



5 **New data on geology of the Southern Urals: a concise summary of research after the
period of EUROPROBE activity**

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5 **Abstract.**

The period of an official activity of the EUROPROBE commission was connected in the Urals with implementation of the URALIDES Program, that stimulated many qualified geologists from the Western research institutes and Universities to come to the region and work with local geologists at actual problems of the Uralian geology. The author tries to answer a question: what interesting results
10 had been obtained in the Southern Urals in the last decade, when the most of foreign researchers left the Urals, and how these results correspond to the scientific conclusions that had been done before.

Key words: Urals, EUROPROBE, URSEIS-95, stratigraphy, tectonics, ophiolites, HP metamorphism, plumes.

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1. Introduction.

The decade between 1992 and 2001 was of a special importance for the geology of the Urals. It was characterized by a sudden surge of a research activity from the side of geologists of western European geoscience communities. They came to see the Urals and apply their skills and knowledge to better understand this famous and extraordinarily rich region. Among the main reasons for this “invasion” one may mention the famous “perestroika” and “glasnost”, followed by the transition to openness of the USSR society and free access to the Urals that used to be almost forbidden for foreigners before the 90-ties. It is enough to say that the first meeting of EUROPROBE in the Urals (May of 1991) took place in the Belayarsk city, in full view of its “top secret” nuclear power station, and the excursions (guided by me) went from the biggest industrial City, Sverdlovsk, in five directions. It was time of great plans and optimistic hopes for better understanding and co-operation between nations. The geology, knowing no political boundaries, was a good ground for it.

The EUROPROBE program was initiated at the 27th International Geological Congress in Moscow, 1984, as a plan for a multidisciplinary research in the Europe, including the European part of the USSR and the whole Urals. The aim of the program, inherited from the earlier International Lithospheric Program (ILP), was a better understanding of a structure and tectonic evolution of lithosphere of the Europe and the dynamic processes that controlled its evolution through time. Following and enhancing the ILP plans, the EUROPROBE went on with organization of seismic profiles aimed to reveal the deep structure of the most interesting territories. Along with these profiles, a great attention was paid to integrated studies of geology, tectonics, geodynamics, geochemistry, petrology and isotopic age of magmatism and metamorphism, paleomagnetic and geothermal studies, basin analysis and some other topics. Among ten target areas of research, corresponding to ten projects, where about 30 countries participated; URALIDES were selected as one of the most attractive. Some



more research programs were approved and realized later, just before the end of the 10-year EUROPROBE's Program or even several years later. The most close to URALIDES were the latest TIMPEBAR (Timan-Pechora-Barentsia) and POLAR URALS programs.

During the time of the EUROPROBE activity, the important financial support was received from the European Science Foundation (ESF), which provided a resource for work of Science and Management committees and allowed to run annual workshops for every project, with some travel money budget. A support was coming also from INTAS (The International Association for Promotion of Co-operation of New Independent States). But main support was to be collected by participants themselves, organized into individual research groups, often multi-national, from National Science Foundations and Councils of their countries.

In the Southern Urals, the main and most expensive task was a >400 km-long URSEIS-95 seismic profile, a base of a complex seismic experiment. The work was accomplished by co-operative efforts of International consortium (Russia, Germany, USA and Spain), with participation of Spetsgeofizika, Bazhenovskaya Expedition, Bashneftegeofizika (Russia), DEKORP GFZ and Karlsruhe University (Germany), INSTOC Cornell University (USA), ICTJA-CSIC (Barcelona, Spain). The special feature of the work done was a combination of several methods of study. The CDP combined acquisition by means of vibration and explosion excitation was accompanied by a wide-angle experiment. All the acquisition work was made during one field season of 1995, and the following processing and interpretation took several next years. The results were regularly published in the western and Russian literature. The Profile was recommended as the most ambitious and successful project (Berzin et al., 1996; Carbonell et al., 1996; Echtler, 1996; Knapp et al. 1996, Morozov, ed., 2001 and others). Along with the geophysical research, a lot of geological field work had been done during all these years. The most stable and long-lasting co-operation was organized in these years in the Southern Urals between the geologists of the Institute of Geology in Ufa (Ufimian Scientific Centre) and colleagues from the Instituto de la Ciencias de la Tierra Jaume Almera – CSIC, Barcelona; Universidad de Oviedo, Spain; Max-Planck-Institut für Kernphysik, Heidelberg, Germany; Institut für Geologische Wissenschaften und Geiseltalmuseum, Martin-Luther-Universität Halle-Wittenberg, Halle, Germany; Geologisches Institut der RWTH, Aachen; Technical University, Berlin; Institut für



