Precambrian Moho offset and tectonic stability of the East European platform from the URSEIS deep seismic profile

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ABSTRACT

Deep seismic reflection data from the 1995 Urals Seismic Experiment and Integrated Studies (URSEIS) transect of the Southern Urals document a distinct ~5 km vertical offset of the Moho beneath the Uralian foreland, here named the Makarovo fault zone. This offset does not disrupt the overlying Riphean sedimentary section, nor does it correlate with any major surface lineaments or known Phanerozoic subduction features. It is thus interpreted to be an Archean or Early Proterozoic fault zone (possibly a terrane boundary) that disrupts an even older Moho. Most important is the implication that this structure and the Moho it offsets were not significantly modified by two subsequent cycles of continental collision that affected this region, the Baikalian (700–570 Ma) and the late Paleozoic Uralian (350–230 Ma) orogenic phases. Similarly, the pronounced reflectivity of the Moho beneath the Uralian foreland must also be a Precambrian signature, not a young feature, as would be implied by certain recent thermo-rheological and reflectivity models that associate a reflective lower crust and Moho with areas that underwent pronounced synorogenic or postorogenic collapse. The Makarovo fault zone provides yet another demonstration that relicts of ancient tectonic processes can survive for long periods of time in the lower crust, and that the Moho can be a key marker horizon in delineating the tectonic evolution of the lithosphere.

INTRODUCTION

Since the identification of the Moho as a prominent seismic velocity boundary (Mohorovicic, 1910), seismologic and petrologic studies have associated the Moho with the fundamental tectonic boundary between crust and upper mantle, corresponding to major contrasts in petrology, seismic wave velocity, density, and rheology (e.g., Jarchow and Thompson, 1989). Seismic reflection studies over the past 20 years have been used to argue that the position and reflective character of the Moho correlate with tectonic environment (Allmendinger et al., 1987; Cook, 1995; Steer; 1996), and in that respect the Moho is an important indicator of tectonic history (Allmendinger et al., 1987; Nelson, 1991).

Of particular interest is short-wavelength Moho topography, including apparent fault offsets, which have now been observed in several areas of the world from both seismic reflection and refraction surveys. These Moho offsets have been attributed to Phanerozoic features: vertical penetration of strike-slip faults down to the upper mantle (Faber and Bamford, 1981; McBride and Brown, 1986; Lemiszki and Brown, 1988; McBride, 1995; Doll et al., 1997); brittle, late-tectonic crustal extension (Hauser et al., 1987); interwedging of lower crust during collision (Frei et al., 1989); or small scale faulting or intrusions at the Moho (Cook, 1995). There is also evidence for preservation of Precambrian Moho topography beneath the Baltic shield (1.89–1.86 Ga; BABEL Working Group, 1990), the Superior Province of Canada (2.69 Ga; Calvert et al., 1995), central Australia (ca. 1.1–1.45 Ga; Goleby et al., 1990), and possibly the British Caledonides (Warner et al., 1996).

This paper presents results from the URSEIS (Urals Seismic Experiment and Integrated Studies) profile (Carbonell et al., 1996; Echtler et al., 1996; Knapp et al., 1996) that was carried out in the Southern Urals in 1995. These data document a new Moho fault zone with an ~5 km offset beneath the Uralian foreland of the East European platform. This step in the Moho is not only at least 1.6 Ga, but also has been preserved through two major subsequent orogenies.

GEOLOGIC SETTING

The Uralian orogen of central Russia (Fig. 1) forms the modern geographic boundary between Europe and Asia, and constitutes one of the major orogenic belts of Paleozoic age involved in the assembly of the Pangean supercontinent. The foreland fold and thrust belt of the Southern Urals forms a west-vergent thrust system involving both Paleozoic and Precambrian strata (Fig. 1; Zonenshain et al., 1990; Brown et al., 1996). Riphean units, deposited in a series of graben (e.g., Kaltasy graben) that mark the Late Proterozoic breakup of the East European continental crust, reach thicknesses in excess of 15–18 km (Zonenshain et al., 1990). Overlying Vendian strata consisting of conglomerates and turbidites are considered to represent foreland basin deposits of the Baikalian orogeny, a wide-spread Late Proterozoic compressional event. The transition between the foreland basin and the foreland fold and thrust belt is a wide zone of deformation in which the Permian rocks have been folded into ramp anticlines cored by blind thrusts (Fig. 1; Skripiy and Yunusov, 1989; Brown et al., 1996).

