Geological Society, London, Special Publications

The evolution of the Uralian orogen

Victor N. Puchkov

Geological Society, London, Special Publications 2009; v. 327; p. 161-195
doi:10.1144/SP327.9

Notes

The evolution of the Uralian orogen

VICTOR N. PUCHKOV

K. Marx st. 16/2, Institute of Geology, Ufimian Scientific Centre, Russian Academy of Sciences, 450 000 Ufa, Russia (e-mail: puchkv@anrb.ru)

Abstract: The Uralian orogen is located along the western flank of a huge (>4000 km long) intracontinental Uralo-Mongolian mobile belt. The orogen developed mainly between the Late Devonian and the Late Permian, with a brief resumption of orogenic activity in the Lower Jurassic and Pliocene–Quaternary time. Although its evolution is commonly related to the Variscides of Western Europe, its very distinctive features argue against a simple geodynamic connection. To a first order, the evolution of Uralian orogen shows similarities with the 'Wilson cycle', beginning with epi-continental rifting (Late Cambrian–Lower Ordovician) followed by passive margin (since Middle Ordovician) development, onset of subduction and arc-related magmatism (Late Ordovician) followed by arc–continent collision (Late Devonian in the south and Early Carboniferous in the north) and continent–continent collision (beginning in the mid-Carboniferous). In detail, however, the Uralides preserve a number of rare features. Oceanic (Ordovician to Lower Devonian) and island–arc (Ordovician to Lower Carboniferous) complexes are particularly well preserved as is the foreland belt in the Southern Urals, which exhibits very limited shortening of deformed Mesoproterozoic to Permian sediments. Geophysical studies indicate the presence of 'cold', isostatically equilibrated root. Other characteristic features include a Silurian platinum-rich belt of subduction-related layered plutons, a simultaneous development of orogenic and rift-related magmatism, a succession of collisions that are both diachronous and oblique, and a single dominant stage of transpressive deformation after the Early Carboniferous. The end result is a pronounced bi-vergent structure. The Uralides are also characterized by Meso-Cenozoic post-orogenic stage and plume-related tectonics in Ordovician, Devonian and especially Triassic time. The evolution of the Uralides is consistent with the development and destruction of a Palaeouralian ocean to form part of a giant Uralo-Mongolian orogen, which involved an interaction of cratonic Baltica and Siberia with a young and rheologically weak Kazakhstanian continent. The Uralides are characterized by protracted and recurrent orogenesis, interrupted in the Triassic by tectonothermal activity associated with the Uralo-Siberian superplume.

Introduction

The last general review of the structural and tectonic evolution of the Uralian orogen was published in English more than 10 years ago (Puchkov 1997). Since then, the stimulus created by the international EUROPROBE *Uralides* Project has resulted in considerable advances in the understanding of the geology of the Urals. However, most publications in English are concerned with the evolution of the Southern and Middle Urals (Brown *et al.* 2006*a*, 2008, and references therein). This publication provides an overview of the tectonic evolution of the Uralian orogen as a whole, incorporating a wealth of recently published data, and compares this evolution with that of the European Variscides and Mesozoic-Cenozoic orogens.

The Uralian orogen *sensu stricto* partly coincides geographically with the young, neotectonic (Pliocene–Quaternary) Urals mountains, and occurs between three former, Palaeozoic continents: Baltica, Kazakhstania and Siberia (Fig. 1). In the Early Palaeozoic, these continents were separated by the Palaeouralian and Central Asian oceans. The continents and oceans were partly inherited from the Proterozoic (Vernikovsky *et al.* 2004; Puchkov 2005). The Central Asian (or Palaeo-Asian) ocean existed before the Late Neoproterozoic as the portion of the Palaeo-Pacific Ocean, which surrounded a considerable part of the Siberian continent. A complete separation of this continent from Rodinia by 750 Ma resulted in the birth of the Palaeo-Asian ocean (Li *et al.* 2008).

The E–NE margin of Baltica was modified by the Ediacarian deformational and accretionary events of the Timanian orogeny (Puchkov 1997; Gee *et al.* 2006). A close resemblance of Timanides and Cadomides pointed out by the author (Puchkov 1997) has led to an idea of their immediate lateral connection, supporting a notion of a supercontinent (Pannotia, Dalziel 1992; or Panterra, Puchkov 2000), welded by Ediacarian orogenies. Several variants of such a connection have been suggested, depending on what side of Baltica was thought to

From: MURPHY, J. B., KEPPIE, J. D. & HYNES, A. J. (eds) *Ancient Orogens and Modern Analogues.* Geological Society, London, Special Publications, **327**, 161–195.
DOI: 10.1144/SP327.9 0305-8719/09/$15.00

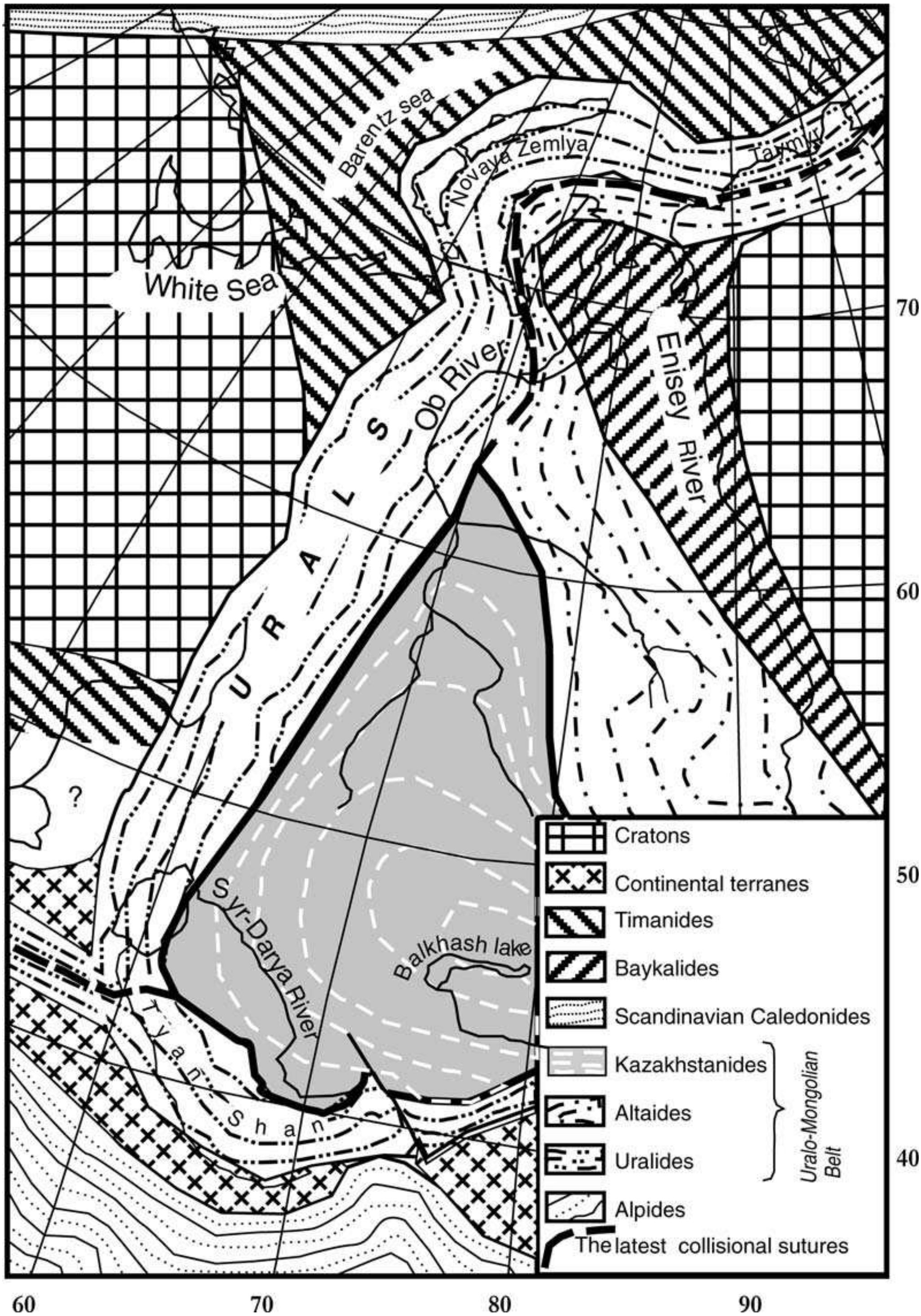

Fig. 1. Position and linkages of the Urals in the structure of the Central Eurasia.

be attached to Gondwana (e.g. Linneman *et al.* 1998; Puchkov 2000; Cocks & Torsvik 2006). Unfortunately the APWP of Baltica is still very poorly constrained by existing palaeomagnetic data and additional work is required to distinguish between these hypotheses.

The Timanian/Cadomian orogeny was followed by Late Cambrian–Early Ordovician rifting and passive margin development (Puchkov 2005; Pease *et al.* 2008). These events led to the development of the Palaeouralian ocean, which contained some younger microcontinents (the continent that rifted-away from Baltica is not identified yet). The Mid- to Late Palaeozoic history of the Uralian orogen can be described in terms of formation of an island-arc crust (Late Ordovician–Devonian) and followed by Late Devonian–Early Carboniferous accretion of the island-arcs and other microcontinents with the continental margin of Baltica, which by that time had merged with Laurentia to form Laurussia (Brown *et al.* 1997, 2006*a–c*). Kazakhstania formed in the Ordovician–Silurian as a result of subduction-driven accretion of crust around small Neoproterozoic microcontinents (Puchkov 1996*a*). Its collision with the terranes previously accreted to the margins of Laurussia and Siberia started in the Late Bashkirian, after the intervening oceanic crust was completely subducted. This continent–continent collision continued into Permian time, and resulted in the formation of huge foldbelt, variously known as Uralo-Mongolian (Muratov 1979) or Uralo-Okhotskian (Khain 2001) belt, a fundamental event in the assembly of Pangaea. The narrow western flank of the orogen is known as the Uralides, and the more extensive central and eastern flank of the belt is called the Altaides (Sengör *et al.* 1993). However the positioning of the Kazakhstanian continent as a separate Mid-Palaeozoic structure (Figs 1 & 2) suggests that the Kazakhstanides should be excluded from the Altaides.

An attempt to formalize the term 'Uralides' was made by Puchkov (2003), who noted that the northern continuation of the western zones of the Urals is represented by the Pay-Khoy-Novozemelian foldbelt, which was the result of the younger (Early Jurassic) collision between Laurussia and Siberia. More southern parts of the Urals were also deformed by this collision, though the intensity and structural expression are not as prominent.

To the south, Late Palaeozoic collisional structures of the Urals continue in the south-southwestwards vergent fold-and-thrust belt of the Southern Tyan-Shan. Like the Urals, this Late Palaeozoic belt is bordered to the NE and north by the Early Caledonides of Kazakhstania, where the Northern Tyan-Shan occurs (Fig. 1). Attempts to trace Late Palaeozoic structural features from the Uralides

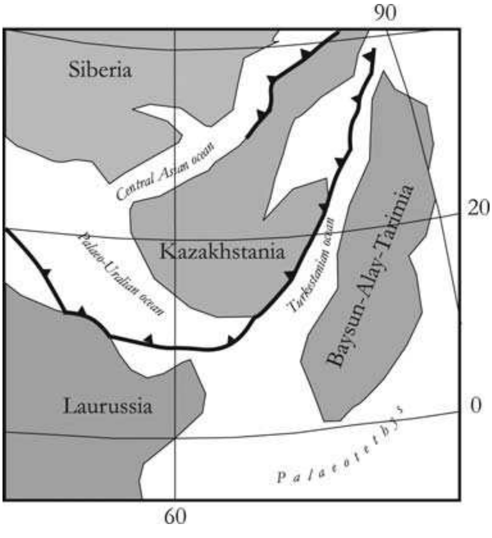

Fig. 2. A tentative reconstruction of the Central Eurasia for the Late Devonian (after YUGGEO2002, simplified).

into the Southern Tyan-Shan have been thwarted by the higher degree of shortening and lack of Devonian island arc development in the latter foldbelt. However, palaeocontinental reconstructions and modern structural connections (Figs 1 & 2) suggest a genetic linkage. The evolution of Southern Tyan-Shan is related to the subduction of the Turkestanian ocean (Burtman 2006), that in the Ordovician to Carboniferous time was a direct continuation of the Palaeouralian ocean (Puchkov 2000; Didenko *et al.* 2001; YUGGEO 2002; Biske 2006). The Middle to Late Palaeozoic evolution of the Uralian and Southern Tyan-Shan continental margins has a striking resemblance (Puchkov 1996*a*). The end of orogenic activity in the Southern Tyan-Shan is accompanied by Upper Permian and Lower Triassic continental molasse followed by the development of a stable platform in the whole Tyan-Shan, which lasted until strong intra-plate deformation of the Pliocene–Quaternary age propagated from the Alpine-Himalayan orogenic system, resulting in renewed mountain building (Burtman 2006; Biske 2006; Trifonov 2008).

Comparison between the Uralides, Variscides and Appalachians

The development of the Ural orogenic belt has traditionally been interpreted to be one of the Late Palaeozoic Variscide (or Hercynide) orogenic belts (Shatsky 1965; International Committee 1982). However, results of geological studies of the last few decades, enhanced by EUROPROBE, have shown such fundamental differences with the

Variscides that this interpretation is no longer considered valid (Brown *et al.* 2006*a*). Instead the Urals is treated as a separate orogenic belt, the main part of the Uralides.

In western Europe, tectonic events leading to the development of the Variscan (also known as Hercynian) orogenic belts (*sensu stricto*) occurred between the Famennian and Late Carboniferous (Fig. 3). Famennian flysch deposits, thought to represent the onset of orogenesis, continued until the end of the Lower Carboniferous, and were followed by molasse deposits which continued until the end of the Carboniferous. Devono-Carboniferous tectonothermal activity accompanied a pre-collisional closure of the Rheic (Saxo-Thuringian) ocean, collisional deformation, granitoid intrusions and metamorphism (including HP–LT type; Franke 2000; Ricken *et al.* 2000). Permian rocks are characterized by rift-related magmatism and the formation of ensialic basins within a wrench regime, and are followed by Triassic terrigenous and evaporitic deposits in graben structures. The Permian–Triassic events reflect post-orogenic extension (Schwab 1984; Ziegler 1999). The Alleghanian orogeny in the southern Appalachians and Ouachita continued, albeit in a weakened manner, into the Early Permian (Engelder 2007). In the Triassic, the Variscide and Appalachian orogenic belts were characterized by horsts and grabens that strongly influenced the formation of platform oil and gas deposits, especially in the North Sea (Lützner *et al.* 1979; Beutler 1979; Schwab 1984; Ziegler 1999; Khain 2001; Franke 2000).

The Uralides have a much more protracted history of orogenesis than the Variscides, with tectonic events continuing into the Jurassic. In the southern Uralides, syn-orogenic flysch deposition began in the Late Frasnian (Brown *et al.* 2006*b*). Further to the north, collision started in the Visean (Puchkov 2002*a*). This strongly diachronous

TIME	TECTONIC EVENTS	
	VARISCIDES	URALIDES
Neogene andQuaternary	RIFTING, VOLCANISM BASIN SEDIMENTATION	INTRACONTINENTAL COLLISION PENEPLAIN
Palaeogene	RIFTING FORMATION OF PENEPLAIN AND BASINS	PENEPLAIN FORMATION WITH SEA INGRESSIONS
Cretaceous		
Jurassic		PENEPLAIN FORMATION INTRACONTINENTAL COLLISION
Triassic	RIFTING	PENEPLAI AND BASIN FORMATION RIFTING AND LIP VOLCANISM
Permian	WRENCH TECTONICS, INTRAPLATE BI-MODAL VOLCANISM	CONTINENT–CONTINENT COLLISION
Carboniferous	CONTINENT–CONTINENT COLLISION	SUBDUCTION AND DIACHRONOUS ARC–CONTINENT COLLISION
Upper Devonian	INTRAOCEANIC AND MARGINAL S UBDUCTION	

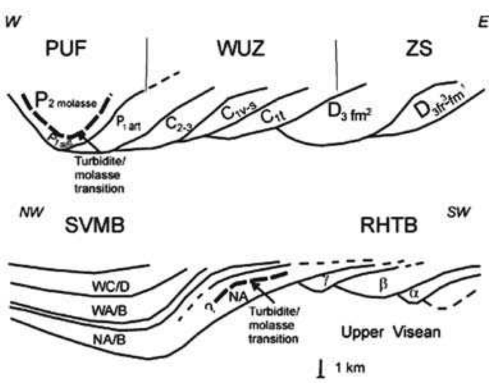

Fig. 3. To the left: correlation of orogenic and post-orogenic (intraplate) events in the Variscides and Uralides. To the right: a comparison of idealized sections across the foreland flysch and molasse basins: Preuralian (Southern Urals) after Puchkov (2000) and Central European Variscides, after Ricken *et al.* (2000). PUF, Preuralian foredeep; WUZ, West Uralian zone; ZS, Zilair synclinorium, Stages; art, Asselian to Artinskian stages; v-s, Vizean and Serpukhovian (= *c*. Lower Namurian); t, Tournaisian; fm, Famennian; fr-fm, Frasnian and Famennian; SVMB, Subvariscan molasse basin; RHTB, Renohercynian turbidite basin; WC/D, Westphalian stage (= *c*. the Moscovian stage of the Urals) the upper part; WA/B, Westphalian stage, the lower part; NA/B, Namurian stage (= *c*. Lower Bashkirian and Serpukhovian stages of the Urals); NA, Namurian stage, the lower part (mostly Serpukhovian stage); α, β, γ, the units of the Upper Visean substage. Thick lines, the lower boundary of molasse.

arc-continent collision was accompanied by HP–LT metamorphism (Brown *et al.* 2006*b*; Puchkov 2008, and references therein). In Bashkirian time, continent–continent (Laurussia–Kazakhstania) collision commenced and continued intermittently until the end of the Permian. The early stage of this collision was accompanied by flysch deposition, periodically interrupted by relatively deep-water sediments of a starved type. In the Kungurian (Uppermost Priuralian), evaporite deposition occurred in the southern to northern parts of the Urals, but in its polar area the Kungurian deposits filling the Preuralian foredeep are dominated by flysch and coal-bearing sediments. Late Permian strata are dominated by alluvial to lacustrine molasse deposits and are weakly deformed in the frontal part of the foreland fold-and-thrust belt (Puchkov 2000). At the beginning of the Triassic, tectonic movements connected with Large Igneous Province (LIP) formation led to the accumulation of molasse-like sediments. Voluminous mafic magmatism began in the earliest Triassic, approximately at 250 Ma according to Rb–Sr, Sm–Nd (Anderichev *et al.* 2005) and Ar–Ar (Reichov *et al.* 2007) age data, suggesting a correlation of these events with the contemporaneous events in Siberia and the hypothesis of a single Uralo-Siberian superplume.

The latest collisional events in the Uralides took place in the Early Jurassic, with increasing intensity from the South to the North, and represents the terminal collision between Baltica (Laurussia) and Siberia loose blocks united into Pangaea. The effects of this collision are well exposed in the Pai-Khoy Range, Novaya Zemlya islands and Taymyr.

Tectonic zones of the Urals (Fig. 4)

The Uralides are divided into several north–south striking structural zones, giving the Urals a general appearance of an approximately linear fold-belt, in contrast to the more strongly oroclinal and more mosaic chains of the European Variscides, Alps or Kazakhstanides (Franke 2000; Khain 2001; Agard & Lemoine, 2005).

The Urals is divided into the following structural zones, which are from west to east (Fig. 4; Puchkov 1997, 2000):

(1) A – the Preuralian foredeep, which inherited the western part of a bigger and long-living orogenic basin. It is filled mostly by Permian preflysch (deep-water condensed sediments), flysch and molasse.

(2) B – the West Uralian megazone, predominantly consisting of Palaeozoic shelf and deep-water passive margin sediments. This zone was affected by intense fold-and-thrust

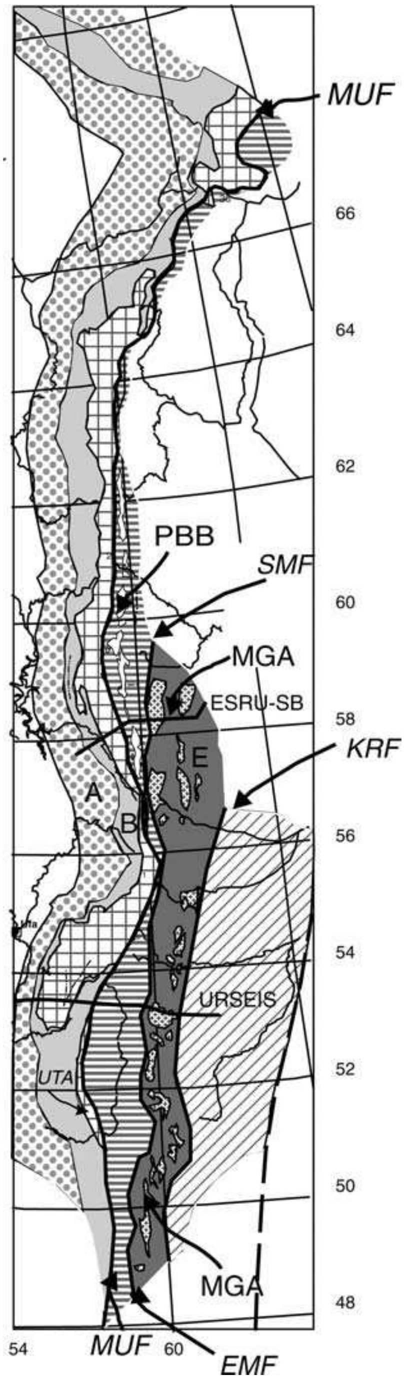

Fig. 4. Tectonic zones of the Urals (explanations in the text). Abbreviations: PBB, Platinum-bearing Belt; MGA, Main Granitic Axis; MUF, Main Uralian Fault; EMF, East Magnitogorsk Fault; SMF, Serov–Mauk Fault; KRF, Kartaly (‘Troitsk’) Fault. URSEIS and ESRU–SB, lines of seismic profiles described in the text.

deformation, and includes klippe containing easterly-derived ophiolites and arc volcanics (Puchkov 2002*a*).

