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The Maimecha–Kotui alkaline-ultramafic province of the northern Siberian platform, Russia

The Maimecha–Kotui province, in the northern part of the Siberian platform, is one of the few world regions where effusive and intrusive alkaline-ultramafic magmatism coincides spatially and temporally over a very short time period. Flood-basalts and kimberlites of the same age (Lower Triassic) also occur.

Magmatic events began with a volcanic series which are divided into five suites. Later, multi-phase intrusive complexes appeared associated with carbon-

atites. Magmatic activity in the province ended with the development of a dyke complex and intrusion of basic, alkaline and alkaline-ultramafic rocks, kimberlite dykes and explosion pipes. The genesis of this rich variety of igneous and volcanic rocks is still problematic. This, with their mineral resource potential (including diamonds, PGE minerals, magnetite and perovskite ores), demands further intensive studies involving international teams of geoscientists.

Figure 1 Geological map of the Maimecha–Kotui province.

Figure 2 Geological map and stratigraphy of the L Triassic volcanic sequence.

1 Quaternary sediments;	7 Pravoboyarskaya suite
2 Maimechinskaya suite (meimechites);	(tuffs and tuffites);
3 Delkanskaya suite, upper subsuite	8 Aridzhanskaya suite (olivine
(basalts, andesites, dacites, trachy-	melanephelinites, nephelinites, melilites,
basalts, trachyandesites, picrite porphyrites);	augites, limburgites, alkaline picrites);
4 Delkanskaya suite, lower subsuite	9 Permian sandstones, alevrolites, shales,
(melanephelinites, nephelinites, melilites,	alkaline basalts and their tuffs;
olivine nephelinites, analcimites);	10 Palaeozoic carbonate sediments;
5 Kogotokskaya suite, upper subsuite	11 Guli intrusive complex of ultramafic and
(trachybasalts, shoshonites, basalts);	alkaline rocks and carbonatites;
6 Kogotokskaya suite, lower subsuite	12 dolerite sills and dykes;
(basalts);	13 geological boundaries

Introduction

Investigation of the Maimecha-Kotui province started in 1937 when G G Moor identified augites, limburgites, and ijolites in a collection of samples from the left bank of the Maimecha river and V S Sobolev predicted the presence of a huge alkaline province in the north of Central Siberia.

Among the known areas of alkaline-ultramafic magmatism in Eurasia, Africa, South and North America, the Maimecha-Kotui province is of special interest due to its unusual scale and extreme richness of petrological variety. Here, in early Triassic, a thick volcanic sequence and innumerable intrusive complexes, including carbonatites, hypabyssal bodies, kimberlitic dykes and pipes developed.

The variety of igneous rocks, their diverse composition and excellent exposure give the region worldwide significance for the

potential resolution of a series of petrological, geological and mineral resources problems.

Geological setting and structure

The Maimecha-Kotui province occupies an area of 70 000 km² and its geological structure is determined by a position at the northern margin of Siberian platform (Figure 1). A major part of the territory is composed of Upper Proterozoic carbonate-terrigenous sediments covering discordantly an Archaean-Lower Proterozoic crystalline basement which crops out in the south-east (Anabar shield). In the north, there is a cover of terrigenous Permian sediments and a sequence of Mesozoic ultramafic lavas partly overlain by younger sediments of the Khatanga trough.

Tectono-magmatic activity during the formation of the sedimentary cover of the Siberian platform gave the province a block-type structure and magmatic events of two major stages—Upper Proterozoic and Early Triassic. Upper Proterozoic dykes and sills of dolerite (900–1100 Ma) are associated with Ryphean terrigenous carbonate sediments exposed along the right bank of the Kotui river. The sills extend up to scores of kilometres and range from 200 to 250 m in thickness.

An exceptionally wide range of magmatism resulted from the Early Triassic tectono-magmatic activity. The earliest igneous products were innumerable dykes and sills of dolerites; with major concentrations of sills emplaced in a sequence of Permian sediments. The dykes, of mainly north-western strike, extend up to 100 km and cut the Lower Palaeozoic sediments. Later alkaline-ultramafic igneous, extrusive and effusive rocks are represented by four clearly distinguished groups:

- 1 effusive eruptions of alkaline-ultramafic and alkaline rocks with related dykes, sills and explosion pipes;
- 2 complex massifs of alkaline-ultramafic rocks (associated with carbonatites);
- 3 post-intrusive dykes and explosion pipes of alkaline-ultramafic rocks and
- 4 dykes and pipes of kimberlites.

Volcanism

Lower Triassic volcanic rocks are exposed in the north-west of the province along the north-western margin of the Siberian platform and dip partly under younger sediments of the Khatanga trough. Block-

type tectonics and lateral variations in composition complicate their study. However, major features of the stratigraphy have been determined (Figure 2). The rocks have been classified into five suites, namely (from bottom to top): Pravoboyarskaya and its facial analogue—Aridzhanskaya, Kogotokskaya, Delkanskaya, and Maimechinskaya (Butakova, Egorov, 1962; Zhuk-Pochekutov and others, 1965; Shikhovina, 1959).

