The Effect of Differentiation Processes in Tholeiite-Basalt Melts on the Rare Elements Distribution

G. Albina Kopylova, S. Sargylana Gogoleva
Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, Yakutsk, Russia
kopylova@diamond.ysn.ru

Abstract. Basite magmatism has been manifested repeatedly for a long time in various geodynamic structures within the eastern part of the Siberian platform. In the Middle Paleozoic, it was related to rifting processes, and in the Late Paleozoic-Early Mesozoic – to the initiation and development of trap synclises. Differences of the geodynamic regime of magma formation are displayed in the material composition of rocks. This report presents a generalizing study of the petro-geochemical features of the tholeiitic basaltic melts formed in different geodynamic settings. The initial magmas composition changes significantly at different stages of the magmatic system development. Using multicomponent analysis, we reviewed the impact of the fractionation processes of the basal melt, which occurred under various PT conditions, on its material composition. Among the trapp bodies there are powerful differentiated intrusions. A significant change of the composition occurs during the intra-chamber differentiation of the melt in a sequence of rock strata varied from the basic magnesian to felsic alkaline rocks. In the resulting series of rocks, the content of rare elements included in the lattice of the early femic phases decreases, as well as the accumulation of almost all incompatible elements. The evolution of melts of normal alkalinity occurs with an increase of REE content and their insignificant separation. Intrusions that have undergone the stage of high-pressure fractionation in the deep transitional chamber are of particular importance. As a result of such differentiation, a peculiar group of rocks is formed in the cross section of the Middle Paleozoic bodies, such as monzonite-porphyries in one case and anorthosite gabbro-dolerites - in the other. It is established that the monzoitoid type of differentiation is characterized by accumulation of LREE, LIL and elements of the zirconium group Nb, Ta, Hf and Y. Isolation of anorthosite gabbro-dolerites in the cross-section of bodies, as well as an increase in the content of aluminum, calcium, and strontium in them, is an indication of the anorthositic tendency of magmatic melt differentiation. When the basite-tholeiite melt interacts with the mantle reducing fluid in the deep core, its metallization occurs with the release of drop-liquid separations of native iron up to the formation of its large segregations. Intrusions with a large-scale content of native iron are found among the trap formations of Siberia. All this leads to a decrease in the total concentration and activity of iron in the partially metallized silicate matrix, there is a significant increase in the content of MgO and trace elements-Ni, Co, Cr. The Fe-phase-containing intrusives are characterized by minimal LIL, HFSE, and REE contents. Start your abstract here… 250 to 500 words concise and factual abstract is required. The abstract should include the purpose of research, principal results and major conclusions. References should be avoided, if it is essential, only cite the author(s) and year(s) without giving reference list. Prepare your abstract in this file and upload it into the registration web field.
1. Introduction
Basite magmatism in the eastern part of the Siberian Platform has been manifested repeatedly for a long time in different geodynamic settings [1]. In the Middle Paleozoic, it is associated with the processes of rifting, and in the Late Paleozoic-Early Mesozoic – with the laying and development of trap syneclises. In the Middle Paleozoic, extended dike belts are formed. The trap formation is represented by powerful interplastic sill intrusions that occupy large areas and are differentiated to varying degrees. The geochemical features of igneous rocks largely depend on the chemical composition and mineralogy of the parent rocks and melts. The content of the main and impurity elements can change significantly as you move towards the surface. In this paper, the influence of fractionation processes on the change in the initial composition of the basite melt is considered. The work is based on the results of chemical and trace element characteristics of different-age basites of the eastern part of the Siberian platform. The determination of rock-forming elements was carried out by the classical method of silicate analysis in the OFCHMA DPMGI SB RAS, rare elements were analyzed by inductively coupled plasma mass spectrometry (ICP-MS) on the Elan 6100 DRC device in the standard mode. State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results.

After first paragraph, other paragraphs are indented as you can see in this paragraph. After Introduction, divide your article into clearly defined and numbered sections.

