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Two mantle sources, two plumbing systems: tholeiitic and alkaline magmatism of the Maymecha River basin, Siberian flood volcanic province

Abstract Rocks of two distinctly different magma series are found in a ~4000-m-thick sequence of lavas and tuffs in the Maymecha River basin which is part of the Siberian flood-volcanic province. The *tholeiites* are typical low-Ti continental flood basalts with remarkably restricted, petrologically evolved compositions. They have basaltic MgO contents, moderate concentrations of incompatible trace elements, moderate fractionation of incompatible from compatible elements, distinct negative Ta(Nb) anomalies, and ε_{Nd} values of 0 to +2. The primary magmas were derived from a relatively shallow mantle source, and evolved in large crustal magma chambers where they acquired their relatively uniform compositions and became contaminated with continental crust. An *alkaline series*, in contrast, contains a wide range of rock types, from meymechite and picrite to trachytes, with a wide range of compositions (MgO from 0.7 to 38 wt%, SiO_2 from 40 to 69 wt%, Ce from 14 to 320 ppm), high concentrations of incompatible elements and extreme fractionation of incompatible from compatible elements ($Al_2O_3/TiO_2 \sim 1$; Sm/Yb up to 11). These rocks lack Ta(Nb) anomalies and have a broad range of ε_{Nd} values, from −2 to +5. The parental magmas are believed to have formed by low-degree melting at extreme mantle depths (>200 km). They bypassed the large crustal magma chambers and ascended rapidly to the surface, a consequence, perhaps, of high volatile contents in the primary magmas. The tholeiitic series dominates the lower part of the sequence and the alkaline series the upper part; at the interface, the two types are interlayered. The succession thus provides evidence of a radical change in the site of mantle melting, and the simultaneous operation of two very different crustal plumbing systems, during the evolution of this flood-volcanic province.

Introduction

In many continental flood-volcanic sequences there is a striking contrast between the uniformity of the chemical compositions of tholeiitic basalts, and the chemical and petrographic diversity of other volcanic rock types. In the Noril'sk section of the Siberian flood-volcanic province, for example, a sequence of alkali basalts, trachybasalts and picrites with highly variable compositions is overlain by over 2000 m of remarkably monotonous basaltic lavas and tuffs. Much the same pattern is seen in other flood-basalt sequences, such as the Deccan and Karoo (e.g. Cox 1988; Erlank 1984; Lightfoot and Hawkesworth 1988; Lightfoot et al. 1990a; Peng et al. 1993).

The Siberian flood volcanics have been the object of intensive study. In addition to long-standing programmes by Russian geologists (e.g. Makarenko 1976; Zhuralev 1986; Zolotukhin and Al'mukhamedov 1988), three international groups have undertaken detailed geochemical investigations (i.e. Lightfoot et al. 1990b, 1993, 1994; Sharma et al. 1991, 1992; Wooden et al. 1993; Czamanske et al. 1994; Fedorenko et al. 1996). The attention of two groups has been on the Noril'sk-Talnakh region (Fig. 1), a major centre of Cu-Ni-PGE mining, and that of the third on the Putorana plateau. The three research teams, working with similar methods on similar samples, came up with three radically different interpretations of the petrogenesis of the basalts.

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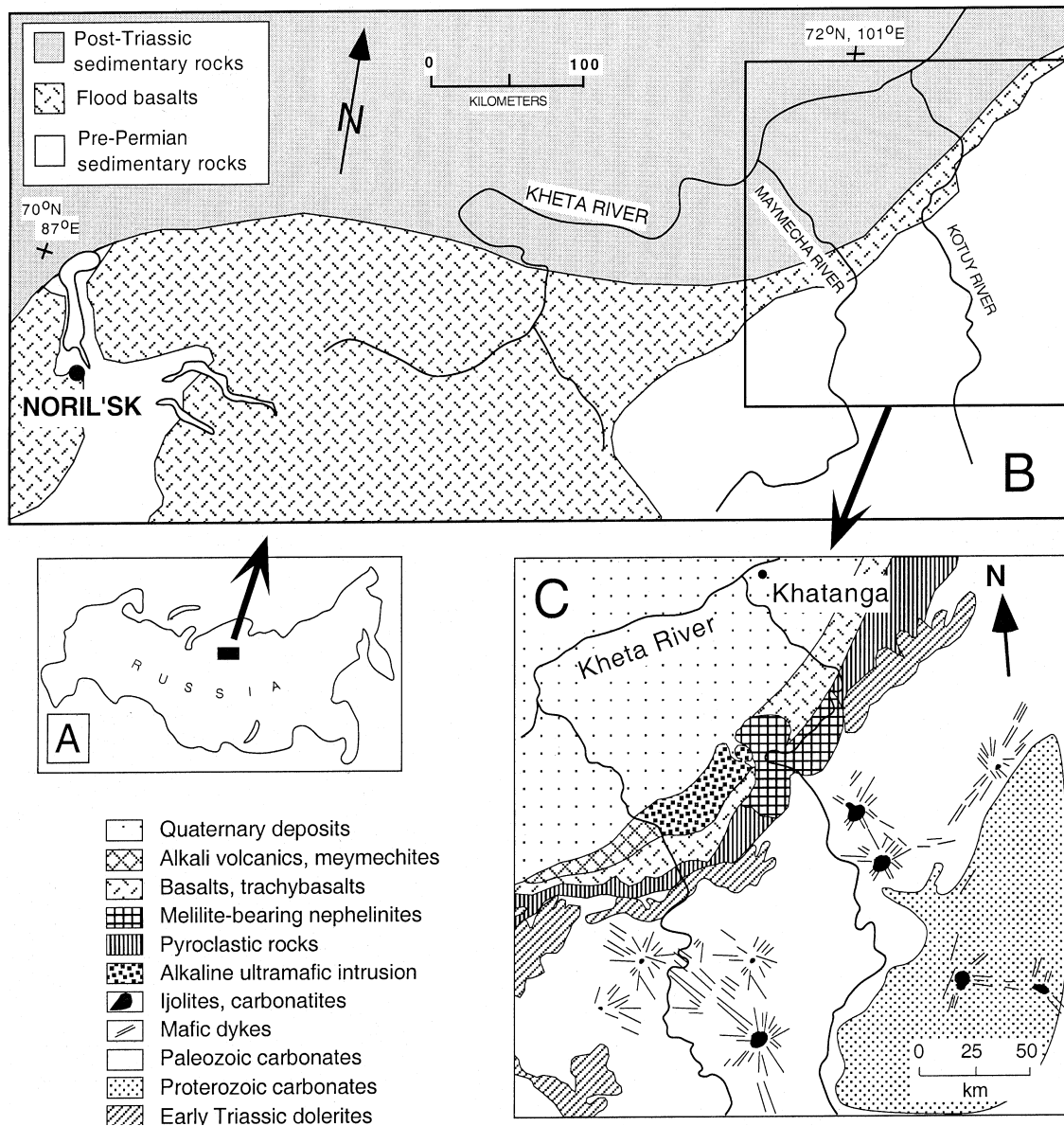
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Fig. 1 Map showing the locations and geology of the Noril'sk and Maymecha-Kotuy regions (modified from Fedorenko and Czamanske, 1997)

Each group recognised that some magma types (the alkaline magmas and the Gudchikhinsky picrites) came more or less directly from a deep mantle source, and each also acknowledged that basalts of the Nadezhdinsky Suite had been contaminated by continental crust. But to explain the origin of the 2000-m-thick sequence of flood basalts that forms the upper part of the volcanic pile in this region and in the Putorana area ~110 km to the east, Lightfoot and co-workers (Lightfoot et al. 1990b, 1993, 1994) advocated partial melting in the lithospheric mantle; Sharma and co-workers (Sharma et al. 1991, 1992) suggested derivation directly from a mantle plume; Fedorenko et al. (1996) preferred a MORB-like source; and Wooden et al. (1993) proposed that plume-derived magmas evolved and interacted with continental crust in open-system magma chambers.