The Pravoboyarskaya suite is composed of basic tuffs and tuffites overlying the Permian sediments. Its thickness varies from 250 to 400 m.

The Aridzhanskaya suite, 300–500 m thick, is at the same stratigraphical level and lies discordantly on Permian terrigenous sediments. In the lower parts of the Kotui river, where the suite is exposed over an area of 30 × 80 km², there is a basal layer of alkaline-ultramafic tuffs 20–25 m thick. Higher in the succession, flows of melanephelinites, melilitites, their olivine varieties, augites, lim-

burgites, alkaline picrites and shoshonites alternate with each other. Excellent sections are exposed in cliffs along the Kotui river.

The Kogotokskay suite is divided into two subsuites. The lower one, with a thickness of 400–500 m, is composed of basaltic flows which are in contact with flood-basalts, of substantially similar major-element composition, in the south-east and north-west of the platform. The upper subsuite comprises subalkaline olivine basalts and trachybasalts alternating with flows of trachybasaltic andesites, andesites, shoshonites and trachytes. The suite thickness for various areas of the province is 350–400 m. Sections are exposed along the Kotui and Maimecha rivers and their tributaries.

The Delkanskay suite crops out locally in the left banks of the Maimecha river in a region with a complex dislocated block structure and is less studied than the other suites. However, two subsuites may also be distinguished here. A lower subsuite, 500–545 m in thickness, has an alkaline-ultramafic composition with a prevalence of melanephelinites and melilitites, melancimites, limburgites, augites and alkaline picrites. The upper subsuite, 400–500 m thick, is composed mainly of trachybasalt-trachyte. In addition, there are flows of ultramafic foidites, andesites, rhyolites and trachytes.

The Maimechinskay suite completes the volcanic sequence of the province and is composed of ultramafic lavas—meimechites. Flows, sometimes alternating with tuffs, cover concordantly the Delkanskay suite in a field of up to 60 km² in the lower parts of the Maimecha river. According to several estimates the suite thickness varies from 400 up to 2000 m (Butakova, Egorov, 1962; Vasiliev, Zolotukhin, 1975; Egorov, 1991). Meimechites are unique volcanic rocks of ultramafic composition occurring mostly in the

Maimecha–Kotui province. They are dark grey, almost black with a massive, layered and porphyritic structure. The only phenocrysts are are of magnesian olivine (0.3–0.8 cm and larger) while the ground-mass reveals various degrees of crystallinity, changing from vitrophyric and microlitic to completely crystalline when it is composed of titaniferous clinopyroxene. Accessory minerals include chrome-spinelides, Ti-magnetite, biotite, perovskite and sulphides. The meimechites have typically high MgO (up to 35 wt %), low alkalis (0.4–0.6 wt %) and increased REE contents comparable with kimberlites. Several determinations show that the age of Aridzhanskay and Maimechinskay suites is 249 and 250 Ma, respectively. Thus, we may conclude that several kilometres thickness of volcanic material were generated in a very short period of nearly one million years. (Basu and others, 1995; Arndt and others, 1995)

However, it is suggested by others (Dalrymple and others, 1995) that magmatic activity lasted for ten million years.

Alkaline-ultramafic and carbonatite intrusive complexes

More than 50 multiphase intrusive complexes have been discovered in the Maimecha–Kotui province. Outcrop areas vary widely. The largest complex covers 1500 km²; two are 42 to 56 km², three 11 to 18 km², and four 3 to 7 km². The others measure from 10 to 100 m². All the complexes are concentrated along submeridional faults and bear common structural features. They have a cylinder-like morphology and intrude Palaeozoic terrigenous-carbonate rocks whose layers may be vertical near the contacts. Petrographical compositions are diverse but the whole set of rocks does not change significantly from complex to complex. The majority of geologists consider these rocks, which usually have been emplaced concentrically, to have a multiphase origin and distinguish the following succession:

- 1 dunites (olivinites, peridotites);
- 2 melilitite rocks;
- 3 jacupirangites–melteigites and related alkaline mafic rocks;
- 4 ijolites;
- 5 nepheline and alkaline aegirine syenites;
- 6 rocks of a phoscorite series;
- 7 carbonatites.

All phases are represented in only two massifs—Guli and Kugda where together with subphases (such as ijolite-pegmatites, early carbonatites, etc.) they make up circular bodies. In terms of composition, the intrusive complexes of Maimecha–Kotui may be divided into three groups:

- 1 massifs with a prevalence of ultramafic rocks (Guli, Bor-Uryakh, Kugda);
- 2 massifs with a prevalence of ijolites (Odikhincha, Magan, and the majority of other province massifs);
- 3 massifs with a prevalence of carbonatites (Essey, Dalbykha).

