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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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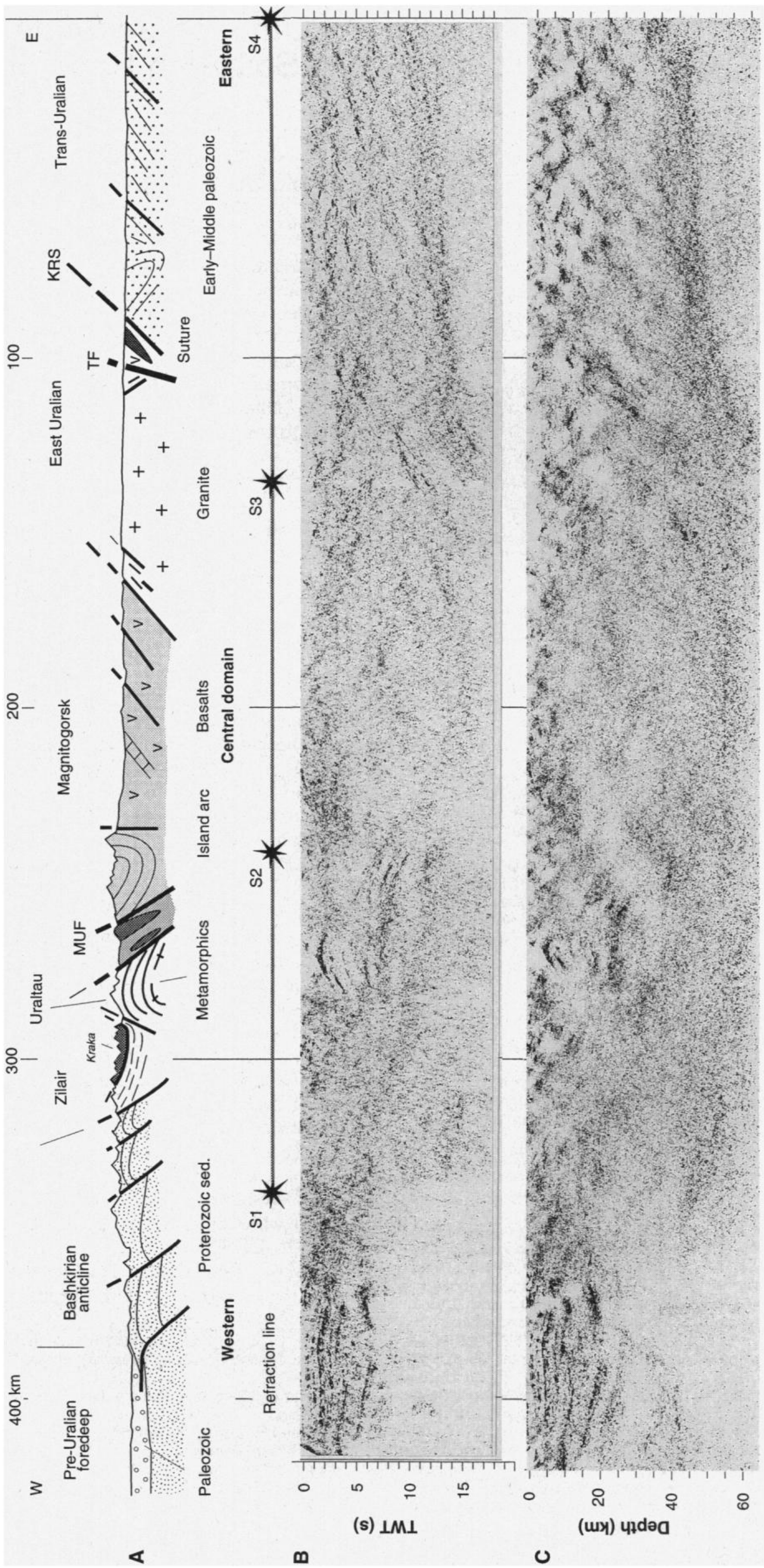

Fig. 1. (**A**) Simplified tectonic and geologic cross section of the southern Ural Mountains along the URSEIS '95 transect [see location in figure 1 of (*13*)]. The topographic profile is exaggerated 10:1. TF, Troitsk fault. (**B**) Unmigrated vibroseis section displayed down to 18-s TWT (eastern 420 of 465 km). (**C**) Migrated and depth-converted vibroseis section.

reflective, concave-downward reflections are interpreted as an antiformal structure of intensely deformed and metamorphosed rocks of the Central Uralian zone, which extend westward beneath the allochthonous Zilair nappe and the Kraka ophiolitic unit (8).

To the west of and below this concave reflection package, a set of continuous, gently east-dipping reflections extends to a depth of 30 km. Beneath the Bashkirian anticline of the Uralian foreland (Fig. 1), four steeply east-dipping reflection packages extend from near the surface down to ~30 km. These reflections truncate several subhorizontal to gently east-dipping bands of reflections and correspond to west-vergent thrusts that imbricate the Paleozoic platform sequence and underlying Proterozoic strata outcropping in the foreland.

