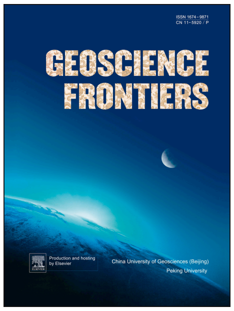


Petrology, geochemistry and source characteristics of the Burpala alkaline massif, North Baikal

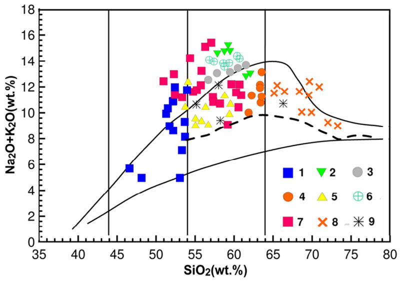
N.V. Vladykin, I.A. Sotnikova

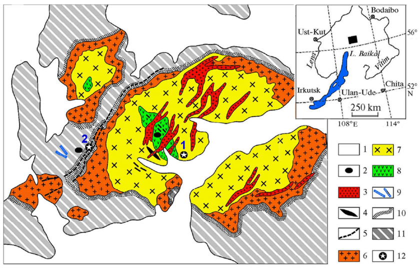
PII: S1674-9871(16)30032-9
DOI: 10.1016/j.gsf.2016.04.006
Reference: GSF 450

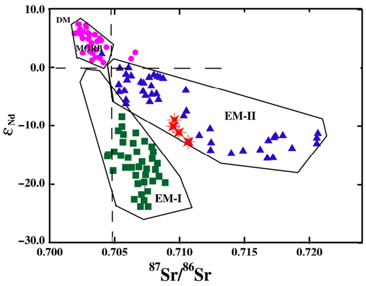
To appear in: *Geoscience Frontiers*

Received Date: 11 July 2015
Revised Date: 24 February 2016
Accepted Date: 26 April 2016

Please cite this article as: Vladykin, N.V., Sotnikova, I.A., Petrology, geochemistry and source characteristics of the Burpala alkaline massif, North Baikal, *Geoscience Frontiers* (2016), doi: 10.1016/j.gsf.2016.04.006.


Na2O+K2O(wt.%)
SiO2(wt.%)
0
2
4
6
8
10
12
14
16
18
35
40
45
50
55
60
65
70
75
80
1
2
3
4
5
6
7
8
9


Bodaibo
Ust-Kut
56°
Lena
L. Baikal
Vitim
Irkutsk
Ulan-Ude
Chita
52° N
250 km
108°E
114°
1
2
1
2
3
4
5
6
7
8
9
10
11
12


ε Nd
10.0
0.0
-10.0
-20.0
-30.0
0.700
0.705
0.710
0.715
0.720
87Sr/86Sr
DM
MORB
EM-II
EM-I

Petrology, geochemistry and source characteristics of the Burpala alkaline massif, North Baikal

N. V. Vladykin*, I. A. Sotnikova

Vinogradov Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences,
1A Favorsky Str., Irkutsk 664033, Russia.
**Corresponding author: Email: vlad@igc.irk.ru ,*

ABSTRACT

The Burpala alkaline massif contains rocks with more than 50 minerals rich in Zr, Nb, Ti, Th, Be and rare earth elements (REE). The rocks vary in composition from shonkinite, melanocratic syenite, nepheline and alkali syenites to alaskite and alkali granite and contain up to 10% LILE and HSFE, 3.6% of REE and varying amounts of other trace elements (4% Zr, 0.5% Y, 0.5% Nb, 0.5% Th and 0.1% U). Geological and geochemical data suggest that all the rocks in the Burpala massif were derived from alkaline magma enriched in rare earth elements.. The extreme products of magma fractionation are REE rich pegmatites, apatite–fluorite bearing rocks and carbonatites. The Sr and Nd isotope data suggest that the source of primary melt is enriched mantle (EM-II). We correlate the massif to mantle plume impact on the active margin of the Siberian continent.

Keywords: Syenite; Pegmatite, Rare metal and rare earths; Petrology; Geochemistry.

1. Introduction

The Burpala alkaline massif is located in the North Baikal Highland and occurs at height of about 3500 m (Fig. 1). The North Baikal alkaline province is composed of the largest Synnyr ultrapotassic alkaline massif (covering an area of over 800 km^2) and some smaller massifs of alkaline rocks (Zhidkov, 1961). Over 50 minerals rich in Zr, Nb, Ti, Th, Be, and REE have been identified in the rare-metal syenite of this massif (Sotnikova, 2009). The rocks contain up to 10% of LILE and HSFE, 3.6% of REE and varying amount of other trace elements (4% Zr, 0.5% Y, 0.5% Nb, 0.5% Th and 0.1% U) of economic grade (Vladykin, 1997; Vladykin and Miuzaki, 2001; Sotnikova, 2009, 2012). Hence the study of the Burpala massif is critical to understand the processes of formation of large rare-metal provinces with strategic mineral resources. In this paper, we integrate data on the geology, age, element and isotope geochemistry of the intrusive rocks and rare metal mineralization in the Burpala massif. We also attempt to relate this massif to the alkaline magmatism in Central Asian fold belt (Vladykin, 1997; Kovalenko et al., 2002, 2006; Yarmolyuk and Kovalenko, 2003; Yarmolyuk and Kuz'min, 2012).

2. Geological setting of the Burpala massif

The Burpala massif is a concentrically zoned intrusion covering an area about 250 km^2. It intrudes into the Vendian terrigenous rocks of the Kholodninsky Formation (Fig. 1). The temporal sequence of the main magmatic units in the massif is summarized in Table 1. Shonkinite and melanocratic syenite dikes, which cut the country rocks in the western margin of the massif, have been considered as the early intrusive phase (Fig. 1). The dikes vary in size from 1 to 5 m width and extend for about 100 m. The emplacement of alkaline magma of the main intrusive phase and its fractionation resulted in the formation of nepheline syenite, pulaskite and quartz syenite. Nepheline syenite occupies the center of the massif (Fig. 1) and the other parts are composed of pulaskite. Close to the contact with country rocks, pulaskite transforms to alkaline quartz syenite. The intrusive contact between pulaskite and quartz syenite and country rocks (sandstone and siltstone) is sharp. In the contact zone (50–100 m) the country rocks experienced intense metasomatic modification, resulting in the formation of cordierite and biotite hornfels. A series of small rare-metal pegmatite veins of 10 cm to 1 m thick and 3 to10 m long are observed in nepheline syenite.

The vein phase occupies about 30% of the massif area. The earliest dikes of fine- and medium-grained leuco- and mesocratic nepheline and alkali syenites cut across the rocks of the main phase. The dikes of eudialyte–sodalite syenite (mariupolite) (1–3 m thick and some hundred meters in extent) occur in the central massif. Similar rocks were reported from the Ukranian shield (Dumańska-Słowik et al., 2015) in West Bengal, India (Mitchell and Chakrabarty, 2012) and other main shield environments.

The rare-metal pegmatites are fine-equigranular (medium and locally coarse-grained) rocks frequently displaying banded or trachytic texture. Three areas with presumably economic dikes and veins of rare-metal pegmatites have been mapped and contoured (Figs. 1, 2). The first area is hosted by the left wall of the Left Upper Creek close to the drainage divide. The rare-metal pegmatite veins found in nepheline syenite contain pegmatoid segregations enriched in rare-element minerals. This poorly studied zone extends to the northern contact of the massif, where larger bodies are noticed. The second britholite-bearing area is located at the right wall of the Right Upper Creek (Fig. 2) enclosing several bodies of rare-metal pegmatites with britholite. The largest body, up to 20 m in thick, is extended up to 50 m. The third area occurs at the western contact of the massif (Fig. 1). Two ore zones extend for 10 km in the area (Fig. 2), where numerous near-vertical rare-metal pegmatite veins containing about 30% rare-element minerals have been documented in the trenches. The thickness of pegmatite bodies varies from 1 to 10 m in the upper parts of slopes and up to 15–10 m in the lower parts within the vertical range of 250–300 m. Separate veins of rare-metal syenite possibly merge into a single large body at deeper levels.

