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Tectonics of the Urals and adjacent part of the West-Siberian platform basement: Main features of geology and development

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ABSTRACT

The Urals had undergone two main complete cycles of geodynamic development in the Riphean–Mesozoic time. The first one took place in the Riphean and Vendian and was completed by formation of the Timanides; the second is dated as Paleozoic–Early Mesozoic, belongs to the Uralides and can be divided into eight stages: (1) Continental riftogenesis (Cambrian – Early Ordovician). (2) Oceanic spreading (Middle-Late Ordovician). (3) Main subduction (Late Ordovician – Early Carboniferous). (4) Early collision (Late Devonian – Early Carboniferous) between the Magnitogorsk island arc and the passive margin of the Laurussia continent. (5) Late subduction of a relict oceanic crust of the Paleouralian ocean (Early-Carboniferous-Bashkirian). (6) Collision of Laurussian and Kazakhstanian continents. (7) A limited post-collisional extension and superplume magmatism (Triassic). (8) Thrust-and-fold deformation in the Early Jurassic time. Structure of the West Siberian plate is divided into three structural stages: (1) Folding of basement composed of rock complexes of almost exclusively Paleozoic age; (2) Riftogenesis with eruption of Early Triassic basalts (occasionally with some rhyolites), covered by terrigenous series of the Middle and Upper Triassic; (3) Deposition of a platform cover comprising Jurassic and younger sedimentary complexes, practically undeformed, which contain almost all deposits of oil and gas in the Western Siberia. The basement of the western part of the West Siberian plate is a prolongation of the structural zones of the eastern sector of Uralides, while the basement of the eastern part of the plate belongs to the Siberian craton and its folded margin. A huge block of the Kazakhstanides is situated to the east of the Uralides, beneath the platform cover and pinches out to the north. These main domains of the basement are divided by two major ophiolite sutures – Valerianovsk and Chara. Wide distribution of Triassic volcanogenic complexes under the platform cover of the West Siberian plate makes a principal difference from the Urals. Ophiolites are widely distributed under the platform cover of the West Siberian plate (especially in its central and western parts). Completion of Paleozoic geodynamic evolution of this region resulted from the collision of three continents (Laurussia, Siberia and Kazakhstania) accompanied by folding, highamplitude thrusting, intrusion of granite plutons, metamorphism and formation of a new crust of continental type. The time of these events which consolidated Paleozoic complexes of basement of future West Siberian megabasin is determined as Early Permian for the Cis-Uralian part of the platform. In the beginning of Triassic rifting, formation of a graben system, took place. A final stage of compressional deformation, mostly in the exposed part of the Urals, Pay–Khoy and Novaya Zemlya, occurred in the Lower Jurassic.

1. Introduction

The Urals is one of the most famous examples of fold belts with a complete Wilson cycle of evolution. A large number of publications including numerous monographs are devoted to problems of geological structure and evolution of Urals (Peive et al., 1977; Puchkov, 2000, 2010; Ivanov et al., 1986; Ivanov, 1998; Yazeva and Bochkarev, 1998; Brown et al., 2002; Morozov, 2006; Kashubin et al., 2006; Gee and Pease, 2004 and many others). In the last 10–15 years several major geological–geophysical projects were carried out; seismic and structural profiles across the Southern and Middle Urals were acquired (URSEIS-95 and ESRU-SB: position of the profiles is shown in Fig. 1).

The Urals is distinguished by a number of specific features such as an exceptionally wide distribution and good preservation of

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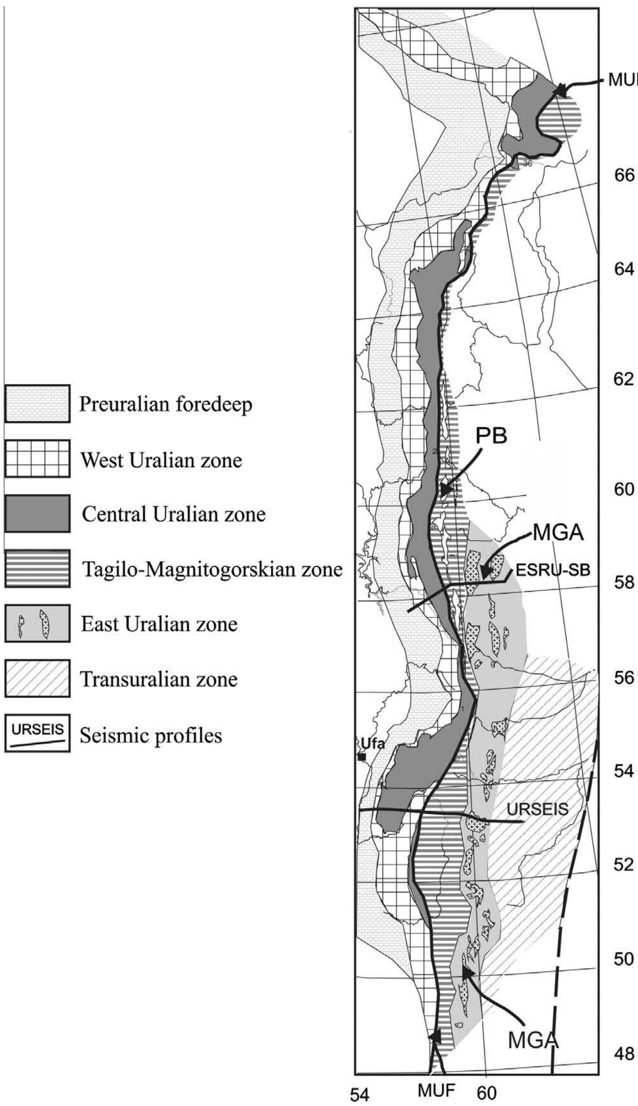

Fig. 1. Tectonic zones of the Urals (Uralide stage). Abbreviations: MUF – Main Uralian Fault, PB – Platiniferous Belt, MGA – Main Granitic Axis, described in the text.

ophiolites and island arc complexes, presence of Platinum-bearing intrusive belt and a Uralian belt of high-pressure metamorphism. Geophysical data show the presence of a "cold", isostatically equilibrated "mountain root" under the central part of the Uralian bivergent orogen.

Geographically the Urals is divided into five segments – Southern (including Mygodzhary), Middle, Northern, Cis-Polar and Polar. Further to the north the western Uralian structural zones are continued into the Pai-Khoy – Novaya Semlya fold belt.

The Urals is divided into six meridional structural megazones subparallel to the margin of the East European platform. The western megazones are traced at the earth surface along the whole extent of the belt; the eastern ones are exposed only in the Southern and Middle Urals and disappear gradually to the north under the Mesozoic–Cenozoic sedimentary cover of the young West Siberian basin. The South Tien Shan fold belt is a most probable prolongation of the Urals to the southeast. The comparative study of the Urals and Tien Shan indicates that analogs of many Paleozoic complexes of Urals are situated in South Tien Shan (although between the structures of these two regions there are quite essential distinctions); at the same time, the Uralian-like Paleozoic rock assemblages (Devonian ophiolites and island-arc volcanics, Famenian–Tournaisian flysch series) are traced to Caucasus beneath the Pre-Caspian depression.

Of six megazones of the Urals (Fig. 1), the westernmost three form the Uralian paleocontinental sector – a former passive margin of Baltica/Laurussia paleocontinent, and the last three – a paleooceanic sector, a collage of ophiolites, island arcs and microcontinental terranes of Paleo-Uralian ocean. The boundary between these sectors is represented by an ophiolite-hosting suture of the Main Uralian fault (Fig. 1).

2. The tectonic megazones of the Uralides

The Pre-Uralian foredeep (in Fig. 1) filled up by terrigenous sediments (pre-flysch deep-water condensed sediments, flysch, evaporites and molasse) of the Upper Paleozoic and partly Triassic age with thickness up to 5–6 km. In the south of the Urals the initiation of the foredeep was accompanied by accumulation of the Late Carboniferous – Early Permian flysch series. The flysch grades to the west into condensed (so-named pre-flysch) series composed mostly of alternation of relatively deep-water dark-colored shales, marls and limestones. Usually it is supposed (Peive et al., 1977) that the formation of the condensed pre-flysch series at the bottom of the flysch succession was connected with a subsidence of a continental margin under the weight of tectonic sheets composed of island arc complexes and thrust from the east. A forebulge and an east-facing structural step have formed along the western side of the unloaded part of the depression. They were migrating with time to the west, being marked, respectively, by erosional gaps and a chain of reef massifs.

The flysch series, dated as the Mid-Carboniferous to Lower Permian, was formed during the epoch of active collision, thrusting and orogeny. This process was accompanied by a migration of the depression to the west, onto the platform, which is well determined by the age change of the carbonate (platform) base of the depression. In the Kungurian time the flysch was partly substituted by evaporites, which finally filled up and obliterated the deep-water depression.

