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Palaeozoic tectonic evolution of the Middle Urals in the light of the ESRU seismic experiments

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Abstract: A new compilation of deep seismic reflection data, in combination with the results of recent geological and isotopic investigations, provides the basis for significantly refined structural and evolutionary models of the Middle Urals. Many of the major structural boundaries observed at the surface (e.g. Main Uralian Thrust, Main Uralian Normal Fault, Serov–Mauk Fault, Prianitchnikova Shear Zone) can be followed on the seismic reflection data to depths of 8–15 km. Only a few features can be traced through the horizontal to shallow dipping zones of middle-crustal reflectivity that extend beneath much of the Middle Urals. Exceptions might be the Deevo Thrust and a newly discovered deep band of moderately dipping reflections beneath the West Siberian Basin that may represent the remnants of an ancient subduction zone. The reflectivity of the lower crust and Moho are similar beneath the hinterland of the Urals and below the western part of the West Siberian Basin, suggesting that in both places they have the same extensional origin. Accretion of various exotic terranes to the eastern margin of Baltica during Late Palaeozoic time involved considerable shortening of the continental margin. The accreted terranes (e.g. Tagil, Petrokamensk and Alapaevsk Arc Complexes) consist mostly of island-arc material formed during Mid- and Late Palaeozoic time. Closely associated with the island arcs are several high-grade metamorphic complexes (e.g. Salda and Murzinka–Adui Complexes) that were exhumed during and after Late Palaeozoic convergence. Towards the end of the orogeny, several north–south-trending strike-slip faults (e.g. Sisert Fault) were active. After the orogeny, major periods of tectonism and magmatism in the Middle Urals resulted in the extrusion of the Siberian trap basalts, crustal stretching and/or underplating, and the formation of the West Siberian Basin, the planet's largest intracontinental sedimentary basin. Finally, a period of renewed thrust faulting, often reactivating older faults, led to the inversion of the Mesozoic basins.

Keywords: Uralide Orogen, West Siberian Basin, Palaeozoic, Mesozoic, seismic profiling.

The results of three centuries of Russian exploration in the Urals (see reviews by Ivanov *et al.* (1975) and Puchkov (1997)) have provided a solid foundation for recent multinational geoscientific studies under the auspices of EUROPROBE, the European section of the International Lithosphere Programme. The combined geological and geophysical URSEIS project in the Southern Urals (Berzin *et al.* 1996; Carbonell *et al.* 1996; Echtler *et al.* 1996; Knapp *et al.* 1996) included a deep seismic reflection profile of 465 km length across the orogen at latitude 54°N (Fig. 1). URSEIS was the first to reveal the bivergent character of the orogen, with east-dipping structures in the west and west-dipping ones in the east. The ESRU (EUROPROBE Seismic Reflection profiling in the Urals) project, reported in this paper, started in 1993. Up to now, it has involved the acquisition of four deep reflection seismic datasets in the Middle Urals (Juhlin *et al.* 1995, 1996, 1997, 1998; Friberg *et al.* 2000b) at latitude 58°N (Fig. 1). They crossed the orogen in the vicinity of the Urals superdeep drillhole, SG-4 (currently at *c.* 6 km depth).

Although several tectonic reconstructions exist for the Urals, most of them are biased by observations made in the Southern Urals (e.g. Ivanov *et al.* 1975; Zonenshain *et al.* 1990; Matte *et al.* 1993; Echtler *et al.* 1996; Puchkov 1997; Brown *et al.* 1998). In this paper, we present a new cross-section and a novel evolutionary model for the Middle Urals that are based on the ESRU deep seismic reflection datasets, interpretations of established and recently obtained geological knowledge, and key isotopic and associated information.

Regional geology

The Uralian orogeny was the result of Late Palaeozoic accretion of oceanic, mostly island-arc terranes, to the eastern margin of Baltica (Hamilton 1970; Ivanov *et al.* 1975; Zonenshain *et al.* 1990; Sengör *et al.* 1993). The orogen can be traced for more than 2000 km from the Barents Sea in the north to near the Caspian Sea in the south. Flanking the orogen to the west and east are Late Palaeozoic and younger sedimentary basins (Fig. 1). The eastern part of the orogen from the Middle Urals and northwards is largely covered by Triassic and younger sediments of the West Siberian Basin. In the Southern Urals, the orogen plunges beneath the Cretaceous Pre-Caspian Basin in the south and west. The Uralian foreland is transitional into platform sediments that extend westwards to the Baltic Sea. The Uralide orogen differs from other Palaeozoic orogenic belts in that it has a crustal root, which appears to be absent in the Caledonide (Matthews & Cheadle 1986), Variscide (Meissner *et al.* 1987) and Appalachian (McBride & Nelson 1991) orogens.

The Middle Urals is the most poorly exposed region of the Urals. Understanding of the geology there is heavily dependent on borehole and geophysical data. The following

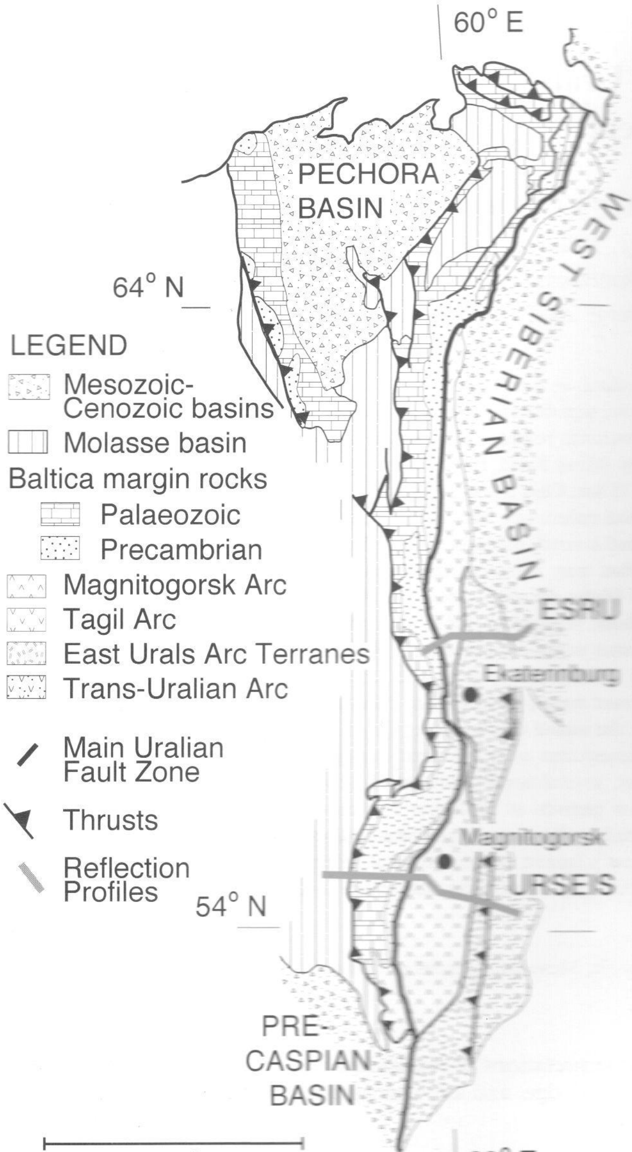

Fig. 1. Generalized tectonic map of the Urals (modified from Ivanov *et al.* 1975) showing location of deep (>20 s travel time) URSEIS and ESRU reflection seismic profiles.

brief west-to-east description of the Middle Urals geology is to a large extent based on Russian material, but it also incorporates findings from the last decade of EUROPROBE investigations.

Middle Urals foreland

Neoproterozoic rocks are exposed in the foreland of the Middle Urals (western region in Figs. 2 and 3) in the Kvarkush Anticline. They consist of poly-deformed phyllites, psammites and marbles of probable Late Riphean age, younging up via Lower Vendian tillites into Upper Vendian Molasse (Antsigin *et al.* 1994). Blueschists are reported from narrow shear zones within the Upper Riphean and Lower Vendian strata (Sobolev *et al.* 1986), but generally these rocks are metamorphosed to greenschist facies. The Upper Vendian deposits are less deformed than the underlying rocks, and their metamorphic grade never reaches greenschist facies (Sobolev *et al.* 1964).

