Crustal Root Beneath the Urals: Wide-Angle Seismic Evidence

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Wide-angle reflection and refraction data acquired as part of the URSEIS '95 geophysical experiment across the southern Uralide orogen provide evidence for a 12- to 15-kilometer-thick crustal root, yielding a total crustal thickness of 55 to 58 kilometers. Strong reflections from the Mohorovičić discontinuity (Moho) at relatively small precritical distances suggest that the crust-mantle transition beneath the crustal root is a sharp feature. The derived *P*- and *S*-wave velocity models constrain key physical properties of the crust, including the depth of the mafic rocks of the Magnitogorsk volcanic arc and the existence of a lower crustal zone of possible basic rock enrichment beneath the East Uralian zone.

The preservation of a crustal root beneath the Uralide orogen is an anomalous feature when compared to other Paleozoic orogenic belts. The existence of this root had been based on seismic studies (*1*, *2*) and gravity measurements (*3*). In order to constrain the seismic velocity structure of the southern Urals, refraction profiles were acquired as part of the URSEIS '95 geophysical study across the orogen, from Sterlitamak in the west to the Kazakstan border in the east (*4*). The wide-angle seismic data provide information on the structure and physical properties of the crust and an image of the topography of the crust-to-mantle transition zone (Moho).

The geometry (*4*) of the wide-angle seismic profiles was designed to optimize recording of reflections at near-critical distances and to provide velocity control for the near-vertical reflection experiments, particularly at Moho depths. A 340-km-long, wide-angle reflection and refraction profile was acquired coincident with the (normal incidence) common midpoint profile (*5*), a perpendicular profile, and two fan deployments. A total of 30 tons of explosives was distributed among 14 shots, with charge sizes ranging between 1.5 and 3 tons. The seismic energy was recorded by 50 three-component digital recording instruments (REFTEK, Dallas, and Lennartz, Tübingen). The east-west profile consisted of four shots at 120-km intervals. The north-south profile (perpendicular to the main line) consisted of one shot, which was used to constrain the velocity along strike of the orogen. The off-line fan profiles consisted of two shots, recorded at distances of 100 to 120 km, which sampled the lateral velocity variation of the deep crust and upper mantle.

Reflected and refracted phases (PmP and Pn) can be identified on the different shot records and correlated from shot to shot (Figs. 1 and 2). These phases are characterized by high amplitudes and provide the basis for dividing the crust into four velocity levels: upper, middle, and lower crust, and upper mantle (Fig. 1). The focusing of backscattered energy by dipping structures above the lower crust (Main Uralian fault and Kartaly reflection sequence) can account for events with anomalous moveouts (curvature of an event as a function of offset) in the shot gathers.

First arrivals at offsets of less than 70 km imply lateral variations in velocities at shallow depths (5.0 to 6.0 km/s) that can be correlated with the surface geology (Figs. 1 and 2). The velocities increase with depth to 6.2 to 6.3 km/s in the upper crust (depth of 5 to 7 km), about 6.6 km/s