Shallow-water and subaerial molasse, Upper Permian to Triassic in age, migrated to the west in relation to the flysch and have been formed at the stage of attenuation of the orogenic processes in the Urals. Probably the load on the platform margin decreased and the platform began to rise. The age of the basal layers of the foredeep becomes younger to the west and north, reflecting a migration of the basin from east to west and probably from south to north. The western parts of the depression are mainly characterized by gently sloping platform structures. Crest-shaped, swell-like, box-like and more compound compressed folds (including overturned and isoclinal ones) of Uralian strike belonging to the Uralian linear folding are typical for the eastern parts. The above-described folds are complicated by linear sulfate-salt diapiric folds and thrusts, flattening gradually at depth and merging with detachment surfaces.

The West-Uralian megazone (in Fig. 1) was in the Paleozoic a passive (Atlantic-type) margin of the East European platform, i.e. transitional area from the platform to the Uralian paleoocean situated in the east. Here two regional zones of sedimentation are distinguished, in the Ordovician to Carboniferous time: the western – Belsk-Elets one, comprising paleoshelf terrigenous–carbonate series and the eastern – Zilair–Lemva, with terrigenous-siliceous-shale deposits, interpreted (Puchkov, 1979 and others) as an area of passive continental margin. Only in the Carboniferous time the new structure (above-described Pre-Uralian foredeep depression) has originated.

Shelf complexes in the external (Belsk-Elets) zone overlie practically undestroyed but somewhat thinned crystalline basement and originally had platform features. The presence of reefal, bioherm, organogenic-detrital and other limestones and also dolomites, quartz sandstones of coastal-marine origin is usual here. The sections begin with the Lower Ordovician terrigenous-oligomyctic series overlying graben facies or directly covering crystalline basement. Upwards it is succeeded by the Middle-Upper Ordovician terrigenous-limestone–dolomite series. Silurian – Carboniferous deposits are represented mainly by shallow-water stratified limestones with layers of well-sorted quartz sandstones (Emsian, coal-bearing Lower Carboniferous and other series).

Zilair–Lemva structural zone is represented by six isolated areas of development of bathyal complexes. Three stages of evolution of this zone are distinguished: (1) initial (riftogenic); (2) mature (passive continental margin); (3) pre-orogenic (greywacke flysch stage). For the rift stage, shallow-water terrigenous molasse-like series with alkaline and subalkaline-basalt volcanic rocks are most typical. A stage of passive continental margin in the major part of the Urals began in the Middle Ordovician when a continental slope was formed, and started to descend. This is shown by an accumulation of siliceous-shaly sediments which are frequently condensed. Early Silurian deposits are represented everywhere by black shale series with graptolites. Colored chert, cherty breccias and sandstones with rare horizons of deep-water argillaceous limestone are deposited in the southern areas until the Frasnian and in the north – up to the Bashkirian time inclusively. The upper part of the sections in the Southern Urals is represented by thick series of greywacke flysch (the Famennian–Tournaisian Zilair Series) formed as a result of erosion of volcanogenic-sedimentary formations. In the northern areas flysch appeared somewhat later – in the Early Carboniferous (Yayu Formation). The compression which began at that time caused a complete closure of the Zilair–Lemva zone. This process was accompanied by the origin of west-vergent fold-and-thrust structures above detachment surfaces and the westward overthrusting of the deposits formed in the Zilair–Lemva zone. Overthrusting of bathyal complexes onto the shelf margin is proved by structural drilling at the western slope of the Middle and Polar Urals.

In the Sakmara, Kraka and some other areas ophiolites, volcanogenic-sedimentary and intrusive island arc formations are also thrusted over the sedimentary complexes of passive continental margin.

The Central Uralian megazone (in Fig. 1) is mainly composed of metamorphosed Precambrian and Early Paleozoic rocks which form the axial, most uplifted part of the Ural Mountains. At the same time, practically non-metamorphosed Precambrian rock complexes are exposed in big uplifts of the Southern and Middle Urals (Bashkirian and Kvarkush meganticlinoria). So Bashkirian meganticlinorium of the Southern Urals is composed of the Riphean (Meso- and partly Neoproterozoic) shallow-water terrigenous–carbonate series (thickness up to 15 km) with moderate volume of subalkaline volcanic rocks and intrusions of a rift origin, approximately at the levels of 1750–1650, 1380–1350, 730–700 Ma.

The crystalline basement of the East European platform, covered by the Riphean and Vendian (Meso- and Neoproterozoic) deposits, is exposed in the Taratash block. Rock assemblages metamorphosed here mostly in granulite and amphibolite facies are correlated with Karelides although include more ancient (Archaean) complexes.

The Ural-Tau antiform (Southern Urals) has a peculiar position. Until the middle of 1980s of the last century a viewpoint predominated is that it a Precambrian structure, the lower part of which is represented by Middle Riphean (Upper Mesoproterozoic) eclogite–glaucophane-schist Maksiutovo complex and the upper part – by thick Upper Riphean–Vendian (Neoproterozoic) terrigenous Suvanyak complex. As a result, Ural-Tau was confidently regarded as a part of a Precambrian structure of the Central Uralian zone (and practically was its synonym). However numerous occurences of Paleozoic fossils make us now to abandon this viewpoint.

The above-described three megazones were formed in a process of deformation of the passive continental margin of Laurussia continent (East European platform). Only some allochthons (upper tectonic sheets of the Sakmara and Kraka ones in the Southern Urals, Nyazepetrovsk sheet of the Middle Urals) were transported tectonically from the east, i.e. from paleo-oceanic sector part of the Uralian fold belt.

2.1. The Main Uralian fault (MUF)

The MUF represents a typical ophiolite suture of a variable width (sometimes up to 20 and more km) as a relic of an extinct fore-arc trench of Paleo-Uralian ocean. Wide distribution of serpentinite mélange and tectonic megabreccias traced at distances of hundreds km (Sakmara–Voznesensk zone of the Southern Urals, Ray-Iz-Kharamatalou zone of the Polar Urals and others), is typical for MUF. Zones of dislocational metamorphism, blastomylonites also characterize this fault. The all-Uralian belt of eclogite–glaucophane-schist metamorphism is traced along the fault as an interrupted belt. The reflected waves survey have shown that the fault surface dips eastward usually at a different angle, 35–55° (up to 90° at the latitude of the Ufimian promontory) and divides the complexes of an ancient continent and Paleozoic oceanic and island arc rock assemblages thrust over them.

Formation of MUF was a long and multistage process. Initially it apparently was a riftogenic extension fault (a normal fault in the upper, fragile part of the Earth crust, substituted by zones of plastic flow in the middle and lower parts). The time of a full break-up of the continental crust in Urals is just before the Late Arenig, i.e. 480 Ma. In the Middle Paleozoic, MUF experienced a stage of quiescence, dividing the passive continental margin and oceanic basin. A collision of the Late Paleozoic Magnitogorsk island arc and paleocontinent started in the Southern Urals in the Early Famennian (in the northern areas approximately 30 Ma later) and has transformed MUF into a thrust. Structural, paleomagnetic, paleogeographic and other data testify that the collision between the Laurussia continent (East European platform) and Uralian island arc terrains was not frontal but oblique (Ivanov, 2000; Puchkov, 2000 and others).

The Tagil–Magnitogorsk megazone (in Fig. 1) is situated directly eastward of MUF and is not an all-of-a-piece structure. The Megazone is distinctly divided into two zones (island arc terrains) of different age but similar composition: ancient Tagil and younger Magnitogorsk zones. The Tagil zone originated in the Middle Ordovician and Magnitogorsk one – in the Early Devonian.

The Tagil zone is traced from the northern part of the Middle Urals, to the Northern, Cis-Polar and Polar Urals. But the problem of presence of its fragments in the Southern Urals is a matter of discussion.

The Magnitogorsk zone composes the largest part of the eastern slope of the Southern Urals. Its dislocated fragments are exposed also in the Middle Urals to the east of the Tagil zone.

In both Tagil and Magnitogorsk zones tholeiitic low-potassic pillow basalts with thickness of 1.5–2.5 km compose the lower parts of volcanogenic successions. Underlying formation is represented by poorly exposed sheeted-dyke diabase complex. Basalts are associated as a rule only with altered hyaloclastics and thin layers of jasper. The latter contains sufficiently abundant complexes of conodonts of Middle – Upper Ordovician in the Tagil zone and of Emsian in the Magnitogorsk one. In general, the successions of the Tagil and Magnitogorsk zones consist of the following greenstone-altered formations (from below upwards): (1) Sodium basaltic, (2) Sodium rhyolite-basaltic, (3) Andesite–dacitic, (4) Andesite–basaltic, (5) Andesitic, and (6) Basalt-trachyte-trachyrhyolitic. At that, the age difference between the formations in both sequences is preserved, from bottom to top. The Lower Devonian subalkaline volcanogenic formations of the Tagil zone are covered by Lower – Middle Devonian bauxite-bearing limestone. In the Magnitogorsk zone subalkaline volcanogenic formations appeared only in the Upper Devonian; they are replaced facially by flysch and covered by limestone with tholeiitic and subalkaline volcanic rocks.