MAKAROVO FAULT ZONE

Within the East European platform, the URSEIS Vibroseis profile (Echtler et al., 1996) provides a high-resolution image of the upper 7.0 s (~20 km) of the crust, representing the Paleozoic and Riphean sediments of the Kaltasy basin. The dynamite section (Knapp et al., 1996; Steer, 1996) provides a clear image of the lower crust and upper mantle (Fig. 2A), including a Moho that appears as a sharp, continuous, subhorizontal reflection at 13.0 s (40–42 km) beneath the western end of the profile (Knapp et al., 1996). These reflections appear to cease beneath the center of the Kaltasy basin, then reappear to the east about 1.5 s deeper (43–45 km) as an arched band of prominent reflections. We named this ~5 km step in the Moho (assuming an interval

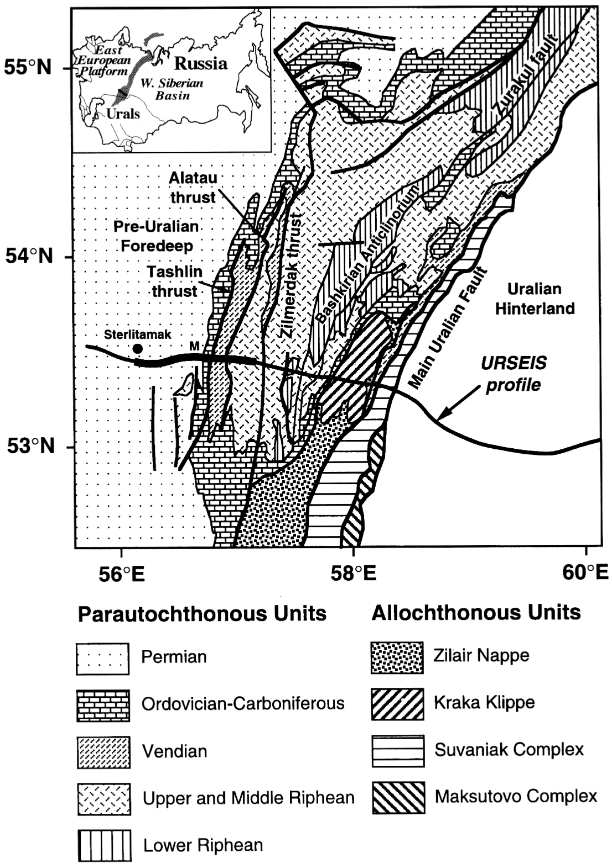


Figure 1. Location map of URSEIS deep seismic profile showing distribution of geologic units in foreland of Southern Urals. Inset shows location of Ural Mountain. Bold black line shows portion of profile discussed in text and presented in Figures 2A and 3. M indicates approximate surface position above Makarovo fault zone.

velocity of 7.1 km/s; Carbonell et al., 1996) the Makarovo fault zone, after the small town directly above it (Fig. 2A). The presence of a near-vertical, nonreflective zone (5–10 km in width) in the lower crust above the offset (Fig. 2A) could be interpreted as structural disruption associated with the Makarovo fault zone. Thus, our preferred interpretation is that the Makarovo fault zone is a subvertical shear zone that penetrates from the lower crust into the mantle. This geometry suggests a strike-slip origin similar to other crustal-penetrating strike-slip faults recognized worldwide (e.g., McBride and Brown, 1986).

Key to interpretation of the age of the Makarovo fault zone are the prominent, continuous reflections that represent the overlying Riphean and Vendian strata in the upper seismic section down to 15–18 km depth (6.5 to 7.0 s in Fig. 2, A and B). A minimum Riphean age for most of this reflection sequence is provided both by outcrop and deep boreholes that were drilled on the western flanks of the Uralian foredeep and Bashkirian anticlinorium (Shikhan—3972 m; Kulgunino—4683 m; Skripiy and Yunusov, 1989). Although clearly disrupted by east-dipping thrust faulting associated with Uralian compression (Tashlin thrust; Fig. 2B), these strata show no obvious disruption anywhere within the Riphean section that can be simply related to the underlying Moho offset. Thus, these flat-lying, relatively undeformed, sedimentary layers limit the age of the Makarovo fault zone to be Precambrian, i.e., at least 1.6 Ga.

