PLUME-RELATED GRANITE-RHYOLITE MAGMATISM

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Plume-related magmatism is widespread and its existence is well-founded. Mostly, plume-related magmatism is represented by trap rocks, oceanic island basalts (OIB) and oceanic plateau basalts (OPB), although the composition of plume-related igneous products is very diverse. Among others, silicic igneous rocks – rhyolites and granites – play a prominent role. Two main types of plume magmatism are recognised. The former comprises Large Igneous Provinces (LIP) and is thought to be born at the core-mantle boundary within structures called superswells, which produce giant, short-lived mantle upwellings resulting in abundant magmatism on the earth's surface. The latter is represented by time-progressive linear volcanic chains formed by single plumes – thin upward mantle flows being continuously active during longer periods of time. It is shown that the relative volume of silicic magmatism strongly depends on the type of the earth's crust. Among continental trap basalts, silicic magmatism is usually present, being subordinate to the basalts in volume, and belongs to the bimodal type. However, in some cases, continental LIPs are formed predominantly by silicic rocks (silicic LIPS, or SLIPS). Oceanic LIPs are mainly basaltic comprising an insignificant or no amount of silicic rocks. Time-progressive volcanic chains are rarely found on the continents and, as a rule, include a significant silicic component. Oceanic chains are comprised mostly of basalts (OIB), although at the top of volcanoes there are more acid and alkaline differentiates, which, however, usually lack rhyolites and granites, except for the cases when the relics of the continental crust or anomalously thick mafic crust are present. The analysis suggests that the melting of continental crust plays an important role in the formation of plume-related rhyolite-granite magmatism. As for the Urals, the presence of plume-related magmatism in its history has been proven relatively recently. Plume events characterised by the presence of (rhyolite)-granite components include Mashak (1380–1385 Ma), Igonino (707–732 Ma), Mankhambo (mainly Cambrian), Ordovician Kidryasovo, Stepninsky (Permian) and Urals-Siberian (Triassic).

Keywords: *rhyolites, granites, plumes, underplating, LIP, time-progressive volcanic chains*

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INTRODUCTION

Plume-related magmatism is well-studied. Most of its manifestations are represented by basic volcanites (trap rocks and swarms of dolerite dykes considered as feeders; basalts of oceanic islands and plateaus). However, the spectrum of magmatic manifestations associated with plumes is extremely wide: formation of kimberlites, carbonatites, picrites, alkaline basaltoids, as well as layered basic intrusions. A significant role is also played by acid igneous rocks – granites and rhyolites, with the outcrops of either granites or acid effusive rocks, which depends on the depth of the erosional truncation [Ernst, 2014].

Plumes constitute a part of the global thermochemical convection system: ascending subvertical currents of mantle convection which are deep-seated and therefore manifested on the Earth's surface as intraplate activity zones that do not depend directly on linear interplate structures – subduction and MOR (mid-ocean ridge) zones – although they can interact with them, as well as cause the formation of linear structures (active rifts) by themselves [Puchkov, 2016].

It is reasonable to distinguish between two types of plume manifestations. The first type includes large igneous provinces (LIP) having a volcanic-product volume of 1–10 million km^3 or more and an area of 1–10 million km^2 [Ernst, 2014]. They are characterised by short activity pulses, usually from 0.5 to several million years, whereas in the case of repeated pulses, their total activity can last up to 20 Ma, rarely longer. The LIPs are commonly attributed to the activity of superplumes – giant upwellings of mantle material from the core-mantle boundary within two vast areas characterised by slow propagation of bipolar S-waves. These two areas are referred to as superswells: South Pacific (Tuzo) and African (Jason). Superswells also constitute the birthplace of smaller single plumes, which, unlike superplumes, trigger much more constant volcanic activity (lasting up to 80 Ma in some cases). Smaller single plumes are less prone to fluctuations and occupy a relatively constant position; therefore, when interacting with moving lithospheric plates they cause the formation of volcanic chains (sometimes discontinuous or with swells) that exhibit linear consistent time progression (time-progressive volcanic chains, TPVC). Such volcanoes were originally called hot spots; this term is still used today; however, it is not a substitute for the term 'plume'. While LIPs and hot spots are only 'symptoms' of the process, superplumes and single plumes are equivalent to a 'diagnosis'.

PLUME-RELATED GRANITE-RHYOLITE MAGMATISM (GLOBAL PERSPECTIVE)

The role of plumes in the generation of granite and rhyolite magmatism is largely determined by how powerful their pulses were and what type of crust they affected. Continental LIPs (Columbia River, Afro-Arabian, Karoo, Kalkarindji, Keweenaw, Ural-Siberian, etc.) are mostly characterised by trap magmatism; however, as a rule, rhyolites and acid pyroclastic rocks are present in a subordinate amount in their cross-sections. In general, the magmatism is of a contrasting nature. In addition, the dating of intrusive rocks from the LIP periphery in some cases reveals that granites (mainly A-type) also belong to trap provinces [Vernikovski et al., 2003]. The analysis of acid volcanic products usually indicates a significant role of contamination associated with the assimilation of rocks from the anhydrous lower layer of the continental crust (granulites, amphibolites) induced by the powerful thermal effect of high-temperature basic magma in the course of underplating. Nevertheless, alternative mechanisms for the formation of acid magma are not excluded [Ernst, 2014 and references in this monograph].