Along the western border of the paleo–island arc sector of Urals, in the western part of the Tagil zone, near the MUF a unique Platiniferous belt extends for more than 900 km. This huge geological object is represented in the Middle, Northern and Cis-Polar Urals by a chain of thirteen concentric-zonal isometric or stretched massifs. They are composed of dunite, clinopyroxenite, olivine and two-pyroxene gabbro, granitoids and are typical representatives of zonal mafic–ultramafic massifs of so-called Ural-Alaskan type. The considerable difference of this association from ophiolites (and other oceanic associations) is an absence of harzburgite, sheeted dyke complex and basalts, and also in relatively high contents of Fe in dunites and also Sr in gabbroids (more 300 g/t). Owing to gravity and seismic methods Platiniferous massifs are traced to sufficiently great depths (6–8 km) as steeply eastward-dipping bodies. It is shown (Ivanov, 1998 and others) that the rock associations of the Platiniferous belt are connected with the island arc development, i.e. melting at different depths above the subduction zone (suprasubduction magmatism stopped here 415–420 Ma ago). Their suprasubductional origin is proved by their resemblance with gabbroid and ultramafic xenoliths from volcanic rocks of recent island arcs, by geochemical characteristics and other data.

The island arc magmatism in the Tagil and Magnitogorsk zones called forth a diversity and wide development of intrusive complexes comparable to effusive rocks. Intrusions of M-type tonalites and plagiogranites associated with hornblende gabbro (gabbro–plagiogranite and gabbro–tonalite complexes) are connected with initial episodes of island arc magmatism. Later on, they were changed by gabbro–granitoid associations with I-type granites with geochemistry that evolved from potassic-sodium calc-alkaline to potassic subalkaline type in the process of an island arc evolution.

Volcano-sedimentary series of the Tagil–Magnitogorsk megazone in the Northern and Southern Urals usually compose relatively simple structures. Volcanic series frequently preserve here their primary textures; relics of volcanic buildups are often present. The volcanic series in the Middle Urals are more intensely tectonized compared to the Southern Urals, crushed against the rigid block of Ufimian promontory; this was accompanied by formation of backthrusts in the east of the Middle Urals. The absence of uplifts of sialic Precambrian metamorphic rocks is a characteristic feature of the whole megazone.

One of the main differences between the Tagil and Magnitogorsk zones (besides their ages) is that the first was the ensialic island arc but the second – ensimatic. Devonian volcanic series of Magnitogorsk zone have geochemical features typical for suprasubduction complexes, such as negative anomalies of Nb, Ta, Zr, Hf, Y and enhanced concentrations of LIL elements (K, Rb, Ba, Cs) and LREE (Ivanov et al., 1986; Yazeva and Bochkarev, 1998; Kosarev et al., 2005). They do not show any signs of contamination by continental crust and can be considered as ensimatic island arc complexes formed above an east-dipping subduction zone.

Petrological and geochemical analyses of Late Ordovician – Silurian volcanic formations of Tagil zone (data of V.N. Smirnov and others) show that the evolution of volcanism consisted in a gradual change from calc-alkaline rocks to rocks of a subalkaline trend. Eruption of small volumes of subalkaline volcanics took place already at the initial stage of the zone formation. Later on, their share increased gradually; the final Lower Devonian Tura trachybasalt–trachyte volcanic complex is already completely composed of subalkaline varieties. Volcanic associations with tholeiitic trend of differentiation typical for ensimatic island arcs is absent in the Tagil zone. Spider diagrams of basalts show all peculiarities of island arc associations: well expressed maxima of Sr, Ba content; distinct Nb, Th and weak Ce minima. Thus it is possible to consider the Tagil paleo–island arc as an analog of recent ensialic island arcs. According to gravimetry data, volcanogenic series in the central part of the Tagil zone are underlain by relatively “light” rocks which can be identified as rocks of ancient continental crust. Occurences of xenogenic garnets (analogous by composition to garnets of metamorphic rocks) and zircons with precambrian dates in volcanic rocks of the Tagil zone also can be regarded as an evidence of contamination of island arc magmas by a substance of the ancient crust from the basement of the island arc.

The idea of early mobilistic publications that formations of an oceanic stage (of middle-oceanic ridges and oceanic plateaus) are widespread in the Tagil–Magnitogorsk megazone, have not been confirmed. The series of initial tholeitic basalts, sheeted-dyke complexes, etc., described as oceanic, were later attributed to initial island arc (mainly back-arc) formations (Ivanov et al., 1986, etc.). Rocks of the oceanic stage of evolution in the Urals are practically absent because the paleooceanic crust was very easily absorbed in a subduction process.

It should be noted that recently (Tessalina et al., 2005; Popov and Belyatski, 2006; Savelyeva et al., 2006; Fershtater et al., 2009; Puchkov, 2010) many ancient dates (510–885 Ma – by Sm–Nd and U–Pb methods) were acquired, from the Uralian gabbro–ultramafic massifs, both of alpine-type and Platinum-bearing associations. In relation to ophiolites it was not clear how this dating correlates with sufficiently numerous (many tens) and very reliable Ordovician (mostly Late Arenig – Middle Ordovician) age definitions (by representative conodont complexes from syngenetic jasper layers) of ophiolitic basalts (Ivanov et al., 1986; Ivanov, 1998; Puchkov, 2000, etc.) of the same ophiolite association. By the way no one example is known of reliable dating of all members of ophiolite association in the same complex or massif. Data of the last years allow to suppose different ages of ophiolite members composing a single complex (at that, the lower ultramafic–gabbro parts of ophiolite sections are probably considerably older than tholeiitic basalts and sheeted-dyke complex).

The eastern boundary of the Tagil–Magnitogorsk megazone goes along the East-Magnitogorsk mélange zone in the Southern Urals and along Serov-Mauk fault controlled by mélange serpentinites in the Middle and southern part of the Northern Urals.

The East-Uralian megazone (in Fig. 1). This part of the Urals differs from the adjacent Tagil–Magnitogorsk megazone in a wide development of granitoids and gneisses, in a presence of microcontinental blocks of pre-Paleozoic crystalline crust of sialic type, as well as generally in a continental type of the crust with a well expressed granite layer. Along with some relics of a sedimentary cover, the major part of volcano-sedimentary rocks and dismembered ophiolites belong to overthrusts. This megazone hosts the so-called “Main Granite Axis” of the Urals, where the major part of Paleozoic granites of the province is located. Magmatism of back-arc basins is limited to gabbro–tonalite associations of M-type. The next in the time succession, the active continental margin stage of development was characterized by intrusion of granodiorite and tonalite–granodiorite I-type batholiths, often having quite big (up to 100 km length) dimensions. At the later episodes, calc-alkaline tonalite–granodiorite magmatism changed to a subalkaline one, but the areal development of subalkaline rocks of this stage is insignificant. The collisional stage of development of the Urals is characterized by formation of batholith-like intrusions of crustal anatectic granites.

Isotope characteristics of "The main granite axis" granites in the Southern Urals allow to assume that initially they were formed above the Late Paleozoic subduction zone (Ivanov et al., 1986); the late stages of this process are associated with palingenesis of a continental crust thickened as a consequence of intensive convergence of crustal blocks within the system of east-vergent thrusts inherited from the Early Carboniferous-Bashkirian subduction zone. This system is established reliably in the seismic profiles URSEIS-95 and ESRU-SB (Deep structure and geodynamics of the South Ural, 2001; Kashubin et al., 2006 and others).

In general, the East-Uralian megazone (uplift) is represented mainly by intrusive and metamorphic rocks of moderate pressures – that is – by formations of lower and middle parts of the earth's crust. This process of formation of continental crust was completed in the Late Paleozoic (Permian).

The eastern boundary of the megazone is the Kartaly fault.

The Transuralian megazone (in Fig. 1), the most eastern structure of the "exposed" Urals has, quite probably, an accretional nature. In the Transuralian megazone rather fragmentary Paleozoic volcanogenic and sedimentary series are developed. Among the pre-Carboniferous formations, complexes of different types are distinguished: (1) blocks of crystalline schists of Precambrian (?) age; (2) Ordovician terrigenous–volcanogenic rift complexes; (3) Middle-Upper Ordovician ophiolites composing narrow submeridional zones (Denisovskaya, Varnenskaya); (4) Silurian volcanogenic-sedimentary island-arc complexes; (5) Middle-Late Devonian deep-water cherty-shale series. All these series are overlain by the Early Carboniferous suprasubductional calc-alkaline volcanics composing the post-accretional complex. The Carboniferous structure is subdivided (from east to west) into the Valerianovskaya, Borovskaya and Ubaganskaya zones. All of them are overlain by Mezo-Cenozoic platform cover and differ only in details. According to the data of drilling, mostly Carboniferous (mainly Early Carboniferous) complexes are developed here. Sedimentary deposits are represented by shallow-water limestones and terrigenous sandy-shale series. Volcanogenic-sedimentary and volcanogenic series are widespread, being represented by andesite and andesite-basalt porphyrites and their tuffs. Volcanics together with intrusions of basic and intermediate composition form a single volcano-plutonic association.