Less attention has been placed on the suite of exotic, more alkaline rocks that are best exposed in the Maymecha River basin at the NE margin of the volcanic plateau some 500 km from Noril'sk (Fig. 1). A meymechite flow has recently been dated at 245 ± 1 Ma using the $^{40}Ar^{-39}$ Ar method (Dalrymple et al. 1995), a value that is only 5 million years less than the 251 ± 0.3 Ma U-Pb zircon age (Kamo et al. 1996) for the peak of Siberian flood volcanism. Preliminary U-Pb age data (S.L. Kamo, unpublished) indicate that the difference may be much less. Geological, geochemical and paleomagnetic data (e.g. Gusev 1970) have been used by Fedorenko and Czamanske (1997) to correlate the lower part of the Maymecha volcanic sequence with the main volcanic sequence, as shown in Fig. 2.

Fig. 2 Stratigraphic sections of the Noril'sk region (Wooden et al. 1993) and Maymecha River basin (Fedorenko and Czamanske 1997). The Sm-Yb ratios are shown to illustrate the differences between the two magma series. Note that both the Ivakinsky Suite of the Noril'sk region and the Pravoboyarsky Suite of the Maymecha River basin lie with insignificant disconformity on sedimentary rocks of the Middle Carboniferous to Upper Permian Tungusskaya Series. For lack of data we have not shown the Kakanchansky Suite (a tuff unit), which lies between the Gudchikhinsky and Tuklonsky Suites of the Noril'sk section
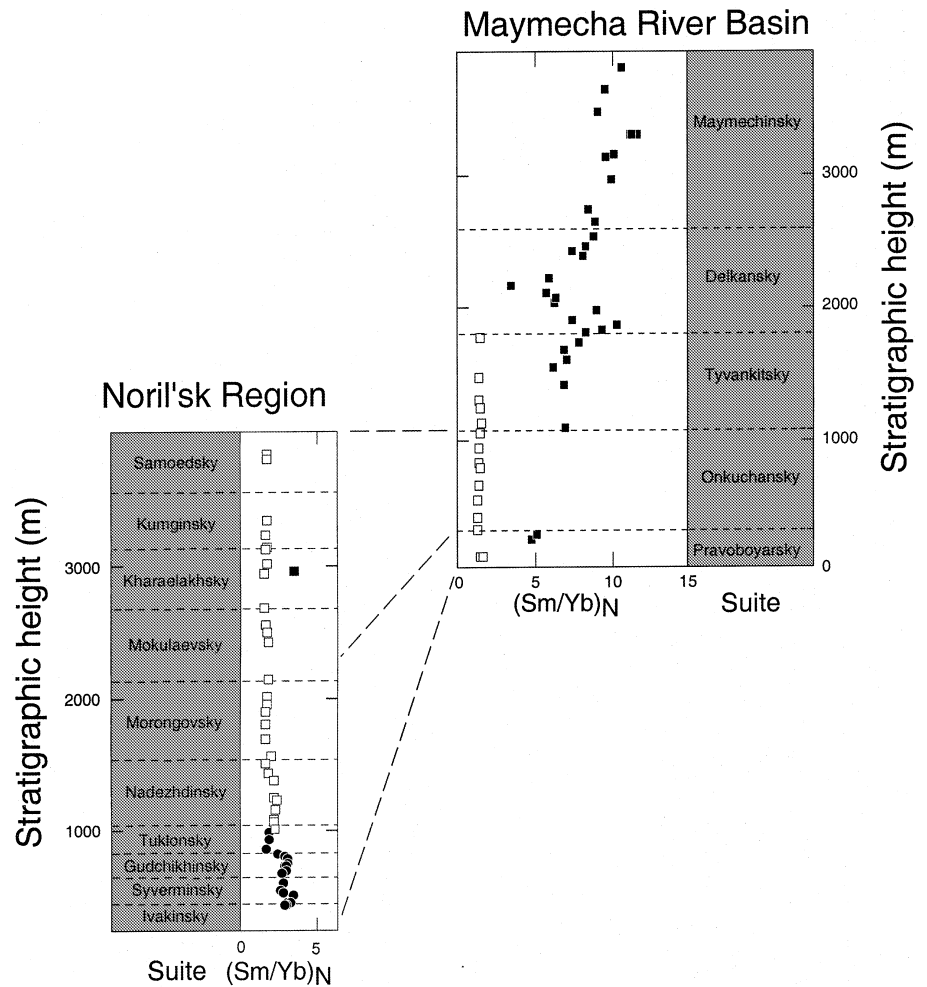
By using information from the two regions, it is possible to establish a composite stratigraphic section for > 6000 m of volcanic rocks. This section (Fig. 2) highlights the contrast between the relative uniformity of the tholeiites and the diversity among the other rock types. The lowermost part of the sequence, as found in the Noril'sk region, consists of a suite of heterogeneous subalkaline and alkaline basalts, trachybasalts and picrites. It is followed by the crust-contaminated basalts of the Nadezhdinsky Suite and then by a ~2500-m-thick sequence dominated by monotonous tholeiitic basalt. Tholeiites persist to the top of the volcanic pile in the western and southern part of the province, but in the Maymecha River basin, they are at first accompanied, and then succeeded, by exotic and compositionally diverse rocks – trachybasalt, trachyandesite, rhyodacite, nephelinite, picrite and meymechite.

This paper focuses on the changing character of the volcanic rock types of the Maymecha River basin, and the information this provides about the nature of their mantle sources, the conditions of mantle melting, and, in particular, the manner in which the resultant magmas traversed the lithosphere and crust.

Geological background

The geology of the Maymecha River basin, and its place in the Siberian flood basalt province, are described by Fedorenko and Czamanske (1997) and references therein. That publication also provides a detailed account of the volcanic stratigraphy, the nature of the lava flows and tuffs, and their petrography. Only a brief outline is given here.

The Maymecha–Kotuy region is located in the northern part of the Siberian Platform at its boundary with the Yenisey–Khatanga trough, ~500 km ENE of Noril'sk and 300–500 km NW of the Anabar Shield (Fig. 1). An Archean basement is overlain by 2000 m of Upper Proterozoic sandstones, gravels and dolomites; followed by ~2000 m of Lower Cambrian to Lower Carboniferous limestones, dolomites and marls; and finally by ~300 m of Middle Carboniferous to Upper Permian sandstones, argillites and coals of the Tungusskaya Series.

The ~4000-m-thick Maymecha–Kotuy volcanic sequence lies with insignificant disconformity on Tungusskaya Series rocks (Shikhorina 1970). Because of regional uplift to the east, the volcanic sequence is much more complete in the Maymecha River basin than to the east in the Kotuy River basin. The overall volcanic sequence in the Maymecha River basin is subdivided into the following suites: (1) the 600-m-thick Arydzhansky Suite of melilite-bearing nephelinites, which are exposed only in the Kotuy River basin; (2) the 320-m-thick Pravoboyarsky Suite, composed mainly of basaltic tuffs; (3) the 750-m-thick Onkuchansky Suite, composed

only of low-Ti, tholeiitic basalts; (4) the ~700-m-thick Tyvankitsky Suite, consisting of alternating low-Ti and high-Ti mafic lavas; (5) the 850-m-thick Delkansky Suite, predominately composed of high-Ti mafic lavas, but ranging to felsic compositions; (6) the 1400-m-thick Maymechinsky Suite, composed of meymechitic, picritic and limburgitic lavas.

Extensive sills and abundant dikes in the Maymecha River basin have been subdivided into numerous petrographic and chemical varieties (Zhabin and Surina 1970; Fedorenko and Czamanske 1997). The large ultramafic and alkaline Guli intrusive-volcanic complex cuts some of the lavas at the northern edge of the area. On the basis of 202 comprehensive chemical analyses, Fedorenko and Czamanske (1997, their Fig. 5) established compositional correlations between these intrusive rocks and the volcanic sequence.