Magmatic areas dominated by acid rocks (SiO_2 > > 65 wt %) are distinguished as a separate type of LIPs, parallel to substantially basitic LIPs sensu stricto. These provinces are called silicic LIPS [Bryan, Ernst, 2008; Bryan, Ferrari, 2013; Ernst, 2014]. As the Russian version of the term, we propose *kremnekislye KMP* (*KKMP*). Terminologically, the above-described mafic LIPs (MLIPs) and silicic LIPs (SLIPs) can be contrasted. The examples of SLIPs include Whitsunday (Western Australia – Oceania), Kennedy – Connors – Auburn (Northeast Australia), Gawler (Southeast Australia), Sierra Madre Occidental (Mexico), Chon Aike (South America – Antarctica), Malani (India – Seychelles – Madagascar), as well as Guibey and Xiongier (China). Late Paleozoic – early Mesozoic giant granite batholiths of the Central Asian Orogenic Belt (Angara-Vitim, or Barguzin; Khangai; Khentey) probably belong to this type as well [Yarmolyuk et al., 2014]. According to [Ernst, 2014], SLIPs exhibit the following features. 1. SLIPs are characterised by large area extents and volumes of extrusive magmatism, which are equal to or only several times smaller than those of MLIPs. 2. In terms of composition, dacite-rhyolite volcanites and granites, transitional between calc-alkaline I-type and A-type, constitute > 80% of the volume; with S granites being present in rarer cases. 3. The lithology of volcanites is dominated by rhyolite ignimbrites. 4. The duration of magmatic activity is up to 40 Ma, with individual pulses lasting 3–10 Ma. 5. SLIPs are formed only on the continental crust and are often located on paleo- and modern continental borders. They result from the anatexis of easily melted hydrous lower crust under the influence of high temperatures caused by non-subduction and non-orogenic conditions (most likely, plume-related underplating).

On the oceanic crust, superplumes form vast volcanic plateaus. As compared to the continental provinces, they are not older than the Mesozoic as evidenced by the fact that the older subducted oceanic crust can only be identified from ophiolites found in folded belts. The largest plateaus in the Pacific Ocean include Ontong Java, Hikurangi, Manihiki, as well as Shatsky and Hess rises. As a rule, granite-rhyolite inclusions are not characteristic of in their cross-sections. Volcanic plateaus formed in the Atlantic-type oceans are different in nature: North Atlantic Igneous Province, Sierra Leone, Rio Grande, Maud Rise, Kerguelen Plateau, etc. These plateaus can include both epioceanic and epicontinental (microcontinents, volcanic passive continental margins) parts. The initial stage of their development is epicontinental rifting which, to one degree or another, is usually accompanied by the formation of acid rocks as in the case of MLIPs described above (LIPs s.str.). However, as the process evolved, rift magmatism was replaced by mantle-related basitic magmatism; with rift complexes most often being found deeply buried. Nevertheless, acid igneous rocks sometimes outcrop: granites from the Isle of Skye in Scotland; granites and rhyolites from the Kerguelen Plateau, etc. [North Atlantic Igneous Province…, 2002; Ariskin, 2017].

The ability of single plumes forming time-progressive volcanic chains to produce granite-rhyolite igneous complexes also largely depends on the presence of continental crust, its relics or a simatic crust of anomalous thickness. Epioceanic volcanoes having a granite-rhyolite component are extremely rare; with the acid component being usually represented by trachytes, as well as highly alkaline rocks similar to them [Mazarovich, 2000; Rohde et al., 2013; see also GeoMan.ru: geography library www.geoman.ru/books/item/f00/s00/z0000077/st222.shtml]. Ascension Island could be cited as an exception; however, the volcano located on the island is very young and not connected to any volcanic chains. Of all the islands of the Canary Archipelago, only Gran Canaria, the largest of the Canary Islands, is distinguished by the presence of rhyolites. Rhyolites are also found on Jan Mayen Island, with very few peralkaline rhyolites being noted on Easter Island. The Icelandic plume occupies a special place among single plumes. In this case, the presence of acid volcanites, being estimated at 7%, is noticeable [Ariskin, 2017]. Granites are present as well. The volcanic structure formed by the Icelandic plume together with the Mid-Atlantic Ridge (MAR) is distinguished by an unusually large size, with the crust reaching up to 40 km in thickness, which could be a favourable condition for the anatexis of the lower crust, where both temperature and pressure are elevated. Nevertheless, the possibility of crystallization-differentiation in basaltic magma, as a rule, is not excluded.

Regular magmatic chains on the continental crust are quite rare. Some of the volcanic chains do not display a clear time sequence, which may be related to the complex dynamic interaction of the plume with the thick lithosphere (its jamming, shearing, strong deflection by mantle wind, etc.). Nevertheless, there are several examples of epicontinental magmatic chains that contain granites and / or rhyolites exhibiting time progression. In particular, they include well-known rhyolite calderas of the Yellowstone Plume [Smith et al., 2009], with the age gradually increasing to the west (from <1.0 Ma to 16.4 Ma). Nigerian anorogenic ring complexes of alkaline granites, granosyenites and volcanites, dated to be between 141 Ma in the south and 213 Ma in the north, constitute another example. The volcanic rocks preserved in the calderas demonstrate the evolution of melts from olivine basalts through hawaiites and mugearites to trachytes and rhyolite ignimbrites [Bowden, Kinnaird, 1984; Kinnaird et al., 2016]. One more example is related to the bimodal Gawler SLIP (Southeast Australia), from which a chain of granite massifs is traced across the entire continent [Ernst, 2014]. The age of magmatism consistently varies from 1.595 Ma in the south to 1.500 Ma in the north.

