TECTONICS, VOL. 25, TC1002, doi:10.1029/2005TC001834, 2006

Structural architecture of the southern and middle Urals foreland from reflection seismic profiles

D. Brown,[1] C. Juhlin,[2] A. Tryggvason,[2] M. Friberg,[3] A. Rybalka,[4] V. Puchkov,[5]
and G. Petrov[6]

Received 14 April 2005; revised 14 September 2005; accepted 29 September 2005; published 17 January 2006.

[1] The Urals Seismic Experiment and Integrated Studies (URSEIS), Mikhailovsky, and Europrobe's Seismic Reflection Profiling in the Urals (ESRU) reflection seismic profiles provide constraints for the construction of balanced and restored geological cross sections across the southern and middle Urals foreland. The profiles image the transition from the undeformed foreland basin to the frontal structure of the foreland thrust and fold belt, the location of the basal detachment, and the location of the ramp down into the middle or lower crust. In the URSEIS and ESRU profiles, the transition into the undeformed foreland basin is imaged as an emergent west-vergent thrust that deforms a westward thickening package of reflections related to synorogenic sediments, whereas in the Mikhailovsky profile, it is a buried system of imbricate thrusts. In all three data sets, the western flank of the foreland thrust and fold belt is imaged in the seismic data as an imbricate thrust system developed above a basal detachment located in either the upper part of the Neoproterozoic basement sediments or the lower part of the Paleozoic continental margin sediments. Truncation of reflections related to the undeformed sediments in the footwall to the imbricate thrust system mark the location of the ramp down of the basal detachment into the middle or lower crust beneath the basement-cored anticlines along the eastern flank of the thrust belt. The URSEIS and ESRU profiles image the basement-cored anticlines as predominantly east dipping reflections that extend into the middle and lower crust. Rocks in these anticlines record at least one phase of pre-Uralide deformation and, at least in part, the reflectivity is due to this deformation event. Balanced and restored cross sections constructed along the three profiles indicate that the minimum shortening is about 20–25 km. **Citation:** Brown, D., C. Juhlin, A. Tryggvason, M. Friberg, A. Rybalka, V. Puchkov, and G. Petrov (2006), Structural architecture of the southern and middle Urals foreland from reflection seismic profiles, *Tectonics*, *25*, TC1002, doi:10.1029/2005TC001834.

1. Introduction

[2] The Uralides (Figure 1) is a collisional orogenic belt that developed by subduction-accretion processes and final continent-continent collision during the Middle to Late Paleozoic [*Hamilton*, 1970; *Zonenshain et al.*, 1984, 1990]. In recent years, the acquisition and integration of new geophysical and surface structural geology data have helped to define the crustal architecture of the Uralides, which in turn has provided significant data for use in the interpretation of the tectonic evolution of the orogen. To date, however, these integrated studies have focused largely on the crustal-scale structure of the orogen and on the architecture of the arc-continent collision zone [e.g., *Juhlin et al.*, 1998; *Friberg et al.*, 2002; *Tryggvason et al.*, 2001; *Brown et al.*, 1998, 2002; *Steer et al.*, 1998; *Alvarez-Marron*, 2002], with less emphasis on the structure of the foreland thrust and fold belt. In this paper, we investigate the structural architecture, timing of development, and the amount of shortening of the western Uralide foreland thrust and fold belt along three reflection seismic transects (Figure 1). Reflection seismic data (the Urals Seismic Experiment and Integrated Studies (URSEIS), Mikhailovsky, and Europrobe's Seismic Reflection Profiling in the Urals (ESRU) profiles) form the main data set, together with surface geology from our own mapping and published 1:200,000-scale geological maps (Geology of the USSR: 1:200,000 Urals Map Series). Two of the reflection seismic profiles, Mikhailovsky (MIK in Figure 1) and a westward extension of ESRU are new, having been recently acquired in the middle Urals [*Kashubin et al.*, 2005]. In the southern Urals, balanced and restored cross sections have been previously constructed across the foreland thrust and fold belt [*Brown et al.*, 1997; *Perez-Estaun et al.*, 1997]. In this paper, the URSEIS data are fully integrated with surface structural geology data.

2. Geological Framework

[3] The collisional tectonic evolution of the western Uralides began in the Middle Devonian when the continen-

---

[1] Instituto de Ciencias de la Tierra "Jaume Almera," Consejo Superior de Investigaciones Científicas, Barcelona, Spain.
[2] Department of Earth Sciences, Uppsala University, Uppsala, Sweden.
[3] Committee for Infrastructure/General Director's Office, Swedish Research Council, Stockholm, Sweden.
[4] Bazhenov Geophysical Expedition, Urals Geological Survey Expedition, Scheelite, Russia.
[5] Ufimian Geoscience Centre, Russian Academy of Scienes, Ufa, Russia.
[6] Urals Geological Survey Expedition, Ekaterinburg, Russia.

0278-7407/06/2005TC001834

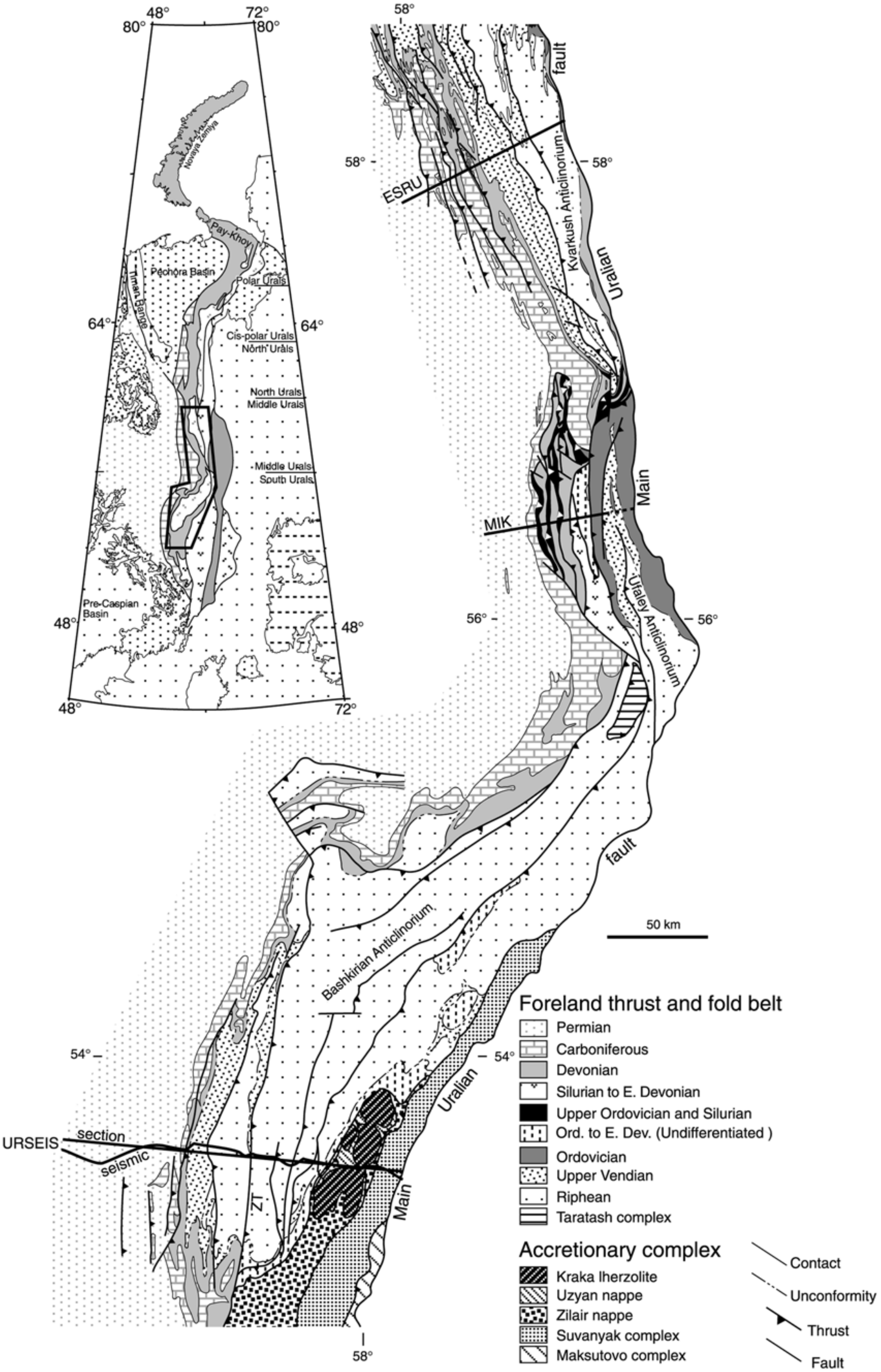
48°
72°
80°
80°
Novaya Zemlya
Pay-Khoy
Pechora Basin
Timan Range
Polar Urals
64°
64°
Cis-polar Urals
North Urals
North Urals
Middle Urals
Middle Urals
South Urals
Pre-Caspian Basin
48°
48°
48°
72°
58°
58°
58°
fault
ESRU
Kvarkush Anticlinorium
Uralian
Main
MIK
Ufaley Anticlinorium
56°
56°
fault
50 km
Bashkirian Anticlinorium
54°
54°
Uralian
URSEIS
section
seismic
ZT
Main
58°
Foreland thrust and fold belt
Permian
Carboniferous
Devonian
Silurian to E. Devonian
Upper Ordovician and Silurian
Ord. to E. Dev. (Undifferentiated)
Ordovician
Upper Vendian
Riphean
Taratash complex
Accretionary complex
Kraka lherzolite
Uzyan nappe
Zilair nappe
Suvanyak complex
Maksutovo complex
Contact
Unconformity
Thrust
Fault