For the Transuralian megazone, rather complicated tectonics is typical; numerous strike-slip faults, thrusts, zones of serpentinitic mélange and blastomylonites are present. According to the data of geological survey, structural studies, as well as of the "URSEIS" seismic profile the main structural elements here have an eastern vergency.

Relations of the most significant geological formations of the Southern Urals are represented in Fig. 2.

3. The main features of the Urals deep structure

The "URSEIS-95" should be specially noted as a complex seismic profile across the Southern Urals, made by an international team of geophysicists of Russia, Germany, Spain and USA. This seismoprofile, 465 km long (CDP method with explosive and vibrational sources plus wide-angle deep seismic profile with acquisition of reflected and refracted waves from 6 powerful explosions), is now one of the most representative in the world. Based on the "URSEIS-95" data, revealing the main features of the deep structure of the Urals (Echtler et al., 1996; Deep structure and geodynamics of the South Ural, 2001), the Uralian folded belt can be divided into three big domains (segments): western, central and eastern (Fig. 3).

The western domain includes the Pre-uralian foredeep, West-Uralian and Central-Uralian megazones and is limited from the east by the MUF. The central domain corresponds to the Magnitogorsk and the East-Uralian megazones. The eastern domain is the territory to the east of the Kartaly fault, representing the eastern boundary of the East-Uralian megazone. MOHO boundary, well traced in

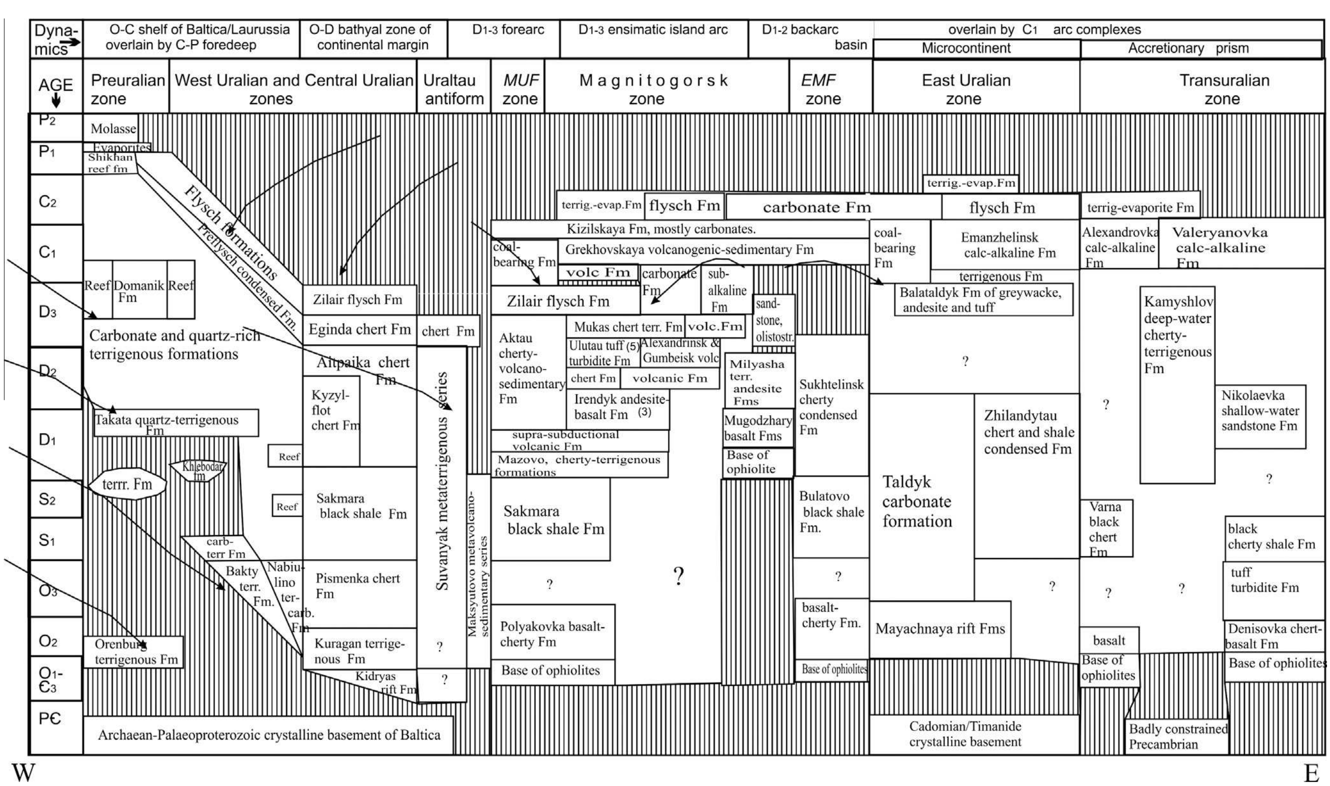

Fig. 2. Most significant geological formations of the Southern Urals. The arrows show the directions of clastic material transportation.

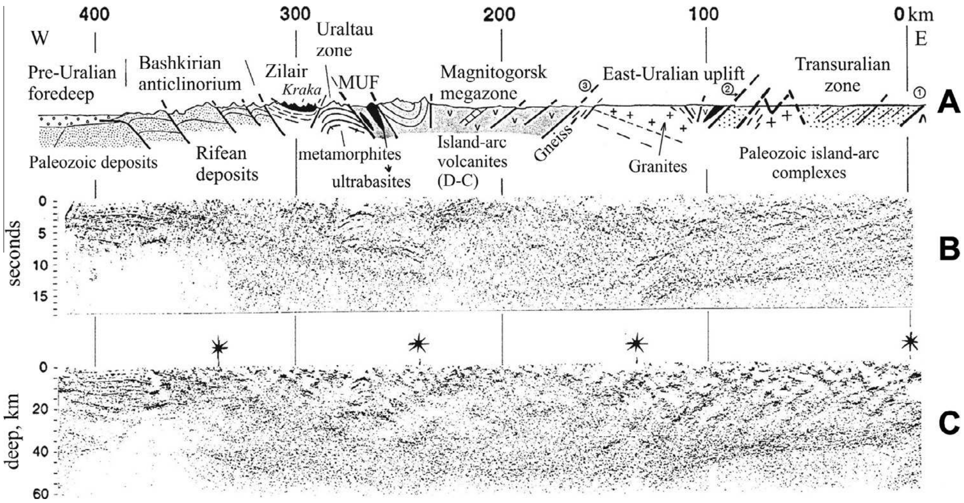

Fig. 3. Profile through the Southern Urals along the seismoprofile URSEIS 1995 on the line Sterlitamak – Nikolaevka (Echtler et al., 1996); (A) on the base of authors data. A – Simplified geologo-tectonic profile (topographical mountain relief is given in scale 1:10); B and C – vibroseismic profiles, (B) temporal (on vertical: (time of double way – TWT) – to 18 s.) and (C) – the migrating one. Figures in circles are the fault zones: 1 – Nikolaevskaya, 2 – Kartalinskaya, 3 – Polotskaya. Black asterisks show the biggest points of DSS explosions.

the western and eastern domains, gradually descends to the central part of the orogen from depths of about 40 km to 55 km. Further on, under the central domain the MOHO boundary loses its clearness and acquires a "diffuse" character, but still can be recorded by refracted waves at the depth of about 58 km, forming a clear "crustal root" (established earlier by Russian researchers). A good-quality high-resolution URSEIS-95 seismoprofile demonstrated quite well a general bi-vergent structure of the Urals.

Of a special interest is the eastern part of the Urseis-95 profile, giving an important new information for understanding of the structure of the Uralian eastern zones and in particular, revealing an oblique truncation of their crustal structures into the MOHO boundary (Echtler et al., 1996). This gives every ground for assuming that either the MOHO boundary is younger than the crust – for example, overprinted in the result of a phase transition, or (more probably) is a huge tectonic detachment, formed during the Late Paleozoic collision, as it is shown in the last section of Fig. 11. Strong and extensive reflectors revealed by the URSEIS in the crust of the eastern domain dip to the west under the angles of 30–40° and are traced to the depths of 40 km and more, not truncating at, but rather merging with the MOHO surface. At the earth's surface they are identified as big regional fault zones composed mostly of mylonites, blastomylonites, serpentinitic mélanges. Of these tectonic sutures the most significant are the Nikolayevka and the Kartaly fault zones. In big fault zones of the east of the Urals, a series of dislocations is established, left-lateral wrench faults among them, which can be associated with an oblique (north–north–western) direction of subduction and subsequent collision between the terrains of the Urals and the margin of the East-European platform.

For the Central domain situated between the Kartaly fault zone and the MUF, strong clear traceable reflectors are not very characteristic. Moreover, for the Magnitogorsk zone a scattered diffuse character of reflections is typical (Deep structure and geodynamics of the South Ural, 2001 and others). However, the most diffuse zone, 8–10 km deep and 50 km wide, is flat and corresponds to the Gebyk granite massif, demonstrating that the massif is not a batholith.