Summing up the review of international literature sources, it should be noted that granite-rhyolite occupies a prominent place among the products of plume-related intraplate magmatism; with plumes being an independent geodynamic factor of granite-rhyolite magmatism along with orogeny, subduction and the spreading of oceanic crust. Moreover, the volume of granite-rhyolite magmatism depends on the type of crust substratum – oceanic or continental. In the latter case, the volume is significantly higher. This alone suggests that the melting of the continental or transitional crust plays an important role in the origin of magmatism, as confirmed by numerous analytical data. However, the possibility of granites and rhyolites forming due to the remelting of rocks from the oceanic crust (basaltoids and amphibolites) is undeniable. According to experimental data [Khodorevskaya, 2017], this depends on the fluid composition and the features of the fluid regime (in particular, during amphibolite dehydration) or on the interaction of metabasites with aqueous-saline (Na, K)Cl fluid, which is related to seawater. Moreover, there is a possibility that other alternative mechanisms were involved.

PLUME-RELATED GRANITE-RHYOLITE MAGMATISM OF THE URALS

Lately, increased attention has been paid to the magmatic complexes of the Urals (mainly the western slope), which, judging by many indications, are plume-related [Puchkov et al., 2013, Puchkov, 2018a, б; Kholodnov et al., 2017; etc.]. Only some of them have a distinctive granite-rhyolite component. A brief description of the complexes is given below.

Mashak complex (1380–1385 Ma)

This complex, developed within the Bashkirian Mega-Anticlinorium (BMA), mainly corresponds to the Mashak suite of the Middle Riphean basement (RF2), in the lower parts represented by basalts and subordinate rhyolites, as well as by terrigenous strata (from conglomerates to shales). The suite is developed in the axial and eastern regions of the Bashkirian Anticlinorium, disappearing abruptly to the west in a washout (at a distance of 20 km). This fact, together with the intraplate rift nature of the chemism exhibited by volcanites [Ernst et al., 2006], suggests outcropping of the western flank of the graben, having a distinct Ural strike. The volcanites of the Mashak suite, developed in its lower part, are represented by a typical contrasting rhyolite-basalt series. Rhyolites can be found in the Mashak cross-section throughout most of the Bashkirian Mega-Anticlinorium (Fig. 1). When discussing the genesis of acidic volcanites, it is necessary to consider that among zircons (syngenetic to the eruption process), the presence of more ancient xenogenic varieties (in particular, minerals aged 1597 ± 27 Ma) was established [Krasnobaev et al., 2013a; Puchkov et al., 2013], which may indicate that the melting of more ancient crust components than the Mashak ones was involved in the formation of silicic magma.

In more detail, the importance of assimilation in the formation of the Mashak suite, consisting of picrites, basalts and rhyolites, has been considered recently [Kovalev et al., 2018a, б]. In some cases, U-Pb age determination for zircons from the basalts of the Mashak suite yielded significantly older ages for most or all of the zircons than the true age of volcanites. Thus, two discordant ages were obtained for five zircon grains sampled from the basaltoids of the Kuzelga subsuite – 1985.0 ± 16.0 (n = 2) and 1892.4 ± 9.7 (n = 3) Ma. In general, the dispersion of ^{206}Pb / ^{238}U ages determined for single crystals ranges from 1496 Ma to 3152 Ma. The authors proposed a mechanism describing the evolution of the primary mantle plume melt in line with the AFC model (Assimilation ± Fractional Crystallization). According to this mechanism, picrite (olivine ± clinopyroxene) originates through fractional crystallization in the primary melt at a temperature of 1100°C and a pressure of 10–11 kbar; the fluid phase accumulates in the uppermost part, whereas ancient host rocks are actively assimilated by basalts, which leads to the formation of rhyolites. In this case, εNd (T) of all rocks in the complex exhibit negative values (from ≈ –1.0 for picrites and basalts to –7.5 for rhyolites), whereas the extrapolated value of the primary melt is positive (mantle).