In some cases, fenite zones with rare-metal mineralization (5–10 m thick) are formed at the contact of rare-metal pegmatites with siltstone of the Kholodninsky Formation.

A large dike of medium to coarse-grained apatite–fluorite rock of 10–20 m thick and up to 300 m length occurs in the vein phase of the Burpala massif. This dike cuts pulaskite of the main phase and, in turn, is crosscut by the alaskite vein. The dike contacts with country rocks look sharp.

Alaskite (leucogranite) and alkali granite occur as numerous dikes of 1 to 100 m thick and 200 m to few kilometers in extent.

Two small dikes of carbonate–silicate rocks, geochemically resembling carbonatite, have been discovered in the central and contact zones of the Burpala massif (Vladykin, 1997). One of them, 20–30 cm thick, crosscuts the nepheline syenite and extends for 50 m.

3. Analytical methods

Representative rock samples collected from the Burpala massive were ground and fused with $LiBO_2$. Over 70 samples were analyzed for major oxides using the SRM-25 multichannel XRF spectrometer (Nauchpribor, Orel, Russia). The XRF spectroscopy was performed with calibration of international standards ST-2 (alkaline nepheline syenite) and J-2 (basalt, Japan). Fe_2O_3 and FeO were separated by titration.

Trace elements were measured by ICP-MS spectroscopy under the standard conditions with Thermo Finnigan Element 2 single-collector at low (LR)-300, medium (MR)-4000, and high (HR)-10000 $M/\Delta M$ resolution. The measurement results and instrumental drift were checked against international standards BHVO-1, STM-1 at every 5–6 samples. The glasses obtained by fusion with $LiBO_2$ were dissolved in ultrapure HNO_3 to prepare sample solutions. TOTALQUANT software was used to process data, and certified multi-element solutions were employed for constructing calibration graphs. Water for solutions was purified using Millipore-ELIX-3 device in Irkutsk. An internal Rh standard was applied to correct the signal drift. The element isotopes were selected with regard to possible interferences with isobaric and molecular ions. Interference corrections were routinely applied to correct analyses of ^{151}Eu isotopes (from

BaO, BaOH) and ^{159}Tb (from NdO, NdOH). The oxide production ratio was <3%. The uncertainties are estimated to be better than 2–10%.

4. Results

4.1 Mineralogic and petrographic features of major intrusive phases

The dikes of melanocratic syenites and shonkinites of the first magmatic stage are composed of K-feldspar (80–60%) and dark-color minerals (20–40%) represented by augite, biotite, and garnet. Minor amounts of magmatic calcite were found in the interstices between K-feldspar grains of shonkinite.

Nepheline syenite is medium-grained and composed of microcline-perthite (60–70%) and nepheline (10–25%). The dark-color minerals (5–10%) are augite and biotite; titanite, zircon, apatite, and magnetite are accessory minerals. Pulaskite has medium-grained structure and shows pronounced trachytic texture caused by the planar orientation of microcline perthite crystals, which occupy 80–85% of the rock volume; nepheline occupies 5–8%; alkaline amphibole (hastingsite) and aegirine-augite are the main dark-color minerals. Astrophyllite is a rare mineral; titanite, zircon, apatite, and magnetite are accessory minerals.

Quartz syenite consists of microcline-perthite (70–80%), quartz (5–10%) and dark-color minerals (5–15%): amphibole (edenite–hastingsite), aegirine diopside, and biotite; titanite, zircon, apatite, and magnetite are accessory minerals.

Syenite dikes are composed of microcline-perthite (60–80%), nepheline (5–10%), alkali amphibole (cataphorite) and aegirine-augite (10–20%). Magmatic calcite is occasionally observed in small amounts. Eudialyte–sodalite syenite veins are composed of perthitic K–Na feldspar (70–90%), sodalite (5–15%), eudialyte (1–10%), arfvedsonite, and aegirine (5–10%). Nepheline is identified in some varieties of eudialyte-sodalite syenite, which was termed as “mariupolite” by Andreev (1981), although they do not contain albite—the major mineral of true mariupolite (Mitchell and Chakrabarty, 2012). In rare-metal pegmatites microcline, albite, aegirine, arfvedsonite, and nepheline are the major minerals, as well as numerous rare element minerals and are discussed in the next section.

Apatite–fluorite dike is composed primarily of apatite (10–30%) and fluorite (20–70%). In the near contact zones of this dike, magnetite (1–10%), biotite (3–15%), diopside augite (2–10%), and nepheline (1–5%) occur. Hambergite and needle-shaped X-ray amorphous zirconium silicate occur as accessory minerals in the apatite–fluorite rock.

The apatite–fluorite dike incorporates calcite (70–90%), microcline (25–10%), and Sr-zeolite brewsterite (1–3%). The second dike, 20 cm thick and 3 m long, is composed of calcite

(75%), quartz (20%) and pyrite (5%); this dike cuts terrigenous rocks of the Kholodninsky Formation.

Alaskite is largely composed of quartz (20–30%), microcline perthite (~70%) and augite (1–5%). Alkali granite consists of quartz (up to 30%), latticed microcline, alkali cataphorite (1–5%) and aegirine (1–5%). Pegmatoid schlierens with rare-metal mineralization (elpidite, Pb-betafite, bafertisite, thorite, strophyllite, neptunite, cryolite) has been found in alkali granite dike (Efimov and Ganzeev, 1972). This mineralization significantly differs from that in rare-metal pegmatites. Similar associations were determined in pegmatites from Strange Lake Canada (Gysi and Williams-Jones, 2013)

4.2 Mineralogy of rare- metal pegmatites

Rare-metal pegmatites in nepheline syenites are composed of microcline, albite, arfvedsonite, aegirine, apatite and fluorite. The rare-element minerals are represented by zircon, astrophyllite, titanite, ilmenite, Sr-perrierite, eudialyte, and levenite (Figs. 3, 4). The rare-metal (britholite) pegmatites from the second group contain segregations consisting of coarse-grained microcline, fine britholite disseminations, and monomineralic britholite aggregates reaching 1.1 m in size.

Fluorite vein with arfvedsonite and aegirine, as well as 10% REE minerals (fluocerite and metamictic REE–Ti silicate) occurs in this area.

The rare-metal syenites in the western area frequently display trachytoid and banded texture caused by non-uniform distribution of arfvedsonite and aegirine. The trachytic texture is conformable to banding. The concentration of rare element minerals reaches 30%. They occur in both melano- and leucocratic segments of the veins. Diverse mineral species are represented by zircon silicates (zircon, eudialyte, levenite, Ti-levenite, wohlerite, burpalite, seidozerite, Ca-seidozerite, osenbuschite, vlasovite, catapleiite, Ca-catapleiite); Ti minerals (titanite, astrophyllite, amsayite, loparite, metaloparite, rinkolite, Mn-neptunite, bafertesite, chevkinite, Mn-ilmenite, pyrophanite, Srperrierite, landauite, rutile, anatase, brookite); REE minerals (loparite, metaloparite, rinkolite, melanocerite, bastnaesite, parasite, fluocerite, ankilite, onazite, TR-apatite); and other rare minerals (hambergite, eudidymite, pyrochlore, thorite, taeniolite, etc.). Melanocerite, rinkoliote, and zircon are present in fenite related to the rare-metal pegmatites. Zircon silicates from rare-metal pegmatites were formed in the following sequence: zircon → levenite type zirconosilicate → eudialyte (Figs. 3, 4; Supplementary File 4).

4.3 Geochemistry of major rock types in the Burpala massif

The chemical compositions of igneous rocks in the Burpala massif are presented in Supplementary Tables 1, 2 and Fig. 5. In the TAS classification diagram the data points of igneous rocks from the Burpala massif show a continuous series from shonkinite and melanocratic syenite of the early phase to alaskite and alkali granite of the final phase.