The Western domain, a territory to the west of the MUF (which dips to the east at the angle of ~45° and is traced to the depth of about 30 km), is characterized by highly reflecting layered crust where the west-vergent structural elements predominate. An antiform of the Uraltau zone can be indicated among the other structures as exclusion. To the west of this antiform and below it, a series of east-dipping reflectors is established, being traced to the depth of 30 km. Under the Bashkirian meganticlinorium one can distinguish (Echtler et al., 1996; Deep structure and geodynamics of the South Ural, 2001) four packs of such reflectors steeply dipping to the east near the surface and gently inclined near the bottom of the crust. In the western side of the profile (380–465 km), a highly reflecting, almost undeformed layered convexo-convex lens of the Vendian and Riphean sedimentary rocks, 15–20 km thick, represents a south-eastern end of the Kama–Belsk aulacogen. The sedimentary series overlies a weakly-reflecting pre-Riphean crystalline basement of the East-European platform, about 24 km thick.

The Middle Uralian ESRU-SB profile (Kashubin et al., 2006 and others) made it possible to obtain some additional data specifying the ideas concerning the crustal structure of the Urals. It is shown that the main Uralian structures – West-Uralian, Central-Uralian, the Tagil–Magnitogorsk and the major part of the East-Uralian megazones are in allochtonous position, that is, they are represented by rootless thrusts.

Similar to the URSEIS-95, this profile shows that the earth's crust of the Urals has a bi-vergent structure. The divide of the upper and middle crust bi-vergence is situated in the Tagil–Magnitogorsk megazone. The lower crust is also bi-vergent, but its divide in the Middle Urals is displaced at 50–60 km to the west. The upper mantle practically lacks of seismic reflectors, except one, gently dipping to the west, and traced to the depths of about 80 km. This tectonic structure enters into the mantle under the Central Uralian megazone and is traced at the depth to the middle part of the area, over which at the surface the Pre-uralian foredeep is established and where the western orographic slope of the Urals Mountains comes to the plain. Probably it is connected with the neo-orogenic structure of the modern Urals mountains. The fragments of gneiss–amphibolite and granulite complexes of the East-Uralian megazone, available for observation, are of the Paleozoic (Devonian–Permian) age and have been formed upon heterogenous substrate (Kashubin et al., 2006 and others).

4. Basement of the west Siberian plate

The structure of the West Siberian plate is divided into three structural stages:

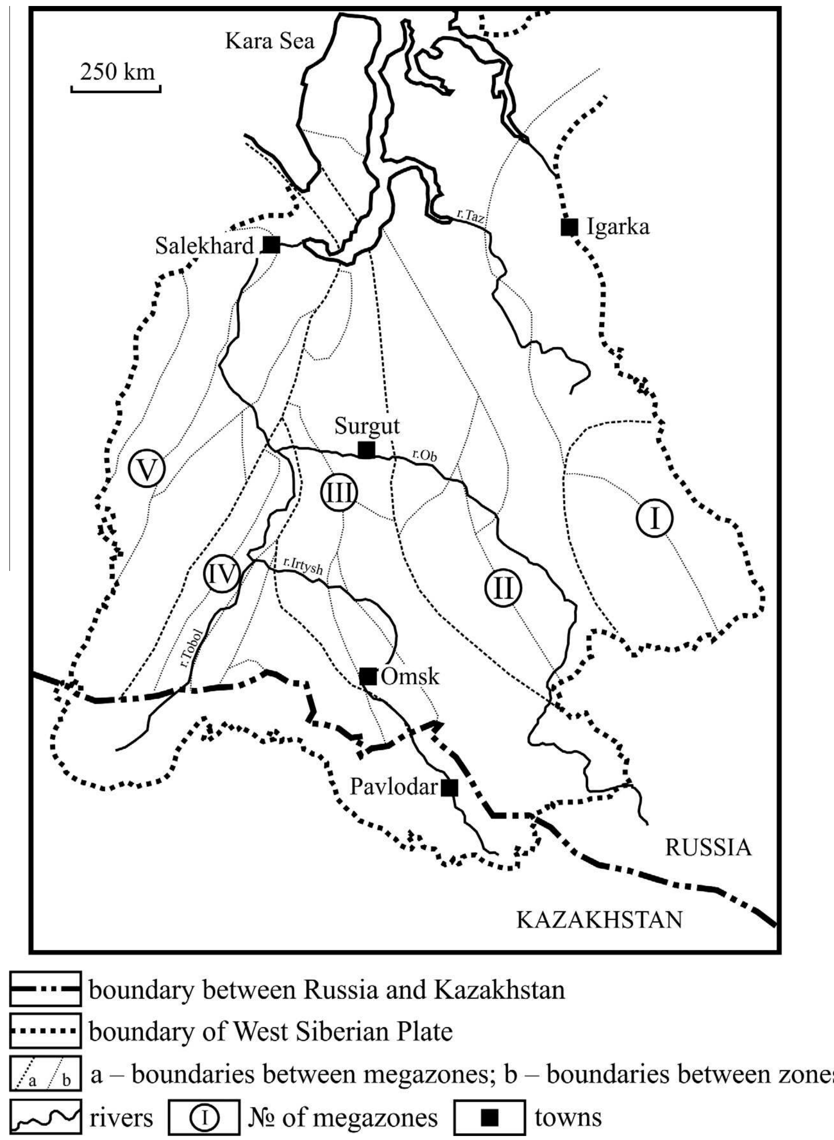

Fig. 4. Megazones in the structure of Paleozoic basement of West Siberian plate (simplified after (Yolkin et al., 2008)). No. of megazones: I – Siberia paleocontinent, II – Uppermost Cambrian – Lowermost Upper Carboniferous complexes, which continue the shelf of the Siberia paleocontinent, III – Altaides Paleozoic complexes, IV – Kazakhstanides Paleozoic complexes, V – Uralides Paleozoic complexes.

(1) Folded basement composed of rock complexes, almost exclusively Paleozoic in age.
(2) Riftogenic structural stage composed of Early Triassic basalts (occasionally with some rhyolites) covered by terrigenous series of the Middle and Upper Triassic.
(3) Platform cover formed by Jurassic and younger sedimentary complexes, practically non-deformed sedimentary complexes, which contain almost all deposits of oil and gas in the Western Siberia. The thickness of the sedimentary cover grows to the north and reaches 6 and more km.

The first two stages represent the basement of West Siberian plate.

The Paleozoic and Triassic complexes of the Pre-Jurassic basement are penetrated by more than 5000 boreholes which are situated mostly in the south and central areas of the West Siberia.

There are more than 20 different schemes of zonation of the West Siberian plate basement (Surkov and Trofimuk, 1986; Yolkin et al., 2001, 2008; Bochkarev et al., 2003; Dobretsov, 2003; Klets et al., 2007; Surkov and Smirnov, 2008 and others). The basement of the western part of the West Siberian plate is a prolongation of the structural zones of the eastern sector of Urals (megazone V in Fig. 4), while the basement of the eastern part of the plate – is composed of complexes of the Central Siberian craton and its folded frame (megazones I – III in Fig. 4). The general feature of zonation schemes for the West Siberian plate is the presence of a huge block of Kazakhstanides (megazone IV in Fig. 4), situated to the east of the Uralides and pinching off to the north (Fig. 4). These main megazones (or domains) are divided by major ophiolite sutures – Valerianovka and Chara.

The Siberian platform with surrounding folded systems is a core of the Siberian domain. Three primary megazones are suggested for it (Yolkin et al., 2001, 2008; Kontorovich et al., 2008). These three megazones form a single region and characterize sedimentation environments on the Siberia paleocontinent (megazone I) and its margin with gradual deepening to the west. The megazone II (Fig. 4) is characterized mostly by shallow-water terrigenous–carbonate series of the Uppermost Cambrian – Lowermost Upper Carboniferous which continue the shelf of the Siberia paleocontinent. The megazone III contains more deep shelf and continental

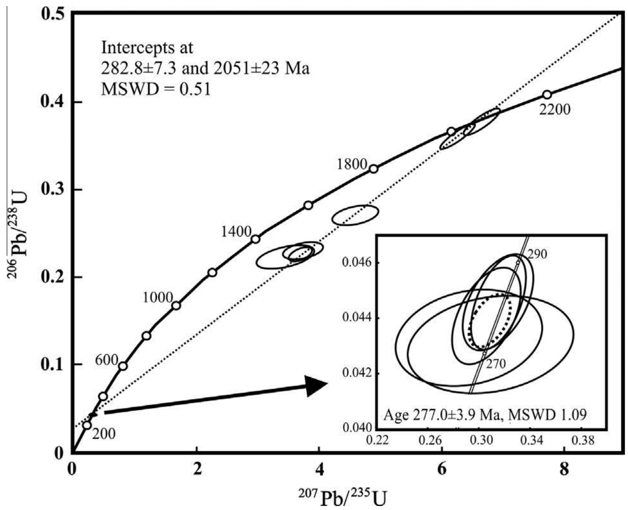

Fig. 5. Graph with concordia for zircons from Tyn'yar granite, Western Siberia (Sample Tyn101/2590 m).

