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Bimodal Volcano-Plutonic Complexes in the Frame of Eastern Member of Mongol-Okhotsk Orogenic Belt, as a Proof of the Time of Final Closure of Mongol-Okhotsk Basin

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1. Introduction

We can ascertain at the example of the modern functioning volcanoes, that their activity accompanies the tectonical rebuilding, that occurred in the Earth's crust. Material and isotope characteristics of volcanological (volcano-plutonic) formations reflect also the processes that occur at such a depth of Earth, which are not reachable for research for today. The decoding of the interdependence assists to better understanding of the evolution of our planet in different temporal intervals. It also helps to imagine the processes of formation or destruction of the continents. One of them is Euro-Asian continent. It's name indicates the binominal structure of Europe and Asia. Once two separated continents united in a single whole, forming by that a superstructure – Central Asian folded belt. And the axis of the structure is the Mongol-Okhotsk orogenic belt (Parfenov et al., 1999). During almost all of the Phanerozoic the formation of the belt was accompanied with the formation of a whole series of the volcanic and volcano-plutonic complexes and by the closure of Mongol-Okhotsk basin. The final stage of the closure of Mongol-Okhotsk basin that occurred at the end of early Cretaceous and was conducted by the formation of the bimodal volcano-plutonic complexes is examined in the article.

The bimodal volcano-plutonic complexes of the basalt-trachybasalt – rhyolitic content of the end of the early Cretaceous (119 – 97 Ma) are separated in the Southern and Northern frame of Eastern member of Mongol-Okhotsk orogenic belt. The rocks of the complexes disappear in the Western direction in the region of wedging of the Eastern member of the belt in the same direction. In eastern direction in the South, their development is limited by the structures of Bureya-Jiamusi terrane, and in the North it is limited by Okhotsk-Koriaksky terrane. The features of the geological structure of bimodal complexes are examined in the very article. The results of geochemical, isotope-geochemical and geo-chronological precision research are also shown in the article (by authors and the literature data). A proposal has been made that the rocks of the examined bimodal complexes correlate with some of the Late Mesozoic – Early Cretaceous intra plate bimodal associations of North-Asian continent by the row of geochemical and isotope geochemical characteristics. And their formation was caused by collision processes that stipulated the closure of the Eastern flank of Mongol-Okhotsk basin by the possible contribution of plume source.

The magmatic formations accompanying the formation of the rift's zone in the frames of different modern continents, reveal considerable variety of geochemical and isotope characteristics. The Euro-Asian continent is not an exception (Types of magma, 2006). Today the models of geodynamic environments for the row of its regions are worked out. They combine the action of the depth plume and the rift's formation (Yarmolyuk & Kovalenko, 2000; Yarmolyuk et al., 2000; Yarmolyuk et al., 2002; Kovalenko et al., 2003; Kozlovsky et al., 2005; Vorontsov et al., 2007). The basic role in formation of magma complexes belongs not only to the source of different nature but also to characteristics of contaminated continental crust that stipulates the formation of contrast volcanism, widely developed in the Central-Asian zone of fold belt (Types of magma, 2006). What is the role of characteristics of lithosphere in the formation of bimodal complexes; does the productivity of the plume remain in the spatiotemporal understanding and can it be the same for the differently aged magmatism? It is possible to come up to the research of these problems if there is the presence of the correct analytic data for the concrete complexes which formation has taken place not only in similar geodynamical environments but also in sequentially changed age intervals. Bimodal volcano-plutonic complexes spatially located in the frames of Eastern link of Mongol-Okhotsk belt are shown in the article (Fig. 1).

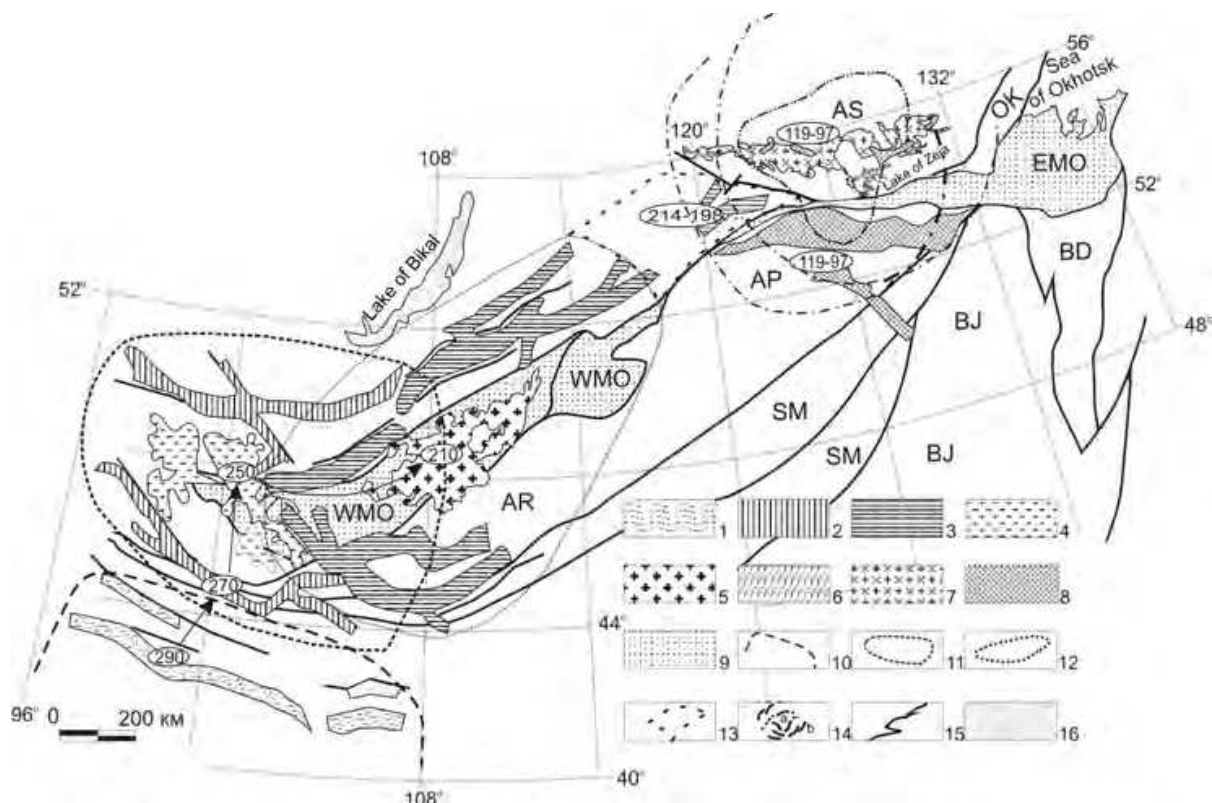


Fig. 1. Structure-tectonical scheme of the dislocation of volcano-plutonic and plutonic complexes of the Late Paleozoic – Mesozoic in the framed of Mongol-Okhotsk orogenic belt. The scheme of the structure of the Western link of Mongol-Okhotsky orogenic belt (WMO), on the East of meridian 120 is made by (Yarmolyuk et al., 2002): 1-3 – the rocks of the bimodal associations and alkali granites: 1 – Late carboniferous – Early Permian, 2 – Permian; 3 – Early Mesozoic; 4 – 5 – granitoid complexes; 4 – Permian; 5 – Early Mesozoic; 6 – collisional alkali – moderate alkali volcano-plutonic complex (Kozak et al., 2004; Strikha, 2006) on the duration of Eastern-Transbaikalian riftous zone (Derbeko, 1998). The scheme of

the structure of the Eastern link of Mongol-Okhotsk orogenic belt (EMO) is made by using the data of (Geological map..., 1999; Parfionov et al., 2003): 7 - Late Jurassic - Early Cretaceous plutonic complex; 8 - the field of the separation of the bimodal volcano-plutonic complexes of the end of Early Cretaceous. 9 - Mongol-Okhotsk orogenic belt. 10 - 12 - the borders of the projection of Mongolian plume by (Types of magmas, 2006) during time periods: 10 - Late Carboniferous - Early Permian, 11 - Permian, 12 - Early Mesozoic, 13 - an assumed continuation of the territory of the affection of the plume of Early Mesozoic by author. 14 - Aldan-Zeisky plume by (Petrishchevsky & Khanchuk, 2006). 15 - Tectonic borders. 16 - water basins. Superterrains and terrains: AR - Argunsky, SM - South Mongolian, BJ - Bureinsko-Jiamusinsky, BD - Badgialsky (Parfionov and others, 2003); Aldano-Stanovoy (Gusev & Khain, 1995); Okhotsk-Koriaksky (Geodynamics, magmatism..., 2006).

They are met as truncated volcanic fields along the Southern and Northern borders of Mongol-Okhotsk orogenic belt about 600 km, from 50 to 400 km wide. The formation of bimodal late Paleozoic - early Mesozoic formations in the frames of Western link of Mongol-Okhotsk belt is connected with collision of North-Asian and Sino-Corean continents (Types of magma, 2006). Collision processes in that region, combined with the dimensioned intraplated processes, by the beginning of the Early Cretaceous (190 Ma) completed by the closure of the Paleozoic ocean and Western part of Mongol-Okhotsk basin (Yarmolyuk & Kovalenko, 1991; Yarmolyuk & Kovalenko, 2000; Yarmolyuk et al., 2000; Kovalenko et al., 2003; Kozlovsky et al., 2005; Types of magma, 2006; Vorontsov et al., 2007).

During the period terrigenous sea sediments basically were accumulated in the East of Mongol-Okhotsk basin. And only about 150 million years ago the continental volcanic and volcano-plutonic complexes began to form, both in the frames of Eastern belt and its rim.

Along the borders of Mongol-Okhotsk belt first the formation of calc-alkali andesite complexes goes, and then there the formation of the bimodal basalt-trachybasalt-rhyolitic complexes goes (Martynyuk et al., 1990; Kozyrev, 2000a; Kozak et al., 2004; Sorokin et al., 2004; Derbeko, et al., 2008a; Derbeko et al., 2008b). The substantial characteristics of the rocks of bimodal complexes of Early Cretaceous, geo-chronological definitions of their age, isotope-geochemical data for some types of volcanites, the comparison of their characteristics with the rocks of the rifting system of Central Asia are shown in the article. The data allow us to make an assumption about the connection between the formation of the bimodal complexes and the collision processes, which took place in the region during the Early Cretaceous and about an active manifestation of the depth plume during the period.

2. Geological position of bimodal complexes

2.1 The contrast volcano-plutonic complexes in the rim of Mongol-Okhotsk orogenic belt were recognized in late 70th, by making the field surveying (Martynyuk et al., 1999). They are composed by volcanogenic-sedimentary thickness, subvolcanic and plutonic bodies. The fields of the development of the complexes are often spatially combined with the fields of volcanites of calc-alkali series and comagmatic, plutonic formations of parti-coloured (diorite-monocite-granodiorite-granite) composition of the Early Cretaceous (Martynyuk et al., 1990; Kozyrev, 2000a; Kozyrev, 2000b; Kozak et al., 2004; Derbeko, 2004; Antonov, 2007). Last years a row of geo-chronological dating of the age of volcanic and plutonic rocks of above listed formations was gained. According to the data, the formation of the volcanites of

bimodal complexes occurred in the time interval from 119 to 97 Ma. The building of the formation of calc-alkali series occurred during the time interval about 140 – 120 Ma (Neimark et al., 1996; Kozyrev, 2002a; Sorokin et al., 2003; Sorokin et al., 2006; Strikha, 2006; Antonov, 2007).