The light rare-earth elements (LREE) and high field strength elements (HFSE), such as niobium and zirconium concentrations show good correlation (Fig. 6). However, some of the deviations show that fractionation was also accompanied by precipitation of mineral concentrators of HFSE. The branched nature of the $(La/Yb)_n$ –$(La/Sm)_n$ diagram indicate that the source magmas have undergone LREE fractionation (Fig. 6). In addition, variations on the La–Eu diagram point to the difference in plagioclase precipitation for different rock groups. $(La/Yb)_n$–$(La/Sm)_n$ variations also suggest that fractionation was controlled both by feldspars and minerals with REE partition coefficient similar to garnets. The major variations of REE and HFSE components found for pegmatites may be determined by the abundance of some rare minerals concentrating REE and other trace elements like apatite and monazite. The average total REE content in rocks from the Burpala massif is higher than the global mean value for syenite (Supplementary Table 2). The REE content in melanocratic syenite of the early phase reaches 3000–4000 ppm, whereas in syenite of the main phase, and in nepheline and eudialyte–sodalite syenites of the vein phase, the REE content is 450–500 ppm.

The rare-metal pegmatites related to the vein phase of the Burpala massif are subdivided into six groups depending on the REE pattern and mineral assemblages (Fig. 7). The first group is characterized by weakly fractionated LREE and almost unfractionated HREE patterns combined with poorly expressed negative Eu anomaly (Fig. 7a, c). This group comprises three varieties of rare-metal pegmatites, where eudyalite, minerals of the levenite–seidozerite group, and catapleiite are the major REE enriched minerals. All these varieties of rare-metal pegmatites are peralkaline rocks with an agpaitic index >1, which contain zirconium silicates, rather than zircon. Astrophyllite is the major REE concentrator in rare-metal pegmatites of the second group. In addition, loparite and zircon silicates vary in amounts. Pegmatites of this group have a sinusoidal REE pattern (Fig. 7b) with fractionated LREE and negative Eu and positive Ho anomalies. The third group of rare-metal pegmatites is distinguished by an assemblage consisting of manganil menite, loparite, and zircon silicates with prevalence of the former minerals. The REE pattern is not fractionated and is devoid of Eu anomaly (Fig. 7c). In the fourth group of rare-metal leucocratic nepheline-bearing pegmatites, the major REE concentrators are loparite and zircon silicates. As shown in Fig. 7, LREEs are fractionated; the negative Eu anomaly is obvious, and HREEs are poorly fractionated. The fifth group is made up of relatively melanocratic aegirine–arfvedsonite rare-metal pegmatites with loparite, ilmenite, and occasional pyrochlore as concentrators of minor elements. The REE pattern is generally similar to that of the fourth group (Fig. 7e). The rare-metal pegmatites of the sixth group are leucocratic rocks composed primarily of albite. Rare element minerals are insignificant in amount. In contrast to the other varieties of rare-metal syenites, the rare-metal pegmatites of this group have a weakly fractionated REE pattern and positive Eu anomaly (Fig. 7).

In rare-metal syenite of the vein phase, as well as in and quartz syenite of the main phase, the total REE content varies widely. All these rocks are characterized by elevated Ba and Sr contents and negative Nd and Ta anomalies. In contrast to shonkinite of the early phase and syenite of the main phase, negative Nb and Ta anomalies in eudialyte–sodalite syenite of the vein phase are expressed less distinctly; in addition, positive Zr and Hf anomalies appear (Fig. 5). Despite the significant difference in ore-bearing mineral assemblages, various rare-metal syenites of the vein phase show similar distribution of minor elements with sharp negative Ba, Nb, Ta, Sr and positive Th, U, Zr, Hf anomalies (Fig. 5).

5 Thermobarometry

Saline inclusions with homogenization temperature above 560°C have been recorded from fluorite in apatite–fluorite rocks (Fig. 8), and inclusions of crystallized melt with homogenization temperature higher than 800°C have been reported in fluorite (Sotnikova et al., 2011). Investigations of fluid inclusions in fluorite shows predominance of Na, Ca and sometimes Mg chlorides in the brines trapped within these inclusions. These rocks are analogs of phoscorites from carbonatite massifs, where fluorite crystallized instead of calcite (Fig. 9). The major and trace element compositions of fluid inclusions were analyzed by ICP-MS (Fig. 3).

The brines of inclusions are dominated by Na and Ca chlorides, and occasionally Mg. The composition is also confirmed by chloride eutectics of inclusion fluids in the interval –53 to –56°C and also by the occurrence of daughter halite identified by its transition into hydrohalite upon freezing (a reverse transition is possible at 0.0–0.5°C). Anisotropic phases are the first to dissolve at 40–80°C. Isotropic chloride crystals dissolve at 460–480°C, which corresponds to salt concentrations 55–57 wt.%, equivalent to NaCl. Brine inclusions are homogenized completely at 520–560°C. The composition of fluids from inclusions is given in Supplementary Table 3 and Fig. 8 containing data on gases, anions, cations, and microelements. The predominant anions are hydrocarbonates and chlorides, and there are also high concentrations of sulfate ions. All these compounds can form solid phases. The predominant cations are sodium and calcium. Judging from analytical data, solid phases include halite, sodium hydrocarbonate, and calcium sulfate.

Microelements are dominated by strontium, barium, boron, iron, manganese, lithium, rubidium, and cesium, i.e. components characteristic of magmatic fluids.

6. Discussion

6.1. Models of origin

Early studies in the 1950s on Burpala massif considered all rare-metal silicate rocks, including rare-metal alkali and Li–F granites, as well as carbonatites to be metasomatic in origin. Therefore, formation of this massif and related rare-metal mineralization was interpreted according to this concept (Zhidkov, 1956; Arkhangel’skaya, 1967; Mineralogiya, 1974; Andreev, 1981). However, subsequent studies challenged the metasomatic origin of alkaline rocks of the Burpala massif by Portnov (1966) and Portnov and Nechaeva (1967), and the concept of magmatic origin has been developed Vladykin, (2005, 2007) and Vladykin and Miuzaki, (2002). It was shown that the rare-metal pegmatites originated from fractionation of a melt, which resulted in the formation of nepheline syenite, pulaskite, and quartz syenite of the early intrusive phase.

The geochemical data also indicate that all varieties of rocks in the Burpala massif are products of alkaline magma fractionation, and that this magma was initially enriched in rare elements. The massif is composed of shonkinite and melanocratic syenite, nepheline and alkali syenites, alaskite and alkali granite. Rare-metal pegmatites, apatite–fluorite rock, and carbonatites are the final products of magmatic differentiation. Based on the available data, we conclude that the apatite–fluorite rocks in the Burpala pluton share genetic nature with foskorites of carbonatite complexes. However, the apatite–fluorite rocks contain fluorite instead of calcite due to the high activity of fluorine in the ore–forming carbonate–chloride fluid.

The shonkinite and melano-syenite enriched in minor elements are correlated to the early phase, and their composition corresponds to that of the primary melt of the massif. The geochemical features of eudialyte–sodalite syenite of the vein phase show transitional phase between rocks of the early and main phases (Fig. 5), whereas the rare-metal syenite (Fig. 5) is distinct. This suggests that peralkaline vein rocks of the Burpala massif are the products of crystallization of residual derivatives of primary magma corresponding to the main phase.

The evolution of primary magma may be essentially controlled by volatiles. It has been shown that hydrous fluids can trigger the mobilization of REE and Zr (Thomas and Davidson, 2012; Gysi and Williams-Jones, 2013). However, abundant F in volatiles might result in immiscibility (Hulsbosch et al., 2016) and formation of apatite – fluorite dike. The carbonatites could also be the result of the liquid immiscibility forming separate phases and their own metallogenic specialization (Pirajno, 2015).

Among igneous rocks of the Burpala massif, the rare-metal pegmatites of the vein phase are the most potential source of REE, Zr, Y, and Nb. These types of rocks related to alkaline magmatism (Smith et al., 2016) are the major source of Zr, U, Th and other lithophile components. Similar type of plume-related deposits is common in the Kola Peninsula in the Khibin massif (Kogarko, et al., 2012). However the ore of the Burpala massif is more complex and variable.

6.2. Isotope and trace element geochemistry

The Rb–Sr and Sm–Nd isotopic compositions of rare-metal pegmatites and carbonatites from the Burpala massif (Fig. 10) lie in the field of the enriched mantle source (EM-II) characteristic of major fold belts (Vladykin, 2005). This trend could result from the mixing of crustal components, although it is difficult to establish a petrogenetic model due to limited data. However, plots in the in Sr–Nd diagram are close to the mixing lines between mantle plume magma and lower crust (Wang et al., 2015).