The Guli massif

The Guli intrusive complex occupies a narrow area between the Maimecha and Kotui rivers at the boundary of Siberian platform and the Khatanga trough (Figure 3). Its position, at the transection of the most active deep-seated faults, has influenced its morphology. The massif intrudes and alters Lower Triassic volcanic rocks: ultramafic foidites of the Aridzhanskay suite; trachybasalts, trachyrhyolites, ultramafic foidites, alkaline picrites and meimechites of the Kogotokskay, Delkanskay and Maimechinskay suites. It has a total area of 1500–1800 km² according to geophysical data. Major intrusive rock types include dunites and various mafic alkaline rocks, while 10% of the area is occupied by melilitoids, ijolites, alkaline syenites and carbonatites. The Guli massif is distinguished from another complexes by: its large size; the prevalence of dunites over other rocks; the active contact of dunites with Lower Triassic volcanic rocks; and the presence of two carbonatite stocks in the centre of intrusion sur-

Figure 3 Geological map of the Guli massif.

1 Kogotokskaya suite (basalts);	rocks with garnet and phlogopite;
2 Delkanskaya suite (alkaline-ultramafic lavas, trachybasalts, andesites);	9 phlogopitised ultrabasic intrusives;
3 relics of volcanic flows over the ultrabasic intrusives;	10 metasomatically altered meimechites;
4 dunites and peridotites;	11 carbonatite stocks;
5 pyroxenites;	12 zone of contact hornfels
6 melanephelinites and nepheline picrites;	13 Quaternary and Mesozoic sediments of the Khatanga trough;
7 meimechites;	14 boundary of Guli pluton according to geophysical data.
8 ijolite-melteigites and metasomatic nepheline-pyroxene	

Figure 4 Geological map of the Odikhincha intrusive complex.

1 vein nepheline syenites;	8 (a) Ryphean siliceous-carbonate sediments
2 (a) ijolites, (b) melanite ijolites	(b) metamorphosed;
3 (a) melaijolites, (b) feldspar melaijolites;	9, 10 (a) Cambrian carbonate sediments (b) metamorphosed;
4 jacupirangites and melteigites;	11 faults;
5 melilite rocks;	12 strike and dip of sedimentary rocks.
6 olivinites;	
7 Ryphean dolerites;	

rounded by successive phases of all other alkaline and alkaline-ultramafic rocks. In other, similar massifs, ultramafic rocks (olivinites) either prevail (Bor-Uryakh massif), or make up the major area of the outcrop (Kugda massif).

The Odikhincha massif

This complex, with an area of 56 km², is located on the right bank of the Kotui river and has intruded Lower Cambrian dolomites (Figure 4). It has a concentric structure in plan and the largest intrusive phases are represented by olivinites, melilite rocks, jacupirangite-melteigites and ijolites. Olivinites occur mostly as xenoliths (up to 5 m) in ijolites and jacupirangites and as large blocks (up to 1 km²). Melilite rocks occur in eastern and northern parts of the massif and make up two relatively large bodies up to 9 km across. In addition, there are xenoliths and rather large blocks of melilite rock (up to 1 km) in ijolites and urtites. Jacupirangites form a huge circular intrusion which has altered the host rocks, while ijolites occupy the central, western and southern parts of the massif in a large stock-like body. Younger veins of alkaline and nepheline syenites cut all other rocks of the massif especially in peripheral parts. Carbonatites form rare thick veins (up to 1 m) in the eastern part of the massif. In all other smaller massifs (Urukite, Magan, Kara-Meni, Nemakit, etc.) the most abundant rocks are ijolites, though olivinites, melilitites, melteigites, and jacupirangites may occur.

The Essey massif

The Essey intrusive complex lies 30 km north of Lake Essey and 200 km inside the northern margin of the Siberian platform (Figure 5). It is related to the Maimecha-Kotui fault and to a large north-westerly trending dislocation associated with the Kharamay kimberlite field.

Ordovician sedimentary carbonates have a vertical dip at the contact with the intrusion. Calcite and dolomite carbonatites are the most common intrusives but rocks of the phosphorite series form bodies in one zone. Jacupirangites and ijolites, with an outcrop area of 0.7 km² are represented by a large circular body broken by the intrusion of phosphorites and carbonatites. The jacupirangites carry xenoliths of pyroxenised olivinites.

The generation of multiphase plutons in the province was followed by alteration of the host rocks and complex interaction with the intrusive phases. The host rocks have suffered:

- 1 dynamic effects including the formation of dome structures and zones of fissures filled with dyke rocks;
- 2 metasomatic alteration leading to accumulation of specific minerals.

The alkaline-ultramafic intrusive complexes of the Maimecha-Kotui province carry large deposits of phlogopite (Guli, Odikhincha), apatite (Guli, Dalbikha, Magan, Essey), ilmeneo-magnetite (Guli, Kugda, Bor-Uryakh) industrial- and gem-chrysolite (Kugda). There are also occurrences of perovskite ore (Kugda), PGE minerals (Guli) and pyrochlore (Dabikha).

Figure 5 Geological map of the Essey intrusive complex.

1 dolomite carbonatites;	6 Ordovician limestones and dolomites;
2 fine-grained calcite carbonatites;	7 limonite-francolite weathering crust;
3 olivine nelsonites;	8 alumophosphatic weathering crust;
4 ore forsterites, phosphorites and magnetites;	9 faults.
5 jacupirangite-melteigites and ijolites;	

Figure 6 Distribution of dyke bodies around the Bor-Uryakh (a) and the Nemakite (b) alkaline-ultramafic intrusives.

