Orogenic Evolution of the Ural Mountains: Results from an Integrated Seismic Experiment

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Results of the URSEIS '95 integrated seismic experiment document the lithospheric structure of an intact Paleozoic collisional orogen in the Ural Mountains. Hybrid-source seismic reflection and refraction data provide images of a crustal-scale collisional fabric and a pronounced crustal root preserved since Paleozoic time. Mantle reflections are observed at depths of more than 150 kilometers, possibly representing the base of the lithosphere. The Urals do not conform to existing models of postorogenic evolution involving large-scale extension, which may be a consequence of an incomplete or arrested collisional process that has led to the preservation of the largest continental landmass.

Current models for orogenic evolution of the continental crust typically invoke syn-orogenic or postorogenic extensional collapse (*1*) driven perhaps by gravitational instability of the crustal column (*2*) or delamination of the lower lithosphere (*3*), or both. There are many examples of compressional belts (Himalayas, Alps, Cordillera, Variscides, Caledonides, and Appalachians) in which large-scale extension has played a significant role in the later stages of orogenic development (*4*). Orogenic belts that formed through closure of an ocean basin and subsequent continental collision may later serve as the focus for continental rifting and formation of a new ocean basin, a process codified as the Wilson cycle of plate tectonics (*5*). An expected consequence of such wholesale re-equilibration of the lithosphere is a return to preorogenic (40 km) or even thinned (30 km) continental crust. Such normal or reduced crustal thicknesses now characterize many older orogens, including the Paleozoic suite of the Variscides, Caledonides, and Appalachians (*6*).

The Uralide orogen of central Russia, the geographic and geologic divide between Europe and Asia, marks the Paleozoic collision zone of the East European craton with the Asian collage of terranes. Together with the Appalachian, Caledonian, and Variscan orogens, the Urals were one of the major zones of continental convergence that contributed to the assembly of the late Paleozoic Pangea supercontinent (*7*, *8*). Tectonic evolution of the Urals (*9*) began with rifting and the development of a passive continental margin on the East European platform in latest Cambrian to early Ordovician time, followed by Middle Paleozoic rifting of microcontinental fragments, the formation of island arcs and back-arc basins, and assembly of these terranes within the Uralian paleo-ocean. The final collision of Eastern Europe with this complex collage and the Siberian craton took place in Late Carboniferous and Permian time. In contrast to the classic Alpine or Himalayan style of orogeny, involving collision between large continental masses, the Altaids developed through the assembly of a collage of island-arc and microcontinental fragments that subsequently impacted the East European margin in the Late Paleozoic (*8*).

The southern Urals have been divided into six longitudinal tectonic zones (*10*), including from west to east the Pre-Uralian foredeep (foreland basin), West Uralian zone (foreland fold and thrust belt), Central Uralian zone, Magnitogorsk zone (island arc complex), East Uralian zone (microcontinental terranes and the principal magmatic axis), and Trans-Uralian zone (accreted island arc terranes). The first three zones, comprised of autochthonous and para-autochthonous units of the East European platform, are separated from the latter three zones of accreted allochthonous terranes by the Main Uralian fault, the inferred principal suture zone of the orogen.

The Uralide orogen is distinct from other Paleozoic orogens because it has (i) a pronounced crustal root (*11*), (ii) relatively minor syn- or postcollisional extension, (iii) low terrestrial heat flow along the Magnitogorsk zone (20 to 30 mW/m^2), (iv) well-preserved ophiolite and volcanic-arc assemblages, and (v) extensive outcrops of high-pressure, low-temperature metamorphic rocks (blueschist and eclogite facies) in the footwall of the main suture zone.

The URSEIS '95 project is an integrated seismic experiment designed by scientists from Russia, Germany, the United States, and Spain to provide understanding of (i) the crustal-scale structure of the Urals, (ii) the geometry, velocity structure, and reflective character of the crustal root and Moho boundary (the Mohorovičić discontinuity), and (iii) upper mantle structure. The seismic survey consists of three main components: (i) a 465-km, near-vertical-incidence, vibroseis-source reflection survey (*12*), (ii) a coincident near-vertical-incidence, explosive-source

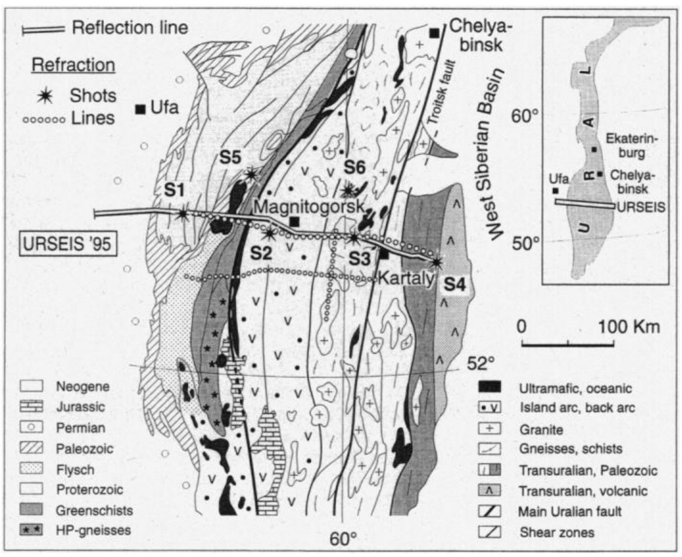

Fig. 1. Generalized tectonic map of the southern Urals, showing the location of the seismic reflection line (coincident vibroseis and dynamite profiles) and station locations and shot points (wide-angle reflection and refraction survey).