Because an apparent change in traveltime could be due to a lateral variation in seismic velocity instead of reflector depth, consideration must be given to the possibility that the Makarovo "offset" is simply an artifact of "velocity pull-down." However, because there is little indication of a lateral velocity change within the well-defined Riphean-Vendian sequence, any such change must be restricted to the underlying basement. In that case, the 1.5 s offset would imply a 25% decrease in lower crustal velocity from west to east (e.g., 6.0 to 4.75 km/s). Although wide-angle velocity estimates (Carbonell et al., 1996) do not extend this far west, such a change is clearly unrealistic. Therefore we interpret a real change in depth to the crust-mantle boundary across this zone.

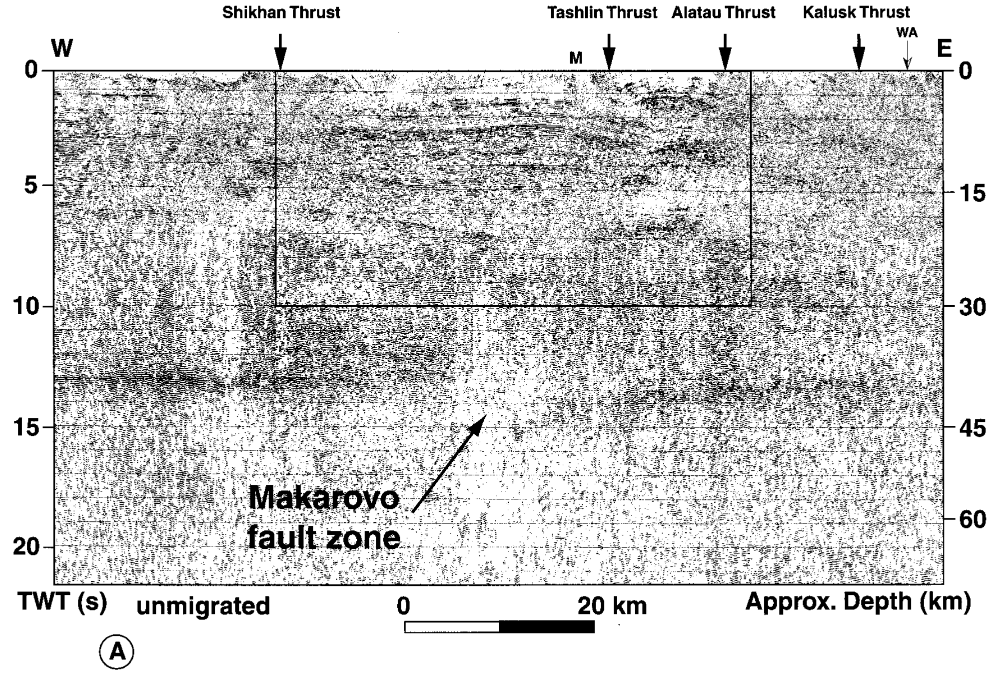
The Makarovo fault zone may in fact juxtapose two different crustal domains; the Moho to the west is a sharp and flat horizon, whereas the Moho to the east shows an arcuate geometry of weaker reflections. There is no obvious variation in signal penetration or change in spread geometry spatially correlated with the Makarovo fault zone (Steer, 1996). Thus we interpret the difference in the Moho reflectivity on either side of the offset as representing a significant geologic contrast, perhaps marking the join between two of the many continental fragments that Zonenshain et al. (1990) argued to have accreted to form the basement of the East European platform more than 1.6 b.y. ago. We speculate that it served as a terrane boundary (possibly strike slip) in Archean or Early Proterozoic time that was subsequently buried.