The Palaeozoic sequences in the western foreland (Figs. 2 and 3) include Lower Devonian terrigeneous coarse-grained clastic material, Middle to Upper Devonian shallow-water marine sediments dominated by carbonates, and Lower Carboniferous coal-bearing sandstone with dolomite, limestone and subordinate shale. These are overlain by Upper Carboniferous and Lower Permian molasses deposits, including continentally derived conglomerates (Puchkov 1997). The Palaeozoic sediments west of the Kvarkush Anticline show no signs of metamorphism. Deformation increases from west to east in such a way that progressively lower stratigraphic units are exposed to the east (Sobolev *et al.* 1964). In the eastern foreland, east of the Kvarkush Anticline and adjacent to the Main Uralian Thrust (Fig. 2), the Palaeozoic rocks have a strong penetrative cleavage and are metamorphosed to lowermost greenschist facies (Sobolev *et al.* 1964). The sequence comprises Lower Ordovician conglomerates and carbonates overlain by Upper Ordovician to Middle Devonian limestone with occasional phyllite and quartzite (Antsigin *et al.* 1994; Puchkov 1997). Throughout the foreland there is a marked unconformity between the Lower and Middle Devonian sequences.

Separated from these Palaeozoic sequences by the Main Uralian Thrust (Fig. 2) are quartzites and mica-schists together with intrusive rocks, including layered ultramafic bodies, mafic dyke swarms and subordinate granites. These rocks of the Main Uralian Fault Zone are considered to be of Ordovician age (Antsigin *et al.* 1994). However, recent single zircon Pb-evaporation data from a deformed granite body have yielded a Late Proterozoic (581 ± 3 Ma) intrusive age (Beckholmen *et al.* 1999). The contact between these Baltica margin assemblages and former oceanic and island-arc terranes to the east is the Main Uralian Normal Fault, a steeply east-dipping greenschist-facies shear zone with down-to-the-east fabric overprinting the earlier deformation (Beckholmen & Juhlin 1997; Juhlin *et al.* 1998).

Tagil arc

East of the Main Uralian Normal Fault is the Tagil Arc (Fig. 2). This intra-oceanic island arc was active from Late Ordovician to Mid-Devonian time (Fig. 3). It has a weak lateral zoning with predominantly andesitic magmatism in the west and trachytes in the east (Yazeva & Bochkarev 1996; Bosch *et al.* 1997). Underlying the volcanic rocks of the Tagil Arc to the east is the Serov–Mauk Serpentinite Belt, which, apart from serpentinites, contains dolerite dykes, gabbros and plagiogranites similar to the easternmost rocks of the Tagil Arc (Antsigin *et al.* 1994). The serpentinites can be traced as a prominent magnetic anomaly throughout the Middle and Northern Urals (Sobolev *et al.* 1964). The Silurian island-arc rocks of the Tagil Arc are unconformably overlain by Lower Devonian clastic sediments and Middle to Upper Devonian limestones (Antsigin *et al.* 1994). A second phase of andesitic volcanism is recorded in the eastern part of the Tagil Arc during Mid- and Late Devonian time (Fig. 3; Yazeva & Bocharev 1994).

Hinterland metamorphic complexes

At the latitude of the SG-4 drillhole, the Serov–Mauk Serpentinite Belt is juxtaposed against high-grade gneisses of

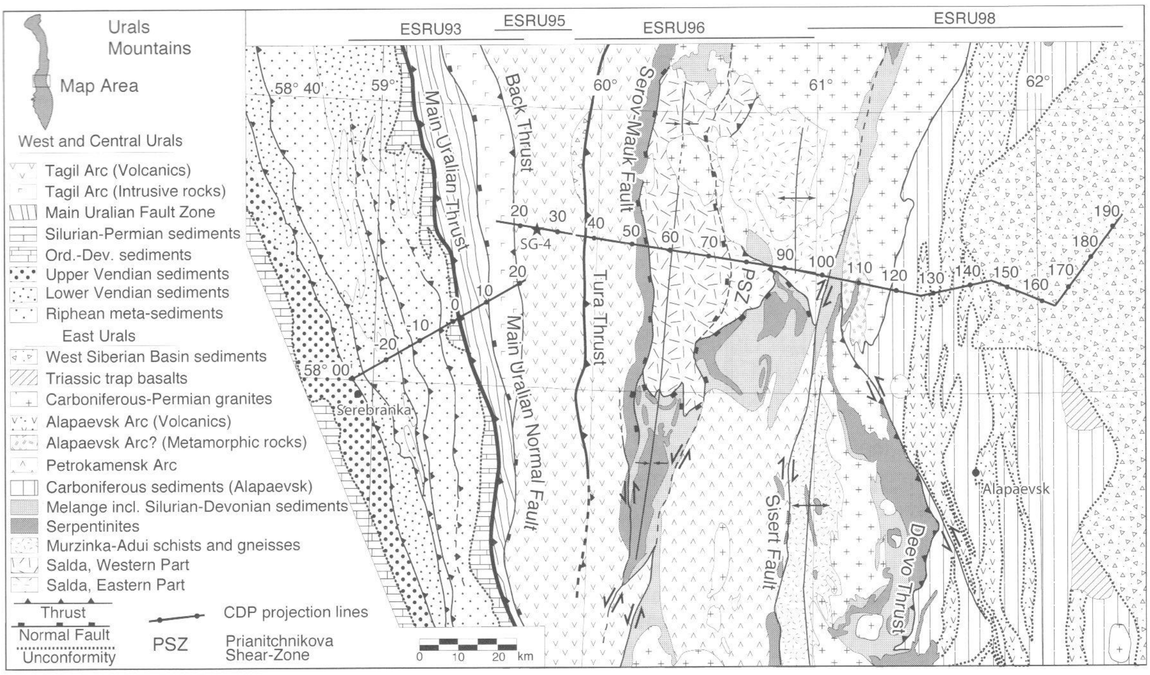

Fig. 2. Geological sketch map of the Middle Urals (based on Sobolev *et al.* 1964) with ESRU surveys shown. The extent of the individual survey lines is indicated at the top of the figure. Numbering refers to kilometres along the CDP line with km 0 at the Main Uralian Thrust. The West and Central Urals are defined to include the areas with highest topography. They roughly correspond to the area west of the Serov–Mauk Fault. The East Urals, with practically no topographic relief, mostly lie to the east of the Serov–Mauk Fault.

the Salda Metamorphic Complex, exposed within the footwall of the steeply west-dipping Serov–Mauk Fault (Fig. 2); the latter shows oblique normal movement (Friberg & Petrov 1998). This Palaeozoic high-grade complex (Friberg & Petrov 1998; Friberg *et al.* 2000a; Petrov *et al.* 2000) consists of granulite- to amphibolite-facies felsic and mafic orthogneisses (Fig. 3). The west-dipping Prianitchnikova Shear Zone separates it into a western and an eastern part. The oldest rocks in the western part are mafic to ultramafic gneisses exposed east of the Serov–Mauk Fault. Zircons from these gneisses have minimum ages of 500 Ma (Friberg *et al.* 2000a). The mafic gneisses are intruded by Lower Carboniferous (359 ± 5, 357 ± 7 and 343 ± 9 Ma) subduction-related gabbro–diorites and plagiogranites under granulite-facies conditions (Friberg & Petrov 1998; Friberg *et al.* 2000a; Petrov *et al.* 2000). The eastern part of the Salda Complex is dominated by metamorphosed granodiorites, but diorites, gabbros and pyroxenites are also present. These rocks display clear prograde metamorphism that peaks in granulite facies (Petrov *et al.* 2000). Single zircon Pb-evaporation data yield Early Devonian (393 ± 5 Ma) intrusive ages (Friberg *et al.* 2000a).