2. Petrogeochemical characteristics of basites
Differences in the geodynamic setting of magma generation are well displayed in compositional variations of the rocks [2]. The difference in the geodynamic regime of magma formation is recorded in the material composition of rocks of different formations (Table 1). Magmatites of trap syneclises are characterized by a moderate content of alkalis, coherent and meltophilic (incompatible) elements and insignificant fractionation of REE. The derivatives of rift magmatism of the Devonian are characterized by an increased content of Ti, P, K, all incompatible elements, a high degree of differentiation of REE content and, in the case of granophyres is minimum. When Zn and Co exh...
contents of iron (17, 20% FeO), titanium (2, 13% TiO2) and HFSE (Ti, Zr, Hf, Nb and V) whose geochemical history in the basites is related to oxide ore minerals and, partly, to clinopyroxene. The Sr minimum is less pronounced in them than in the gabbro-pegmatite schlieren, and the Eu minimum is virtually absent. Multi-element diagrams for all differentiates of the Lower Tomba intrusive clearly show a Ta-Nb minimum, which is typical for traps magmatism of the Siberian platform.

A special place is occupied by intrusives that have passed the stage of high-pressure fractionation in a deep intermediate source. When interacting in a deep intermediate chamber of a basite-tholeiite melt with a mantle reducing fluid, it metallizes with the release of droplet-liquid segregations of native iron up to the formation of its large segregations. Intrusives with a large-scale content of native iron are found among trap formations in Siberia [4]. The article uses data from the Maymechinsk and Aikhal intrusions. Common to these intrusions is the presence in their composition of two parageneses of rock-forming crystals. The early magmatic paragenesis is represented by porphyry crystals of bitovnite (An87-78), in the center of which there are often fused cores of anorthite-bitovnite and rounded grains of chrysotile-hyalosiderite (Fa28-36). The pre-introchamber generation is supplemented by accessories – moissanite and spinelides, which fix the reducing conditions of the early stage of the evolution of the basalt melt. These minerals, which are incompatible with the intra-chamber environment, indicate an active pre-intra-chamber stage of the evolution of the basalt melt in the environment of an intermediate hearth. The transition of a part of the silicate iron to the nulvalent state leads to a decrease in its content in the gabbro-dolerites of intrusions. At the same time, there is a significant increase in the contents of MgO and CaO (Table 1). The presence of the stage of early fractionation of the melt was also reflected in the behavior of the impurity elements. The presence of early magmatic olivine and pyroxene in dolerites determined the contents of the siderophilic elements associated with them - Ni, Co, Cr. This group of intrusives is characterized by the minimum contents of large ion lithophyls - Rb, K, Ba, Th, U and high field strength elements of the titanium group - Zr, Hf, Ta, Y, Nb. Compared to typical mafic rocks, the amount of rare earth elements (∑REE = 58.9-36.2 g/t) here significantly decreases with practically similar values of the ratio (La / Yb) n. The peculiarities of the behavior of incompatible elements are reflected in the spider-diagrams (figure 1b). The compositional spectra of dolerites of all Fe-phase massifs are almost identical and are located closely parallel. The REE distribution is characterized by moderate fractionation: (La / Yb) n = 2.2-3.4, the Eu / Eu * values are close to unity. The spider diagrams clearly show the maximum of strontium - a characteristic feature of intrusions formed by melt evolving under pre-chamber conditions with fractionation of early magmatic high-calcium plagioclase. A similar peak in the Sr content is not observed in the spectra of the distribution of ordinary traps.

The Nyurba dike is a good example of the manifestation of both intrachamber crystallization and the monzoitoid tendency of differentiation of the basic melt. The rocks of the marginal zones of the dike are replaced by quartz gabbro-dolerites, and its central part is filled with monzonite-porphyries of the second intrusion phase. A low value of Mg#=36, reduced Ni, Co and Cr contents, and large amounts of alkalies in the rocks of the marginal zones testify to a high degree of pre-chamber differentiation of the melt which was further differentiated in intra-chamber conditions with the formation of rocks still more enriched in SiO2, K2O and incompatible elements and depleted in compatible ones. But the process of intra-chamber differentiation alone cannot explain a sharp increase in SiO2 and K amounts in the direction from quartz gabbro-dolerites to monzonite porphyries. This may be related to a long-term evolution of the alkaline basaltic melt as a result of its retardation in an intermediate chamber (15-20 km deep from the paleosurface, at P=5-8 kbar). The repeated pulsation opening of the magma conductor caused a discontinuity of the already partially crystallized dike. The monzoitoid melt in the form of the second phase penetrated into the central part of the dike, forming clear contacts with quartz gabbro-dolerites. Such a process was designated as a monzoitoid type of basalt melt differentiation [5]. The maximum contents of Rb, Ba, Th, U, and all elements of the zirconium group-Nb, Ta, Hf, and Y – have been established in monzonite porphyries (figure 1c). The content of REE also increases (∑REE=618.8), the ratio (La/Yb) n increases to the values of 9.6. At the same time, compared to other dike differentiates, they have relatively low Sr contents and a maximum negative europium anomaly (Eu/Eu*=0.65), which is undoubtedly determined by the absence of high-calcium plagioclase in monzonite porphyries. The initial subalkaline nature of the melt predetermined low concentrations of siderophile elements Ni, Co, Cr in
alkaline basites, and during intra-chamber differentiation, their additional decrease occurred, reaching a minimum in quartz gabbro-dolerites and monzonite porphyries.