DISCUSSION

From the above discussion, the Makarovo fault zone represents a relict (at least 1.6 Ga) structure preserved in the lower crust and uppermost mantle. Kusznir and Matthews (1988) suggested that mountain topography should decay through a combination of isostatically coupled surface erosion and lower crust-upper mantle ductile flow. These same authors argued that the short and long wavelength components of a Moho step could persist for long geologic times, especially in the case of strike-slip faults as is interpreted for the Makarovo fault zone.

However, the geologic history of this area is more complex than that represented by simple thermo-mechanical relaxation of a single orogenic event. Since formation of the Makarovo fault zone, the East European platform has undergone several episodes of rifting and compression, the biggest events being the Baikalian (700–570 Ma) and the Uralian (350–230 Ma) orogenic phases. The effects of the Baikalian orogeny can be seen from the Northern Urals (Timan-Pechora area) to the Southern Urals, where the Baikalian fold and thrust front coincides with the axis of the Bashkirian anticline (Gee et al., 1996). Evidence for Baikalian deformation within the Kaltasy basin can be observed in the Riphean and Vendian rocks that locally exhibit middle amphibolite facies metamorphism, as well as the widespread development of foliation and retrogression of granulitic Archean rocks and greenschist facies mylonite zones. Subsequently these rocks were again metamorphosed at low greenschist (locally amphibolite) facies during the Uralian event in Late Carboniferous–Early Permian time (Skripiy and Yunusov, 1989; Zonenshain et al., 1990; Brown et al., 1996).

How the Makarovo fault zone survived these events remains unclear. For example, consider



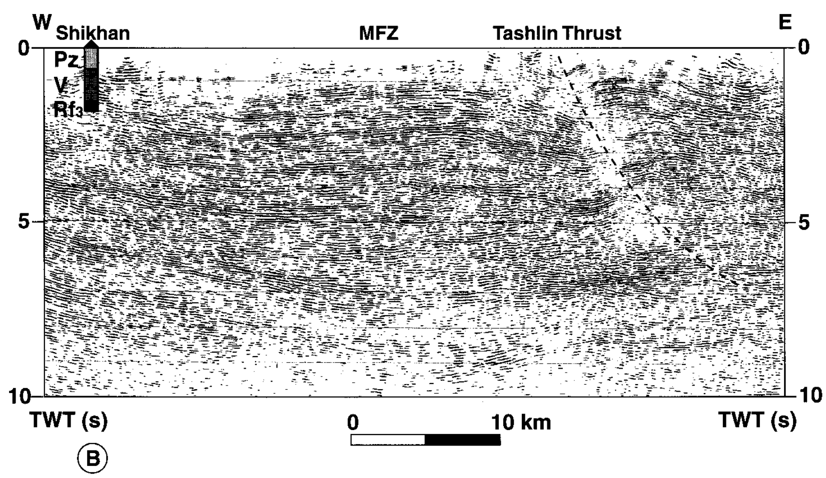


Figure 2. A: Composite unmigrated seismic section displaying position of Makarovo fault zone beneath Kaltasy basin. First ~7.0 s are Vibroseis data; remainder are dynamite seismic data. Box shows portion of seismic line enlarged in B. M indicates location of town of Makarovo; WA refers to western termination of URSEIS wide-angle survey. Time-to-depth conversion was performed by extrapolating URSEIS wide-angle velocities further west. B: Migrated version of seismic section within box in A. Gently deformed Riphean strata are continuous across underlying Makarovo fault zone. TWT is two-way traveltime.

the ~15–18 km of Late Proterozoic sediments that were deposited on the pre-Riphean continental crust within the Kaltasy basin. Substantial crustal thinning must have occurred to make room for this load, yet in a manner that failed to "heal" the Makarovo offset. As for Uralian compression, the geometry of the Tashlin thrust (Figs. 2A and B) suggests that upper crustal convergence was accommodated above a regional decollement so that such shortening may have bypassed the Makarovo fault zone.