Figure 1

tal margin of Baltica was subducted eastward (present coordinates) beneath the Magnitogorsk and Tagil volcanic arcs and, at least in the southern Urals, an accretionary complex developed on the subducting continental margin [*Puchkov*, 1997; *Brown et al.*, 1998; *Brown and Spadea*, 1999]. This accretionary complex, which includes high-pressure rocks and ophiolite fragments, formed a subaerial mountain range that by the Late Devonian supplied sediments to a foreland basin along its western flank and to a suture basin that developed on the colliding Magnitogorsk arc [*Willner et al.*, 2002; *Gorozhanina and Puchkov*, 2001]. The timing and processes involved during the collision of the Tagil arc in the middle Urals is less well constrained, although it is generally thought to have occurred in the Early Carboniferous and perhaps to have resulted in the emplacement of an accretionary complex that currently outcrops in the Bardym thrust stack [e.g., *Zhivkovich and Chekhovich*, 1986; *Puchkov*, 2002]. Following arc-continent collision, sediment deposition continued across the continental margin until the latest Carboniferous. By the latest Carboniferous, the paleo-Uralian ocean basin to the east had closed, and the Kazakhstan plate collided with the eastern flank of Baltica [*Hamilton*, 1970; *Zonenshain et al.*, 1984, 1990]. Continent-continent collision continued throughout the Permian to the Early Triassic, resulting in the westward thrusting of the Baltica continental margin to form a foreland thrust and fold belt and the concomitant development of a foreland basin [*Kamaletdinov*, 1974; *Puchkov*, 1997; *Brown et al.*, 1997].

[4] Throughout the southern and middle Urals, the foreland thrust and fold belt deforms syntectonic Late Carboniferous to Early Triassic sediments of the foreland basin, Paleozoic continental margin rocks, the Archean and Proterozoic basement and, in the southern Urals, the Middle to Late Devonian arc-continent collision accretionary complex (Figure 1) [*Ablizin et al.*, 1982; *Zhivkovich and Chekhovich*, 1985; *Kamaletdinov*, 1974; *Giese et al.*, 1999; *Brown et al.*, 2004]. In the middle Urals, between approximately 56°N and 59°N, the thrust belt is a narrow, overall N-S trending, west-verging basement-involved thrust stack measuring ~50–90 km in width from the Main Uralian fault (the arc-continent suture) to the frontal folds [*Ablizin et al.*, 1982; *Zhivkovich and Chekhovich*, 1985]. To date, balanced and restored cross sections and, consequently, the amount of shortening have not been determined for the middle Urals part of the foreland thrust and fold belt. By far the best studied area of the foreland thrust and fold belt structure is in the southern Urals, from approximately 56°N to 51°N [*Kamaletdinov*, 1974; *Bastida et al.*, 1997; *Brown et al.*, 1997, 1998, 1999, 2004; *Perez-Estaun et al.*, 1997; *Giese et al.*, 1999; *Alvarez-Marron et al.*, 2000], where it forms a ~150 km wide, west vergent thrust stack. On the basis of balanced and restored cross sections constructed from surface geology, the minimum amount of Paleozoic shortening recorded in the thrust belt in the southern Urals has been estimated to be about 20 km [*Perez-Estaun et al.*, 1997; *Brown et al.*, 1997].

3. Lithostratigraphy

[5] The lithostratigraphy of the western foreland thrust and fold belt of the southern and middle Urals is quite variable along strike. Here we present a synthesis of the lithostratigraphy along the three transects (Figure 2). Throughout this paper, the basement is taken to be the Archean and Proterozoic rocks of the East European Craton upon which the Paleozoic passive margin of Baltica was built. Along the entire length of the southern and middle Urals, the basement that outcrops on the eastern flank of the foreland thrust and fold belt was affected by a Late Vendian to Early Cambrian tectonothermal event and is juxtaposed against basement unaffected by this event along a fault zone [*Puchkov*, 1997; *Giese et al.*, 1999; *Glasmacher et al.*, 1999, 2001] (Figure 2). The Upper Vendian sediments themselves are thought to have been deposited in a foreland basin setting [*Brown et al.*, 1996; *Puchkov*, 1997] and were undeformed before the Uralide orogeny. The Paleozoic continental margin sediments are termed preorogenic, and the Paleozoic to Mesozoic sediments of the foreland basin are synorogenic. The tectonostratigraphy developed during the Late Devonian to Early Carboniferous arc-continent collisions is collectively referred to as the accretionary complex (Figure 2).

3.1. URSEIS Transect

[6] The oldest basement stratigraphy of the foreland thrust and fold belt along the URSEIS transect in the southern Urals consists of Archean to Early Proterozoic intermediate to felsic gneisses (Figure 2a). The gneisses are unconformably overlain by approximately 12,000 m of Lower Riphean to Vendian clastic sediments, limestones and marly limestones, volcanic, and subvolcanic rocks [*Kozlov et al.*, 1989; *Maslov et al.*, 1997]. The Upper Vendian sediments consist of about 1500 m of feldspar-bearing sandstones containing a unit of polymictic conglomerates. The Paleozoic continental margin sediments (preorogenic) along the URSEIS transect (Figure 1) consist of ~3000 m of Ordovician through Carboniferous carbonates with minor clastics at the base [*Puchkov*, 1997; *Proust et al.*, 1998]. East of the Zilmerdak fault, the Ordovician overlies the deformed and metamorphosed Riphean along an angular unconformity. The Ordovician and Silurian sediments are not everywhere present, and westward the Devonian sediments unconformably overlie the Upper Vendian. Along the URSEIS transect, in the east, the continental margin sediments are structurally overlain by an accretionary complex (Figure 2a) along a shear zone developed in

Figure 1. Geological map of the foreland thrust and fold belt in the southern and middle Urals. The locations of the URSEIS, Mikhailovsky (MIK), and ESRU transects are shown; ZT, Zilmerdak thrust. Note that the URSEIS cross section shown in Figure 3 is constructed along a straight line (marked "section"), whereas the seismic profile is a crooked line projection (marked "seismic").

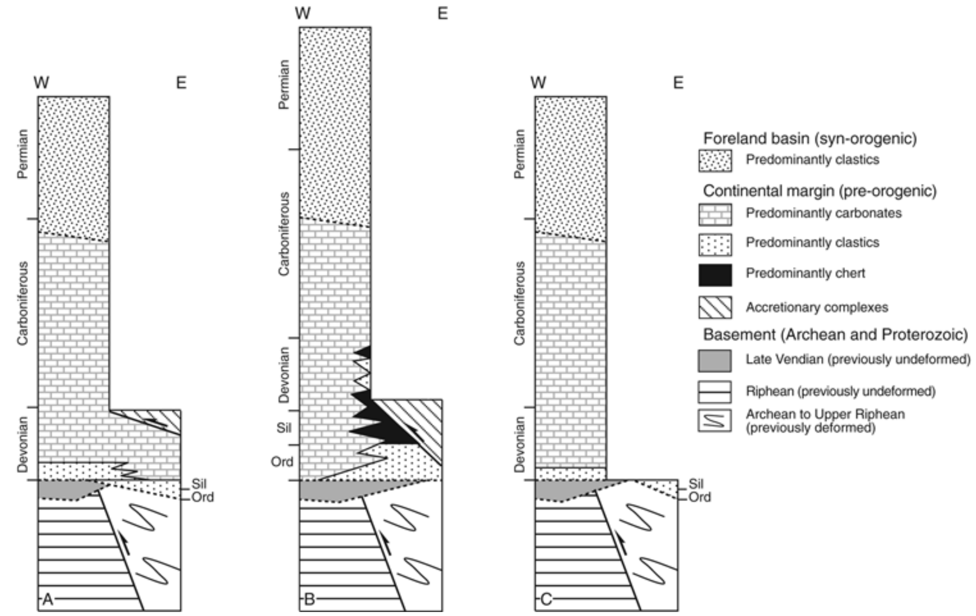

Figure 2. Simplified tectonostratigraphy of the Uralide foreland thrust and fold belt for (a) the URSEIS transect, (b) the Mikhailovsky transect, and (c) the ESRU transect. See text for more detailed descriptions.

Middle Devonian carbonates [*Brown et al.*, 1997; *Alvarez-Marron et al.*, 2000; *Fernández et al.*, 2004]. The accretionary complex is composed of offscraped continental margin sediments (Suvanyak Complex) that are structurally beneath approximately 5000 m of Late Frasnian and Famennian clastics (Zilair Formation) that were sourced predominantly from the accretionary complex itself [*Brown et al.*, 1998; *Alvarez-Marron et al.*, 2000; *Willner et al.*, 2002]. The Zilair Formation is structurally overlain by Ordovician and Silurian fine-grained clastics in the Uzyan Nappe and by the Kraka lherzolite massif. The foreland basin sequences (synorogenic) consist of more than 3000 m of westward thinning Late Carboniferous and Permian bioclastics, marls, limestones, reefal limestones, and evaporites, locally overlain by thin Upper Permian and Lower Triassic conglomerates and sandstones [*Chuvashov and Diupina*, 1973; *Chuvashov et al.*, 1993].