- 1 alkaline-ultramafic massifs;
- 2 alkaline-ultramafic dykes;
- 3 dolerite dykes;
- 4 dykes and faults.

Hypabyssal alkaline-ultramafic magmatism

Hypabyssal phases are represented by dykes and explosion pipes cutting the massifs, forming dyke swarms around intrusive centres and tracing regional faults systems as linear fields of large extent (Figure 6). Such fields may reach 100 km in length with widths of 15–30 km. Zhabin and Surina (1970) have distinguished several linear fields in which alkaline-ultramafic intrusive complexes are localised along faults. The dyke bodies are usually plate-like, have insignificant lengths (10–50 m) and thicknesses in the region of 0.5–1 m. The observed relationships between dykes suggests the following order of emplacement: augites, limburgites, melilitites, olivine melanephelinites, melanephelinites, nephelinites, phonolites, shonkinites, alkaline syenite-porphyrates, alnöites, syenite breccias. Petrographical composition of the dykes is very similar to that of the volcanic rocks.

Kimberlites

Kimberlites occur as dykes and explosion pipes emplaced in the latest stages of province magmatism. They are found in two areas.

The Dalbykh field lies between the Maimecha and Kotui rivers and includes several isometric bodies (Krasnoyarskaya, Zheltenkay, Krokhotulia pipes) composed of carbonatised breccias of mica kimberlite with accessory pyrope and picro-ilmenite.

The Kharamai field is located 60 km south-east of Essey in Cambrian dolomites. It contains 150 pipes and dykes in an area of 1000 km² with the majority concentrated in 150 km². Pipes with a rounded or elongated morphology in plan prevail. Breccias composing the pipes are cut by veins of massive kimberlite. Kimberlite breccias carry innumerable mantle xenoliths and the kimberlites themselves contain pyrope, picro-ilmenite and accessory diamond (Kirichenko, Makarov, 1989).

Geochemistry

Tables 1–4 and Figure 7 show average compositions of the major suites—volcanic rocks (including meimechites), intrusive complexes, hypabyssal rocks, and kimberlites. Meimechites are unique ultramafic lavas with high content of MgO (up to 35 wt %), low alkali contents (~0.5 wt %) and high REE concentration (Figure 8) attracting the attention of many researchers (Arndt and others, 1995; Basu and others, 1995; Sobolev and others, 1972) as possible primary melts from which all rocks in the province evolved. It is possible to distinguish three associations of volcanic rocks: a) basalts; b) alkaline ultramafics, basic and andesitic rocks; and c) meimechites (Sobolev and Slutskii, 1984; Kogarko, Ryabchikov, 1995).

Compositional variations in the alkaline lavas, the presence of olivine and pyroxene in phenocrysts, their chemistry and zonality suggest that fractional crystallisation was dominant. We have modelled this for the supposed primary melts meimechite and alkaline picrite using REE partition coefficients in the mineral–melt system and concluded that fractional crystallisation of a melt with meimechite composition does not yield residual liquids corresponding to the alkaline volcanic rocks of the region. The modelled differentiation of magmas with a picrite composition does result in alkaline volcanic rocks. Similar REE patterns in meimechites and picrites however, suggest that they are genetically related at the primary melt stage (Figure 8). Different REE patterns are revealed by basalts of the Kogotokskaya suite which are similar to those of flood-basalts of the Siberian platform. We have estimated PT parameters of liquidus phase crystallisation in the source melts and differentiates. For meimechites, the maximum temperature of olivine–melt equilibrium was found to be $1562 \pm 20^\circ\text{C}$, for alkaline picrites it is lower— $1480 \pm 64^\circ\text{C}$, for alkaline-ultramafic lavas (melanephelinites, nephelinites, etc.)— $1450 \pm 40^\circ\text{C}$, for olivine basalts of the Kogotokskaya suite— $1390 \pm 30^\circ\text{C}$ (Laguta, 1993).

Intrusive complexes of ultramafic and alkaline rocks with carbonatites were also studied. Average chemical compositions are given in Table 2. Among intrusive rocks of the first phase we may distinguish not only dunites, olivinites and pyroxenites, but also peridotites, pyroxenised dunites, ore pyroxenites, ore olivinites, etc. The second phase is represented by monomineralic melilitolites as well as another varieties (kugdites, okaites, etc.). Other intrusive phases are also represented and their interaction often caused the appearance of rocks transitional in composition. As with many of the volcanic rocks the intrusive ones are SiO₂-undersaturated (dunite olivinite, melilitolites jakupirangite-urtite, etc.) and have increasing contents of TiO₂, Al₂O₃, CaO and alkalis with decreasing MgO. Their compositions (excluding phoscorites and carbonatites) fall within the trend of volcanic rock differentiation (Figure 7).

Not one of the proposed petrogenetic models (fractional or gravitational crystallisation, liquation, development of independent chambers, independent generation of ultramafic and alkaline rocks development of volcanic–plutonic systems, etc.) explains completely the observed succession of intrusive phases from dunite through alkaline rocks to carbonatites and the presence of monomineralic rocks (dunites, olivinites, melilitolites, varieties of phoscorites, and carbonatites).