Mineralogie, und Lagerstättenlehre Institut für Geologie, RWTH, Aachen, Germany; Institut für Mineralogie und Geophysik, Ruhr-Universität, Bochum, Germany; Geological Survey of Finland. More episodically several other teams worked in the Southern Urals, with a participation of geologists from the Institute of Geology and Geochemistry; Institute of Geophysics (RAS), Ekaterinburg; Geological Institute of Moscow(RAS); Moscow State University; Institute of Mineralogy, Miass. They co-operated with geologists from the Universities of Udine, Napoli, Modena and Genova, Italy; Natural History Museum, London; Southampton Oceanography Centre; NERC Isotopy Geosciences Laboratory, Keyworth, Nottingham, UK; Dalhousie University, Canada; BRGM, France; GFZ, Postdam, Germany; University of Granada, University of Jaén Spain; Geological Institute, ETH, Zurich, Switzerland; Uppsala University, Sweden. The teams have published tens of scientific papers in many leading peer-reviewed geological journals. In addition, several special issues of such journals, dedicated to the geology of the Urals were published (Pérez-Estaún, Brown, Gee, eds., 1997; Meyer, Kisters, Stroink, eds., 1999; Brown, Juhlin, Puchkov, eds, 2003).

The final events of the main EUROPROBE campaign were publications of two big volumes, partially summarizing the work that had been done (Gee, Stephenson, eds., 2006 and Pavlenkova, ed., 2006). Of a special interest, concerning the developments in the URALIDES program as a whole, are papers of Brown et al., Matte, Kashubin et al., Bosch et al. and Gee et al. in the first of the volumes, and Chapter 4, edited by Puchkov, Kashubin and Perez-Estaun (2006) in the second volume.

The decade of 90-ths was very difficult for Russian geology. Eltsin's political and economical reforms, realized under seemingly attractive slogans of democracy, market economy, privatization, etc, turned out to be ill-conceived and badly organized adventure and have led to a destruction of industry (and Geological Survey as well), break-off of business ties, outright banditism, sharp drop of GDP and living standards, low financing and irregular payments of salaries in science and other factors that negatively influenced the level of scientific research in the country. In this conditions, the arrival of foreign colleagues that had finance providing for field research and laboratory analyses permitted to continue the scientific studies of the Urals geology at a relatively decent level and reach a progress. Although the USSR geologists belonged to one of the strongest professional community in the world, providing for knowledge of 1/6 of the land with its richest deposits, a co-operation with so many



representatives of different, English-speaking scientific schools enriched them with many ideas of modern science and gave an impetus for a further development.

The aim of this paper is not to describe the achievements of this period, which are well known and easy to find in published English-language literature, and probably deserve a special analysis, but to summarize, at least partially, what interesting had been done in geology of the Southern Urals in the latest decade (2006–2016).

2. Stratigraphy. Although the stratigraphy was not in the main preferences of the URALIDES project, its achievements were in the background of all conclusions made in the result of structural and geodynamic studies of the Urals.

2.1. Precambrian. The Precambrian stratigraphy was always a priority with geologists of the Southern Urals, because the ~15 km-thick section of weakly metamorphosed Proterozoic sediments of the Bashkirian meganticlinorium was accepted as the stratotype of the Riphean, which is still present in the Russian Stratigraphic Code and General Stratigraphic Scale of Russia (GSSR), being widely used for geological mapping and prospecting. The works on this Scale went on until recently (e.g., Kozlov, 2014). In the last decade, these studies were supported by more deep study of volcanism and isotope age determinations with application of modern methods, which were almost unavailable in earlier time, except the invaluable data obtained by U. Glasmacher under the URALIDES project.

The Riphean sediments comprise volcanic rocks of several levels, which permitted us to refine the stratigraphic scheme, based first of all on new isotopic ages, obtained with new techniques. Our work was stimulated by understanding that the International Scheme (ISS) of division of Meso- and Neoproterozoic into systems/periods of equal duration (200 Ma) contradicts to traditional principles of stratigraphy.

Until recently, the Riphean was subdivided into three systems (periods): the Lower – Burzyanian, Middle – Yurmatinian and Late – Karatavian. We added to it the Uppermost (Terminal) Arshinian system (see below). The isotope ages of the boundaries of these strata were updated (Puchkov et al., 2014).



The base of the Riphean section is situated at 200 - 400 m lower than volcanics of the Navysh Subformation, at the base of polymictic sandstones of the Ai Formation (Burzyanian series), which overlies high-metamorphosed Archean-Paleoproterozoic Taratash crystalline complex with an angular unconformity (Sergeeva et al., 2013). The isotopic study of events in the Taratash complex dates the last episode of granitisation under conditions of the amphibolite facies in the crystalline basement of this region as 1777 ± 79 Ma (Krasnobaev et al., 2011) and is also in accordance with data (Sindern et al., 2006; Ronkin et al., 2012) on the minimal age of granites of the complex (1800 Ma). It makes the lower age limit for the base of the Riphean.