The rare-metal mineralization in the Burpala massif is primarily linked with rare-metal pegmatites with anomalously high REE, Zr, Y and Nb contents, which allow us to regard this massif as promising for mining REE minerals. The evidence presented in this study significantly contributes to understanding the rare-metal magmatism in the geological history of the fold framework of the Siberian Platform. Our data not only point out the early Permian impulse of alkaline magmatism, but also provide insights on its tectonic setting. In addition to the Burpala massif, the coeval ultrapotassic syenite (295 Ma) and Yaksha massifs formed in the northern Baikal region are also potential zones (Pokrovsky and Zhidkov, 1993; Pokrovsky, 2000). This makes it possible to extrapolate the conclusion onto the early Permian alkaline magmatism over the entire North Baikal zone, including the rare-metal (Ta, Nb, Zr, Y, REE) Akit massif located in this zone.

7. Conclusions

(1) The Burpala alkaline massif hosts over 50 minerals rich in rare metals and rare-earth elements.

(2) The formation of the massif is correlate to mantle plume event and forms part of the regional alkaline magmatic province of North Baikal.

(3) The major and trace element data for the different rocks types in the Burpala massif establish their common parentage.

(4) The fluid inclusions from fluorite-bearing agpaitic rocks indicate high temperatures of crystallization ranging from 500 to 800°C.

(5) The Sr and Nd isotope data suggest that the primary magmas were generated from the enriched mantle (EM- II) source.

Acknowledgements

This study was supported by the Russian Foundation for Basic Research (Project No. 144504057-r-Siberia). We are grateful to I. Safonova and I. Ashchepkov for their inputs to improve the manuscript.

References

Andreev, G.V., 1981. Petrology of Potassic, Nepheline, and Alkali Syenites. Novosibirsk, Nauka 185 p. (in Russian)

Arkhangel’skaya, V.V. 1967. Duration of formation of some alkaline massifs in the Baikal mountain region. Doklady Akademii Nauk SSSR. 605–607.

Chakhmouradian, A.R., Mumin, A.H., Demény, A., Elliott, B., 2008. Postorogenic carbonatites at Eden Lake, Trans-Hudson Orogen (northern Manitoba, Canada): geological setting, mineralogy and geochemistry. Lithos 103, 503-526.

Doroshkevich, A.G., Ripp, G.S., Sergeev, S.A., and Konopel’ko, D.L. 2012a, U–Pb (SRIMP-II) geochronology of the Mukhal alkaline massif, western. Transbaikal region. Russian Geology and Geophysics.. 53, 169–174.

Doroshkevich, A.G., Ripp, G.S., Izbrodin, I.A., and Savatenkov, V.M. 2012b. Alkaline magmatism of the Vitim province, West Transbaikalia, Russia: Age, mineralogical, geochemical, and isotope (O, C, D, Sr, Nd) data. Lithos. 157–172.

Dumańska-Słowik M., Wesełucha-Birczyńska A., Pieczka ,A. 2015. Micas from mariupolite of the Oktiabrski massif (SE Ukraine): An insight into the host rock evolution – Geochemical data supported by Raman microspectroscopy. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 137, 817-826.

Ernst, R.E. 2014. Large igneous provinces. Cambridge University Press.

Grechishchev, O.K., Zhmodik, S.M., and Shcherbov, B.L. 2010. Redkometal’noe mestorozhdenie Ulug-Tanzek (The Ulug-Tanzek Rare-Metal Deposit). Novosibirsk: GEO, (in Russian)

Gysi, A.P., Williams-Jones, A. E. 2013. Hydrothermal mobilization of pegmatite-hosted REE and Zr at Strange Lake, Canada: A reaction path model. Geochimica et Cosmochimica Acta, 122, 324-352

Hulsbosch, N., Boiron, M.-C., Dewaele, S., Muchez, P. 2016. Fluid fractionation of tungsten during granite–pegmatite differentiation and the metal source of peribatholitic W quartz veins:

Evidence from the Karagwe-Ankole Belt (Rwanda). Geochimica et Cosmochimica Acta, 175, 299-318

Kogarko, L.N., Lahaye, Y., Brey, G.P. 2010. Plume-related mantle source of super-large rare metal deposits from the Lovozero and Khibina massifs on the Kola Peninsula, Eastern part of Baltic Shield: Sr, Nd and Hf isotope systematics. Mineralogy and Petrology, 98, 197–208

Kotov, A.B., Vladykin, N.V, Yarmolyuk, V.V, Sal'nikova, E.B., Sotnikova, I.A., Yakovleva, S.Z. 2013, Permian age of the Burpala alkaline pluton, northern Transbaikalia: Geodynamic implications. Doklady Earth Sciences. 453, 1082–1085.

Kovalenko, V.I., Yarmolyuk, V.V., Vladykin, N.V., et al., 2002 Epochs of formation, geodynamic setting, and sources of rare metal magmatism in Central Asia. Petrology. 10, 199–221.

Kovalenko, V.I., Yarmolyuk, V.V., Andreeva, I.A., et al., 2006. Rare-Metal Magmatism: Rock Associations, Magma Composition and Sources, Geodynamic Settings), Moscow: IGEM RAN. (in Russian)

Litvinovsky, B.A., Zanvilevich, A.N., Alakshin, A.M., and Podladchikov, Yu.Yu., 1992. Angara–Vitim Batholith—the Largest Granitod Pluton. Novosibirsk, Nauka, 254 p. (in Russian).

Litvinovsky, B.A., Jahn, B.M., Zanvilevich, A.N., Saunders, A., et al., 2002 Petrogenesis of syenite-granite suite from Bryansky Complex (Transbaikalia, Russia): Implicationsfor the origin of A-type granitoid magmas, Russian Geology and Geophysics. 189, 105–133.

Mineralogy of Alkaline Massifs and Related Deposits), Ed.: Semenov., Moscow. Nauka, 1974. 178 p (in Russian).

McDonough, W.F., Sun S.S., 1995. The Composition of the Earth. Chemical Geology 120, 223-253.

Mitchell, R.H., Chakrabarty, A.S. 2012. Paragenesis and decomposition assemblage of a Mn-rich eudialyte from the Sushina peralkaline nepheline syenite gneiss, Paschim Banga, Lithos 152, 218-226.

Pirajno, F. 2015. Intracontinental anorogenic alkaline magmatism and carbonatites, associated mineral systems and the mantle plume connection. Gondwana Research, 27, 1181-1216.

Pokrovsky, B.G., Zhidkov, A.Ya. 1993. Source of matter for ultrapotassic alkaline rocks of the Synnyr and South Sakun massifs in Transbaikalia from isotopic data. Petrology. 1, 195–204.

Pokrovsky, B.G. 2000. Crustal Contamination of Mantle-Derived Magmas from Isotope Geochemistry. Moscow, Nauka. (in Russian)

Portnov, A.M. 1966., Mineralogy of alkaline pegmatites in the Burpala massif. PhD Dissertation, Moscow, (in Russian) 154 p.

Portnov, A.M. and Nechaeva, E.A. 1967 Nephelinization in contact zones of the Burpala alkaline massif, Izvestia Akademii Nauk SSSR, Ser. Geol. 5, 71–75.

Ripp, G.S, Vladykin, N.V., Doroshkevich, A.G., and Sotnikova, I.A. 2006, The Akit massif of alkaline rocks and related mineralization (North Baikal region), in: Deep Magmatism, Its Sources and Plumes), Irkutsk: Institute of Geochemistry, SB RAS, 2, 285–304.

Smith, M.P., Moore, K., Kavecsánszki, D., Finch, A.A., Kynicky, J., Wall, F. 2016. From mantle to critical zone: A review of large and giant sized deposits of the rare earth elements. Geoscience Frontiers, doi:10.1016/j.gsf.2015.12.006

Sotnikova, I.A., 2009 Mineralogy and geochemistry of rare-metal alkaline rocks in the North Baikal region, Phd Dissertation, Irkutsk: Institute of Geochemistry, SB, RAS. (in Russian)

Sotnikova, I.A., Prokof’ev, V.Yu., and Vladykin, N.V. 2011. Genesis of apatite–fluorite rock in the Burpala pluton, Doklady Earth Sciences. 441, 1703–1705.