3.2. Mikhailovsky Transect

[7] Along the Mikhailovsky transect, an entire section of the Proterozoic sediments is not exposed, but it is estimated to be about 7 km thick [*Puchkov*, 2002]. In the Ufaley anticlinorium (Figure 1), the Precambrian comprises greenschist to upper amphibolite facies metamorphic rocks whose protoliths are thought to have been Riphean to Upper Vendian sediments (Geology of the USSR: 1:200,000 Urals Map Series). These rocks record Late Vendian and Late Paleozoic metamorphic overprints [e.g., *Echtler et al.*, 1997].

[8] The Paleozoic along the Mikhailovsky transect (Figure 2b) displays pronounced lithological changes from west to east, with four main depositional environments being recognized: foreland basin, continental shelf, continental slope, and island arc [*Puchkov and Ivanov*, 1982; *Zhivkovich and Chekhovich*, 1985]. The Paleozoic of the continental shelf deposits comprises about 1200 m of Ordovician clastics with carbonates predominating in the upper part in the west and, locally, intercalations of basalt and rhyolite [*Puchkov*, 2002]. In the eastern part of the transect, the Silurian comprises approximately 500 m of carbonate with interbeds of clastics, whereas westward, it partly comprises about 600 m of reef limestone [*Zhivkovich and Chekhovich*, 1985]. The Devonian in the eastern part of the transect comprises about 1100 m of predominantly carbonates with intercalations of clastics. In the west, the Pragian to Eifelian part of the section comprises about 1000 m of massive limestone [*Zhivkovich and Chekhovich*, 1985]. The Lower and part of the Upper (Bashkirian) Carboniferous comprises about 1000 m of predominantly carbonates with intercalations of clastics. The Upper Carboniferous foreland basin sediments are composed of about 1000 m of westward thinning polymictic clastics with layers of limestone. Only the Lower Permian is present along the Mikhailovsky transect, where it consists of about 2000 m of westward thinning polymictic clastics with intercalations of limestone. The Paleozoic continental slope deposits are present along the central part of the transect, in the so-called Bardym thrust stack. The Ordovician sediments consist of about 200 m of Llandeilian to Ashgillian clastics, with interbeds of limestone, diabase, and tuffs [*Puchkov and Ivanov*, 1982]. The Silurian is made up of about 350 m of predominantly chert. The Devonian consists of about 1000 m of chert, clastics, and basalt. The volcanic arc deposits in the Bardym thrust stack

consist of about 1000 m of Silurian to Lower Devonian andesite, andesitic basalt, tuffs, and rare chert, overlain by about 300 m of Lower Devonian (?) trachybasalt, trachyandesite, and tuff.

3.3. ESRU Transect

[9] In the middle Urals, along the ESRU transect (Figure 2c), the outcropping basement stratigraphy consists of approximately 7000 m of Upper Riphean to Lower Vendian clastic sediments with minor intercalated limestone and basalt. In the Kvarkush anticlinorium, these rocks were deformed and metamorphosed during the Early Cambrian, prior to the Uralide orogeny [*Beckholmen and Glodny*, 2004]. The westward thinning Upper Vendian sequences are composed of about 2700 m of interbedded siltstone, shale, and polymictic sandstone. Ordovician and Silurian units are found only along the eastern flank of the Kvarkush anticlinorium (Figure 1), where they are composed of about 1000 m of deformed limestone and clastics. Along the western flank of the Kvarkush anticlinorium, the Paleozoic continental margin sequences unconformably overlie the Late Vendian along the Lower Devonian (Emsian) Takatinian sandstone (Figure 2c). Here the continental margin sequences consist of about 2200 m of predominantly limestone intercalated with clastics. Along the part of the ESRU profile discussed in this paper, the foreland basin sequences are composed of about 2300 m of latest Carboniferous to Early Permian intercalated limestone and clastics, becoming predominantly clastic upward.

4. Structure of the Foreland Thrust and Fold Belt

[10] Since 1993 three deep reflection seismic profiles have been acquired in the Urals. These are the URSEIS profile in the southern Urals and the Mikhailovsky and ESRU profiles in the middle Urals (Figure 1). Crustal scale images derived from these profiles have been presented elsewhere [*Echtler et al.*, 1996; *Knapp et al.*, 1996; *Steer et al.*, 1998; *Tryggvason et al.*, 2001; *Juhlin et al.*, 1998; *Friberg et al.*, 2002; *Brown et al.*, 2002; *Kashubin et al.*, 2005], and their acquisition parameters and processing flow can be found in these publications. Here we present only that part of each profile that corresponds to the foreland thrust and fold belt and the transition into the undeformed foreland basin. Below, the reflection seismic data are described together with the outcropping geology along the three transects, balanced and restored cross sections are presented, and the minimum amount of shortening is given. Structures imaged in the basement in the reflection seismic data and which do not affect, or are not affected by, the foreland thrust and fold belt are not discussed.

[11] In the southern Urals, the structure of the foreland thrust and fold belt is well constrained by surface geology [*Giese et al.*, 1999; *Perez-Estaun et al.*, 1997; *Brown et al.*, 1996, 1997, 1999], although along the URSEIS transect the structural interpretation has not been previously fully integrated with the seismic data. The URSEIS geological cross section is constructed along a straight line (marked "section" in Figure 1), whereas the seismic profile (URSEIS) is a crooked line projection (marked "seismic" in Figure 1). Consequently, there are differences in the distances between structures indicated on the cross section and those on the seismic profile in Figure 3. In the middle Urals, the Mikhailovsky (MIK in Figure 1) and ESRU geological cross sections are not as well constrained by surface geology because of poor exposure. Both cross sections in the middle Urals are constructed along the straight line projection of the seismic profiles. The geological cross sections were constructed using an average lithostratigraphic thickness template determined for each transect, line length, and area balanced, and restored.

4.1. URSEIS Transect

[12] The westernmost 40 km of the URSEIS transect comprises an approximately 14 km thick package of predominantly subhorizontal, continuous reflections (Figures 3a and 3b) that are related to the Riphean to Permian sediments that unconformably overlie the poorly reflective Archean crystalline basement. A relatively strong, gently west dipping reflection at about 1 km depth (Figure 4a) coincides with the base of the Permian foreland basin sediments intersected by boreholes [e.g., *Skripiy and Yunusov*, 1989]. The deformation front (herein defined as the boundary between faulted and folded rocks in the thrust belt and nonfaulted and nonfolded rocks in the foreland) of the foreland thrust and fold belt in this area is located near km 1, where the Shikhan thrust affects the foreland basin sediments [*Skripiy and Yunusov*, 1989; *Puchkov*, 1997]. On the basis of borehole data [*Skripiy and Yunusov*, 1989] and the URSEIS reflection seismic data, the basal detachment in the western 28 km of the data is interpreted to be located at about 3.5 to 4 km depth, within the Upper Riphean sediments (Figure 4a). From about km 28 eastward, the basal thrust appears to ramp down into the middle and possibly lower crust, cutting the slightly east dipping reflections related to the Riphean sediments at about km 40 (marked "Cut-off" in Figure 5a). From the Tashly thrust at km 30 to the Alatau thrust at km 43, reflections related to the Precambrian sediments outline the Tashly anticline that developed at the ramp up from the middle or lower crust (Figure 5a). No clear basal detachment is imaged to the east of about km 49. We therefore interpret the ramp down to the middle or lower crust to extend eastward, along the interface between reflective upper and middle crust characterized by generally east dipping reflectivity and poorly to nonreflective crust below (Figure 3b). From the Tashly thrust to the Main Uralian fault at km 141, the middle and upper crust is characterized by predominantly east dipping reflectivity related to the Precambrian basement rocks in the Bashkirian anticlinorium. The structure within a large portion of the basement rocks in the Bashikirian anticlinorium (such as west-dipping middle crustal reflectivity imaged between km 130 to 140 in Figure 3b) is related to a Late Vendian tectonothermal event [*Giese et al.*, 1999; *Glasmacher et al.*, 1999, 2001, 2004; *Brown et al.*, 1996, 1997, 1999]. This Late Vendian