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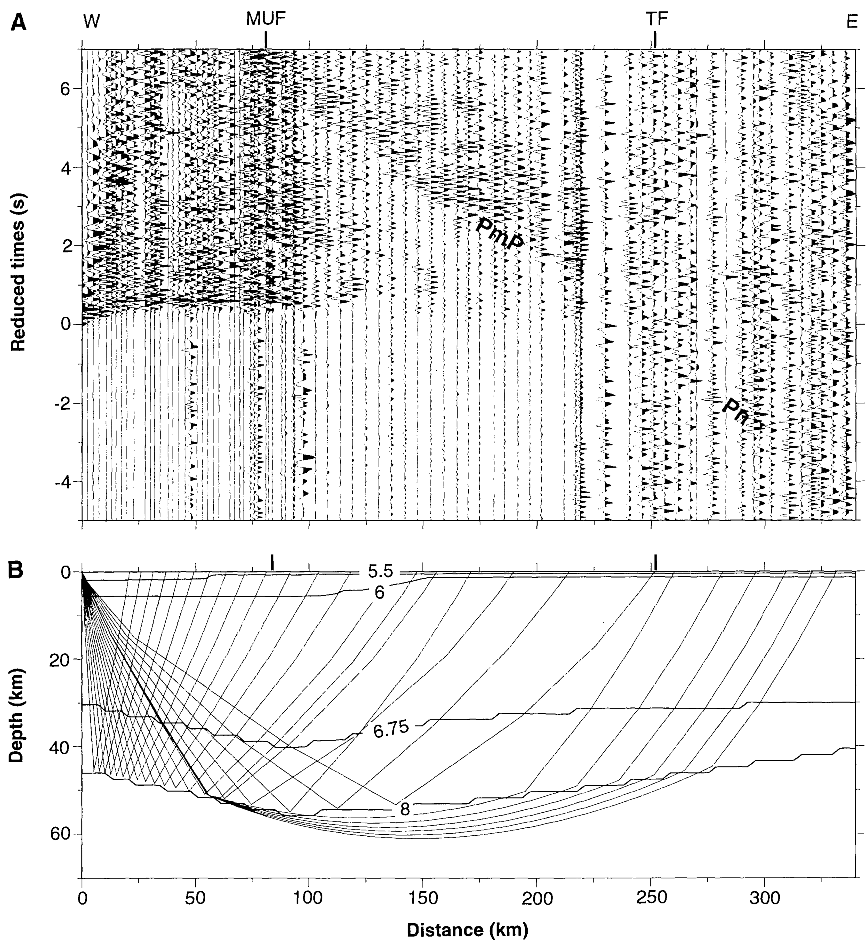

Fig. 1. (**A**) *P*-wave record section for shot 1. Interpreted arrivals: PmP, Moho reflection; Pn, upper mantle head wave. (**B**) Ray-tracing diagram displaying the coverage and resolution of the crust-mantle boundary. Isovelocity contour lines for 5.5, 6.0, 6.75, and 8 km/s are also drawn. This velocity model was derived by forward modeling of the travel times of the interpreted phases. The arrows labeled MUF and TF mark the surface location of the Main Uralian and Troisk faults, respectively. The distance axis in the bottom figure refers to the distance from the shot location. Distance 0 marks the surface location of the shot [see S1 in figure 1 of (*4*)].

within the middle crust (~10 to 30 km), and 6.8 to 7.4 km/s in the lower crust (from 30 to 35 km down to the Moho). An increase in the average velocities throughout the crustal column within the central part of the profile (Magnitogorsk zone) is interpreted as evidence for an increase in mafic content (at upper crustal levels) and metamorphic grade (in the middle to lower crust) in the core of the orogen. The proposed layered velocity model is nonunique but generates theoretical travel-time branches that are in agreement (to within ±0.1 s) with the interpreted arrivals for all of the sections.

A 1.5- to 2.0-s delay in travel times for the Moho reflection (PmP) from shot 1 as compared with shot 4 provides the major evidence for an increase in crustal thickness beneath the Uralide orogen. The Moho depth varies from between 42 and 45 km at the edges of the profile to between 55 and 60 km beneath the central part. The continuity of the Moho along the profile is constrained by the smoothly varying PmP and Pn arrivals, which indicate that there are no marked steps in the Moho within the area of illumination. The relatively narrow wavelet and prominent high amplitudes of the PmP and SmS phases at precritical distances suggest a relatively thin (approximately a first-order discontinuity) crust-mantle transition zone. The Pn and Sn head waves are characterized by velocities of 8.0 to 8.2 km/s and 4.5 to 4.7 km/s, respectively.

