recorded several normal-incidence and wide-angle reflection profiles over the Archean gneiss terrane of southern Minnesota [Boyd et al., 1991]. In this paper, we show results from a preliminary analysis of the wide-angle recordings.

Archean Terranes in Minnesota

The study area (Figure 1) consists of two distinct Archean terranes, an older granite-gneiss terrane to the south and a younger greenstone terrane to the north. The 3500 - 3800 Ma old rocks of the gneiss terrane exposed in the Minnesota River Valley [i.e. Sims et al., 1980] are the oldest rocks in the United States. The granite-gneiss and greenstone terranes are separated by the Great Lakes Tectonic Zone [Sims et al., 1980]. Analyses of aeromagnetic data [Smithson and Johnson, 1989] and seismic reflection data [Gibbs et al., 1984; Smithson and Johnson, 1989] suggest that the zone is bounded by several major northward dipping faults. Distinct Moho reflections from normal-incidence seismic data are not identified beneath or north of the Great Lakes Tectonic Zone, but appear farther south in the Minnesota River Valley [Boyd et al., 1991].

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Acquisition, Processing and Data Description

This study evaluates recordings of large-offset shots into the normal-incidence deployments located on the southern boundary of the Great Lakes Tectonic Zone (Figure 1). The receiver arrays consisted of two slaved, 96-channel recording systems with a group spacing of 50 m, for a nominal recording aperture of 9 km. Sources for the wide-angle recordings included both vibrators and untimed quarry blasts. Source-receiver offsets ranged between 60 and 108 km. Four trucks generated 32-s long, linear sweeps of 10 - 42 Hz; 20 to 34 sweeps were generated at each source point. The

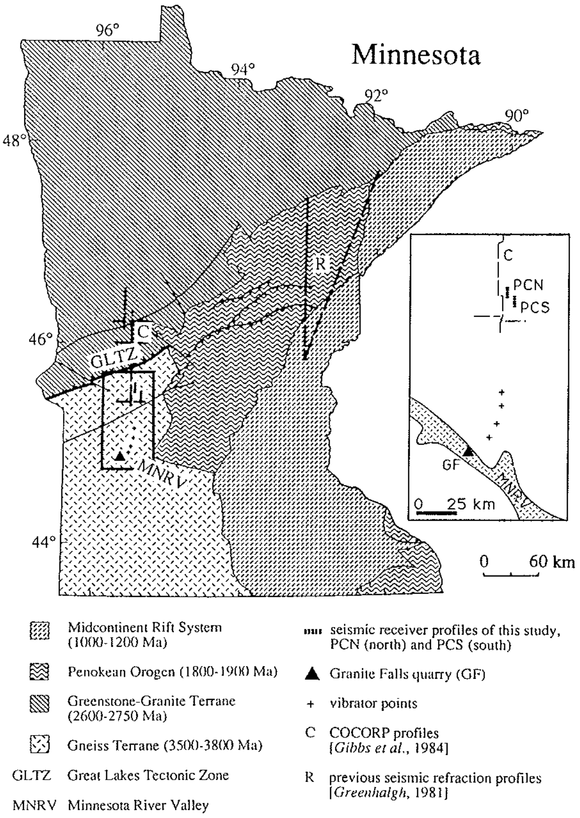

Fig. 1. Geologic map of Minnesota showing seismic source and receiver locations. Ages are from Sims et al. [1980].

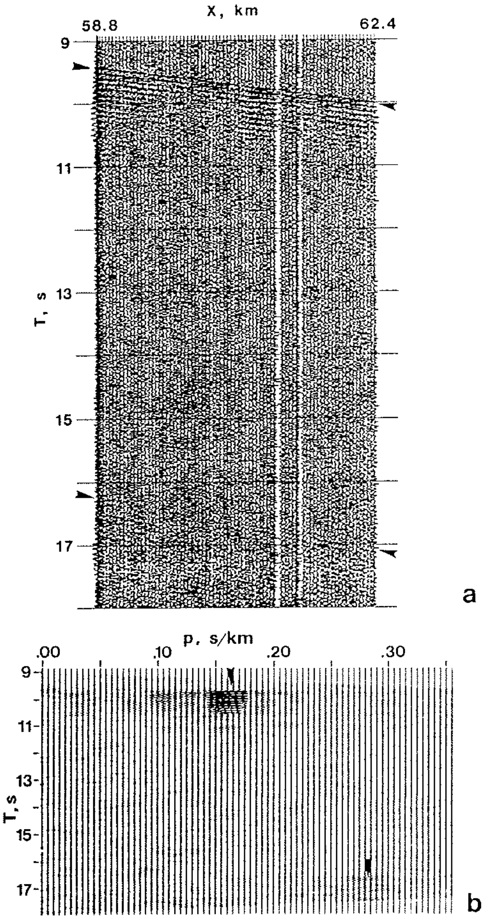

Fig. 2. (a) Vibrator recording (vertical stack of 20 sweeps). (b) Corresponding slant stack (T-p). Note the strong, direct P-wave and corresponding S-wave arrivals (arrows).

quarry blasts were detonated as series of delayed charges (ripple-fired). Shot patterns consisted of 39 - 43 holes with 90 - 100 kg of explosive per hole; total source duration for each blast was about 0.4 s.