The Murzinka–Adui Metamorphic Complex to the SE of the Salda Complex is separated from the latter by the Petrokamensk Arc and the Sisert dextral strike-slip fault (Fig. 2). This fault can be traced as a narrow north–south-trending lineament along the entire length of the Middle Urals (Sobolev *et al.* 1964; Echtler *et al.* 1997). Single zircon evaporation data from felsic gneisses in the Murzinka–Adui Complex give a Mid-Devonian (372 ± 9 Ma) intrusive age (Friberg *et al.* 2000a).

The Salda and Murzinka–Adui Metamorphic Complexes are overlain by a greenschist-facies tectonic mélange composed of serpentinite bodies and a variety of volcanic and sedimentary rocks containing fossils ranging in age from Late Ordovician to Early Devonian time (Fig. 3; Sobolev *et al.* 1964; Antsigin *et al.* 1994).

Eastern volcanic rocks

South of the Salda Complex, overlying the tectonic mélange, are the Petrokamensk Arc volcanic rocks (Friberg & Petrov 1998). Here, the volcanic activity started in latest Silurian time and ceased in Late Devonian time (Fig. 3). The volcanic rocks are dominated by andesites with subordinate basalts and rhyolites. Metamorphic grade never exceeds greenschist facies (Sobolev *et al.* 1964).

West of the city of Alapaevsk (Fig. 2), a major west-dipping shear zone, the Deevo Thrust, separates the Murzinka–Adui Metamorphic Complex from the underlying Alapaevsk Arc volcanic rocks and sediments (Friberg & Petrov 1998; Juhlin *et al.* 1998). Associated with the Deevo Thrust is a serpentinite mélange, including Devonian volcaniclastic rocks, metamorphosed gabbro, diorites and granitoids (Sobolev *et al.* 1964). Further north along the ESRU seismic lines, this contact is disrupted by the Sisert Fault (Fig. 2). According to Antsigin *et al.* (1994), volcanic sequences in the Alapaevsk Arc are of Mid- and Late Devonian age. They include lavas and volcaniclastic rocks of basaltic and andesitic composition together with cogenetic gabbros, plagiogranites and granites. Overlying clastic material derived from the volcanic rocks is estimated to be of Late Devonian to Early Carboniferous age. These in turn are overlain by Lower Carboniferous limestones (Sobolev *et al.* 1964). The sequence ends with Upper Carboniferous continental-facies molasse deposits, including redbeds and coal-bearing strata (Fig. 3; Antsigin *et al.* 1994). Similar continental deposits, ranging in age from Late Carboniferous to Late Permian time, are reported to cover large parts of western Siberia (Czamanske *et al.* 1998).

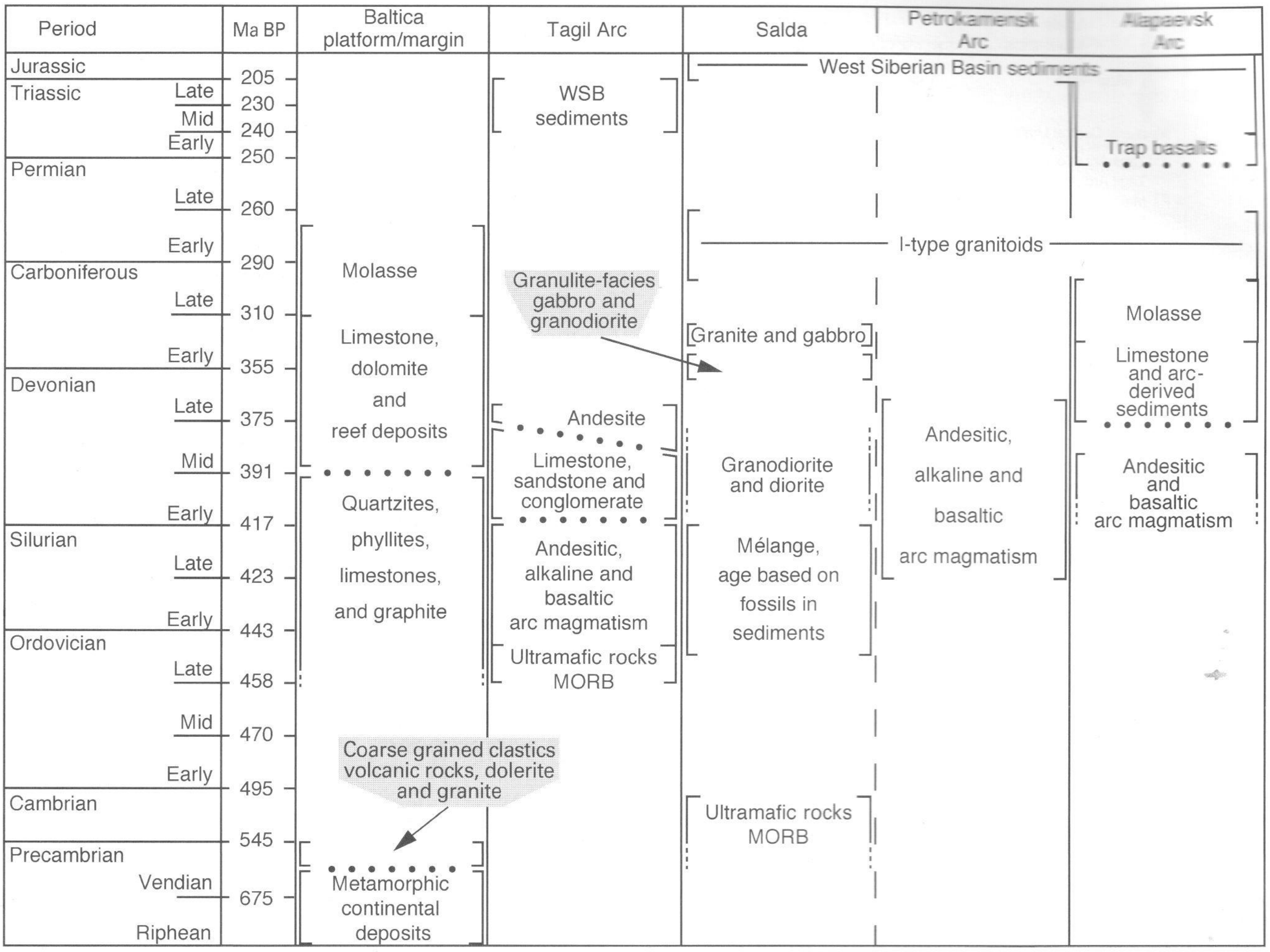

Fig. 3. Simplified stratigraphic sections for the main tectonic units exposed along the ESRU seismic lines based on data from Sobolev *et al.* (1964), Antsigin *et al.* (1994), Puchkov (1997), Friberg & Petrov (1998) and Friberg *et al.* (2000a). Correlation between absolute and stratigraphic ages is based on Snelling (1985) and modified according to Tucker & McKerrow (1995).

The entire Alapaevsk section is deformed by east-vergent folds and thrusts (Mogilev 1975).

Late to post-orogenic events

Carboniferous and Permian granitoid batholiths with associated subordinate diorite and gabbro intrusions are found throughout the hinterland of the Middle Urals east of the Tagil Arc (Fig. 2; Sobolev *et al.* 1964; Fershtater *et al.* 1997; Montero *et al.* 2000). Bea *et al.* (1997) showed that one of these, the Verkh–Isetsk massif exposed in the southern Middle Urals, consists of two phases of intrusion, one of Late Carboniferous age and one of Early Permian age. The latter is derived as a partial melt from the Late Carboniferous phase at shallow crustal levels (P <4 kbar).

The hinterland of the Middle Urals is strongly influenced by north–south-trending strike-slip faults (e.g. Sisert Fault in Fig. 2). These are traceable for hundreds of kilometres along the orogen. They affect all Palaeozoic rocks in the area, including the Permian granites (Sobolev *et al.* 1964; Sengör *et al.* 1993).