The horizontal component recordings provide a shear-wave velocity model that, in general, parallels the one for *P*-wave velocities (V_P). These physical properties provide constraints on the nature of the crust (6). Poisson's ratio and the V_P/V_S ratio are particularly sensitive to quartz content: whereas most of the rock-forming minerals have Poisson's ratio within the range 0.25 to 0.30, quartz has a value of 0.08. Therefore, the vertical and lateral variations in the V_P/V_S crustal image (Fig. 3) can be associated with rock types. The high V_P/V_S values (1.9 to 2.0) correlate with the mafic and ultramafic rocks of the Kraka massif and the Magnitogorsk volcanic arc; low values (1.6 to 1.7) in the middle and lower crust beneath the East Uralian zone suggest rocks with felsic affinities. Polarization analysis of the shear-wave arrivals indicates localized anisotropy within the lower crust.

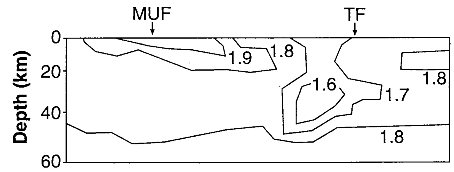

Fig. 3. The V_P/V_S ratio model for the southern Urals. The high values can be interpreted to represent mafic and ultramafic rocks, and the low values, rocks with felsic affinities. The high values at shallow depths coincide with the surface locations of the Kraka massif and the Magnitogorsk volcanic arc, and the low values coincide with the Chebik granitic massif. MUF and TF indicate the surface locations of the Main Uralian and Troisk faults.

The lateral continuity of the PcP phase reflected from the top of the lower crust is indicative of a well-defined horizon, suggesting a significant change in physical properties at this level. The PmP/PcP amplitude ratios suggest that localized lamination at the top of the lower crust can account for amplitude anomalies of the PcP arrival. Within the lower crust, a change is observed in the reflectivity pattern across the central zone of the profile. Shots 2 and 3 display long wave-train arrivals within the lower crust that in some cases interferes with and masks the Moho reflection (PmP). The fan profiles display a set of reflections above the crust-mantle transition zone favoring a possible lower crustal boudinage structure (*2*).

Although the Moho does not appear as a clear, sharp boundary within the crustal root zone in the normal-incidence seismic reflection data (5), the wide-angle seismic reflection and refraction data document a crustal root zone that is ~15 km thick beneath the southern Urals, consistent with previous interpretations [for example, (*2*)].