Sotnikova, I.A. and Vladykin, N.V. 2012 Geology and petrochemistry of deep ultarare-metal Burpala alkaline massif, in Glubinnyi magmatizm, ego istochniki i plyumy (Deep Magmatism, Its Sources and Plumes). Irkutsk: Institute of Geochemistry SB RAS, pp. 256–266.

Sugorakova, A.M., Yarmolyuk, V.V., Lebedev, V.I., Lykhin, D.A. 2011 Late Paleozoic alkali granitic magmatism of Tuva and its relation to intraplate activity within the Siberian paleocontinent. Doklady Earth Sciences. 439, 1070–1075.

Thomas, R., Davidson, P. 2012. Water in granite and pegmatite-forming melts. Ore Geology Reviews, 46, 32-46.

Tsygankov, A.A., Matukov, D.I., Berezhnaya, N.G., et al., 2007 Magma sources and stages of emplacement of Late Paleozoic granitoids in western Transbaikalia. Russian Geology and Geophysics., 48, 156–180.

Vasyukova, O, Williams-Jones A.E. 2015. Fluoride–silicate melt immiscibility and its role in REE ore formation: Evidence from the Strange Lake rare metal deposit, Québec-Labrador, Canada. Geochimica et Cosmochimica Acta. 139, 110–130.

Vladykin, N.V. 1997. Petrology and ore potential of potassic alkaline rocks in Mongolia–Okhotsk magmatic area, Doctoral Dissertation, Irkutsk: Institute of Geochemistry, Siberian Branch, RAS, 467 p.

Vladykin, N.V., Miuzaki, T. 2001. Burpala—unique massif of alkaline rocks, in: Alkaline Magmatism of the Earth. Proceedings of Scientific School, Moscow. Institute of Geochemistry RAN, 73–75. (in Russian)

Vladykin, N.V., Miuzaki, T. 2002. Geology, Geochemistry, and Geophysics at Turn of the 20th–21st Centuries. Proceedings of RFBR Conference, Irkutsk: Inst. Earth’s Crust, Siberian Branch, RAS, 193–195.

Vladykin, N.V. 2005. Geochemistry of Sr and Nd isotopes in alkaline and carbonatite complexes of Siberia and Mongolia and some geodynamic implications. in: Sources of Deep-seated Magmatism and Plumes, Irkutsk: Inst. Geochem., Siberian Branch, RAS,. 13–30.

Wang, H.-Z., Chen, P.-R., Sun, L.-Q., Ling, H.-F. Zhao, Y.-D., Lan, H.-F. 2015. Magma mixing and crust–mantle interaction in Southeast China during the Early Cretaceous: Evidence from the Furongshan granite porphyry and mafic microgranular enclaves. Journal of Asian Earth Sciences 111, 72-87

Wang, Y., Santosh, M., Luo, Z., Hao J. 2015. Large igneous provinces linked to supercontinent assembly . Journal of Geodynamics. 85, 1-10

Yarmolyuk, V.V., Litvinovsky, B.A., Kovalenko, V.I., et al. 2001. Formation stages and sources of the peralkaline granitoid magmatism of the northern Mongolia–Transbaikalia Rift Belt during the Permian and Triassic, Petrology. 9, 302–328.

Yarmolyuk, V.V. and Kovalenko, V.I., 2003. Deep geodynamics and mantle plumes: Their role in the formation of the Central Asian Fold belt. Petrology. 11, 504–531.

Yarmolyuk, V.V., Nikiforov, A.V., Sal’nikova, E.B., et al. 2010 Rare-metal granitoids of the Ulug-Tanzek deposit (eastern Tyva): Age and tectonic setting. Doklady Earth Sciences. 430, 95–100.

Yarmolyuk, V.V., Lykhin, D.A., Shuriga, T.N., et al. 2011. Age, composition of rocks, and geological setting of the Snezhnoe beryllium deposit: Substantiation of the Late Paleozoic East Sayan rare-metal zone, Russia. Geology of Ore Deposits. 53, 390–400.

Yarmolyuk, V.V. and Kuz’min, M.I. 2012. Late Paleozoic and Early Mesozoic rare-metal magmatism of Central Asia: Stages, provinces, and formation settings. Geology of Ore Deposits. 54, 313–333.

Zhidkov, A.Ya., Burtpala and Synnyr alkaline intrusions in northern Baikal region, Phd Dissertation, Leningrad, 1956. (in Russian)

Zhidkov, A.Ya. 1961. A new North Baikal alkaline province and some features of nepheline occurrence in their rocks, Doklady Akademii Nauk SSSR. 140, 181–184.

Figure captions

Figure 1. Schematic geological map of Burpala massif. (1) Quaternary sediments, (2) carbonatite, (3) alaskite and alkali granite, (4) apatite–fluorite rock, (5) rare-metal pegmatite, (6) quartz syenite, (7) pulaskite, (8) nepheline syenite, (9) shonkinite and melanocratic syenite, (10) hornfels, (11) Upper Vendian sandstone and siltstone of Kholodninsky Formation, (12) location of samples for U–Pb geochronological study: 1, sample Bur 30510 and 2, sample Bur 31310.

Figure 2. Schematic geological map of the western area. (1) Sandstone and siltstone of the Kholdninsky Formation; (2) horhfels; (3) pulaskite; (4) quartz syenite; (5) zone of rare-metal pegmatite veins: (a) mapped and (b) inferred; (6) apatite–fluorite ore; (7) shonkinite and melanocratic syenite.

Figure 3 Levenite at the contact of zircon–eudialyte. Fsp, microcline; Arf, arfvedsonite; Zr, zircon; Eud, eudialyte; Lov, lovenite; Ne, nepheline. Magn. ×20.

Figure 4. **P**hotomicrographs of A-A'(left: lovenite + albite + arfvedsonite; right: catapleite (red) + albite), B-B' (left: loparite twins; right: zircon poikilocrystals), C-C'(Burpalite twins), D-D' (Melanocerite tetrahedrons).

Figure 5. Chemical composition of igneous rocks from Burpala massif plotted on TAS classification diagram. (1) Shonkinite and melanocratic syenite, (2) nepheline syenite, (3) pulaskite, (4) quartz syenite, (5) nepheline and alkali syenites (veins), (6) eudyalite-sodalite syenite (veins), (7) rare-metal pegmatite (veins), (8) alaskite and alkali granite (veins), (9) fenite.

Figure 6. Correlations between the rare earth elements and other trace elements normalized to primitive mantle (after McDonough and Sun, 1995). (1) syenite of main phase and shonkinite; (2) eudialyte–sodalite syenite (mariupolite); (3) pegmatite; (4) Fenite; (5) apatite–fluorite ore; (6) carbonatite.

Figure 7. Trace element distribution and primitive mantle-normalized REE pattern of rare-metal pegmatites from Burpala massif. Rare-metal in igneous rocks from Burpala massif: (a) syenite of main phase and shonkinite; (b) eudialyte–sodalite syenite (mariupolite); (c) pegmatite; (d) fenite; (e) apatite–fluorite ore; (f) carbonatite. Normalization to primitive mantle only after McDonough and Sun (1991).

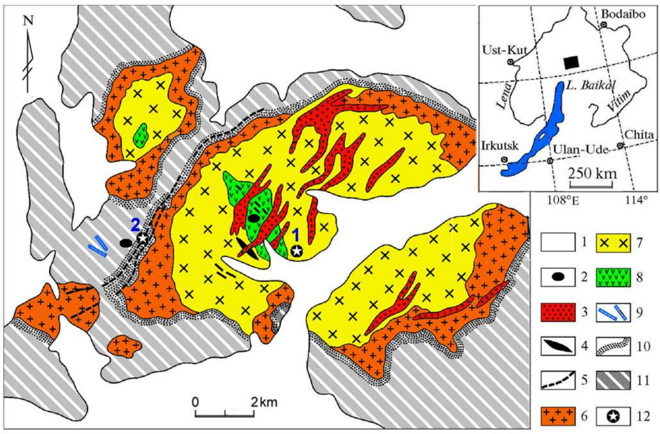
Figure 8. Multiphase fluid inclusions of chloride brines in fluorite of Burpala massif. a, c, e, f–parallel nicols; b, d–crossed nicols. Scale: 50 μm.