Trap basalts of Early Triassic age cover large parts of western Siberia and the eastern Urals from the Middle Urals and northwards (Fig. 3). Where present, they form the basement to the West Siberian Basin (Renne & Basu 1991; Kamo *et al.* 1996). The Triassic and Lower Jurassic sediments of this basin extend further west and overlie the Palaeozoic rocks in the North and Middle Urals east of the Main Uralian Fault Zone (Fig. 1).

According to Khain (1985), the Palaeozoic Urals were eroded down to a peneplain by the end of Jurassic time, with platform sediments covering most of the orogen. The present-day topography is due to Late Oligocene uplift and compression (Borisevich 1992). This event is recorded in thrusts inverting Mesozoic basins in the Middle and Northern Urals (Fig. 2).

The ESRU seismic data

The 56 km long ESRU93 reflection seismic line is oriented in a SW–NE direction (Fig. 2). It begins near the western edge of the Kvarkush Anticline, crosses the Main Uralian Fault Zone and ends in the western part of the Tagil Arc (Juhlin *et al.* 1995). The 25 km long ESRU95 survey focuses on the geology near the SG-4 borehole (Fig. 2; Juhlin *et al.* 1997). There is an 800 m gap between the ESRU95 line and its eastward continuation, the 80 km long ESRU96 line (Fig. 2; Juhlin *et al.* 1998). ESRU96 images the eastern part of the Tagil Arc and most of the Salda Metamorphic Complex. The western end of the ESRU98 seismic line has a 2.5 km overlap with the eastern end of ESRU96 (Fig. 2). It starts in the eastern region of the Salda Metamorphic Complex, and passes eastwards over a narrow zone of mélange and metamorphic rocks of unknown origin to Alapaevsk volcanic rocks and sediments. The eastern end of the ESRU98 line has a northeastern trend and Palaeozoic rocks along it are completely covered by Mesozoic strata of the West Siberian Basin (Fig. 2; Friberg *et al.* 2000b).

To construct an image across the orogen, we have merged the ESRU datasets and projected the combined sections onto a geological map (Fig. 4). The line drawings were made individually for each dataset using an automatic picking routine based on coherency. Line drawings are more suitable than variable-area–wiggle plots for displaying large seismic sections at a size appropriate for publication. Furthermore, the ESRU variable-area–wiggle data did not migrate well, largely because of the discontinuous nature of the reflections and relatively high noise levels. Sample migrated variable-area plots are shown for the upper 18 km of the western part of ESRU93 and lower section of ESRU98 Line 4 in Fig. 5a and b, respectively. For more detailed descriptions of the individual features imaged by the ESRU seismic data we refer to the publications byJuhlin *et al.* (1995, 1997, 1998), Knapp *et al.* (1998), Ayarza *et al.* (2000b) and Friberg *et al.* (2000b).

To facilitate comparisons between the datasets, we have made the common depth point (CDP) numbering and kilometre scale consistent with Juhlin *et al.* (1998); CDP 0 and km 0 were set at the approximate location of the Main Uralian Thrust on the ESRU93 CDP line. To produce the migrated line drawing in Fig. 6a, we have used the same velocities as Juhlin *et al.* (1998); they are the root-mean-square velocities derived from the GRANIT refraction seismic experiment (Juhlin *et al.* 1996). For migration, the line drawings were grouped as follows: (1) ESRU93; (2) ESRU95 and -96; (3) ESRU98 Lines 1–3; (4) ESRU98 Line 4. This procedure avoided incorrect migration of events around bends and corners. In addition, the ESRU96 section was extended 10 km to the east and Line 1 of the ESRU98 survey was lengthened 10 km to the west, thus yielding an overlap between the two sections at km 88–105. In this manner, events could migrate into the extended zones. The overlap zone is shown by dashed lines in Fig. 6a. Similarly, the ESRU93 section was extended 5 km to the NE to show the SW-dipping events that would otherwise migrate off the section. This extension results in the projected lines being slightly different at km 20 in Figs. 4 and 6.

To allow comparison of the ESRU data with the results from the UWARS (Thouvenot *et al.* 1995) wide-angle reflection and the GRANIT (Juhlin *et al.* 1996) refraction seismic surveys, the interpreted crustal thicknesses from these experiments have been projected onto the CDP lines (Fig. 6a).

Interpretation of the seismic data

Upper crust

Many reflectors imaged on the ESRU seismic sections correlate with tectonic boundaries. In the eastern foreland (SW of km 0; Fig. 5a), there are NE-dipping reflections from SW-vergent thrusts, some related to pre-Palaeozoic deformation, others associated with uplift of Upper Proterozoic rocks now exposed in the Kvarkush Anticline (e.g. the fault referred to in this paper as the Serebranka Thrust (ST in Fig. 6a)). The deformation continues further west, but west of the ESRU seismic surveys it is largely confined to the overlying Palaeozoic rocks. Between km –30 and km –25, the presumed Late Proterozoic strata are imaged as flat-lying reflections down to 8 km (Fig. 5a, PS in Fig. 6a).

The Main Uralian Thrust (km 0, MUT in Fig. 6a) in the Middle Urals places the deformed outer margin of Baltica in the hanging wall onto Baltica continental crust with overlying sediments in the footwall. At km 10, steeply dipping reflections mark the contact between the deformed former continental margin and oceanic terranes to the east. The interpretation that this contact is a major normal fault, the Main Uralian Normal Fault (MUNF in Fig. 5a; Juhlin *et al.* 1993; Friberg & Petrov 1998; Knapp *et al.* 1998) is consistent with geological data (Beckholmen & Juhlin 1997). Ayarza *et al.* (2000a) suggested that the Main Uralian Fault Zone (the region between the Main Uralian Thrust (MUT) and the Main Uralian Normal Fault (MUNF) in Fig. 6a) may have been subjected to strike-slip movement throughout the Middle Urals. However, structural data that may be used to assess this proposal are lacking. We interpret the SW-dipping reflections that project to the surface at km 20 to originate from a back-thrust (BT in Fig. 6a), active during accretion of the Tagil Arc to the continent. This back-thrusting placed layered intrusions and sheeted dyke complexes with mid-ocean ridge basalt (MORB) chemistry, intruded by plutons with island-arc affinity (Schmelev *et al.* 1997), onto the volcanic rocks of the Tagil Arc. These SW-dipping reflections are truncated by reflections from the Main Uralian Normal Fault.

Further east and not well imaged by the ESRU data, the gently to moderately east-dipping Tura Thrust (km 38) emplaces Silurian volcanic rocks and Lower Devonian limestones onto Triassic units. The hanging-wall rocks show intense mylonitization near the thrust. However, reconstructions based on coal-mining exploration data indicate only a few hundred metres of movement on this fault since Triassic time (Sokolov, pers. comm.). We propose that post-Triassic deformation reactivated an older structure established in Palaeozoic time. Detailed analyses of older reflection seismic data (Sokolov 1993) suggest that the latest movement on the Tura Thrust truncates the Serov–Mauk Fault at 7 km depth. The Serov–Mauk Fault (km 50, SMF in Fig. 6a) is imaged by weak west-dipping reflectivity down to *c.* 7 km. To the east are high-grade gneisses of the Salda Metamorphic Complex (km 50–101), which are dissected by the Prianitchnikova Shear Zone (km 70–80, PSZ in Fig. 6a). The latter is a thrust that imbricates the high-grade rocks. It appears to be cut by a normal fault (km 70, NF1 in Fig. 6a) that has not been identified in the surface geology; its existence is based on an interpretation of the seismic section by Juhlin *et al.* (1998).

At km 101, the seismic section crosses the Sisert Fault (SF in Fig. 6a). The change in reflective character from km 90 to km 105 could be partly due to the merging of two datasets with different acquisition parameters (Juhlin *et al.* 1998; Friberg *et al.* 2000b). Nevertheless, it is clear that no reflections in the upper and middle crust can be traced across the Sisert Fault (Fig. 6a).