The fields of the volcanic and intrusive formations of bimodal series are developed along Southern and Northern borders of Eastern link of Mongol-Okhotsk belt till it's wedging on the West – Aginsky “threshold” (Geodymanic, magmatism..., 2006). They disappear here, but later they show up in the frames of western link of Mongol-Okhotsk belt with the age of the Early Mesozoic and earlier (Yarmoluk & Kovalenko, 1991; Gordienko, 1987; Yarmoluk & Kovalenko, 2000; Yarmoluk et al., 2000; Yarmoluk et al., 2002). By the data of Zhang Hun and others (Zhang Hun et al., 2000), bimodal formations are not registered on the neighboring territory of China, which means that, in Southern direction of their development is limited by the river Amur. In the Northern frames, the rocks are met in the limits of Aldan-Stanovoy terrane (Gusev & Khain, 1995) as rare uncoordinated strongly truncated volcanic fields.

Paleovolcanic structures that are formed with the formations of bimodal complexes, by the character of volcanic activity represent paleovolcanoes of central-claflike type. They form volcanic fields from 2 to first hundreds km². The differences thickness, the percentage ratio of covering, vent and subvolcanic components are stated in their structure, but the consistency of the geologic profiles of the covering facies mostly held out. It consists in being timed to the base of the profile's cover of trachyandesitic basaltes, andesitic basaltes, andesites, trachyandesites, trachybasaltes, interstratified with tuffosandstones, tuffogravelites and tuffoconglomerates. The middle part of the profile is composed of rhyolites, rhyolitic dacites, trachydacites, dacites, perlites, tuffs and ignimbrites. In some of the volcanic fields, the profile finishes with the cover of trachyandesites, andesites, andesibasaltes. The percentage ratio of the rocks of the complex out of its general mass is 35-60%, middle – 10-40%, acid – 20-30%, tuffogenous-sedimentary – 10-15%.

In the frames of volcanic fields and close to them, the bodies of vent facies with the square of exit equal 2 km² are stated. They are represented by agglomerates, lapillies and psammitic tuffs, clastolavas of acid rarely medium content. Subvolcanic bodies that are comagmatic to the covers form not significant shafts and dykes.

2.2 Age

The age of bimodal rocks in Southern frames (Galkinsky volcano-plutonic complex) is determined by the complex of bivalvia mollusk (pelecipodes) and phyllopodous crustaceas (konchostrak) found in ashes tuffs and tuffalevrolites. They characterize the lowest layers of upper Cretaceous (Kozyrev, 2000b). The data of isotope dating by U-Pb method on the zircons from of rhyolites correlated to 117.1; 117.6 Ma, and on trachydacites – 117±1 Ma (definitions of the Institute of Geology and Geochronology of Precambrian, Saint-Petersburg). Comparable age was obtained with ⁴⁰Ar-³⁹Ar dating of analogous rocks, and for the rocks of the basic – medium content lower data was obtained 105 – 97 Ma (Kozyrev, 2000a; Kozyrev, 2000ba; Sorokin et al., 2004; Sorokin et al., 2006). According to the data of the author the age of trachyandesites from the fundamental outcrop in the basin of the Mokhovoy stream (sample d2063-7), identified by ⁴⁰Ar-³⁹Ar method (the definitions of V.A. Ponomarchuk, Institute of Geology and Mineralogy SD RAS), was 114.7±1.6 Ma (Derbeko, 2009).

Summarizing what was said, it can be stated, that formation of Galkinsky complex occurred in the following order: trachyandesitic basaltes of the lower part of the open-cast - 118.7 ± 0.9 Ma, rhyolites, trachyrhyolites - 118.7 ± 0.4 ; 117 ± 1 ; 117.1 ; 117.6 ; 115.3 ± 1.5 Ma and trachyandesites 115 Ma (middle part of the section); trachyandesites, andesites of the normal row that are close to trachyandesite types by their content - 105.9; 100; 97 Ma and rhyolites - 97 ± 5 Ma. Thus, it can be assumed almost an uninterrupted stage of magmatic activity, which lasted during 119-97 Ma ago, which means it subsided in the very beginning of the Late Cretaceous. By the dating of plutogenic rocks of the complex by Rb-Sr method (by the data of geological survey 1978th) for the quartz monocyte an age of 117.2 Ma was obtained. Later, by the Ar-Ar method the age of subcalic granites was stated like 118 Ma (Sorokin & Ponomarchuk, 2002).

The age of the rocks of bimodal volcano-plutonic complexes in the Northern frames of Mongol-Okhotsk belt (Bomnasky volcano-plutonic complex) according to the data of geological mapping of 80th - 90th is 112 ± 8 - 99 ± 7 Ma (definition by K/Ar method by trachyrhyolites) and 98 ± 6 by andesites; 101 ± 2 and 101 ± 4 Ma (Neimark et al., 1996; U/Pb method, definitions by Up/Pb method by granocienite and dacites); 117 ± 0.8 and 109 Ma (Antonov et al., 2001, definitions by Rb/Sr method by quartz diorite and quartz monocyte); 108.6 ± 1.3 and 110.3 ± 2.9 Ma (Strikha & Rodionov, 2006, definitions by U/Pb method by granites, leikogranites).

Summing the available geochronological datings it can be said that, the formation of the rocks of the bimodal complexes in the frames of the Eastern link of Mongol-Okhotsk belt occurred simultaneously during 119 – 97 Ma.

3. Analytical methods of the research

The research of the gross geochemical composition of the rocks took place using the RFA methods (petrogenic components Sr, Zr, Nb) in the Institute of Geology and Nature Management Far Eastern Branch Russian Academy of Science and in the Institute of Geochemistry Siberian Branch Russian Academy of Science (Irkutsk, Russia), ICP-MS – in the Institute of Geochemistry Siberian Branch Russian Academy of Science (Irkutsk) and Institute of Tectonics and Geophysics Far Eastern Branch Russian Academy of Science (Khabarovsk, Russia). For the analysis of micro elements by the ICP-MS technology, a worn-out sample received an acid decomposition in HF and HNO₃ in fluoroplastic containers.

⁴⁰Ar/³⁹Ar isotope chronological research of the sample d2063-7 was made in the Institute of Geology and Mineralogy SB RAS (Novosibirsk, Russia) with the usage of mass-spectrometer MI-1201V. Correction of the obtained data was made by a standard method taking into account the atmosphere contamination and interfering peak of side neutron-induced reactions. Isochronous constructions in ³⁹Ar/⁴⁰Ar - ³⁶Ar/⁴⁰Ar coordinates were produced by polynominal method of minimal square.

Rb/Sr and Sm/Nd isotope research is made in IGGD RAS. Isotope composition Rb, Sr, Sm and Nd are measured by numerous collector mass-spectrometer Finnigan MAT-261 and TRITON TI in static rate. The accuracy of the determination of the concentrations of Rb, Sr, Sm, Nd was ± 0.05 % (2 σ).

The author used the original samples from authors' collection and data from the published works to analyze the rocks (Kozyrev, 2000a; Sorokin et al., 2003; Sorokin et al., 2006; Strikha, 2006; Antonov, 2007).

4. The composition of the bimodal volcano-plutonic complexes

4.1 The description of the rocks of bimodal complex in Southern frames

Volcano-plutonic complex in the frames of Southern belt (Galkinsky) is formed by the rocks of basic-middle and acid contents. Lavas of basic-medium content are shown by porphyritic differences with almond-rocks and massive structures. By the association of the porphyritic discharges trachybasaltes, trachyandesitic basaltes are separated on plagioclase, pyroxene, pyroxene-amphibole, olivine-pyroxene, olivine-amphibole; trachyandesites and andesites – olivine-pyroxene, plagioclase, pyroxene, amphibole-pyroxene, amphibole. Phenocrysts (to 30%): clinopyroxenes (augite and diopside), orthopyroxene (hypersthene and enstatite), sometimes opacitized, plagioclase (An_{10-36} labradorite - andesite), usual and basaltic amphibole, biotite, sanidine, olivine. Heightened alkalinity of lavas of basic-medium content is conditioned by the presence of the feldspar or red-brown biotite in the matrix of the rocks, rarely – sanidine in disseminations. The basic mass (90-70%) in plagioclase differences has an intersertal structure, in others – doleritic, phylotacsitic, trachytoid, microophite. It consists of the volcano glass with laths of plagioclase, granules of ortho- and clinopyroxenes, amphiboles, ripples of biotite, ore minerals. Accessory minerals are grothite, apatite, titanomagnetite, magnetite.

Rhyolites, trachytoid rhyolites, rhyolitic dacites with fluidal, massive or amygdaloidal texture form pink and light violet – light gray flows with the interlayers of perlites, tuffs and ignimbrites. Phenocrysts in lavas with porphyritic structure are represented by zonal plagioclase (An_{10-36}), potassic feldspar quartz, biotite, sometimes basaltic amphibole (to 3%). Phenocrysts of sanidine are present in some types of trahyrhyolites. By the data in sections of most high alumina rhyolites, singular granules of cordierite, spherulite of tridymite are found in the basic mass. The basic mass (to 80%) is of quartz- feldspar content with the scales of biotite, sometimes with small granules of amphibole, having perlitic, micropoikilitic, microspherulitic (spherulites of sanidine with albitic center) or microfelsitic structure.

Among tuffs the ashy aleurolites and psammitic varieties of acid, rarely basic-medium content, sometimes an admixture of lappilies up to 60% are registered.

Granitoids, comagmatic to Galkinsky complex, correlate with subalkalic granites, subalkalic leucogranites, granitoids, quartz diorites, quartz monocytes by their content. Rock forming minerals of plutonic varieties are identical to volcanites, and among each other, they differ only by percentage of minerals.

The bimodal content of the rocks of the complex is determined by two ranges of the content of SiO_2 : 47-64 и 72-78 wt.% with almost absolute absence of intermediate varieties (Fig. 2).

Volcanites, with the content of SiO_2 47-64 wt.% (Fig. 2a), are characterized by mostly moderate alkalinity. The amount of K_2O , same as the content of Fe (Fig. 3), with changing weakly of Na_2O content, is unevenly growing proportionally to the content of SiO_2 . These are high alumina ($Al_2O_3 = 15.22-17.30$ wt.%), moderate – low magnesia, low titaniferous (<2 wt.%) formations. They belong to high potassic calcareous-alkaline series (in singular cases - shoshonite) (Fig. 2b).

Volcanites with the content of SiO_2 72-78 wt.% are characterized by normal, rarely moderate alkalinity, with the growth of the content of SiO_2 generate alkalinity is getting lower (from 9.13 to 7.13 wt.%). The content of Na_2O reduces by slowly changing concentration of K_2O . These are low alumina ($Al_2O_3 = 11.15-13.96$ wt.%), low magnesia, mostly ferruginous (Fig. 3), low titaniferous formations. They belong to high potassic calcareous-alkaline series (Fig. 2b).