(3) C – the Central Uralian megazone, where the Precambrian (predominantly Meso- and Neoproterozoic) crystalline basement of the Urals is exhumed. This basement is traced by geophysical data under the A, B and C megazones. Basically, these megazones were formed as a result of deformation of the continental margin of Baltica, although some allochthons, and partly the Ural-Tau antiform (UTA) were derived from more eastern oceanic structures.

(4) D – the Tagilo–Magnitogorskian megazone, bordered to the west by serpentinitic mélange within the Main Uralian Fault zone (MUF) and to the east by the East Magnitogorsk Fault (EMF) and Serov-Mauk Fault zones (SMF). This megazone predominantly consists of Ordovician–Lower Carboniferous complexes of oceanic crust and ensimatic island arc, including the Platinum-bearing Belt of layered basic-ultramafic massifs (PBB), overlain by platformal carbonate and rift-related volcanic rocks.

(5) E – the East Uralian zone, bordered to the west by the East Magnitogorskian mélange zone (EMF) and to the east by the Kartaly (Troitsk) Fault (KRF) (Fig. 4). This zone comprises Proterozoic gneisses and schists overlain by weakly metamorphosed Ordovician to Devonian sedimentary clastic strata and by tectonically emplaced sheets of Palaeozoic (Ordovician–Lower Carboniferous) oceanic and island arc complexes. The East Uralian Zone is intruded by voluminous Late Palaeozoic granite bodies which define the Main Granitic Axis (MGA) of the Urals (Puchkov *et al.* 1986).

(6) F – the Transuralian zone, the easternmost zone of the Urals has probably an accretionary nature. It contains pre-Carboniferous complexes which preserve a variety of tectonic settings, including Proterozoic blocks of gneisses, crystalline schists and weakly metamorphosed sediments, Ordovician rift (coarse terrigenous and volcanic) and oceanic (ophiolite) deposits, Silurian island-arc complexes and Devonian deep-water deposits overlain unconformably by the Lower Carboniferous suprasubductional volcanogenic strata, which form a post-accretionary overstep complex.

Zones D–F, together with MUF, are traditionally interpreted to comprise of vestiges of the palaeoceanic component of the Urals, relics of the Palaeouralian ocean (Peyve *et al.* 1977; Puchkov 2000). As ophiolites with MORB signatures are poorly preserved in most orogens, the abundance of ophiolites in the eastern zones of the Uralian orogen is a rather anomalous feature, compared to many other orogens.

All megazones are either exposed or are near the Earth's surface only in the Southern Urals. To the north, the easternmost zones are covered by the Mesozoic and Cenozoic strata of the West Siberian basin, and in the Northern and Polar areas only the Preuralian foredeep, West Uralian, Central Uralian and western part of the Tagil-Magnitogorskian megazone are exposed.

Structural development of the Urals (Fig. 5)

In general, the Urals comprise the following first-order structural stages: (1) Archaean–Palaeoproterozoic development of cratonic basement; (2) Meso-Neoproterozoic rift and basin development, followed by orogenesis that culminated with the formation of Timanide orogen along the periphery of Baltica; (3) Palaeozoic–Lower Jurassic development of the Uralides; (4) Middle Jurassic–Palaeogene–Miocene (platform); and (5) Pliocene–Quaternary (neo-orogenic) activity which is a far-field effect of Alpine-Himalayan orogenesis. In this paper we focus on the

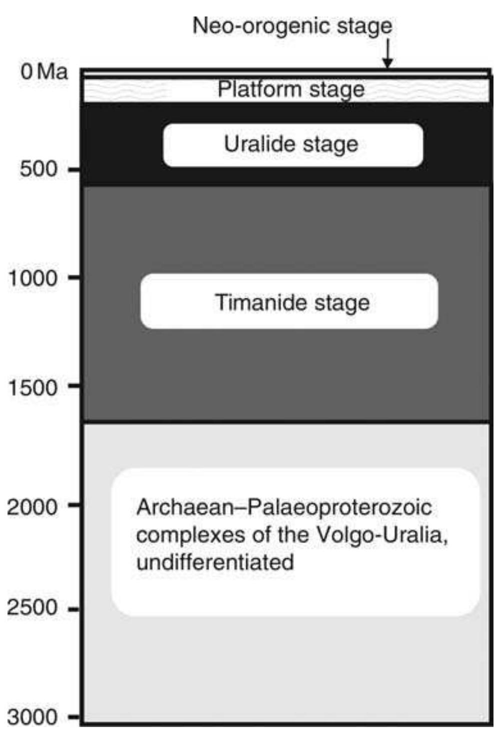

Fig. 5. Structural stages of the Urals.

Palaeozoic–Lower Jurassic stage as an example of a full Wilson cycle leading to formation of the Uralide orogen.

The Uralides (Fig. 6)

The Uralides consist of the following stages of development: (1) rifting of Baltica continental crust, composed of a cratonic crystalline basement and the Neoproterozoic Timanide foldbelt; (2) formation of an oceanic basin and microcontinents; (3) subduction of the oceanic crust and consequent arc generation; (4) arc-continent collision, followed by (5) continent–continent (Laurussia–Kazakhstania and then Laurussia–Siberia) collisions.

Rifting stage of the Uralides: a precursor of the Palaeouralian ocean

On a global scale, rifting and development of the Palaeouralian ocean episode was preceded by a series of pene-contemporaneous collisions and orogenies (Cadomian, Timanian, Brasilian, Panafrican) associated with the assembly of the supercontinent Pannotia (or Panterra) in the Ediacarian time. The Palaeouralian ocean was formed as a result of a breakup of this supercontinent in the Late Cambrian–Ordovician time (Puchkov 2000). Two other possible scenarios for the origin of the ocean have been suggested. According to Zonenshain *et al.* (1990), a system of rifts formed in the Early Ordovician at the eastern margin of East European continent. Rifting gradually changed to oceanic spreading and the generation of a series of microcontinental fragments (Uvat-Khantymansian, Uraltau, Mugodzharian) which formed adjacent to the boundary between the new-formed Palaeouralian ocean and the older, Asiatian ocean. Alternatively, some researchers (Scarrow *et al.* 2001; Samygin & Ruzhentsev 2003) maintain that Palaeouralian ocean was inherited from the Proterozoic time, implying no distinction between the development of the eastern and western flanks of the Uralo-Mongolian orogenic belt in the Early Palaeozoic. However, there are several strong arguments against the latter interpretation. First, the contrasting orientation of the structural grain of the Timanides and Uralides (especially in the North) support the idea of a continental breakup preceding the formation of the Uralian ophiolites. This interpretation is supported by the pattern of strong NW-trending magnetic anomalies of the Timan-Pechora province, positive anomalies reflecting vast fields of rift and island-arc volcanics, and negative anomalies associated with granites and metamorphic rocks (Fig. 7). These anomalies are truncated by the N–NE-trending magnetic anomalies which correspond to the MUF and palaeo-oceanic structures of the Uralides. Second, the lower age limit of the ophiolites attributed to the Palaeouralian ocean, as determined by recent studies of conodonts, is Arenig–Llandeilian (correlated with two unnamed stages between Tremadocian and Darriwilian (Gradstein *et al.* 2004) and is clearly younger than the Ediacarian–Tremadocian age that would be expected if there was uninterrupted ocean development (Puchkov 2005; Borozdina *et al.* 2004; Borozdina 2006; Smirnov *et al.* 2006). These ages are very different from the relics of the Palaeoasian ocean in Altaides and Kazakhstanides, where Cambrian ophiolites occur. Third, the presence of the Ordovician rift complexes along the margins of the former Baltica continent from one side, and the microcontinent(s) incorporated into the East Uralian and Transuralian zones support the former interpretation (Fig. 8).

A detailed description of the Uralian Early Palaeozoic rift facies in the western slope of the Urals is given in Puchkov (2002*a*, and references therein). Typically, the rift facies consists of Uppermost Cambrian–Tremadocian to Middle Ordovician coarse terrigenous sediments (conglomerates, sandstones, siltstones of very variable thickness, combined with interlayered subalkaline flows and tuffs). They overlie unconformably the crystalline basement and are overlain either by shelf or deep-water facies, reflecting the development of eastern passive continental margin of Baltica. Although the rift facies of the eastern zones of the Urals (Kliuzhina 1985; Snachev *et al.* 2006) resemble them lithologically, their age is restricted to the Middle Ordovician.

Alkaline carbonatite-bearing complexes (mostly miaskites) in the western part of the Middle Urals (Levin *et al.* 1997), originally thought to be a manifestation of this rifting event (Samygin *et al.* 1998; Puchkov 2000) have been re-interpreted to post-date rifting, on the basis of Rb–Sr and U–Pb isotopic data which indicate a latest Ordovician to Silurian age (Puchkov 2006*a*; Nedosekova *et al.* 2006, and references therein). These intrusions are oblique to the Uralian structural grain, and may be analogous to the Early Cretaceous Monteregian alkaline intrusions in eastern Canada or the more or less contemporaneous hot spot tracks of Eastern Brazil (Bell 2001; Cobbold e*t al.* 2001). Probable Late Ordovician–Early Silurian plume-related complexes also occur in more northern parts of the Urals (e.g. monzogabbro-syenite-porphyry as indicated by the 447 $\pm$ 8 Ma U–Pb (SHRIMP) age of the Verkhneserebryansky complex (Petrov 2006) or REE-rich phases of subalkaline granitoids in the North of the Urals, dated as 420–460 Ma by Rb–Sr and U–Pb methods (Udoratina & Larionov 2005).

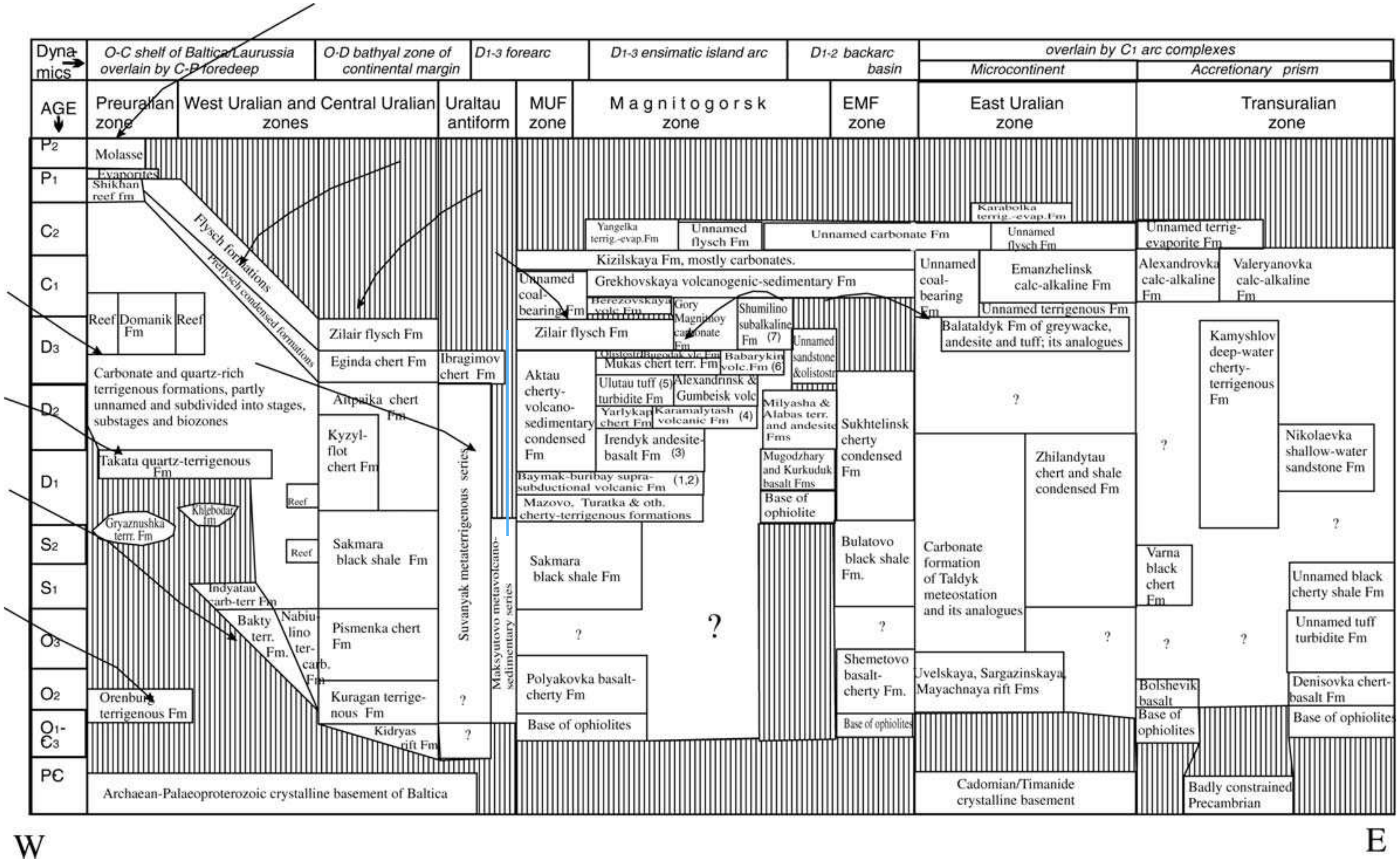

Fig. 6. A tectonostratigraphic chart of the Uralides in the Southern Urals. All the formations are tentatively restored to their initial, autochthonous positions. Arrows show a provenance of terrigenous material. (After Maslov *et al*. 2008, strongly modified.)

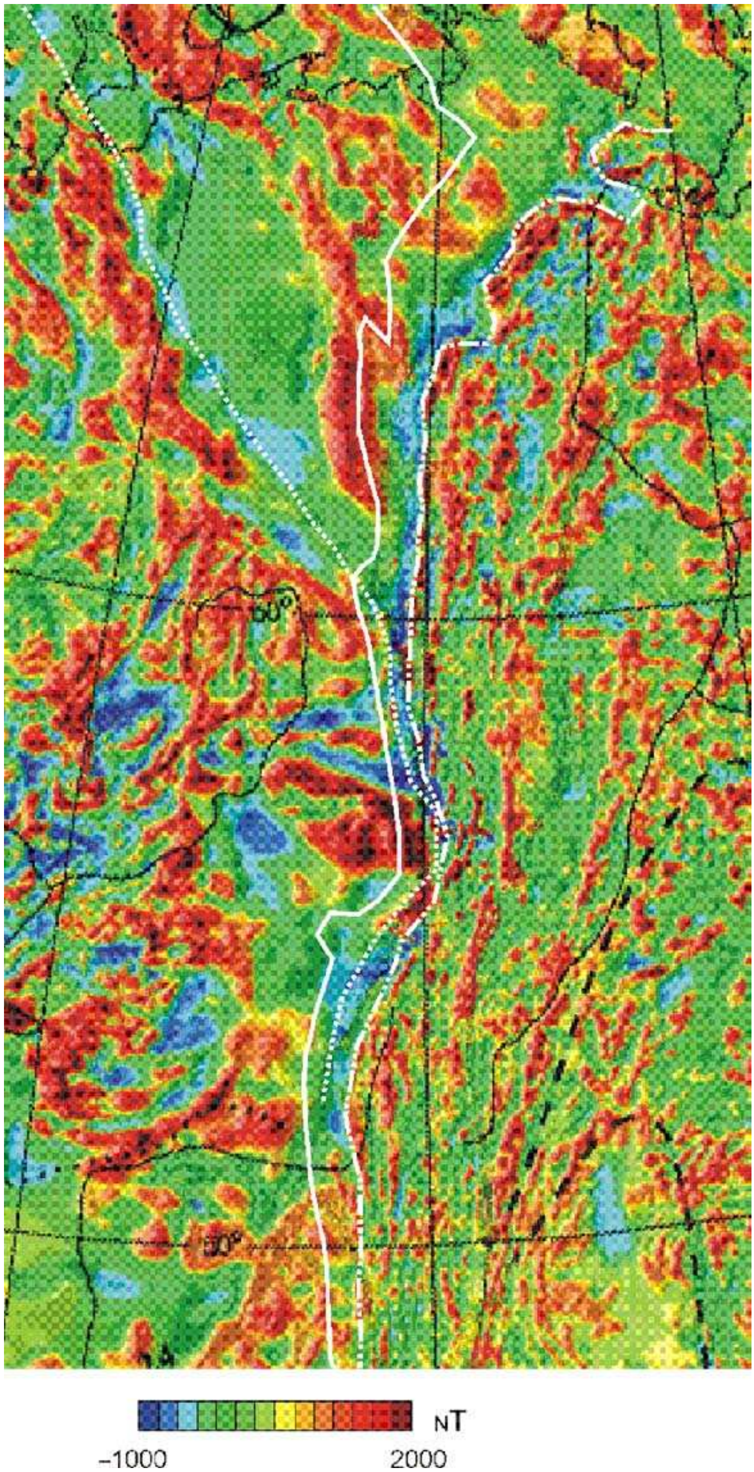

Fig. 7. Magnetic anomalies of eastern Baltica (after Jorgensen *et al.* 1995, with data processed by CONOCO Inc., USA). White dotted line, Timanian deformation front; white solid line, Uralide deformation front; white dot-and-dash line, the Main Uralian Fault.

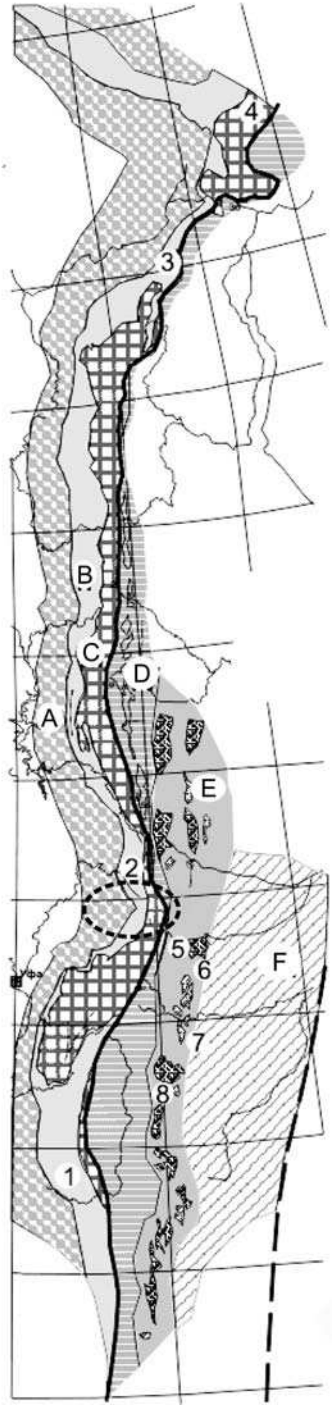

Fig. 8. The position of the Early Palaeozoic rift/plume related complexes. I–VI, tectonic zones of the Urals (correspond to A, B, C, D, E, F in Fig. 4, with the same symbols); 1–8, localities where the Lower Palaeozoic graben formations are developed; 1, Sakmarian;

The origin of the Palaeouralian ocean ophiolites

The aforementioned continental rifting within Baltica led to oceanic spreading and formation of ophiolites. The unusual abundance of ophiolites is a special feature of the Uralian orogen. Several studies report on the petrology, geochemistry, structure and metallogeny of the Uralian ophiolites (e.g. Savelieva 1987; Savelieva & Nesbitt 1996; Saveliev 1997; Melcher *et al.* 1999; Spadea *et al.* 2003; Savelieva *et al.* 2006*a*, *b*). The general consensus is that the 'ideal' section of the Uralian ophiolites consists of (from top to bottom):

(1) Tholeiitic basalts (mostly pillow lavas) with layers of pelagic sediments (typically cherts containing relics of half-dissolved radiolarians). The age of these basalts, constrained by many occurrences of conodonts, is never older than Arenigian–Llandeilian (see earlier comment). In the Tagil zone, ophiolitic complexes are overlain by Upper Ordovician island-arc formations, whereas in the Magnitogorskian zone, the condensed oceanic sediments overlie Ordovician–Llandoverian basalts, and persist until the onset of island arc magmatism in the Early Devonian;

(2) Dyke-in-dyke sheeted complexes, which are common in the Urals, in contrast to some other orogens (e.g. the Alps);

(3) Alpine-type gabbro;

(4) Banded dunite-wehrlite-clinopyroxenite complexes, interpreted to reflect a fossil MOHO boundary; and

(5) Peridotite complexes, represented by lherzolites, harzburgites and dunites in different proportions and combinations.

However, in detail not all ophiolitic complexes display this simple sequence. For example, Ishkinino, Ivanovka and Dergamysh Ni–Co-rich pyrite deposits in the MUF zone are attributed to ocean-floor black smokers and overlie and partly penetrate peridotitic host-rock, devoid of the several 'standard' members of the ophiolite section. Similar features occur in modern Atlantic thermal fields (e.g. Logachev and Rainbow fields), although their geodynamic setting may not support the direct analogy. The deposits rather belong to the relics of Magnitogorsk forearc (Jonas 2004; Melekesceva 2007).

Fig. 8. (*Continued*) 2, Bardym; 3, Lemva; 4, Baydarata; 5, Samar; 6, Sargaza; Uvelka; 8, Mayachnaya. Dashed-line ellipse, location of possible plume-related alkaline complexes Vishnevogorsk and other).