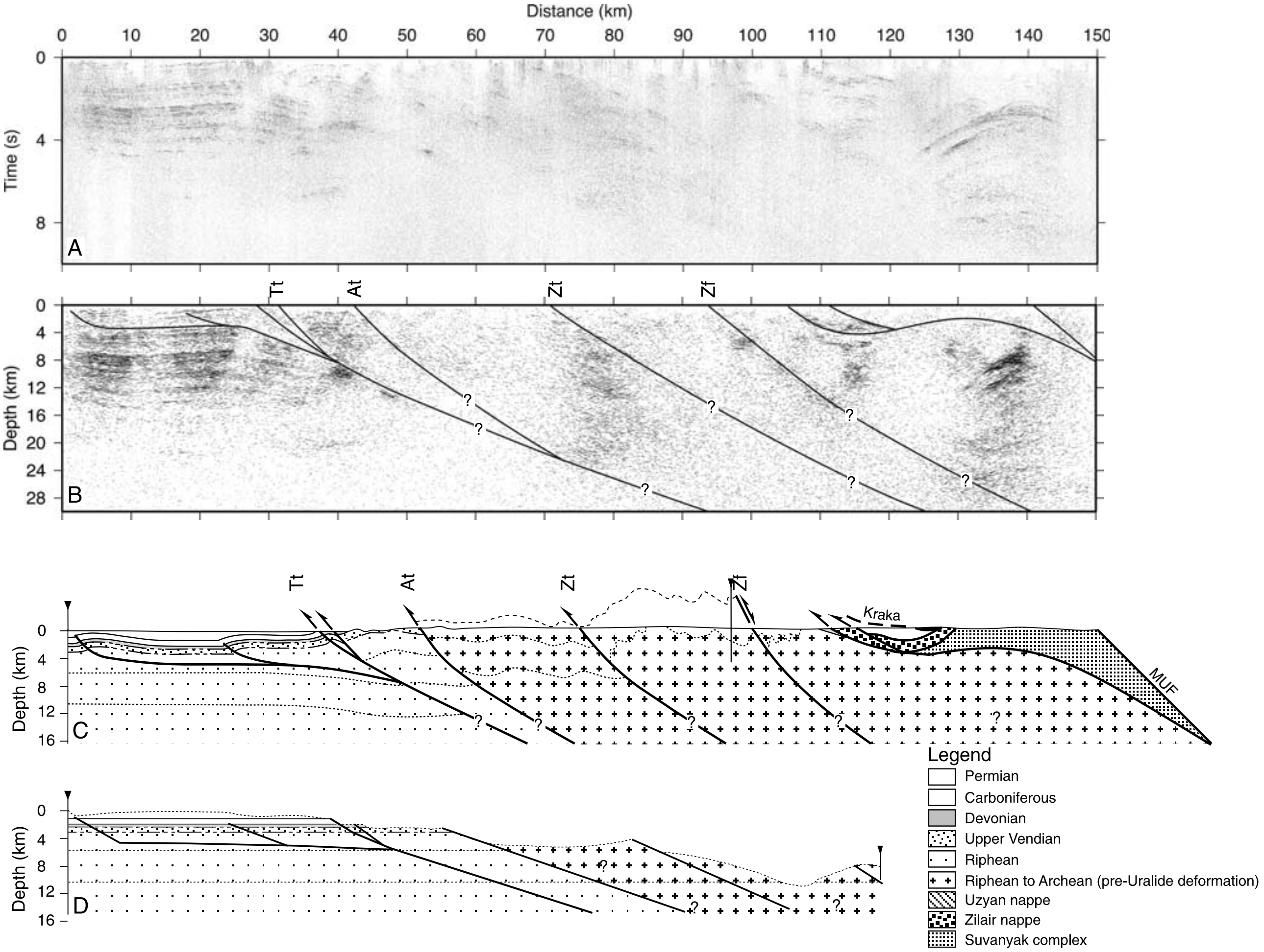

Figure 3. (a) Unmigrated time section of the URSEIS reflection seismic data. (b) Interpreted line drawing of the coherency-filtered, depth-migrated URSEIS data. (c) Balanced geological cross section along the URSEIS transect: Tt, Tashly thrust; At, Alatau thrust; Zt, Zilmerdak thrust; Zf, Zuratkul fault; and MUF, Main Uralian fault. Note that because the seismic data are plotted on a crooked line and the cross section is on a straight line, there are differences in the distances between individual features such as thrusts. (d) Restored cross section for the western part of the URSEIS transect. See text for discussion.

structure was only mildly overprinted during the Late Carboniferous to Early Triassic part of the Uralide orogeny, as individual thrusts were reactivated and accumulated minor amounts of displacement [*Giese et al.*, 1999; *Perez-Estaun et al.*, 1997; *Brown et al.*, 1997, 1999]. We therefore interpret the reflectivity within the Bashkirian anticlinorium to be mostly a product of the Late Vendian deformation and metamorphism. The Zilmerdak thrust and the Zuratkul fault appear at the surface in the URSEIS data at about km 71 and km 94, respectively, but are difficult to trace into the subsurface. They are interpreted to coincide with weak, steeply east dipping reflections (Figure 3b). From about km 106 to the Main Uralian fault, the upper 4 to 5 km of the URSEIS data image the arc-continent collision accretionary complex. Below the accretionary complex, strong, moderately west dipping to subhorizontal reflections are interpreted to be related to the Ripehan and Archean basement. The Main Uralian fault is poorly imaged in the URSEIS data.

[13] Uralide shortening along the URSEIS transect can only be determined with confidence for the westernmost 35 km, where the presence of Paleozoic continental margin and foreland basin sediments allow this part of the cross section to be balanced and restored (Figures 3c and 3d). Eastward, from the Tashly thrust to the Zuratkul fault, the section has been balanced and restored using the Middle Riphean sediments. In this way, the minimum shortening determined for this part of the URSEIS transect is 20 km. This calculation assumes only minor pre-Uralide deformation between the Tashly thrust and the Zuratkul fault, an assumption that fits well with a section across the southern termination of the Bashkirian anticlinorium [*Brown et al.*, 1997], where control is provided by Paleozoic sediments (Figure 1). East of the Zuratkul fault we have no control on

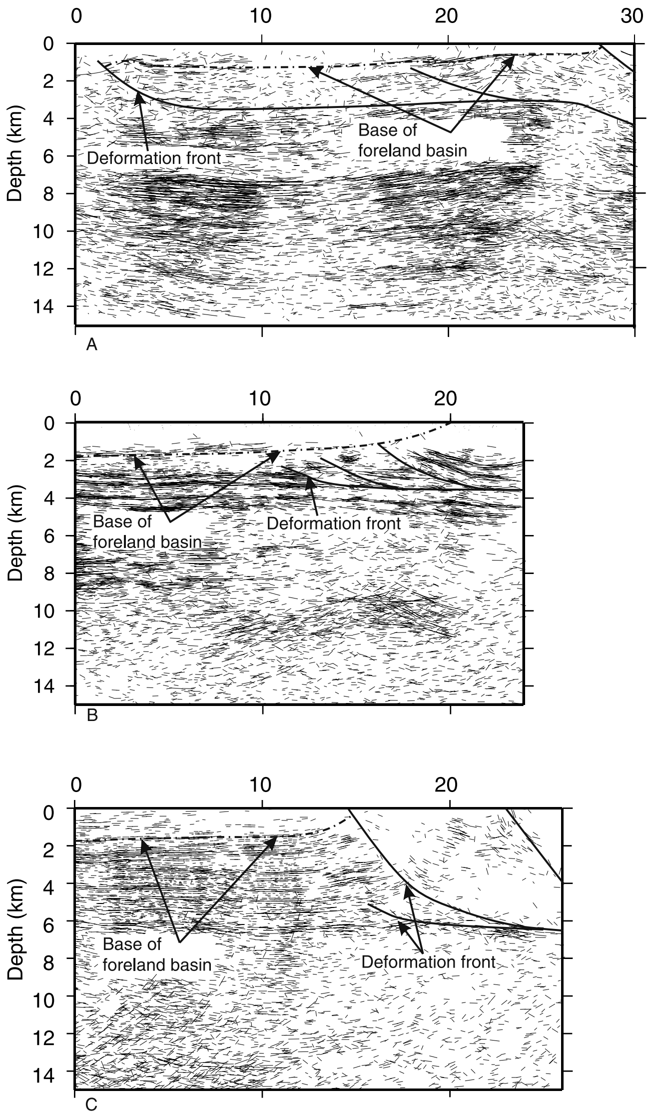

Figure 4. (a) Window of the depth-migrated line drawing of the deformation front and transition into the undeformed foreland basin in the URSEIS data. (b) Window of the depth-migrated line drawing of the deformation front and transition into the undeformed foreland basin in the Mikhailovsky data. (c) Window of the depth-migrated line drawing of the deformation front and transition into the undeformed foreland basin in the ESRU data.

the amount of Uralide shortening, although in sections farther south it appears to be minor [*Brown et al.*, 2004].