Most of the lavas form well-developed flows with upper amygdaloidal zones, as is typical of lava flows in the Noril'sk region (Fedorenko et al. 1996). The meymechites, in contrast, form a thick sequence of massive, non-amygdaloidal units with few recognizable flow contacts. Subordinate mafic to felsic tuffs are present throughout the sequence. Most low-Ti tholeiites are aphyric or contain sparse plagioclase phenocrysts. Lavas of the alkaline series normally are porphyritic. Potassium-feldspar, rare clinopyroxene, amphibole and Fe-Ti oxides are phenocryst phases in felsic rocks, clinopyroxene in mafic alkaline rocks, plagioclase in the basalts, and olivine in the ultramafic rocks. As in most other sequences of continental flood basalt, the volcanic rocks were subjected to hydrothermal alteration under zeolite-facies metamorphic conditions.

Sampling and analytical methods

All the samples analysed in this study were collected by V. Fedorenko during the 1991 and 1994 field seasons. Sample locations and petrographic descriptions are provided by Fedorenko and Czamanske (1997), as is an account of the analytical procedure and a comprehensive table of analytical data for 50 selected samples covering the entire volcanic sequence of the Maymecha River basin. Analytical data for the full suite of 126 volcanic rocks and 76 intrusive rocks are available from the authors.

Isotopic data were obtained for the critical subset of samples listed in Table 1. Neodymium and Sr isotope compositions were determined at Géosciences Rennes using a procedure based on Eichrom® resins. Strontium was isolated using 100 μl columns filled with Sr-spec resin, successively flushed with 2M HNO_3 and H_2O. Total blanks were lower than 80 pg. The REE (rare-earth elements) were separated using 100 μl columns filled with TrU-spec resin and 3M and 0.05M HNO_3; neodymium was further isolated from the other REE using the classical HDEHP-teflon procedure. Total blanks were 20 pg. Isotopic measurements were performed on a MAT 262 Finnigan mass spectrometer by normalizing to $^{88}Sr/^{86}Sr = 8.375209$ and $^{146}Nd/^{144}Nd = 0.7219$. Static measurements of NBS 987 gave an average value of 0.710259 ± 19 (2σ, 30 measurements) during the course of analyses; semi-dynamic measurements of the in-house standard Rennes-Ames gave an average of 0.511961 ± 13 (2σ, 50 measurements) corresponding to a $^{143}Nd/^{144}Nd$ of 0.511856 for La Jolla standard. No correction was applied to the measured values.

Results

Stratigraphic variations

The manner in which chemical compositions vary through the Maymecha stratigraphic sequence is shown in Fig. 3. The Pravoboyarsky Suite, the oldest in the basin, contains lavas belonging to the two principal rock series. The two stratigraphically lowest samples are basaltic tuffs with chemical compositions similar to those of overlying tholeiitic basalts, but with slightly elevated SiO_2, K_2O, La/Sm and Th/Ta. Two other samples from the same suite are alkaline, classified on a petrographic basis as trachybasalt (sample 1–34) and limburgite (1–48). They have distinctly lower SiO_2 and Th/Ta, and higher K_2O, TiO_2, Ce and Tb/Yb, than the tholeiitic tuffs.

The overlying Onkuchansky Suite consists entirely of tholeiitic basalts, mostly lavas, but with rare tuffs. The compositions of these rocks vary little from base to top of the suite, except for a decrease in Th/Ta and small increases in the concentrations of TiO_2 and incompatible trace elements such as the L (light) REE and Th.

Then follows the Tyvankitsky Suite, which, like the Pravoboyarsky, contains examples of the two magma series – tholeiitic basaltic flows with compositions like those in the underlying suites, and lavas and tuffs of the alkaline series with compositions ranging from trachybasalt to trachyte. Lavas of the two series alternate throughout the suite, either as individual lava flows or packets each containing two to several tens of flows.

The overlying two suites consist entirely of rocks of the alkaline series. The Delkansky Suite contains a diverse assemblage of nephelinites, trachybasalts, trachyandesites and felsic lavas and tuffs with highly variable compositions. The uppermost Maymechinsky Suite is composed predominately of meymechites, with picrites and limburgites in its lower part. The compositions of these rocks change progressively upwards: an increase in MgO is accompanied by decreases in SiO_2, K_2O, TiO_2 and La/Sm, and an increase in Tb/Yb.

General chemical variations

The major- and trace-element characteristics of the volcanic rocks of the Maymecha River basin are illustrated in Figs. 4–9 and summarized in Table 2. A contrast between the vast range of compositions in the alkaline series and the restricted range for the tholeiitic series is immediately apparent. The MgO contents of the tholeiites range only from 6 to 8 wt%, compared with a range of 0.2 to 38 wt% in the alkaline series. Silica contents in the tholeiites vary from 48 to 52 wt% (except for two samples of Pravoboyarsky tuff with 54 and 55 wt%) in the tholeiites, compared with 40 to 68 wt% in alkaline series rocks. For trace-element concentrations and ratios, a similar pattern is seen, as also illustrated in Figs. 4–7.

The tholeiites have compositions typical of continental flood basalts and are directly comparable with low-Ti basalts from the Karoo, Paraná or Deccan provinces (e.g. Cox 1988; Erlank 1984; Lightfoot and Hawkesworth 1988; Lightfoot et al. 1990a; Peng et al. 1993). They show modest enrichment of incompatible trace elements, and pronounced, negative Ta(Nb) anomalies (Fig. 5). Primitive mantle normalized H (heavy) REE patterns are almost flat. Tholeiites from the Maymecha River basin have compositions indistinguishable from those of the upper suites (Morongovsky

to Samoedsky) in the Noril'sk region, an essential element in the stratigraphic correlation presented in Fig. 2.

Rocks of the alkaline series form semi-continuous trends in variation diagrams. As MgO decreases from 38 wt% in the meymechites to <1 wt% in felsic lavas and tuffs, SiO_2 increases progressively and continuously, from 40 to 69 wt%. In many of the variation diagrams in Fig. 4, there are inflections at about 10% MgO: CaO increases steadily up to this point, then declines; SiO_2 and Al_2O_3 show a moderate increase to the inflection point, and a more rapid increase thereafter, to reach maximum values near 18 wt% Al_2O_3 in certain trachytes. Immobile incompatible trace elements such as Th and the REE show patterns similar to that of Al_2O_3, but with a wider scatter. Titanium oxide reaches a maximum of ∼5 wt% in lavas containing 6–8 wt% MgO, then declines to lower concentrations in more felsic rocks.

Rocks of the alkaline series have very high concentrations of incompatible trace elements. These rocks do not have negative Ta(Nb) anomalies and the greatest relative enrichment is seen at Ta, which reaches 335 times the primitive mantle value in some picrites (Fig. 5). Normalized values of Ba, K, and Th, the most incompatible elements in normal mantle assemblages, are similar to, or lower than, those of Ta and La, and many samples have pronounced negative K anomalies. Normalized trace-element patterns have very strong slopes resulting from strong depletion of the more compatible elements. In certain samples whose normalized Ta and La values reach 100, Yb and Lu values are only 2–3, distinctly less than in the tholeiitic basalts. Ratios of La/Yb and Tb/Yb are extremely high.

Isotopic compositions show only a crude correlation with trace-element characteristics (Fig. 6), but the distinction between the two magma series is maintained. In the tholeiites, $\varepsilon_{Nd(T=251Ma)}$ has a narrow range, from 0 to +1.7, and initial $^{87}Sr/^{86}Sr$ ranges only from 0.7044 to 0.7055. In the alkaline series, a single trachyandesite from the Delkansky Suite has a relatively enriched isotopic composition ($\varepsilon_{Nd} = -1.7$, $^{87}Sr/^{86}Sr = 0.7049$). The isotopic compositions of the remaining samples correspond to an isotopically depleted, but heterogeneous, source: ε_{Nd} ranges ranges from 0 to +6 and $^{87}Sr/^{86}Sr$ from 0.7033 to 0.7049.