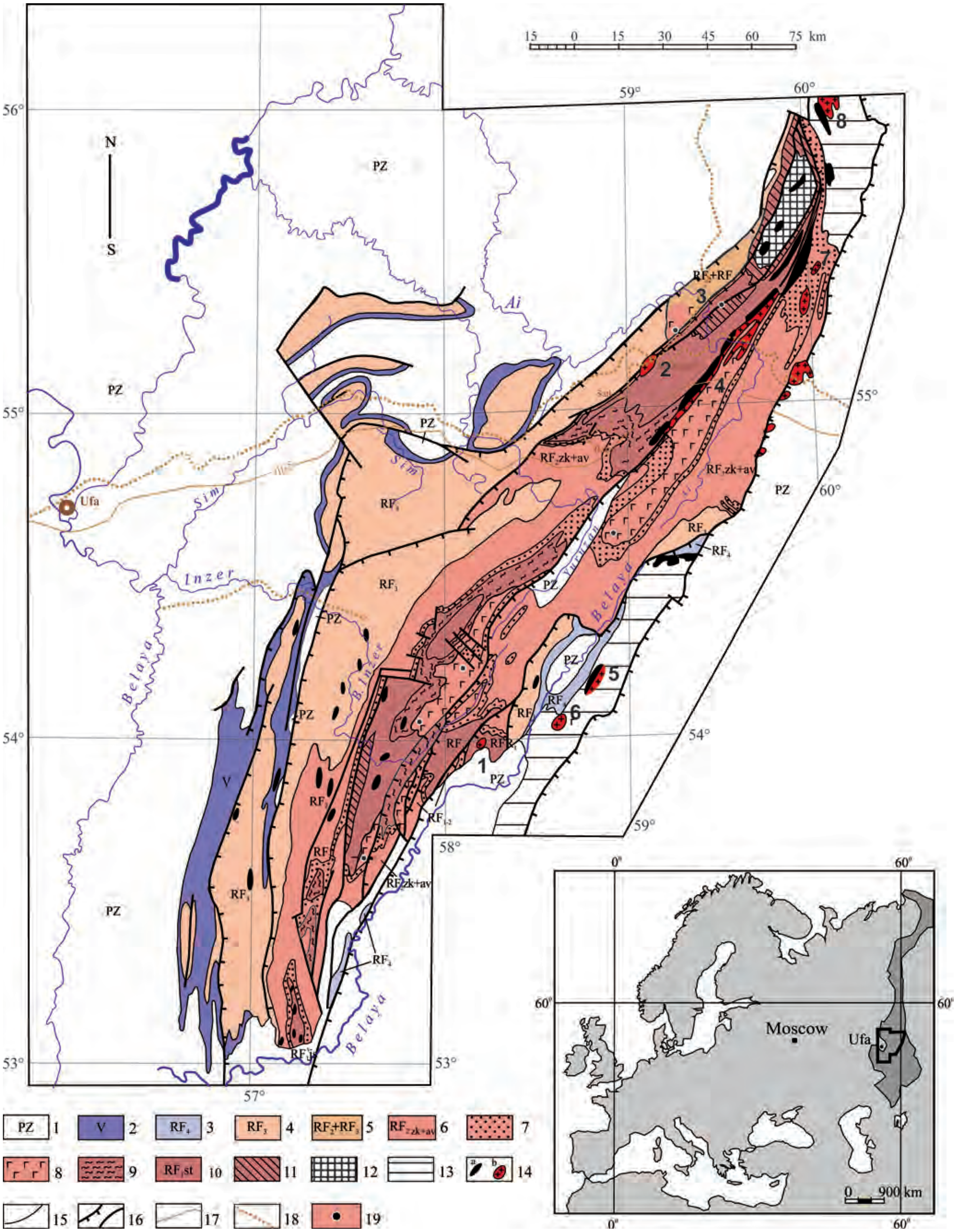

Fig. 1. Map showing the location of the silicic igneous rocks of Mashak, Igonino, Mankhambo and Kidryasovo (?) plume events in the Baskirian mega-anticlinorium and Ufaley anticlinorium (Southern Urals).

1–5 – undivided deposits: 1 – Paleozoic (PZ), 2 – Vendian (V), 3 – Terminal Riphean (RF_4), 4 – Upper Riphean (RF_3), 5 – Middle-Upper Riphean (RF_2 + RF_3); 6–11 – suites: 6 – undivided Zigazino-Komarov and Avzyan (RF_2 zk-av), 7 – Zigalga (Middle Riphean), 8 – Mashak (Middle Riphean), 9 – Bakal (Yusha), 10 – Lower Riphean Satka (Suran), 11 – Lower Riphean Ai (Bolsheinzer); 12 – Taratash complex; 13 – Uraltau and Ufaley metamorphic complexes; 14 – igneous rocks: gabbro (a) and granites (b); 15 – geological boundaries; 16 – main tectonic dislocations (thrusts and faults); 17 – highways; 18 – railroads; 19 – sampling points for zircons in the rhyolites of the Mashak suite and in the dikes of the Mashak age.
Numbers in the scheme denote silicic intrusions: 1–4 – Mashak complex: 1 – Akhmerovo, 2 – Berdyaush pluton, 3 – Bagrusha rhyolite dykes, 4 – Ryabinovo and Gubensk massifs; 5, 6 – Igonino complex: 5 – Barangulovo massif, 6 – Mazara massif; 7 – Yurma massif (Cambrian); 8 – Kozlinogorsk gabbro-syenite-granite association (Ordovician).

In addition to volcanites, intrusive silicic complexes occur in the BMA at the Mashak age level (see Fig. 1), which, among others, include Berdyaush rapakivi granites in association with syenites and gabbro xenoliths. To the north of the Berdyaush massif, the Bagrush complex of rhyolite dykes is developed on the strike of folded structures. Further to the northeast, there are Ryabin and Guba granites, which are closely associated with the gabbroid Kusa-Kopan complex, forming with it a contrasting association. A spatially isolated, more eastern location is occupied by the Akhmerovo granite massif. The results of absolute dating indicate that all these objects belong to the Mashak event [Krasnobaev et al., 2007a; Puchkov et al., 2013 and references given in this work; etc.].