The vibroseis records (Figure 2a) were vertically stacked using a diversity stacking routine and then band-pass filtered (10 - 42 Hz). Travel times for the untimed quarry blasts (Figure 3) were estimated by using group velocities measured for first arrivals on shot gathers for the timed vibrator sources. To provide estimates of the arrival times and apparent slownesses of coherent arrivals, we slant stacked each shot gather (Figure 2b). Semblance was used to design a coherency filter [Stoffa et al., 1981] which was applied to each slant stack to suppress artifacts due to spatial aliasing and other incoherent noise.

On the vibroseis records, first arrivals appear with ray parameters between 0.155 and 0.165 s/km (apparent velocity: 6.06 - 6.45 km/s). A large-amplitude event at T = 16.6 s in the slant stack for the nearest vibrator point (Figure 2b) is interpreted as the direct S-wave arrival. If one assumes identical ray paths, the ratio of travel times for the direct P- and S-wave arrivals suggests a V_p/V_s ratio (averaged along the ray path) of 1.71 ± 0.02, where the uncertainty is estimated from the uncertainties in travel time (± 0.1 s). This estimate is independent of dip. If one assumes an isotropic medium, this corresponds to an average Poisson's ratio of 0.24 ± 0.01.

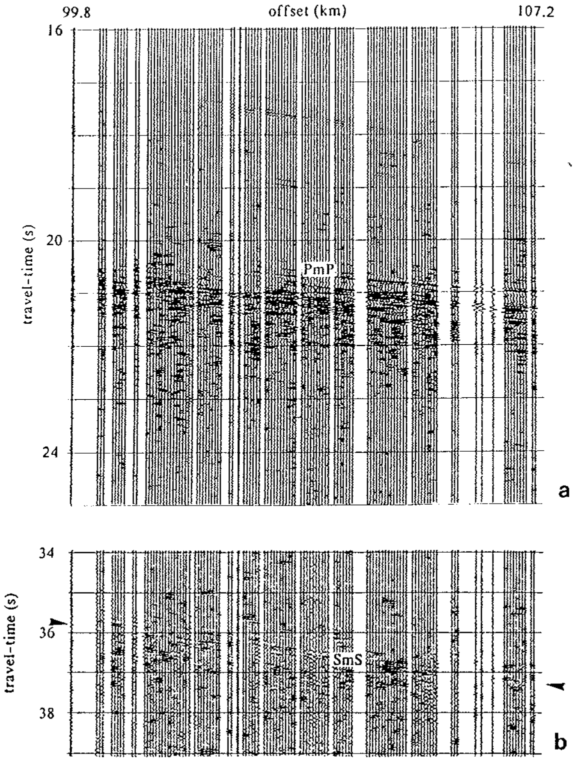

Fig. 3. Shot gather showing (a) P_mP and (b) S_mS arrivals for an untimed quarry blast. Travel times were estimated from group velocities from timed far-offset vibrator recordings.

Ray parameters measured for events interpreted as P-wave reflections from the Moho (P_mP) range from 0.07 s/km at 77 km offset to 0.10 s/km at 103 km (Figures 4 and 5). If one assumes zero dip, these values correspond to precritical reflection, indicating a rather deep Moho and/or high P-wave velocities near the base of the crust. Slant stacks of the quarry blast recordings reveal the 0.4 s duration of the quarry blast source (Figure 4). We identify a strong, subcritical P_mP arrival at 20.5 s two-way travel time (Figure 4a), a much weaker P_mS/S_mP arrival at 27.7 s (Figure 4a), and a strong, subcritical S_mS arrival at 36.2 s (Figure 4b). The ratio of travel times for P_mP and S_mS suggests a ratio of P- and S-wave velocities (again, averaged along ray paths which we assume are identical) of 1.76 ± 0.03. As before, if one assumes an isotropic crust, this estimate for V_p/V_s corresponds to an average Poisson's ratio for the crust of 0.26 ± 0.01.