Discussion

Influences on Magma Compositions

Alteration

The Siberian flood volcanics are ∼251Ma old and have been altered following their eruption and burial. This process changed the concentrations of elements such as Cs, Rb, Ba, K and Sr, which either scatter broadly and incoherently when plotted in variation diagrams (e.g. Fig. 4), or plot off normal magmatic trends. For example, the CaO and Rb contents of meymechites and picrites define trends with intercepts on the MgO axis

between 35 and 45 wt%, values less than the ∼52 wt% intercepts given by immobile elements such as Al and Ce, and less than the MgO contents of the olivine phenocrysts in these lavas. This sign of element mobility is most clearly manifested in a preferential loss of these elements from the more magnesian samples. In the discussion that follows, emphasis will be placed on elements such as Al, Ti, Fe, Cr, Th and the rare-earth and high-field-strength elements, which generally show coherent behaviour.

Fractional crystallization and accumulation

Sobolev et al. (1991) and Arndt et al. (1995) estimated the composition of the parental meymechite liquid using the compositions of chilled margins and inclusions in olivine grains, and the forsterite content of the olivine itself. This liquid, whose composition is shown in Fig. 4, contains 25% MgO. Meymechite samples with higher MgO contents have accumulated olivine, either as phenocrysts or xenocrysts.

The semi-continuous trends illustrated in Fig. 4 are consistent with a co-magmatic relation between rocks of the alkaline series. The inflections in these trends might be attributed to changes in the major fractionating phase, from olivine in more magnesian magmas (MgO >12 wt%), to clinopyroxene in less magnesian magmas. The progressive increase in Al_2O_3 with decreasing MgO indicates an absence of significant plagioclase fractionation, and the pronounced drop in TiO_2 contents in samples containing <6 wt% MgO may be due to oxide fractionation. The inferred fractionating phases correspond to phenocrysts observed in the field and in thin section and also are consistent with types of cumulate rocks in the Guli complex, which is believed to be co-magmatic with the alkaline lavas (Fedorenko and Czamanske 1997).

An attempt was made to reproduce the trends illustrated in Fig. 4 using the estimated parental meymechite liquid and the MELTS program of Ghiorso and Sack (1995). Runs were made for an anhydrous parental liquid at 1 atm and 5 kbar and for a liquid with 1% H_2O at 5 kbar. The correspondance between the theoretical results and the chemical data is closest for 1 atm dry and 5 kbar hydrous runs, which reproduce the onset of clinopyroxene fractionation at about 11% MgO (Fig. 4). In the 5 kbar dry run, this fractionation starts too soon. This result suggests that the bulk of the fractional crystallization in magmas of the alkaline series may have taken place at relatively shallow depths.

Chemical features that cannot be explained by fractional crystallization

Certain variations in trace-element ratios and isotopic compositions are far too large to have been caused by

Table 1 Major and trace element and isotope compositions; all data are normalized to 100% on a volatile-free basis (*LOI* loss on ignition)

Sample no	1FG-44	1FG-48	1FG-58	1FG-150	1FG-162	1FG-165	1FG-185
Strat. Unit	Pb	Pb	On	On	Tv	Tv	Tv
Strat. height (m)	120	275	420	930	1095	1120	1460
Rock type	Basalt	Limburgite	Basalt	Basalt	Trachybasalt	Basalt	Basalt
SiO_2 (wt%)	52.33	47.46	49.76	49.36	49.46	48.98	49.98
TiO_2	1.21	4.24	1.3	1.52	4.16	1.81	1.36
Al_2O_3	15.39	10.48	15.65	15.08	12.9	15.27	15.3
FeOT	9.55	13.24	11.74	12.72	11.61	13.65	11.75
MnO	0.17	0.15	0.2	0.22	0.19	0.22	0.2
MgO	6.9	7.43	7.48	7.12	6.05	6.59	6.98
CaO	10.54	12.67	11.37	10.86	8.57	10.43	11.63
Na_2O	2.79	2.29	2.13	2.44	2.61	2.51	2.31
K_2O	0.9	1.46	0.19	0.44	3.57	0.31	0.31
P_2O_5	0.21	0.59	0.19	0.24	0.88	0.22	0.19
LOI	4.16	4.61	2.71	3.5	4.15	4.49	0.96
Ba (ppm)	164	485	54	140	1400	92	98
Co	48	51	49	51	35	52	49
Cr	112	410	114	128	54	106	144
Cu	102	136	104	84	61	186	140
Hf	2.57	8.24	2.33	2.97	15.42	3.05	2.46
Ni	132	174	140	106	80	100	91
Rb	20	39	< 10	< 10	72	< 10	< 10
Sc	35	31	37	34	16	35	37
Sr	154	620	190	205	1450	210	205
Ta	0.399	3.34	0.238	0.375	8.293	0.394	0.331
Th	1.85	4.46	0.98	1.3	13.18	1.13	1.1
U	0.51	0.97	0.29	0.49	2.07	0.41	0.34
V	300	350	390	300	260	310	310
Y	19	27	26	28	32	24	27
Zn	96	100	86	68	109	102	91
Zr	98	350	90	116	650	120	106
La	11.5	46.5	7.3	9.7	115.7	8.7	8.1
Ce	23.8	99.7	16.7	21.8	234.3	20.4	17.9
Nd	13	53.5	10.4	14.7	106.3	13.3	10.4
Sm	3.57	11.91	3.16	4.31	20.88	4.49	3.61
Eu	1.12	3.2	1.06	1.29	5.32	1.4	1.21
Gd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Tb	0.686	1.298	0.688	0.789	1.909	0.863	0.723
Yb	2.48	2.42	2.574	3.166	3.114	2.986	2.758
Lu	0.353	0.309	0.361	0.449	0.398	0.422	0.38
Sr^b	161	635	189	204	1477	210	209
$^{87}Rb/^{86}Sr$	0.367	0.178	0.149	0.138	0.140	0.134	0.138
$^{87}Sr/^{86}Sr_{(m)}$	0.706810	0.704808	0.705292	0.705077	0.704810	0.704927	0.705115
±	7	5	4	9	7	6	6
$^{87}Sr/^{86}Sr_{(251)}$	0.70550	0.70417	0.70476	0.70459	0.70431	0.70445	0.70462
Nd^b	13.52	56.35	11.03	14.84	111.16	14.07	11.91
Sm^b	3.42	11.33	3.16	4.15	19.43	4.1	3.4
$^{147}Sm/^{144}Nd$	0.1531	0.1216	0.1735	0.1691	0.1057	0.1764	0.1726
$^{143}Nd/^{144}Nd_{(m)}$	0.512560	0.512571	0.512644	0.512693	0.512569	0.512693	0.512660
±	7	6	6	9	6	11	8
$\varepsilon_{Nd}(251)$	−0.12	+1.10	+0.86	+1.96	+1.57	+1.72	+1.20

fractional crystallization. The absolute concentrations of major elements such as Al_2O_3 and TiO_2 and of immobile, incompatible trace elements such as Th, Ta and the REE vary widely in the Delkansky picrites: some fall on the calculated fractionation trends, others plot below or above them. The La/Sm ratios in the picrites vary from 4 to 9, Sm/Yb from 5 to 11, and ε_{Nd} from −1.7 to +6 (Figs. 6–8). The low ε_{Nd} of trachyandesite 1FG-100 probably is due to contamination with older crustal rocks, but the other variations point to differences in the conditions of melting and/or the compositions of the mantle source(s).

It appears, therefore, that there was a variety of parental magmas for rocks of the alkaline series. These magmas had a relatively small but significant range of isotope and trace-element ratios, and each was derived from a different site or source in the mantle. These magmas then fractionally crystallized at a relatively shallow level before reaching the surface.