Between km 101 and km 120, metamorphic rocks of unknown origin are exposed. These are unconformably overlain by Lower Carboniferous limestones of the Alapaevsk unit and cut by a Permian granite (Grevtsova *et al.* 1970; Friberg *et al.* 2000a). Further east, the boundary between the Permian granite and the overlying Lower Carboniferous limestones of the Alapaevsk Arc to the east coincides with strong

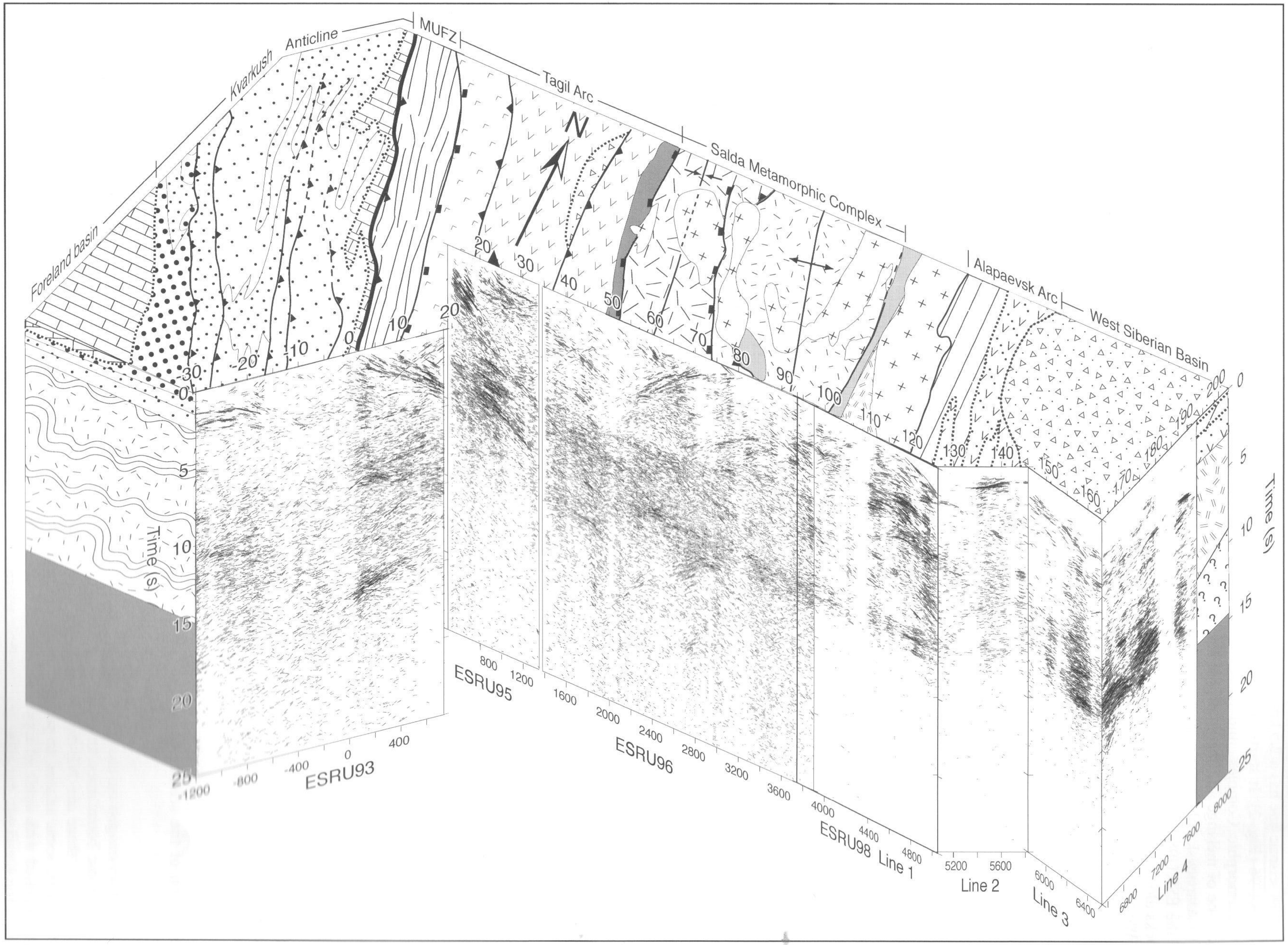

Fig. 4. Geological map plotted above automatic line drawings made from ESRU seismic reflection profiles. Patterns showing geological units are described in Fig. 2. MUFZ, Main Uralian Fault Zone.

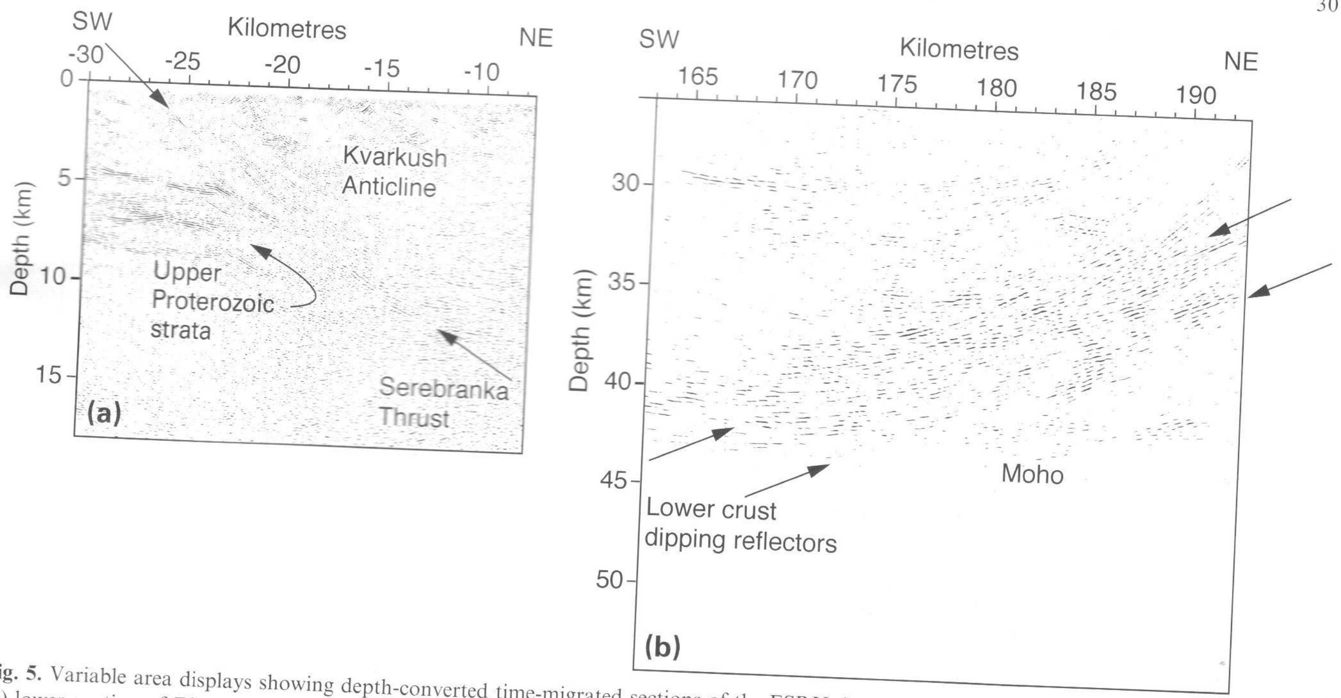

Fig. 5. Variable area displays showing depth-converted time-migrated sections of the ESRU data. (**a**) Upper portion of westernmost ESRU93; (**b**) lower portion of ESRU98 Line 4.

east-dipping reflectivity (km 120). As there is no sign of contact metamorphism in the limestones (Sobolev *et al.* 1964), we interpret this to be a normal fault (NF2 in Fig. 6a). The relatively transparent upper part of the crust east of km 120 to the end of the seismic section coincides with deformed sedimentary and volcanic units of the Alapaevsk Arc and overlying molasse. Underneath, the reflectivity is probably associated with deformed island-arc basement rocks similar to the Salda and Murzinka–Adui Metamorphic Complexes.