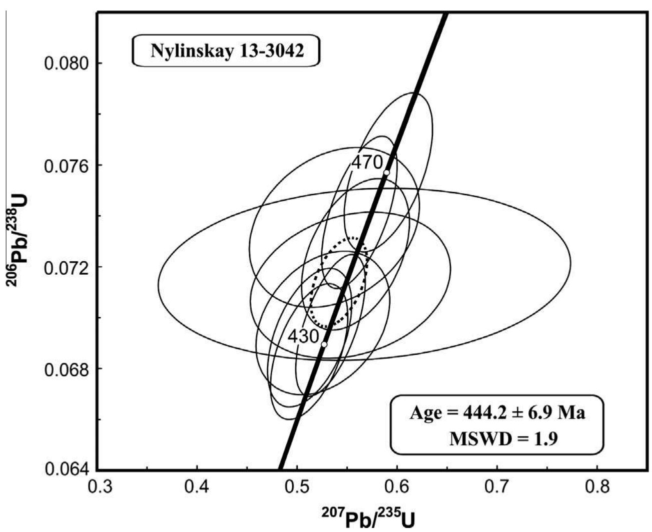

Fig. 6. Graph with concordia for zircons from Nylinskay granite, Western Siberia (Sample Ny13/3042 m).

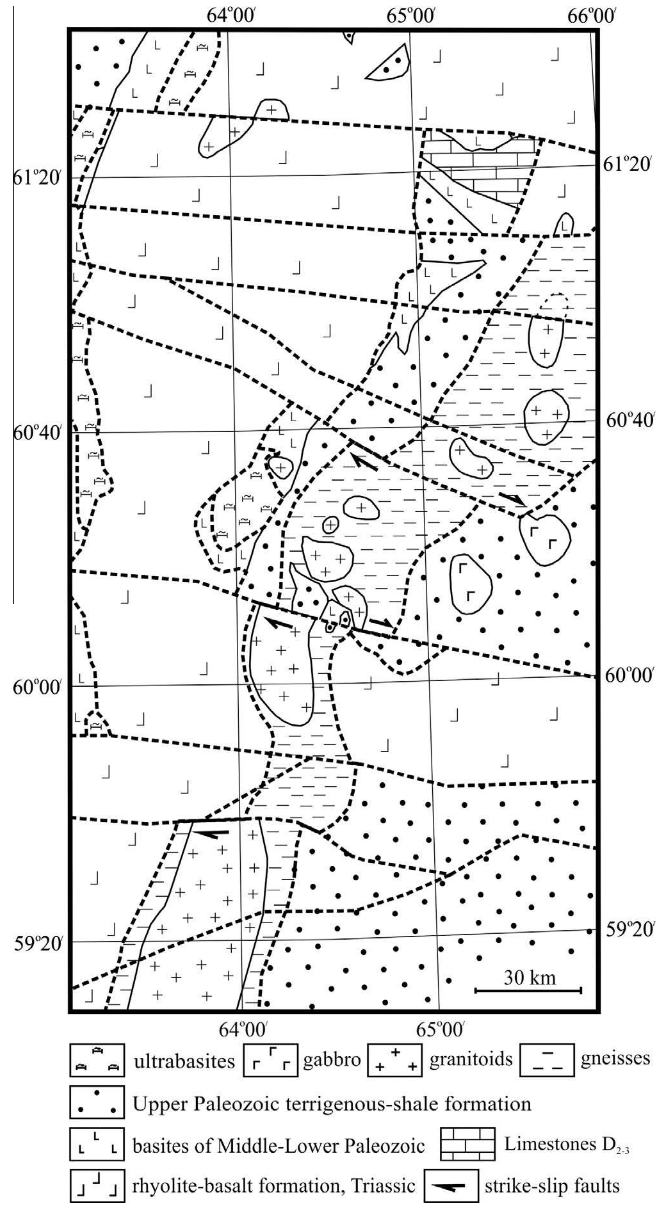

Fig. 7. Schematic geological map of the Shaim oil–gas-bearing area pre-Jurassic basement.

slope facies and also volcanogenic complexes. It is supposed (Kontorovich et al., 2003) that all three described megazones (including Siberian platform) are underlain by a single Precambrian (Lower Riphean) crystalline basement. An Early Permian subvolcanic body of potassic rhyolite–granite contain fairly numerous relict zircons of 2051 ± 23 Ma age (Ivanov and Erokhin, 2011; see Fig. 5). Evidently, the granite magma interacted with ancient granite-metamorphic basement.

Starting from the Late Riphean and up to the Cambrian the extension and fragmentation of Siberian domain took place (Yolkin et al., 2008). The first break-up of the continental crust with its separation took place at the Early-Middle Riphean boundary, with formation of turbidite complexes and ophiolites. The evidence of the last impulse of riftogenesis probably are basaltic rocks similar to back-arc and middle-ocean ridge basalts (Saraev et al., 2004).

At the present time there are many disputable issues concerning the problems of evolution of Kazakhstanides (megazone IV, Fig. 4). The whole history of evolution of this structural unit of West Siberia is discussed (Dobretsov and Buslov, 2007), along with details, such as a question if some separate structures belong to Kazakhstanides. Generally it is considered (Bochkarev et al., 2003; Yergaliev et al., 1995) that the southern part of this megazone represents the northern submerged periphery of Kokshetau massif. To the north of it Krasnoleninsky dome is situated. Probably both of these Precambrian blocks had been united in Frasnian. Until now, the assumption about a presence of Precambrian in Krasnoleninsky dome is not proved. Granitoid intrusions of this (Kazakhstan) domain are considerably older (440–450 Ma according to SHRIMP-II U/Pb dating – see Fig. 6) than in the Pre-Uralian area (280–290 Ma). Subplatform environments in the limits of Kazakhstanides established by the end of the Late Devonian (Yergaliev et al., 1995). To the west of the domain, a sufficiently narrow shelf was evidently situated in the Early Carboniferous, where accumulation of terrigenous–carbonate sediments of considerable thickness took place (Yolkin et al., 2001).

Kazakhstanides are separated from the Pre-Uralian part of the West Siberian plate by Valerianovka suture which is traced by

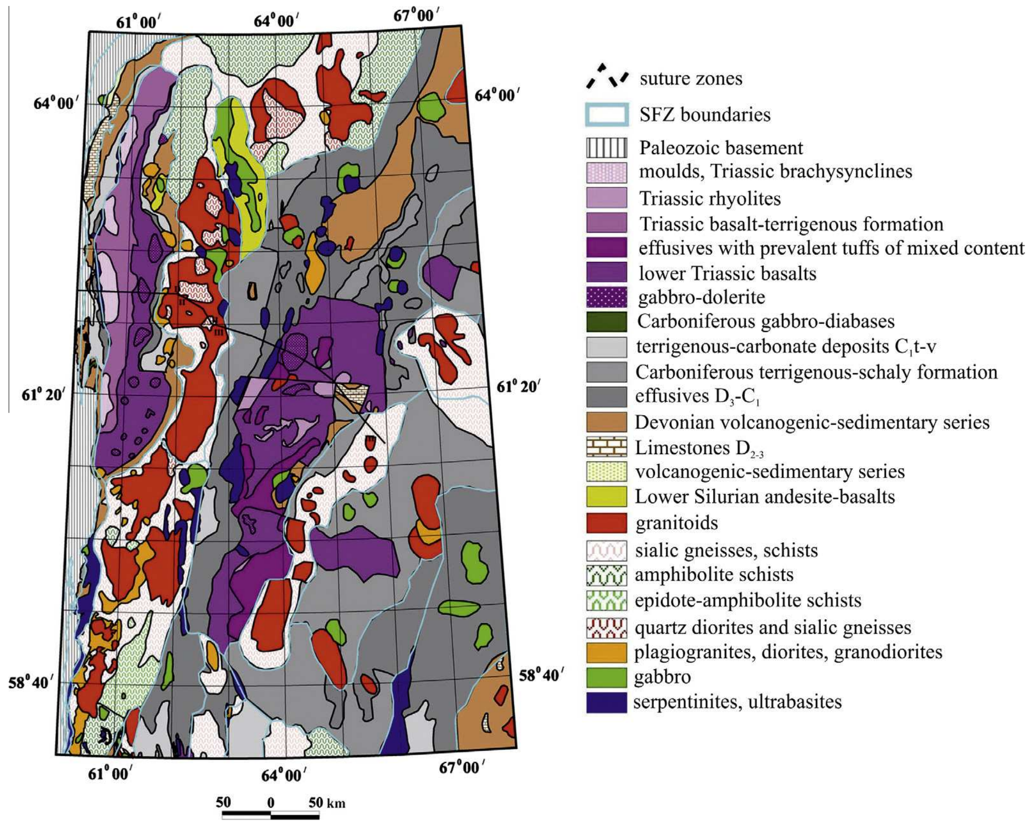

Fig. 8. Schematic geological map of the pre-Jurassic basement of western part of West Siberian plate (Ivanov et al., 2009).