1FG-100	1FG-200	2FG-60	2FG-64	2FG-89	2FG-83	2FG-83[a]	G3-233.4	G3-100
Tv	Dl	Dl	Dl	Dl	Mm	Mm	Mm	Mm1
1670	1850	2155	2210	2535	2635	2635	3470	3640
Trachyandesite	Nephelinite	Trachydacite	Trachybasalt	Trachybasalt	Picrite lava	Picrite lava	Meymechite	Meymechite
53.7	43.09	68.92	47.24	49.11	49.59		40.73	40.38
2.78	4.2	0.79	3.08	3.86	3.66		2.24	4.89
15.93	9.81	15.87	14.34	15.67	5.37		2.53	5.27
9.05	13.05	2.73	11.42	10.79	11.74		13.09	16.07
0.18	0.22	0.04	0.2	0.25	0.17		0.19	0.22
2.85	10.06	0.34	6.76	4.86	13.79		35.02	15.83
7.12	15.25	0.14	9.84	8.24	11.65		5.22	14.45
4.31	2.46	5.4	4.36	3.51	0.32		0.16	0.34
3.14	0.99	5.62	2.07	2.63	3.2		0.5	1.87
0.94	0.85	0.14	0.7	1.08	0.52		0.31	0.67
1.54	3.63	1.05	0.79	2.4	4.65		5.64	3.45
1250	1900	1100	710	1300	800		198	510
20	59	2	45	36	63		120	90
<1	200	7	144	60	890		2500	940
15	198	20	49	108	110		78	124
11.71	9.14	25.9	6.75	15.56	7.55		3.98	8.52
10	146	5	80	50	340		1550	430
85	49	118	45	36	33		11	55
11	31	2	21	14	24		15	30
1750	2400	172	1150	1950	740		295	850
5.903	10.356	12.543	4.953	9.358	6.35		2.41	5.75
9.65	13.18	19.66	6.32	16.21	7.82		2.94	6.02
2.49	1.83	2.97	1.62	4.04	2.23		0.69	1.52
160	340	37	280	280	280		150	360
38	10	71	20	37	12		11	26
104	84	174	88	112	85		98	116
520	465	1100	315	750	335		178	395
105.3	136.2	105.6	68.6	155.6	83.2		31.3	75
207.5	243	324.2	133.1	317.3	160		64.6	148
95.8	93.9	82.3	57.7	142.3	69		33.9	70.9
19.23	15.56	15.28	10.83	25.47	11.6		6.51	13.7
4.74	3.83	3.67	2.94	6.48	3.03		1.66	3.76
n.d.	n.d.	n.d.	n.d.	n.d.	8.21		4.7	9.57
1.684	1.159	1.893	1.018	2.046	0.968		0.56	1.17
2.919	1.578	4.611	1.905	3.019	1.36		0.746	1.49
0.394	0.194	0.571	0.246	0.351	0.175		0.093	0.182
1736	2429	165	1108	1939	763	758	314	897
0.137	0.058	1.936	0.110	0.052	0.126	0.126	0.105	0.183
0.705386	0.704078	0.711509	0.704038	0.704113	0.704674	0.704664	0.703643	0.703922
6	6	9	4	6	7	6	7	6
0.70490	0.70387	0.70460	0.70364	0.70393	0.70422	0.70421	0.70327	0.70327
103.45	103.06	86.66	61.81	151.78	67.99	67.67	32.73	74.56
17.77	15.00	14.69	10.39	24.59	10.93	10.99	5.93	13.31
0.1038	0.0880	0.1025	0.1016	0.0979	0.0972	0.0982	0.1095	0.1079
0.512400	0.512593	0.512566	0.512607	0.512633	0.512621	0.512627	0.512740	0.512762
5	3	8	11	5	4	5	10	6
−1.67	+2.61	+1.62	+2.44	+3.07	+2.86	+2.94	+4.79	+5.27

Abbreviations of suite names: *Pb* Pravoboyarsky, *On* Onkuchaksky, *Tv* Tyvankitsky, *Dl* Delkansky, *Mm* Maymechinsky
[a] duplicate analysis [b] isotope dilution data

Conditions of mantle melting during the formation of meymechites and associated magmas

Four aspects of the chemical composition of meymechites and picrites place strong constraints on the conditions of melting and compositions of their mantle source(s):

1. The high MgO contents in meymechitic liquids, which are estimated from olivine compositions (Arndt et al. 1995) and studies of melt inclusions (Sobolev et al. 1991) to have been between 25 and 27 wt%. The high MgO is accompanied by high Ni (~1000 ppm) and Cr (~2000 ppm).

2. Very high concentrations of incompatible trace elements. For Ta, the most highly enriched element,
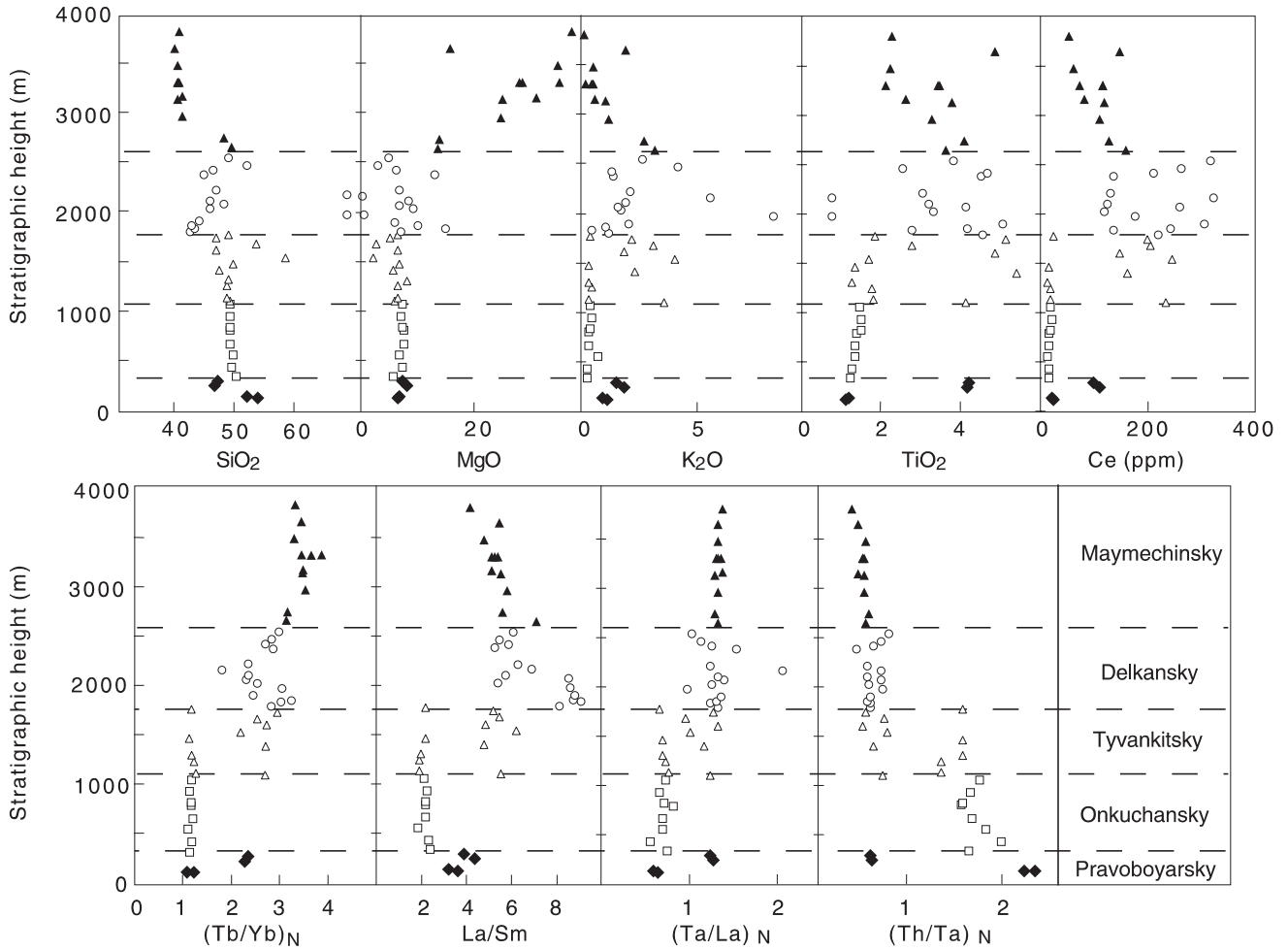
Fig. 3 Variations in the concentrations of selected major and trace elements within the stratigraphic section of the Maymecha River basin

concentrations range from 50 to 335 times the primitive mantle value.