The age of the Navysh Formation at the western limb of the Taratash uplift was determined as 1752 ± 11 Ma, U-Pb analysis of them at SHRIMP II (VSEGEI) (Krasnobaev et al., 2013c).

At the base of the Middle Riphean (Yurmatinian system) the Mashak volcanogenic-terrigenous Formation is situated. Two zircon samples from Mashak rhyolites were analyzed by U-Pb CA-IDTIMS method in the Boise University (USA) and the dates of 1381.1 ± 0.7 Ma and 1380.2 ± 0.5 Ma were obtained (Puchkov et al., 2009). It was close to the precision date of the Main Bakal dike, sampled by us and analyzed in the isotope laboratory of the Toronto University (Canada): 1385.3 ± 1.4 Ma (U-Pb method, baddeleyite) (Ernst et al., 2006). The dike cuts the Bakal Formation and is comagmatic to the Mashak basalts. A new series of U-Pb zircon analyses was made in VSEGEI (SHRIMP). An average weighted date of rhyolites for 4 samples was 1383 ± 3 Ma; a presence of rare ancient crystals was also registered (1597 ± 27 Ma) (Krasnobaev et al., 2013a). In the same time, two samples of zircons were sent to SHRIMP in Australia (one new and one—for a control). Both gave practically the same results: 1386 ± 5 и 1386 ± 6 Ma (Puchkov et al., 2013). This laboratory has also reported a presence of some older crystals: 1420 - 1550 Ma; they are interpreted as inherited from a substrate. All the dated samples are situated ca. 300 - 400 m above the base of the Yurmatinian series and therefore we proposed the age of the boundary between the Burzyanian and Yurmatinian series at ca. 1400 Ma.

In the area of the Tirlyan syncline of the Southern Urals the Paleozoic sediments overlie unconformably a thick (up to 1.5 km) series of terrigenous deposits, including tillite-like conglomerates. In the middle of the section there is a considerable unit of volcanogenic and volcano-sedimentary deposits. It overlies with an erosional contact the Uk Formation of the Upper Riphean. Until recently,



this series was described as an Arshinian Formation and attributed to the Lower Vendian . We suggested to change the rank of the unit and regard it as a series (Kozlov et al., 2011). The study of zircons extracted from the volcanic rocks of Igonino Formation of this series permitted to come to a conclusion of a polychronous character of the Arshinian volcanism, with two main stages of its evolution with average levels of 707.0 ± 2.3 and 732.1 ± 1.7 Ma (Krasnobaev et al., 2012). Taking into account that the age of the base of the Vendian is accepted now at 600 ± 10 Ma and opinions of the majority of specialists that allow the position of the Vendian/Riphean boundary not lower than 635 - 650 Ma, we suggest a new straton in the top of the Riphean – as the Terminal, uppermost Riphean.

These data permitted to correlate the Riphean scheme with the Meso– and Neoproterozoic units of the ISS and also suggest a correlation with the Chinese scheme (Sinian to Changcheng units) (Table 1).

The Uralian section characterizes only the easternmost part of an extensive basin, which occupied in the Meso-Neoproterozoic a considerable part of the Volgo-Uralian oil and gas province (VUP), have thickness of 0 to 10 km and is concealed under a Paleozoic sedimentary cover, 2–3 km thick. In the Province, a couple of dozens deep boreholes penetrated the Proterozoic deposits, and it permitted to construct the stratigraphic scheme of the VUP part of the basin, which have the same fundamental features as in the Southern Urals, though differ in many details. The correlation between the Uralian and VUP stratigraphic schemes serves much for the refinement of the latter. Moreover, it was shown that a stratigraphic section of a unique 5–km deep borehole in the Urals, 1–Kulgunino (Kozlov et al., 2011), is transitional and can be described as a combination of the Uralian and platform schemes. As for the oil and gas prospects of the Riphean section, they are still uncertain, because the quantity of the deep boreholes is insufficient. Anyway, a possibility of discovering of new deep deposits cannot be discarded and needs a further consideration.

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2.2. Paleozoic. The most important results in the stratigraphy of the Paleozoic during the last decades were connected with the study of conodonts supported by knowledge of some other orthostratigraphic faunas. The results and their impact on the paleogeodynamics were summarized at the end of the XX century by V. Puchkov (2000).



The progress in the stratigraphy of the Ordovician of the territory to the west of the Main Uralian Fault had been marked by recent publication of Mavrinskaya, Yakupov (2016), based on conodonts and chitinozoans, with carbon isotope analysis, made in Syktyvkar isotope laboratory, revealing in the studied sections the global Hirnantian event. Of publications on stratigraphy of the Ordovician of the Sakmara allochthon, the book of Korinevsky (2013) and Ryazantsev's thesis (2012) must be mentioned. The importance of the latter is also in presenting proofs for an existence of the Ordovician Guberlya island arc, first suggested by Zonenshain et al., (1990).