Table 3 shows the average compositions of dykes which are similar to volcanic rocks (meimechites, alkaline picrites, nephelinites, melilitites, etc.) pointing to a common origin. Dykes forming radial swarms around intrusive complexes are mainly alkaline-ultramafic and alkaline.

The average compositions of kimberlites are given in Table 4 and Figure 7. Small pipes of the Dalbykh field to the south of Gu' pluton are altered by crustal weathering. Kimberlites of the Kharamai field have been studied more thoroughly. Their average composition is intermediate between those of southern and northern Yakutian kimberlites.

Figure 7 MgO-oxide variation diagrams for magmatic rocks of the province (data are in Tables 1–4).

1 effusive rocks; 2 intrusive rocks; 3 hypabyssal rocks; 4 kimberlites.

Petrogenesis and geodynamic setting

Magmatic activity in stable continental cratons is related to the ascent of hot and less dense mantle plumes. The Maimecha–Kotui province lies in the northern part of the Siberian platform, a huge stable craton where the appearance of widespread flood-basalt volcanism coincides with collision of the Karsk continent and Siberian platform leading to the Taimyr orogenesis (242–249 Ma) (Vernikovskiy, 1995). Volcanism occurred at the Permian–Triassic boundary (Renne, Basu, 1991; Basu and others, 1995; Campbell and others, 1992; Dalrymple and others, 1995).

Magmatic evolution in the Maimecha–Kotui province (253 Ma) (Basu and others, 1995) started with development of alkaline and alkaline-ultramafic magmatism. It was followed by tholeiitic flood-basalt and alkaline magmatism, and finally by alkaline-ultramafic lavas (246 Ma) clearly related to rifting and to faults across the Taimyr folded system. These faults may reflect extension following

plume development. Two types of rifting have been distinguished. ‘Spreading’ rifting is related to flood-basalts; ‘concentrated’ rifting leads to ultramafic, subalkaline, alkaline and alkaline ultramafic volcanic eruptions and subvolcanic intrusions. Concentrated rifting provides quick surface access for melts and the eruption of primary ultramafic as well as basic and alkaline differentiates. Spreading rifting leads to a more gradual rise of melts to the surface resulting in sills and, then, huge fields of flood-basalt.

The depth of origin of the primary ultramafic melts was not less than 200 km (Arndt and others, 1993). The meimechite melt contained ~25% MgO according to a study of melt inclusions by Sobolev and others (1991). The temperature at the start of olivine crystallisation was ~1600°C. Temperatures of tholeiite flood-basalts according to the study of inclusions was not less than 1200–1250°C (Sobolev, Kostyuk, 1975), while the ultramafic–mafic differentiated intrusions of the Norilsk region had a temperature of generation of not less than 1350°C (Bulgakova, 1971). Primary melts of these intrusions contained ~10–12% MgO (Zolotukhin, Vasiliev, 1967). Fractionation of such primary melts with a feldspar picrite composition and MgO ~ 12 wt % could produce the whole variety of tholeiite flood-basalts of Siberian platform. However, without additional input of alkalis it is impossible to account for the subalkaline, alkaline and alkaline-ultramafic rocks (Zolotukhin and others, 1989).

The role of fractional crystallisation was especially important in producing the rich variety of rocks of the Maimecha–Kotui province (Gladkikh, 1995). There should

Figure 8 REE pattern for volcanic rocks of the Maimecha-Kotui province.

- 1 ultramafic and basic alkaline rocks of the Arydzhanskay and Delkansskay suites;
- 2 basalts of the Kogotokskay suite;
- 3 meimechites.

be several primary melts with different MgO contents and alkalinity. From what is known of the relative amounts and successions of the various magma types, it may be concluded that deep-seated melting from non alkaline mantle material at very low levels of melting (1%) could not have produced the observed volume of alkaline rocks. The change from an alkaline effusive phase (Arydzhanskay suite) to normal tholeiite (Kogotokskay suite) and then to alkaline and alkaline-ultramafic rocks demands an explanation as to why the degree melting changed as it did. Also it is necessary to explain a succession of intrusive phases which show increasing alkalinity (dunites-olivinites - pyroxenites - alkaline basites - nepheline syenites - carbonatites).

The relationships between tholeiite, alkaline and alkaline-ultramafic melts in the Maimecha-Kotui province is unclear. There may have been a system of unrelated, variously deep-seated magmatic chambers with independent melts undergoing fractional crystallisation or, there may have been a single chamber with fractional crystallisation. It is also possible that there was a system of variously deep-seated magmatic chambers with primary magmas of various Mg content and affected by alkaline fluids. Thus, ultrabasic and basic melts may have become alkaline-ultramafic and alkaline melts with subsequent fractional crystallisation.