Anorthosite type of melt differentiation is realized in deep conditions [6]. The main feature of such a melt evolution is the separation of anorthosite gabbro-dolerites in the section of bodies. Among the Middle Paleozoic intrusives, the Ust-Khannya intrusive of anorthosite gabbro-dolerites is known. The intrusive contains minerals incompatible with the conditions of intra-chamber differentiation of the tholeiitic melt at the hypabyssal level-anorthite-bitovnite, chrysolite, chrome-spinelide, moissanite, garnet, distene, native and intermetallic compounds. The formation of such bodies took place in the setting of a deep intermediate chamber during the closure of magma-permeable zones. The melt began to evolve at a depth of 35–40 km from the paleosurface at a pressure of at least 10 kbar, and as the results of homogenization of melt inclusions in bitovnite at a temperature of 1450–1300 °C showed. Under such conditions, the first silicates to crystallize are forsterite-chrysolite olivine and plagioclase of anorthite.

Table 1. Chemical (wt. %) and microelement (g/t) composition of basites of the Siberian platform

|                | Lower Tomba intrusion: | Nyurba dyke: | Anorthosite gabbro-dolerites |
|----------------|------------------------|--------------|-------------------------------|
|                | gabbro-dolerites       |              |                               |
|                | with native iron       |              |                               |
|                | from intrusions        |              |                               |
| Permian        |                        |              |                               |
| Devonian       |                        |              |                               |
| n=396          | n=156                  | 72-13        | 75-9                         |
|                |                        | 71-8         | 72-16                        |
|                |                        | 35-14        | 579-3                        |
|                |                        | 16           | 5                            |
| SiO₂           | 48,57                  | 48,43        | 46,7                         |
|                | 45,7                   | 48,2         | 48,2                         |
|                | 9                      | 5            | 8                            |
|                |                        | 58,6         | 5                            |
|                |                        | 48,7         | 5                            |
|                |                        | 49,5         | 45,4                         |
|                |                        | 50,4         | 45,2                         |
|                |                        | 46,9         | 46,1                         |
|                |                        | 46,0         | 46,1                         |
| TiO₂           | 1,48                   | 2,78         | 1,14                         |
|                | 1,29                   | 1,46         | 1,37                         |
|                | 1,60                   | 2,13         | 1,74                         |
|                | 0,93                   | 1,06         | 1,37                         |
|                | 3,1                    | 3,17         | 2,52                         |
|                | 2,52                   | 2,64         | 3,38                         |
| Al₂O₃          | 14,62                  | 13,76        | 14,3                         |
|                | 13,5                   | 14,2         | 14,4                         |
|                | 12,1                   | 14,1         | 14,4                         |
|                | 14,5                   | 16,1         | 14,6                         |
|                | 15,4                   | 16,9         | 12,9                         |
|                | 12,9                   | 12,3         | 11,5                         |
| Fe₂O₃          | 3,88                   | 3,95         | 7,89                         |
|                | 4,54                   | 4,83         | 5,20                         |
|                | 5,51                   | 7,89         | 10,1                         |
|                | 0,94                   | 3,00         | 4,44                         |
|                | 4,44                   | 2,72         | 3,00                         |
|                | 6,87                   | 4,89         | 3,38                         |
| FeO            | 9,35                   | 9,94         | 10,1                         |
|                | 10,7                   | 10,7         | 10,1                         |
|                | 8,08                   | 8,71         | 10,1                         |
|                | 10,1                   | 9,44         | 8,78                         |
|                | 7,47                   | 7,47         | 8,78                         |
|                | 8,16                   | 9,51         | 6,5                          |
|                | 9,51                   | 12,3         | 8,16                         |
| MnO            | 0,19                   | 0,19         | 0,27                         |
|                | 0,20                   | 0,19         | 0,27                         |
|                | 0,13                   | 0,15         | 0,15                         |
|                | 0,27                   | 0,15         | 0,15                         |
|                | 0,19                   | 0,19         | 0,15                         |