The geochemistry of the Berdyaush pluton (BP) has been most fully studied. Its belonging to A-granites and geochemical closeness to Mashak rhyolites are well-founded [Larin, 2011]. Some researchers suggested granites having a mantle source. However, according to the latest data on the Hf isotope composition of zircons [Ronkin, 2017], rapakivi granites, quartz syenodiorites and nepheline syenites from the BP cannot originate from predominantly mantle melts, given that the range of extrapolated values εHf (1383)–(3.7–9.4) lies within the area well below the CHUR line. The observed regularity is in good agreement with the data of the Sm-Nd isotopic systematics of BP rapakivi granites, determining εNd(t) (–5.0 ± ± 0.4)–(–7.3 ± 0.3). Another argument in favour of the above is the difference in the spectra of REE distribution in gabbro zircons and other BP rocks. Similar data is presented in the article by V. Kholodnova et al. [2017]. The presence of gabbro xenoliths in BP, as well as their being derivatives of a substantially depleted mantle, where εNd = +4.0 ... +4.9, can confirm the popular idea that the crust melting during the formation of rapakivi granites is attributed to magmatic underplating caused by the subcontinental mantle rising up [Ernst, 2014].

Igonino complex (706–735 Ma)

It is our understanding that the complex belongs to the lower reaches of the Arshinian (uppermost, or terminal, Riphean, RF4) approximately covering an interval of 750–600 Ma and named after the Igonino suite, developed within the Arshinian stratotype in the Tirlyan trough [Kozlov et al., 2011]. According to the U-Pb analysis of zircons, the Igonino suite, which is mainly represented by basaltoids and is devoid of rocks more acidic than dacites, was formed during two main stages (pulses) of evolution dated at 707.0 ± 2.3 and 732.1 ± 1.7 Ma [Krasnobaev et al., 2012]. In terms of chemism, the Igonino volcanic complex reveals similarities with the basalts of the East African Rift System and probably could be classified as an intraplate-riftogenic / plume-induced formation of active rifts [Maslov et al., 2018]. The Barangulovo and Mazara granite massifs, which, together with the associating gabbros, belong to the contrasting gabbro-granite Barangulovo complex, are of close age. Gabbro zircons and granite zircons of the Barangulovo massif were earlier dated at (728 ± 8 Ma) and (723 ± 10 Ma), respectively, using the SHRIMP method [Krasnobaev et al., 2007б]. The early and final (slightly younger) stages of granite formation in the Mazara massif were dated at 746.6 ± 24.3 Ma and 709.1 ± 5.2 Ma, respectively [Krasnobaev et al., 2017]. Therefore, the gabbro-granite Barangulovo complex could belong to the same stage of plume activity as Igonino volcanites. A detailed study of zircons from the Mazara massif reveals its primary source (substratum). According to SHRIMP dating, the granite substratum of the massif is estimated to be between 1527 Ma and 1548 Ma, with its final evolutionary stage being concordantly dated at 1388 ± 16 Ma, which is close to the Mesoproterozoic Mashak stage of magmatism. This could indicate the involvement of rocks from the Mesoproterozoic crust in the melting. At the same time, the granites of the Akhmerovo massif are closest to those of the Mazara massif and could serve as its substratum [Krasnobaev et al., 2017]. The melting could result from the abovementioned underplating associated with a new plume event.

Kiryabino complex (670–680 Ma)

The complex in question was named after the Kiryabino layered massif (peridotite-pyroxenite-gabbro) dated to 680.0 ± 3.4 Ma [Krasnobaev et al., 2013б]. The igneous rocks of close age have a relatively limited distribution in the Bashkirian and Kvarkush mega-anticlinoria, as well as in the Onega Graben; thus their belonging to the LIP is at issue. The complex includes the Zhuravlik wehrlite-gabbro-granodiorite massif (671.0 ± 7.5 Ma), as well as the Troitsk granosyenite massif (671.0 ± 24.0 Ma) [Petrov et al., 2005].

Mankhambo complex (564–485 Ma)

The complex in question is named after the largest A-granite massif in the north of the Urals. We believe it is transgressively overlapped by the quartzites and arkoses of the Ordovician Telpos suite and is of Cambrian age (Fig. 2). The complex is represented by A-granites, associating gabbros, as well as a contrasting basalt-rhyolite complex of volcanites. A-granites (anorogenic, alkaline, anhydrous) constitute a special genetic group, as evidenced by the multiple meanings attached to the letter. Firstly, the name reflects the geodynamic situation associated with the predominant development of granites, which gravitate towards the stable (cratonised) areas of the earth's crust, most frequently occurring in rift zones and within the interior of continental plates. Secondly, the granites are characterised by the increased alkalinity indicating their belonging to the differentiates of alkaline basaltic magmas. Thirdly, they exhibit low water saturation, which is typical of the melting products of lower crust granulites. A-granites from the north of the Urals are associated with gabbros and are comagmatic with the volcanites of a contrasting association; with their formation being presumably related to underplating.