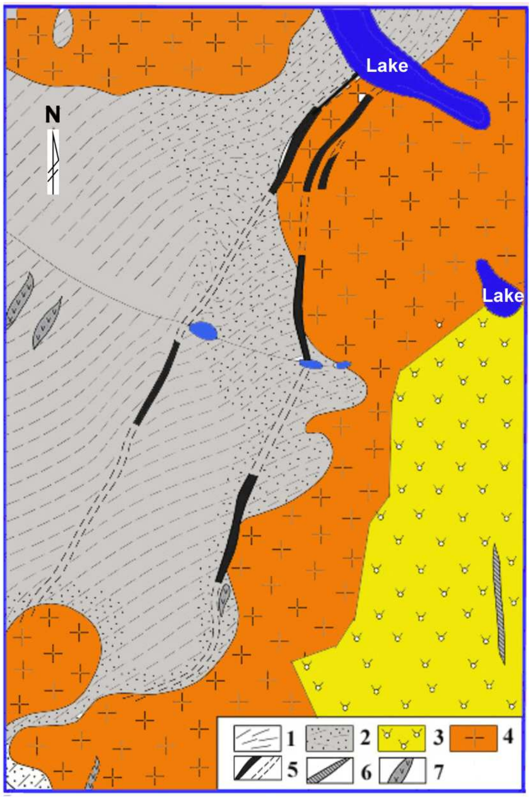
Figure 9. Concentrations of different components in fluid inclusions in fluorite of Burpala deposit. There are four groups: gases, anions, cations and trace elements.

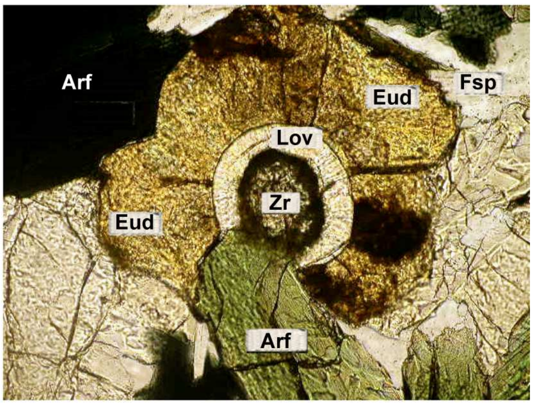
Figure 10. Sr–Nd isotopic systematics of alkaline rocks from Burpala massif (after Vladykin, 2005).

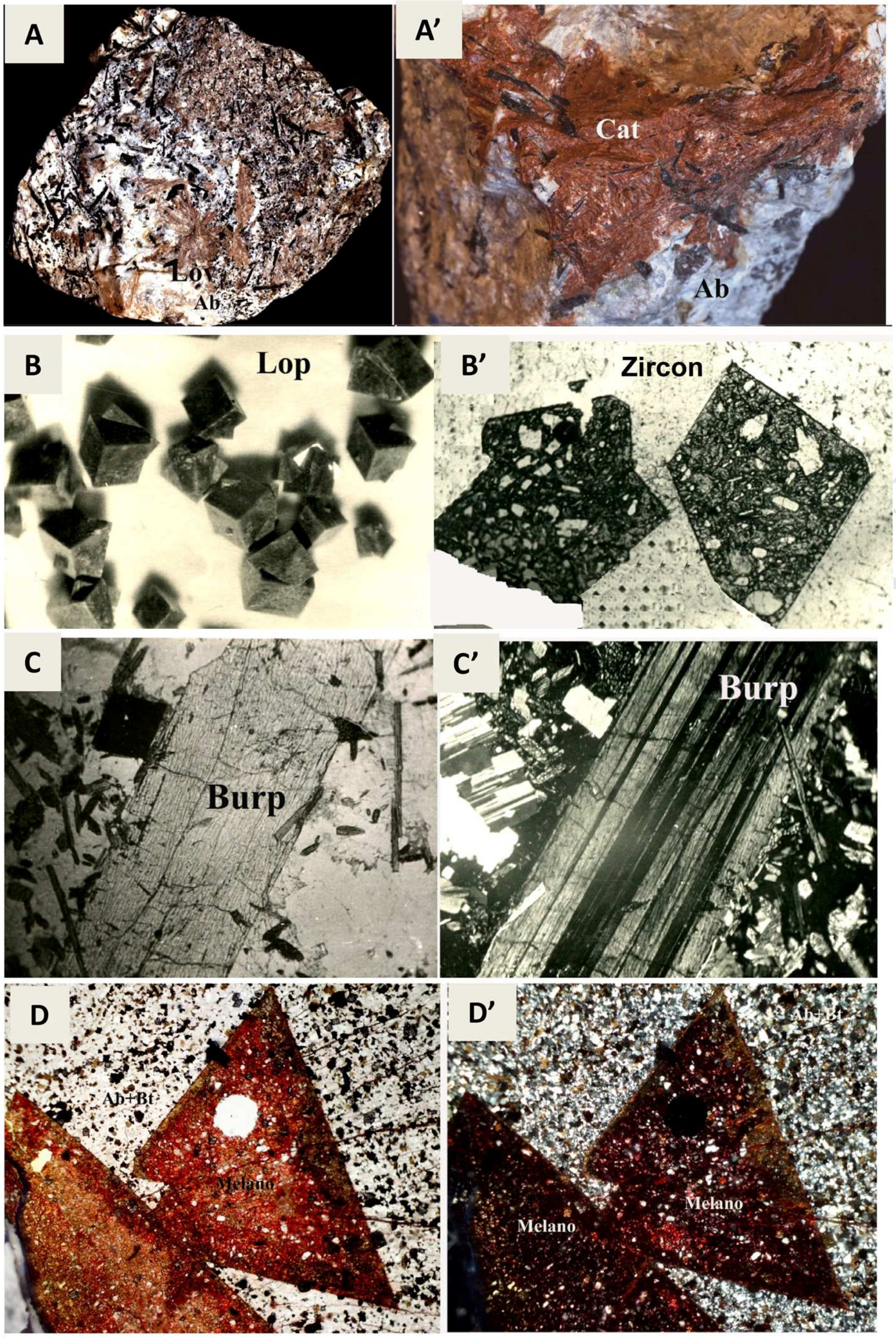
Vein phase	**Carbonatite** ↑ **Alaskite and alkali granite** ↑ **Apatite–fluorite rock** ↑ **Rare-metal pegmatite** ↑ **Eudyalite–sodalite syenite** ↑ **Nepheline and alkali syenites**
Main phase	**Quartz syenite** ↑ **Pulaskite** ↑ **Nepheline syenite**
Early phase	**Shonkinite and melanocratic syenite**

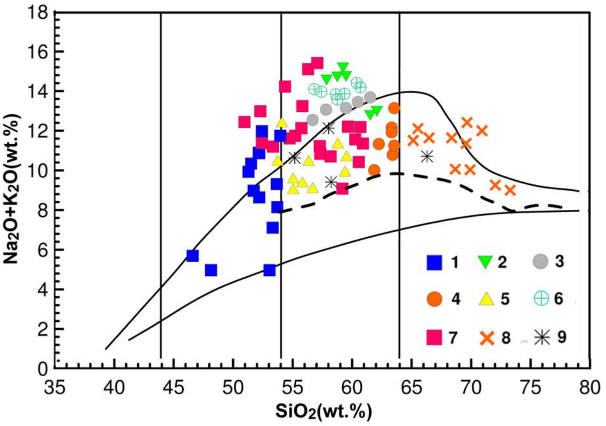
Table 1 Temporal sequence of igneous rocks from Burpala massif (Vladykin, 1997; Sotnikova, 2009).