3. Relatively low concentrations of the most incompatible elements (Rb, Ba, Th and U), which are relatively depleted compared with more compatible elements such as Ta and La.

4. Extremely low concentrations of moderately compatible major and trace elements, as expressed by remarkably low Al_2O_3/TiO_2 (∼1.1 compared to ∼20 in primitive mantle) and strongly sloping REE patterns [$(Sm/Yb)_N$ ∼ 8–10; $(Tb/Yb)_N$ ∼ 3.0–3.6].

The firmest constraint comes from the high concentrations of MgO, Ni and Cr, coupled with the high concentrations of incompatible trace elements. Herzberg and Zhang (1996) have shown that only at very high pressures can a magma containing 25 wt% MgO be produced by near-solidus melting of dry mantle peridotite (melting of a volatile-bearing source is discussed later). Although magma with comparable MgO content may form at lower pressure if the degree of melting is very high, such a magma would have low concentrations of incompatible trace elements, with a composition more like komatiite than meymechite. Using the equations of Herzberg and Zhang (1996) it is possible to estimate the pressure and depth required to give the major-element composition of the parental meymechite, if it formed by low-degree partial melting of peridotite KLB-1. The best constraint is provided by the very low Al_2O_3 content (∼4 wt% in rocks with 25 wt% MgO; Al_2O_3/TiO_2 ∼1.1), which, together with the high MgO, is consistent with melting at 8–10 GPa (a depth of 250–300 km). The low Al_2O_3 contents of high-pressure liquids result from enhanced stability of garnet at high pressures. The modal proportion of garnet increases as pyroxene is accomodated into the garnet structure and, at low degrees of melting, a high proportion of garnet remains in the residue. This has a pronounced effect on trace elements and is the likely cause of the extreme fractionation of HREE in the meymechites.

The high concentrations of incompatible elements constrain the degree of partial melting. To explain the level of enrichment of Ta, which reaches about 100 times primitive mantle levels in the parental meymechite liquid, the percentage of partial melting must
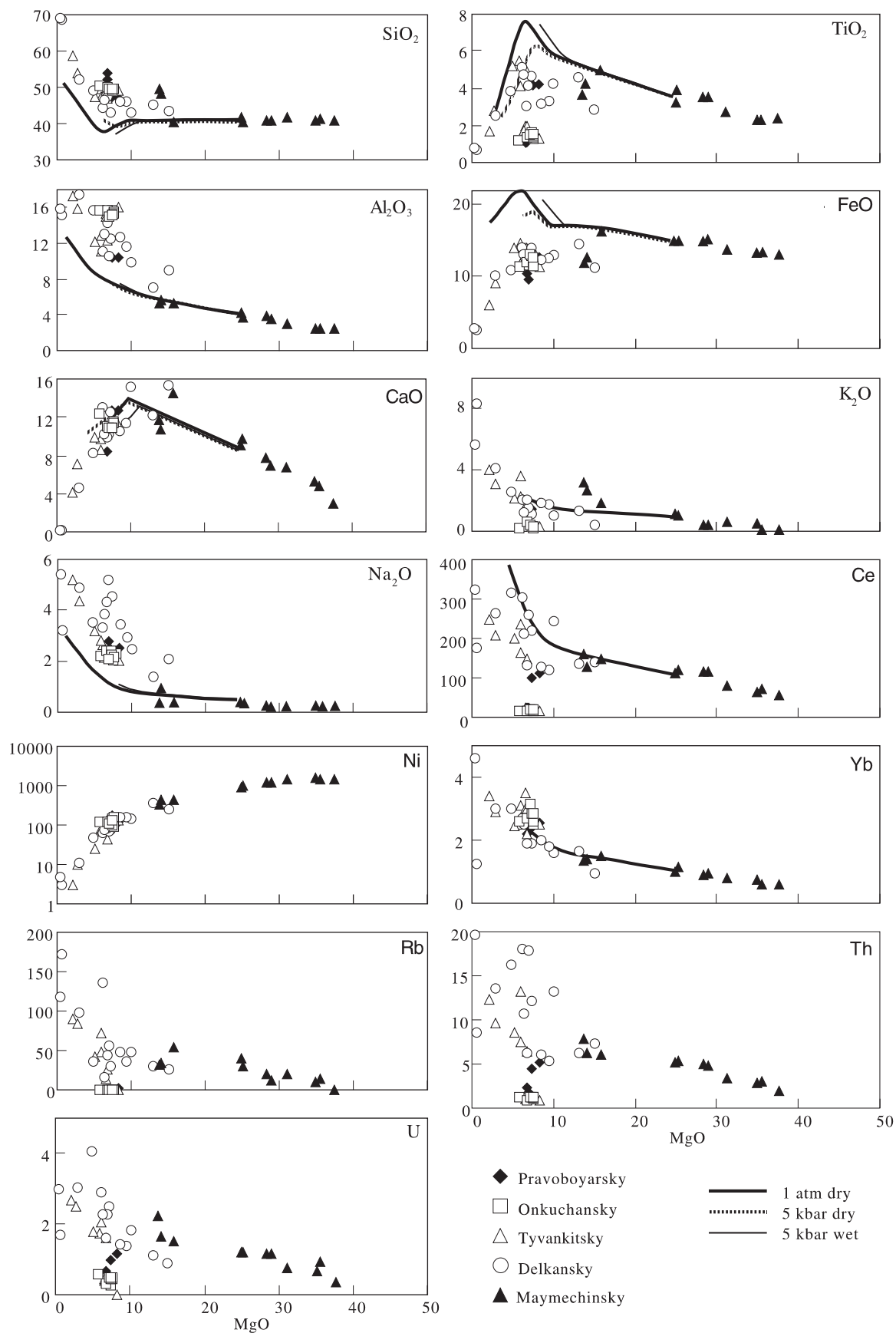
Fig. 4 Variation diagrams with major and trace elements for the volcanic suites of the Maymecha River basin
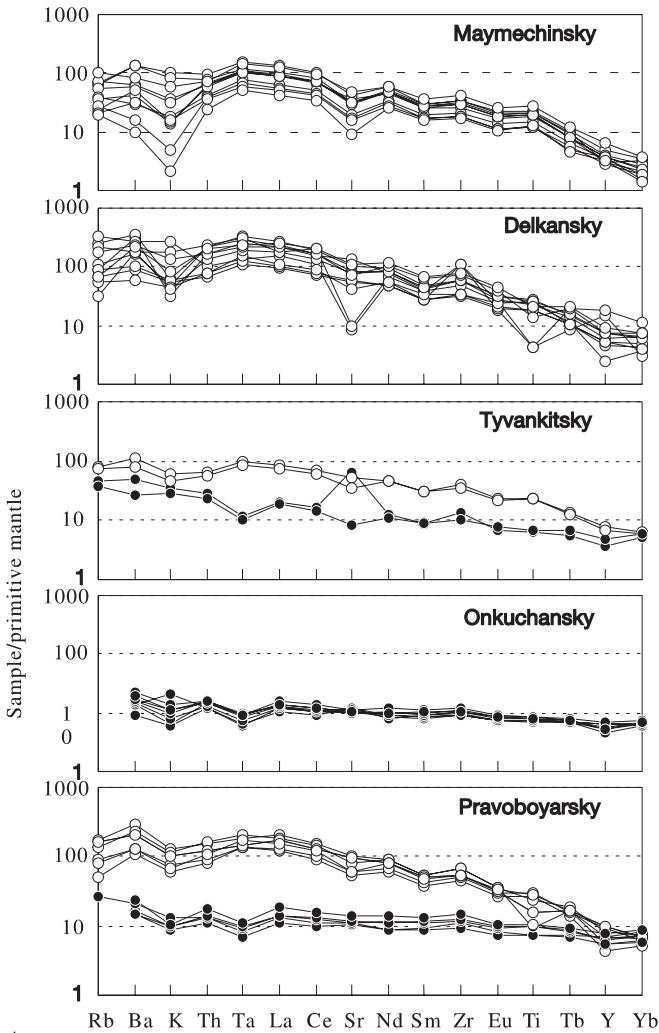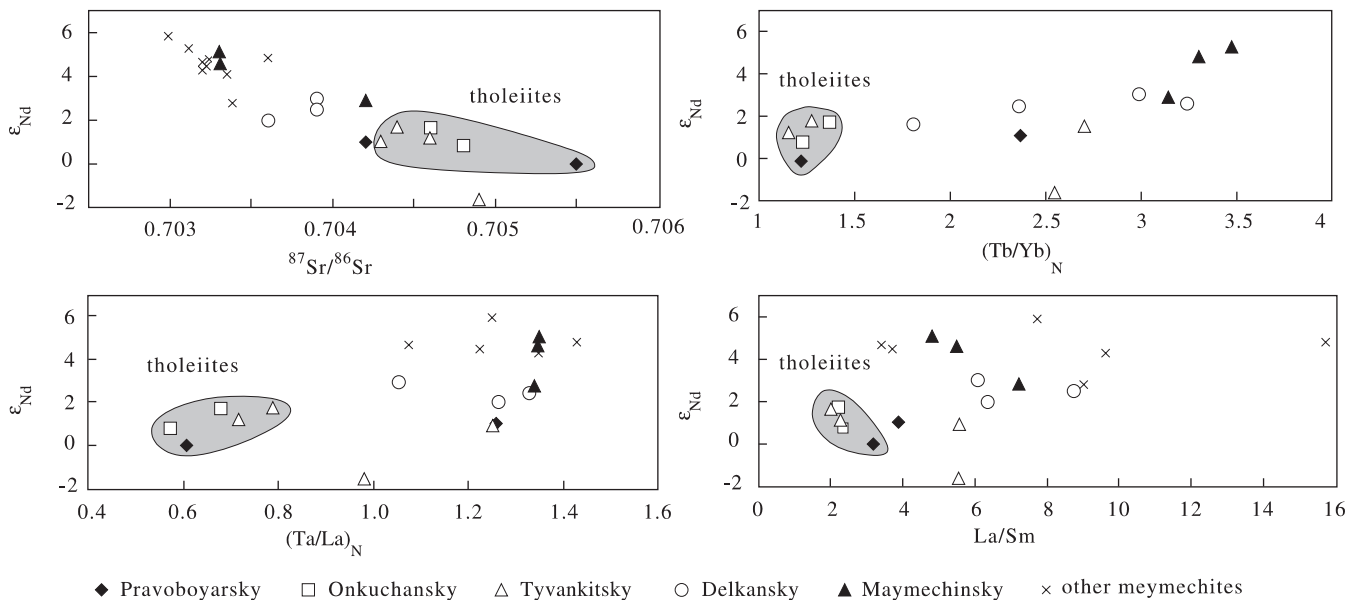
Fig. 5 Incompatible trace elements, normalized to primitive mantle values of Hofmann (1988). (Samples of the tholeiitic series *filled circles*, samples of the alkaline series *open circles*)