The difficulty of defining the boundaries of this complex, as well as interpreting its geodynamic situation in the Urals lies in the fact that in some areas it is closely connected to and sometimes intertwined with subduction-orogenic I-granites and comagmatic volcanic series; in terms of absolute age, A-granites follow I-granites, with the age of the former sometimes overlapping with that of the latter, thus creating an impression of a peculiar geodynamic chaos. Both types of granites are particularly widespread in the Subpolar Urals [Makhlaev, 1998; Kuznetsov et al., 2007]. I-granitoids are represented by a wide range of rocks from quartz diorites to leucogranites, in petrochemical diagrams corresponding to the areas of convergent geodynamic settings and active continental margins. These include the Maldy, partially Naroda, Vangyr, Lapchavozh and Ilyaiz massifs associated with the volcanites of successively differentiated basalt-andesite-dacite series. These massifs form gabbro-diorite-granodiorite-granite series of the specified geodynamic settings. The absolute ages of zircons determined using the methods of thermionic lead emission and the U-Pb dating (including the SHRIMP) range from the Terminal Riphean to the Cambrian (from 695 ± ± 19 to 515 ± 8 Ma, with the overwhelming predominance of Vendian ages). A-granites represented by Lemva, Tynagota, Naroda (partially), Khartes, Keftalyk, Tynagot, Kozhim, Mankhambo and other massifs exhibit a narrow spectrum of compositions, with leucocratic varieties prevailing. In terms of petrochemistry, they are related to magmatic formations of divergent geodynamic settings. Age datings (Pb-Pb, U-Pb, SHRIMP) range from 564 Ma to 487 Ma (the end

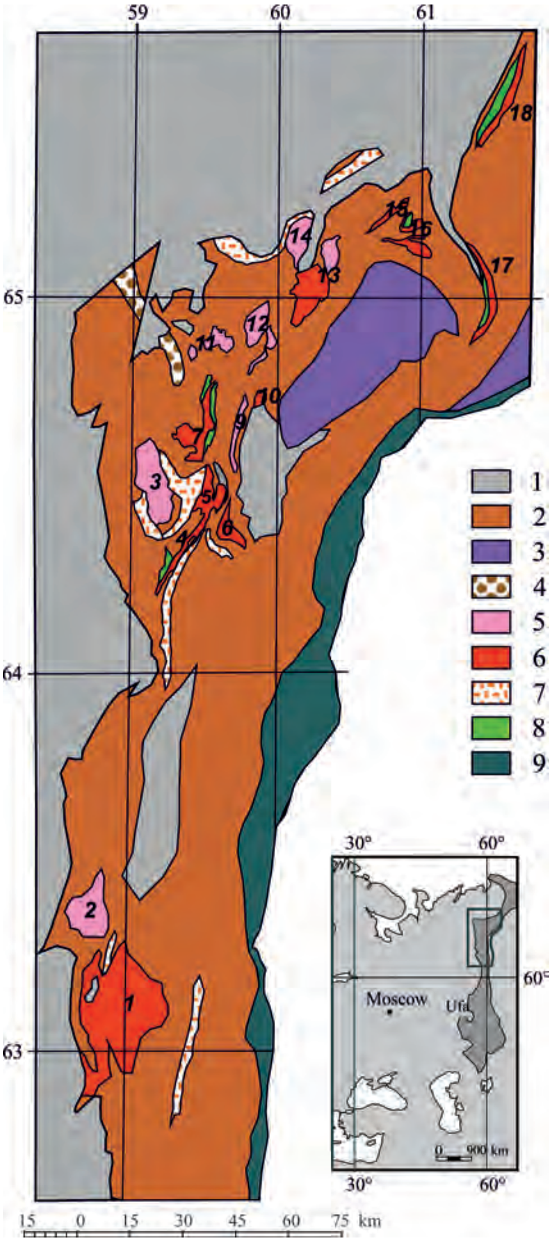

Fig. 2. Map of the Late Proterozoic–Cambrian granite massifs in the Nether-Polar Urals [Puchkov, 1975; Makhlaev, 1998; Kuznetsov et al., 2007].

1 – Paleozoic (Ordovician and younger) sedimentary formations; 2 – Riphean (Meso- and Neoproterozoic) deposits; 3 – Paleoproterozoic metamorphic complex; 4 – Vendian (Ediacaran) polymictic deposits (molasse of Timanides), 5 – I-granites (gabbro-diorite-granodiorite-granite series) predominantly of Vendian ages; 6 – predominantly leucocratic A-granites (mainly Cambrian); 7 – rhyolites of the Neoproterozoic-Cambrian age, undivided; 8 – gabbro of the contrasting gabbro-granite series; 9 – crystalline rocks of the Main Ural Fault.
The numbers in the scheme denote intrusive massifs: *1* – Mankhambo; *2* – Ilyaiz; *3* – Maly Patok; *4* – Torgovaya; *5* – Keftalyk; *6* – Khartes; *7* – Neroyka-Patok; *8* – Vangyr; *9* – Salner; *10* – Nyarta; *11* – Vodorazdel; *12* – Parnuk, Gorodkov and Mankhobeyu; *13* – Naroda; *14* – Maldy; *15* – Khatalamba-Lapcha; *16* – Kozhim; *17* – Tynagota; *18* – Lemva.

of the Vendian period and practically entire Cambrian period), which practically overlap with those of the Ordovician magmatites of the Kidryasovo plume event (see below).