4.2. Mikhailovsky Transect

[14] The westernmost part of the Mikhailovsky profile is characterized by an up to 9 km thick package of horizontal reflections that are interpreted to be related to the Riphean to Permian sediments that overlie the weakly reflective Archean crystalline basement (Figures 6a and 6b). A moderately west dipping band of reflections beginning at about km 20 and reaching approximately 2 km depth at the western end of the profile is interpreted to mark the base of the westward thickening Late Carboniferous and Permian foreland basin sediments (Figure 4b). The deformation front is characterized by the truncation of reflections related to the preorogenic continental margin sediments, giving way to parallel reflections at about km 11 (Figure 4b). This relationship is interpreted to represent a buried thrust front that extends from km 11 to km 24, and does not appear to affect the base of the foreland basin sediments. The pattern of reflections suggest that individual thrusts have well-developed fault-related folds and only minor displacement. The basal detachment appears to be developed at the top of a set of strong, slightly east dipping, roughly parallel reflections that extend from the western end of the profile to about km 56 where they are truncated (Figure 6b). These reflections are interpreted to be related to the Upper Vendian and Ordovician sediments. The truncation of this set of

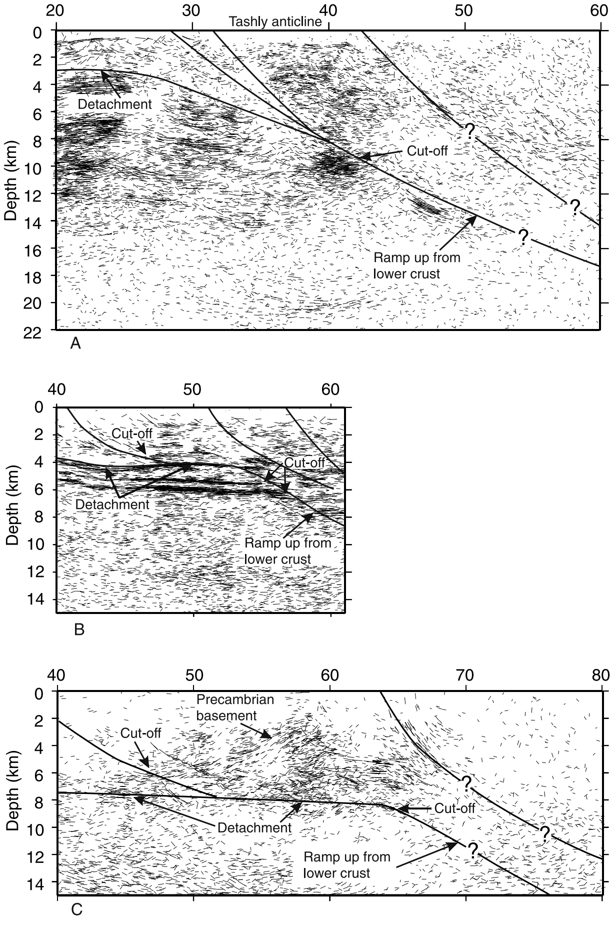

Figure 5. (a) Window of the depth-migrated line drawing of the ramp down to the lower crust in the URSEIS data. Note the basement cutoff. (b) Window of the depth-migrated line drawing of the ramp down to the lower crust in the Mikhailovsky data. Note the basement cutoffs. (c) Window of the depth-migrated line drawing of the ramp down to the lower crust in the ESRU data. Note the basement cutoffs.

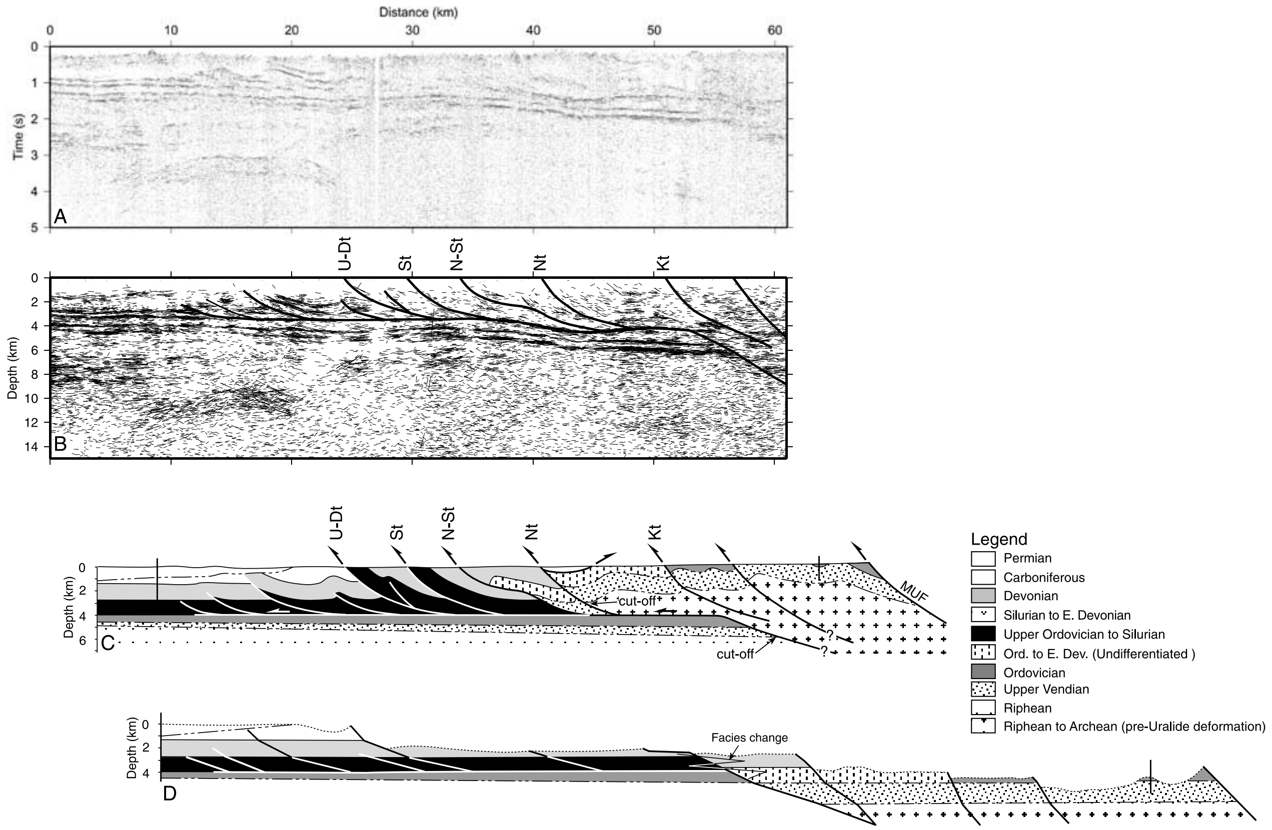

Figure 6. (a) Unmigrated time section of the Mikhailovsky reflection seismic data. (b) Interpreted line drawing of the coherency-filtered, depth-migrated Mikhailovsky data. (c) Balanced geological cross section along the Mikhailovsky transect: U-Dt, Ufa-Demid thrust; St, Sergi thrust; N-St, Nizhniesergi thrust; Nt, Nyazepetzov; Kt, Konovalosk thrust; and MUF, Main Uralian fault. (d) Restored cross section for the western part of the Mikhailovsky transect. See text for discussion.

reflections at km 56 is interpreted to be the location of a ramp up from the middle or lower crust (Figure 5b) which uplifts the basement, exposing it at the surface in the Ufaley anticlinorium. The outcropping Ufa-Demid thrust, at about km 25 (Figures 6b and 6c), ramps up from the basal detachment, cutting a set of reflections in its footwall, and places Upper Ordovician carbonates on top of Carboniferous (Bashkirian) carbonates. Eastward, the Sergi thrust, which outcrops at about km 29, is weakly imaged in the seismic data as east-dipping reflections that appear to cut subhorizontal reflections in the footwall (Figure 6b). The Sergi thrust places Silurian carbonates on top of Middle Devonian carbonates. The Nizhnie-Sergi thrust, which outcrops at about km 34, marks a major facies change from continental margin carbonates to slope clastics and is the base of the Bardym thrust stack. In the seismic data, the Nizhnie-Sergi thrust is interpreted to coincide with eastward dipping reflections that shallow in the subsurface before merging with the basal detachment at about km 45, giving it a ramp flat geometry. This fits with borehole data farther north, near the town of Nizhnie-Sergi, which show that Silurian clastics in the Bardym thrust stack overlie Lower to Middle Devonian continental margin carbonates along the Nizhnie-Sergi thrust [*Zhivkovich and Chekhovich*, 1986]. The Nyazepetzov thrust outcrops at the surface at about km 41 and is interpreted to coincide with steeply east dipping reflections that interrupt roughly horizontal reflections in the footwall. The Nyazepetzov thrust appears to merge with the basal detachment at about km 48. The roughly horizontal band of reflections imaged in its hanging wall at about km 47 is thought to be related to the Upper Vendian and Ordovician sediments that have been thrust up over the ramp, forming a hanging wall cutoff (Figure 5b). The Konovalovsk thrust, which outcrops at about km 51, and places Ordovician rift facies sediments and basalts on top of undifferentiated Ordovician to Devonian shelf clastics (Figure 6c), is not well imaged in the seismic data.