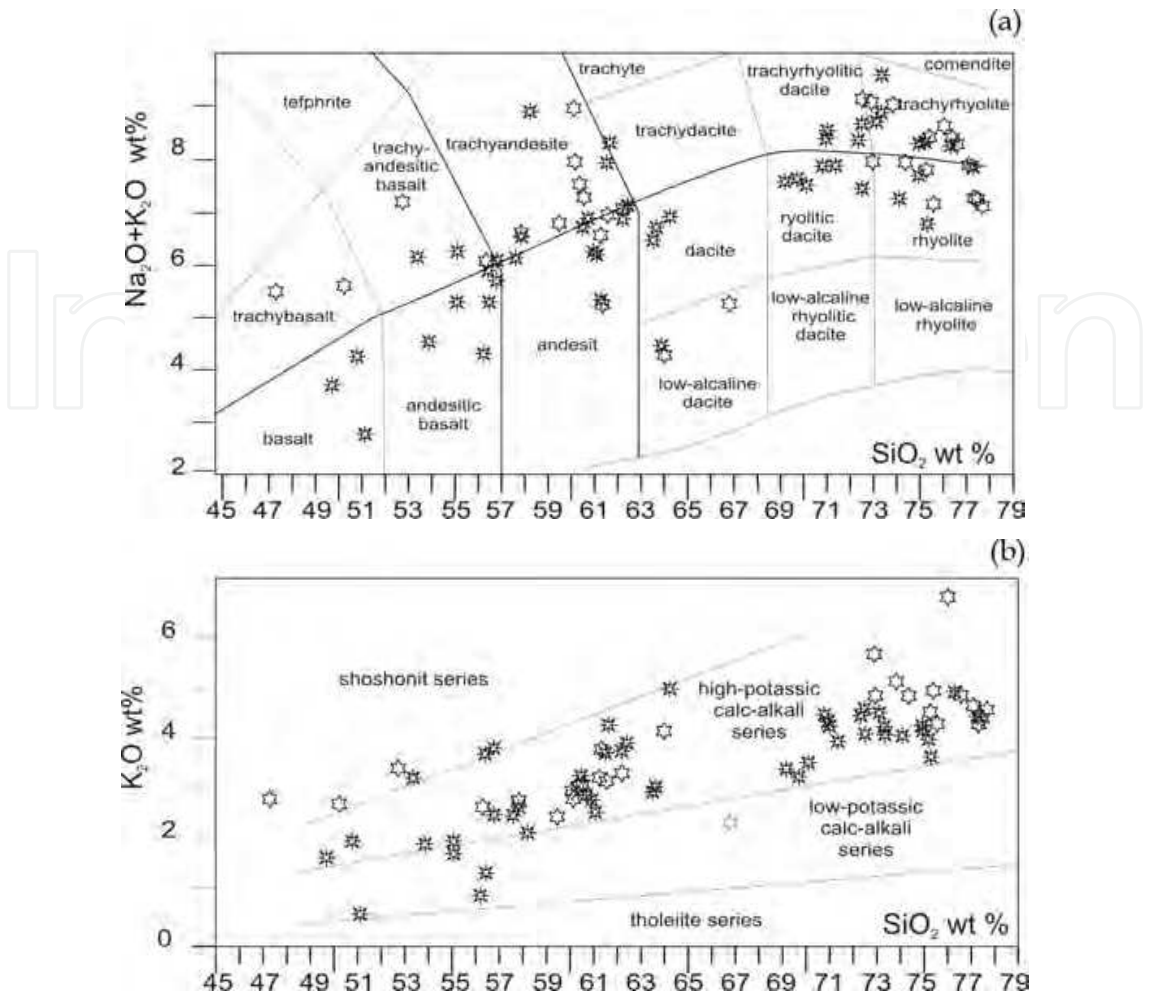


Fig. 2. Classification diagrams for the rocks of bimodal volcano-plutonic complexes of the framing of Mongol-Okhotsk orogenic belt. Northern framing – Bomnasky complex (1) and on the South – Galkinsky (2): a) (Na₂O+K₂O) - SiO₂ (Magmatic rocks, 1983); b) K₂O+SiO₂ (Le Bas et al., 1986).

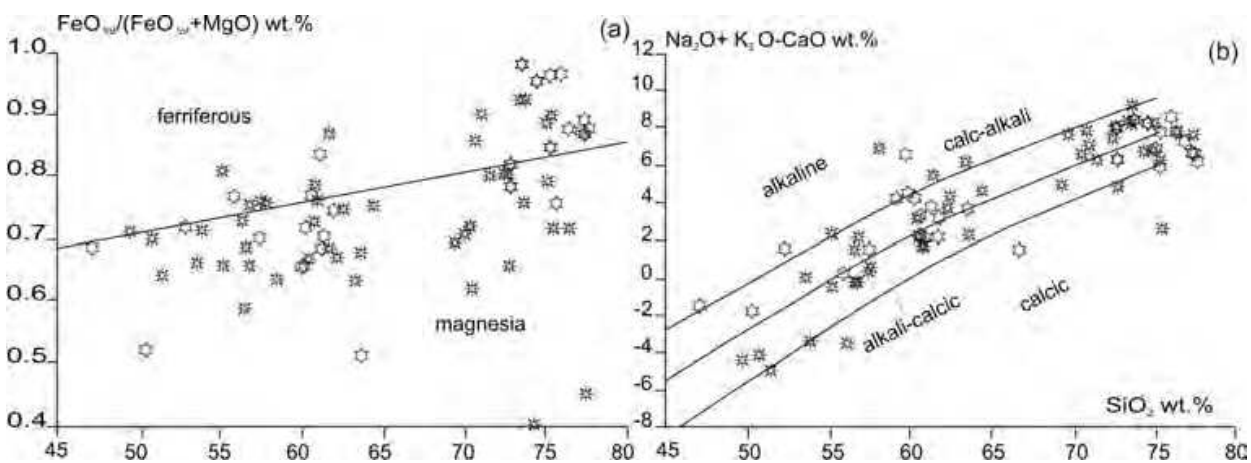


Fig. 3. Classification diagrams: a) FeO_{tot} / (FeO_{tot} +MgO) - SiO₂; б) (Na₂O+K₂O-CaO) - SiO₂; (Frost et al., 2001) for the rocks of the volcano-plutonic complexes of bimodal series. The conventional signs of the rocks are on Fig. 2.

4.2 The description of the rocks of bimodal complex in northern frames

The volcano-plutonic complex in Northern frames of the belt (Bomnakskiy) is formed by the rocks of basic-medium and acid contents. Lavas of basic- medium contents are represented by porphyritic differences with massive, rarely amygdaloidal textures. By the association of porphyritic discharge, the rocks of basic-middle content are represented by basalts, trachyte andesite basalts and andesite basalts, plagioclase, plagioclase-pyroxene, pyroxene-amphibolic, rarely olivine-pyroxene. Among trachyandesites and andesites following types are separated: plagioclase, pyroxene, amphibolic- pyroxene, amphibolic. Particularly, porphyric phenocrysts (to 45-50%) are represented by clinopyroxene (diopside), orthopyroxene (hypersthene, ferrohypersthene), plagioclase (An₆₁₋₃₅), usual amphibolic, biotite, rarely – olivine. Often, glomeroporphyritic joints of plagioclase or pyroxenes with titanomagnetites are found. The basic mass (up to 55 %) has got a pilotaxitic, doleritic, trachytoid or mikrophytal structures. It consists of volcanic glass with laths of plagioclase (An₅₀₋₃₅), granules of ortho- and clinopyroxenes, amphibolics, ripples of biotite, ore mineral. Accessory minerals are sphene, apatite, titanomagnetite, magnetite.

Rhyolitic dacites, rhyolites, trachyrhyolitic dacites, trachyrhyolites with fluidal or massive texture are forming flows with intercalation of perlites, tuffs and ignimbrites. Phenocrysts in lavas with porphyric structure are represented by zonal plagioclase (An₁₀₋₂₈), potassic feldspar, quartz, biotite, rarely usual amphibolic (less than 5%), singular and very small granules of pyroxene. Phenocrysts of sanidine are present in some types of trachyrhyolites. The basic mass (up to 90%) of quartz – feldspar content with the ripples of biotite, rarely with small granules of feldspar, has got perlitic, micropoicilitic, microfelsitic or microferrolitic (spherulite of potassic feldspar with albite or quartz center) structures.

The bimodal content of the rocks of Bomnaksky complex is determined by two diapasons of the content of SiO₂: 49-64 and 69-78 wt.% (Fig. 2).

Volcanites with the content of SiO₂ 49-64 wt.% (Fig. 2a) are characterized by moderate and normal alkalinity, with straight correlation between general alkalinity and the content of SiO₂. The content of Na₂O is unstable, and the amount of K₂O irregularly changes from 1.7 to 4.2 wt.%. This are highalumina (Al₂O₃ = 15.65-18.86 wt.%), mostly magnesian (moderate-to low magnesian, Fig. 3a), low titaniferous (TiO₂ < 2 wt.%) formations. They belong to low-high potassic calcareous-alkaline series; singular trials get into the field of shoshonite series (Fig. 2b).

Volcanites with the content of SiO₂ 69-78 wt.% are characterized by normal – moderate alkalinity (Fig. 2a). With the content of SiO₂ = 73 wt.%, general alkalinity is decreased. These are low potassic (Al₂O₃ = 10.55-14.99 wt.%), low magnesian, low titaniferous formations. They belong to highpotassic calcareous-alkaline series (Fig 2b).

Plutonic formations, which are comagmatic with volcanites of the bimodal complexes, are represented by diorites, monocytes, quartz diorites, quartz monocytes, granodiarites, quartz sienites, subalkalic granites, granites, subalkalic leucogranites, leucogranites. Intrusions are forming large irregularly-shaped bodies, stocks and dikes. Large massifs have complicated structure, where almost all varieties of magmatic rocks of the complex are included. As a rule, low intrusions are monorocks. The rock forming minerals of plutonic rocks are identical with volcanites and they differ only in percentage ratio of the minerals. The plutonic formations of the acid content relate to the granites of A-type, as far as granitoids, which are comagmatic to volcanites of medium-basic content, correlate with the formations of I-and S-types (Fig. 4)