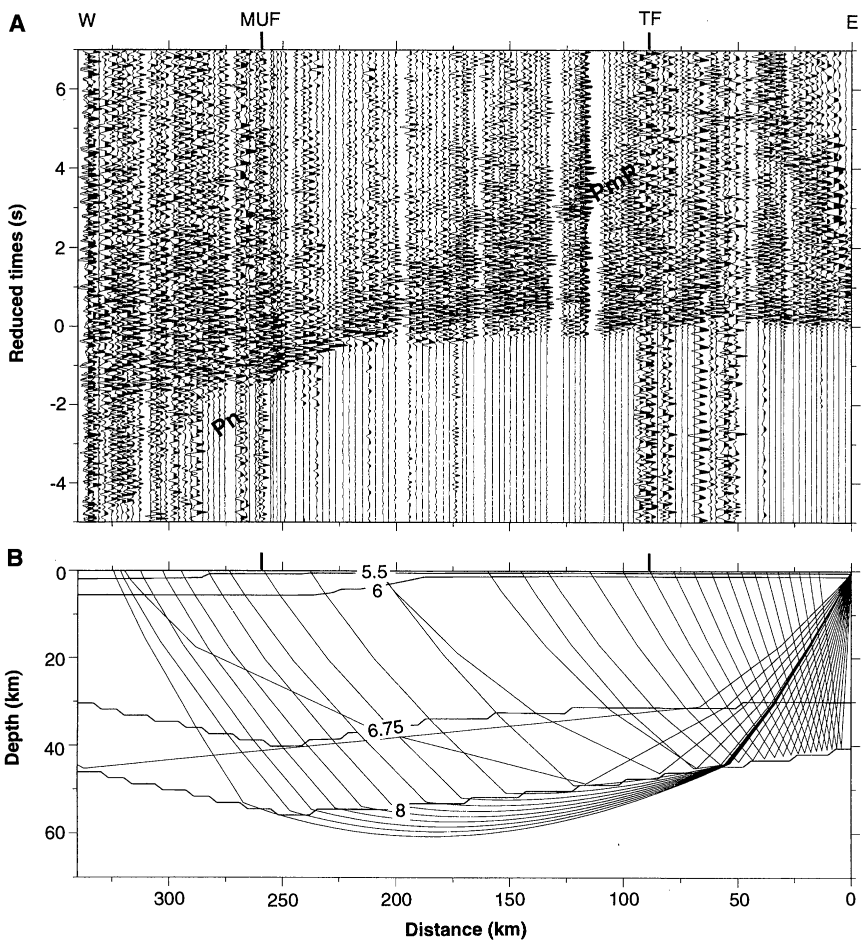

Fig. 2. (**A**) *P*-wave record section for shot 4. See Fig. 1 for interpreted arrivals. (**B**) Ray-tracing diagram, illustrating the sampling of the Moho discontinuity for this shot. (The labeling is the same as in Fig. 1.) Distance 0 marks the location of the shot [see S4 in figure 1 of (*4*)].

REFERENCES AND NOTES

1. V. S. Druzhinin *et al.*, in *Seismorazvedka pri Poiskakh Mestorozhdeniy Tsvetnykh Metallov na Urale* (Geologicheskiy Fond RSFSR, Moscow, 1981), pp. 103–119; V. S. Druzhinin *et al.*, *Opyt Glubinnykh Seismicheskikh na Urale* (NTO Gornoe, Sverdlovsk, Russia, 1982); A. V. Egorkin and A. V. Mikhaltsev, in *Superdeep Continental Drilling and Deep Geophysical Sounding*, K. Fuchs *et al.*, Eds. (Springer-Verlag, Heidelberg, Germany, 1990), pp. 111–119.
2. F. Thouvenot *et al.*, *Tectonophysics* **250**, 1 (1995).
3. A. V. Rybalka *et al.*, EUROPROBE Urals Project (European Science Foundation, Strasbourg, France, in press).
4. R. Berzin *et al.*, *Science* **274**, 220 (1996).

5. J. H. Knapp *et al.*, *ibid.*, p. 226; H. P. Echtler *et al.*, *ibid.*, p. 224.
6. N. I. Christensen and D. M. Fountain, *Geol. Soc. Am. Bull.* **86**, 227 (1975).
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Preserved Collisional Crustal Structure of the Southern Urals Revealed by Vibroseis Profiling

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The vibroseis reflection profiling component of the URSEIS '95 experiment provides a high-resolution crustal-scale image of the unextended southern Uralide orogen. A marked lateral and vertical variation of reflectivity throughout the entire crust differentiates the former margin of the East European craton to the west from accreted terranes to the east. Between these regions is a less reflective zone corresponding to the Magnitogorsk volcanic arc and the crustal root zone. Continuous reflections and reflective domains that correlate at the surface with major tectonic features define a bivergent orogen in which the Paleozoic collisional structure has been largely preserved.

The southern Uralide orogen developed from collisional accretion of volcanic arc and microcontinental fragments along the continental margin of the East European craton during the Late Paleozoic (*1*). The vibroseis common mid-point (CMP) reflection component of the URSEIS '95 experiment in the southern Urals (*2*) primarily addressed the crustal structure of the orogen, including the geometry and extent of terrane boundaries, major crustal shear zones, and the geometry and character of the Mohorovičić discontinuity (Moho) and crustal root. These data provide a high-resolution crustal-scale image of the unextended southern Urals (Fig. 1). Correlation of the seismic section with the surface geology (*3*) provides a control on the age of reflections and insight into the deep structure of the different tectonic units and terranes. The seismic image (*4*) of the stacked (Fig. 1B) and migrated (Fig. 1C) sections varies along the length of the profile, with highly reflective domains in the east and west and a diffusely reflective domain in the central region.