Inversion

We combined picks from slant stacks of individual shot gathers (Figure 5) into a single composite $\tau(p)$ section (Figure 6a) and inverted for averaged, 1-D structure using the extremal method [Garmany et al., 1979]. To avoid bias caused by misidentification of precritical reflections as postcritical, we kept the total number of picks in our composite section to a minimum. Our $\tau(p)$ picks include three arrivals identified as refractions and postcritical reflections

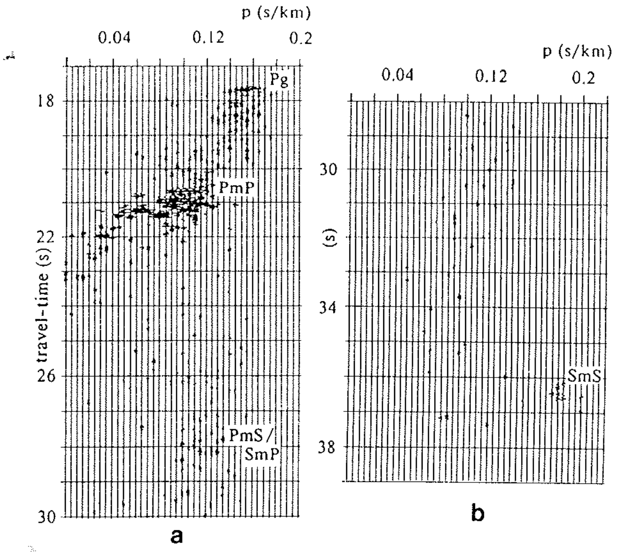

Fig. 4. Coherency-filtered slant stacks (T-p) of quarry blast record (max. offset 107.2 km), (a) P_mP and P_mS, (b) S_mS arrivals.

from within the crust and four arrivals identified as precritical reflections from the Moho (Figures 5 and 6a). The latter do not provide direct estimates of interval velocities but do provide multiple constraints on average crustal velocity and total crustal thickness [Hawman and Phinney, 1992]. The picks also include one estimate of differential τ [Hawman and Phinney, 1992] for one of the untimed quarry blasts. The uncertainties assigned to the τ picks incorporate the uncertainties in picking arrivals due to limited bandwidth, second-order errors due to uncertainties in ray parameter, and uncertainties in first-arrival group velocities for the quarry blast data. They do not include estimates of scatter due to lateral variations in velocity structure. We used the linear formulation of the inverse problem, specifying the layer slownesses and inverting for layer thicknesses. The value chosen for the surface slowness (0.185 s/km; 5.41 km/s) was based on apparent velocities of first arrivals (refractions from basement) measured on source gathers recorded at offsets between 0 and 9 km. For the bottom layers we chose a rather small slowness value (0.134 s/km; 7.48 km/s) to allow for the possibility of high velocities near the base of the crust as inferred by the work of Greenhalgh [1981]. Extremal inversion shows, however, that these high velocities are not required by the data.

The slowness-depth bounds derived by extremal inversion are rather broad (Figure 6b). The picks corresponding to crustal phases (Figure 6a) are sufficient to constrain depths fairly adequately in the slowness range 0.185 - 0.160 s/km (5.41 - 6.25 km/s) but do little to constrain depths for smaller target slownesses. The disparity in shape observed for the upper and lower bounds is typical of extremal bounds derived from sparse data sets [Hawman and Phinney, 1992]. Note that jumps in the minimum depth bound occur only at target slownesses corresponding to sampled ray parameters. This is because minimum depth bounds are derived from integration paths in $\tau(p)$ that are characterized by a minimum possible slope $d\tau/dp$ near the target slowness [Garmany et al., 1979].

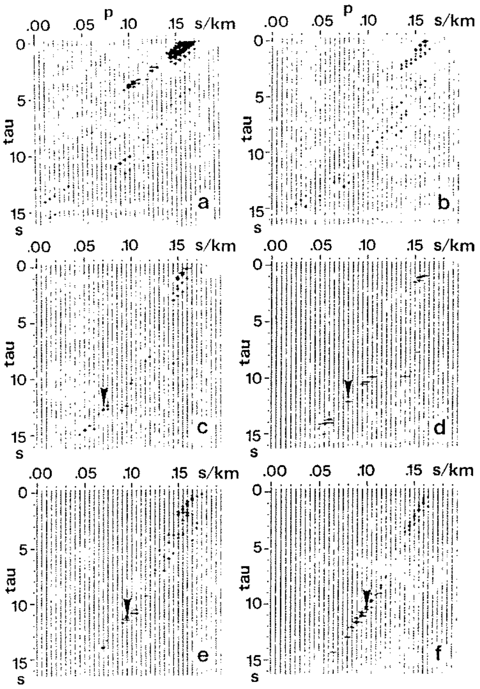

Fig. 5. Coherency-filtered slant stacks (τ-p) from all quarry blast and vibrator records from which arrivals were picked for extremal inversion. Arrows mark events interpreted as precritical P-wave reflections from the Moho. (a - d) vibrator sources; (e) and (f) untimed quarry blast sources. Offsets centered about: (a) 60 km, (b) 69 km, (c) 77 km, (d) 85 km, (e) 92 km, (f) 103 km.