The overlapping of I- and A-granite ages demonstrated using the example of the neighbouring Ilyaiz (519.7 ± 6.3–491.0 ± 5.0 Ma) and Mankhambo (522.0 ± 6.0–507.2 ± 5.5 Ma) massifs is paradoxical [Udoratina et al., 2017] and may indicate either a partial coexistence of contrasting collision and plume geodynamic mechanisms, originating from different depths; or different substrates, whose melting leads to the formation of different granites (in this case, the Ilyaiz massif is also plume-related). It is known that, in some cases, SLIPs are characterised by the presence of I-granites [Ernst, 2014]. An abnormally high volume of granitoids in plume products could result from high temperatures that remained in the lithosphere following the Timan orogeny, which caused large-scale melting in the crust.

The development of Cambrian A-granites along with I-type granites is characteristic not only of the Subpolar Urals. It was noted in the Polar and Subpolar Urals, Northern Urals (Isherim block), Middle Urals (Ufaley block) and even in the north of the Bashkirian anticlinorium (Yurma massif) [Petrov et al., 2005; Shardakova, 2016; Shardakova, 2017; Shuyskiy et al., 2017; and etc.]. These complexes represented by an uneven broken line to the west of the Main Ural Fault preceded the opening of the Paleoural Ocean in the Early Ordovician, accompanied by the emergence of the Kidryasovo rift complex with the eruption of mainly basic rocks, which reflects the formation of a crust-free oceanic opening, where the continental crust could no longer be melted due to its absence.

Mankhambo A-granites were formed in the presence of slight upward movements of the earth's surface: other than in olistoliths, Cambrian deposits are practically unknown in the Urals and Ural area – only at the very end of the Cambrian, terrigenous deposits began to accumulate locally, which turned into a large-scale accumulation of graben facies in the early Ordovician period.

Kidryasovo complex (475–460 Ma)

The formation of graben facies – coarse clastic strata, whose thickness varies greatly from place to place and whose formation is accompanied mainly by subalkaline basic volcanism – constitutes a direct harbinger of the East European continent splitting against the backdrop of intensified plume-related processes, which ultimately led to the emergence of the Paleoural Ocean and its eastern bound – passive continental margin of the volcanic type [Puchkov, 2002; Puchkov, 2010]. Graben facies, untouched by erosion and not buried by sediments, are dotted along the entire western slope of the Urals, from the Sakmara zone to Baidarat. At the same time, rhyolites and granites are rather poorly developed. In the Middle Urals near the MUF (Main Ural Fault) zone, there is the Kozinsk suite which supposedly belongs to Ordovician rift formations. It constitutes a thick (up to 3000 m) stratum of quartzitic sandstones and conglomerates containing interbeds of marbles, tufas, basalts, trachybasalts, as well as occasional rhyolites. The subalkaline volcanites of the Polar Urals include faunistically dated acid effusives (Molyudshor Suite) and rhyolite dykes [Puchkov, 1979; Soboleva et al., 2010]. Further north, in the Baidarat zone, the Cambrian(?)–Tremadocian sediments are represented by sandstones, aleurolites and shists; being overlain by the Lower-Middle Ordovician stratum of mottled structure, represented by limestones, schists and aleurolites with basalts, trachybasalts, as well as rhyolites [Puchkov, 2002 and references in this article].

Of particular note is the Kozlinogorsk gabbro-syenite-granite association developed in the Ufaley block of the Middle Urals [Tevelev et al., 2015], which was considered to be Permian and then dated by the cited authors at 476–470 Ma (Floian). The granitoids are moderately alkaline; the whole series is intraplate in terms of its geochemical parameters. Issues concerning the age of the association, as well as its belonging to one or another complex, are debatable. An alternative point of view regarding the age of the association is held by G. Shardakova et al. [2015]. The age determined from the biotites contained in the gabbro using the Ar-Ar method was estimated at 457.8 ± 5.8 Ma. In addition, according to the preliminary results, the vast majority of U-Pb datings of granite zircons yielded ages between 449 Ma and 480 Ma. On the basis of new datings, the authors classified the Kozlinogorsk group of intrusions as Late Ordovician. It is assumed that formations which are spatially combined, similar in composition, but somewhat heterogeneous in ages could be combined into this group, therefore even younger ages can be obtained for alkaline rocks from different intrusions. A similar point of view is held by A. Krasnobaev, who worked with zircon fractions from the alkaline rocks of this association. We believe that it is justifiable to compare it with other known alkaline complexes of the Urals, where, in some cases, carbonatites are known to occur. Most of them are concentrated east of the MUF zone. Among them, the Ilmeny-Vishnevogorsky complex (IVC) is most fully studied. The initial age of its heterogeneous rocks is dated at 440–420 Ma, with isotopic data indicating a significant role of mantle material in the substrate. Such interpretation suggests that the Kozlinogorsk gabbro-granite association might belong to the Ushat complex which is the next one in terms of age.

Ushat complex (440–450 Ma)

This complex was named after a section on the western side of the Taratash Rise (Ushat River). A number of outcropping subalkaline basaltoids of the BMA, which belong to the Ai and Mashak suites, were the sources of zircons falling in a narrow age range of 435–455 Ma [Krasnobaev et al., 2018]. On the western slope of the Middle Urals, this magmatic stage manifested itself in the syenite-porphyries of the Verkhnyaya-Serebryanka complex (447 ± 8 Ma [Petrov et al., 2005]). Similar events previously identified in the Southern Urals include the emergence of the most part of the Ilmeny-Vishnevogorsky alkaline carbonatite complex (410–446 Ma), which then underwent transformations at the Late Devonian and Permian collision boundaries with the formation of several types of pegmatites. The issue of the Kozlinogorsk gabbros, syenites and granites belonging to this complex remains unsolved. The analogues of the Ushat complex include the Monteregian group of alkaline intrusions on the Canadian Atlantic coast [Puchkov, 2010].