|                | 0,15                   | 0,15         | 0,15                         |
| MgO            | 7,04                   | 5,84         | 4,19                         |
|                | 8,23                   | 6,86         | 4,19                         |
|                | 6,14                   | 4,71         | 10,2                         |
|                | 8,96                   | 3,88         | 3,54                         |
|                | 3,54                   | 3,32         | 5,94                         |
|                | 3,32                   | 7,12         | 5,94                         |
| CaO            | 10,77                  | 9,63         | 8,80                         |
|                | 11,6                   | 10,6         | 8,80                         |
|                | 11,6                   | 10,6         | 8,80                         |
|                | 10,7                   | 9,2          | 7,62                         |
|                | 9,2                    | 7,4          | 3,23                         |
|                | 3,23                   | 9,2          | 8,90                         |
| Na₂O           | 2,23                   | 2,30         | 2,10                         |
|                | 1,84                   | 2,10         | 2,45                         |
|                | 3,45                   | 2,66         | 2,00                         |
|                | 2,00                   | 1,74         | 3,22                         |
|                | 3,22                   | 3,05         | 2,82                         |
| K₂O            | 0,64                   | 1,30         | 0,54                         |
|                | 0,54                   | 0,50         | 0,26                         |
|                | 0,26                   | 0,87         | 0,38                         |
|                | 0,38                   | 0,33         | 1,86                         |
|                | 0,33                   | 1,21         | 5,06                         |
| P₂O₅           | 0,19                   | 0,36         | 0,15                         |
|                | 0,15                   | 0,16         | 0,47                         |
|                | 0,47                   | 0,27         | 0,12                         |
|                | 0,12                   | 0,09         | 0,72                         |
|                | 0,72                   | 0,72         | 0,75                         |
|                | 0,72                   | 0,72         | 0,38                         |
| Mg#            | 50,4                   | 44           | 50                           |
|                | 48                     | 17           | 33                           |
|                | 63                     | 61           | 35                           |
|                | 61                     | 35           | 33                           |
|                | 45                     | 43           | 45                           |
| Rb              | 14,2                   | 23,9         | 15,0                         |
|                | 14                     | 15,0         | 29                           |
|                | 15,0                   | 29           | 17                           |
|                | 0,31                   | 7,63         | 38,0                         |
|                | 7,63                   | 32,7         | 4,18                         |
|                | 32,7                   | 35,7         | 24,6                         |
| Ba              | 167                    | 247          | 92                           |
|                | 167                    | 247          | 92                           |
|                | 280                    | 128          | 128                          |
|                | 8,77                   | 88,5         | 88,5                         |
|                | 252                    | 221          | 629                          |
|                | 629                    | 491          | 296                          |
| Element | Permian | Devonian |
|---------|---------|----------|
| Th      | 1.41    | 2.42     |
| U       | 0.53    | 0.72     |
| Nb      | 7.01    | 27.1     |
| Ta      | 0.46    | 1.91     |
| Zr      | 118     | 216      |
| Hf      | 2.98    | 5.36     |
| Y       | 29.2    | 32.3     |
| Sr      | 237     | 376      |
| La      | 9.92    | 23.2     |
| Ce      | 22.4    | 53.4     |
| Pr      | 2.96    | 7.08     |
| Nd      | 14.2    | 30.7     |
| Sm      | 3.93    | 7.09     |
| Eu      | 1.29    | 2.15     |
| Gd      | 4.49    | 7.06     |
| Tb      | 0.77    | 1.1      |
| Dy      | 4.93    | 6.49     |
| Ho      | 1.04    | 1.32     |
| Er      | 2.97    | 3.45     |
| Tm      | 0.54    | 0.30     |
| Yb      | 2.74    | 3.11     |
| Lu      | 0.41    | 0.45     |
| Ni      | 137     | 96       |
| Co      | 50      | 46       |
| Cr      | 316     | 138      |
| V       | 299     | 317      |
| Cu      | 176     | 165      |
| ΣP3Э   | 73      | 147      |
| (La/Yb) | 2.6     | 5.7      |
| Eu/Eu* | 0.94    | 0.92     |
| Nb/Nb* | 0.63    | 1.22     |

Permian and Devonian - average contents, n – number of analyses; differentiates of the Lower Tomba intrusion: 72-13 – troktolite gabbro-dolerite, 75-9 – olivine-containing dolerite, 71-8 gabbro-pegmatite, 72-16 – ferrogabbro; gabbro-dolerites from intrusions with native iron – 49-7 and Aii-3; Nyurba dyke: 579,1 and 827 – quartz gabbro-dolerites.