The Triassic strata of the West Siberian Basin extend to no more than 200 m depth in our investigation area (Sobolev *et al.* 1964), too thin to be imaged reliably by the ESRU98 data. The eastern margin of the basin coincides with the surface projection of moderately east-dipping reflectivity (NF3 in Fig. 6a). It appears to offset the boundary between the more transparent upper part of the Alapaevsk Arc and the more reflective crust below. This could be a fault that delineates the present-day eastern boundary of the West Siberian Basin.

Middle crust

The middle crust under the eastern margin of Baltica and the Tagil and Salda terranes (km −10 to km 100, Fig. 6a) is characterized by discontinuous subhorizontal reflectivity. To the west and east, the reflectivity decreases. In the west, the boundary between the highly reflective and less reflective middle crust is approximately coincident with the Serebranka Thrust. In the east, the strong reflectivity terminates against the Sisert Fault.

West of the Main Uralian Fault Zone, the middle-crustal reflectivity is probably related to formation of the passive continental margin, before Mid-Ordovician time. The origin of middle-crustal reflectivity beneath the remnant arc terranes is speculative. It may be due to structures that developed as the arcs were formed or due to structures created during their accretion to the continent (Steer *et al.* 1995). Moreover, the possibility that it represents a post-orogenic extensional fabric cannot be ruled out (Steer *et al.* 1995; Koyi *et al.* 1999).

The only well-defined dipping structure observed in the middle crust is inferred to be the subsurface extension of the Deevo Thrust (DT in Fig. 6a and previously referred to as the Trans-Uralian Thrust by Juhlin *et al.* (1998)). This moderately west-dipping structure is visible from km 90 at *c.* 18 km depth to km −5 at *c.* 50 km depth, where it possibly cuts the Moho defined by the UWARS and ESRU datasets. However, it does not continue across the Moho defined by the GRANIT velocity model (Fig. 6a). Our interpretation is that the Sisert Fault truncates the upper portion of the Deevo Thrust at *c.* 15 km depth (Fig. 6b) at this latitude. Because the Sisert Fault has experienced significant right-lateral movement (Fig. 2; Echtler *et al.* 1997; Friberg *et al.* 2000b) the surface outcrop of the Deevo Thrust occurs south of the ESRU lines. Approximately 15 km west of the city of Alapaevsk, it is a major tectonic boundary that places serpentinite mélange eastwards on top of the molasse (Fig. 2; Sobolev *et al.* 1964). Approximately 50 km of right-lateral movement on the Sisert Fault will be sufficient to yield the geometries of the geological units and faults depicted in Figs. 2 and 6b. Such a movement is consistent with the observation that rocks exposed in the Murzinka–Adui Complex are similar in age, chemistry and metamorphism to those in the eastern part of the Salda Complex (Grevtsova *et al.* 1970; Antsigin *et al.* 1994; Friberg *et al.* 2000a).

Because the Deevo Thrust can be traced as a gently west-dipping structure through the middle and lower crust, it has to cut the Main Uralian Fault Zone in the middle crust below the surface expression of the Tagil or Petrokamensk–Salda Arcs. This is schematically shown in Fig. 6b. Our interpretation explains why the Main Uralian Fault Zone cannot be traced into the lower crust, even though it is the principal suture between Baltica and the accreted arcs.

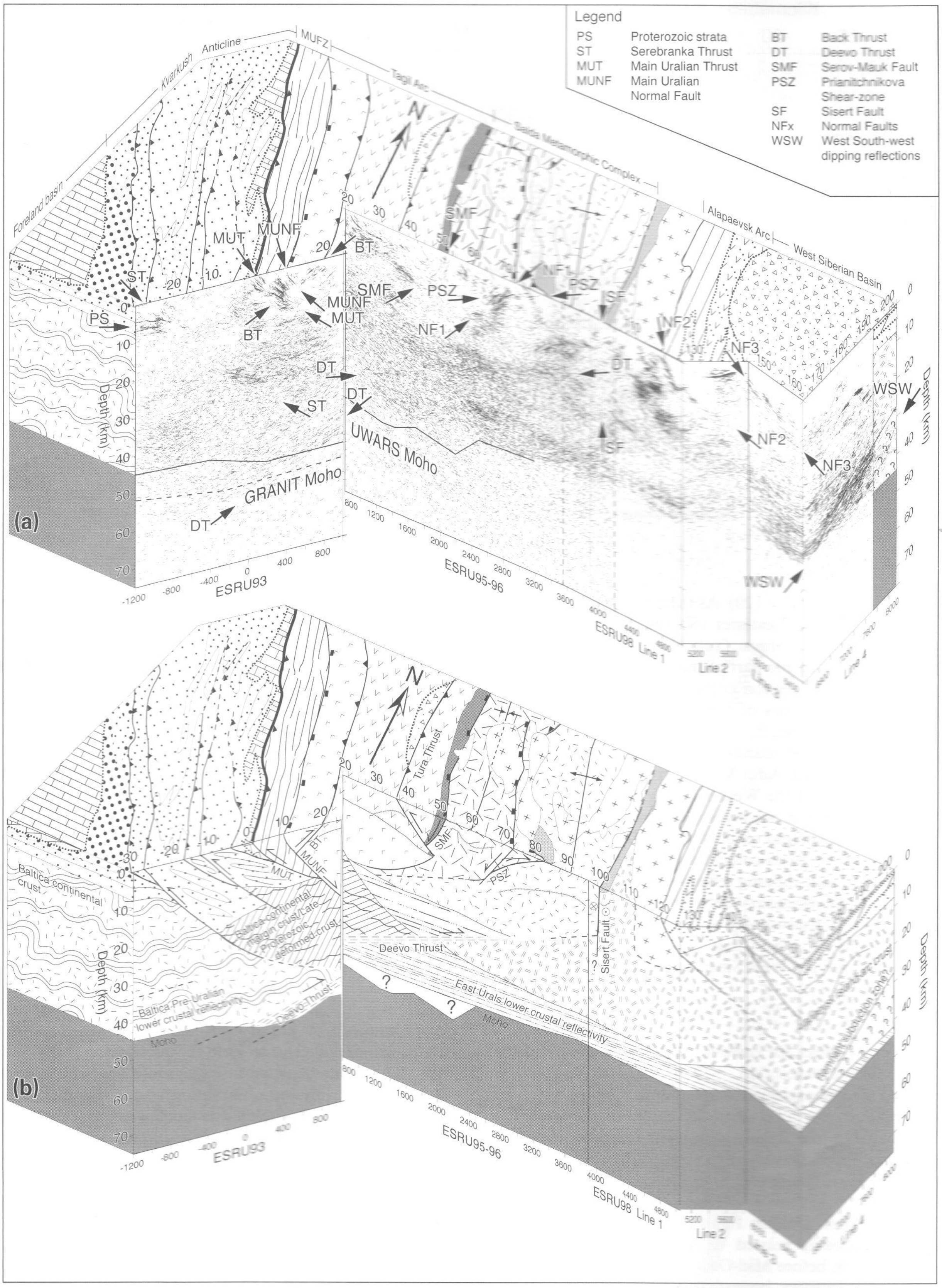

Fig. 6. Interpretation of migrated seismic sections. (**a**) Depth-migrated line drawing with the main features indicated by arrows. The abbreviations are explained in the text and in the top right corner of the figure. (**b**) Sketch showing the depth projection of main geological units.

Lower crust and Moho

Juhlin *et al.* (1998) interpreted the reflective lower crust and Moho under the portion of Baltica SW of km −15 to be a pre-Uralian feature, similar in character and origin to that observed in the lower crust elsewhere below the continent; for example, beneath the Baltic Sea, the Moho is found at 43–50 km depth and is commonly overlain by discontinuous subhorizontal reflectivity (Babel Working Group 1990).