The progress in Silurian stratigraphy where well-studied graptolites play the main role is not so conspicuous, with the exception of some episodic publications, where conodonts could be used.

The progress in the Devonian conodont-based stratigraphy, mainly in the Magnitogorsk zone, was much more evident and solid, being summarized in the books of Maslov and Artyushkova (2010), Artyushkova (2014), that were the results of a long and tough work. The specific feature of this research was that the conodonts were collected in shale and jaspers among effusives, and work with such material needs a special approach in field and laboratory (see also Puchkov, 2000).

The most recent results of research on stratigraphy of the Carboniferous and Permian deposits were summarized in the materials of the Carboniferous–Permian Congress in Kazan, 2015. The importance of Carboniferous and Lower Permian sections of the Southern Urals for the development of the International Stratigraphical Scheme was demonstrated in two field excursions: “Carboniferous...” (2015), and “Southern Urals. Deep water successions...” (2015).

Generally speaking, the Southern Urals is extraordinary “rich” with type sections and candidates for establishment of Global Section Stratotypes and Points (GSSP), compared to all the regions of Russia (Riphean stratotype and bases of Global stages: Serpukhovian, Asselian, Gzhelian, Sakmarian, Artinskian and Kungurian). Bashkirian stage was also established in the Southern Urals, although its boundaries do not meet very strict conditions for GSSP establishment. The work on all of them, with an international participation, went on constantly during the last decade and before.

Mesozoic and Cenozoic stratigraphy has shown a small progress in the last decades, with the exception of the most young strata, where the work of the Laboratory of Cenozoic in the IG USC RAS (Ufa) resulted in a formation of updated stratigraphic schemes of the Neogene and Quaternary,



which also was favorable for a better understanding of the neo-orogenic stage of the Urals development (Danukalova et al., 2002, Puchkov, Danukalova, 2009 and some latest publications).

3. General geology, tectonics and geodynamics. Active work on geology of the Urals and Cis-Urals was prolonged in the last decade by V. Puchkov and his colleagues. My personal experience in all tectonic zones and all latitudes of the Urals, obtained during more than half-century-long research activity, permitted me to write a book with an analysis of most important and insufficiently clarified questions of stratigraphy, tectonics, geodynamics and metallogeny and give a general overview of the foldbelt, using all the available materials, including those obtained under the EUROPROBE Program (Puchkov, 2010). It was in fact, an extension and enhancement of the previous book (Puchkov, 2000). The material of the next book is organized according to a structural-historical principle. The book is divided, apart of an Introduction and Conclusion, into 5 Chapters corresponding to 5 structural and historical stages, established in the whole territory: Archean-Paleoproterozoic, a time of formation of the Volgo-Uralia continent and its amalgamation with other blocks into Baltica continent; Riphean-Vendian (Meso- and Neoproterozoic), a stage that was finished with formation of Timanides; Paleozoic-Early Mesozoic stage, corresponding to a development of the Uralides; Mid-Jurassic-Miocene platform stage; Pliocene-Quaternary neo-orogenic stage. When necessary, the actual questions of stratigraphy are discussed, schemes of structural zonation for every stage are given, problems of a structural geology and geodynamics of sedimentary and magmatic complexes are arranged in a chronological order; every chapter is concluded with a characteristics of metallogeny, closely connected with a previous discussion. Ideologically, the book is based on plate and plume tectonics, in their modern versions. All captions for the figures in the book are bi-lingual; the book is provided with an English Summary. It is available at the site of the Institute of Geology, Ufa. In 2011 the book was awarded of Academician A.D. Archangelsky Premium for outstanding works in a regional geology.

The English-language digests of Chapters 3–5 is published as (Puchkov, 2009b, 2013b), and an updated analysis of the Uralian metallogeny is given in a separate paper (Puchkov, 2016a).

3.1. Structural research. The progress was made in the research of tectonics of the part of Uralides, concealed under the Mesozoic–Cenozoic cover of the West Siberian plate, based on



geophysics and study of boreholes. The results of this study were combined with the knowledge of tectonics of the exposed part of Uralides and structural correlation was made (Ivanov et al., 2013).

Interpretation of seismic materials aiming at a better understanding of a deep structure of the Urals, that was an important chapter of the URALIDES Project, was also going on, including a re-
5 interpretation of some parts of the regional URSEIS-95 and ESRU-SB-93-95 profiles. The Candidate of Science thesis of A. Rybalka (2015), who defended it successfully in the last year, was dedicated to the ESRU-SB-93-95 seismic profile. Being for many years a leading specialist in Bazhenovskaya expedition, he did much to the success of the work on this profile. Not dwelling much upon the results, I want to pick out one of important conclusions of this work, that was absent in previous interpretations
10 of the profile. It was a conclusion of a presence below the Urals of a reflector, gently (under 30 degrees) dipping to the west, that is traced through the whole crust and upper mantle to the depth of about 80 km. It is situated just under the modern Urals Mountains and probably plays an important role in their formation. In fact, underthrusting of the Transuralian block under the Urals could be the cause of the neo-orogenic movements. In the Southern Urals a presence of such underthrusting is not registered, but
15 it could be explained by problems of acquisition of primary data.