Mg(I)-MgII x100/(MgII + FeII sum), Eu/Eu* = Eu/Eu*(Smn x Gdn) 1/2; Nb/Nb* = 0.3618 xNb/√(La*Th).
**Figure 1.** Distribution of rare elements in basic rocks of the Siberian platform. Normalized to the primitive mantle [7]. a – Permian-Triassic Nizhne-Tomba differentiated intrusion: 1 - troctolite dolerites, 2 - olivine gabbro-dolerites, 3 - ferro-gabbros, 4 - gabbro-pegmatites; b, c - intrusions with...
monzonitoid-type differentiation: Middle Paleozoic basites – Maymechinsk and Aikhal intrusives (b), Nyurba dyke Precambrian basites (c): 1 - dolerites, 2 - monzonite-porphyries; d - intrusions with anorthosite-type differentiation: Middle Paleozoic basites – Ust-Khanniya intrusion: 1- anorthosite gabbro-dolerites, 2 - olivine-bearing dolerites

3. Conclusions

The behavior of impurity elements at different stages of the evolution of tholeiite-basalt melts is considered. The main role in the material composition of magmatic melts is played by the geodynamic situation, PT-melting conditions, the depth of origin and the composition of the mantle substrate. The composition of the parent magmas changes significantly during the processes of fractional-crystallization differentiation. It takes place at various stages of the existence of the magmatic system. Fractional crystallization in situ leads to a classical decrease in the concentrations of siderophilic elements and enrichment of residual melts with incompatible elements. When the reducing fluid interacts with the basalt melt, the silicate melt is metallized in the mantle intermediate hearth. During the evolution of alkaline melts in moderately deep crustal chambers, the accumulation of light rare earths of the cerium group actively occurs, which leads to a significant separation of REE and high ratios (La/Yb)n are characteristic of rocks of the monzoitoid type. A striking indicator of the differentiation processes in the deep intermediate foci is the Sr distribution. At the pre-chamber or early intra-chamber stage of the melt evolution, the element content always increases relatively. In the final alkaline differentiation products, the minimum Sr values are fixed against the background of the growth of all incompatible elements. Eu2+ often behaves like strontium in highly alkaline rocks.

The main conclusions of the study may be presented in a short Conclusions section, which may stand alone or form a subsection of a Discussion or Results and Discussion section.

Aknowlegments. The study was carried out according to the plan of research and development work of the Diamond and Precious Metal Geology Institute SB RAS (Project 0381-2019-0003) and was financially supported by the RFBR under Project No. 18-45-140043 p_a.

References
[1] A.V. Prokopiev, L.M. Parfenov, M.D. Tomshin, and I.I. Kolodeznikov. Cover of the Siberian platform and adjacent fold-and-thrust belts // Tectonics, Geodynamics and Metallogeny of the Republic of Sakha (Yakutia) [in Russian]. MAIK Science/Interperiodika, Moscow, pp. 113–155, 2001.
[2] Interpretation of geochemical data // ed. E.V. Sklyarov. Moscow. Intermet Engineering, pp. 287, 2001.
[3] M.D. Tomshin, A.G. Kopylova, and R.F. Salikhov. Nizhne-Tombinsky trap complex (north-east of the Tunguska synclise) // Domestic Geology. No. 5, pp. 52-62, 2016.
[4] B.V. Oleinikov, A.V. Okruigin, M.D. Tomshin, V.K. Levashov, A.S. Varganov, A.G. Kopylova, and Y.U. Pankov. Native Iron Formation in Platform Basic Rocks: Yakutian Scientific Center, Siberian Branch of the Russian, Academy of Sciences: Yakutsk, Russia, 1985 (In Russian).
[5] O.V. Koroleva. Compositional features and genesis of basic and intermediate magmatic rock associations in the Siberian and Hindustan platforms. //Traps of Siberia and Deccan: similarities and differences. Novosibirsk: Nauka, pp. 39-63, 1991.
[6] B.V. Oleinikov, and M.D. Tomshin. Deep-level differentiation of magma of platformal basites // DAN SSSR, V. 231, no. 1, pp. 177-180, 1976.
[7] S. Sun, and W.F. McDonough. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes.// Geol. Soc. Amer. Spec. Publ., vol. 42., pp. 313-345, 1989.