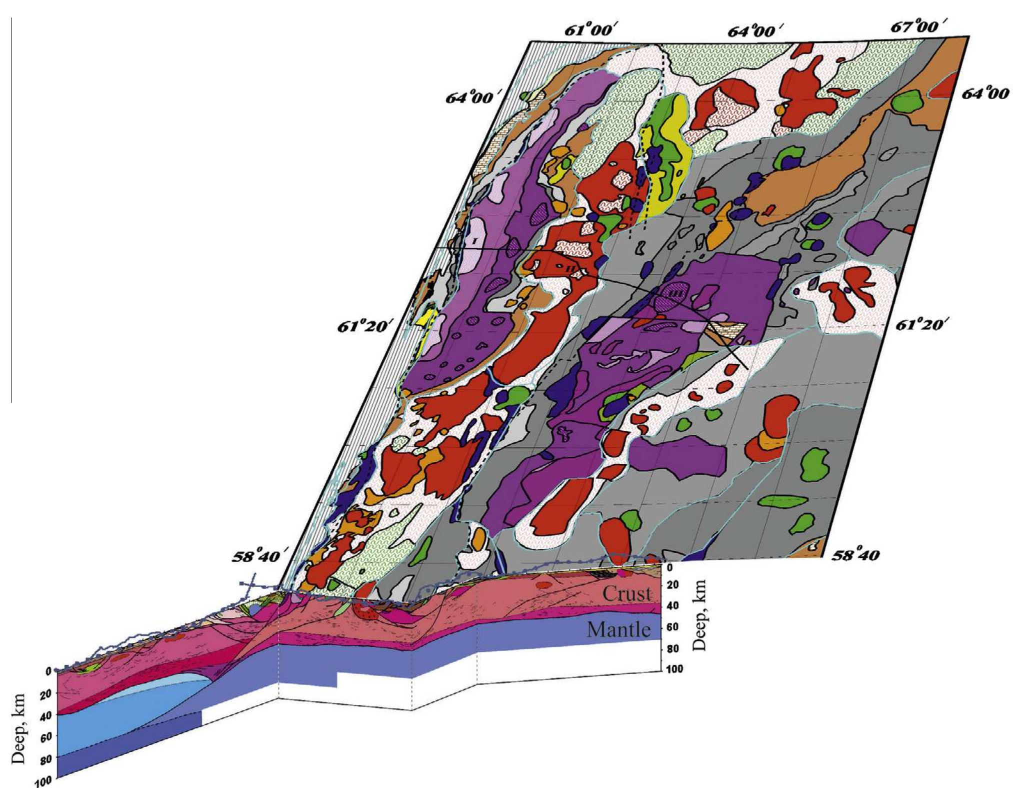

Fig. 9. The comparison of seismic-geological model along Middle Urals transsect with geological map of the pre-Jurassic basement of the western part of West Siberian plate (Ivanov et al., 2010).

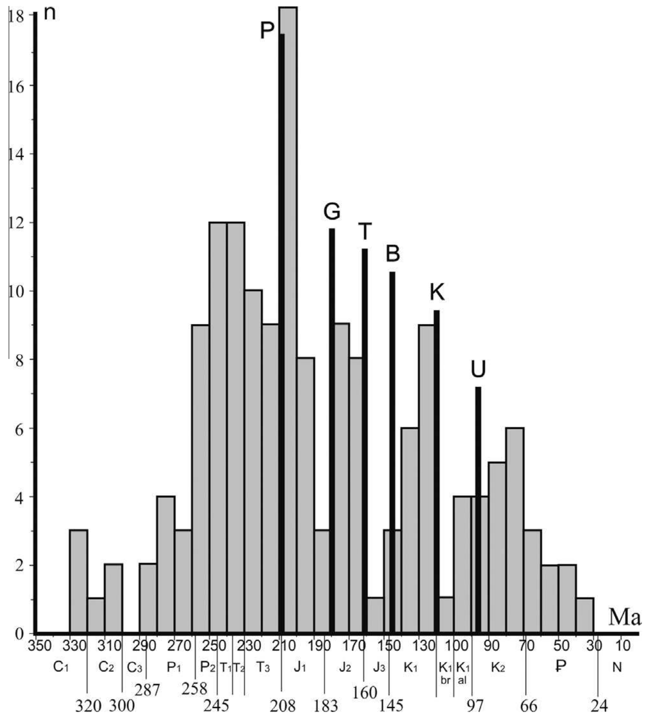

Fig. 10. K-Ar age distribution of volcanic rocks of the Turin series of the Western Siberia (from 167 analyses). Horizons: P – Pre-Jurassic sediments, G – goreloy (sherkalinskoy) formation, T – Tyumen formation, B – Bazhenov formation, K – koshayskoy (alymskoy) formation, U – Uvat formation.

geophysical data to the depth not less than 20–30 km (Dyakonova et al., 2008).

Chara suture is situated between the Kazakhstanides and Siberian domain. The age of ophiolites here is determined as a Visean–Serpukhovian boundary of the Early Carboniferous (Iwata et al., 1997). Most of these and other regional faults of the West Siberian plate basement have a strike-slip component (amplitude of displacements reaches hundreds of km). According to paleomagnetic data, it is connected with a clockwise rotation of Siberian domain in relation to the East-European craton (Buslov et al., 2003; Kazanski and Metyolkin, 2008; Buslov, 2011).

Cis-Uralian part of the West Siberian plate (megazone V, Fig. 4) is composed of complexes of the eastern island arc sector of the Urals (Ivanov, 1998; Ivanov et al., 2009). As a result of mapping of large segments of this area (Fig. 7) a new scheme of zonation of the western part of the basement of the West Siberian plate basement was made and a simplified (scale 1:1,000,000) geological map for Pre-Uralian part of Pre-Jurassic basement of the West Siberian plate compiled (Fig. 8) (Ivanov et al., 2009).

A normal fault along the western flank of North-Sos'va Triassic graben is the boundary between the Urals and West Siberian young platform. This boundary fault extends along the exposed Urals in submeridional direction to its Cis-Polar part at a distance of 350 km. Study of magmatic and metamorphic complexes, volcanogenic among them (including ophiolites), terrigenous-shale and carbonate series of Urals and western part of the West Siberia show their obvious resemblance. The structure of the plate basement has much in common with the exposed Urals. As in the Urals, in the basement of the Western Siberia, two periods of ophiolitic magmatism – Ordovician and Devonian are determined (Sm/Nd dating, as well as conodonts and radiolarians from jasper interlayers). According to geochemical characteristics, the mafic complexes were formed in island arc (probably back arc) conditions.

At the same time, considerable differences between the Urals and basement of the West Siberia were discovered. In the limits of the exposed Urals (with diversity of disjunctive fault system) Late Paleozoic submeridional sinistral strike-slip faults predominate over the others. In the basement of the western part of the West Siberian megabasin a system of dextral sublatitudinal strike-slip faults was revealed (see Fig. 9). These faults have

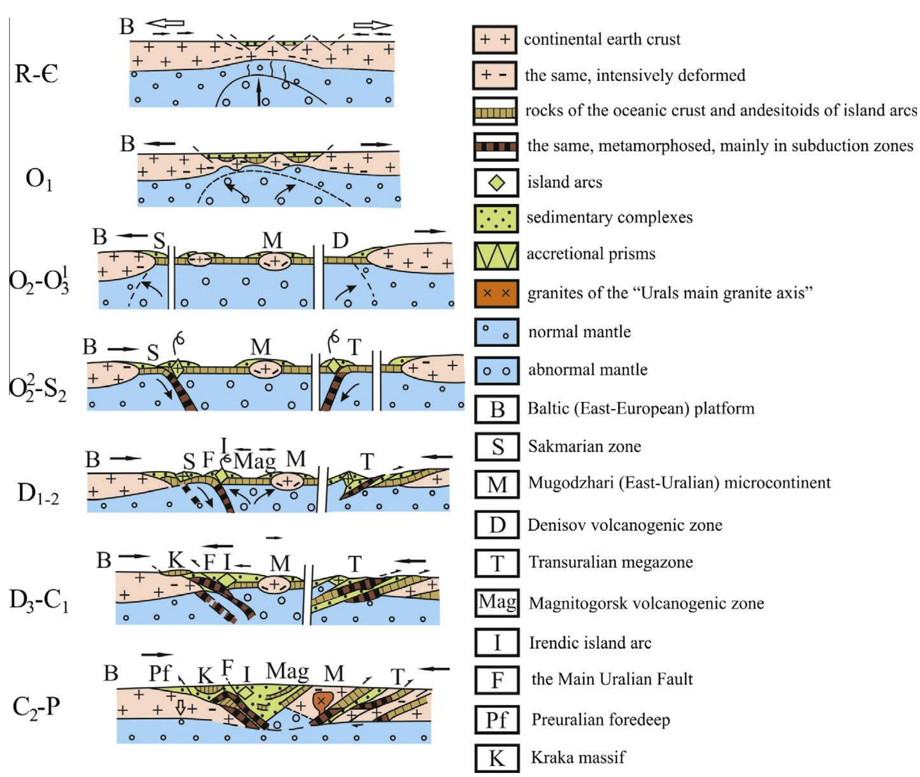

Fig. 11. A scheme of the Southern Urals development in the Paleozoic. Arrows show movement directions.