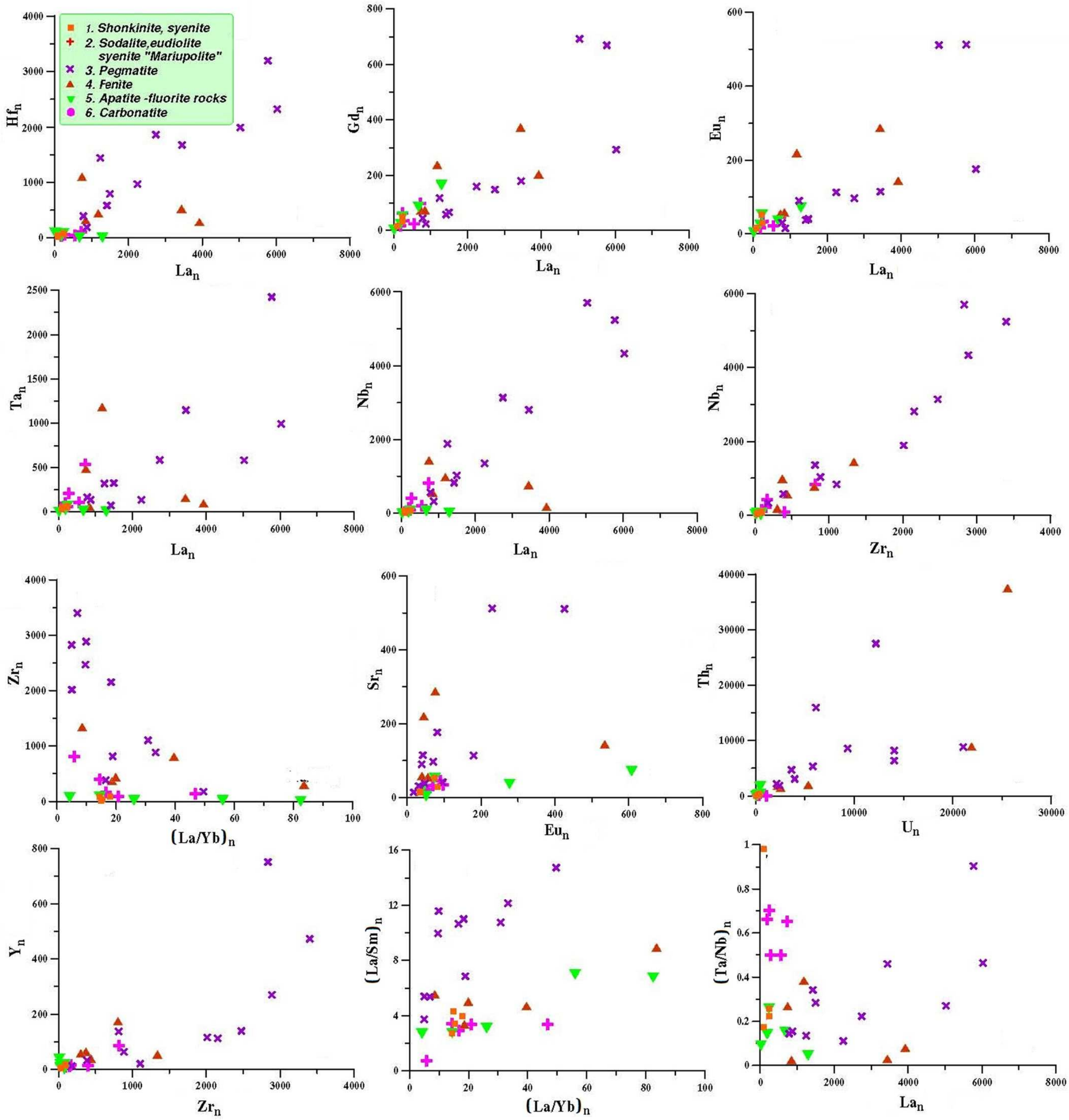

N
Bodaibo
Ust-Kut
56°
L. Baikal
Lena
Vitim
Chita
52°
N
Irkutsk
Ulan-Ude
250 km
108°E
114°
1
2
0
2km
1
2
3
4
5
6
7
8
9
10
11
12