Savelieva *et al.* (2006*a*) classified the Uralian ophiolites into three groups according to their inferred geodynamic setting:

(1) Complete sections of ophiolites (e.g. Kempirsay massif) or their fragments in the south of Magnitogorsk, East Uralian or Denisovka zones), include restite peridotite and overlying succession of plutonic gabbro, parallel diabase dyke complexes and tholeiitic lavas formed in a MOR setting (Savelieva & Nesbitt 1996). However, a supra-subduction geochemical component has been documented in ophiolites in the southern part of the Kempirsay massif (Melcher *et al.* 1999);

(2) Massifs of a lherzolite type representing fairly low depleted lithospheric mantle (e.g. Kraka, Nurali) have a simple evolutionary history consisting of enriched peridotite and dunite associated with less abundant amphibole gabbro (Savelieva 1987). These characteristics are thought to reflect a low degree of partial melting of a mantle diapir, followed by rapid uplift, a scenario typical of rifting that immediately precedes oceanic spreading. Alternatively, Spadea *et al.* (2003) propose a more dynamic history for these massifs, involving re-fertilization of a depleted mantle by basaltic magma, by analogy with Lanzo massif of Alps, which however is also thought to be indicative of pre-spreading rifting (Müntener *et al.* 2005); and

(3) According to the general geodynamic reconstructions of Saveliev (1997), the huge Polar Urals massifs such as Voykar-Synya, Ray-Iz and Syum-Keu, are integrated into a system of allochthons, composed of complexes of two island arcs – Tagil-Schuchya (O_3–S_1) and Voykar (S_2–D_3). The restites in these massifs are strongly depleted and preserve evidence of interaction with basaltic magma. The sections consist of multi-phase intrusions of gabbro and diabase, interpreted by Savelieva *et al.* (2006*a*) to reflect the development of a marginal basin when an island arc rifted apart in the Late Silurian-Early Devonian. Therefore this spreading was related to the development of a second island arc. This interpretation, however, may be an over-simplification as the presence of two island arcs suggests the existence of older (Ordovician–Lower Silurian?) ophiolites corresponding to the older of the two arcs. Indeed, Ar–Ar data from the banded complex of Voykar-Synya and Khadata massifs (primary amphibole, fresh plagioclase and clinopyroxene of gabbro) yield 420–490 Ma ages. In addition the Khadata spreading dikes yield a *c*. 423 Ma age and the Voykar sheeted dykes, described by Remizov (2004) as island arc complex, were dated at 426–444 Ma (Didenko *et al.* 2001). Khain *et al.* (2004) dated zircons from a plagiogranite dyke in the parallel dyke complex of the Voykar-Synya massif at 490 ± 7 Ma. The above data indicate that the generation of these ophiolites is probably more complicated than the current geodynamic models purported to explain them.

This complicated scenario is highlighted by recent age data (Gurskaya & Smelova 2003; Savelieva *et al.* 2006*a*; Tessalina *et al.* 2005; Batanova *et al.* 2007; Krasnobaev *et al.* 2008), which yield Neoproterozoic–Ediacarian (536–885 Ma) and some older dates for many of the ultramafic and alpine-type gabbro complexes that were previously regarded as Palaeozoic. These data include Re–Os and Sm–Nd mineral isochrons and U–Pb analyses of zircons. In general, however, most of published age data support also an Ordovician–Lower Devonian age of alteration processes for most of the complexes (summarized by Puchkov 2000 and well illustrated by Krasnobaev *et al.* 2008). Two contrasting explanations have been proposed. According to Tessalina *et al.* (2005), the ultramafic complexes are Neoproterozoic ophiolites and represent relics of the oceanic crust developed during Timanide orogenesis. Alternatively, Puchkov (2006*b*) suggests that the Neoproterozoic dates in the Palaeozoic ophiolites reflect a relict signature preserved in the mantle part of the younger ophiolites (peridotites and partly ex-eclogitic mantle gabbro), notwithstanding the overprinting during subsequent processes of ophiolite formation. The possibility of preservation of ancient mantle zircons and their contamination of younger MOR and island arc volcanics has recently been underlined (Sharkov *et al.* 2004; Bortnikov *et al* 2005; Puchkov *et al.* 2006).

Despite the above complexities, the age of ophiolite basalts determined by conodonts, is never older in the Urals than Arenigian–Llandeilian (see again the earlier comment).

The passive margin of the continent

Simultaneously with oceanic development, the continental margin of Baltica started to develop by rifting in the Ordovician (Fig. 9). The identity of the conjugate margin to this rift is not known. By the end of the Silurian, Baltica had collided with Laurentia to form Laurussia (Ziegler 1999). The development of the margin is described in detail by Puchkov (2002*a*), and only a general summary is given here. Typically, the succession starts with uppermost Cambrian–Lower Ordovician coarse terrigenous deposits, in some cases accompanied

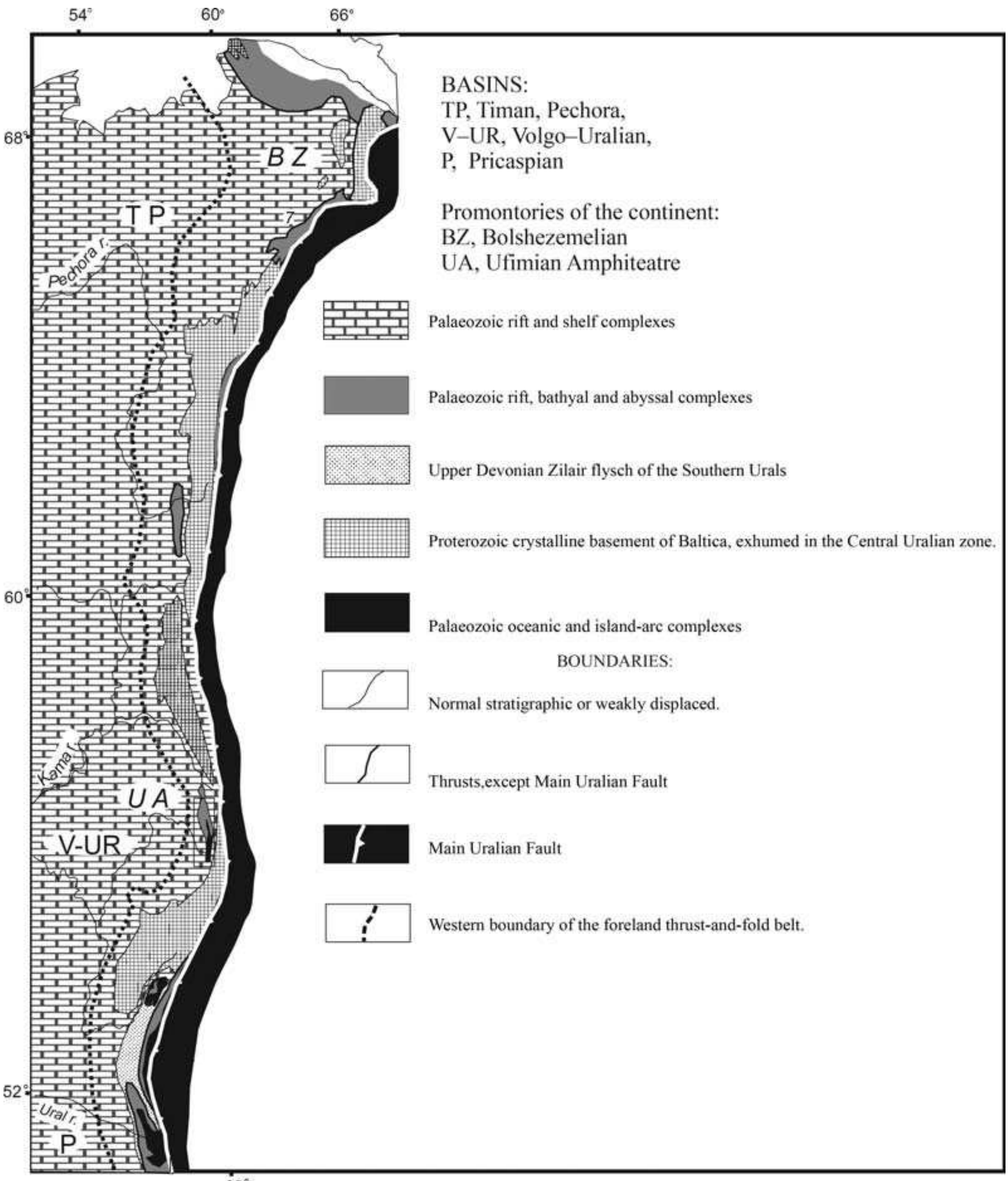

Fig. 9. Major structural elements and complexes of Laurussia/Baltica passive margin involved into the Urals (from Puchkov 2002, with minor changes).

by minor volcanic rocks (see above). The margin is classified as a non-volcanic type (in a classification of Geoffroy 2005).

Two facies were established early in the passive margin development – an inner (shelf) and an outer (continental slope, grading to continental rise) (Fig. 6). Generally, shelf sediments are represented by shallow-water carbonates (limestones, dolomitic limestones, dolomites) and terrigenous sediments with west-derived (Smirnov 1957) oligomictic, quartz sandstones. Regressions are marked by barrier reefs at the outer margin of the shelf zone, while the transgressions favour a formation of deep-water, starved basins with condensed facies of marls and oil shales (called 'domanik' in Russia), surrounded by reefs and bioherms.

The outer, continental slope and rise (bathyal) sections consist of thick westerly-derived quartz sandstones, and thin, condensed units consisting of shales, cherts and minor limestones (Puchkov 1979, 2000). Fauna are mostly pelagic: radiolarians, conodonts, graptolites and rare goniatites. The paucity of limestones indicate a transition to abyssal conditions.

The upper strata of the outer facies consist of polymictic, flysch deposits signifying a sharp change of provenance that is connected with the start of orogenesis (Puchkov 1979; Willner *et al.* 2002, 2004). This change of provenance is diachronous: it is earlier in the east and south of the western slope of the Urals; in the Southern Urals it occurs in the uppermost Frasnian, but in the Polar Urals it starts in the Early Visean.

Puchkov (1979) drew attention to the similarity of these deposits with analogous geodynamic settings in other orogens. For example, eastern Laurentia was bordered by deep-water sediments in the Ordovician that are preserved in the allochthons formed during the generation of the Appalachian orogen. In some cases (e.g. Ouachita), the deep-water facies persisted, like in the Polar Urals, through most of the Palaeozoic (from the lowermost Ordovician until the Carboniferous).

Subduction of oceanic crust

The Urals is characterized by an exceptionally good preservation of subduction complexes, which permits reconstruction of the development of at least three subduction zones in place and time: Tagil (Late Ordovician–Early Devonian), Magnitogorsk (Early–Late Devonian) and Valerianovka (Tournaisian–Early Bashkirian) (Fig. 10).

The Late Ordovician–Early Devonian Tagil arc (Fig 10, to the left)

The oldest (Tagil) arc complexes are developed in the Middle, Northern, Cis-Polar and Polar parts of the Tagilo–Magnitogorskian zone. The best sections, well constrained by conodonts, are preserved in the southern part of the Tagil synclinorium (synform). According to recent stratigraphic and petrochemical studies (Narkissova 2005; Borozdina 2006), the oldest ensimatic island-arc succession is predominately represented by the basaltic (O_3), basalt-plagiorhyolitic (O_3) and basalt–andesite–plagiodacite (S_1) volcanic associations. The latter two have calc-alkaline affinities (Narkissova 2005). The overlying Silurian association (S_1ll_2–S_2w_1) is represented by flysch consisting of interbedded black cherty siltstones, tuffites and tuffaceous sandstones (arc slope deposits), overlain by andesites, dacites, basalts and very abundant tuffs. In the Wenlockian, the volcanic rocks are laterally equivalent to reefal limestones (All-Russian Committee 1993). These biohermal deposits persisted until the Pridolian as an unstable, narrow carbonate shelf on the perimeter of the island arc. The above Silurian complexes are substituted laterally by a volcanic association (S_1ll_3–S_2ld_1), represented by basalts, andesites and tuffs with rare layers of cherty siltstones. After the Late Ludlovian, the marine conditions partly changed to continental conditions: the Pridolian association is represented by predominant coarse-grained red-coloured polymictic terrigenous-volcanogenic deposits with fragments of the older rocks; such as volcanics, with sublakalic and alkalic basalts being predominant. The island arc succession is terminated by a very specific association (S_2pr–D_1lh), preserved in the axial part of the Tagil synform, which resembles the underlying Pridolian association, and includes shoshonitic mafic to intermediate volcanic rocks (Narkissova 2005) and minor flysch-like volcaniclastic deposits.

The volcanism of the Tagil arc evolved from a uniformly tholeiitic affinity to a differentiated calc-alkaline and then to subalkalic shoshonitic affinity, suggesting deeper levels of partial melting in mantle with time, a trend that is opposite to the typical trend in rift and superplume zones (Dobretsov *et al.* 2001). Geochemically, the volcanics are typical of ensimatic island arcs (Narkissova 2005; Borozdina 2006). Basalts retrieved from the superdeep SG-4 borehole exhibit a distinct Ta–Nb minimum. In general, the volcanics are depleted in Nb,Ta, Zr, Ti, Y and enriched in K, Rb, Ba, Pb relatively to N–MORB. The geochemical trends of contemporaneous volcanics suggest an eastward (in modern co-ordinates) dipping subduction zone (Narkissova 2005).

The Tagil arc is also known for the presence of gabbro-ultramafic massifs composing a gigantic (*c.* 1000 km) linear, platinum-bearing belt (PBB on Fig. 4). The concentric-zonal massifs consist of dunites, clinopyroxenites, gabbro and plagiogranites, and mafic rocks comprise up to 80% of the belt. Disseminated platinum is hosted by dunites, and industrial deposits are represented mostly by modern (or reworked Meso-Cenozoic) placers. The geodynamic significance of the belt is controversial: models vary from a rift (Efimov 1993) to a supra-subduction zone setting (Ivanov *et al.* 2006). The age of the belt, determined by several methods as 420–430 Ma, and the similarity of petrogenetic-indicating trace and rare earth elements with island-arc tholeiites (Ivanov *et al.* 2006) supports the supra-subduction zone model. Such belts are rare in modern arc environments, but possible analogues occur in the northern part

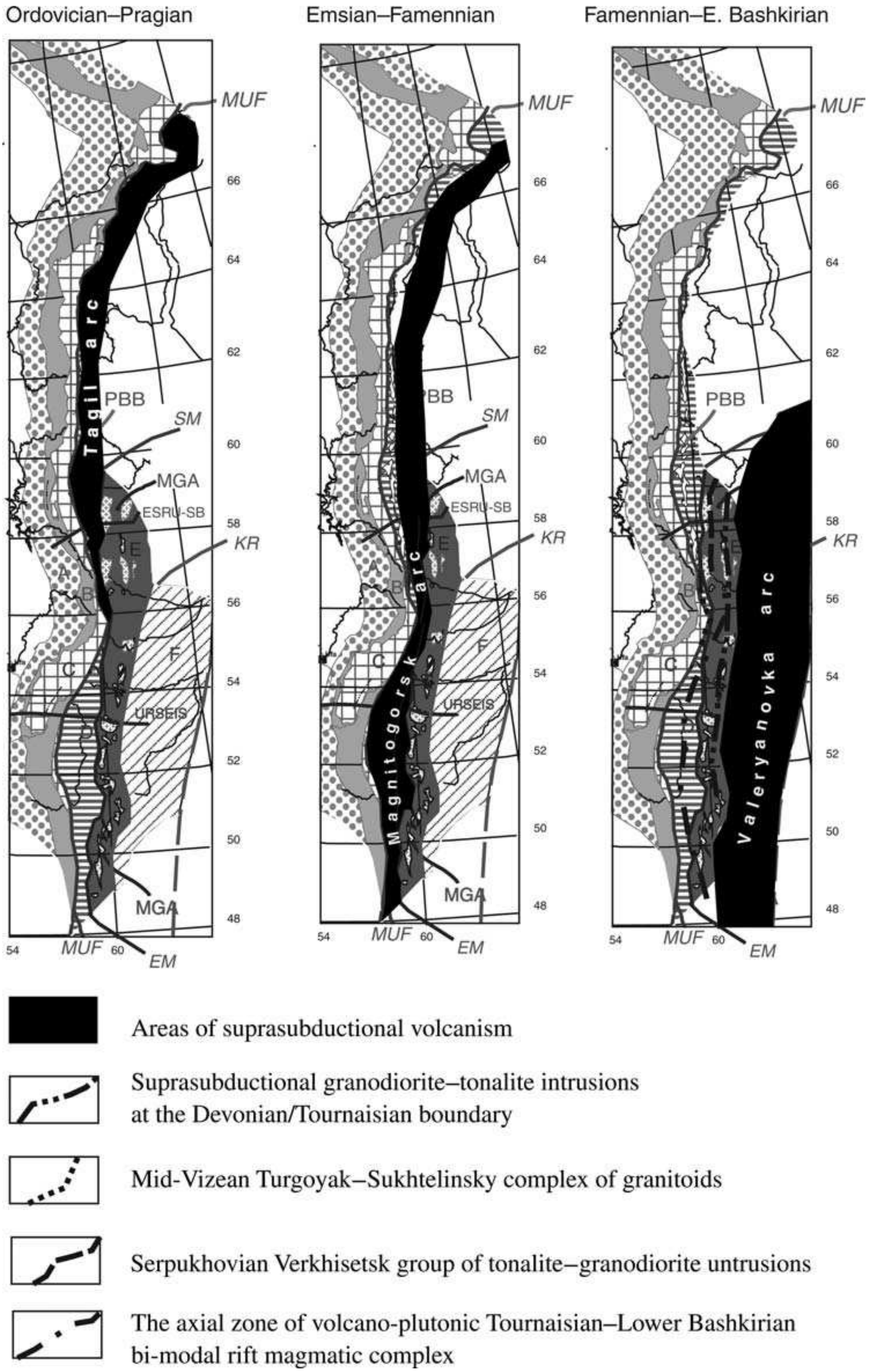

Fig. 10. The distribution of magmatism of three main stages of subduction: Ordovician–Early Devonian (Tagil): Early Devonian–Famennian (Magnitogorsk); Tournaisian–Early Bashkirian (Valerianovka and contemporaneous to it).

of the circum-Pacific ring, and are known as Alaskan type (Burns 1985).

Ordovician–Early Devonian island-arc volcanism was followed by the development of a relatively stable carbonate shelf which caps the western part of the island arc complexes. After that time the Tagil arc was dismembered and by the Emsian, it was a terrane that accreted to the Magnitogorsk island arc, an event that coincided with the formation of the Magnitogorsk arc itself (see below). The location of the subduction zone changed and the region became characterized by presence of two sub-zones: the western, Petropavlovsk and the eastern, Turyinsk sub-zones.

The Petropavlovsk sub-zone contains Lower to Middle Devonian shallow-water limestones and bauxite, followed in the Late Devonian by deep-water cherty shales and polymictic terrigenous sediments. In the Turyinsk sub-zone, sedimentary strata (shallow-water limestones, shales and cherty shales) are interlayered with andesites, basalts, tuffs and volcanogenic sandstones (All-Russian Committee 1993). Yazeva & Bochkarev (1993) point out that these thick (up to 4–5 km) Devonian volcanic layers occur with comagmatic intrusions in volcano-plutonic complexes. Geochemical parameters (in particular, Rb and Sr contents) indicate that the thickness of the crust was *c.* 30 km (Yazeva & Bochkarev 1993), which implies that the new arc was ensialic, in contrast with the Ordovician–Lower Devonian ensimatic Tagil island arc.

Devonian Magnitigorsk arc (Fig. 10, centre)

The development of the Magnitogorsk arc in the Southern Urals was more or less synchronous with the dismemberment of the Tagil arc. The location of the Turinsk zone of Tagil arc along the extension of the Magnitogorsk arc suggests that the Magnitogorsk subduction zone was inherited from the Tagil zone. The Middle–Upper Devonian calc-alkaline complexes can be traced northward to the Polar Urals.

However, in the Southern Urals, island arc development was preceded by a long period of quiescence, expressed by the deposition of deep-water oceanic cherts and carbonaceous cherty shales accompanied by basalts in the Ordovician and Llandoverian. Most of the Silurian is represented by 300 m of distal, condensed cherty shales. They are considered to represent the sedimentary cover of the ophiolites. Non-volcanic sections of the Lower Devonian (Lochkovian–lowermost Emsian) are represented by either deep-water terrigenous chert, argillaceous cherty sediments of Masovo, Turatka, Ishkinino and other formations or bioherm limestones (Artiushkova & Maslov 2003; Fig. 6). This stratigraphic level includes also olistostromes developed locally with and within serpentinitic mélanges of the Main Uralian fault. The bioherms and olistostromes are local indicators of buckling of the oceanic crust at the onset of subduction and are related to an early, non-volcanic stage of subduction.

Volcanic complexes of the Magnitogorsk arc in the Southern Urals are well studied (Brown *et al.* 2001, 2006*b*; Kosarev *et al.* 2005, 2006, and references therein). The volcanic succession, represented by a characteristic interlayering of tholeiitic basalts, bimodal basalt-rhyolite and regularly differentiated basalt-andesite-dacite-rhyolite series, comprises the following units (the local names are partly shown in Figure 6, and numbered correspondingly):

(1) A bimodal rhyolite-basalt series that overlies a tholeiite-boninite unit (Emsian);
(2) Basalt-andesite-dacite-rhyolitic series (Upper Emsian);
(3) Andesite-basalt series (uppermost Emsian–Lower Eifelian);
(4) Bimodal rhyolite-basalt series (Upper Eifelian);
(5) Basalt-andesite-dacite-rhyolite series (Givetian–Lower Frasnian);
(6) Basalt-andesite formation (Upper Frasnian);
(7) Local shoshonite-absarokite formation (Famennian). In addition, subduction-related 370–350 Ma granitoid intrusions of calc-alkaline affinity are developed in the northern part of Magnitogorsk synclinorium (Bea *et al.* 2002); and
(8) These intrusions are unconformably overlain by Lower Carboniferous volcanics dominated by tholeiitic basalt in the west and by more widely developed subalkaline bimodal basalt-rhyolite in the east. They are accompanied by a chain of coeval (335–315 Ma, Bea *et al.* 2002) bimodal gabbro-granitoid intrusions (Magnitogorsk-type plutons). Both volcanic and intrusive bimodal series, according to their field relationships, mineralogy and geochemistry, suggest an extensional or passive within-plate non-arc origin and are probably produced by undepleted lherzolites (Bochkarev & Yazeva 2000; Fershtater *et al.* 2006). This magmatism may be related to a slab break-off of the Magnitogorsk subduction zone which gave way to a melt from the less depleted, deeper mantle under it (Kosarev *et al.* 2006).