The upper crust of the Trans-Uralian zone (Fig. 1A) is dominated by discontinuous, east-dipping reflections and diffractions to a depth of ~20 km that migrate to small-scaled centers, giving rise to areas of high and low reflectivity. In contrast, the middle and lower crust is dominated by west-dipping (30° to 40°) reflections that can be traced for tens of kilometers, from supracrustal levels to a depth of ~40 km. These prominent west-dipping reflections project to the surface and correlate with shear zones within accreted Paleozoic island arcs and oceanic terranes (*5*), implying an east-vergent, thick-skinned thrust stack (Fig. 1A). The continuous west-dipping events merge downward, with a narrow subhorizontal zone that dips westward from 40 to 55 km depth. The base of this zone corresponds to a marked boundary between high crustal reflectivity and seismically transparent upper mantle and is interpreted to be the Moho. Interpretation of the geometric relation of the continuous Moho reflection with the overlying crustal reflections remains equivocal. Truncation of these accretionary structures by the Moho reflection would imply that the Moho is younger than the early orogenic (Devonian) crustal-scale imbrication of the Trans-Uralian terranes. Alternatively, soling of these crustal structures into the Moho could imply that they are coeval with the Moho and that crustal deformation was decoupled from the mantle lithosphere at the Moho boundary during the accretionary process. The deepening of the Moho toward the orogenic root may be evidence for a previously unrecognized Late Permian intracontinental shortening event.

Immediately east of the surface trace of the Troitsk fault (Fig. 1), a thick, west-dipping reflective package, here named the Kartaly reflection sequence (KRS), can be traced from about 10 to 50 km depth. The KRS, which defines the western limit of the eastern reflective domain, correlates at the surface with a shear zone that marks a terrane boundary between island arcs of the Trans-Uralian zone and microcontinental crust of the East Uralian zone (Fig. 1).

The central domain, located between the KRS and the Main Uralian fault (MUF), is characterized by a discontinuous reflective pattern. Exposed at the surface of the East Uralian zone (Fig. 1A) is the Early Permian Chebik granite (*6*), which forms part of the main axis of orogenic magmatism in the Urals and correlates with a shallow (5 to 8 km thick) nonreflective zone on the seismic section. Beneath this nonreflective zone, a 15-km-thick series of east-dipping mid-crustal reflections are imaged whose down-dip projections are truncated by the KRS. To the extent that dipping crustal-scale reflections would not be preserved during voluminous magmatism and heating of the crust, a post–Early Permian age is inferred for the KRS, which perhaps represents a reworked east-vergent suture related to late-orogenic intracontinental convergence.

To the west (160 to 260 km away), diffuse reflective energy is observed, with the strongest amplitudes occurring in the upper crust. At the surface, this portion of the central domain coincides with the Magnitogorsk zone (Fig. 1A) and is comprised of unmetamorphosed to low-grade metamorphic oceanic and volcanic arc rocks folded into a broad synform. The lack of clear reflectivity may be related to the presence of steeply dipping structures within the orogenic axis. The zone corresponding to the crustal root does not exhibit a reflective Moho or distinct vertical zonation in reflectivity.

The western domain, the area to the west of the MUF, is characterized by a highly reflective crust dominated by east-dipping structures within the imbricated former East European continental margin and overlying allochthons (*7*). A moderately reflective band dipping ~45° between 210 to 260 km along the transect can be traced to mid-crustal levels (20 to 25 km deep). This event appears to truncate shallow reflections to the east and west and correlates at the surface with the MUF, the inferred main suture zone of the orogen. West of the MUF, a set of highly

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