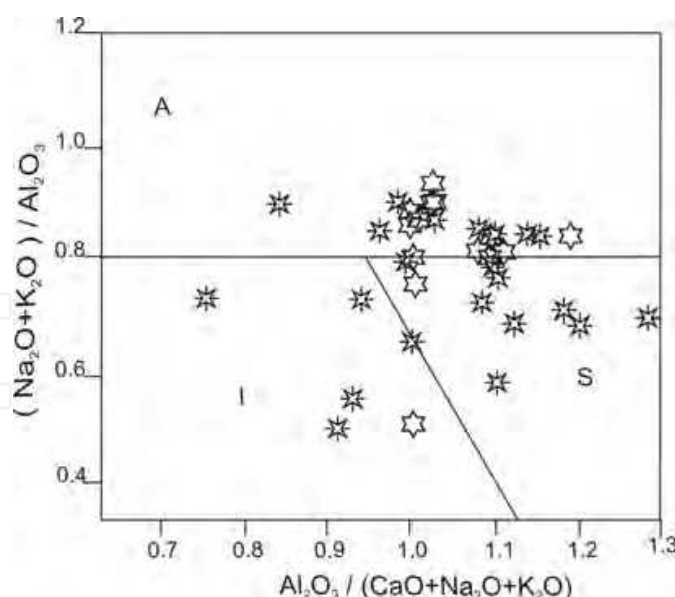
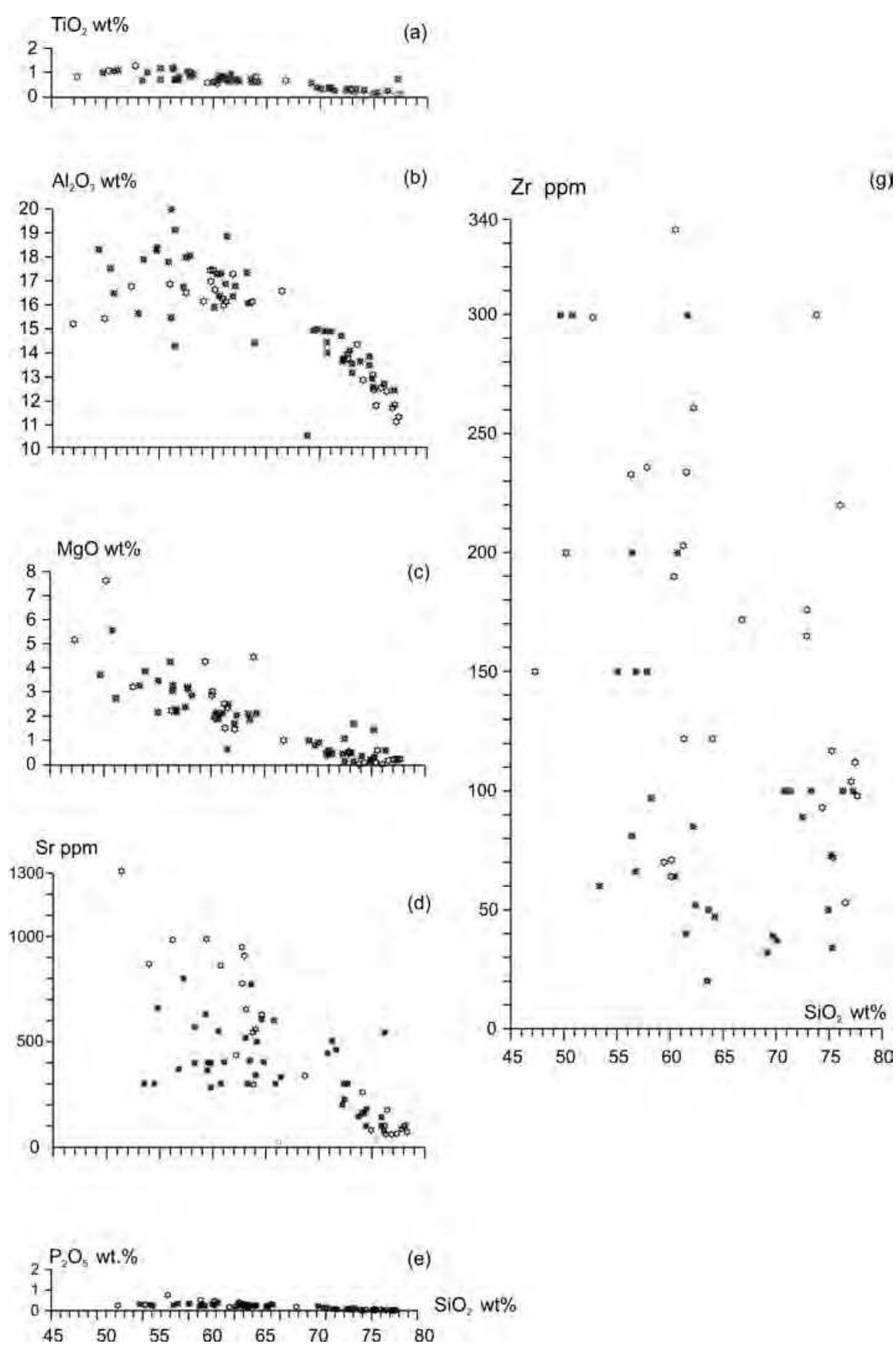


Fig. 4. A diagram for the separation A-, S-, I- types of granitoids by petrochemical indications (Chappell & White, 1974; Maeda, 1990). The conventional signs of the rocks are on Fig. 2.

A correlation analysis was made by sampling, formed out of 84 samples and including all the varieties of the rocks of the bimodal complexes of Southern and Northern frames of Western link of Mongol-Okhotsky belt (Fig. 5). Two associations of elements were singled out - $\text{SiO}_2\text{-K}_2\text{O}$ and $\text{TiO}_2\text{-P}_2\text{O}_5\text{-FeO-CaO-Al}_2\text{O}_3\text{-MnO-MgO-Sr-Ba-Zr}$, which are connected with each other by negative correlation dependences. Positive correlation relation with silica is noted for Rb ($r = 0.566$ with $r5\% = 0.514$) и Nb ($r = 0.342$ with $r5\% = 0.514$) (Fig. 5j, 5k), fuzzy negative one for Y ($r = -0.601$ with $r5\% = 0.514$) (Fig. 5h). Thereby, a single trend of correlation reveals almost in all examined correlations of petrogenic and rare-earth elements with SiO_2 , which is typical for bimodal series.

4.3 Geochemical characteristics of the rocks of the bimodal complexes

All the rocks of bimodal complexes are enriched in light rare-earth elements $(\text{La/Yb})_n = 5.5\text{-}33.6$ (10 – 20 values prevail), in which the accumulation of the La relative to Sm $(\text{La/Sm})_n = 2.9\text{-}10.5$ is significantly shown (3 – 4 values prevail), as far as the level of fractioning of heavy lanthanoids is lower $(\text{Gd/Yb})_n = 0.9\text{-}3.9$ (Fig. 6a). The accumulation of the rare-earth elements is happening parallelly to the manifestation of the Eu anomaly, which depth depends on the grade of plagioclase fractioning. Correspondingly Eu minimum in basic – medium rocks is weakly shown and it correlates to $\text{Eu/Eu}^* = 0.70\text{-}0.95$ for the rocks in the Southern frames, $0.50\text{-}0.75$ – for the rocks in Northern frames of the belt. It is deeper in acid formations ($\text{Eu/Eu}^* = 0.33\text{-}0.59$ and $0.16\text{-}0.77$ accordingly). Multielemental spectra are characterized by stable negative anomalies Nb, Ta and Ti for all the varieties of the rocks and very changeable anomaly Sr: for granitoids and acid volcanites it is negative and for the basic – medium rocks it is from weakly negative to almost positive (Fig 6b). The content of Ba, Rb, Th, K is marked by positive anomalies (Fig. 6b). It should be mentioned, that differences in the contents of such elements as Zr, Hf and Rb take place in the content of microelements between bimodal complexes of Northern and Southern frames.



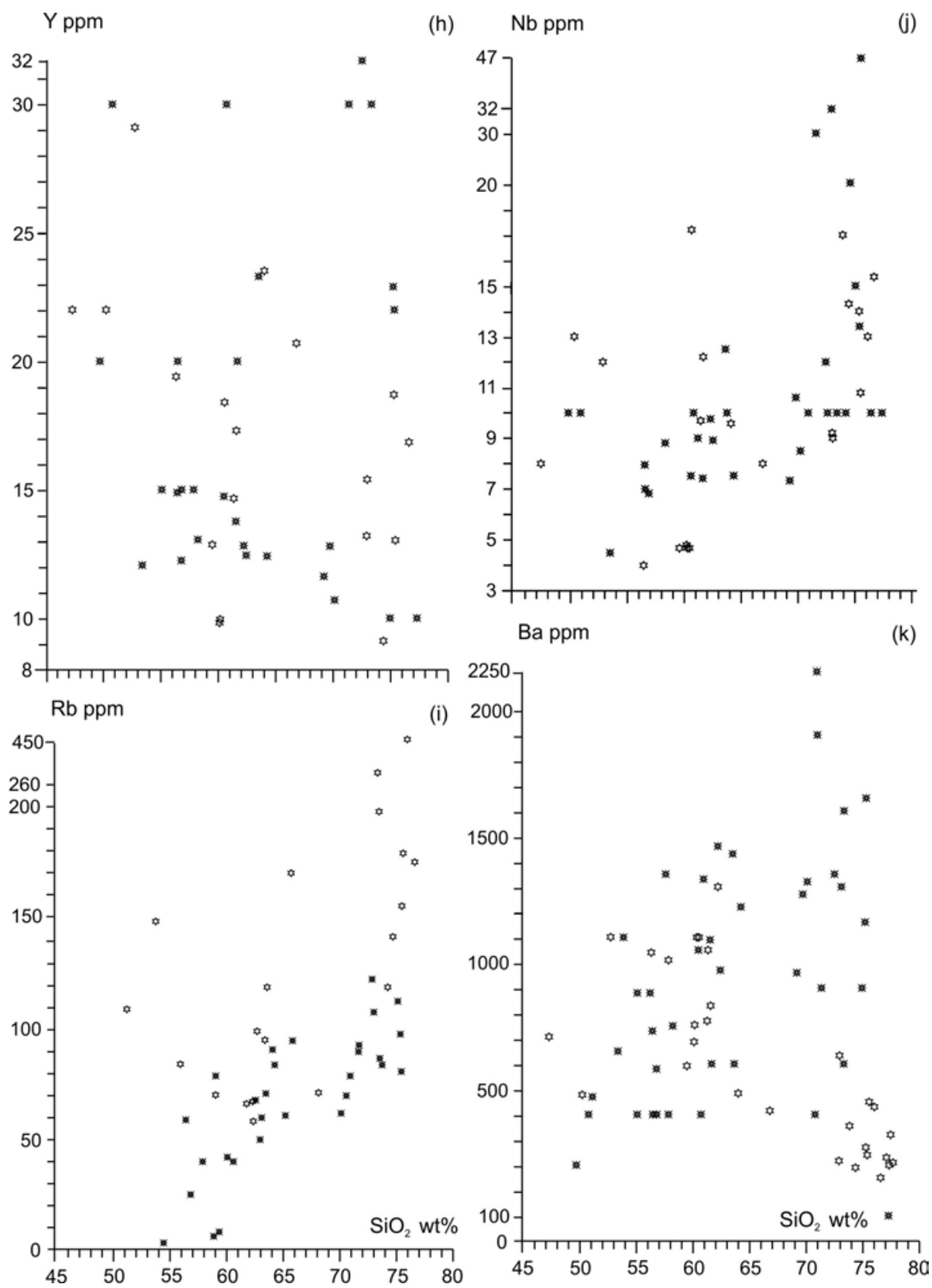


Fig. 5. The correlations of the content of petrogenetic and rare elements to the content of SiO₂ in the rocks of volcano-plutonic complexes of bimodal series. The conventional signs of the rocks are on Fig. 2.