Notwithstanding differences in composition, magmatic and tectonic affinities, all the Devonian volcanic series share geochemical traits typical of a supra-subduction zone origin, such as negative Nb, Ta, Zr, Hf, Y anomalies, and elevated concentrations of large ion lithophile (LIL) elements

(K, Rb, Ba, Cs) and LREE. They show no signs of contamination by continental crust and are interpreted as ensimatic arc complexes.

There are many parallels with a development of the Tagil arc, including the alkaline trend towards the upper member of the succession. Trace element abundances for contemporaneous volcanic rocks are consistent with an eastward-dipping subduction zone. To the west and east of the main volcanic body of the arc, mostly in mélanges of the MUF and EMF zones and associated allochthons, condensed cherty-terrigenous series contemporaneous to the arc are developed, corresponding to the forearc and backarc basins (Fig. 6).

It looks like the ophiolite basement of the arc is mostly Ordovician in age, except the Mugodzhary section, where the Emsian basalts and cherts of Mugodzhary and Kurkuduk formations overlie a large-scale Aktogay sheeted dyke complex, gabbro and serpentinites, composing a Lower Devonian ophiolite (Fig. 6). The ophiolite is tentatively interpreted as a result of a backarc spreading.

The collision of the Magnitogorsk arc with the passive margin of Laurussia

The collision of the Magnitogorsk arc with the passive margin of Laurussia (former Baltica) has been described in several recent publications (Brown & Puchkov 2004; Brown *et al.* 2006*b*, and references therein) and is briefly summarized here (Figs 11 & 12). Since the Early Devonian, an island arc formed within the Uralian palaeocean above an east-dipping subduction zone. Collision of the arc with Laurussia occurred in the Late Devonian and was accompanied by the following events:

(1) scraping-up of the deep-water sediments of the continental passive margin by the rigid wedge (backstop) of the arc and the formation of an accretionary prism;
(2) jamming of the subduction zone followed by a jump in the location of the subduction zone;
(3) slab break-off and opening of a slab window permitting the deeper, more fertile and hotter mantle to produce subalkaline, non-subduction volcanics;
(4) uplift of the buoyant continental part of the slab, exhumation and erosion of UHP(?) and HP–LT metamorphic complexes and their erosion;
(5) formation of the accretionary cordillera of Uraltau antiform (comparable to accretionary avolcanic arc of Indonesia) and two flysch basins flanking both sides of it: forearc and foredeep basins (Fig. 13); and
(6) formation of the suture zone of the Main Uralian Fault, which divides the accretionary prism on the continent from the remnant of the island arc.

In summary, the Southern Urals Magnitogorsk arc was formed in the Early Devonian upon Ordovician–Early Devonian oceanic crust (Puchkov 2000; Snachev *et al.* 2006) and developed until it collided with the passive continental margin of Laurussia in the Late Devonian. Due to the oblique orientation of the subduction zone relative to the continental margin, collision at this time did not take place along the whole length of the passive margin of Laurussia continent. To the north of the Ufimian promontory, the margin of Laurussia shows no evidence of the Late Devonian arc–continent collision.

Two remarkable Late Devonian events in the Southern Urals can be regarded (along with direct structural data) as important indicators of the transition from subduction to collision. The first is the deposition of the Zilair greywacke flysch formation of the eastern provenance (uppermost Frasnian–Famennian) which overlies Frasnian deep-water and Famennian shallow-water deposits of the continental margin of Laurussia. The second is a culmination of a HP–LT metamorphism at 372–378 Ma that provides additional evidence for the end of subduction and the onset of collision.

As for the metamorphism, its age range in the subduction zone should be broadly contemporaneous with the subduction, and its oldest products should be older than the supra-subductional volcanism. However, it is not clear if the products of this early metamorphism were preserved and then exhumed or if they were completely entrained by the slab. The Magnitogorsk arc appears to have these products preserved and then exhumed. In the serpentinitic mélange of MUF, along the margin of the Magnitogorsk arc, garnet pyroxenites (metamorphic basites) occur. The best documented occurrence where P–T parameters of their origin are determined as 1.5–2 GPa, 800–1200 °C is in the Mindyak peridotite massif of MUF (Pushkarev 2001). Its age was determined by two methods: Sm–Nd isochron is 406–399 Ma (Gaggero *et al.* 1997); whereas U–Pb analysis of zircons yield an age of 410 ± 5 Ma, which is interpreted as a metamorphic age (Saveliev *et al.* 2001). A Pb–Pb analysis of zircon cores yield an age of 467 Ma, and is interpreted as a protolith age (Gaggero *et al.* 1997). The age of garnet pyroxenite from the Bayguskarovo occurrence is $416 \pm 6{,}1$ U–Pb SHRIMP (Tretyakov *et al.* 2008). A series of Ar–Ar age determinations of phengite, whose interpretation depends on mineral dimensions and temperature conditions of equilibration, has been

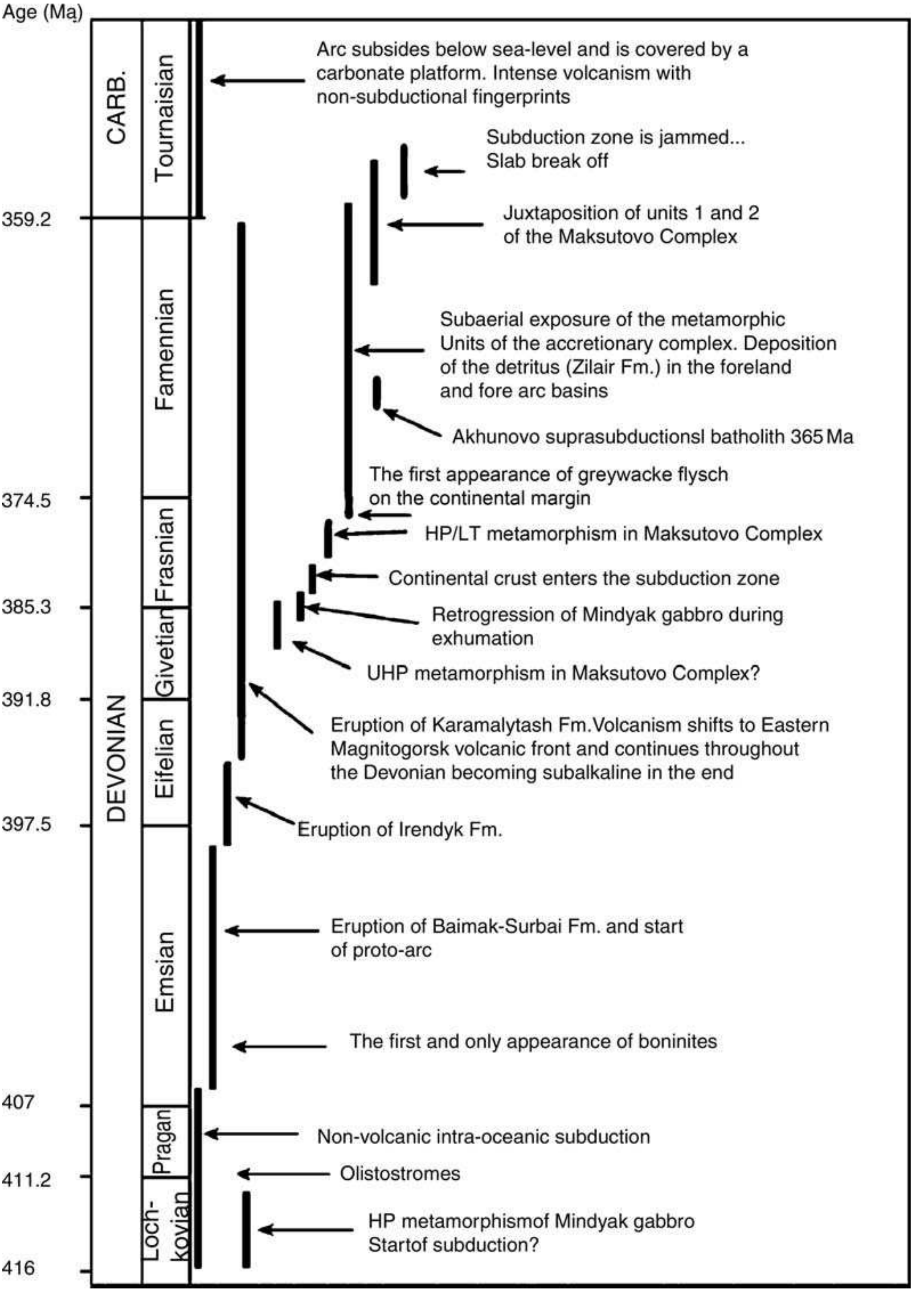

Fig. 11. Time/process evolutionary diagram for intra-oceanic subduction and arc-continent collision in the Southern Urals (after Brown *et al.* 2006*b*, with added information given in bold).

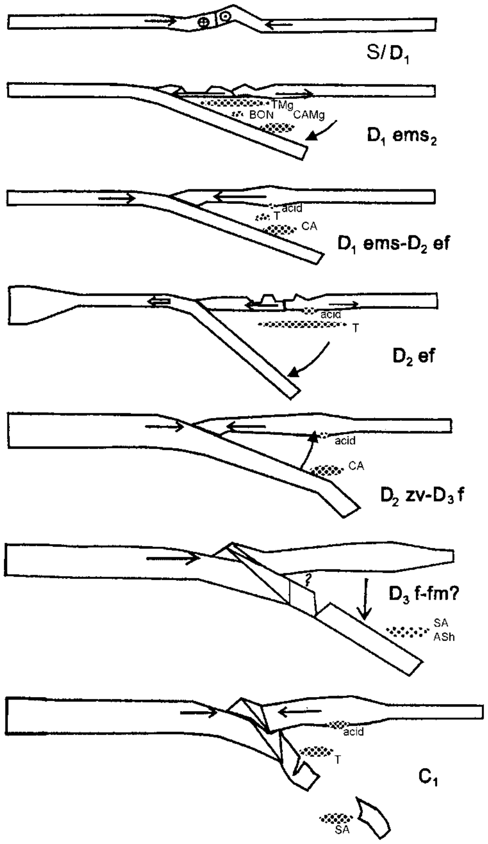

Fig. 12. A model for development of the Magnitogorsk arc and subduction zone (Kosarev *et al.* 2006, slightly modified). Dotted lenses, supposed zones of melting of initial magmas of different petrogenetic types: T, tholeiitic; BON, boninitic; TMg, tholeiitic magnesial; CA, calc-alkaline; ASh, absarokite-shoshonite; SA, subalkaline. Stages of the Devonian: em, Emsian; ef, Eifelian; gv, Givetian; f, Frasnian; fm, Famennian.

done for a succession of samples across the contact between eclogite and garnet glaucophane schist from Maksiutovo complex. The age range of phengites is from 400 Ma at *c.* 500 °C to *c.* 379 Ma at the final closure temperature of the system (*c.* 370 °C). The Ar–Ar age of glaucophanes from the same sample is 411–389 Ma (Lepesin *et al.* 2006). The peak of Ar–Ar ages obtained from detrital phengites of the Zilair series clusters around 400 Ma (Willner *et al.* 2004). U–Pb SHRIMP dating of zircons from Maksiutovo eclogites yielded 388 ± 4 Ma (Leech & Willingshofer 2004). These older (Lower and Middle Devonian) dates of metamorphism are consistent with the cooling action of the subducting slab, causing the closure of isotopic systems.

The younger ages of the metamorphic rocks cluster around 375–380 Ma and probably are consistent with the general exhumation of the HP–LT metamorphic rocks of the Southern Urals. The rocks are divided into two units, established by Zakharov & Puchkov (1994) and by many later researchers.

The age of the start of general cooling and exhumation (reviewed by Brown *et al.* 2006*b*) for the eclogite facies metamorphism of the lower unit of the Maksutovo Complex is thought to be Frasnian in age, with a mean value of 378 ± 6 Ma according to many isotopic determinations (Matte *et al.* 1993; Lennykh *et al.* 1995; Beane & Connelly 2000; Hetzel & Romer 2000; Glodny *et al.* 1999, 2002). The upper unit was metamorphosed together with the lower unit, suggesting juxtaposition during exhumation at a higher crustal level by 360 ± 8 Ma (Rb–Sr and Ar–Ar methods; Beane & Connelly 2000; Hetzel & Romer 2000).

In the Polar Urals, isotope dating of HP–LT metamorphism of the Marun-Keu complex of eclogites and related metamorphic rocks was reviewed recently by Petrov *et al.* (2005). According to Shatsky *et al.* (2000), the Sm–Nd isotopic analyses of garnet, clinopyroxene and whole rock gave 366 ± 8.5 Ma for the hornblende eclogite and 339 ± 16 Ma for the kyanite eclogite. Rb–Sr whole-rock dating of the eclogites (Glodny *et al.* 1999) gave 358 ± 3 Ma. According to the data of Glodny *et al.* (2003, 2004), the concordant U–Pb age data for the metamorphic zircon domains are between 353 and 362 Ma, coincident with the age of metamorphism as inferred from Rb–Sr internal mineral isochrons (an average value of 355.5 + 1.4 Ma).

The eclogite–glaucophane Nerka-Yu and Parus-Shor complexes in the southernmost Polar Urals yielded 351 ± 3.6 and 352 ± 3.6 Ma (^{40}Ar–^{39}Ar ages, Ivanov *et al.* 2000). Sm–Nd dating of glaucophane schists of the Salatim belt (Northern Urals) gave 370 ± 35 Ma. Taken together, these dates characterize an Upper Famennian-Middle Tournaisian age of HP–LT metamorphism and the beginning of its exhumation. These data are supported by the Lower Visean age of the oldest known Palaeozoic easterly-derived polymictic sandstones and conglomerates on the continental margin of Laurussia, to the west of the Main Uralian Fault, in the Polar and Northern Urals (Puchkov 2002*a*, and references therein).

Developing the oblique collision model of Puchkov (1996*b*), Ivanov (2001) calculated an average rate of subduction, which led to a gradual northward-shifting collision, of 2.75–2.80 cm. However according to recent data, the diachroneity of events at the end of the Devonian and beginning of the Carboniferous show no gradual south–north

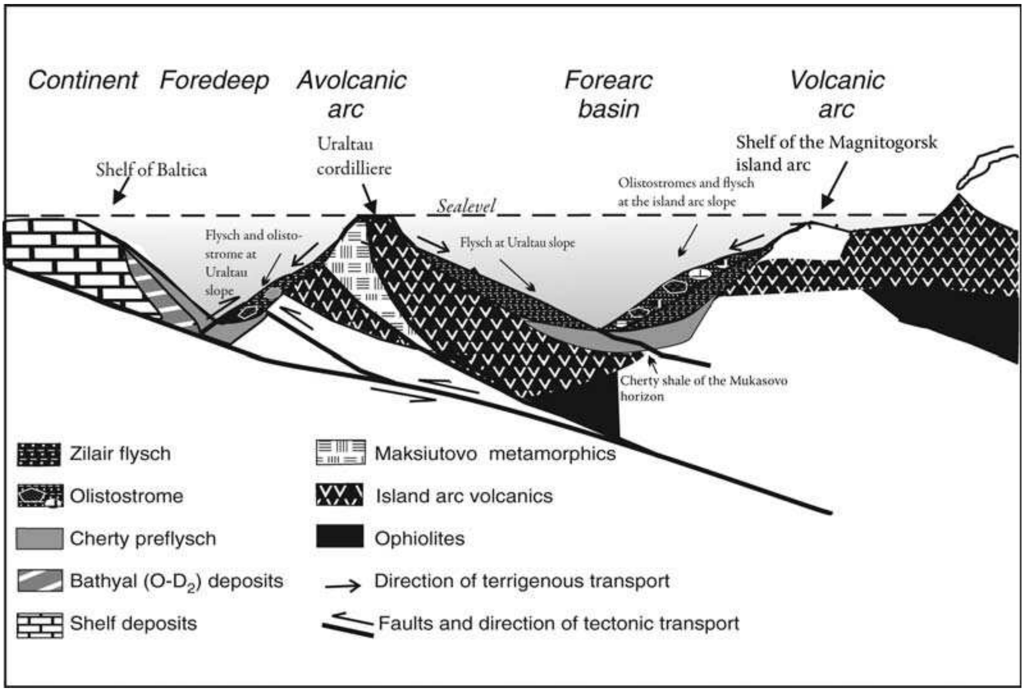

Fig. 13. Reconstructed geological section across the Magnitogorsk arc, in the Famennian time.

pattern, implying that behaviour of the subduction zone is more complex.

The collision of the Magnitogorsk arc with Laurussia may have occurred in two discrete stages (Fig. 14). First, collision in the Southern Urals occurred by the Famennian, and a triangular-shaped gap was left between the arc and the continent, similar to the modern Bengal Bay, Northwest Australian Bay or the South China Sea. Second, in the Early Carboniferous, the northern half of the arc was bent to the west and docked to the continental margin. At this stage subduction in the south virtually ceased, but in the north, increasing velocity of subduction resulted in increasing intensity of the HP–LT metamorphism in the same direction (from glaucophane schists of the Salatim belt and Cis-Polar Urals to eclogites of the Polar Urals). In the Middle Urals, these events were immediately followed by intrusion of Turgoyak-Syrostan group of granitoids (335–330 Ma), that was described by Fershtater *et al.* (2006) as ‘granitoids connected with tensional structures’. This group can be correlated by the age with the Magnitogorsk within-plate gabbro-granite series (see below).

Unfortunately there is no support for this model from the data on the Early Carboniferous volcanism in the northern part of the Magnitogorsk arc. But the lack of data may be because the eastern limb of this arc is concealed in the Northern to Polar Urals under the Mesozoic–Cenozoic cover of the West Siberian plate.

The above-described Early Carboniferous (Tournaisian–Visean) stage of subduction was followed in the Middle Urals by a Serpukhovian stage, as indicated by the Verkhisetsk chain of granitoids (320 Ma) (Fig. 10), related by Fershtater *et al.* (2006) to another east-dipping subduction zone.

Early Carboniferous-Bashkirian Valerianovka subduction zone(s) (Fig. 10, to the right)

By the middle of the Lower Carboniferous, the suture zone was established along the whole length of the MUF (Puchkov 2000, 2002*a*). The above-mentioned chain of 335–330 Ma (mid-Visean) massifs (Turgoyak–Syrostan group of granites) intrude the suture zone (Fershtater *et al.* 2006) and therefore post-date the Magnitogorsk subduction, providing an upper age limit for MUF. This conclusion is supported by the age of the Ufaley intrusion (concordant U–Pb, 316 ± 1 Ma, Early Bashkirian), which seals the Main Uralian Fault in the Northern part of the Ufimian promontory (Hetzel & Romer 1999).

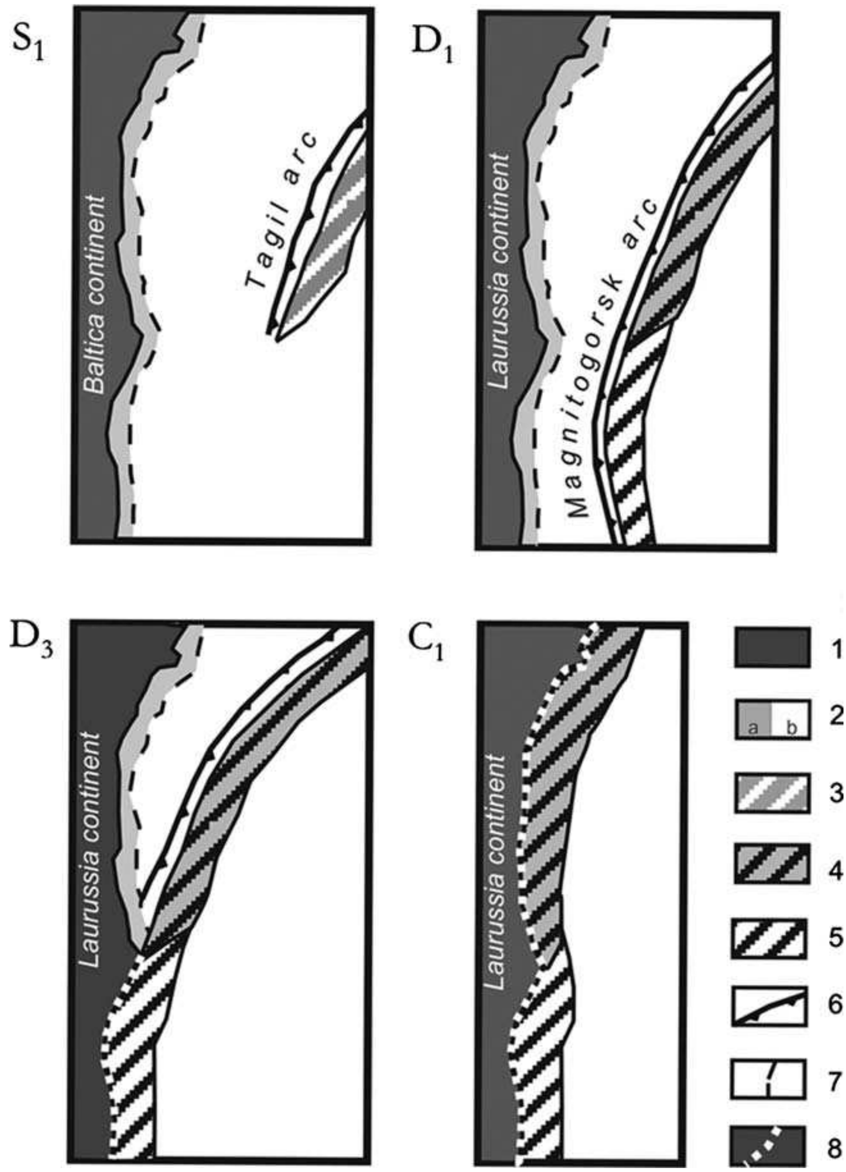

Fig. 14. A model for a two-stage Upper Devonian–Lower Carboniferous arc-continent collision in the Urals. 1, continental crust; 2a, transitional crust; 2b, oceanic crust; 3, Tagil island arc; 4 and 5, Magnitogorsk island arc; 4; ensialic (epi-tagilian); 5; ensimatic (Magnitogorsk arc *sensu stricto*); 6, subduction zone; 7, continent–ocean boundary; 8, suture zone of the Main Uralian fault.