The first two suggestions do not explain the observed features of the province. The most likely is a third explanation—the existence of several isolated chambers with melts of meimechite-picrite and feldspar-picrite which fractionated independently. The melts appeared due to melting of the plume material with decrease of pressure during its rise and decompression in faults. $^3\text{He}/^4\text{He}$ ratios, increasing 12.7 times relative to the atmospheric ratio, suggest a lower mantle origin of the plume (Basu and others, 1995).

Isotope compositions of Siberian platform plumes, mantle and crustal substrates as well as major rock-types from Maimecha-Kotui and flood-basalts of the Siberian platform are shown in Figure 9 (Basu and others, 1995). Sr-Nd isotope data are compared with those for another regions (Sharma and others, 1992; DePaolo and Wasserburg, 1979; Basu and others, 1995). Primary ϵ_{Nd} for the Siberian plume is determined as $+1.8 \pm 0.7$ (Sharma and others, 1992) for samples from relatively uncontaminated lavas of Putorana (Figure 9). The same values were found in four samples from the lower part of the Maimecha-Kotui stratigraphic succession. However, four samples from upper part, including three meimechites, show a shift towards a depleted mantle (MORB) component (Basu and others, 1995). Thus, the early stage of volcanism in the Maimecha-Kotui province reflects a mixing of plume and depleted asthenosphere material. The final stage of flood-basalt volcanism in the Putorana and Norilsk areas demonstrates an interaction between plume and continental lithospheric mantle materials (Figure 9). The interaction of the plume produced from the lower mantle, with sub-oceanic mantle for the early stage is also supported by REE distribution and Ce/Pb ratios (Basu and others, 1995).

Taking into account the large volume of basalts near the Permian-Triassic boundary several researchers have suggested (Campbell and others, 1992; Lightfoot and others, 1990; Sharma and others, 1992) that the main source of magmas was the mantle plume itself. Others believe (Arndt and others, 1995) that the position of meimechites at the end of flood-basalts trend may be evidence that alkaline rocks were also produced from the plume (see Figure 9). We join the opinion that alkaline magmatism of the Maimecha-Kotui province and tholeiite magmas of the Siberian flood-basalt province are related by geodynamical and geochemical processes involving a high ^3He plume (Basu and others, 1995).

Further study

The economic potential of the Maimecha-Kotui province has not been completely assessed. The Kharamai kimberlite field was discovered in 1979 and dyke bodies and explosion pipes of alkaline-ultramafic composition are widespread. Alluvial and bedrock diamonds are known and there is significant potential for discovering further considerable occurrences. No less important is the need for further study to help resolve basic petrological problems. In this respect the province has a series of advantages that should provide opportunities to explain:

- 1 the causes of spatial and temporal associations of flood-basaltic, alkaline-ultramafic and kimberlitic magmatism in platform settings (Zolotukhin, Vasiliev, 1987);
- 2 the relations between ultramafic, alkaline-ultramafic and basic types of magmatism in volcanic sequences as well as composite alkaline-ultramafic complexes with carbonatites (Vasiliev, Zolotukhin, 1975);
- 3 the alkalisation of basic and ultramafic melts by deep-seated fluids; and
- 4 ore genesis in relation to alkaline and alkaline-ultramafic intrusive complexes and the role of metasomatism.

Conclusions

The Maimecha-Kotui province of the north of Siberian platform has a complex magmatic history and an extraordinary variety of early Triassic alkaline, alkaline-ultramafic, tholeiite and kimberlite rocks.

Researchers have traced the genetic links between various phases of magmatism and magmatic chambers located at different depths for different periods of activity. However, there are still many unresolved problems such as relation between tholeiite, alkaline and alkaline-ultramafic magmatism and the origin of the whole range of magmatic products. The Maimecha-Kotui province could provide rich fields of study for international research groups.

Figure 9 Initial ϵ_{Nd} and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of eight Maimecha-Kotui samples (Basu and others, 1995).

1 meimechite;	DM depleted mantle (MORB);
2 olivine nephelinite;	BE bulk chondritic earth;
3 olivine basalt;	SCLM subcontinental lithospheric
4 nepheline analcimate;	mantle;
5 trachybasalt;	LCC lower continental crust.
6 basalt;	