have been extremely low; less than 1%, if Ta is assumed to be perfectly incompatible and if concentrations of trace elements in the source were at primitive mantle levels.

It is possible that the source had higher trace-element concentrations than primitive mantle, either because of metasomatic enrichment, or because it had an eclogitic or pyroxenitic, rather than a peridotitic composition. If the source had three times primitive mantle concentrations of Ta, ~3% partial melting would suffice. Yet there are several reasons to question derivation from a strongly enriched source. First, the relative depletion of Rb, Ba and Th compared with Ta and La probably is a source feature because these elements are not normally fractionated from one another during partial melting. The low-K contents (Fig. 5) may be due to residual phlogopite, but this mineral has little effect on the concentrations of other elements. The relatively low concentrations of the most highly incompatible elements cast doubt on models involving source enrichment through metasomatism, because any process capable of increasing the concentrations of Ta and La should have had a more pronounced influence on the more incompatible elements. As was shown by Hofmann (1988), a "hump-shape" in the trace-element profiles (Fig. 5) is best explained in terms of remelting of a source that had been depleted in highly incompatible elements through earlier melt extraction.

The second constraint comes from the high-MgO, -Ni and -Cr contents of the meymechites, which suggest that the source contained olivine and had a dominantly peridotitic, rather than a pyroxenitic or eclogitic composition. It is difficult to imagine how

Fig. 6 Nd and Sr isotopic compositions, plotted against selected trace-element ratios. The additional isotope results, identified in the legend as *other meymechites* are from Arndt et al. (1995) and Horan et al. (1995). The *shaded field* encloses samples of the tholeiitic series ▼
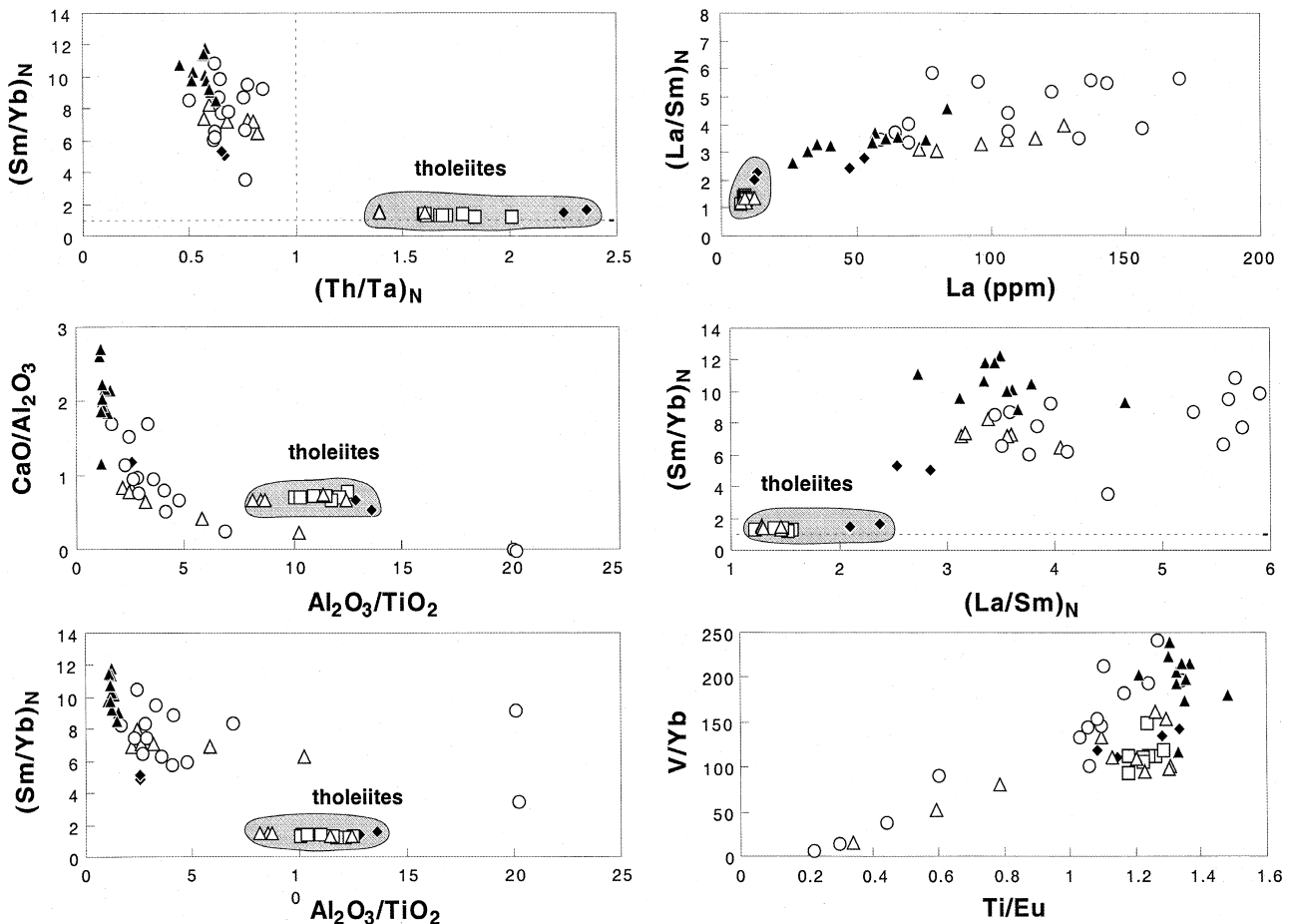
Fig. 7 Correlations between selected ratios of major and trace elements. Symbols as in Fig. 4

liquid containing 25–27 wt% MgO and 1000 ppm Ni could have been derived from mafic rather than ultramafic material.