Some additional work had been done for a better understanding of the URSEIS profile as well. As it was pointed out by Znamenskiy et al. (2013), the pattern of reflectors in the eastern part of the profile, to the east of Kartaly town and Kartaly (Troitsk) regional fault, is organized as a typical flower structure, which supports and specifies the idea of a wide development of strike-slips in this part of the
20 Urals.

In the last years, the work on interpretation of seismic profiles crossing the footwall structures of the Main Uralian Fault, that was made by international teams, was continued, because new materials were obtained, so several new papers on this subject were published, supplying previous interpretations with some more details (Svetlakova et al., 2007, 2008; Puchkov, Svetlakova, 2014).

25 **3.2. Plume tectonics.** Very important innovation that appeared in the book (Puchkov, 2010) and the following publications (Puchkov et al., 2013, 2016; Puchkov, 2012, 2013c, 2016 b) was a theme of probable plume events in the Urals, a point that was not raised until the middle of zero years of the new century. Before these publications, some papers of a general theoretical trend, belonging to the



same author, appeared as a contribution to a world-wide discussion: “Do plumes exist?” (Puchkov, 2003, 2009a).

Petrogenetic, geochemical studies and isotope age determinations of flood basalts, dolerites, trachybasalts, picrite-basalts, rapakiwi granites, layered mafic-ultramafic intrusions and also alkaline
5 and carbonatite magmatic complexes of the western zones of the Urals, along with coeval magmatic complexes of adjacent and faraway territories permits to put forward a preliminary list of objects – “candidates” at attribution to Large Igneous Provinces (LIPs). Their petro-geochemical properties distinguish them from MOR and subduction types; they are characterized by wide areas of development, very short periods of activity and independence of their areas from earlier geological
10 structures (Ernst, 2014).

As it was mentioned before, in the Southern Urals near the base of the Lower Riphean (Uppermost Paleoproterozoic and Lower Mesoproterozoic), covering crystalline Taratash complex dated as Archean and Lower Paleoproterozoic, there are volcanic deposits of the Navysh Subformation, represented mostly by trachybasalts. The age of the unit was determined as 1752 ± 11 Ma (SHRIMP,
15 zircons) (Krasnobaev et al., 2013c). It turns out that volcanic rocks of the age level of 1750–1780 Ma are developed not only in some other places of Baltica, but also in the Northern Africa, Siberia, Laurentia and North China, being by that time parts of Nuna supercontinent (Puchkov, 2013c; Youbi et al. 2013). Therefore they may belong to a LIP.

Higher up the section of the Riphean, at the base of the Middle Riphean
20 (Mid-Mesoproterozoic), rhyolites of the Mashak Formation were dated by SHRIMP and CA-IDTIMS U–Pb methods in three isotopic laboratories as 1380–1385 Ma (see above). The same ages have also rapakiwi granites, layered gabbro (Kusa–Kopan Intrusion), carbonatites (Sibirka) and dolerite dykes and sills widely developed in the Southern Urals and encountered in boreholes of East European platform; magmatic rocks of the same age are traced to Greenland, Laurentia and Siberian cratons and
25 date the beginning of Nuna supercontinent break-up (Puchkov et al., 2013; Puchkov, 2013c; El Bahat, 2013).

Less confidently we may speak of the younger Neoproterozoic magmatic complexes of the Southern Urals as LIPs, dated as ca. 720 Ma (compare with data of Ernst, 2014) and 680 Ma –



Arshinian and Kiryabinka complexes (Kozlov et al., 2011; Krasnobaev et al., 2013b); they need a further study (Puchkov, 2016a,b).

The study of dolerite dykes and volcanics in the western slope of the Urals has revealed three main Paleozoic volcanic events. The first one, represented by subalkaline volcanics is connected with
5 rift process started at ca. 490 Ma, the beginning of the Ordovician, that has led to oceanic spreading and formation of the Paleouralian ocean. They accompanied the formation of the Baltica passive margin (Puchkov, 2002) that can be attributed to a plume-connected volcanogenic type (Melancholina, 2011). The comparable and contemporaneous rifting events, accompanied by volcanism, took place in the Lower–Middle Ordovician along the eastern (in modern co-ordinates) margin of the Siberian continent
10 (Bulgakova, 1991). As it is shown by paleomagnetic data (e.g. Svyazhina et al., 2003, Paverman, 2016), the “upside-down” position of the Siberia, and sub–longitudinal strike of the Uralian margin could suggest close, vis–a–vis positions of the margins, and their volcanism may belong to the same superplume episode, occurring above the same superswell.