[15] The Mikhailovsky seismic data do not extend as far east as the Main Uralian fault, so the easternmost 8 km of the cross section (Figure 6c) is interpreted from published geological maps. West of the Nizhnie-Sergi thrust, the cross section has been balanced and Paleozoic continental margin and foreland basin sediments restored (Figure 6d). This restoration allows the hanging wall cutoff above Nizhnie-Sergi thrust to be restored to the footwall cutoff at the ramp up from the lower crust. East of the Nizhnie-Sergi thrust, the

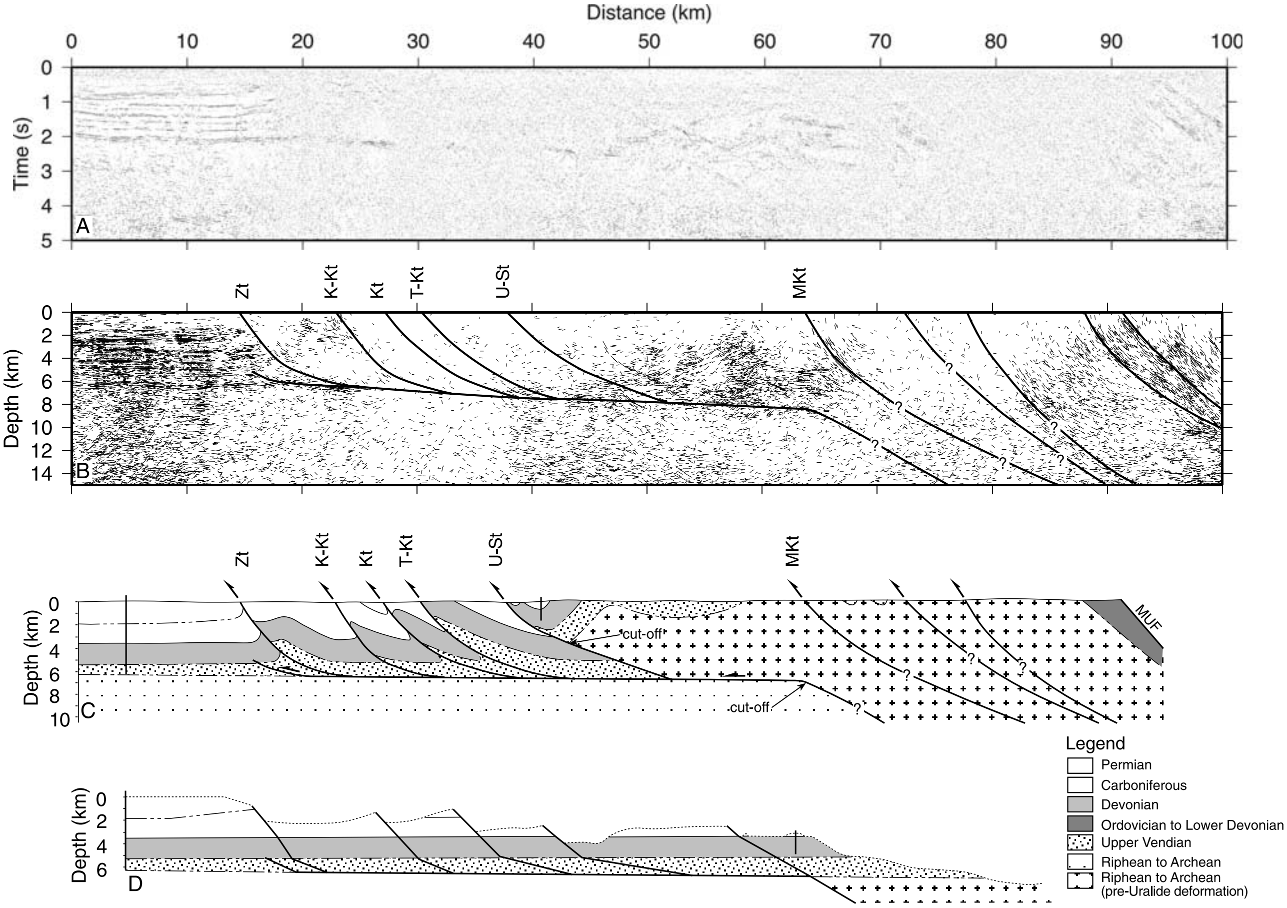

Figure 7. (a) Unmigrated time section of the ESRU reflection seismic data. (b) Interpreted line drawing of the coherency-filtered, depth-migrated ESRU data. (c) Balanced geological cross section along the ESRU transect: Zt, Zhuravlinsky thrust; K-Kt, Kumysh-Kyn thrust; Kt, Kyn thrust; T-Kt, Talitsa-Kamenny thrust; U-St, Ust-Serebryanka thrust; MKt, Mid-Kvarkush thrust; and MUF, Main Uralian fault. (d) Restored cross section for the western part of the ESRU transect. See text for discussion.

Paleozoic and Upper Vendian sediments have been bed length balanced and restored. The minimum shortening determined in this way is 23 km.

4.3. ESRU Transect

[16] The westernmost 15 km of the ESRU seismic profile images an approximately 6 km thick package of roughly horizontal, parallel reflections that are interpreted to image the undeformed Upper Vendian to Permian sediments that overlie the moderately reflective Riphean sediments (Figure 7). An increase in reflectivity between 1.5 and 2 km depth is interpreted to coincide with the base of the foreland basin sediments, which appears to dip slightly westward. The deformation front is marked by the truncation of the upper crustal reflections at about km 15, coinciding with the outcropping location of the Zhuravlinsky thrust (Figure 7c). The basal detachment is interpreted to occur along a slightly east dipping band of discontinuous reflections at about 6 km depth (Figure 7b) that extends from beneath the frontal thrust at about km 15 until approximately km 64. The truncation at km 64 appears to be the location at which the basal detachment ramps down into the middle or lower crust (Figure 5c). At approximately km 23, the reflections in the hanging wall anticline to the Zhuravlinsky thrust are cut by the Kumysh-Kyn thrust. Eastward, the internal structure of the foreland thrust and fold belt is poorly imaged in the ESRU data, and thrust locations and geometries have been interpreted from published maps. An increase in reflectivity along the western flank of the Kvarkush anticlinorium, between about km 45 and km 65 and at 2 to 6 km depth, is interpreted to be related to basement rocks (Figures 7b and 7c) that were deformed and metamorphosed prior to the Uralide orogeny [e.g., *Ablizin et al.*, 1982; *Beckholmen and Glodny*, 2004]. Between km 65 and 88, the previously deformed Precambrian basement rocks outcropping in the Kvarkush anticlinorium are imaged as moderately to steeply east dipping reflections that can be traced into the middle and lower crust [see also *Juhlin et al.*, 1998; *Friberg et al.*, 2002; *Brown et al.*, 2002; *Kashubin et al.*, 2005]. An approximately 4 km thick band of steeply east dipping reflections that reaches the surface between km 88 and 92

is associated with strongly deformed Early Ordovician to Middle Devonian shelf sediments [*Puchkov*, 1997]. From km 92 eastward is the Tagil volcanic arc.

[17] The ESRU imbricate thrust system has been balanced and the Paleozoic continental margin and Upper Vendian basement have been restored (Figures 7c and 7d). This restoration allows the hanging wall cutoff above the Ust-Serebryanka thrust (Figure 5c) to be restored to the footwall cutoff at the ramp up from the lower crust. This restoration gives a minimum shortening of 21 km. We have no control on Paleozoic shortening in the eastern half of the Kvarkush anticlinorium.

5. Discussion and Conclusions

[18] The structural architecture of the Uralide foreland thrust and fold belt in the southern and middle Urals is that of a narrow imbricate thrust system that formed along the foreland flank of a connecting system of broad, basement-cored anticlines. The reflection seismic data indicate that the imbricate thrust system developed above a shallow, subhorizontal, approximately 40 to 50 km long basal detachment that is located either in the previously undeformed basement sediments (Upper Riphean in the URSEIS transect and Upper Vendian in the ESRU transect) or in the Lower Paleozoic sediments (Mikhailovsky transect). Along the URSEIS and ESRU transects, the eastern margin of the synorogenic foreland basin sediments was incorporated into the imbricate trust system. In the Mikhailovsky seismic data, the imbricate thrust system appears to terminate as a buried thrust front and may not affect the foreland basin sediments. It has been suggested that foreland thrust and fold belts may develop above multiple detachment levels, with a shallow detachment at or near the basement cover interface and another one, or more, beneath it, at midcrustal levels [*Mosar*, 1999; *Pfiffner et al.*, 2000; *Lacombe and Mouthereau*, 2002]. In the URSEIS, Mikhailovsky, and ESRU seismic data, there is sufficient evidence provided by the subhorizontal reflectivity imaged beneath the imbricate thrust system (i.e., undeformed Riphean sediments) and by the continuous, flat, gently east dipping nature of the basal detachment itself (i.e., it is not folded or faulted), to suggest that this part of the thrust belt developed above a single, shallow detachment.

[19] It is not clear from the seismic data, however, where the basal detachment is located beneath the basement-cored anticlines, or if one exists. Nevertheless, it appears, on the basis of the truncation of reflections in the footwall to the imbricate thrust system in all three seismic profiles (Figure 5), that there is a ramp down into the middle or lower crust, which suggests the possibility of a detachment level being present. In all three transects, the subhorizontal reflectivity imaged beneath the imbricate thrust system indicates that it developed above Proterozoic sediments that were undeformed prior to the Uralide orogeny and which remain undeformed today. Eastward, all units were affected by pre-Uralide deformation, and the reflectivity is diffuse and overall east dipping. We therefore suggest that the ramp down into the middle or lower crust is located at the western limit of the pre-Uralide structures in the basement. *Perez-Estaun et al.* [1997], *Brown et al.* [1997, 1999], and *Giese et al.* [1999] pointed out that the control exerted by preexisting basement structures was perhaps the most important process in the development of the southern Urals foreland thrust and fold belt. The data sets presented here indicate that this process was active within the basement-cored anticlines along the entire southern and middle Urals foreland thrust and fold belt. We suggest that reactivation of the preexisting basement faults acted to focus the deformation along a predetermined set of structures whose orientation subparallel to that of the developing Uralide structural grain favored extensive basement involvement in the thrust belt.