W–N–W strike with amplitudes of 6–16 km and cause "en echelon" displacement of the main regional structures. Strike-slip faults divide the basement into several blocks with a length about 40–50 km; each next northern block is displaced eastward (and not unfrequently is submerged) in relation to more southern one. This strike-slip system has been formed in the Middle – Late Triassic (in some places later) probably as a result of sublatitudinal extension of crust and deepening of its northern part. This has caused, at first, the origin of Triassic graben system filled by volcanogenic and terrigenous–volcanogenic series, and after that – the whole West Siberian gas-and-oil megabasin. Wide distribution of Triassic volcanogenic complexes in the basement of the West Siberian plate makes its principal difference with the Urals.

Ophiolites and other mafic–ultramafic complexes are widely distributed in the basement of the West Siberian plate (especially in its central and western parts). These complexes are situated along big faults which divide sedimentation zones of different types (Surkov and Trofimuk, 1986; Ivanov et al., 2009). Ophiolites are often dismembered and aggregated tectonically with other rocks. Most representative is a Paleozoic ophiolite complex composed of tectonized serpentinite, gabbroid, plagiogranite, basalts with jasper interlayers containing Late Ordovician radiolarians and conodonts (Ivanov et al., 2009). This ophiolite complex has been described in the limits of Shaim gas-and-oil area of the Cis-Uralian megazone. It is the most ancient complex in the basement structure of the western part of the West Siberia. In all probability spinel lherzolite is a relict of melanocratic basement of an Early Paleozoic (Uralian?) paleoocean.

Paleozoic geodynamic evolution of these regions ended in a result of collision accompanied by folding, tectonic aggregation, intrusion of granite plutons, metamorthism and formation of new crust of continental type. The time of these events which consolidated Paleozoic basement complexes of future West Siberian megabasin is determined as Early Permian for the Cis-Uralian part of the plate. Relatively low $^{87}Sr/^{86}Sr$ ratio in granites (Isr = 0.7046–0.7047) of the western part of the West Siberia indicates that a melting substrate of these granites probably consisted of Paleozoic complexes with a considerable portion of mantle source, i.e. oceanic and island arc, material. Three types of granites are distinguished. Among them rocks of monzodiorite–granite series predominate (age of all series is 280 Ma); they are similar to analogous granitouds from the eastern sector of the exposed Urals.

Triassic period was very important in the post-Paleozoic evolution of the basement of West Siberia. In the Triassic (mostly in the beginning of it (Medvedev et al., 2003; Reichow et al., 2009)) rifting, formation of the graben system, also uplift of intrusive and metamorphic complexes, forming cores of "anticlinoria", took place.

Appearance of megablocks composed of deep-crust complexes at the surface took place as a result their uplift to the level of the upper crust in a process of a break-up and/or extension of the latter. Probably the extension began in the Early Triassic. Triassic volcanism is the result of a dissipated riftogenesis in a period of a Triassic post-collisional sublatitudinal extension of the Urals and origin of the West Siberian megabasin which are closely associated.

The tectonic activization in Mesozoic was characterized by K–Ar method (Fedorov et al., 2004). It is known that Triassic basalts and rhyolites are covered by Jurassic sediments with unconformity. Therefore considerable part of dates for volcanic rocks (younger than 230 Ma) show not the time of their origin, but the time of their secondary alteration which are connected with phases of tectonic-thermal activity of region. The following phases of endogenic activities are distinguished (Fig. 10): (1) Late Permian – Early and Middle Triassic (with peak of 250–230 Ma) – rifting and intensive volcanism; (2) Early Jurassic (201–200 Ma) – short but intensive growth of tectonic activity accompanied by uplift of the territory; (3) Middle Jurassic (180–160 Ma) – differential uplift and general submergence of the territory, accumulation of continental sediments; (4) Early Cretaceous (with peak 130–120 Ma) – new phase of tectonic activity, formation of sand-clayey marine clinoform series; (5) Late Cretaceous – Early Paleogene (with peak 80–70 Ma) – tectonic activity with slow attenuation. With phases of attenuation of tectonic activities there was connected accumulation of separate horizons of argillaceous deposits (end of the Early – beginning of the Middle Jurassic, the Late Jurassic – beginning of the Early Cretaceous, the Early Aptian).

5. Conclusion

The overview of numerous data shows that in the Riphean–Mesozoic time the Urals had undergone two main complete cycles of geodynamic development. The first one took place in the Riphean and Vendian and resulted in a formation of Timanides; the second one is dated as Paleozoic–Early Mesozoic and its final processes were associated with formation of the Uralide orogen. The second cycle (Fig. 11) is better studied and allows to distinguish more clearly a number of stages partially superimposed one upon another owing to a diachroneity of processes.

1. *The stage of continental riftogenesis* (Cambrian – Early Ordovician). The general uplift of the province with subsequent formation of the all-Uralian rift. From bottom to top (and from West to East) the volume of volcanics is gradually increasing while their alkalinity is decreasing.
2. *The stage of oceanic spreading (the Middle-Late Ordovician).* Spreading and ophiolite formation in the Urals began in the Late Arenigian. It is proved by the conodont datings of Akai, Sugrali, Polyakovka, Denisovka, Kaban and other series of tholeiite basalts, up to 250 assemblages are established: *Periodon flabellum – P. aculeatus zgierzensis; Periodon aculeatus aculeatus – P. aculeatus zgierzensis – Pygodus serrus; Periodon aculeatus aculeatus – Pygodus aculeatus – Pygodus anserinus.* This gives every ground for assuming that the spreading has lasted for at least 25–30 Ma, and the width of the Ordovician Urals paleoocean was not less than 600–800 km. These numbers can be still bigger if taken into account that the Southern Urals spreading ended in the Llandoverian.
3. *The island-arc stage (the Late Ordovician – Early Carboniferous).* The eastern Urals sector consists of two main different-age island-arc terrains – the Tagil (Ordovician – Lower Devonian) and the Magnitogorsk one (Lower Devonian – Carboniferous) though they have a rather similar structure. However in the western part of the Tagil terrain, deep magmatic suprasubductional complexes are exhumed, represented by a chain of so-called Platiniferous belt stratified massifs; according to gravity data, a presence of a gabbroid belt can be assumed in the depth of the Magnitogorsk terrain as well.
4. *The Early collisional stage (the Late Devonian – Early Carboniferous).* Collision of the Magnitogorsk island arc and passive margin of the Laurussia continent. The direction of the collision was oblique (north-western).
5. *The late subductional stage: subduction of the relict oceanic crust of the Paleouralian ocean (the Early Carboniferous – Bashkirian)* During the accretion of the Transuralian zone, a subduction of oceanic crust was directed under the East-Uralian zone, leading to the formation of a tonalite–granodiorite component of the Main Granite Axis of the Urals and thick suprasubductional

volcanism in the Uralian eastern zones. Bearing in mind the lack of a characteristic subductional magmatism and changes of paleogeographical situation, the Late Bashkirian time was the moment when the subduction gave place to a collision.

6. *The collision of Laurussian and Kazakhstanian continents*. Collision and orogeny (as a consequence of collision) were expressed in a gradual disappearance of sedimentation in the territory of all Uralian zones situated to the east of the MUF. In the pre-Permian and especially in the Permian time these zones became areas of intense erosion providing terrigenous material for the Pre-uralian foredeep which migrated to the west before the west-vergent overthrust front. Simultaneously under the East-Uralian and Transuralian zones a thick system of east-vergent overthrusts developed, affecting the earth crust at its whole depth and associated with MOHO which served as a surface of tectonic detachment. The increase of the crust thickness in the East-Uralian zone came as a consequence of this, and has lead to the change of a suprasubductional granite magmatism to the anatectic one.
7. *The limited post-collisional spreading and superplume magmatism (Triassic) stage*. Formation of a system of normal faults and coal-bearing grabens of the Urals. Appearance of the Transuralian and Polar Urals basalts. According to the recent isotope data a thick trapp volcanism began to pour out practically simultaneously at a huge territory from the Urals to the Central Siberia (about 250 Ma) and continued on in the form of impulses for about 20 Ma (Reichov et al., 2009).
8. *A short orogenic* impulse took place at the end of the Early Jurassic time; the influence of this orogeny strengthens to the north of the Urals and becomes the main orogenic stage in the Pai-Khoi and Novaya Zemlya, where the folded belt had been just formed in the Jurassic time. Triassic deposits in the south of the region were affected by the deformations of this time in the limits of its eastern sector (Chelyabinsk and other grabens) where the Upper Triassic and older sediments had been deformed in a series of simple thrusts (Rasulov, 1982).

Post-Uralian history of development (the Jurassic to the present time) includes platform and neo-orogenic stages.

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