Other Moho offsets interpreted as Precambrian in age have been attributed to Early Proterozoic (1.89–1.86 Ga) subduction in the Baltic shield (BABEL Working Group, 1990), or Archean (~2.69 Ga) subduction in the Superior Province of Canada (Calvert et al., 1995). However, the timing of these offsets is based on indirect and highly interpretative association with surface features mapped in the vicinity. The geometrical link is more direct in the case of the Arunta block of central Australia, where a major reverse offset in the Moho projects upward along dipping reflections to tie with an outcropping Paleozoic fault that is believed to have reactivated a Middle Proterozoic terrane boundary (Goleby et al., 1990). A Precambrian origin has been also suggested for the Flannan reflector of northern Scotland (Warner et al., 1996), a prominent mantle reflector that disrupts or offsets the Moho. However, this age is based on largely indirect arguments, such as no evident correlation of this reflector to Phanerozoic deformation patterns. Among these examples, the Makarovo fault zone is unique in two respects: (1) its Precambrian age is much better constrained by virtue of the undeformed Riphean-Vendian sedimentary strata deposited within the overlying Kaltasy basin; (2) it appears not to have been reactivated (in terms of major vertical offset) in spite of being located in an area that subsequently underwent two major orogenic events (e.g., Baikalian and Uralian).

As a corollary to the age arguments presented here, the URSEIS seismic data constitute a new demonstration that Precambrian lower crust can be highly reflective, and that the corresponding Moho can be seismically sharp. Any deformation or magmatism (shearing, underplating) strong enough to generate reflectivity throughout the lower crust and/or modify the reflective nature of the Moho would presumably have "erased" Moho offsets of the scale of the Makarovo fault zone. Thus, in contrast to previous suggestions (Klemperer et al., 1986; Allmendinger et al., 1987; Nelson, 1991; Wernicke, 1990), Moho topography is not required to be a transient feature that always reequilibrates or adjusts itself in response to crustal thickening or thinning events.

CONCLUSIONS

Seismic reflection data through the Uralian foreland image the Makarovo fault zone as a preserved, ~5 km vertical offset on the Moho within the East European cratonal margin (Fig. 3). The change in morphology and reflective pattern of the Moho across the Makarovo fault zone, associated with lack of reflectivity vertically above it,

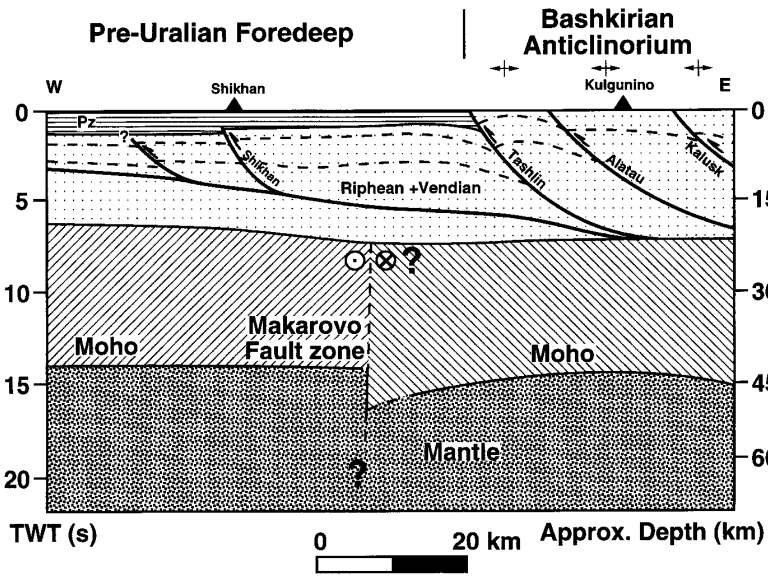


Figure 3. Simplified geologic model of Southern Uralian foreland, showing Makarovo fault zone as possible relict strike-slip terrane boundary predating deposition of overlying Riphean strata. Area covered is same as in Figure 2A. TWT is two-way traveltime. Major named thrust faults are labeled.

suggests that it may have been a strike-slip terrane boundary during the Archean or Early Proterozoic time.

Stratigraphic continuity within the Riphean-Vendian strata deposited within the Kaltasy basin suggests that the Makarovo fault zone is a relict structure, older than 1.6 Ga. Apparently, the Makarovo fault zone, and implicitly the Moho it offsets, have not been significantly modified since Precambrian time, in spite of two major subsequent orogenies (Baikalian and Uralian). Thus, the Moho is not required to fully remobilize in response to collision and extension events.

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