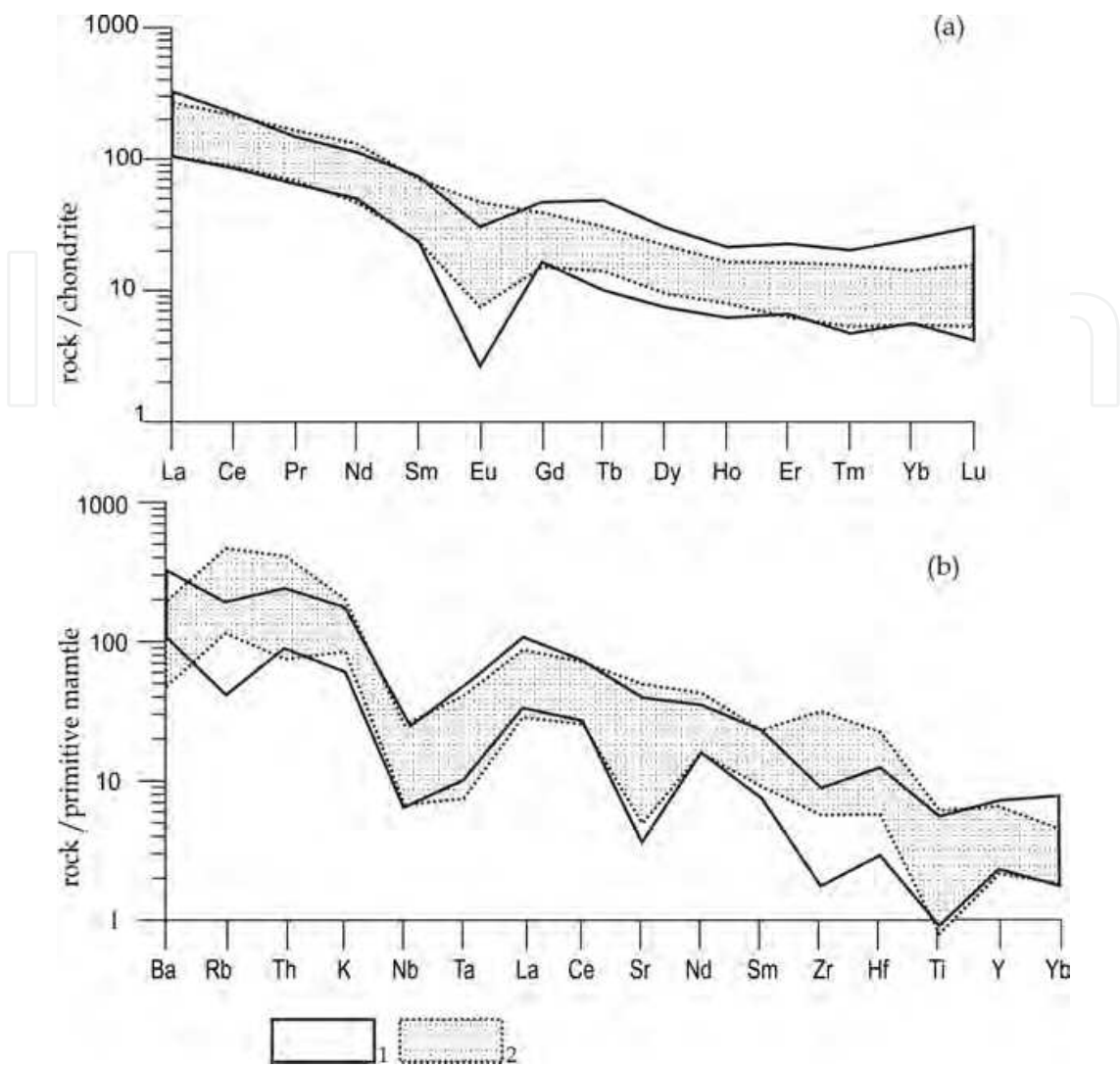


Fig. 6. Concentrations of the rear elements standardized to the composition of Chondrite (a) and primitive mantel (b). Compositions of chondrite C1 and primitive mantel are brought according to the data (Sun & McDonough, 1989). Northern frames – Bomnasky complex (1) and Southern - Galkinsky (2).

The rocks of the examined bimodal complexes are close to some magmatic formations, were developed on the Western continuation of Mongol-Okhotsk orogenic belt and separated in Mongol-Okhotsk rifting zone, by bimodal character of development of the granitoids of A-type and by the row of geochemical characteristics (Vorontsov et al., 2007). The manifestations of the sharp minimums Nb, Ta, Ti, and maximums in Ba, Rb, Th, K contents are typical for the rocks of the researched complexes, the same is for the formations of the rifting zone, but in the frames of the Eastern link, the alkali-salic rocks are absent. The content of highly charged elements are lower: Nb, Ta, и Zr, Hf, and by the growth of silica content, the content of Ba и Zr is mostly reducing (Fig. 5k: fig. 5i).

4.4 Isotope characteristics

The formations of the Galkinsky bimodal complex are characterized by staunch isotope structures with variations of the correlation $^{87}\text{Sr}/^{86}\text{Sr}= 0.7057\text{-}0.7063, 0.7081\text{-}0.7084$ and wide

interval of the values of $\epsilon\text{Nd}_{(T)} = (-0.6) - (-3.6)$ (Kozyrev, 2000a; Sorokin et al., 2006). The model Nd age - $T_{\text{Nd}}(\text{DM-2st})$ - correlates with a very narrow interval 975-1314 Ma., which might show the substantial homogeneity of substratum of melting with crustal component of late Riphean. For the formations of Bomnasky bimodal complex, the following correlation is typical: $^{87}\text{Sr}/^{86}\text{Sr} = 0.70592-0.70620, 0.70648-0.70773$ with pretty narrow interval - $\epsilon\text{Nd}_{(T)} = (-11.77) - (-12.20)$ (Kozyrev, 2000a; Striha & Rodionov, 2006). This might show a substantial homogeneity of substratum of melting with crustal component of early Proterozoic.

5. Discussion of the results

The substantial composition of the described bimodal volcano-plutonic complexes depends on the changes of the mineral composition of the forming rocks: the decrease of the role of dark colored minerals and growth of the role of feldspar-quartz component is mentioned in the rocks; this might be an evidence of fractional crystallization. From trachybasaltes-basaltes to trachyrhyolites a considerable decrease in Sr and Ba content is also happening. The enrichment of residual melt is mentioned against the background of a sharp decrease of the elements. On the other side, irregular, often reduced, content of MgO (to 7.67 wt.%), Ni (to 63 ppm), Co (mostly 10-20 ppm) is denying the straight connection of it's melting out of mantle peridotites (Palme & O'Neill, 2003). This fact is confirmed by low correlations of Nb/Ta (6.1-16.0, an exception is the value for trachyandesitic basaltes of Galkinsky complex even 30); as for the rocks of mantel provenance the value is close to 17.5 (Green, 1995). For the formation of the possible mantle sources, that affected the formation of the rocks of examined complexes, the behavior of the pairs of incompatible elements was analyzed. The elements have got an ability to accumulate in residual melt independently from the magma content (Fig. 7). Pairs of the residual-elements by the differentiation (anatexis) of magmas, the product of different sources, are displayed on logarithmic diagrams of their content as straight lines, crossing the sources compositions, and accumulating in residual magmas in the process of their differentiation. Analysis of the correlation of the concentrations of residual-elements' pairs (Fig. 7) shows the proximity of the bimodal series' rocks by similar correlations of model source of the island ark with the participation of enriched sources like OIB, CC and source like MORB. One can't deny the collaboration of crystallizational, which affects the accumulation of the elements.

Figure 7f shows, that almost all the varieties of the bimodal complexes' rocks are plotted in the area of high ratios $\text{Th}/\text{Ta} = 9.7-41.4$ (the model value of the source LAB close to 9) with relatively constant value of correlation Nb/U (Fig. 7a). An exception is the data for some granitoids, where the concentration of SiO_2 is higher than 75%. The affection of the process of magmas differentiation on the value of correlation Th/Ta can be checked with an index of magmas differentiation, denominated by the content of niobium and silica. Fig. 5 shows that the concentration of niobium is accompanied by growth of SiO_2 content. This is corresponding with the degree of differentiation of magmas and decrease of the degree of the melt of the source. The values for the middle content of CC are considerably exceeding, as the growth of the content of silica is happening at the correlation of Th/Ta ; so it can be considered, that the process is more connected with the differentiation of magmas that are forming the bimodal complexes, but with that we should not except the role of the mixture of such sources like MORB, IAB, CC.

We should notice the correlation Nb/U (Fig. 7a), which value basically fits the size of field of undersubductional source of LAB. The increase of the content of Nb and SiO₂ is accompanied by an insignificant reduction of the value of Eu/Eu* (from 0.86-0.95 to 0.16-0.23).

This demonstrates that there was differentiation with the growth of silica acidity with the participation of fractioning of feldspar. This is pretty characteristic of subductional calc-alkali magmatic associations. It can be stated, that the formations of the bimodal complexes are a result of upper continental crust assimilation. As it was already mentioned (Fig.7j), for all the varieties of the bimodal complexes' rocks a straight correlation Nb and SiO₂ is stated. For the formations with the content of SiO₂ < 57 wt.% participation of the sources IAB - M-MORB - E-MORB is possible with the growth of the content of Nb from IAB to E-MORB. Therefore the growth of Nb occurs by relatively weak changing content of silica, which might confirm the affection of this source on the magma's structure, but not the affection of the magma's differentiations. By the growth of the content of SiO₂ (57-64 wt.%), where the straight correlation between Nb and SiO₂ is more apparent, the participation of the magmas' differentiation and assimilation of the continental crust and their magmas might be proposed. Further, with the growth of the content of SiO₂ (>64 wt.%) and Nb (to 47 ppm), when the straight relation between Nb and SiO₂ significantly moves away from the composition of CC, forming a hyperbola, the basic part in forming the acid rocks of the bimodal complexes, more likely, belongs to differentiation of magmas.

If we take a look at geochemical diagrams with the shown values of different characteristics of the sources and mantle processes according to data (Sun & McDonough, 1989; Hofman & Jochum, 1996; Niu & Batiza, 1997 et al.). The formations of the examined complexes are pretty distant from the deplicated source of mantle on those diagrams (correlations Th_n/Ba_n-Th_n/La_n; Sr_n/Ce_n-Nb_n/La_n; Nb/Th-Zr/Nb; La/Yb-Th/Ta etc.) and points of their content are concentrated close to the values of enriched mantle (EM). By the data of correlations Ti/Y (380-162 and 225-43); Lu/Hf (0.04-0.10 and 0.05-0.32); Sm_n/Yb_n - the basic part of the values fits the interval 3.5-5 and 2-4 in basic-medium and acid varieties correspondingly. A conclusion can be made there. A component of the bimodal complexes of medium-basic composition was formed at more significant depth and might be less enriched in the crustal material. It is confirmed by the analysis of the correlations of Rb/Sr: 0.01-0.32 for medium-basic rocks and 0.14-3.98 for acid types. It is known, that these correlations for the rocks of similar composition of continental crust and granite-metamorphic stratum are 0.02 and 0.32 (Taylor & McLennan, 1985).

It is stated in the diagram Ba/K - ⁸⁷Sr/⁸⁶Sr (Fig. 8) that the inclusion in the magmatic process of the continental sedimentary materials starts already with the formation of the rocks of middle-basic content. It is present, although the figurative dots are significantly removed aside of trend of contamination, at the formation of acid varieties. All this allows us to assume, that by the formation of acid varieties the process of differentiation of magmatic materials has had an important meaning. And figurative dots of mostly basic volcanites (Fig. 8) are removed to the trend of an enriched source.