Pronounced lower-crustal reflectivity is also observed throughout the hinterland east of km 0. In the west, it seems to continue above the Moho depression (km −10 to km 50; Juhlin *et al.* 1996, 1998; Thouvenot *et al.* 1995) that roughly corresponds to the surface expression of the Tagil Arc. It terminates against the Deevo Thrust. In the east it can be traced beneath the west-dipping reflectivity observed in the lower crust east of km 165 (Fig. 5b and 6a). East of km 50, pronounced lower-crustal reflectivity forms a 4–7 km thick band that consistently has its base at 43–45 km depth. Assuming this base to be the Moho, the ESRU data demonstrate that the Moho and lower crust in the hinterland of the Middle Urals can be traced as a relatively continuous feature eastwards beneath the West Siberian Basin.

Explanations for the zone of diffuse reflectivity above the 48–50 km deep Moho (Thouvenot *et al.* 1995; Juhlin *et al.* 1996, 1998) and the overlying region of stronger reflectivity between 35 and 45 km depth (below the Tagil Arc) are speculative. Possibilities include the following: (1) the region above the Moho is made up of less reflective Baltica margin crust. (2) The lowermost crust in this area consists of underplated material (Holland & Lambert 1975). (3) The strong reflections in the middle and lower crust are the result of stretching that occurred above the present-day crustal root. Numerical studies by Koyi *et al.* (1999) suggested that lower-crustal reflectivity under the Middle Urals may be the result of isostatic rebound of an orogenic root zone after compression ceased: their model implies that buoyant uplift of the root could result in ductile flow in the lower and middle crust with little effect on the upper brittle crust. (4) Stretching and thinning that produced the West Siberian Basin propagated as far west as the Main Uralian Normal Fault, but did not affect the lowermost crust below the Tagil Arc (Friberg *et al.* 2000b). Lower-crustal reflectivity, similar to that observed east of km 0, is observed across the Caledonides in the eastern North Sea (Mona Lisa Working Group 1997), where the crust has been affected by significant extension after the Caledonian orogeny. The geological interpretation in Fig. 6b is based on the fourth model.

The pronounced and gently dipping reflectivities observed in the lower crust on ESRU98 Line 4 (Fig. 4) have been analysed using a pseudo-3D data processing routine. They are found to originate from reflectors dipping 23° towards S64°W (Friberg *et al.* 2000b). Upon migration, it is evident that they are truncated by subhorizontal reflectivity at *c.* 43 km depth (Figs. 5b and 6a), such that they do not continue across the Moho. Friberg *et al.* (2000b) speculated that these reflections could originate from a remnant subduction zone above which the Alapaevsk Arc was built.

Suggested Palaeozoic tectonic evolution of the Middle Urals based on ESRU reflection seismic data and surface geological observations

The time of formation of Baltica's eastern passive margin (present coordinates) is not well constrained. It developed after the Vendian orogeny, probably in Mid- or Late Cambrian time (Fig. 7a), and remained as a passive margin until Early Carboniferous time (Puchkov 1997). The geochemical zoning of magmatic rocks in the Tagil Arc Complex implies eastward intra-oceanic subduction outboard of Baltica in Early Silurian time (Fig. 7b). During Late Silurian time, magmatism migrated away from the Tagil Arc to the Petrokamensk Arc and the Salda Metamorphic Complex. Subduction-related magmatism was active in the Petrokamensk–Salda Arc until Late Devonian time (Fig. 7c). Minor Devonian andesitic magmatic rocks in the eastern part of the Tagil Arc are probably related to this magmatic event. As magma is generated at fairly constant depths above subduction zones (Tatsumi & Eggins 1995), migrating arc magmatism may result from: (1) a change in angle of subduction; (2) movement of the initial arc towards the trench and out of the melting zone as a result of tectonic erosion at the base of the overriding plate; or (3) a combination of these two processes. The last two models are more likely for the Middle Urals, as no intra-oceanic accretionary complex is present west of the Tagil Arc, thus implying erosive subduction.

On the basis of the Tagil and Petrokamensk–Salda relationship discussed above and the absence of prominent reflectivity, such as observed from the Main Uralian Fault Zone and the Deevo Thrust (Fig. 4), we do not interpret the Serov–Mauk Serpentinite Belt as a major terrane boundary. Instead, we interpret the associated Serov–Mauk Fault and the tectonic mélange separating the overlying Tagil and Petrokamensk volcanic rocks from the underlying high-grade rocks of the Salda Metamorphic Complex (Fig. 2) to be a detachment along which the Salda Complex was exposed (Fig. 6b). Further support for this interpretation is found in the southern part of the study area (Fig. 2), where the serpentinite mélange that separates the Tagil and Petrokamensk island-arc volcanic rocks is flat-lying and only gently folded. Moreover, the otherwise strong westward drop in metamorphic grade is absent at this southern location, implying that there was no or only minor normal displacement along the southward projection of the Serov-Mauk Fault.

In Mid-Devonian time, the depositional environment changed on the Baltica platform. Clastic deposits eroded off the continent began to appear (Fig. 7c). Soon thereafter, the sedimentation changed into a distal marine environment. This may be explained by loading of the Baltica lithosphere as the sea between Baltica and the converging Tagil Arc closed. This loading would have been contemporaneous with formation of the Alapaevsk Arc outboard of the still active Petrokamensk–Salda Arc (Fig. 7c). Petrochemical data that indicate the polarity of subduction are lacking from the Alapaevsk region. One possibility is that the WSW-dipping reflections observed in the easternmost part of the ESRU98 data represent remnants of this subduction (Figs. 5b and 6a). This would require two active subduction zones dipping towards each other. Present-day analogues are rare, but a similar relation is observed beneath the northern part of the Philippines (Mukasa *et al.* 1994). An alternative model would have the two subduction zones with the same polarity, but this model has no support in the seismic data.

During Early Carboniferous time, sedimentation on the Baltica platform returned to continental facies. One speculative interpretation for this change in sediment environment is that the subducted slab broke off, thus generating a buoyancy that resulted in uplift of Baltica (Fig. 7d). This would have been synchronous with the emplacement of intrusions at the