With the demise of the Magnitogorskian arc, subduction did not terminate in the Urals as a whole. Ensialic subduction (either island arc or Andean-type or maybe two subduction zones of different type) of uncertain polarity began in the latest Devonian and lasted until the Mid-Bashkirian in the eastern Urals. The Main Granitic Axis of the Urals (Fig. 4) developed first as a chain of suprasubductional tonalite–granodiorite massifs by the end of the Famennian or the beginning of the Tournaisian (*c*. 360 Ma), when the southern part of the Magnitogorsk subduction zone ceased to operate (Bea *et al.* 2002; Fershtater *et al.* 2006). Simultaneously, immediately to the east, a wide NNE-trending band of calc-alkaline and partly within-plate volcanic rocks and associated plutonic complexes ranging up to mid-Bashkirian in age were formed, suggesting a close affinity with the massifs of the Main Granitic Axis (All-Russian Committee 1993; Tevelev *et al.* 2005; Fershtater *et al.* 2006). The Lower Carboniferous (320 Ma) tonalite-granodiorite massifs occur in the Middle Urals, situated to the east of the Serov-Mauk suture zone (i.e. Verkhisetsk massif and others located to the east of the former Magnitogorsk volcano-plutonic arc).

According to Fershtater *et al.* (2006), increases in K_2O and REE abundances in the granodiorites to the east indicate that subduction had an eastern polarity. However, Kosarev & Puchkov (1999) point out that K_2O concentrations in the Lower Carboniferous volcanic rocks in the eastern Urals increase westward, suggesting a western polarity for the subduction zone. Of the same opinion are Tevelev *et al.* (2005) for the Uralian Lower Carboniferous volcanics, but they propose that the volcanism occurred in a wrench regime and that the easternmost Valeryanovka volcanic band belonged to Kazakhstanides and developed over a separate subduction zone with eastern polarity. Brown *et al.* (2006*a*) also suggest two oppositely dipping subduction zones, whereas Matte (2006) suggests a westerly dip for several subduction zones. Such a difference in opinion is explained by the complicated nature of the process, involvement of wrench tectonics, and the rather poor exposure of the complexes.

Calc-alkaline volcanic complexes in the Urals abruptly stopped forming by the mid-Bashkirian, signifying the end of a wide-scale subduction of an oceanic crust and transition to a continent-continent-type collision.

Continent–continent collision and formation of the orogen

The main Late Bashkirian to Permian stage of collision

The collision between Laurussia and Kazakhstania that resulted in mountain building in the southern and middle Urals has been described recently by Brown *et al.* (2006*a*), and its main events are summarized here. The external (palaeogeographic and magmatic) expressions of the orogeny, including the northern-to-polar and eastern (epi-Kazakhstanian) regions are emphasized in this synthesis.

By the Mid-Bashkirian, subduction had ceased and collisional processes between Laurussia and Kazakhstania began first as a formation of linear uplifts and basins, documented in the Southern Urals (Puchkov 2000). In the Late Bashkirian and Moscovian, widespread marine flysch were deposited in troughs separated by more slowly subsiding shelf zones and intensely eroded uplifted crustal blocks. As uplift continued, the basins contracted and inverted. By the Kasimovian time, the territory east of MUF was dominated by erosion and subaerial deposits. To the west of MUF, a deep-water foredeep trough was filled by easterly-derived flysch, prograding to the west (Puchkov 2000). A westerly prograding foreland fold-and-thrust belt was developed along the eastern margin of the foredeep, which deformed and uplifted flysch of its eastern limb. The diachroneity of these processes is documented by detailed studies of resedimented conodonts within these strata (Gorozhanina & Pazukhin 2007). In the Gzhelian–Sakmarian, the thrusting and crustal thickening created a hot crustal root in the Southern Urals, which resulted in generation of 305–290 Ma syn-collisional granites of the Main Granitic axis (Fig. 2), followed by 10–15 km of erosion (Fershtater *et al.* 2006). Crustal thickness may reach 65 km (the modern crust thickness of the East Uralian zone is up to 50 km; see below), similar to modern orogens. Tuff layers in deep-water sections of Gzhelian to Lower Kungurian preflysch and distal flysch of Preuralian foredeep may represent volcanic equivalents of this magmatic activity (Davydov *et al.* 2002).

Syn-collisional granite magmatism migrated northward, and is thought to be a manifestation of the oblique, diachronous character of collision (305–290 Ma for the southern Uralian granites, 265 Ma for the Kisegach massif, 250–255 Ma for Murzinka and Adui massifs of the Middle Urals, Fershtater *et al.* 2006). The idea of the transpressive character of orogenic deformation is supported by structural studies (e.g. Pliusnin 1966; Znamensky 2007). A change from thrust-dominated tectonics to sinistral transpression occurred in the Southern Urals (Znamensky 2007), explaining the K-rich concentric-zoned post-tectonic *c.* 283 Ma rift-related granite-monzonite massifs at the northern end of Magnitogorsk synclinorium (Ferstater *et al.* 2006) and the occurrence of *c.* 301–310 Ma lamproite dykes in the Southern Urals (Pribavkin *et al.* 2006).

Post-collisional granite magmatism in each region was followed by uplift and erosion, and the diachroneity of the magmatism is exemplified by the presence of the Late Permian marine sediments with Tethyan fauna in the Southern Urals that is coeval with granite magmatism in the Middle Urals (e.g. Chuvashov *et al.* 1984).

An interlude: LIP formation and localized rifting

At the Permian–Triassic boundary, the waning effects of orogenesis were overprinted by the formation of the vast Uralo-Siberian LIP, extending from Taymyr in the north to the Kuznetsk and Turgay basins in the south and from the Tunguska basin in the east to the Urals in the west. Volcanism started locally with alkaline basalts and minor rhyolites. Ar–Ar data (Ivanov *et al.* 2005) suggest that the bulk of the volcanism initiated in Siberia at the Permian–Triassic boundary but probably continued for 22–26 Ma, with several short surges. Recent Ar–Ar dates for plagioclase from basalts in the Polar Urals (249.5 ± 0.7 Ma) and in the east of the Southern Urals (243.3 ± 0.6 Ma) (Reichov *et al.* 2007) support the simultaneous beginning of the LIP formation over a vast region followed by a more protracted period of reduced magmatism.

In contrast with eastern Siberia, the Early Triassic history of the Urals is dominated by considerable uplift, erosion and formation of thick coarse-grained alluvial to proluvial sediments that resemble orogenic molasse but are attributed to the effects of the Uralo–Siberian distributed rifting and LIP magmatism. Examples include the huge Triassic Koltogorsk–Urengoy graben of Western Siberia, the newly-identified Severososvinsky graben in the subsurface of the Cis-Polar Urals (Ivanov *et al.* 2004), and the eastern parts of the LIP (Kurenkov *et al.* 2002; Ryabov & Grib 2005).

The Cimmerian orogeny

A short pulse of orogeny occurred at the end of the early Jurassic, and its effects differ along the strike of the Uralides. The Triassic deposits of the Southern Urals are affected by this orogeny only in the Trans-Uralian zone (Chelyabinsk and other graben-like depressions), where Upper Triassic and older deposits are deformed by thrusting (Rasulov 1982), followed by uplift and peneplanation during the Middle and Upper Jurassic, and deposition of Upper Cretaceous marine deposits.

In the Northern Urals, three ‘grabens’ (Mostovskoi, Volchansky, Bogoslovsk-Veselovsky) (Tuzhikova 1973) containing Upper Triassic coal-bearing sediments were complexly deformed. In the Polar Urals, the Triassic deposits of the foredeep and the Chernyshov and Chernov range are all deformed, and are unconformably overlain by Middle Jurassic strata. However, in the nearby Severososvinsky graben to the east, Triassic and Jurassic deposits are not deformed (Ivanov *et al.* 2004), attesting to the localized nature of Cimmerian orogenic events.

The Pay-Khoy and Novozemelsky ranges were formed in the Cimmerian (Korago *et al.* 1989; Yudin 1994). Cimmerian orogenesis is attributed to a large-scale intra-Pangaean strike-slip faulting, accompanied by block rotation, possibly reflecting lateral escape of Kazakhstania between Laurussia and Siberia and an immediate collision of the latter two (Fig. 1). According to palaeomagnetic data (Kazansky *et al.* 2004), Siberia rotated 30° clockwise between the Triassic and the Late Cretaceous.

Peneplain formation

Rapid uplift and erosion of the Uralide orogen resulted in the formation of a Cretaceous-Palaeogene peneplain (Papulov 1974; Sigov 1969; Amon 2001), and by the Late Jurassic or Early Cretaceous, there was no topographic barrier dividing Europe and Siberia. Buried river-bed deposits along the eastern slope of the Southern and Middle Urals have a north-eastern direction, as revealed by a shallow prospecting drilling. For the Late Cretaceous and Eocene, the existence of short-lived straits connecting the European and Siberian marine basins is hypothesized.

Along the eastern slope of the Southern and Middle Urals, thin marine sediments occur only during maximal transgressions (in the Late Cretaceous and Middle Eocene); more generally, fluviatile deposits occur. To the north, Upper Jurassic and younger marine sediments occur adjacent to the eastern foothills of the modern Ural mountains. The difference between the southern and northern parts of the modern Urals (as expressed by better exposure of the eastern zones in the south), was probably inherited from this time.

Neo-orogeny

In the Pliocene–Quaternary time, a modern chain of moderately high mountains was uplifted, forming a natural drainage divide between Europe and Asia. These mountains are formed in an intra-plate setting, having no precursory suture zone. Convergence is indicated by studies which show that maximum stresses are oriented perpendicular to, or at a high angle to, the strike of the belt and by the identification of a zone with anomalously low heat flow (Golovanova 2006). According to Mikhailov *et al.* (2002), mountain building is accompanied by westward-directed thrusting.

The timing of mountain building is controversial. Until recently, there was a consensus that orogenesis began in the Late Oligocene and continued into the Quaternary inclusive (Trifonov 1999; Rozhdestvensky & Zinyakhina 1997) and that ancient peneplains formed in the Triassic–Jurassic were preserved (Sigov 1969; Borisevich 1992).

On the contrary, Puchkov (2002*b*) pointed out that models proposing Late Oligocene uplift of the Urals are inconsistent with: (1) the occurrence of Miocene oligomictic quartz sands and sandstones (Yakhimovich & Andrianova 1959; Kozlov 1976), which indicate stable non-orogenic conditions of weathering, erosion and deposition in both foredeep terrane and the Urals itself. The first appearance of polymictic sediments, indicating more rapid uplift and erosion, is Late Pliocene in age (Verbitskaya 1964); (2) deep Miocene river incision is best explained by a drop of the Caspian sea level, Messinian crisis, as well documented in the Mediterranean (Milanovsky 1963), rather than by crustal uplift; (3) no well-documented Miocene–Early Pleistocene terraces occur in the river valleys of the Urals; (4) no cave deposits older than Middle-Upper Neopleistocene are found; and (5) the velocities of the modern uplift of the Urals surface are 5–7 mm a^{-1}, which is an order of magnitude faster than the time needed to build the Urals mountains since Oligocene.

On the other hand, fission-track (Seward *et al.* 1997; Glasmacher *et al.* 2002) and unpublished U/Th–He data show that the relief of the axial part of the Southern Urals was not completely stabilized by the Late Cretaceous. Puchkov & Danukalova (2004) demonstrated that the altitudes of the base of shallow marine Upper Cretaceous deposits increase progressively in the direction of the mountain ridge, disappearing at elevations of 500 m. Therefore no Triassic–Jurassic planation surfaces can be preserved in the modern surface. The depth of erosion since the Cretaceous is between 1000 and 2000 m (depending on the thermal gradient), and these numbers are several times greater than the previous estimates.

The deep structure of the Urals

The main milestones of the study

Fifteen regional deep seismic survey (DSS) profiles, made between 1961 and 1993 permit the definition of the Moho surface beneath the Urals and demonstrated its layered seismic structure and the anomalous character of its crust. In particular, these surveys suggest the presence of a crustal 'root' under the Tagil–Magnitogorsk zone and a complex compositional transition zone in the lower crust, with V_p velocities between 7.2 and 7.8 km/s (Druzhinin *et al.* 1976). Puchkov & Svetlakova (1993) placed these results into a plate tectonic context for the first time, by interpreting a DSS profile in the Middle Urals as an indicator of the bi-vergent character of the Uralian orogen.

Reflection profiles made between 1964 and the early 1990s in the Magnitogorsk and Tagil zones (e.g. Menshikov *et al.* 1983; Sokolov 1992) revealed the inclined reflectors that define synclinoria and anticlinoria, and along-strike variations in the morphology of the Main Uralian fault. In the 1980s, state oil company surveys along the western slope of the Urals (e.g. Skripiy & Yunusov 1989; Sobornov & Bushuev 1992), combined with drilling, helped to solve some structural problems in the Uralian foreland. In 1993, the commencement of the EUROPROBE Programme 'Uralides', involved acquisition and interpretation of seismic data along two regional profiles (the Southern and Middle Urals) and re-interpretation of some existing shorter profiles. A combined geological and multicomponent geophysical URSEIS-95 project in the Southern Urals (Berzin *et al.* 1996; Carbonell *et al.* 1996; Echtler *et al.* 1996; Knapp *et al.* 1996; Suleimanov 2006), included a *c.* 500 km-long seismic reflection line across most of the orogen at a latitude of Kraka and Gebyk massifs. The ESRU-SB profile, ultimately *c.* 440 km long, crossed the Middle Urals where the 'superdeep' SG-4 borehole (currently *c.* 5.5 km deep) is located (Kashubin *et al.* 2006, and references therein).

The URSEIS profile (Fig. 15)

The interpretation given here is based on combined (vibroseis and explosion) seismic section along the geotraverse profile, after Suleimanov (2006), Spets-Geofizika. The coherency-filtered, depth-migrated vibroseis data by Tryggvason *et al.* (2001) were also used as an alternative source of information for the upper and middle crust. Along with generally accepted conclusions (Brown *et al.* 2008, and references therein), the following interpretations contain some latest original inferences of the author.

From 500 km (in the Preuralian foredeep), to the Main Uralian Fault at *c.* 275 km, the survey characterizes the structure of the foreland fold-and-thrust belt (Fig. 15). From 500–*c.* 420 km, subhorizontal, moderately coherent reflectivity in the upper 5 km corresponds to weakly deformed Palaeozoic foreland basin (foredeep) and platform margin shelf rocks of Ordovician–Lower Permian age (Brown *et al.* 2006*b*). Below this, to approximately 20 km depth, strongly coherent, subhorizontal reflectivity is interpreted to represent undeformed Meso- and Neoproterozoic strata of the SSE prolongation of the Kama-Belsk aulacogen. The base of the reflectivity here is thought to represent the unconformity between undeformed and low-metamorphic Mesoproterozoic strata and the non-reflective Archaean-Palaeoproterozoic crystalline basement (Dianconescu *et al.* 1998; Echtler *et al.* 1996). The sedimentary prism, almost 20 km thick, has a convex lens-like shape, consistent with the interpretation that the prism represents an inverted aulacogen. Beneath the crystalline basement, at *c.* 430 km the Moho is cut by Makarovo normal (?) fault, with up to 5 km of amplitude – probably related to the rift nature of the aulacogen (Fig. 15).

To the east, the upper and middle crust has weak, gently east-dipping reflectivity that, between

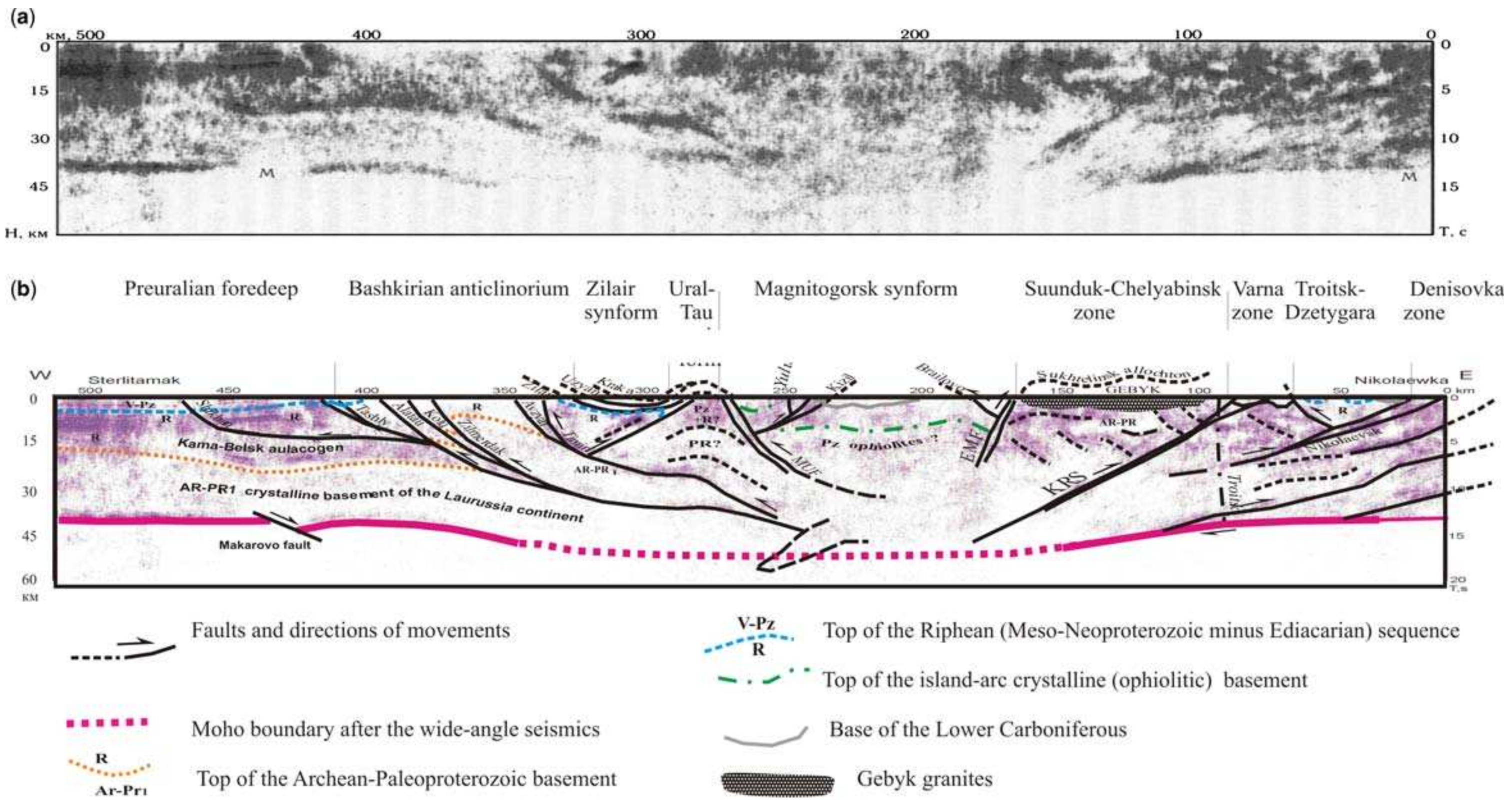

Fig. 15. (**a**) Uninterpreted combined (vibro- and explosion) seismic section along the URSEIS geotraverse profile (the seismic data after Suleimanov 2006, SpetsGeofizika). (**b**) Geological interpretation, overlain on the profile. See Figure 4 for location.

420 km and the MUF is concave downward. This reflectivity is associated with the Precambrian rocks in the Bashkirian Anticlinorium which, in its eastern part, was deformed during the Timanide orogeny (Puchkov 2000). The base of the reflectivity is usually interpreted to be the basal detachment contact between Mesoproterozoic strata and the Archaean–Palaeoproterozoic crystalline basement. However, according to structural studies, large anticlines of the central and eastern part of the Bashkirian anticlinoria have detached blocks of the crystalline basement beneath them, close to the surface. Taratash anticline in the north exposes such Precambrian core in the surface.

The lower crust beneath the foreland fold-and-thrust belt is weakly- to non-reflective, though the Moho boundary can be traced by explosion seismic data further to the east, towards the MUF. Close to the MUF, the deep-seated Uraltau antiform is clearly imaged and the MUF fault is traced as a gently concave structure, mainly by a loss of reflections from the Precambrian rocks and assuming that the base of the island-arc complex in the hanging wall of MUF is transparent. The Zilair synform and Uraltau antiform immediately to the west of the MUF form a dynamic couple, with the antiform making a tectonic wedge downthrusted to the west under the antiform.

From the MUF to *c.* 180 km, the Magnitogorsk arc is almost non-reflective in the upper crust, though the east-vergent Kizil thrust is clearly imaged in the coherency-filtered vibroseis data (Tryggvason *et al.* 2001) and its interpretation is supported by deep drilling and recent short seismic reflection profiles. The middle and lower crust is relatively transparent. The contact between the Magnitogorsk arc and the East Uralian Zone at *c.* 180 km (the East Magnitogorsk Fault and suture zone) is imaged by a sharp change from almost transparent crust in the west to coherent, highly reflective, middle crust to the east. In the East Uralian Zone, from *c.* 180–100 km, the upper crust is nearly transparent down to about 8 km, corresponding to the Gebyk granite. Below this, a series of short east-dipping and subhorizontal reflectors are descending into the middle crust. The lower crust is almost transparent or semi-transparent, except in the east, where a zone with strong west-dipping reflectivity extends downward and westward from the Trans-Uralian Zone (a continuation of Kartaly reflections; see below).