The demonstration of the rock's characteristics on the diagrams, helping to identify the conditions of melting in mantle source (Brandshaw et al., 1993; Gill, 1981 et al.), showed that initial magmas formed by the melt of granet-spinel lherzolite (degree of the melt is in limits 1- 5%), containing not more than 4% of granet. Geochemical characteristics also allow us to analyze the role of the processes of partly melting of mantle substratum and fractional

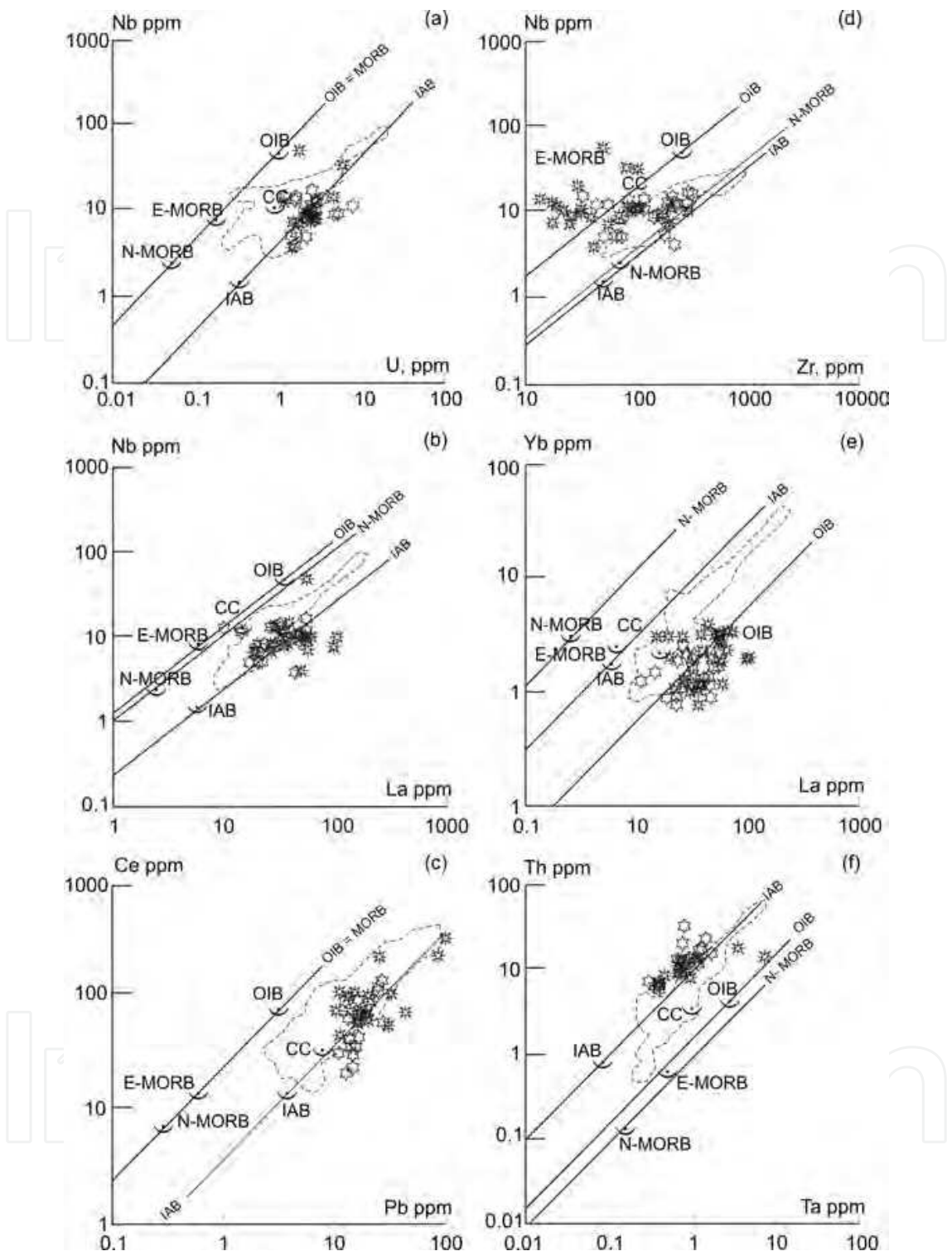


Fig. 7. The variations of the concentrations of incompatible microelements in the rocks of volcano-plutonic bimodal complexes of the framing of Mongol-Okhotsky orogenic belt. The model compositions of basalts of middle-oceanic mountain ridges normal (N-MORB) and enriched (E-MORB), of ocean islands (OIB) and island arcs (IAB), continental crust (CC). The lines of even correlations for the appropriate sources and correlations for the Paleozoic bimodal associations of Western link of Mongol-Okhotsk orogenic belt (dotted line) from the work of (Kovalenko et al., 2010). The conventional signs of the rocks are on Fig. 2.

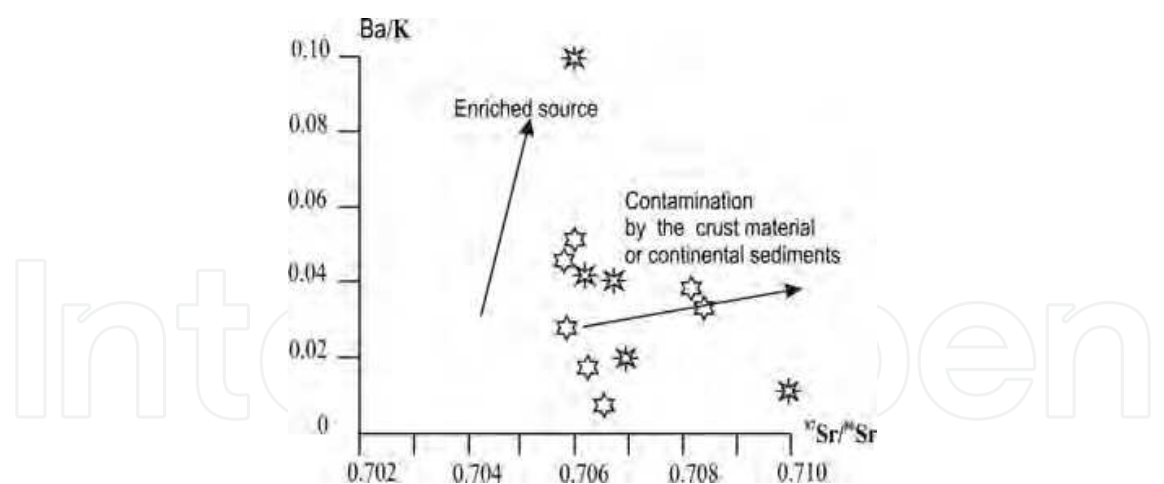


Fig. 8. The location of the content of the rocks of bimodal volcano-plutonic complexes is on the diagram $^{87}\text{Sr}/^{86}\text{Sr}$ – Ba/K (Poulet, 1995). The conventional signs of the rocks are on Fig. 2.

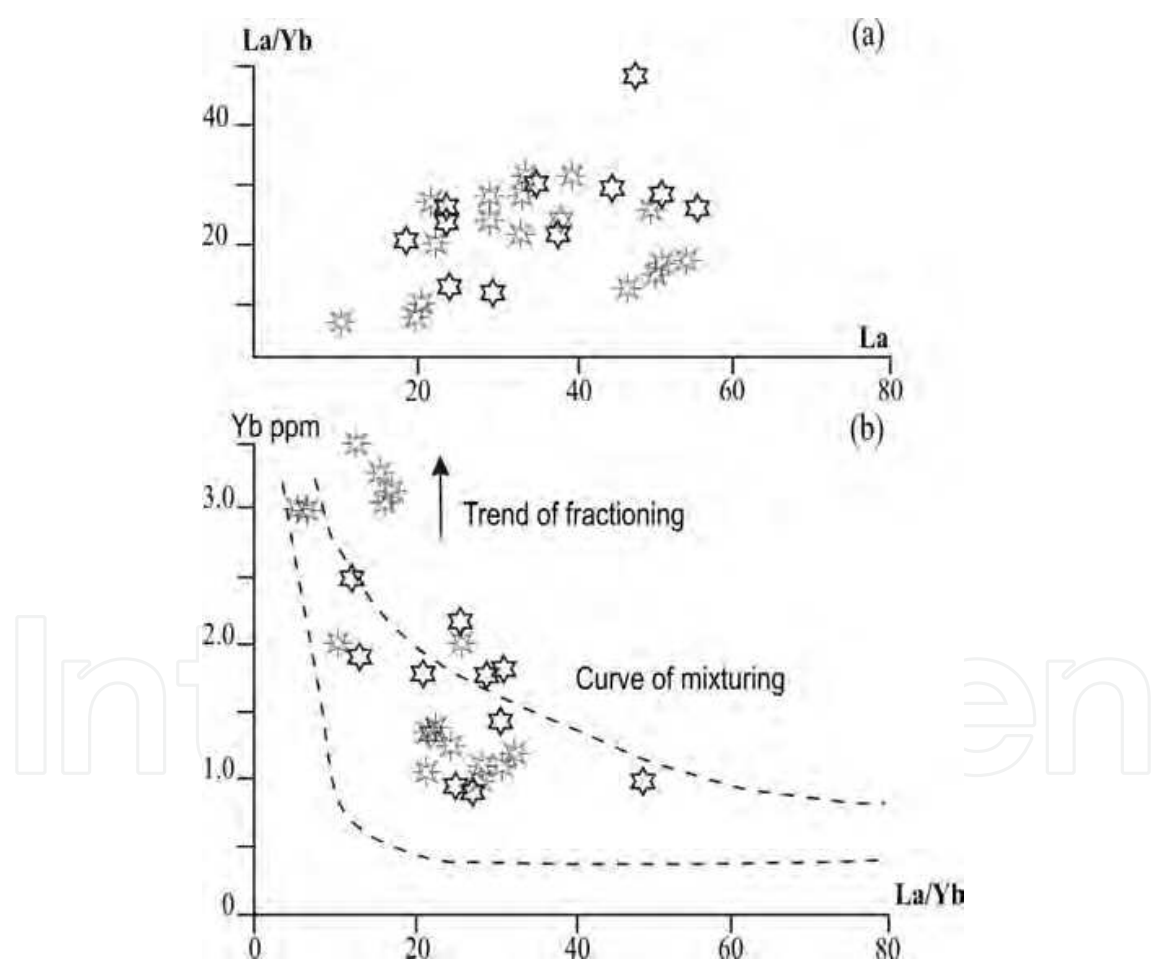


Fig. 9. The location of the compositions of the rocks of basic – middle content of bimodal complexes on the diagrams: a) La – La /Yb, б) La/Yb – Yb. Trend of fractioning and lines of mixing by (Shaw et al., 2003). The conventional signs of the rocks are on Fig. 2.

crystallization of primary magmas. It is stated that by the fractioning of abyssal magmas the content of La significantly varies, and the correlation of La/Yb is changing relatively weak.

This is reflecting the location of figurative points of volcanites of basic-medium content of bimodal complexes on the diagram of correlation of the elements (Fig. 9a).

On the correlational diagram of La/Yb - Yb (Fig. 9b) they are located in the area of trend of melting mixture, that were formed by the partial melting both spinel and granet - lherzolites, that contain mica (Shaw et al., 2003). But a part of figurative points and Galkinsky and Bomnasky complexes are strongly attached to a trend of fractioning. About the participation of granet and spinel peridotites in the formation of the rocks of the examined bimodal complexes says the dependence of normalized to chondrite (by Sun & McDonough, 1989) correlation of (Tb/Yb)_n from the value of correlation K/Nb (Wang et al., 2002). For Galkinsky complex the value of (Tb/Yb)_n = 2.08-2.66, and for Bomnasky - (Tb/Yb)_n = 1.66-1.78; 1.8-2.88. It can be proposed, that the formation of the rocks of Galkinsky and complex occurred in the zone of stability of granet. The formations of Bomnasky complex were formed both in a zone of stability of granet and in the less depths, where the melts are equilibrium to spinel partial protolites. Probably, this is an explanation of the differences of geochemical characteristics of the examined bimodal complexes.

Isotope data of volcanites and plutonic formations coordinate with isotope characteristics of containing than blocks of the earth's crust. Thus in the Southern frames they lay over the Northern edge of Amur continent, in it's composition the formations of Riphean folding with corresponding crust sources: $T_{Nd}(DM-2st) = 975-1314$ Ma. And in the Northern frames the rocks of the bimodal complex are overlying the formations of Stanovoy terrane (Southern framing of Siberian platform). Early Proterozoic formations are widely developed there. The characteristics of the crust source of the bimodal complex ($T_{Nd}(DM-2st) = 1901-1937$ Ma) correlate to the time period.