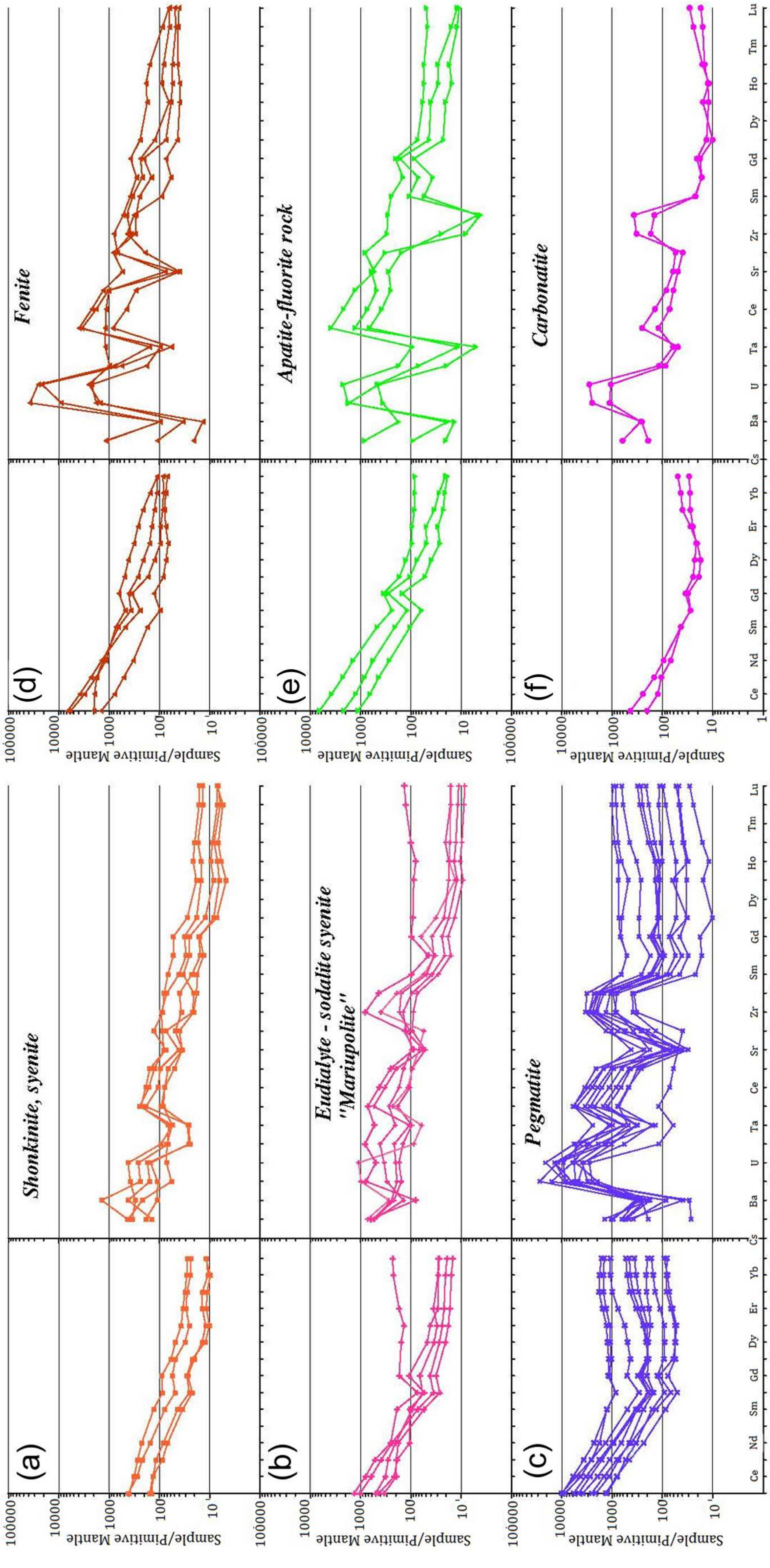

Lake
N
Lake
1
2
3
4
5
6
7

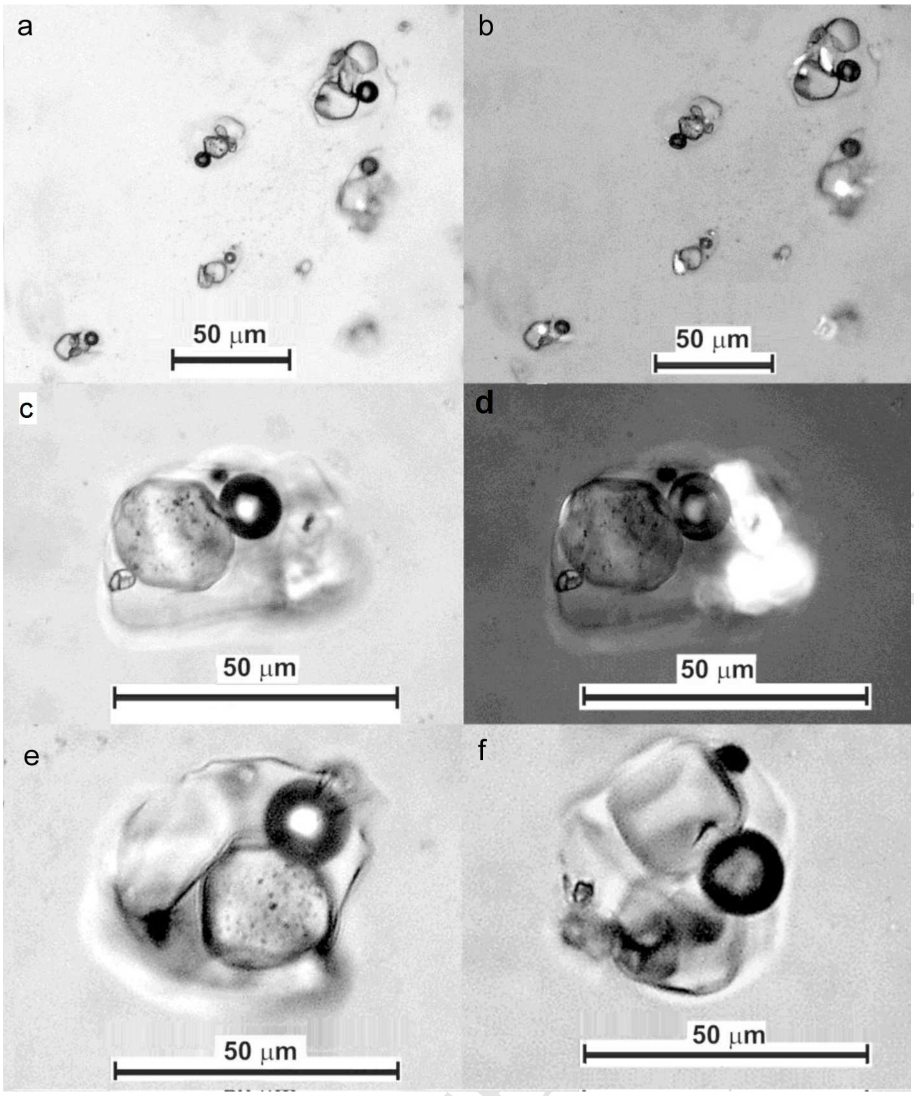

Arf
Eud
Fsp
Lov
Zr
Eud
Arf

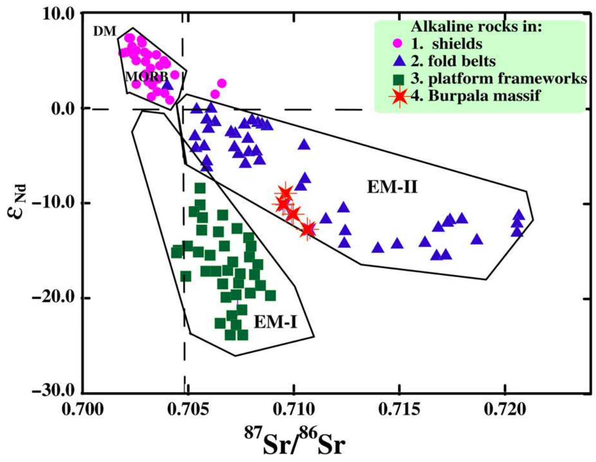

A
Lov
Ab
A'
Cat
Ab
B
Lop
B'
Zircon
C
Burp
C'
Burp
D
Ab+Bt
Melano
D'
Ab+Bt
Melano
Melano

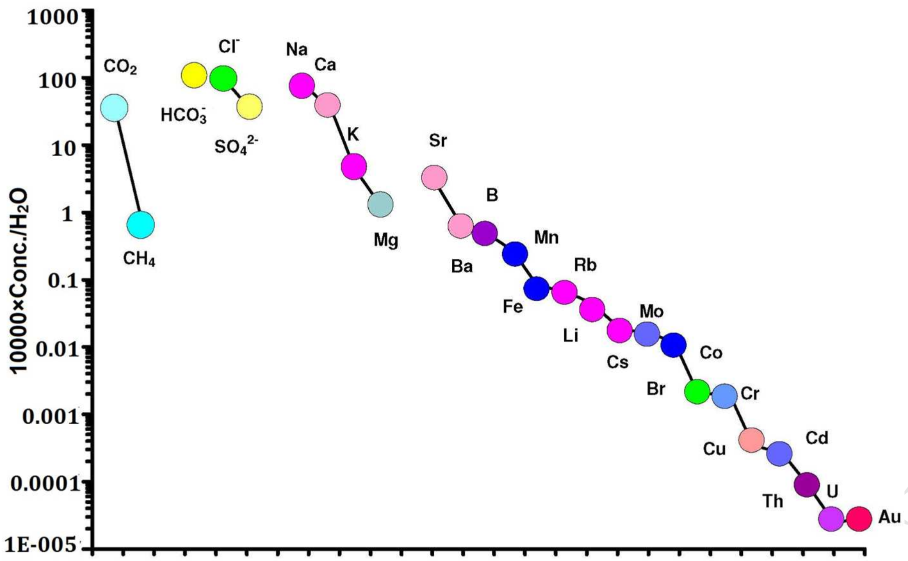

Na$_2$O+K$_2$O(wt.%)
SiO$_2$(wt.%)
0
2
4
6
8
10
12
14
16
18
35
40
45
50
55
60
65
70
75
80
1
2
3
4
5
6
7
8
9


1. Shonkinite, syenite
2. Sodalite,eudiolite syenite "Mariupolite"
3. Pegmatite
4. Fenite
5. Apatite -fluorite rocks
6. Carbonatite
Hf$_n$
La$_n$
Gd$_n$
Eu$_n$
Ta$_n$
Nb$_n$
Zr$_n$
(La/Yb)$_n$
Sr$_n$
Th$_n$
U$_n$
Y$_n$
(La/Sm)$_n$
(Ta/Nb)$_n$
0
1000
2000
3000
4000
6000
8000
200
400
600
800
500
1500
2500
10000
20000
30000
40000
20
40
60
80
100
4
8
12
16
0.2
0.4
0.6
0.8
1


(a)
Shonkinite, syenite
(b)
Eudialyte - sodalite syenite
"Mariupolite"
(c)
Pegmatite
(d)
Fenite
(e)
Apatite-fluorite rock
(f)
Carbonatite
Sample/Pimitive Mantle
100000
10000
1000
100
10
1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Cs Rb Ba Th U Nb Ta La Ce Pr Sr Nd Zr Hf Sm Eu Gd Tb Dy Y Ho Er Tm Yb Lu


a
50 µm
b
50 µm
c
50 µm
d
50 µm
e
50 µm
f
50 µm


DM
MORB
EM-I
EM-II
Alkaline rocks in:
● 1. shields
▲ 2. fold belts
■ 3. platform frameworks
✶ 4. Burpala massif
10.0
0.0
−10.0
−20.0
−30.0
ε_{Nd}
0.700
0.705
0.710
0.715
0.720
$^{87}Sr/^{86}Sr$


1000
100
10
1
0.1
0.01
0.001
0.0001
1E-005
10000×Conc./H_2O
CO_2
CH_4
HCO_3^-
Cl^-
SO_4^{2-}
Na
Ca
K
Mg
Sr
Ba
B
Mn
Fe
Rb
Li
Cs
Mo
Co
Br
Cr
Cu
Cd
Th
U
Au

Research highlights

- Burpala alkaline massif is unique for hosting more than 50 minerals rich in rare metal and REE
- Sr and Nd isotope data suggest enriched mantle (EM-II) source for the mamga
- Mantle plume beneath active margin of the Siberian continent triggered the alkaline magmatism