Timaiz dyke-sill complex belonging to the western slope of the Urals (400–360 Ma, mainly 380–360 Ma)

In an earlier work [Puchkov et al., 2016] we demonstrated that Devonian dyke swarms and associated effusive rocks – whose origin is closely related to the formation of the Devonian Kola-Dneprovsky LIP – were present in this complex from the western slope of the Urals, as well as in Pay-Khoy and Novaya Zemlya. Granitoids and rhyolites are practically absent in this complex. There is only data [Simakov, 1972] on the presence of a microgabbro-syenogranite-alaskite association in the upper the Pechora River intruding the Middle Devonian rocks and dated at 276 ± 13 and 296 ± 12 Ma (Lower Permian) using the K-Ar method; however, most likely, these ages are underestimated (otherwise there is nothing to tie them to). Their Devonian age is not ruled out. In addition, we can name only a single dyolite dyke in the Devonian Aptechnogorsk complex (Nizhniye Sergi, Middle Urals).

Stepninsky monzonite-granite complex (280–285 Ma)

The geological unit in question was named after the Permian Stepninsky monzodiorite-granite complex represented by a chain of intrusions extending from the northwest to the southeast (Uysky, Vandyshevsky, Biryukovsky, Stepninsky). The intrusions intersect three structural zones of the Southern Urals and the overlying fold structure. The complex in question was described in detail in [Fershtater, 2013]. Preliminary data on the age of massifs (281 ± 2, 281 ± 2, 280 ± 2 and 286 ± 2 Ma, respectively), which were obtained using SHRIMP-2 (VSEGEI), indicate their Early Permian age. The plume nature of the complex has been suggested for a long time, which is based on the overlying character of intrusions [Puchkov et al., 1986]. In terms of its geochemical features [Snachev et al., 2018], the range of rocks from the Stepninsky complex clearly fits into two main reference trends: monzonite (monzogabbros, monzodiorites, syenites) and calc-alkaline; which indicates that different mechanisms were involved in the formation of intermediate-basic and acid rocks. At the same time, gabbros are found within the OIB (ocean-island basalt) fields, which makes them similar to rift/plume complexes of mantle origin. The formation of acid rocks exhibiting the calc-alkaline trend can be explained by the melting of the crust rather than by subduction which ended there long ago. Initially, we assumed that granites exhibited a regular time progression; however, it was not confirmed, which is very rare for a fold area.

Triassic Ural-Siberian (250–230 Ma)

A Triassic LIP, partially including the territory of the Ural-Novaya Zemlya fold zone, covers a vast territory of Siberia; thus, this province should be called Ural-Siberian. Magmatic events which occurred at the Permian-Triassic boundary are considered to be the manifestations of a giant superplume. In the Urals and the Ural region, these include the outwellings of Triassic trappean basalts, occurring from Turgay to Pay-Khoy. In the Polar Urals and Siberia, the outwellings of trappean rocks began simultaneously at the Permian-Triassic boundary (250 Ma ago). Acid effusives, which give a contrasting character to basalt eruptions, are characterised by a highly subordinate distribution and are found in the Middle Urals, east of Kamensk-Uralsky (in the Borisovo and Pershino quarries, dated as the Early Triassic using the U-Pb method) [Puchkov, 2010 and references in this work]. It is known, that Triassic traps occur in the grabens of the West Siberian basin overlying the following Ural structures: North Sosva, Danilovo and Polovinkino [Ivanov et al., 2016]. Moreover, only the Danilovo graben is characterised by the presence of a contrasting basalt-rhyolite formation, which could be due to a more sialic composition of the basement.

In [Puchkov, 2010] we examined the data presented in the works on the Triassic datings derived from small acid intrusions, spatially isolated from Triassic volcanites (Malaya-Cheka and Kisinet complexes), as well as from the Murzin-Aduy collision granites [Popov, 2003; Tevelev et al., 2009]. These datings are quite contradictory; thus, they do not give a clear indication that the formation of these granitoids coincided with the onset of trap magmatism. Nevertheless, our attempt to confirm the Triassic age of the alkaline granitoids from the Malaya Cheka complex led to the conclusion about its Carboniferous age [Salikhov et al., 2013].

CONCLUSION

A general review of the conditions under which plume processes can lead to the formation of silicic melts, as well as the consideration of rhyolite-granite magmatism as a component of plume magmatism using a number of volcanic and intrusive complexes of the Urals as an example, suggest that, along with the spreading, subduction and collision, plume tectonics is a powerful independent factor regulating silicic magmatism on the continental and transitional crust. In some cases, it can be associated with active-type rifting, which is the consequence of deeply originating plume-related processes – not their cause. However, in many cases, no signs of grabens or their relics are observed. As for the reasons behind the formation of acid melts, it is impossible to deny the possibility of basaltic magma differentiation or its segregation; however, it seems that the main reason, remains to be the melting of the crust and, in particular, its more ancient silicic components under the influence of the initial plume-related basic magma.

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