The crust of the Trans-Uralian Zone is imaged as west-dipping, strongly coherent reflectivity called the Kartaly Reflection Sequence (KRS, Fig. 15), which merges with the Moho in a system of thrusts; in this region the Moho appears as a near-horizontal detachment fault. The boundary between the East Uralian and Trans-Uralian zones is thought to be a regional fault called Kartaly or (wrongly) Troitsk fault located immediately to the east of Dzhabyk massif and traced in the SSW and NNE directions where it is interpreted as a wrench fault of a considerable amplitude.

In the western and eastern parts of the profile, the Moho is imaged in the URSEIS combined (vibro- and dynamite) reflection data to a depth of *c.* 50 km but cannot be traced in the deeper, central portion of the profile. The Moho has been determined from wide-angle data to occur at a maximum depth of 55 km (Carbonell *et al.* 1998). Although there is some bias between the wide-angle and CDP data, a cloudy reflection under this depth at *c.* 250 km, can be tentatively interpreted as a wedge of the lower crust protruding into the mantle (compare with a much better imaged wedge of the lower crust in the ESRU-SB profile, see below) (Fig. 16).

The ESRU-SB profile (Fig. 16)

The latest interpretation of crustal structure of the Middle Urals at latitude 56–62° based on seismic reflection data obtained by yearly installments since 1993 (ESRU-SB profile) was given recently by Kashubin *et al.* (2006), Rybalka *et al.* (2006) and Brown *et al.* (2008). From –100 km in the Preuralian foredeep to *c.* –25 km in the east, the upper crust has a flat-lying reflectivity, interpreted to represent an undeformed foredeep orogenic basin and platformal deposits (up to *c.* –65 km). In contrast, to the east, the steeply east-dipping shallow reflectivity of the 'thin-skinned' fold-and-thrust foreland occurs (Fig. 16). Both undeformed and steeply-dipping reflections are underlain by a gently east-dipping zone of reflections at a depth of *c.* 5–8 km that is interpreted as a low-angle unconformity surface between the platform cover of Ediacarian and Palaeozoic age and the older Neoproterozoic (Upper Riphean), that is transformed in the east into a basal detachment of the fold-and-thrust belt (Brown *et al.* 2006*c*). At *c.* –25 km this reflectivity is abruptly truncated by a series of steep east-dipping concave reflectors corresponding probably to listric-like faults, traced into the middle crust to a depth of 25–30 km. This type of reflectivity persists from a distance mark of 25 km to the MUF zone. The zone is characterized by several pronounced closely-spaced reflectors dipping to the east at angles of 45°–60° between 0 and 10 km, imaging an imbrication zone of the strongly deformed margin of Laurussia continent. From –20–10 km, the steeply east-dipping reflectors represent 'thick-skinned' deformation in the Precambrian-cored Kvarkush anticlinorium and Early Palaeozoic hanging wall.

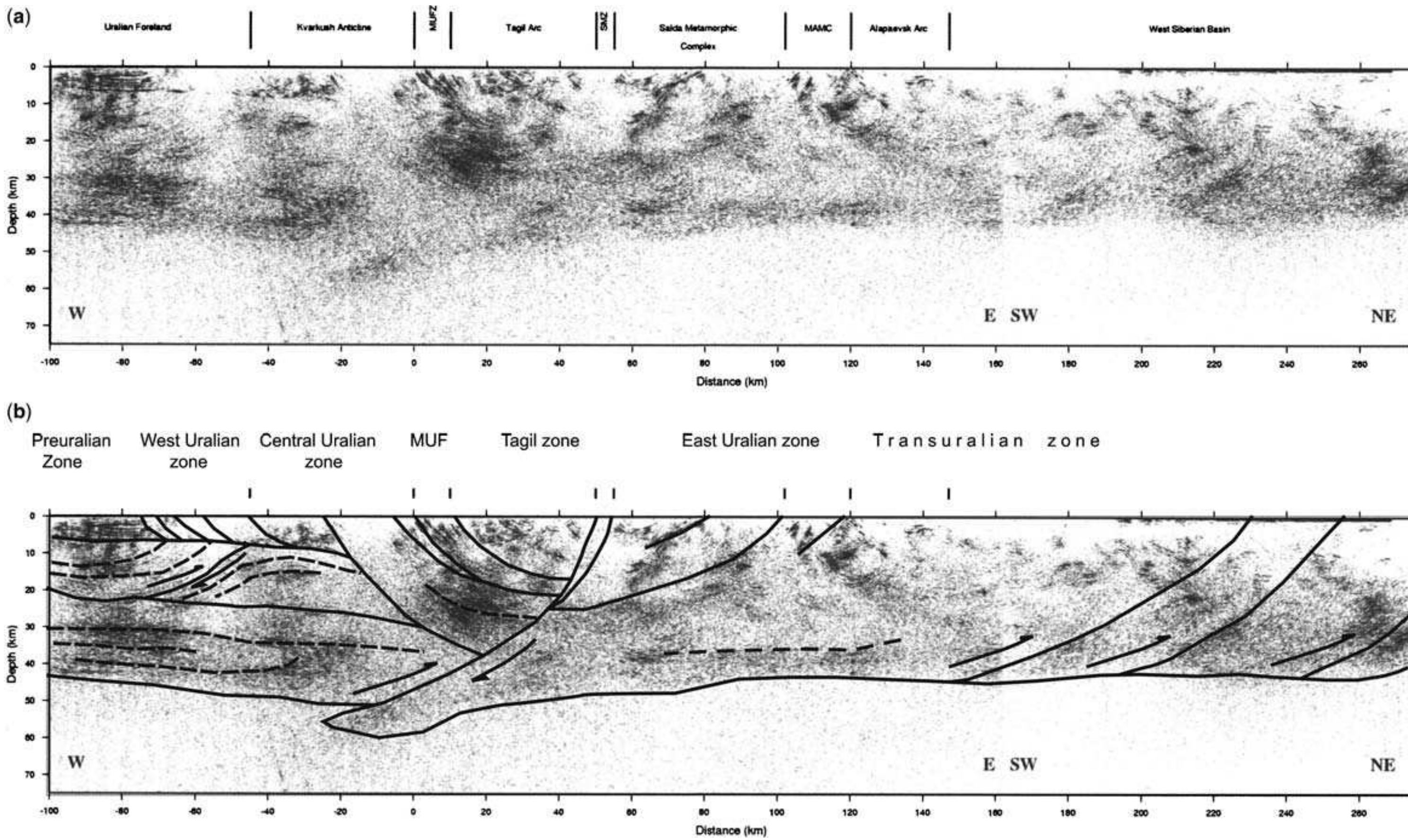

Fig. 16. Seismic cross-sections (**a**) Uninterpreted, and (**b**) Interpreted line drawings of the coherency filtered, depth-migrated ESRU-SB data (Kashubin *et al.* 2006 Rybalka *et al.* 2006). See Figure 4 for location. Abbreviations in the Figure A: MUFZ, Main Uralian Fault zone; SMZ, Serov-Mauk Fault zone; MAMC, Murzinka-Aduy metamorphic complex.

Below the undeformed foreland basin and the basal detachment of the fold-and-thrust belt, the middle crust exhibits wave-like concave to convex reflectivity down to approximately 25 km depth. From 25 km to *c.* 42 km depth, the lower crust is characterized by more coherent and strong, subhorizontal reflectivity. The middle crustal reflectivity probably images the Neoproterozoic and Mesoproterozoic sedimentary rocks, and the lower crustal reflectivity images Archaean–Palaeoproterozoic crystalline basement rocks of the Laurussian margin, though there is a striking difference between the reflectance character of the crystalline basement here and in the URSEIS. The character of crustal reflectivity in the deep part of the section suggests that it is unaffected by the Uralide deformation which also makes a difference between the profiles (Brown *et al.* 2006*c*; Kashubin *et al.* 2006). On the other hand, the reflectivity pattern of the middle crust suggests that at −100 to *c.* −20 km, the 15 or more kilometre-thick Meso- and Neoproterozoic strata form a large synform that is underthrust by an antiformal tectonic wedge composed of the rocks of the same age. The structure is characteristic of a Timanian foreland deformation, but also resembles the wedge-like relationships between the Uraltau antiform and Zilair synform imaged by URSEIS, though their relationships had been formed by the Uralide orogeny.

The Moho surface is traced here as a gently east-dipping boundary between highly reflective lower crust and almost transparent mantle at a depth of 42–45 km. From about *c.* 10–50 km, the upper crust of the Tagil arc is imaged as an open synform, thrust to the west over the Meso-Neoproterozoic rocks of Kvarkush aniclinorium. The Tagil synform is asymmetric, and its eastern limb is limited by a serpentinite mélange of the Serov-Mauk fault zone, separating the synform from the Salda metamorphic complex. The mélange zone is transparent and its western boundary can be traced along abrupt truncations of Tagil reflectors, suggesting a westerly dip of the zone at an angle of 60°. The zone can be traced tentatively into the lower crust along weak and diffuse reflectors, changing the steep western dip of the zone to a gentler 30° close to Moho surface.

The Salda metamorphic complex of probable island-arc nature (Rybalka *et al.* 2006), situated between 55 and 103 km, is characterized by a series of west-dipping reflections, which can be traced under the Tagil synform and Central Uralian zone together with the Serov-Mauk fault. This portion of the crust, correlated with the Salda zone, is wedge-like, protruding down into the mantle under the western slope of the Urals to a depth of 60 km.

The next zone to the east, Murzinka-Adui zone (103–120 km), is represented at the surface by Neoproterozoic metamorphic rocks and Permian granites, and together with the Salda zone belongs to the East Uralian megazone. The character of its reflectivity in the upper crust is incoherent and patchy, and does not permit recognition of its detailed structure. Further east, from 120–180 km within the Trans-Uralian zone, the upper crustal structure is more difficult to interpret owing to both poor surface exposure and the almost complete absence of coherent reflectors in the upper 10-km of the profile.

From *c.* 180 km to the end of the profile (260 km), the platformal Cretaceous and Cenozoic strata of the West Siberian Basin appear to be characterized by a zone of good subhorizontal reflectivity which thickens to the east up to 1.5 km at 260 km. The details of the profile imaged by Rybalka *et al.* (2006) show a relief of the Palaeozoic–Cretaceous unconformity surface, which is strongly uneven probably due to pre-Cretaceous grabens, flexures and river-bed incisions. Under the platformal cover, the structure of the Trans-Uralian zone reveals a series of west-dipping reflectors, merging with the Moho at a depth of *c.* 40 km, in a manner similar to that seen in the KRS of the URSEIS profile, although not as bright.

In general, the Moho is very well defined along the whole profile as a sharp boundary between highly reflective lower crust and an almost transparent mantle. The crust thickens from *c.* 42–43 km in both the west and east to nearly 60 km beneath the Central Uralian zone. The above-mentioned wedge of the lower crust protruding into the mantle gives here the impression that the eastern limb of the orogen is thrust under the former Laurussian lower crust and Moho.

Discussion

The development of the Uralides in the Palaeozoic preserves many of the characteristics of a full Wilson cycle. However, if the concept of such a cycle is restricted to a classical 'accordion-type' development, wherein the continent that rifted away returns back to collide (as it was in the case of Rheic ocean), then the development of the Uralides does not conform with the idea. According to palaeomagnetic data and geodynamic reconstructions (e.g. Puchkov 2000; Kurenkov *et al.* 2002; Svyazhina *et al.* 2003; Levashova *et al.* 2003), between Ordovician and Early Permian time, the microcontinents of the East Uralian zone and Kokchetav block of Kazakhstania were transported at least 2000 km from north to south parallel to the margin of Baltica. Kazakhstania as a whole intervened between Siberia and Baltica in the Devonian, and Siberia rotated clockwise at 90° – probably because of the arrival of Kazakhstania. Kazakhstania was squeezed between accreted margins of Siberia and Laurussia, forming a pronounced horseshoe-like orocline (Fig. 1). It looks more like a rock'n'roll dance than an accordion-like motion. On the other hand, only a minority of orogens belongs to the regular 'accordion' type, and therefore we prefer to follow to a more liberal understanding of Wilson cycle.

The rift processes at the beginning of the cycle are demonstrated by a profound difference between the strikes of Timanide structures and the Main Uralian Fault to the north of the Poliud Range (Fig. 7). The accompanying sedimentary deposits are characterized by irregularly distributed coarse-grained polymictic to arkosic sediments unconformably overlying the basement and accompanied by subalkaline basaltic volcanism. Similar formations on the sialic blocks of the East Uralian and Transuralian zones are *c.* 15–20 Ma younger than those in the Western zones, indicating that the East Uralian microcontinent was not previously detached from the same place where it finally docked.

The suggested Early Palaeozoic plume magmatism described above is considerably younger than the rifting event, and is only indirectly connected, possibly in an analogous manner to the relationship between the transverse chain of the Cretaceous Monteregian alkaline with carbonatite intrusions of eastern North America and the Mesozoic rifts along the margin of the Atlantic Ocean.

Widespread development of ophiolite complexes, almost unprecedented among the Palaeozoic or earlier foldbelts, is one of the most important characteristics of the Uralides. Ophiolites appear to represent anomalous portions of the oceanic tract (Aden and Red sea-type, supra-subduction zone basalts, Lanzo-type mantle blocks) whereas most typical MORB appears to have been almost eliminated by subduction. Island-arc complexes are also widely spread in the Uralides, and subsequent uplift and erosion offers a rare possibility of studying the deeper structure of an island arc, than is available for study in modern island arcs. The internal structure of the arcs exhibits a moderate strain (Brown *et al.* 2001). According to Alvarez-Marron (2002) the Uralides 'may be seen as a factory for "making" new continental crust in contrast to the Variscides which is a factory for "recycling" existing continental crust'.

One of the possible explanations for the exceptionally good preservation of oceanic complexes in the Uralides is the low rigidity of the Kazakhstanian plate, which became continental crust only in the Silurian (Puchkov 1996*a*). The deep-seated deformation of the whole crust with the Moho as a detachment, in the young, eastern limb of the Uralides (see above), absorbed a considerable part of strain. The preservation of ophiolites may depend on strain. In zones of higher strain, ophiolites are squeezed from sutures as allochthonous sheets aided by the formation of rheologically weak serpentinites which may also have acted as a lubricant. This interpretation is supported by experiments that demonstrate the rheological weakness of serpentinite (e.g. Escartin *et al.* 1997; Hilairet *et al.* 2007) and by structural studies in the foreland fold-and-thrust belt of the Southern and Middle Urals, where shortening deduced from balanced geological sections is anomalously low (14–17%, Brown *et al.* 1997). Shortening increases to the north, and in the Mikhailovsk and Serebryansk profiles it is *c.* 30% (calculated after Brown *et al.* 2006*c*). In the Cis-Polar and Polar Urals, however, shortening can be still much greater, judging by the upper section of figure 4 in Puchkov (1997); see also Yudin (1994). This may be explained by the wedging-out of Kazakstania to the north, where two rigid cratons, Laurussia and Siberia, come into contact.

Modern analogies to the arc-continent collision in the Urals include the Indonesian, Taiwan, Tyrrhenian and Greater Antilles arcs. The evolution is similar to that proposed for the Taconian arc in the Appalachian orogen, and the mid-Devonian arc collision with Baltica along the margins of the Rheic Ocean.

Another striking feature of the Uralides, is a long duration and recurrence of orogenic events – from the Devonian until the Early Jurassic, which is comparable to the duration of Appalachian orogenic activity. The oblique, transpressive character and the diachroneity of the continent–continent collision in the Urals is similar to that of the Alleghenian orogeny (Engelder 2007). But the absence of Caledonian collisions, from the Ordovician to the Middle Devonian, is another striking feature of the Uralides.

The characteristics of two regional profiles transecting the orogen, confirm the bi-vergent symmetry of it. Alternatively, uniformly vergent orogens may be part of a bigger, bi-vergent one, that has been dismembered and dispersed by subsequent tectonic events (e.g. Greenland and Scandinavian Caledonides) or its lacking limb overlain by a younger orogen (e.g. a Variscan basement of Alps).

In the western Uralides, where the foreland is cratonic (i.e. ancient and characterized by a thick and rigid lithosphere), the crystalline basement and Moho surface are not affected, or only partly affected, by the main Uralide orogenesis. In the eastern Uralides, however, the Moho is interpreted as a detachment, and the crust is deformed to great depths, an interpretation which supports the idea of a comparative weakness of the Palaeozoic crust and lithosphere as a whole.

In the west, the regional and local profiles show an abrupt transition from 'thin-skinned' – to thick-skinned tectonics along a sharp ramp due to an abrupt change in the plasticity of the rocks. In the east we do not see any 'thin-skinned' tectonics at all. This may reflect the incompleteness of the eastern part of the profiles (URSEIS had been stopped at a state border with Kazakhstan and ESRU – in swamps of Siberia) (Fig. 4). On the other hand, Late Palaeozoic orogenic processes reached much farther to the east than the initial boundary between Uralides and Kazakhstanides (Fig. 1). In the Central Kazakhstanian Caledonides, orogenic processes are documented by Permian deformation of different styles, voluminous Late Palaeozoic syn-orogenic granite and deposition of the contemporaneous molasse in huge intermontane basins such as Chu-Sarysu and Teniz (YUGGEO 2002). Where the Upper Palaeozoic epi-Caledonian sedimentary cover is preserved, as in the Greater Karatau, the east-vergent 'thin-skinned' tectonics was developed during the Upper Carboniferous and Permian (Alekseiev 2008).

Concluding remarks

Extremely good preservation of oceanic and island-arc complexes and low degree of shortening in the foreland belt are unprecedented in the Palaeozoic orogens and give the Uralides a real individuality. Many other features of the Urals are also rare, such as its well-preserved bi-lateral structure, island-arc related platinum-bearing belt, demonstrative arc-continent collision, diachroneity of collisions, a combination of orogenic and rift-related magmatism in a single stage of transpressive deformation of the lithosphere, and the preservation of a heavy, relatively 'cold', isostatically equilibrated root. On a plate scale, however, the history of the Uralides follows the main stages of a Wilson cycle, modified somewhat by episodes of plume-related tectonics and magmatism in the Early Palaeozoic and Triassic.

Fieldwork campaigns, workshops and informal discussions in more than a decade of co-operation with prominent European and American geologists during the activity of the *EUROPROBE* Commission in the Urals have considerably stimulated the work of the author. The author acknowledges also the importance of his participation in the *IGCP-453* '*Uniformitarianism revisited: a comparison between modern and ancient orogens*', which ultimately inspired him to write this paper. The financial support of the Department of Earth's Sciences of the Russian Academy of Sciences, *Program No. 10 The Central Asian mobile belt: geodynamics and stages of the Earth's crust formation* must be also highly appreciated. The last, but not the least of my expression of gratitude is to the reviewers, V. Ramos and R. Ernst and to B. Murphy, the editor, who helped greatly at the last stages of the work.

References

AGARD, P. & LEMOINE, M. 2005. *Faces of the Alps: Structure and Geodynamic Evolution*. Commission of the geological map of the world, Paris.

ALEKSEIEV, D. V. 2008. Kinematics of the Variscan Ural and Tian-Shan junction area. *Geologie de la France*, **2**, 75.

ALL-RUSSIAN STRATIGRAPHIC COMMITTEE. 1993. *Stratigraphic Schemes of the Urals: Precambrian and Paleozoic*. Ekaterinburg, 151 scheme (in Russian).

ALVAREZ-MARRON, J. 2002. Tectonic processes during collisional orogenesis from comparison of the Southern Urals with the Central Variscides. *In*: BROWN, D., JUHLIN, C. & PUCHKOV, V. (eds) *Mountain Building in the Uralides: Pangea to Present*. American Geophysical Union, Geophysical Monograph, **132**, 83–100.

AMON, E. O. 2001. The marine equatorial basin of the Uralian region in the Mid- and Late Cretaceous epoch. *The Geology and Geophysics*, **42**, 471–483 (in Russian).

ANDREICHEV, V. L., RONKIN, YU. K., LEPIKHINA, O. P. & LITVINENKO, A. F. 2005. *Rb–Sr and Sm–Nd Isotopic-geochronometric Systems in Basalts of the Polar Cis-Urals*. Syktyvkar, Geoprint (in Russian).

ARTIUSHKOVA, O. V. & MASLOV, V. A. 2003. Lower Devonian (pre-Upper Emsian) deposits of the Magnitogorsk megazone. *Geological Sbornik*, IG USC RAS, **3**, 80–87 (in Russian).

BATANOVA, V. G., BRUEGMANN, G., BELOUSOV, I. A., SAVELIEVA, G. N. & SOBOLEV, A. V. 2007. The processes of melting and migration of melts in mantle based on a study of highly siderophile elements and their isotopes. *In*: GALIMOV, E. M. (ed.) *XVIII Vinogradov Symposium on Geochemistry of Isotopes*. V., GEOKHI, 40–41 (in Russian).

BEA, F., FERSHTATER, G. & MONTERO, P. 2002. Granitoids of the Urals: implications for the evolution of the orogen. *In*: BROWN, D., JUHLIN, C. & PUCHKOV, V. (eds) *Mountain Building in the Uralides: Pangea to Present*. American Geophysical Union, Geophysical Monograph, **132**, 211–232.

BEANE, R. J. & CONNELLY, J. H. 2000. ^{40}Ar–^{39}Ar, U–Pb and Sm–Nd constraints on the timing of metamorphic events in the Maksyutov Complex, Southern Ural Mountains. *Journal of the Geological Society, London*, **157**, 811–822.

BELL, K. 2001. Carbonatites: relationships to mantle-plume activity. *In*: ERNST, R. E. & BUCHAN, K. L. (eds) *Mantle Plumes: Their Identification Through Time*. Geological Society of America Special Paper, **352**, 267–290.