According to the primary isotope compositions Sr and Nd in the formation of the rocks of the examined complex, the affection of the mantle can not be expected. The mantle is enriched in radiogenic ^{87}Sr - EM-II (Fig. 10) for the Southern framing and EM-I - for the Northern framing of Mongol-Okhotsk belt. More likely, the differences of the composition of the sources are connected with the differences of the composition of the foundation, in which frames of the complexes were formed.

To take a good look at the possible affection of the plume on the magmatic late Mesozoic process in the region we use a calculation (Fitton et al., 1997), this determines the probability of the presence of the plume source: $\Delta Nb = 1.74 + \log(Nb/Y) - 1.92 * \log(Zr/Y)$. According to the shown formula, for some basic - medium varieties of the complexes positive values are typical - ΔNb (+1.548 до +0.049) or very close to them $\Delta Nb = -0.013$, this might testify in favor of the proposal about primary formation of the rocks under the affection of the plume source. Moreover the identifying factors for the basic rocks of the mantle plumes are their moderate enrichment (Fig. 6a); values of the relations $(La/Sm)_n > 1.8$ и $(Ce/Yb)_n > 7$ (Schilling et al., 1983; Le Roe et al., 1983). Except singular values, these correlations for medium - basic rocks are $(La/Sm)_n = 2.9-5.8$; $(Ce/Yb)_n = 8.0-27.0$. The correlation Nb/Y - Zr/Y (Fig. 10) is also about the affection of the plume source.

The fields of the model composition of basalts: oceanic islands (OIB), medium-oceanic ridges normal (N-MORB), island arc (ARC), oceanic plateau (OPB). Magmatic sources: primitive mantle (PM), abyssal depleted mantle (DEP), low abyssal depleted mantle (DE), recycled component (REC), enriched component (EN), upper crust (UC), enriched mantle with high Rb/Sr (EMII), enriched mantle with high Nd/Sm (EMI), enriched mantle with high U/PB. Arrow signs reflect the effect of the volumetric melting (F) and subductional enrichment (SUB).

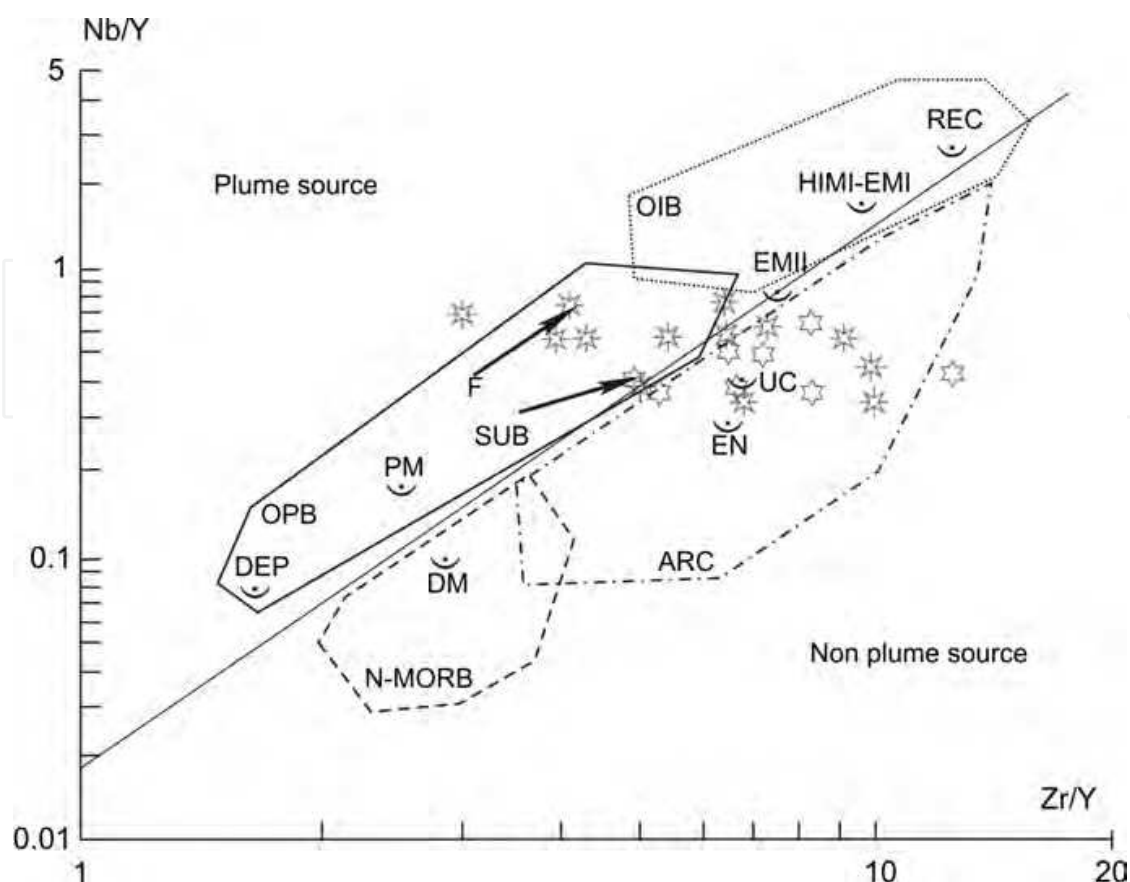


Fig. 10. The location of the rocks of the basic – medium composition of bimodal volcano-plutonic complexes on the diagram in the coordinates of pair correlations of Zr/Y - Nb/Y in ratio to typical basalts and magmatic sources by (Condi, 2005). The conventional signs of the rocks are on Fig. 2.

Late Mesozoic – Cainozoic concentric-zonal structure – Aldan-Zeisky plume was separated by the data of geophysical research, spatial parameters and peculiarities of the spreading of the viscous subcrustal layer (Petrishchevsky & Khanchuk, 2008). The authors consider that the central part of the plume was inverted (dropped) and continues to cave not long time ago (early Cretaceous). Location of the central part of Aldan-Zeisky plume practically is a contour of the location of the bimodal complexes in the frames of Eastern link of Mongol-Okhotsk orogenic belt (Fig. 1).

It was already mentioned about the resemblance of a few geochemical characteristics of the rocks of the researched complexes with such characteristics of the formations of the late Paleozoic – Mesozoic Central-Asian rifting systems. This fact illustrates Fig. 7, where the figurative points of the rocks of the bimodal complexes of the Eastern flank of Mongol-Okhotsk orogenic belt or partially cover them.

On the diagram $I_0^{Sr} - \epsilon Nd_{(T)}$ (Fig. 11) the figurative points of Galkinsky complex get into the frames of the fields of the compositions of Early – Late Mesozoic intraplate magmatic formations of Central-Asia are translocated to the area EM-II. The figurative points of Bomnaksy complex (Northern framing) are translocated to the area of an enriched source EM-I.

To this differences relay: the presence of normal alkalinity in the composition of the examined complexes of the volcanites. Also, there are relatively low concentrations of the highly charged elements: Nb, Ta, Zr, Hf.

Such characteristics make them closer to their products of subductional origin. Pretty low statistics of isotope data of the foundation rocks in the area of the development of magmatites of the bimodal complexes do not allow us to give a unique explanation to these facts. We can only make a proposal that the crust material coming into the magmas chambers was enriched with subductional component. That led to a partly mixture and the affection of the inherited characteristics of the foundation rocks on the formation of the bimodal complex.

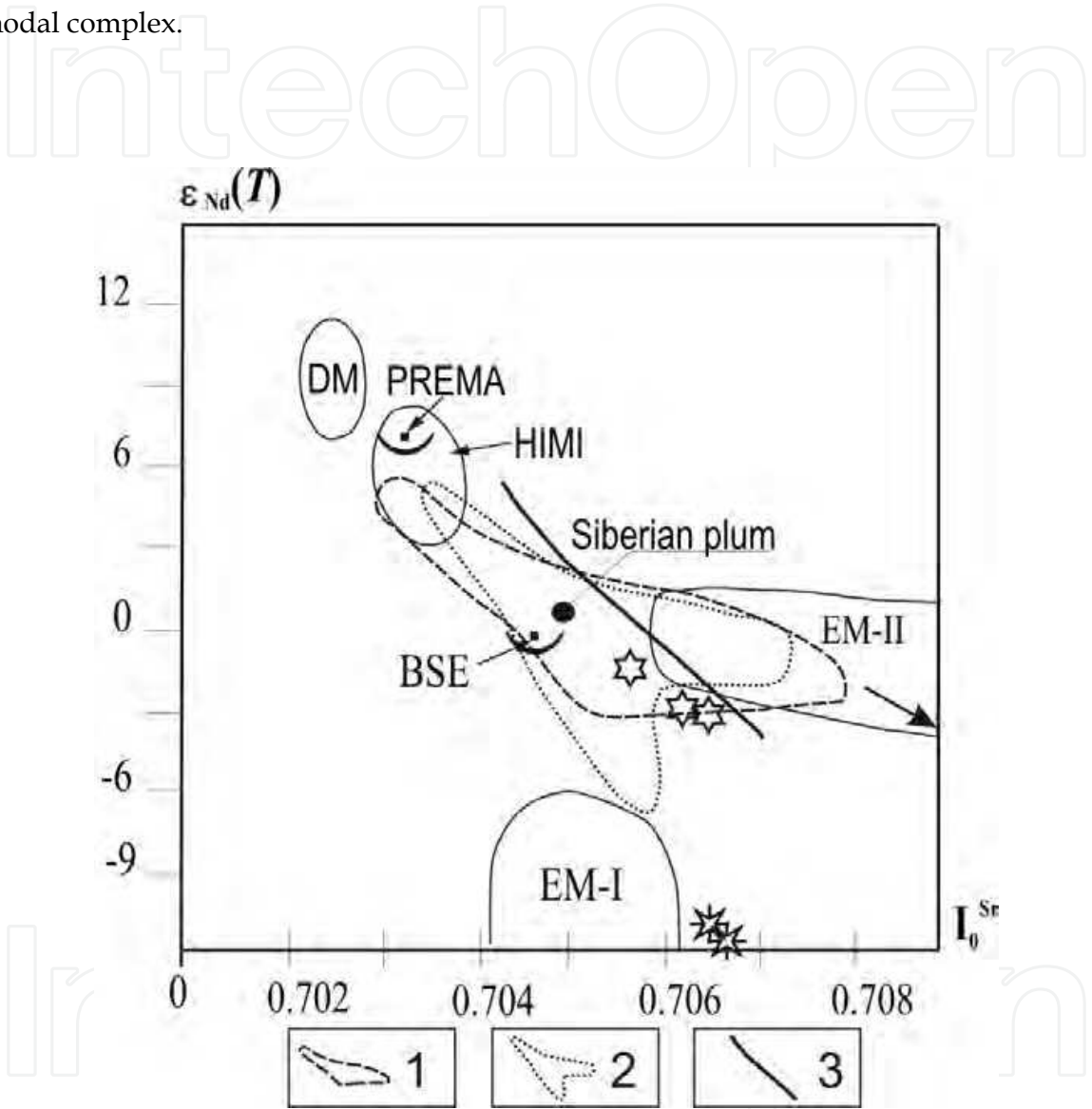


Fig. 11. Correlation of the composition of the rocks of the bimodal volcano-plutonic complexes of Eastern frames of Mongol-Okhotsk belt with the fields of intraplate magmatic rocks of Central Asia and typical sources of mantle by primary isotope compositions of Sr and Nd. The fields of rocks: 1 – Early Mesozoic and 2 – Late Paleozoic of Central Asia. 3 – trend of correlation of the composition of the basalts of the bimodal series of Early Mesozoic Mongol-Transbaikalian region by (Yarmolyuk et al., 2002). The data from the work (Types of magma, 2006) and data PREMA and BSE from (Zindler & Hart, 1986) were used to make a diagram. The conventional signs of the rocks are on Fig. 2.