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survey (*13*), and (iii) a 340-km, explosive-source, wide-angle reflection and refraction survey, including a cross line and two off-line fan-recording shots (*14*) (Fig. 1). The transect extends from the East European platform in the Uralian foreland to the West Siberian basin, crossing the Bashkirian foreland fold and thrust belt, the Kraka ophiolite, the Main Uralian fault (suture zone), a collage of oceanic and microcontinental terranes in the hinterland, and the main axis of orogenic magmatism. The data were acquired from June to November 1995. Each of these experimental elements was designed for definition of specific aspects of the Uralian lithosphere (vibroseis for crustal resolution, explosive source for mantle lithosphere, wide angle for velocity structure and Moho), and the resulting data sets were processed accordingly. As a result, the resolution and appearance of the processed data vary.

Here we summarize the lithospheric model (Fig. 2) for the Urals, which integrates data from all of these experiments. The collisional fabric is preserved as seismic reflectors that distinguish different tectonic elements of the orogen. The bivergent collisional geometry, illustrated by west-vergent crustal-scale nappes in the west and east-vergent crustal-scale shear zones in the east, is separated by a central zone comprising the Magnitogorsk and East Uralian zones (Fig. 2). The Main Uralian fault is only weakly reflective down to the middle crust, unlike the Kartaly shear zone, which may represent a more fundamental suture in the orogen.

Moho reflectivity varies in strength and character along the transect, being clearly defined at the base of the strongly reflective crust in the foreland and hinterland. The position of the Moho, interpreted to be the base of prominent crustal reflectivity, implies that the crust is ~40 to 42 km thick in the East European platform and the western edge of the West Siberian basin, deepening to a minimum of 55 km before disappearing into a diffuse zone of reflectivity beneath the orogenic axis. Refraction results show a crustal thickness within this root of 55 to 58 km, consistent with a downward decrease in reflectivity on the vertical-incidence reflection data (*14*). Numerous mantle reflectors and fabrics are observed, providing an image of the lithospheric mantle, including reflectors with two-way travel times from 35 to 45 s. The position of this feature corresponds with inferred depths for the lithosphere-asthenosphere boundary.

To a first order, a substantial crustal root would appear to be at odds with available gravity data for the Urals, which show a relatively subdued Bouguer minimum (~ -40 mgal, or -4×10^{-4} m/s^2) over the axis of the orogen. Kruse and McNutt (*15*), however, argued from a flexural modeling approach that a dense crustal or mantle lithosphere load is in part responsible for the crustal root in the Urals. Maximum elevations in the southern Urals are ~1600 m, and most topographic relief occurs in the foreland fold and thrust belt of the Bashkirian anticline. The offset of this topographic axis from the main crustal root suggests that the present topography is unrelated to crustal thickness and represents remnant relief from Paleozoic deformation.

The lack of surface geologic features associated with postorogenic extension and the preservation of the orogenic structural fabric and crustal root suggest that the Urals did not experience significant postorogenic collapse. This history may imply that the Urals evolved near isostasy and never existed as a gravitationally unstable belt of high topography as is found in most modern continental collisions. Such a condition could have been controlled by the abundance of mafic rock at the surface and in the root incorporated in the collision, as well as by an incomplete, or "arrested" collisional process.

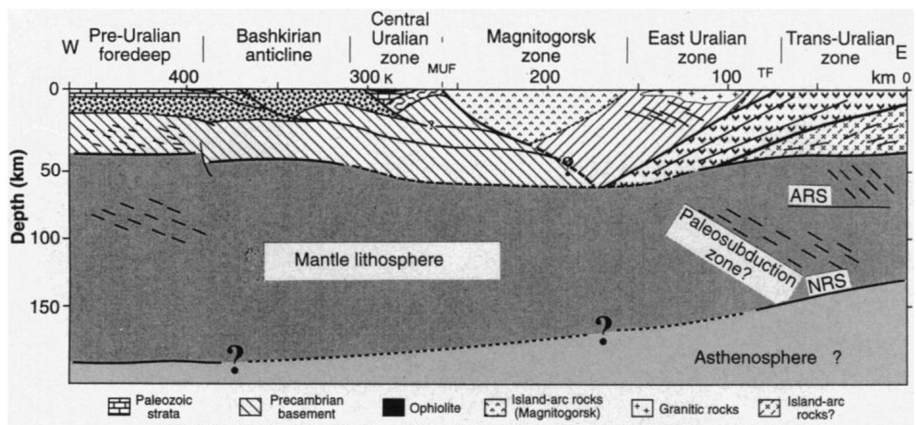

Fig. 2. Lithospheric model of the southern Urals based on the integrated results of the URSEIS '95 experiment emphasizing the bivergent nature and presence of the crustal root beneath the Urals. The Nikolaevka reflection sequence (NRS) and Alexandrovka reflection sequence (ARS) are mantle reflectors, and short dashes represent diffuse mantle reflectivity identified by the explosive-source survey. Solid line weights represent reflection strength and tectonic significance (Main Uralian fault) of features; dashed contacts show interpolated boundaries. K, Kraka; MUF, Main Uralian fault; and TF, Toistsk fault.

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