BERZIN, R., ONCKEN, O., KNAPP, J. H., PEREZ-ESTAUN, A., HISMATULIN, T., YUNUSOV, N. & LIPILIN, A. 1996. Orogenic evolution of the Ural Mountains: results from an integrated seismic experiment. *Science*, **274**, 220–221.

BEUTLER, G. 1979. Verbreitung und Charakter der altkimmerischen Hauptdiskordanz in Mitteleuropa. *Zeitschrift für Geologische Wissenschaften*, **5**, 617–632.

BISKE, YU. S. 2006. *The Foldbelts of the Northern Eurasia. Tyanshan Foldbelt*. St. Petersburg University (in Russian).

BOCHKAREV, V. V. & YAZEVA, R. G. 2000. *Subalkaline Magmatism of the Urals*. Ekaterinburg (in Russian).

BORISEVICH, D. V. 1992. Neotectonics of the Urals. *Geotectonics*, **26**, 41–47 (in Russian).

BOROZDINA, G. N. 2006. *The history of geological development of the Ragil megazone of the Middle and Southern part of the Middle Urals during the Lower Paleozoic*. Candidate of Science thesis, Ekaterinburg, IGG Uralian Branch of Russian Academy (in Russian).

BOROZDINA, G. N., IVANOV, K. S., NASSEDKINA, V. A. & SNIGIREVA, M. P. 2004. On the age and volume of the Shemur formation of the Tagil megazone. *Ezhegodnik-2003*, Institute of Geology and Geophysics, Sverdlovsk, 10–13 (in Russian).

BORTNIKOV, P. S., SAVELIEVA, G. N., MATUKOV, D. I., SERGEEV, S. A., BAREZHNAYA, N. G., LEPEKHINA, E. N. & ANTONOV, A. V. 2005. The age of a zircon from plagiogranites and gabbro after SHRIMP data: pleistocene intrusion in the rift valley of the Mid-Atlantic Ridge, 5°30′6″–5°32′4″N. *Doklady of Russian Academy of Science, Geology*, **404**, 94–99 (in Russian).

BROWN, D. & PUCHKOV, V. 2004. *Arc-continent Collision in the Uralides*. An IGCP-453 'Uniformitarianism revisited: a comparison between modern and ancient orogens' conference and fieldtrip. Design Poligraph Service, Ufa.

BROWN, D., ALVAREZ-MARRON, J., PEREZ-ESTAUN, A., GOROZHANINA, Y., BARYSHEV, V. & PUCHKOV, V. 1997. Geometric and kinematic evolution of the foreland thrust and fold belt in the southern Urals. *Tectonics*, **16**, 551–562.

BROWN, D., ALVAREZ-MARRON, J., PEREZ-ESTAUN, A., PUCHKOV, V., AYARZA, P. & GOROZHANINA, Y. 2001. Structure and evolution of the Magnitogorsk forearc basin: identifying upper crustal processes during arc-continent collision in the Southern Urals. *Tectonics*, **20**, 364–375.

BROWN, D., PUCHKOV, V. N., ALVAREZ-MARRON, J. & PEREZ-ESTAUN, A. 2006*a*. Tectonic processes in the Southern and Middle Urals: an overview. *In*: GEE, D. G. & STEPHENSON, R. A. (eds) *European Lithosphere Dynamics*. Geological Society, London, Memoirs, **32**, 407–419.

BROWN, D., SPADEA, P. *ET AL*. 2006*b*. Arc-continent collision in the Southern Urals. *Earth-Science Reviews*, **79**, 261–287.

BROWN, D., JUHLIN, C., TRYGGVASON, A., FRIBERG, M., PUCHKOV, V., RYBALKA, A. & PETROV, G. 2006*c*. Structural architecture of the southern and middle Urals foreland from reflection seismic profiles. *Tectonics*, **25**, 1–12.

BROWN, D., JUHLIN, C. *ET AL*. 2008. Mountain building processes during continent-continent collision in the Uralides. *Earth-Science Reviews*, **89**, 177–195.

BURNS, L. E. 1985. The Border Ranges ultramafic and mafic complex, south-central Alaska: cumulate fractionates of island-arc volcanics. *Canadian Journal of Earth Sciences*, **22**, 1020–1038.

BURTMAN, V. S. 2006. *Tien Shan and High Asia. Tectonics and Geodynamics in Paleozoic*. Moscow, GEOS (in Russian).

CARBONELL, R., PEREZ-ESTAÚN, A. *ET AL*. 1996. A crustal root beneath the Urals: Wide-angle seismic evidence. *Science*, **274**, 222–224.

CARBONELL, R., LECERF, D., ITZIN, M., GALLART, J. & BROWN, D. 1998. Mapping the Moho beneath the Southern Urals. *Geophysical Research Letters*, **25**, 4229–4233.

CHUVASHOV, B. I., IVANOVA, R. M. & KOLCHINA, A. N. 1984. *The Upper Paleozoic of the Eastern Slope of the Urals*. Uralian Scientific Centre, Sverdlovsk (in Russian).

COBBOLD, P. R., MEISLING, K. E. & MOUNT, V. S. 2001. Reactivation of obliquely rifted margin, Campos and Santos basins, southeastern Brazil. *AAPG Bulletin*, **85**, 1925–1944.

COCKS, L. R. M. & TORSVIK, T. H. 2006. European geography in a global context from the Vendian to the end of Paleozoic. *In*: GEE, D. G. & STEPHENSON, R. A. (eds) *European Lithosphere Dynamics*. Geological Society, London, Memoirs, **32**, 83–95.

DALZIEL, I. 1992. On the organization of American plates in the Neoproterozoic and the breakout of Laurentia. *GSA Today*, **11**, 237–241.

DAVYDOV, V. I., CHERNYKH, V. V., CHUVASHOV, B. I., NORTHRUP, K. J. & SNYDER, V. S. 2002. Volcanic tuff layers in the Upper Paleozoic of the Southern Urals and prospects of creation of exactly calibrated time scale of the Carboniferous. *In*: CHUVASHOV, B. I. (ed.) *Stratigraphy and Paleogeography of the Carboniferous of Eurasia*. Ekaterinburg, Institute of Geology and Geochemistry, 112–123 (in Russian).

DIANCONESCU, C. C., KNAPP, J. H., BROWN, L. D., STEER, D. N. & STILLER, M. 1998. Precambrian Moho offset and tectonic stability of the East European platform from the URSEIS deep seismic profile. *Geology*, **26**, 211–214.

DIDENKO, A. H., KURENKOV, S. A. *ET AL*. 2001. *Tectonic History of the Polar Urals*. M. Nauka (in Russian).

DOBRETSOV, N. L., KIRDYASHKIN, A. G. & KIRDYASHKIN, A. 2001. *The Deep Geodynamics*. Novosibirsk, GEO (in Russian).

DRUZHININ, V. S., RYBALKA, V. M. & SOBOLEV, I. D. 1976. *The Connection of the Tectonics and Magmatism with the Deep Structure after DSS Data*. Sverdlovsk (in Russian).

ECHTLER, H. P., STILLER, M. *ET AL*. 1996. Preserved collisional crustal architecture of the Southern Urals – Vibroseis CMP-profiling. *Science*, **274**, 224–226.

EFIMOV, A. A., EFIMOVA, L. P. & MAEGOV, V. I. 1993. Tectonics of the Platinum-bearing belt of the Urals: relations of complexes and mechanism of structure formation. *Geotectonics*, **3**, 4–46 (in Russian).

ENGELDER, T. 2007. The Alleghanian orogeny of the Appalachian Mountains. *Geologie de la France*, **2**, 94.

ESCARTIN, J., HIRTH, G. & EVANS, B. 1997. Nondilatant brittle deformation of serpentinites: implications for Mohr-Coulomb theory and the strength of faults. *Journal of Geophysical Research*, **102**, B2, 2897.

FERSHTATER, G. B., BEA, F. & MONTERO, P. 2006. Granitoids. *In*: MOROZOV, A. F. (ed.) *Structure and Dynamics of Lithosphere of the Eastern*

Europe, Issue 2. The Results of the EUROPROBE Research. Moscow, GEOKART, GEOS, 449–461 (in Russian).

FRANKE, W. 2000. The Mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. *In*: FRANKE, W., HAAK, V., ONCKEN, O. & TANNER, D. (eds) *Orogenic Processes: Quantification and Modelling in the Variscan Belt*. Geological Society, London, Special Publications, **179**, 35–61.

GAGGERO, L., SPADEA, P. & CORTESOGNO, L. 1997. Geochemical investigation of the igneous rocks from the Nurali ophiolite melange zone, Southern Urals. *Tectonophysics*, **276**, 139–161.

GEE, D. G., BOGOLEPOVA, O. K. & LORENZ, H. 2006. The Timanide, Caledonide and Uralide orogen in the Eurasian high Arctic, and relationships to the palaeocontinents Laurentia, Baltica and Siberia European Lithosphere Dynamics. *In*: GEE, D. G. & STEPHENSON, R. A. (eds) *European Lithosphere Dynamics*. Geological Society, London, Memoirs, **32**, 507–520.

GEOFFROY, L. 2005. Volcanic passive margins. *Comptes Rendu Geoscience*, **337**, 1395–1408.

GLASMACHER, U. A., WAGNER, G. A. & PUCHKOV, V. N. 2002. Thermotectonic evolution of the western fold-and-thrust belt, southern Urals, Russia, as revealed by apatite fission-track data. *Tectonophysics*, **354**, 25–48.

GLODNY, J., AUSTRHEIM, H., MONTERO, P. & RUSIN, A. 1999. The Marun-Keu Metamorphic Complex, Polar Urals, Russia Protolith ages, Eclogite facies fluid-rock interaction, and Exhumation History. *EUG–10 Abstracts*, Cambridge Publications, 80.

GLODNY, J., BINGEN, B., AUSTRHEIM, H., MOLINA, J. F. & RUSIN, A. 2002. Precise eclogitization ages deduced from Rb/Sr mineral systematics: the Maksyutov Complex, Southern Urals, Russia. *Geochimica et Cosmochimica Acta*, **66**, 1221–1235.

GLODNY, J., AUSTERHEM, H., MOLINA, J. F., RUSIN, A. & SEWARD, D. 2003. Rb–Sr record of fluid-rock interaction in eclogites: the Marun-Keu complex, Polar Urals, Russia. *Geochimica et Cosmochimica Acta*, **67**, 4353–4371.

GLODNY, J., PEASE, V. L., MONTERO, P., AUSTERHEIM, H. & RUSIN, A. I. 2004. Protolith ages of eclogites, Marun-Keu Complex, Polar Urals, Russia: implications for the pre- and early Uralian evolution of the northeastern European continental margin. *In*: GEE, D. G. & PEASE, V. L. (eds) *The Neoproterozoic Timanide Orogen of Eastern Baltica*. Geological Society, London, Memoirs, **30**, 87–105.

GOLOVANOVA, I. V. 2006. *The Thermal Field of the Southern Urals*. M. Nauka (in Russian).

GOROZHANINA, E. N. & PAZUKHIN, V. N. 2007. The stages of activization of geodynamic processes in the Late Devonian-Mid-Carboniferous time at the western limb of the Zilair synclinorium and their dating by conodonts. *Geologichesky Sbornik*, **6**, Ufa, Institute of Geology, 55–64 (in Russian).

GRADSTEIN, F. M., OGG, J. G., SMITH, A. G., BLEEKER, W. & LOURENS, L. J. 2004. A new Geologic time scale with special reference to Precambrian and Neogene. *Episodes*, **27**, 83–100.

GURSKAYA, L. I. & SMELOVA, L. V. 2003. Platinum-metal ore formation and structure of Syum-Keu massif (Polar Urals). *Geology of Ore deposits*, **45**, 353–371 (in Russian).

HETZEL, R. & ROMER, R. L. 1999. U–Pb dating of the Verkniy Ufaley intrusion, middle Urals, Russia: a minimum age for subduction and amphibolite facies overprintof the East European continental margin. *Geological Magazine*, **136**, 593–597.

HETZEL, R. & ROMER, R. L. 2000. A moderate exhumation rate for the high-pressure Maksyutov Complex, Southern Urals, Russia. *Geological Journal*, **35**, 327–344.

HILAIRET, N., REYNARD, B., WANG, YANBIN, DANIEL, I., MERKEL, S., NISHIYAMA, N. & PETITGIRARD, S. 2007. High-pressure creep of serpentine, interseismic deformation, and initiation of subduction. *Science*, **318**(5858), 1910–1913.

INTERNATIONAL COMMITTEE OF TECTONIC MAPS. 1982. *Tectonics of Europe and adjacent areas. Variscides, epi-Paleozoic platforms and Alpides. Explanatory note to the International tecnonic map of Europe and adjacent areas, scale 1:2 5000 000*. M. Nauka Publishing House.

IVANOV, A. V., RASSKAZOV, S. V., FEOKTISTOV, G. D., HUAIYU, H. E. & BOVEN, A. 2005. $^{40}Ar–^{39}Ar$ dating of Usol'skii sill in the south-eastern Siberian Traps Large Igneous Province: evidence for long-lived magmatism. *Terra Nova*, **17**, 203–208.

IVANOV, K. S. 2001. The evaluation of paleovelocities of subduction and collision in the origin of the Urals. *Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Section*, **377**, 231–234 (in Russian).

IVANOV, K. S., KARSTEN, L. A. & MALUSKI, G. 2000. The first data on the age of subductional (eclogite-glaucophane) metamorphism in the Polar Urals. *In*: KOROTEEV, V., IVANOV, K. & BOCHKAREV, V. (eds) *Paleozones of Subduction: Nectonics, Magmatism, Metamorphism, Sedimentology*. Ekaterinburg, Urals Branch of Russian Academy of Sciences, 121–128 (in Russian).

IVANOV, K. S., KOROTEEV, V. A. *ET AL*. 2004. The structure of a conjugation zone between Cis-Urals and West Siberian oil-and-gas-bearing basin. *Lithosphere*, **2**, 108–124 (in Russian).

IVANOV, K. S., SHMELEV, V. R., RONKIN, YU. L., SAVELIEVA, G. N. & PUCHKOV, V. N. 2006. Zonal gabbro-ultramafic complexes. *In*: MOROZOV, A. F. (ed.) *Structure and Dynamics of Lithosphere of the Eastern Europe, Issue 2. The Results of the EUROPROBE Research*. Moscow, GEOKART, GEOS, 437–445 (in Russian).

JONAS, P. 2004. Tectonostratigraphy of oceanic crustal terrains hosting serpentinite-associated massive sulphide deposits in the Main Uralian Fault zone (South Urals). *Freiberger Forschungshefte*, **C498**, Technische Universitat Bergakademie Freiberg.

KASHUBIN, S., JUHLIN, C. *ET AL*. 2006. Crustal structure of the Middle Urals based on reflection seismic data. *In*: GEE, D. & STEPHENSON, R. (eds) *European Lithosphere Dynamics*. Geological Society, London, Memoirs, **32**, 427–442.

KAZANSKY, A. YU., METELKIN, D. V., BRAGIN, V. YU., MIKHALTSOV, N. V. & KUNGURTSEV, L. V. 2004. Paleomagnetic data on the Mesozoic complexes of a frame of Siberian platform as a reflection of interpolated transcurrent deformations of the Central Asiatic belt. *In*: SKLYAROV, E. M. (ed.) *The Geodynamic Evolution of Lithosphere of the Central Asiatic Belt. From Ocean to Continent*. **2**, Irkutsk, Institute of the Earth Crust, 151–155.

KHAIN, V. E. 2001. *Tectonics of Continents and Oceans (2000)*. Nauchnyi Mir, Moscow (in Russian).

KHAIN, E. V., FEDOTOVA, A. A., SALNIKOVA, E. B., KOTOV, A. B. & YAKOVLEVA, S. Z. 2004. New U–Pb data on the age of ophiolites of the Polar Urals and development of the margins of the Paleoasiatian ocean in the Late Precambrian and Early Paleozoic. *In*: KOROTEEV, V. A. (ed.) *Geology and Metallogeny of the Ultramafic-mafic and Granitoid Associations of Foldbelts*. Ekaterinburg, Institute of Geology and Geochemistry, 183–186 (in Russian).

KLIUZHINA, M. L. 1985. *Paleogeography of the Urals in the Ordovician*. M. Nauka (in Russian).

KNAPP, J. H., STEER, D. N. *ET AL*. 1996. A lithosphere-scale image of the Southern Urals from explosion-source seismic reflection profiling in URSEIS '95. *Science*, **274**, 226–228.

KORAGO, E. A., KOVALEVA, G. N. & TRUFANOV, G. N. 1989. Formations, tectonics and geological history of the Novozemelian Cimmerides. *Geotectonics*, **6**, 40–61 (in Russian).

KOSAREV, A. M. & PUCHKOV, V. N. 1999. The distribution of K, Ti and Zr in the Silurian-Carboniferous volcanic formations of the Southern Urals in connection with the position of the Paleozoic subduction zone. *Ezhegodnik-1977*. Ufa, Institute of Geology, Ufimian Science Centre. 186–191 (in Russian).

KOSAREV, A. M., PUCHKOV, V. N. & SERAVKIN, I. B. 2005. Petrological-geochemical features of the Early Devonian-Eifelian island arc volcanites of the Magnitogorsk zone in a geodynamical context. *Lithosphere*, **4**, 24–40 (in Russian).

KOSAREV, A. M., PUCHKOV, V. N. & SERAVKIN, I. B. 2006. Petrologo-geochemical character of the Middle Devonian–Early Carboniferous island-arc and collisional volcanic rocks of the Magnitogorsk zone in the geodunamical context. *Lithosphere*, **1**, 3–21 (in Russian).

KOZLOV, V. I. 1976. The coal-bearing deposits of the Paleogene and Neogene of the Tirlyan syncline. *In*: YAKHIMOVICH, V. L. (ed.) *The Problems of Stratigraphy and Correlation of Pliocene and Pleistocene Deposits of the Northern and Southern Parts of the Cis-Urals*. Ufa, Bashkirian Branch of the Academy of Sciences, USSR, 210–227 (in Russian).

KRASNOBAEV, A. A., RUSIN, A. I., RUSIN, I. A. & BUSHARINA, S. V. 2008. Zirconology of lherzolite-garnet pyroxenite-dunite complex of the Uzyan Kraka (S.Urals). *In*: KORTOTEEV, V. A. (ed.) *The Structural-material Complexes and Geodynamic Problems of the Precambrian of Phanerozoic Orogens*. Ekaterinburg, Uralian Branch of Russian Academy of Sciences, 58–61 (in Russian).

KURENKOV, S. A., DIDENKO, A. N. & SIMONOV, V. A. 2002. *The Geodynamics of Paleospreading*. M. GEOS. (in Russian).

LEECH, M. L. & WILLINGSHOFER, E. 2004. Thermal modeling of the UHP Maksyutov Complex in the south Urals. *Earth and Planetary Science Letters*, **226**, 85–99.

LENNYKH, V. I., VALISER, P. M., BEANE, R., LEECH, M. & ERNST, W. G. 1995. Petrotectonic evolution of the Makysutov complex, southern Ural Mountains, Russia: implications for ultrahigh-pressure metamorphism. *International Geology Review*, **37**, 584–600.

LEPEZIN, G. G., TRAVIN, A. V., YUDIN, D. S., VOLKOVA, N. V. & KORSAKOV, A. V. 2006. The age and thermal history of the Maksiutovo metamorphic complex (after Ar–Ar data). *Petrology*, **14**, 1–18.

LEVASHOVA, N. M., DEGTYAREV, K. E., BAZHENOV, M. L., COLLINS, A. Q. & VAN DER VOO, R. 2003. Middle Paleozoic paleomagnetism of east Kazakhstan: post-Middle Devonian rotations in a large-scale orocline in the central Ural-Mongol belt. *Tectonophysics*, **377**, 249–268.

LEVIN, V. YA., RONENSON, B. M. & SAMKOV, V. S. 1997. *Alkaline-carbonatite Complexes of the Urals*. Ekaterinburg (in Russian).

LI, Z. X., BOGDANOVA, S. V. *ET AL*. 2008. Assembly, configuration, and break-up history of Rodinia: a synthesis. *Precambrian Research*, **160**, 179–210.

LINNEMANN, U., GEHMLICH, V., TICHOMIROWA, V. & BUSCHMANN, B. 1998. Introduction to the Pre-Symposium Excursion (part I): the Peri-Gondwanan basement of the Saxothuringian Composite Terrane. Excursion Guide to Saxony, Thüringia, Bohemia. Abstracts. *Schriften des Staatlichen Museums für Mineralogie und Geologie zu Dresden*, 7–13.

LÜTZNER, H., FALK, F. & ELLENBERG, J. 1979. Uebersicht über die Variszische Molasseentwicklung in Mitteleuropa und am Ural. *Zeitschrift für Geologische Wissenschaften*, **9**, 1157–1167.

MASLOV, V. F., ARTIUSHKOVA, O. V., YAKUPOV, R. R. & MAVRINSKAYA, T. M. 2008. The problems of the Lower–Middle Paleozoic stratigraphy of the Southern Urals. *Geologichesky Sbornik*, **7**, 193–204 (in Russian).

MATTE, P. 2006. The Southern Urals: deep subduction, soft collision and weak erosion. *In*: GEE, D. & STEPHENSON, R. (eds) *European Lithosphere Dynamics*. Geological Society, London, Memoirs, **32**, 421–426.

MATTE, P., MALUSKI, H., CABY, R., NICOLAS, A., KEPEZHINSKAS, P. & SOBOLEV, S. 1993. Geodynamic model and $^{39}Ar/^{40}Ar$ dating for the generation and emplacement of the high-pressure (HP) metamorphic rocks in SW Urals. *Academie de Sciences Comptes Rendus*, **317**, 1667–1674.

MELCHER, F., GRUM, W., THALHAMMER, T. V. & THALHAMMER, O. A. R. 1999. The giant chromite deposits at Kempirsai, Urals: constraints from trace element (PGE, REE) and isotope data. *Mineralium Deposita*, **34**, 250–272.

MELEKESTSEVA, I. YU. 2007. *Heterogenous Co-bearing Massive Sulfide Deposits Associated with Ultramafites of Paleo-island Arc Structures*. M. Nauka (in Russian).