The second episode was marked by an eruption of trachytes in the Bashkirian meganticlinorium,
15 and was dated (SHRIMP, zircons) between 435 and 455 Ma. It can be correlated with the early stage of development of Vishnevogorsk plume-related carbonatite complex (Puchkov, 2010, 2016 b; Puchkov et al., 2011; Nedosekova, 2012).

The younger dolerite and basalt complex is Devonian in age and is traced along the western slope of the Urals to Pay–Khoy and Novaya Zemlya. The rocks match excellently with the
20 Middle–Upper Devonian volcano-intrusive complexes of the East European platform including flood basalts, dolerite dykes, alkaline and carbonatite intrusions and kimberlites, and belong to the marginal part of the LIP called Kola–Dnieper (Ernst, 2014; Puchkov et al., 2016). The late, reliably dated stage of the Devonian magmatism of the East European platform and Urals–Novozemelian belt is Frasnian in age. They are well correlated with Yakutsk–Vilui plume episode in the Siberian Craton and probably
25 represent a superplume derived from an active part of a single deep mantle LLSVP (Large Low Shear Wave Velocity Province), the so-called Tuzo superswell (Puchkov et al., 2016 and references therein).

The last but not the least are the Lower Triassic flood basalts, dolerite and rhyolite dikes traced from the easternmost parts of the Southern and Middle Urals to the western margin of the Polar Urals. It



became evident that they belong to the Uralo-Siberian LIP and “African” superswell (Reichow et al., 2009; Puchkov, 2010)

3.3. Geology of ophiolites. Wide development of ophiolites, an association of peridotites, pyroxenites, gabbro, basalts and deep-water sediments (mostly cherty shales and jaspers), is the most characteristic feature of the Urals. Since the International Symposium on geology of ophiolites that took place in Moscow, 1973, and International ophiolite excursion (Efimov et al., 1978), the idea of ophiolites as relics of an ancient oceanic crust became very popular among the Uralian geologists and stimulated a research activity in this direction. Several international groups of researchers worked in the Urals under the URALIDES Program, contributing to the knowledge of geology of such outstanding objects as, first of all, Kempirsay, Khabarny, Kraka and Nurali massifs in the Southern Urals and Voykar, Ray-is and Syum-Keu of the Polar Urals.

The summary of the EUROPROBE research as well as the earlier studies were given by Savelieva et al., (2006a). It was shown that different massifs belong to different geodynamic situations – Middle Oceanic Ridges, transition from epicontinental rift to a passive margin, or island arcs of different ages. The summary of isotopic age determinations (K–Ar, Sm–Nd, Rb–Sr, Sm–Nd, U–Pb systems), supported by paleontologic determinations of age of a sedimentary component of ophiolites permitted to date the ophiolites in the limits of Lower Ordovician–Upper Devonian, admitting that the younger, Devonian ages correspond mostly to the secondary processes of deformation and metamorphism. The Precambrian ages were attributed to the ophiolites of Timanides.

But soon appeared the reliable Precambrian ages, obtained mostly by U–Pb method from zircons, that changed this simple picture. Zircons of Vendian age (585, 3 ± 6 Ma) and a couple of zircons dated as 622 ± 11 Ma and also one grain of 2552 ± 25 Ma were obtained from chromites of a small deposit in dunites of the Voykar massif (Savelieva et al., 2006 b). Puchkov (2006, 2010) discussed this problem in detail. He indicated to more examples of Precambrian isotopic dates (U–Pb, Sm–Nd, Re–Os) for ophiolites that were thought to be Paleozoic. An attention was also attracted to the fact that the lower, peridotite part of the ophiolite sections, called by R. Coleman a “mantle tectonite” belongs to very ancient, restitic mantle, that may preserve relict isotope ratios, corresponding to previous Wilson cycles, that are reflected only in the lower parts of the ophiolite sections. For example, ancient zircons were



found in the Uralian ophiolites, forming quite an assembly of different-aged (from 2000 to 200 Ma) crystals, in dunites, lherzolites and garnet pyroxenites of Kraka massifs (Krasnobaev et al., 2008).

Broadly speaking, the presence itself of zircons in peridotites seemed to be enigmatic. Deficit of silica in peridotites should not permit the origin of zircons – only baddeleyite could form. Therefore, basalt melts were needed to generate zircons. But where they have been?