[20] This study indicates that one of the important characteristics of the southern and middle Urals foreland thrust and fold belt is its small amount of shortening. We recognize that the amount of Uralide shortening in the foreland thrust and fold belt along the three transects can only be determined with confidence in the imbricate thrust system, where the Paleozoic sediments provide a datum for restoration. The absence of Paleozoic sediments in the basement-cored anticlines makes it impossible to determine the exact amount of Uralide shortening. Nevertheless, it is possible to determine a minimum amount of shortening in at least a part of the anticlines by bed length balancing and restoring the previously undeformed Upper Vendian or Upper Riphean sediments. In the southern Urals, the Paleozoic sediments along the Belaya River section [*Brown et al.*, 1997] also provide an important constraint on the shortening in the western part of the Bashkirian anticlinorium. Despite the uncertainties involved, it is clear that the shortening that took place in the Uralide foreland thrust and fold belt is far less than that recorded in other Paleozoic orogens, such as the Variscides or Appalachians, where shortening on the order of hundreds of kilometers has been calculated [e.g., *Perez-Estaun et al.*, 1988; *Evans*, 1989]. One of the factors that may have influenced the amount of shortening in the Uralides was the presence of the preexisting structures in the basement which seem to have acted to partition the deformation into vertical uplift. From the balanced and restored cross sections presented here, uplift of the previously undeformed Upper Vendian sediments (assumed to have been an horizontal datum) in the basement-cored anticlines can be calculated to be on the order of 5 to 8 km. Another factor may have been a relatively weak, far-field stress response in the Baltica margin to the oblique collision taking place with the Kazakhstan plate to the east.

[21] A general agreement exists that the onset of clastic sedimentation in the southern and middle Urals during the Late Carboniferous (upper Bashkirian to Moscovian) marks the beginning of development of the Uralide foreland basin and hence records the early stages of deformation and uplift in the foreland thrust and fold belt [*Mizens*, 1997; *Chuvashov*, 1998; *Proust et al.*, 1998]. Marine sedimentation in the foreland basin continued through the Carboniferous and Early Permian, changing to mainly continental deposition in the Late Permian to earliest Triassic [*Mizens*, 1997; *Chuvashov*, 1998; *Proust et al.*, 1998]. In the URSEIS and ESRU data, the frontal thrusts clearly affect the Lower

Permian foreland basin sediments (in Mikhailovsky this is not so clear), indicating that the deformation in the foreland thrust and fold belt continued at least into the Early Permian. In the southern Urals, field evidence indicates that the Upper Permian and, at least locally, the lowermost Triassic sediments were also deformed, suggesting that deformation continued into the Early Triassic. We stress, however, that care must be taken to distinguish between deformation related to the development of the foreland thrust and fold belt and that related to later, widespread movement of Permian (Kungurian) evaporites. Involvement of the foreland basin sediments in the deformation suggests that the imbricate thrust system likely grew by a foreland propagating deformation sequence. The absence of foreland basin sediments in the basement anticlines makes it difficult to assess the timing or sequence of deformation there. However, modeling of apatite fission track data from the Paleozoic sediments and basement rocks in the Bashkirian and Kvarkush anticlinoriums indicates a phase of heating followed by cooling through the 110°C geotherm between about 300 to 230 Ma [*Seward et al.*, 1997, 2002; *Glasmacher et al.*, 2001, 2004], or Late Carboniferous to Middle Triassic, suggesting that late orogenic activity across the foreland lasted until this time.

[22] **Acknowledgments.** This work was in part funded by MCyT projects BTE2001-5002-E and BTE2002-04618-C02-02. The Swedish Research Council (VR) is gratefully acknowledged for early funding of seismic studies in the Urals.

References

Ablizin, V. D., M. L. Kliuzhina, F. A. Kurbatskaya, and A. M. Kurbatsky (1982), *The Upper Riphean and Vendian of the Western Slope of the Middle Urals* (in Russian), 139 pp., Nauka, Moscow.

Alvarez-Marron, J. (2002), Tectonic processes during collisional orogenesis from comparison of the southern Urals with the central Variscides, in *Mountain Building in the Uralides: Pangea to Present*, *Geophys. Monogr. Ser.*, vol. 132, edited by D. Brown, C. Juhlin, and V. Puchkov, pp. 83–100, AGU, Washington, D. C.

Alvarez-Marron, J., D. Brown, A. Perez-Estaun, V. Puchkov, and Y. Gorozhanina (2000), Accretionary complex structure and kinematics during Paleozoic arc-continent collision in the southern Urals, *Tectonophysics*, *325*, 175–191.

Bastida, F., J. Aller, V. N. Puchkov, C. Juhlin, and A. Oslianski (1997), A cross section through the Zilair Unit (southern Urals), *Tectonophysics*, *276*, 253–264.

Beckholmen, M., and J. Glodny (2004), Timanian blueschist_facies metamorphism in the Kvarkush metamorphic basement, northern Urals, Russia, in *The Neoproterozoic Timanide Orogen of Eastern Baltica*, edited by D. G. Gee and V. Pease, *Geol. Soc. London Mem.*, *30*, 125–134.

Brown, D., and P. Spadea (1999), Processes of forearc and accretionary complex formation during arc-continent collision in the southern Ural mountains, *Geology*, *27*, 649–652.

Brown, D., V. Puchkov, J. Alvarez-Marron, and A. Perez-Estaun (1996), The structural architecture of the footwall to the Main Uralian fault, southern Urals, *Earth Sci. Rev.*, *40*, 125–147.

Brown, D., J. Alvarez-Marron, A. Perez-Estaun, Y. Gorozhanina, V. Baryshev, and V. Puchkov (1997), Geometric and kinematic evolution of the foreland thrust and fold belt in the southern Urals, *Tectonics*, *16*, 551–562.

Brown, D., C. Juhlin, J. Alvarez-Marron, A. Perez-Estaun, and A. Oslianski (1998), Crustal_scale structure and evolution of an arc-continent collision zone in the southern Urals, Russia, *Tectonics*, *17*, 158–171.

Brown, D., J. Alvarez-Marron, A. Perez-Estaun, V. Puchkov, and C. Ayala (1999), Basement influence on foreland thrust and fold belt development: An example from the southern Urals, *Tectonophysics*, *308*, 459–472.

Brown, D., C. Juhlin, A. Tryggvason, D. Steer, P. Ayarza, M. Beckholmen, A. Rybalka, and M. Bliznetsov (2002), The crustal architecture of the southern and middle Urals from the URSEIS, ESRU, and Alapaev reflection seismic surveys, in *Mountain Building in the Uralides: Pangea to Present*, *Geophys. Monogr. Ser.*, vol. 132, edited by D. Brown, C. Juhlin, and V. Puchkov, pp. 33–48, AGU, Washington D. C.

Brown, D., J. Alvarez-Marron, A. Perez-Estaun, Y. Gorozhanina, and V. Puchkov (2004), The structure of the south Urals foreland fold and thrust belt at the transition to the Precaspian basin, *J. Geol. Soc.*, *161*, 813–822.

Chuvashov, V. I. (1998), Dynamics of the evolution of the Uralian foredeep, *Geotectonics*, *32*, 186–200.

Chuvashov, B. I., and G. V. Diupina (1973), *The Upper Paleozoic Terrigenous Sediments of the Western Slope of the Middle Urals* (in Russian), 208 pp., Nauka, Moscow.

Chuvashov, B. I., V. A. Chermynkh, V. V. Chernykh, V. J. Kipin, V. A. Molin, V. P. Ozhgibesov, and P. A. Sofronitsky (1993), *The Permian System: Guides to Geological Excursions in the Uralian Type Localities, Part 2: Southern Urals*, *New Ser.*, vol. 10, Occas. Publ. ESRI, Columbia, S. C.

Echtler, H. P., M. Stiller, F. Steinhoff, C. M. Krawczyk, A. Suleimanov, V. Spiridonov, J. Knapp, Y. Menshikov, J. Alvarez-Marron, and N. Yunusov (1996), Preserved collisional crustal architecture of the southern Urals—Vibroseis CMP-profiling, *Science*, *274*, 224–226.

Echtler, H. P., K. S. Ivanov, Y. L. Ronkin, L. A. Karsten, R. Hetzel, and A. G. Noskov (1997), The tectono-metamorphic evolution of gneiss complexes in the middle Urals, Russia: A reappraisal, *Tectonophysics*, *276*, 229–252.

Evans, M. A. (1989), The structural geometry and evolution of foreland thrust systems, northern Virginia, *Geol. Soc. Am. Bull.*, *101*, 339–354.

Fernández, F. J., D. Brown, J. Alvarez-Marron, D. J. Prior, and A. Perez-Estaun (2004), Microstructure and lattice preferred orientation of calcite mylonites at the base of the southern Urals accretionary prism, *J. Geol. Soc.*, *169*, 1–13.

Friberg, M., C. Juhlin, M. Beckholmen, G. A. Petrov, and A. G. Green (2002), Paleozoic tectonic evolution of the middle Urals in light of the ESRU seismic experiments, *J. Geol. Soc.*, *159*, 295–306.

Giese, U., U. Glasmacher, V. I. Kozlov, I. Matenaar, V. N. Puchkov, L. Stroink, W. Bauer, and S. Ladage (1999), Structural framework of the Bashkirian anticlinorium, SW Urals, *Geol. Rundsch.*, *87*, 526–544.

Glasmacher, U. A., P. Reynolds, A. A. Alekseyev, V. N. Puchkov, K. Taylor, and V. Gorozhanin (1999), ^{40}Ar/^{39}Ar thermochronology west of the Main Uralian fault, southern Urals, Russia, *Geol. Rundsch.*, *87*, 515–525.