Table 1 Average chemical compositions of volcanic rocks (wt % and ppm).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SiO ₂	36.42	38.15	38.23	39.10	39.65	41.44	40.00	42.73	41.52	41.88	41.18	47.05	46.72	45.81	45.19	51.91	58.78	58.52	63.68	58.50
TiO ₂	2.04	3.00	3.35	3.71	3.60	3.66	3.98	4.38	4.84	3.80	4.42	1.71	1.41	3.94	4.54	2.84	1.17	1.16	0.77	1.28
Al ₂ O ₃	2.27	4.44	7.76	9.43	10.07	10.04	11.20	10.57	13.00	9.45	8.92	14.54	14.95	9.13	11.03	15.58	15.92	15.37	15.88	15.52
Fe ₂ O ₃	6.43	7.94	10.17	10.02	8.95	7.71	8.73	7.03	5.67	8.52	7.94	5.81	5.85	5.70	8.15	5.70	5.29	3.46	2.73	4.05
FeO	6.32	6.73	3.57	3.58	4.78	5.78	5.20	5.29	4.84	5.06	6.24	7.09	6.31	7.55	6.06	4.28	3.62	3.17	1.84	1.67
MnO	0.17	0.21	0.22	0.22	0.21	0.22	0.21	0.22	0.29	0.21	0.25	0.20	0.19	0.19	0.20	0.16	0.16	0.13	0.15	0.11
MgO	32.60	20.79	10.93	7.32	8.96	9.24	7.11	6.98	6.34	9.41	8.42	6.80	6.54	9.04	5.78	3.23	2.05	1.96	0.83	1.81
CaO	3.93	9.86	14.03	13.35	13.33	12.59	12.84	11.40	12.11	12.07	11.96	10.50	10.34	10.11	9.17	6.63	4.10	3.35	1.02	3.16
Na ₂ O	0.10	0.45	1.74	2.19	2.91	3.18	3.37	3.69	2.65	2.57	2.75	2.01	2.10	2.27	2.11	3.97	3.49	4.37	1.95	0.58
K ₂ O	0.29	1.00	1.97	3.03	1.32	1.32	1.60	1.64	1.70	1.50	1.45	0.45	0.53	1.71	3.64	3.14	3.94	5.32	11.0	11.86
P ₂ O ₅	0.22	0.42	0.60	0.92	0.68	0.59	0.70	0.61	0.46	0.54	0.67	0.20	0.16	0.53	0.95	0.83	0.55	0.91	0.06	1.06
LOI	7.84	5.98	6.80	6.29	4.49	3.91	4.44	4.19	2.93	4.18	4.28	2.55	3.60	3.05	2.80	1.13	1.34	2.49	0.36	0.98
CO ₂	0.56	0.69	3.29	3.09	1.22	0.74	0.96	1.09	0.10	0.99	2.43	0.68	0.72	0.46	0.94	0.20	0.10	0.30	0.20	0.05
Cu	95	120	345	195	175	161	175	170	130	164	190	175	183	185	162	55	39	21	-	-
Zn	103	63	122	68	104	85	121	115	122	76	75	80	134	114	130	104	115	120	-	-
Co	142	92	49	35	31	58	53	70	42	37	40	46	48	56	51	19	15	13	-	-
Ni	2115	832	45	136	121	271	103	131	102	178	187	94	136	371	124	6	8	9	-	-
Cr	3095	334	28	168	146	304	172	184	126	426	210	176	245	955	146	74	110	125	-	-
Pb	6	5	23	6	7	20	12	16	8	7	8	15	21	22	16	21	19	17	-	-
Ba	234	748	1054	506	520	482	1225	1076	854	556	630	192	122	402	925	1046	1103	1126	-	-
Sr	350	621	1373	1056	1255	1785	1769	1810	1390	854	1054	206	216	640	846	1157	1291	1350	-	-
V	170	245	263	260	255	229	324	426	352	220	243	330	310	315	323	124	180	162	-	-
Be	0	2	5	2	2	4	3	3	2	1	1	1	1	3	4	4	4	4	-	-
Li	0	18	16	7	5	15	13	14	7	5	6	9	11	6	12	5	7	8	-	-
Rb	230	54	52	48	55	23	27	21	16	20	21	6	6	31	84	52	60	62	-	-

1	meimechite	5	olivine nephelinite	9	analcytite	13	basalt	17	andesite
2	alkaline picrite	6	melanephelinite	10	limburgite	14	subalkaline basalt	18	trachyandesite
3	olivine melilitite	7	melilite nephelinite	11	augitite	15	shoshonite	19	trachyte
4	melilitite	8	melanalcytite	12	olivine basalt	16	trachybasalt	20	alkaline trachyte.

Table 2 Average chemical compositions of rocks from alkaline-ultramafic intrusive complexes (wt %).

Table 2		Average chemical compositions of rocks from alkaline-ultramafic intrusive complexes (wt %).													
		1	2	3	4	5	6	7	8	9	10	11	12	13	
	SiO ₂	35.93	35.22	33.74	37.52	40.63	44.59	41.01	43.63	41.91	50.84	62.16	12.01	0.28	
	TiO ₂	0.43	1.30	4.40	1.17	6.10	1.61	3.73	5.42	0.91	0.90	0.60	1.37	0.02	
	Al ₂ O ₃	0.58	0.28	4.05	17.26	2.66	12.08	10.33	11.04	21.23	19.31	15.22	1.03	0.89	
	Cr ₂ O ₃	0.49	0.17	-	-	0.08	-	-	-	-	-	-	-	-	
1	dunite;	Fe ₂ O ₃	6.14	5.44	9.38	5.46	9.10	4.92	8.81	9.91	4.26	4.79	2.92	18.05	1.16
2	olivinite;	FeO	7.77	12.12	6.60	3.35	7.56	5.18	6.60	6.27	2.25	1.95	1.88	9.38	0.32
3	melilitolite;	NiO	0.26	0.13	-	-	-	-	-	-	-	-	-	-	-
4	okaite;	MnO	0.18	0.29	0.18	0.12	0.25	0.21	0.14	0.28	0.09	0.12	0.06	0.67	0.09
5	jacupirangite;	MgO	38.71	41.87	12.01	6.96	10.32	8.41	8.18	4.21	4.31	1.61	1.47	9.94	2.27
6	melteigite;	CaO	0.84	0.91	27.14	17.03	16.56	13.82	12.18	11.16	10.38	4.15	2.10	28.32	52.13
7	melanephelinite;	Na ₂ O	0.13	0.16	1.80	6.66	1.85	5.51	4.67	2.75	9.23	9.56	4.34	0.20	0.05
8	shonkinitite;	K ₂ O	0.06	0.14	0.26	2.78	1.70	2.38	2.83	3.17	3.72	4.68	8.93	0.22	0.03
9	ijolite;	P ₂ O ₅	0.12	0.05	-	-	0.57	0.33	0.20	0.61	0.24	0.29	0.02	12.61	3.51
10	nepheline syenite;	LOI	8.54	1.85	0.44	1.49	1.70	1.05	1.56	1.27	1.87	1.33	0.37	5.69	39.56
11	alkaline syenite;	CO ₂	0.53	0.24	0.47	0.96	0.21	-	0.22	0.28	0.65	1.30	-	4.45	39.50
12	phoscorite;														
13	carbonatite.														