Batanova and Savelieva (2009) gave a review of ideas concerning the transport of basalt melts through the peridotite mantle in spreading zones. The hypothesis of reaction of migrating mantle magmas with wall peridotites and the formation of replacive dunites as a result of this process was discussed. It is shown that dike-like dunites, forming nets within harzburgites and lherzolites, were the channels of basalt melts. In this case, zircons and chromites hosting them could be the refractory trace minerals, left by the basalt magma on its way from relatively deep places of partial melting in the mantle to the Earth's surface. The possible deep origin of these minerals is suggested by presence of diamonds, discovered in chromites of some ophiolite peridotites, including the Ray-Is massif of the Urals (Yang et al., 2014)

The preservation of zircons during so long time, within extreme P–T conditions of mantle also needs an explanation. Recently (Anfilogov et al., 2015), gave the results of experimental studies of interaction between zircon crystals and dunite at 1400–1550°C. It was shown that at 1400°C no interaction of zircon with dunite takes place, and only at higher temperatures an interaction between zircon and olivine occurs, forming eutectoid mixture of baddeleyite and pyroxene grains. Therefore zircon is very resistant to metamorphic changes, and it explains a coexistence of zircons of different ages, formed under repeating high-temperature processes.

3.4. Petrology and geochemistry of igneous and sedimentary rocks. A great work had been done by the group of G. Fershtater on petrology and geochemistry of intrusive rocks of the eastern slope of the Urals, made hand in hand with his colleagues from Granada (Spain) before and during the EUROPROBE activity. The results were summed up recently in his monograph (Fershtater, 2013). More local, but very detailed studies of geology, petrochemistry and chromite ore potential of peridotite Kraka, Talovsky, Mindyak and many other gabbro-peridotite massifs were described in the book of Saveliev et al., 2008. The petrology and geochemistry of intrusive rocks, volcanics and sedimentary



successions, hosting them, in the Bashkirian meganticlinorium were summed up recently in the book of Kovalev et al. (2013). Simultaneously, a special book concerning the characteristics of stratigraphy of the Mashak Formation in stratotype and petrology of its volcanics was published by Ardislamov et al. (2013) Geology and petrogeochemistry of carbonaceous sediments of the Southern Urals were

5 characterized in the monograph of Snachev et al. (2012)

Devonian and Carboniferous volcanic rocks of the Magnitogorsk zone, variable geodynamic conditions of their origin and their position in the relic island arc of Paleozoic time were described in two big papers of Kosarev et al. (2005, 2006).

3.5. Metamorphism. New data on geology of Maksutovo HP–LT complexes. The classic

10 HP–LT metamorphic Maksutovo complex attracted the attention of Russian petrologists at least since the 50–ties of the XXth century, and it was very popular with the participants of the URALIDES Project. More than a dozen papers were published, dedicated to different aspects of geology, geochemistry and petrology of this outstanding eclogite–glaucophane complex. The general opinion, summed up and discussed by Puchkov (2010), was that this complex was formed in a process of

15 Paleozoic subduction of oceanic crust and a subsequent collision of an island arc and continental passive margin. As a consequence of a buoyancy of the subducted continental margin, the metamorphic complexes were uplifted from the depth of 50–70 km and exhumed to the earth's surface. The most of the isotopic age determinations, made by different methods, correspond to the Devonian time, and the beginning of exhumation is dated as ca. 375 Ma, and it is supported by the information that glaucophane

20 clastic grains appear in the Famennian Zilair flysch Formation

More recently, an additional work had been done to obtain more detailed information on types of eclogites (e.g. Alekseev et al, 2006).

Later on, it was established (Kovalev et al., 2015) that protoliths of different varieties of high–pressure eclogites (high-Ti, moderate- and low-Ti eclogites, graphite eclogites, and eclogites of

25 a layered body) were mafic magmatic rocks of different affinity and Paleozoic in age. The petrogeochemical study has shown that the eclogites are close to basalts formed in different geodynamic settings –oceanic and subductional, and now they are juxtaposed. Thermodynamic calculations of mineral assemblages of eclogites showed that low-Ti eclogites (680–700C, 24 kbar), graphite eclogites



(660–710°C, 17–18.8 kbar), and eclogites of the layered body (610–730°C, 16–18 kbar; 410–430°C, 12.5–13 kbar) were formed at similar temperatures but at a large scatter in pressure. It was concluded that the pressure variations were caused by the tectonic juxtaposition of bodies during exhumation of eclogites formed at different depths of subducted slab.

5 On the other hand, there existed an alternative point of view (Dobretsov et al., 1996), who think that the protolith of rocks is Precambrian and experienced ultrahigh-pressure metamorphism (550–600 Ma); the final stage of the high-pressure metamorphism (320–385 Ma) occurred simultaneously with the metamorphic transformations of ophiolites.