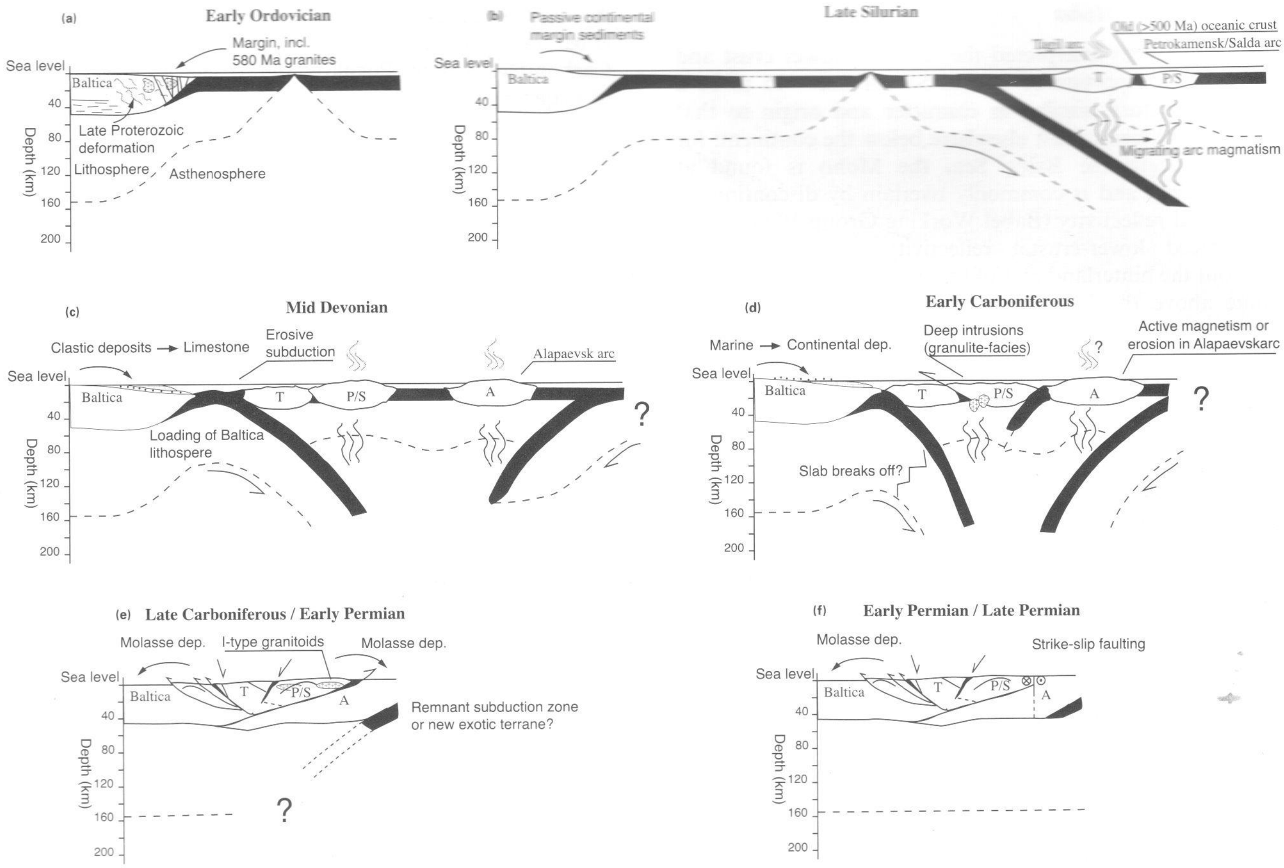

Fig. 7. Suggested Palaeozoic tectonic evolution of the Middle Urals along the ESRU seismic lines.

base of the inactive Petrokamensk–Salda Arc. These deep-seated intrusions, which are now exposed in the Salda Metamorphic Complex (Fig. 2; Friberg *et al.* 2000a; Petrov *et al.* 2000), have no correspondence in the overlying arc volcanic rocks. Furthermore, no sediments deposited from Early Carboniferous to Triassic time are recognized within Tagil and Petrokamensk–Salda Arcs, perhaps indicating that these arcs were elevated above sea level at the same time as the Baltica Platform.

In Late Carboniferous time, the Tagil Arc and the thinned margin of Baltica were thrust westwards along the Main Uralian Thrust onto the continent (Figs. 6b and 7e). Simultaneously, the deeper part of the arc was thrust eastwards along the back-thrust marked BT in Fig. 6a. Continued thrusting may have resulted in the collapse of the hanging wall, yielding an extrusion wedge in the Main Uralian Fault Zone (km 0–10 in Fig. 6b). It presumably also led to imbrication and uplift along the Serebranka Thrust of the Vendian-deformed basement rocks now exposed in the Kvarkush Anticline. These rocks contributed debris to the molasse basin in the foreland. Emplacement of the arc, uplift of the basement and deposition of molasse sediments continued until the end of Early Permian time. At the same time, a molasse basin developed in the hinterland east of the Petrokamensk–Salda Arc. Upper Carboniferous molasse sediments largely cover the Alapaevsk Arc and, although Permian continental deposits are not present in the study area, they have been reported from drill-holes further east (Czamanske *et al.* 1998), where they are in turn covered by West Siberian Basin sediments. In the southern Middle Urals, the suture between the Petrokamensk–Salda and the Alapaevsk Arcs, the Deevo Thrust (Fig. 2), had a serpentine mélange in the hanging wall that was thrust eastwards onto the Late Carboniferous molasse and underlying sediments and volcanic rocks.

When the arcs accreted to the continental margin, the Main Uralian Thrust and Deevo Thrust were active simultaneously, probably causing uplift of the arc material between them. Normal faulting (i.e. along the Main Uralian Normal Fault and Serov–Mauk Fault) led to the unroofing of metamorphic rocks in their footwalls (Figs. 6b and 7c). The normal movements along these faults were significant, as the change in metamorphic grade across them corresponds to 10 km and locally up to 40 km of crust (Friberg *et al.* 2000a; Petrov *et al.* 2000). The high-grade complexes were intensely migmatized as they were uplifted, such that remelted country rocks may have formed batholiths like the Lower Permian Verkh–Isetsk massif (Bea *et al.* 1997).

During or subsequent to the collision and emplacement of the Permian granitoids, north–south-trending strike-slip faults were active in the hinterland of the Middle Urals (Ayarza *et al.* 2000a). Some had a dextral sense of shear (e.g. the Sisert Fault; Echtler *et al.* 1997), whereas others appear to have moved in the opposite direction (Fig. 2). The strike-slip faults only locally followed the major tectonic boundaries (e.g. Sisert–Deevo relation in Figs. 2 and 7f). Consequently, we conclude that they did not control the orogeny, but rather developed at a very late stage of convergence.

The final major episode of magmatism involved the eruption of the Siberian trap basalts at the Permo-Triassic boundary (Renne & Basu 1991; Kamo *et al.* 1996). This event was probably associated with crustal stretching and/or underplating that eliminated any Moho topography in the eastern Urals (Fig. 6b). It certainly resulted in subsidence of the eastern Urals and western Siberia, forming the world's largest intracontinental sedimentary basin. After this event, at least until Early Jurassic time, shallow-water marine and continental sediments were deposited in the hinterland of the Middle Urals and eastwards. Thereafter, new thrusting, together with reactivation of older faults, led to inversion of the Mesozoic basins. It has been suggested (Borisevich 1992) that some of these faults are still active today.

Conclusions

On the basis of a new compilation of deep seismic reflection data, an analysis of the exposed geology and an examination of critical isotopic and related information, we have derived a highly modified structural and evolutionary model for the Middle Urals. Critical features in the deep seismic reflection data are: (1) changes in metamorphic grade and/or style of deformation are coincident with faults that can be identified in the seismic sections (e.g. Serebranka Thrust, Main Uralian Fault Zone, the back-thrust in the western part of the Tagil Arc, Serov–Mauk Fault and Sisert Fault); (2) the Serebranka Thrust marks the western margin of deformation in the pre-Palaeozoic basement of Baltica's former continental margin; (3) the Main Uralian Thrust and Main Uralian Normal Fault both appear to have been truncated by the younger low-angle Deevo Thrust or by younger middle-crustal reflectivity; (4) neither the Deevo Thrust nor the prominent middle-crustal reflectivity can be traced across the Sisert Fault; (5) prominent and moderately WSW-dipping reflections are present in the lower crust beneath the Alapaevsk Arc near the western margin of the West Siberian Basin; (6) reflectivity in the lower crust and the reflective Moho are similar beneath the eastern Urals and the western part of the West Siberian Basin.

Key features of our proposed evolutionary model include: (1) the Baltica passive margin developed after Late Vendian time and remained until the Early Carboniferous collision; (2) the Tagil and Salda–Petrokamensk Arcs were probably built above the same east-directed subduction zone, which was active from Late Ordovician to Early Carboniferous time; (3) the Alapaevesk Arc was located east of the Salda–Petrokamensk Arc (present-day coordinates) and was probably formed as a result of westward subduction in Devonian time; (4) accretion of the arcs to Baltica's margin occurred during Carboniferous time; (5) compression continued into Permian time, with later shortening being largely accommodated by strike-slip faulting in the hinterland; (6) uplift and exposure of the high-grade arc terranes in the Salda and Murzinka–Adui Complexes was to a large extent synchronous with the collision and the emplacement of I-type granitoids; (7) the Permo-Triassic eruption of trap basalts marked the formation of the West Siberian Basin, which extended westwards to the Main Uralian Fault Zone; this event probably removed all remaining Moho topography apart from a minor depression still visible beneath the Tagil Arc; (8) renewed compression led to minor reactivation along older faults and the inversion of some Mesozoic basins.

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