Table 3 Average chemical compositions of hypabyssal (sills, dykes) rocks and explosion pipes (wt %).

Table 3 Average chemical compositions of hypabyssal (sills, dykes) rocks and explosion pipes (wt %).		1	2	3	4	5	6	7	8	9	10	11	12	13	
	SiO ₂	38.12	39.18	38.00	35.95	40.40	39.17	39.60	40.80	41.73	38.16	45.28	52.48	44.85	
	TiO ₂	1.63	3.65	1.90	3.36	3.53	3.84	2.92	2.94	4.03	2.73	0.83	0.48	0.74	
	Al ₂ O ₃	2.39	4.67	10.69	8.73	9.04	6.26	9.74	11.76	7.69	11.58	17.06	20.48	11.76	
	Fe ₂ O ₃	4.88	6.12	7.34	7.99	7.45	4.46	6.05	5.83	7.00	5.56	5.44	3.01	4.74	
	FeO	7.29	8.79	4.52	4.41	7.68	10.11	8.06	8.08	8.48	5.50	2.44	1.34	2.71	
1	meimechite;	MnO	0.16	0.28	0.21	0.22	0.23	0.24	0.18	0.21	0.20	0.16	0.19	0.20	
2	alkaline picrite;	MgO	34.12	22.01	10.12	7.04	8.50	15.85	12.35	8.00	9.37	10.24	3.44	0.98	3.71
3	alnuite;	CaO	3.86	9.56	14.76	19.60	12.92	11.52	13.24	13.69	13.53	13.90	8.13	2.84	13.80
4	melilite nephelinite;	Na ₂ O	0.21	0.77	5.83	3.81	2.00	1.47	2.48	3.69	2.20	2.43	9.35	8.44	6.67
5	limburgite;	K ₂ O	0.27	1.06	2.60	1.86	2.19	2.14	1.46	1.38	1.73	3.65	2.71	4.45	2.56
6	nepheline picrite;	P ₂ O ₅	0.22	0.44	0.70	0.84	0.40	0.42	0.48	0.44	0.47	0.67	0.63	0.10	1.08
7	olivine	Cr ₂ O ₃	0.27	0.23	-	-	0.03	0.08	0.06	0.02	0.03	-	-	-	-
8	melanephelinite;	NiO	0.20	0.12	-	-	-	-	-	-	-	-	-	-	-
9	augite;	LOI	6.88	3.12	3.33	6.18	4.74	4.44	3.38	3.18	3.54	5.43	4.48	5.24	7.68
10	monchikite;														
11	nephelinite;														
12	phonolite;														
13	shonkinite.														

Table 4 Average chemical composition of kimberlites from the Dalbykh (1, 2) and Kharamai (3) fields (wt %).

<i>Table 4 Average chemical composition of kimberlites from the Dalhykh (1, 2) and Kharamai (3) fields (wt %).</i>		1	2	3	
	SiO ₂	23.14	23.49	28.68	
	TiO ₂	0.35	0.36	2.12	
	Al ₂ O ₃	2.17	1.12	3.00	
	Fe ₂ O ₃	3.75	4.09	6.42	
	FeO	3.92	3.96	3.97	
	MnO	0.18	0.17	0.17	
1	Krasnoyarskay pipe;	MgO	27.74	29.39	28.80
2	"Krokhotulia" pipe;	CaO	14.27	14.17	9.94
3	average composition of 35 pipes of the Kharamai field.	Na ₂ O	0.25	0.16	0.18
		K ₂ O	1.07	0.78	1.38
		NiO	0.15	0.15	-
		Cr ₂ O ₃	0.18	0.18	-
		P ₂ O ₅	1.39	1.03	0.76
		LOI	21.44	21.16	14.03
		H ₂ O	1.85	0.98	-
		CO ₂	18.10	17.30	-
	n	3	1	232	

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