Meanwhile, new data had been presented on the conditions of origin and age of the Maksyutov
10 metamorphic complex. The studies of zircons from garnet-glaucophane schists of the complex (Novotashlinskii area) (Krasnobaev et al., 2015) have shown that their substrate was constituted of magmatic gabbroids of Neoproterozoic age (670 Ma). The long-term evolution of zircons encompassed the interval from the Neoproterozoic until the Carboniferous (673.1 ± 5.4 , 592.6 ± 9.4 , 517.0 ± 7.4 , 444.9 ± 4.7 , and 323.0 ± 8.8 Ma) – i.e., from the Terminal Riphean till Vizean.

15 The study of Valizer et al. (2013, 2011) was concentrated on UHP jadeite-bearing eclogites, developed near the village of Karayanovo, and on spatially associated ultramafites that were considered to be formed also under eclogite-facies conditions. A comparison shows that the studied eclogite and ultramafic rocks followed a common P – T – t path. For the jadeite-bearing eclogites, two phases of eclogitization were recognized based on mineralogical data, petrographic observations, and isotope
20 geochronology. The first UHP metamorphic stage (533 ± 4.6 Ma, $P > 4.4$ GPa, $T > 700^\circ\text{C}$) was defined by the assemblage jadeite + grossular-almandine + rutile \pm phengite. This assemblage was later transformed into omphacite + grossular-almandine + phengite + albite + clinozoisite + titanite at a retrograde phase of stage I (392 – 485 ± 2 – 4 Ma, $P > 3.1$ – 3.4 GPa, $T > 633$ – 740°C) with decreasing pressure and temperature. The second prograde phase (360 ± 5 Ma, $P > 1.1$ – 2.2 GPa, $T > 450$ – 550°C) of
25 HP metamorphism was marked by the development of a chlorite rim (almandine–grossular–pyrope–almandine–grossular, diopside, clinozoisite) around the eclogite body. The ultramafites are represented by olivine-enstatite and enstatite rocks. The thermodynamic parameters of formation of the paragenesis are given. The PT conditions are estimated as 800–1240°C and 30–45 kbar. Geochronological data



limits recorded in zircons are in the interval of more than 2 billion years, between 2350 ± 53 Ma and Early Permian (284.9 ± 7.3 Ma), see above. In general, Paleoproterozoic ages characterize the primary basis of the protoliths, while the Permian zircons record the final transformations of previous generations and the formation of new generations. The intermediate age level (545.3 ± 5.5 Ma and 365.3 ± 4.2 Ma) divides the initial stages of formation–transformation of the substrate and the final stage of its metamorphism, caused by shear deformations. It is probable that this age boundary can be considered as an indicator of the UHP metamorphism.

These new data show that the problem of the history of Maksyutovo complex is probably more complicated than it was thought before.

4. Concluding remarks and acknowledgements

Here we touched not all the problems that were being solved during the activity of EUROPROBE and after the end of the URALIDES Program. For example, we did not discuss a lot of work that had been done these years under other international programs, especially those dedicated to the mineral deposits of the Urals (MINURALS, GEODE, CERCAMS and others) – because the resources were not the URALIDES priority. The co-operation of the Uralian geologists with the specialists from western countries always was fruitful and stimulating, and served to a general progress of Earth Sciences. There is hope that this paper will be interesting, especially to many people who participated in the URALIDES Project and might wonder, what happened after they left the Urals.

I wish to express, on behalf of all my colleagues, a deep gratitude to all those who worked with us in field, exposing oneself to changing and not always friendly weather, participated in long and exhausting trips, sharing their expertise, helping to process and analyse samples. A special tribute of memory I want to pay to Andres Pérez-Estaún, an outstanding scientist and a good friend.

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Table 1. Correlation between the International Stratigraphic Scheme of the Proterozoic of the World (The Geological...,2012), Regional Stratigraphic scheme of the Upper Proterozoic of the Urals (Puchkov et al., 2014) and Geological Time Scale of Proterozoic in China (Gao Linzhi et al., 2012).

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International scale			Uralian scale		Chinese scale		Age limit, Ma
Eratheme, Era	System, Period	Age limit, Ma	Eratheme, Era	System, Period	Eratheme, Era	System, Period	Age limit, Ma
Neoproterozoic	Ediacarian	542	Upper (Late) Proterozoic	Vendian	Neo proterozoic	Sinian	542
	Cryogenian	630		Arshinian		Nanhuan	635
	Tonian	850		Karatavian		Quingbaikou	760
Mesoproterozoic	Stenian	1000		Yurmatinian	Meso proterozoic	unnamed	1000
	Ecstasian	1200	Lower (Early) Proterozoic	Burzyanian		Xishan	1200
	Calymmian	1400				Jixian	1400
Paleoproterozoic	Staterian	1600			Paleo proterozoic	Changcheng	1600
	Orosirian	1800				Hutuo	1800
	Rhyacian	2050				unnamed	
	Siderian	2300					
		2500					

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