But Late Mesozoic magmatism in the frames of the Eastern link of Mongol-Okhotsky belt has a row of differences from more ancient analogical magmatism of Central-Asian riftogenesis.

6. Geodynamical reconstructions

In the Mesozoic era, the examined part of the region was enveloped by the collisional processes that were caused by the convergence of North-Asian and Sino- Korean cratons and by the closure of the Eastern flank of the Mongol-Okhotsk basin (Sonenschein et al.; 1990; Parfenov et al., 1999). We should remind that the Late Mesozoic formations of bimodal series have a linear spreading along the Southern and Northern borders of Mongol-Okhotsk belt. Along the Southern border on the East their spreading is framed by the structures of Bureja-Jiamusy superterrane. Along the Northern frame – in the same direction – they are changing into younger calc-alkali formations of Okhotsk-Chukotsky orogenic belt (Fig. 1). Similar formations are not revealed on the South of Mongol-Okhotsk orogenic belt. But the bimodal complexes become widely developed on the West, in frames of Western branch of the examined belt. The bimodal complexes are one of the components of the Early Mesozoic North-Mongolian – East-Transbaikalian rifting zone. A pretty grounded geodynamical model was worked out for the zone (Yarmolyuk & Kovalenko, 2000; Yarmolyuk et al., 2002; Kovalenko et al., 2003; Vorontsov et al., 2004, Vorontsov et al., 2007). The basic point of the model is in simultaneously existing conditions of the pressure of the plume on the area that is under conditions of the collisional pressure.

On the discrimination diagram of the primary isotope characteristics of strontium and neodymium (Fig. 11) the points of the rocks of Galkinsky volcano-plutonic Late Mesozoic complex are close or match with the fields of early and Late Mesozoic intra plate magmatic formations of Central Asia. The points are superposed with the lower part of trend of correlation of basalts of Mongol-Okhotsk area's bimodal series. These correlations for the basic rocks are also brought close to the points that identify the location of the similar characteristics for Siberian plume and BSE.

The figurative points of the formations of the bimodal complexes of acid composition on the diagrams of the tectonic situations are concentrated in the field of the collisional conditions of the formation (in singular cases – intra platform) (Fig. 12a) or on the border of collisional-intra platform conditions of the formation (Fig 12b). A field of basalts of the island arc with a removal and partly location in the field of basalts of the continental rifts and traps is defined for the rocks of the basic-middle content (Fig. 12c).

The obtained data show that the rocks of the bimodal volcano-plutonic complexes that were formed in the frames of the Eastern link of Mongol-Okhotsk orogenic belt correlate with the intro continental formations in Central Asia by series of geochemical characteristics and isotope data. It was stated, that participation of a singular mantle source is possible in the formation of the formation of all late Mesozoic – early Cretaceous volcanites of Central Asia (Yarmoluk & Kovalenko, 2000; Kozlovsky et al., 2006). It is characteristic peculiarity is the high values of the correlation Zr/Hf (38-50). For the rocks of the researched complexes the value Zr/Hf correlates to 34-52 – Southern frame of the belt, 25-66 – Northern frame. This allows us to use the well-known geodynamical model, by the examination of the tectonic script of the formation of Galkinsky and Bomnasky volcano-plutonic complexes.

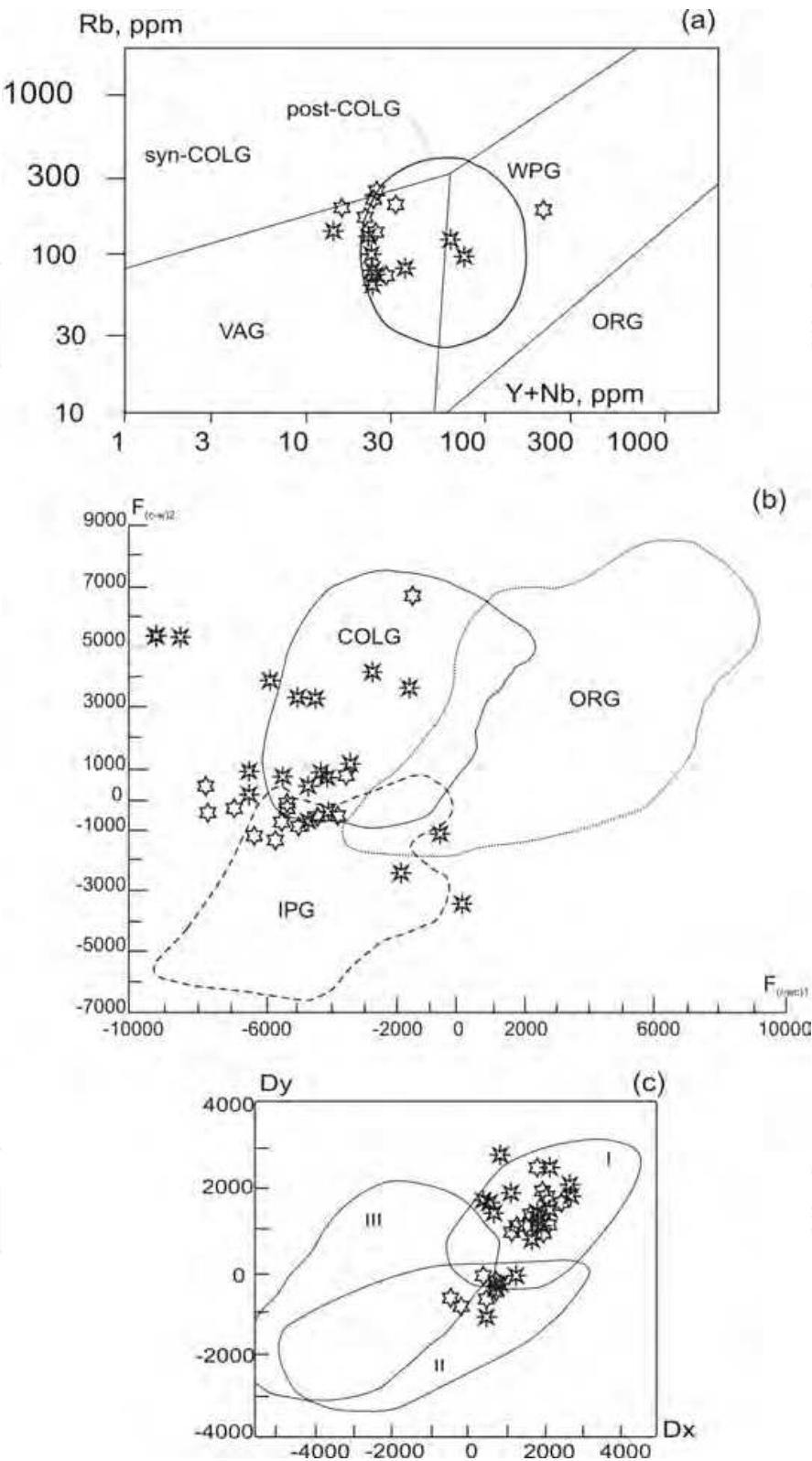


Fig. 12. Discrimination diagrams for the formation of the tectonic situations: a) Rb-Y+Nb (Pearce, 1996) and b) $F_{(c-w)2}/F_{(i-wc)1}$ (Velikoslavinsky, 2003; $F_{(c-w)2} = -752.3 \cdot SiO_2 - 6537.06 \cdot TiO_2 - 25.6 \cdot Al_2O_3 - 928.96 \cdot Fe_2O_3 + 1928.07 \cdot MgO - 464.21 \cdot CaO - 1808.19 \cdot Na_2O - 272.16 \cdot K_2O + 8675.33 \cdot P_2O_5 + 71073.5$; $F_{(i-wc)1} = 2432.42 \cdot SiO_2 + 7900.33 \cdot TiO_2 + 2512.12 \cdot Al_2O_3 +$

1380.23* FeOt + 2616.55* MgO + 3480.51* CaO + 3045.39* Na₂O + 645.91* K₂O - 241285.5) for the salic formations; c) D_x/D_y (Velikoslavinsky & Glebovitsky, 2005; $D_x = (176.94* \text{SiO}_2) - (1217.77* \text{TiO}_2) + (154.51* \text{Al}_2\text{O}_3) - (63.1* \text{FeOt}) - (15.69* \text{MgO}) + (372.43* \text{CaO}) + (104.41* \text{Na}_2\text{O}) - (19.96* \text{K}_2\text{O}) - (873.69* \text{P}_2\text{O}_5) - 11721.488$; $D_y = (94.39* \text{SiO}_2) - (103.3* \text{TiO}_2) + (417.98* \text{Al}_2\text{O}_3) - (55.63* \text{FeOt}) + (57.61* \text{MgO}) + (118.42* \text{CaO}) + (502.02* \text{Na}_2\text{O}) + (6.37* \text{K}_2\text{O}) + (415.31* \text{P}_2\text{O}_5) - 13724.66$) for the basin rocks. The fields of the basalts: I – island arcs, II – traps, III – continental rifts. The conventional signs of the rocks are on the Fig. 2.

7. Conclusion

The bimodal volcano-plutonic complexes of subalkali – normal petrochemical series were formed along the Southern and Northern borders of the eastern flank of Mongol-Okhotsk orogenic belt in the interval 119 – 97 Ma. The duration of the formation of similar complexes (to 35 Ma) is marked for the intercontinental formations of Central Asia (Yarmolyuk et al., 2000; Yarmolyuk et al., 2002; Kovalenko et al., 2003; Voroncov et al, 2007).

Both spinel and garnet peridotites were a protolite for the basaltoids of the complexes, and geochemical characteristics of basaltoids are minimum Ta and Nb with maximum K and Pb, point at their formation in the situation of convergent borders of the plates. The enrichment of the incompatible elements is characteristic for all the varieties of the rocks of the bimodal complexes, with the decreased content of Ta, Nb, Ti and more high presence of Ba, Sr, K и Pb. As A.A. Vorontsov and coauthors notice (Voronysov et al., 2007) these peculiarities are characteristic for all late Paleozoic – early Mesozoic intra plate rocks of Central – Asian riftous system, its development is connected with the overlapping of the continental lithosphere of the plume source.

Thus, it can be stated: the formation of the bimodal complexes in the frames of the Eastern link of Mongol-Okhotsk orogenic belt accompanied the collision of North-Asian and North-Korean continents at the affection of the plume source. The result of this process was a final closure of Mongol-Okhotsk basin at the end of Early Cretaceous: 119-97 Ma.

8. References

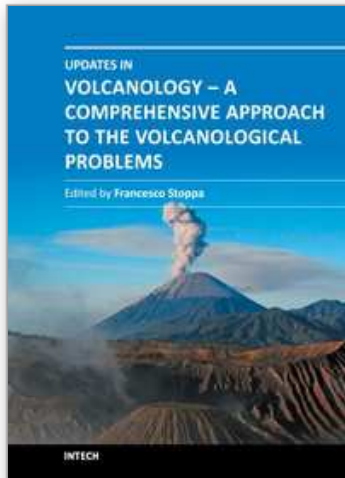
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