Glasmacher, U. A., W. Bauer, U. Giese, P. Reynolds, B. Kober, V. Puchkov, L. Stroink, A. Alekseyev, and A. P. Willner (2001), The metamorphic complex of Beloretzk, SW Urals, Russia—A terrane with a polyphase Meso-to Neoproterozoic thermo-dynamic evolution, *Precambrian Res.*, *110*, 185–213.

Glasmacher, U. A., I. Matenaar, W. Bauer, and V. N. Puchkov (2004), Diagenesis and incipient metamorphism in the western fold-and-thrust belt, SW Urals, Russia, *Int. J. Earth Sci.*, *93*, 361–383.

Gorozhanina, Y., and V. Puchkov (2001), The model of sedimentation in the forearc area of the Magnitogorsk island arc in the Late Devonian (in Russian), in *The Geology and Prospects of the Raw Material Base of Bashkortostan*, pp. 5–12, *Inst. of Geol.*, Ufa, Russia.

Hamilton, W. (1970), The Uralides and the motion of the Russian and Siberian platforms, *Geol. Soc. Am. Bull.*, *81*, 2553–2576.

Juhlin, C., M. Friberg, H. Echtler, A. G. Green, J. Ansorge, T. Hismatulin, and A. Rybalka (1998), Crustal structure of the middle Urals: Results from the (ESRU) Europrobe seismic reflection profiling in the Urals experiments, *Tectonics*, *17*, 710–725.

Kamaletdinov, M. A. (1974), *The Nappe Structures of the Urals* (in Russian), 228 pp., Nauka, Moscow.

Kashubin, S., C. Juhlin, M. Friberg, A. Rybalka, G. Petrov, A. Kashubin, M. Bliznetsov, and D. Steer (2005), Crustal structure of the middle Urals based on reflection seismic data, in *European Lithosphere Dynamics*, edited by D. Gee, and R. Stephenson, *Geol. Soc.*, London, in press.

Knapp, J. H., D. N. Steer, L. D. Brown, R. Berzin, A. Suleimanov, M. Stiller, E. Lüschen, D. Brown, R. Bulgakov, and A. V. Rybalka (1996), A lithosphere-scale image of the southern Urals from explosion-source seismic reflection profiling in URSEIS '95, *Science*, *274*, 226–228.

Kozlov, V. I., A. A. Krasnobaev, N. N. Larionov, A. V. Maslov, N. D. Sergeeva, Y. L. Ronkin, and E. V. Bibikova (1989), *Lower Riphean of the South Urals* (in Russian), 208 pp., Nauka, Moscow.

Lacombe, O., and F. Mouthereau (2002), Basement-involved shortening and deep detachment tectonics in forelands of orogens: Insights from recent collision belts (Taiwan, Western Alps, Pyrenees), *Tectonics*, *21*(4), 1030, doi:10.1029/2001TC901018.

Maslov, A., B. D. Erdtmann, K. S. Ivanov, S. N. Ivanov, and M. T. Krupenin (1997), The main tectonic events, depositional history, and the palaeogeography of the southern Urals during the Riphean–Early Paleozoic, *Tectonophysics*, *276*, 313–335.

Mizens, G. A. (1997), On the stages of formation of the Uralian foredeep, *Geotectonics*, *31*, 374–385.

Mosar, J. (1999), Present-day and future tectonic underplating in the western Swiss Alps: Reconciliation of basement/wrench-faulting and décollement folding of the Jura and Molasse basin in the Alpine foreland, *Earth Planet. Sci. Lett.*, *173*, 143–155.

Perez-Estaun, A., F. Bastida, J. L. Alonso, J. Marquinez, J. Aller, J. Alvarez-Marron, A. Marcos, and J. A. Pulgar (1988), A thin_skinned tectonics model for an arcuate fold and thrust belt: The Cantabrian zone (Variscan Ibero-Armorican arc), *Tectonics*, *7*, 517–537.

Perez-Estaun, A., J. Alvarez-Marron, D. Brown, V. Puchkov, Y. Gorozhanina, and V. Baryshev (1997), Along_strike structural variations in the foreland thrust and fold belt of the southern Urals, *Tectonophysics*, *276*, 265–280.

Pfiffner, O. A., S. Ellis, and C. Beaumont (2000), Collision tectonics in the Swiss Alps: Insight from geodynamic modeling, *Tectonics*, *19*, 1065–1094.

Proust, J. N., B. I. Chuvashov, E. Vennin, and T. Boisseau (1998), Carbonate platform drowning in a foreland setting: The mid-Carboniferous platform in western Urals (Russia), *J. Sediment. Res.*, *68*, 1175–1188.

Puchkov, V. N. (1997), Structure and geodynamics of the Uralian orogen, in *Orogeny Through Time*, edited by J.-P. Burg, and M. Ford, *Geol. Soc. Spec. Publ.*, *121*, 201–236.

Puchkov, V. (2002), Paleozoic evolution of the east European continental margin involved in the Uralide orogeny, in *Mountain Building in the Uralides: Pangea to Present*, *Geophys. Monogr. Ser.*, vol. 132, edited by D. Brown, C. Juhlin, and V. Puchkov, pp. 9–32, AGU, Washington, D. C.

Puchkov, V., and K. Ivanov (1982), *Geology of Allochthonous Bathyal Complexes of the Ufimian Amphitheater* (in Russian), 61 pp., *Sverdlovsk Sci. Cent.*, Ekaterinburg, Russia.

Seward, D., A. Perez-Estaun, and V. Puchkov (1997), Preliminary fission-track results from the southern Urals–Sterlitamak to Magnitogorsk, *Tectonophysics*, *276*, 281–290.

Seward, D., D. Brown, R. Hetzel, M. Friberg, A. Gerdes, G. A. Petrov, and A. Perez-Estaun (2002), The syn- and post-orogenic low temperature events in the southern and middle Urals: Evidence from fission-track analysis, in *Mountain Building in the Uralides: Pangea to Present*, *Geophys. Monogr. Ser.*, vol. 132, edited by D. Brown, C. Juhlin, and V. Puchkov, pp. 257–272, AGU, Washington, D. C.

Skripiy, A. A., and N. K. Yunusov (1989), Tension and compression structures in the articulation zone of the southern Urals and the east European platform, *Geotectonics*, *23*, 515–522.

Steer, D. N., J. H. Knapp, L. D. Brown, H. P. Echtler, D. L. Brown, and R. Berzin (1998), Deep structure of the continental lithosphere in an unextended orogen: An explosive-source seismic reflection profile in the Urals (Urals Seismic Experiment and Integrated Studies (URSEIS 1995)), *Tectonics*, *17*, 143–157.

Tryggvason, A., D. Brown, and A. Perez-Estaun (2001), Crustal architecture of the southern Uralides from true amplitude processing of the URSEIS vibroseis profile, *Tectonics*, *20*, 1040–1052.

Willner, A. P., T. Ermolaeva, Y. Gorozhanina, V. Puchkov, M. Arzhavitina, V. Pazukhin, U. Kramm, and R. Walter (2002), Surface signals of an arc-continent collision: The detritus of the Upper Zilair Formation in the southern Urals, Russia, in *Mountain Building in the Uralides: Pangea to Present*, *Geophys. Monogr. Ser.*, vol. 132, edited by D. Brown, C. Juhlin, and V. Puchkov, pp. 183–210, AGU, Washington, D. C.

Zhivkovich, A. Y., and P. A. Chekhovich(1985), *Paleozoic Formation and Tectonics of the Ufimian Amphitheater* (in Russian), 183 pp., Nauka, Moscow.

Zhivkovich, A. Y., and P. A. Chekhovich (1986), Structure of the central part of the Ufa amphitheater, central Urals, *Geotectonics*, *20*, 129–141.

Zonenshain, L. P., V. G. Korinevsky, V. G. Kazmin, D. M. Pechersky, V. V. Khain, and V. V. Mateveenkov (1984), Plate tectonic model of the south Urals development, *Tectonophysics*, *109*, 95–135.

Zonenshain, L. P., M. I. Kuzmin, and L. M. Natapov (1990), Uralian foldbelt, in *Geology of the USSR: A Plate-Tectonic Synthesis*, *Geodyn. Ser.*, vol. 21, edited by L. P. Zonenshain et al., pp. 27–54, AGU, Washington, D. C.

D. Brown, Instituto de Ciencias de la Tierra "Jaume Almera," CSIC, Lluís Solé I Sabarís s/n, E-08028 Barcelona, Spain. (dbrown@ija.csic.es)

M. Friberg, Committee for Infrastructure/General Director's Office, Swedish Research Council, Regeringsgaten 56, SE-103 78 Stockholm, Sweden.

C. Juhlin and A. Tryggvason, Department of Earth Sciences, Uppsala University, Villavagen 16, SE-752 36 Uppsala, Sweden.

G. Petrov, Urals Geological Survey Expedition, 55 Veinera, Ekaterinburg 620014, Russia.

V. Puchkov, Ufimian Geoscience Centre, Russian Academy of Scienes, ul. Karl Marx 16/2, Ufa, 45 000 Bashkiria, Russia.

A. Rybalka, Bazhenov Geophysical Expedition, UralGeolCom, Scheelite 624051, Russia.