MENSHIKOV, YU. P., KUZNETSOVA, N. V., SHEBUKHOVA, S. V. & NIKISHEVA, G. N. 1983. The tectonics of the northern half of the Magnitogorsk depression after geophysical data. *In*: KHALEVIN, N. (ed.) *The Faults of the Earth's Crust of the Urals and the Methods of Their Study*. Sverdlovsk, Uralian Scientific Centre, 65–78 (in Russian).

MIKHAILOV, V. O., TEVELEV, A. V., BERZIN, R. G., KISELEVA, E. A., SMOLYANINOVA, E. I., SULEIMANOV, A. K. & TIMOSHKINA, E. P. 2002. Constraints on the Neogene-Quaternary Geodynamics of the Southern Urals: comparative study of Neotectonic data and results of Strength and Strain Modelling Along the URSEIS Profile. *In*: BROWN, D., JUHLIN, C. & PUCHKOV, V. (eds) *Mountain Building in the Uralides: Pangea to the Present*. AGU Geophysical Monograph Series, **132**, 273–286.

MILANOVSKI, E. E. 1963. On the paleogeography of the Kaspian basin in the Middle and beginning of the Upper Pliocene. *Bulletin Moscow Society of Nature Studies, Section of Geology*, **38**, 23–26 (in Russian).

MÜNTENER, O., PICCARDO, G. B., POLINO, R. & ZANETTI, A. 2005. Revisiting the Lanzo peridotite (NW Italy): "astenospherization" of ancient mantle lithosphere. *Ofioliti*, **30**, 111–124.

MURATOV, M. V. 1979. The Uralo-Mongolian foldbelt. *In*: MURATOV, M. V. (ed.) *Tectonics of the Uralo-Mongolian Foldbelt*. M. Nauka, 5–11 (in Russian).

NARKISSOVA, V. V. 2005. *Petrochemistry of the Late Ordovician-Early Devonian basaltoids of the Southern part of the Middle Urals (after data on the Uralian superdeep borehole and near-hole area)*. Candidate Dissertation thesis. Moscow University (in Russian).

NEDOSEKOVA, I. L., PRIBAVKIN, S. V., SEROV, P. A. & RONKIN, YU. L. 2006. The isotopic compositions and age of carbonatites of the Ilmeno-Vishnevogorsk alkaline complex. *In*: GALIMOV, E. M. (ed.) *Isotopic Dating of Processes of Ore Formation, Magmatism, Sedimentation and Metamorphism*. M. GEOS, 40–54 (in Russian).

PAPULOV, G. N. 1974. *The Cretaceous Deposits of the Urals*. M. Nauka (in Russian).

PEASE, V., DALY, J. S. *ET AL*. 2008. Baltica in the Cryogenian, 850–630 Ma. *Precambrian Research*, **160**, 46–65.

PETROV, G. A. 2006. *The Geology and Minerageny of the Main Uralian Fault Zone in the Middle Urals*. Ekaterinburg, Uralian Mining University (in Russian).

PETROV, G. A., RONKIN, YU. L., LEPIKHINA, O. P. & POPOVA, O. YU. 2005. High-pressure metamorphism in the Urals – two stages? *Ezhegodnik-2004*. IGG Uralian Branch of RAS, Ekaterinburg. 97–102 (in Russian).

PEYVE, A. V., IVANOV, S. N., NECHEUKHIN, V. M., PERFILYEV, A. S. & PUCHKOV, V. N. 1977. *Tectonics of the Urals. The explanatory notes for the 1:1 000 000-scale tectonic map*. M. Nauka, Moscow (in Russian).

PLIUSNIN, K. P. 1966. Wrench faults of the eastern slope of the Southern Urals. *Geotectonics*, **4**, 57–68 (in Russian).

PRIBAVKIN, S. V., RONKIN, YU. L., TRAVIN, A. V. & PONOMARCHUK, V. A. 2006. The new data on the age of lamproite magmatism of the Urals. *In*: GALIMOV, E. M. (ed.) *III Russian Conference on Isotope Geochronology: Isotopic Dating of Processes Ore Formation, Magmatism, Sedimentation and Metamorphism*. M. GEOS, 123–125.

PUCHKOV, V. N. 1979. *Bathyal Complexes of the Passive Margins of Geosynclines*. M. Nauka, Moscow (in Russian).

PUCHKOV, V. N. 1996*a*. The Paleozoic geology of Asiatic Russia and adjacent territories. *In*: MOULLADE, M. & NAIRN, A. (ed.) *The Phanerozoic Geology of the World I. The Paleozoic, B*. Elsevier, 1–107.

PUCHKOV, V. N. 1996*b*. The origin of the Ural-Novozemelian foldbelt as a result of an uneven, oblique collision of continents. *Geotectonics*, **5**, 66–75 (in Russian).

PUCHKOV, V. N. 1997. Structure and geodynamics of the Uralian orogen. *In*: BURG, J.-P. & FORD, M. (eds) *Orogeny Through Time*. Geological Society, London, Special Publications, **121**, 201–236.

PUCHKOV, V. N. 2000. *Paleogeodynamics of the Middle and Southern Urals*. Ufa, Dauria (in Russian).

PUCHKOV, V. N. 2002*a*. Paleozoic evolution of the East European continental margin involved into the Urals. *In*: BROWN, D., JUHLIN, C. & PUCHKOV, V. (eds) *Mountain Building in the Uralides: Pangea to the Present*. AGU Geophysical Monograph Series, **132**, 9–32.

PUCHKOV, V. N. 2002*b*. Neotectonics of the Urals. *In*: PUCHKOV, V. N. & DANUKALOVA, G. A. (eds) *Upper Pliocene and Pleistocene* of *the Southern Urals Regions INQUA-SEQS'02*, Ufa, 70–72.

PUCHKOV, V. N. 2003. Uralides and Timanides: their structural relationship and position in the geological history of the Uralo-Mongolian foldbelt. *Russian Geology and Geophysics*, **44**, 28–39.

PUCHKOV, V. N. 2005. Evolution of lithosphere: from the Pechora ocean to Timanian orogen, from the Paleouralian ocean to Uralian orogen. *In*: LEONOV, YU. G. (ed.) *Problems of Tectonics of the Central Asia*. M., GEOS, 309–342 (in Russian).

PUCHKOV, V. N. 2006*a*. The outline of the Uralian minerageny. *In*: PYSTIN, M. A. (ed.) *The Problems of Geology and Mineralogy*. Syktyvkar, Geoprint, 195–222 (in Russian).

PUCHKOV, V. N. 2006*b*. On the age of the Uralian ophiolites. *In*: KOROTEEV, V. A. (ed.) *Ophiolites: Geology, Petrology, Metallogeny and Geodynamics*. Ekaterinburg, IG USC RAS, 121–129 (in Russian).

PUCHKOV, V. N. 2008. The diachroneity of arc-continent collision in the Uralides: subduction jump, oblique subduction or ... what? *In*: National Cheng Kung University Tainan. *Arc–continent collision*. Taiwan, 47–51.

PUCHKOV, V. N., RAPOPORT, M. B., FERSHTATER, G. B. & ANANYEVA, E. M. 1986. Tectonic control of the Paleozoic granitoid magmatism in the eastern slope of the Urals. *In*: IVANOV, S. N. (ed.) *Studies of Geology and Metallogeny of the Urals*. UNTs AN SSSR, Sverdlovsk, 85–95 (in Russian).

PUCHKOV, V. N. & SVETLAKOVA, A. N. 1993. The structure of the Urals in the transect of the Troitsk DSS profile. *Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Section*, **333**, 348–351 (in Russian).

PUCHKOV, V. N. & DANUKALOVA, G. A. 2004. New data on the character of tectonic deformations of the

Cretaceous-Paleogene peneplain in the Southern Urals. *In*: PUCHKOV, V. N. (ed.) *Geological Sbornik* **4**. Institute of Geology, Ufimian Geoscience Center, Russian Academy of Science, Ufa, 183–184 (in Russian).

PUCHKOV, V. N., ROSEN, O. M., ZHURAVLEV, D. Z. & BIBIKOVA, E. V. 2006. Contamination of Silurian volcanites of the Tagil synform by Precambrian zircons. *Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Section*, **411**, 1–4 (in Russian).

PUSHKAREV, E. V. 2001. Explosive breccias with inclusiona of mafic and ultramafic high-pressure rocks in the Mindyak lherzolite massif – composition and petrogenetic consequences. *In*: PUCHKOV, V. N. (ed.) *Geology and Prospects of the Raw Materials of Bashkortostan and Adjacent Territories*. Ufa, IG UNC RAS, **1**, 155–168 (in Russian).

RASULOV, A. T. 1982. *The Tectonics of the Early Mesozoic Depressions of the Eastern Slope of the Urals*. Sverdlovsk, Institute of Geology and Geochemistry, Uralian Scientific Centre, USSR (in Russian).

REICHOV, M. K., PRINGLE, M. S. *ET AL*. 2007. New high-precision ^{40}Ar–^{39}Ar ages and geochemical data from the greater Siberian large igneous province: The Biggest gets Bigger. *Abstract of AGU meeting*, San Francisco, 425.

REMIZOV, D. N. 2004. *The Island-arc System of the Polar Urals (Petrology and Evolution of Deep-seated Zones)*. Ekaterinburg, Uralian Branch of Russian Academy (in Russian).

RICKEN, W., SCHRADER, S., ONCKEN, O. & PLESCH, A. 2000. Turbidite basin and mass dynamics related to orogenic wedge growth; the Rheno-Hercynian case. *In*: FRANKE, W., HAAK, V., ONCKEN, O. & TANNER, D. (eds) *Orogenic Processes: Quantification and Modelling in the Variscan Belt*. Geological Society, London, Special Publications, **179**, 257–280.

ROZHDESTVENSKY, A. P. & ZINYAKHINA, I. K. 1997. *The Development of the Relief of the Southern Urals in the Cenozoic, the Neogene Period*. Ufa, IG USC RAS (in Russian).

RYABOV, V. V. & GRIB, D. YE. 2005. Multiphase dykes – an example of dissipated spreading in the North of the Siberian platform. *Geology and Geophysics*, **46**, 471–485 (in Russian).

RYBALKA, A. V., PETROV, G. A., KASHUBIN, S. N. & JUHLIN, C. 2006. The Middle Uralian ESRU transsect. *In*: MOROZOV, A. F. (ed.) *Structure and Dynamics of Lithosphere of the Eastern Europe, Issue 2. The Results of the EUROPROBE Research*. Moscow, GEOKART, GEOS, 390–401 (in Russian).

SAVELIEV, A. A. 1997. Ultramafic-gabbro formations in the structure of ophiolites of the Voikar-Synya massif (Polar Urals). *Geotectonics*, **1**, 48–58 (in Russian).

SAVELIEV, A. A., BIBIKOVA, E. V. & SAVELIEVA, G. N. 2001. Garnet pyroxenites of the Mindyak massif, the position and age of formation. *Bulletin MOIP, Section of Geology*, **1**, 22–29.

SAVELIEVA, G. N. 1987. *Gabbro-Ultramafic Complexes of Ophiolites of the Urals and their Analogues in the Modern crust*. M. Nauka (in Russian).

SAVELIEVA, G. N. & NESBITT, R. Q. 1996. A Synthesis of the stratigraphic and tectonic setting of the Uralian ophiolites. *Journal of Geological Society, London*, **153**, 525–537.

SAVELIEVA, G. N., PUCHKOV, V. N. & SPADEA, P. 2006*a*. The ophiolites of the Urals. Structure and dynamics of lithosphere of the Eastern Europe. *In*: MOROZOV, A. F. (ed.) *Structure and Dynamics of Lithosphere of the Eastern Europe, Issue 2. The Results of the EUROPROBE Research*. Moscow, GEOKART, GEOS, 421–436 (in Russian).

SAVELIEVA, G. N., SHISHKIN, M. A., LARIONOV, A. N., SUSLOV, P. V. & BEREZHNAYA, N. G. 2006*b*. Tectono-magmatic events of the Late Vendian in the mantle complexes of ophiolites of the Polar Urals: data of U–Pb dating of zircons from chromites. *In*: KOROTEEV, V. A. (ed.) *Ophiolites: Geology, Petrology, Metallogeny and Geodynamics*. Ekaterinburg, IG USC RAS, 160–164 (in Russian).

SAMYGIN, S. G., KUZNETSOV, N. B., PAVLENKO, T. I. & DEGTYAREV, K. E. 1998. The structure of the Kyshtym-Miass region of the Southern Urals and a problem of conjugation of Magnitogorsk and Tagil complexes. *In*: LEONOV, YU. G (ed.) *The Urals fundamental Problems of Geodynamics and Stratigraphy*. M. Nauka, 73–92 (in Russian).

SAMYGIN, S. G. & RUZHENTSEV, V. S. 2003. The Uralian paleocean: a model of inheritad development. *Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Section*, **392**, 226–229 (in Russian).

SCARROW, J. H., PEASE, V., FLEUTELOT, C. & DUSHIN, V. 2001. The Late Neoproterozoic Enganepe ophiolite, Polar Urals: an extension of the Cadomian arc? *Precambrian Research*, **110**, 255–275.

SCHWAB, M. 1984. The Harz Mountains. *In*: BANKVITZ, P. (ed.) *Sedimentary and tectonic structures in the Saxoturingian and Rhenohercynian Zones*. Central Institute for Physics of the Earth, Potsdam, 34–77.

SENGÖR, A. M. C., NATAL'IN, B. A. & BURTMAN, V. S. 1993. Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia. *Nature*, **34** (6435), 299 – 307.

SEWARD, D., PEREZ-ESTAUN, A. & PUCHKOV, V. 1997. Preliminary fission-track results from the southern Urals – Sterlitamak to Magnitogorsk. *Tectonophysics*, **276**, 281–290.

SHARKOV, E. V., BORTNIKOV, N. S. & BOGATIKOV, O. A. 2004. The Mesozoic zircon from gabbro-norites of the axial zone of the Mid-Atlantic Ridge, 6°N (the Basin of Markov). *Transactions (Doklady) of the Russian Academy of Sciences/Earth Science Section*, **396**, 675–679 (in Russian).

SHATSKY, N. S. 1965. On the tectonics of Soviet Union (On 10 years after demise of A. D. Archangelsky. *In*: SHATSKY, V. S. (ed.) *Selected publications*. M. Nauka Publishing House, **IV**, 76–84 (in Russian).

SHATSKY, V. S., SIMONOV, V. A. & YAGOUTZ, E. 2000. New data on the age of eclogites of the Polar Urals. *Doklady of Russian Academy*, **371**, 519–523 (in Russian).

SIGOV, A. P. 1969. *The Mesozoic and Cenozoic Metallogeny of the Urals*. M. Nedra. (in Russian).

SKRIPIY, A. A. & YUNUSOV, H. K. 1989. Tension and compression structures in the Articulation zone of the

Southern Urals and the East European Platform. *Geotectonics*, **23**, 515–522 (in Russian).

SMIRNOV, G. A. 1957. *Materials for Paleogeography of the Urals. The Visean Stage*. Sverdlovsk, Mining and Geology Institute (in Russian).

SMIRNOV, V. N., BOROZDINA, G. N., DESYATNICHENKO, L. I., IVANOV, K. S., MEDVEDEVA, T. YU. & FADEICHEVA, I. F. 2006. On the time of opening of the Uralian paleocean (biostratigraphic and geochemical data). *Russian Geology and Geophysics*, **47**, 755–761 (in Russian).

SNACHEV, A. V., PUCHKOV, V. N., SAVELIEV, D. B. & SNACHEV, V. N. 2006. *Geology of the Aramil-Sukhtelinsk Zone of the Urals*. IG USC RAS, Ufa (in Russian).

SOBORNOV, K. O. & BUSHUEV, F. S. 1992. The kinematics of the conjugation zone of the Northern Urals and the Upper Pechora Basin. *Geotectonics*, **1**, 39–51 (in Russian).

SOKOLOV, V. B. 1992. The structure of the Earth's crust of the Urals. *Geotectonics*, **5**, 3–19 (in Russian).

SPADEA, P., ZANETTI, A. & VANUCCI, R. 2003. Mineral chemistry of ultramafic massifs of the Southern Uralides orogenic belt (Russia) and the petrogenesis of the Lower Palaeozoic ophiolites of the Uralian Ocean. *In*: DILEK, Y. & ROBINSON, P. T. (eds) *Ophiolites in Earth History*. Geological Society, London, Special Publications, **218**, 567–596.

SULEIMANOV, A. K. 2006. The CDP works along the URSEIS profile. *In*: MOROZOV, A. F. (ed.) *Structure and Dynamics of Lithosphere of the Eastern Europe, Issue 2. The Results of the EUROPROBE Research*. Moscow, GEOKART, GEOS, 363–373 (in Russian).

TESSALINA, B. S., BOURDON, G., PUSHKAREV, E., CAPMAS, F., BIRCK, J.-L. & GANNOUN, M. 2005. MinUrals – IPGP contribution. Complex Proterozoic to Paleozoic history of the upper mantle recorded in the Urals lherzolite massifs by Re–Os and Sm–Nd systematics. *In*: CERCAMS-6 Workshop Mineral Deposits of the Urals. London, The Natural History Museum, CD.

TEVELEV, A. L. V., DEGTYAREV, K. E. *ET AL*. 2005. Geodynamic situations of formation of the Carboniferous volcanic complexes of the Southern Urals. *In*: NIKISHIN, A. (ed.) *The Studies on the Regional Tectonics of the Urals, Kazahstan and Tyan-Shan*, **1**. Southern Urals. Moscow, Nauka, 213–247.

TRETYAKOV, A. A., RYAZANTSEV, A. V., KUZNETSOV, N. B. & BELOVA, A. A. 2008. The structural position and geochronological dating of granate ultramafics in the Southern Urals. *In*: KARYAKIN, YU. V. (ed.) *The General and Regional Problems of Tectonics and Geodynamics*, **2**. Moscow, GEOS, 343–349 (in Russian).

TRIFONOV, V. G. 1999. *The neotectonics of the Europe*. Nauchny Mir (in Russian).

TRIFONOV, V. G. 2008. The age and mechanisms of the newest mountain building. *In*: KARYAKIN, YU. V. (ed.) *The General and Regional Problems of Tectonics and Geodynamics*. **2**. Moscow, GEOS, 349–353 (in Russian).

TRYGGVASON, A., BROWN, D. & PEREZ-ESTAUN, A. 2001. Crustal architecture of the southern Uralides from true amplitude processing of the URSEIS vibroseis profile. *Tectonics*, **20**, 1040–1052.

TUZHIKOVA, V. I. 1973. *The History of the Lower Mesozoic Coal Accumulation in the Urals*. M. Nauka (in Russian).

UDORATINA, O. V. & LARIONOV, A. N. 2005. The age of granitoids of Taikeu massif (Polar Urals). *In*: YUSHKIN, N. P. (ed.) *The Structure, Geodynamics and Mineragenic Processes in Lithosphere*. Syktyvkar, Geoprint, 346–349 (in Russian).

VERBITSKAYA, N. P. 1964. *The Regional Specific Features of Neotectonics of the Urals*. Leningrad (in Russian).

VERNIKOVSKY, V. A., VERNIKOVSKAYA, A. A., PEASE, V. L. & GEE, D. G. 2004. Neoproterozoic Orogeny along the margins of Siberia. *In*: GEE, D. G. & PEASE, V. (eds) *The Neoproterozoic Timanide Orogen of Eastern Baltica*. Geological Society, London, Memoirs, **30**, 233–248.

WILLNER, A. P., ERMOLAEVA, T. *ET AL*. 2002. Surface Signals of an Arc-Continent Collision: The Detritus of the Upper Devonian Zilair Formation in the Southern Urals, Russia. *In*: BROWN, D., JUHLIN, C. & PUCHKOV, V. (eds) *Mountain Building in the Uralides: Pangea to the Present*. AGU Geophysical Monograph Series, **132**, 183–209.

WILLNER, A. P., WARTHO, J.-A, KRAMM, U. & PUCHKOV, V. N. 2004. Laser ^{40}Ar–^{39}Ar ages of single detrital white mica grains related to the exhumation of Neoproterozoic and Late Devonian high pressure rocks in the Southern Urals (Russia). *Geological Magazine*, **141**, 161–172.

ZAKHAROV, O. A. & PUCHKOV, V. N. 1994. *On the Tectonic Nature of the Maksutovo Complex of the Ural-Tau zone*. Ufimian Science Centre, Ufa (in Russian).

ZIEGLER, P. A. 1999. Evolution of the Arctic-North Atlantic and the Western Tethys. *AAPG Memoir*, **43**, 164–196.

ZNAMENSKY, S. E. 2007. The stages of Late Paleozoic deformations of the Magnitogorsk megazone (Southern Urals). *In*: YUSHKIN, N. P. & SAZONOV, V. N. (eds) *Geodynamics of Formation of Mobile Belts of the Earth*. Ekaterinburg, Institute of Geology and Geochemistry, Uralian Branch of Russian Academy, 108–111 (in Russian).

ZONENSHAIN, L. P., KUZMIN, M. I. & NATAPOV, L. M. 1990. Geology of the USSR, a plate tectonic synthesis. *American Geophysical Union, Geodynamic Series*, **21**, 1–242.

YAKHIMOVICH, V. L. & ANDRIANOVA, O. S. 1959. *The Southern Uralian Brown Coal Basin*. Ufa, Mining-Geological Institute of the Bashkirian Branch of the Academy of Sciences, USSR.

YAZEVA, R. G. & BOCHKAREV, V. V. 1993. Post-collisional magmatism of the Northern Urals. *Geotectonics*, **4**, 56–65 (in Russian).

YUDIN, V. V. 1994. *Orogeny in the Northern Urals and Pai-Khoi*. Nauka, Ekaterinburg (in Russian).

YUGGEO. 2002. *Atlas of Paleogeographic, Structural, Palinspastic and Geoecological Maps of the Central Eurasia*. Almaty (in Russian).