The western end of the section traverses the undeformed East European cratonic crust, including a sequence of Proterozoic sediments up to 20 km thick, imaged as undisturbed reflections above a poorly reflective Archean crystalline crust. From 310 to 350 km along the transect, a boundary between high crustal reflectivity and transparent upper mantle marks the reflection Moho dipping eastward from 40 to 50 km in depth. The lack of reflectivity observed at the base of the crust beneath the western Bashkirian anticline as compared to the explosive seismics (9) may be related to energy loss within the highly reflective sedimentary section (*10*). At the westernmost end of the transect, the Moho boundary is well defined as a horizontal feature at a depth of about 43 km.

The crustal structure of the southern Urals, as imaged by the vibroseis experiment, is that of a preserved bivergent collisional orogen. A marked lateral variation in reflection character and geometry across the orogen provides the basis for division of the image into three reflective domains separated by the MUF and KRS (Fig. 1, A and B). Reflective elements and domains that correlate at the surface with major tectonic structures suggest that the southern Uralide orogen has been preserved. These features indicate the presence of an unextended collision zone and the absence of large-scale re-equilibration processes such as those apparent in other Paleozoic orogens (such as Variscides and Caledonides) (*11*).

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Lithosphere-Scale Seismic Image of the Southern Urals from Explosion-Source Reflection Profiling

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Explosive-source deep seismic reflection data from the southern Ural Mountains of central Russia provided a lithosphere-scale image of the central Eurasian plate that reveals deep reflections (35 to 45 seconds in travel time; ~130 to 170 kilometers deep) from the mantle. The data display laterally variable reflectivity at the base of the crust that deepens beneath the central part of the profile, documenting a crustal thickness of ~55 to 60 kilometers beneath the axis of the orogen. These data provide an image of the structure of the crust and underlying mantle lithosphere in a preserved collisional orogen, perhaps to the base of the lithosphere.

Explosive-source deep seismic reflection profiling was conducted to (i) provide a high-resolution reflection image of the Mohorovičić discontinuity (the base of the crust, known as the Moho) across the entire orogen, (ii) document the lower crustal signature of the presumably unextended Uralian crust, and (iii) search for mantle structures (such as remnants of Paleozoic subduction) beneath the orogen. Experimental design was integrated with a coincident vibroseis survey (*1*).

The 465-km profile displays a reflective crust with a laterally variable reflection signature from the Moho (Fig. 1). On the western and eastern portions of the profile, the Moho is imaged at ~13 s (*2*), deepening toward the orogenic axis, where it is interpreted at the base of a general downward decrease in reflectivity at ~18 to 20 s (Fig. 1). Corresponding crustal thicknesses range from ~42 km beneath the East European platform and the western edge of the West Siberian basin to a projected maximum of 60 km in the central part of the profile. These data provide a near-vertical reflection image of a thickened Uralian crust, confirming earlier observations based on Russian deep seismic sounding data (*3*) and consistent with coincident wide-angle data collected by URSEIS '95 (*4*).

The Moho beneath the Trans-Uralian zone on the eastern end of the profile is imaged as a set of subhorizontal reflections beneath a region of west-dipping reflections and above a much less reflective upper mantle. Beginning at the position of the Troitsk fault, the Moho deepens abruptly into the central part of the profile, where the reflection Moho does not appear as a distinctive feature (Fig. 1). Amplitude decay analysis suggests that this change in Moho character is not an artifact of poor energy penetration; the seismic signal remains above ambient noise down to 25 to 30 s. Projection of the Moho beneath the diffuse lower crustal reflectivity is consistent with refraction results (*4*) and yields a maximum crustal thickness of 60 km. In the west, beneath the East European platform, the Moho is defined by a sharp, subhorizontal, continuous reflection at the base of a reflective lower crust. Further east, at the transition from the Pre-Uralian foredeep to the West Uralian zone, the Moho is offset downward by about 4 km and continues as a broadly arched, concave-downward, 1- to 3-s-thick band of reflections. This arched Moho forms the western flank of the Uralian crustal root and disappears into the diffusely reflective orogenic axis beneath the Central Uralian zone.

Mantle reflection fabrics, imaged primarily beneath the Uralian hinterland, can be categorized into three principal features: (i) gently west-dipping reflections at 35 to 45 s (a depth of ~130 to 170 km) [the Nikolaevka reflection sequence (NRS)], (ii) a subhorizontal band of reflections from 22 to 24 s (~85 km deep) [the Alexandrovka reflection sequence (ARS)], and (iii) a diffuse, east-dipping fabric that characterizes much of the upper mantle in the east (Fig. 2). The ARS consists of a thin (<0.25 s), complex band of subhorizontal reflections at ~24 s, continuous for at least 50 km across strike (Fig. 2). Although the

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