Over ranges of p for which no τ picks are available, the integration paths are free to maintain a level minimum depth bound.

Total crustal thickness (45 - 51 km) and average crustal velocity (6.5 - 7.0 km/s) for individual slowness models corresponding to the extremal depth bounds are constrained largely by the four Moho picks. Velocities at the base of the crust for models corresponding to extremal depths fall between 6.8 and 7.5 km/s. Predicted critical distances for the Moho reflection range from 120 to 180 km. The inversion

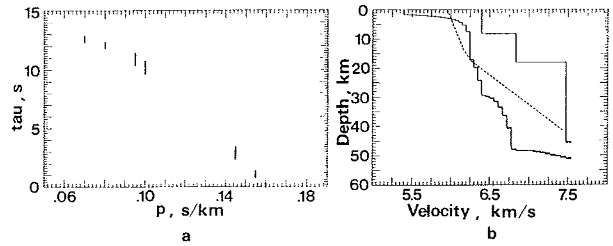

Fig. 6. (a) Composite $\tau(p)$ section showing principal arrivals (refractions and precritical Moho reflections) constructed from partial slant stacks shown in Figure 5. Error bars represent $\pm 1\sigma$ confidence limits. (b) Depth bounds derived by extremal inversion of τ bounds shown in Figure 6a. Note that the depth bounds themselves are not valid velocity models. Dashed line: velocity-depth function derived by Greenhalgh [1981] for eastern Minnesota.

results are consistent with estimates from linear regression of T^2-X^2 data that yield (after correction for refraction effects) an average crustal velocity of 6.7 - 6.9 km/s and a crustal thickness of 47 to 51 km.

Discussion

The slowness-depth models derived by extremal inversion of the Minnesota data predict a normal two-way travel time to the Moho of 13.9 to 14.7 s. Nearly coincident CDP sections obtained by this group and by earlier workers [Gibbs et al., 1984] across and south of the Great Lakes Tectonic Zone, however, show no continuous reflectors within the predicted time interval, even though rather strong reflections appear at two-way times corresponding to depths within the middle to lower crust. This suggests that the absence of Moho reflections at near-normal incidence is due not to inadequate signal penetration but rather to a gradational boundary or a first-order discontinuity or layered zone involving small velocity contrasts. The lower-frequency P_mP arrivals observed in refraction records at offsets greater than 170 km in eastern Minnesota [Greenhalgh, 1981] would be consistent with either model; a steep gradient zone would focus energy in much the same manner as postcritical reflection from a step discontinuity. However, the appearance of strong, relatively high-frequency (20 - 30 Hz) P_mP arrivals in wide-angle vibrator and quarry blast records at precritical offsets along with precritical S_mS and P_mS arrivals observed on the quarry blast records argues against a simple velocity gradient. The interpretation of the Moho as a laminated zone involving small but laterally variable velocity contrasts is supported by the appearance of a prominent but discontinuous multicyclic reflection at 14 s in a CDP profile recorded over the Minnesota River Valley [Boyd et al., 1991], about 100 km southeast of the wide-angle reflection midpoints considered here. A more definitive study of the Moho beneath the study area based on modeling of normal-incidence reflections and relative amplitudes of P_mP, P_mS/S_mP, and S_mS arrivals recorded at postcritical offsets is in preparation.

Average velocities for individual slowness models corresponding to the extremal depth bounds tend to cluster between 6.7 and 6.8 km/s. This range is in agreement with average crustal velocities found for late Proterozoic crust of the Grenville province [Lyons et al., 1980] and Archean crust of the Superior province [Boland and Ellis, 1989]. The crustal thickness bounds are slightly greater than the thickness reported from eastern Minnesota [Greenhalgh, 1981] but are similar to estimates for Archean crust flanking the Kapuskasing structural zone [Boland and Ellis, 1989].

Conclusions

Slant stacks of vibroseis and quarry blast data recorded at offsets between 70 and 108 km in the Archean gneiss terrane of southern Minnesota show numerous events, including precritical reflections from the Moho. Although the data are sparse, observations of broadband, slightly precritical P_mP, S_mS, and P_mS/S_mP reflections on quarry blast records and sporadic Moho reflections on CDP sections are consistent with a layered crust-mantle transition zone involving small velocity contrasts. Preliminary modeling of velocity structure based on extremal inversion of composite P-wave $\tau(p)$ data suggests a crustal thickness between 45 and 51 km. The bounds on average crustal velocity derived by extremel inversion suggest a crust that is intermediate to mafic in average composition. The increase in V_p/V_s from 1.71 ± 0.02 in the near-surface to an average of 1.76 ± 0.03 for the crust is consistent with an increasingly mafic or plagioclase-rich composition with depth.

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