These arguments lead to the conclusion that the source was relatively rich in Ni and depleted in the most incompatible elements, with moderate concentrations of moderately compatible elements. These characteristics would be matched by a mixture of peridotite and basalt; i.e. subducted oceanic lithosphere. Such a source has been postulated by Hofmann and White (1982) and Chauvel et al. (1992) for various types of oceanic island basalt. In Table 3, we show that 2% partial melting of such a source gives a liquid with the trace-element composition of the parental meymechite liquid. (Partition coefficients and other parameters used in the calculation are given in the caption).

The picrites have lower MgO and higher Al_2O_3 contents than the meymechites and are extremely enriched in incompatible trace elements. If they are primary melts from the same source that produced the meymechites, they could have formed at lower pressures, but at extremely low degrees of melting – 0.1% melting of a source with ~3 times primitive mantle abundances. An alternative explanation is that they were derived by fractional crystallization of meymechitic magmas. They

could not have come from magma with the composition of the erupted meymechites (in these the concentrations of trace elements are too low), but could have been derived from more enriched meymechitic melts from another source. In Table 3 we show that 2% melting of a source with a 40% basaltic component produces a magma with $Ta_N \sim 150$ and 815 ppm Ni; 30% fractional crystallization of olivine from this liquid then gives the liquid with trace-element composition of the average picrite.

We emphasize that these calculations do not provide firm constraints on the compositions and conditions that produced the magmas of the alkaline series. In view of the uncertainties in our knowledge of melting mechanisms and partition coefficients at very high pressures, and the latitude that exists in the choice of possible source compositions, they represent only one set of possible solutions to the petrogenetic problems.

The influence of volatiles in the mantle source

A major weakness with the above discussion lies in the presumption that the mantle source was dry. There are several observations that point to the presence of volatile phases during the formation and evolution of the alkaline series:
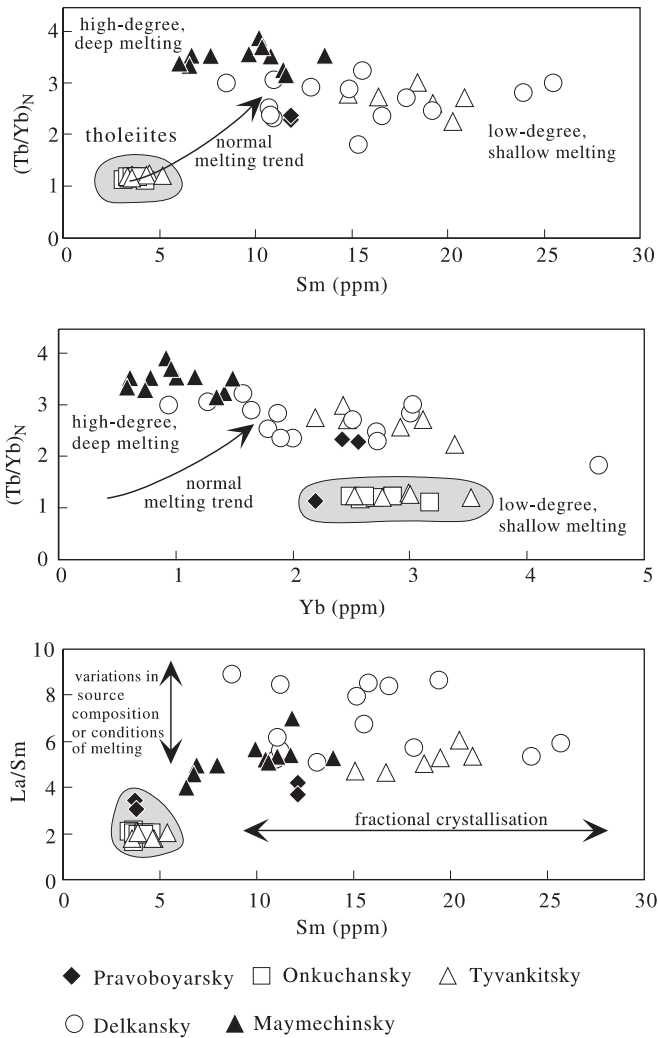
Fig. 8 Relations between ratios and concentrations of La, Tb and Yb, illustrating the marked differences between the two magma series and the internal variations within the alkaline series

1. Biotite is common in the matrices of coarser-grained meymechites. This mineral appears to be a primary, hydroxyl-bearing mica (see discussion of Fedorenko and Czamanske 1997) and provides evidence of low but significant water contents.

2. A lack of plagioclase in the crystallizing assemblages is indicated by the Al_2O_3 contents, which steadily increase as MgO decreases, in all but the most evolved members (Fig. 4). Although related to the Si-undersaturated nature of the magmas, this pattern is also consistent with the presence of water.

3. The presence of two carbonatite bodies in the Guli intrusive-volcanic complex raises the possibility that CO_2 was also present at the site of melting.

Little information is available about the melting behaviour of peridotite at very high pressures in the presence of volatiles, but a major effect will be to decrease the solidus temperature and thus the depth of melting.

On the basis of experiments of Inoue and Sawamoto (1992), Gasparik (1993), Inoue (1994) and Ohtani et al. (1996), a 200 K decrease might allow parental meymechite liquids containing 25 wt% MgO to form at about 3–4 GPa, i.e. at depths and temperatures similar to those estimated for the formation of the other mafic magmas. There is also some evidence that the presence of water increases the stability of garnet (Inoue 1994; Inoue and Sawamoto 1992), but whether this effect is sufficient to explain the extremely low Al_2O_3 and strong fractionation of the HREE remains unknown. On the other hand, studies of glass inclusions in olivine by Sobolev et al. (1991) provide evidence of very high temperatures during melting and suggest that the influence of volatiles may not have been large.

Additional information about melting conditions is provided by differences in trace-element ratios of the meymechites and picrites. Figure 8 shows that Tb/Yb decreases as Yb concentrations increase, a variation opposite to that expected from normal melting processes. Differences in source compositions, or variations in the degree of partial melting, would result in positive correlations between Tb/Yb and Yb. The higher Tb/Yb of the uppermost meymechites suggests that they left a greater proportion of garnet in their residue of melting, a characteristic that we have attributed to melting at greater depths. In this context, it is interesting to observe in the stratigraphic profiles (Figs. 2 and 3) that Tb/Yb increases upwards through the meymechite sequence. It would appear that the depth of melting progressively increased during the course of this magmatic event.

Notwithstanding the uncertainties about the precise effect of volatiles and their influence on phase relations, we can conclude that the meymechites formed by low-degree melting at great to very great depths in the mantle. If the source were relatively dry, the depth may have been as much as 250–300 km; if significant volatiles were present, the depths would have been less, but still greater than for the alkaline rocks at the base of the Noril'sk sequence.

Tholeiites

The restricted range of compositions of the tholeiitic basalts stands in stark contrast with the wide variations in the alkaline series (Figs. 8, 9). Although it has been argued that Siberian flood basalts represent "near-primary" magmas, and that their relatively uniform composition was directly inherited from a homogeneous mantle source (Sharma et al. 1991, 1992; Lightfoot et al. 1990b, 1993, 1994; Fedorenko et al. 1996), we prefer the conclusion reached by Wooden et al. (1993) and Arndt et al. (1993) who proposed that these magmas formed through extensive fractionation of picritic parental magmas in crustal magma chambers. The following features of the tholeiites are critical to this interpretation:
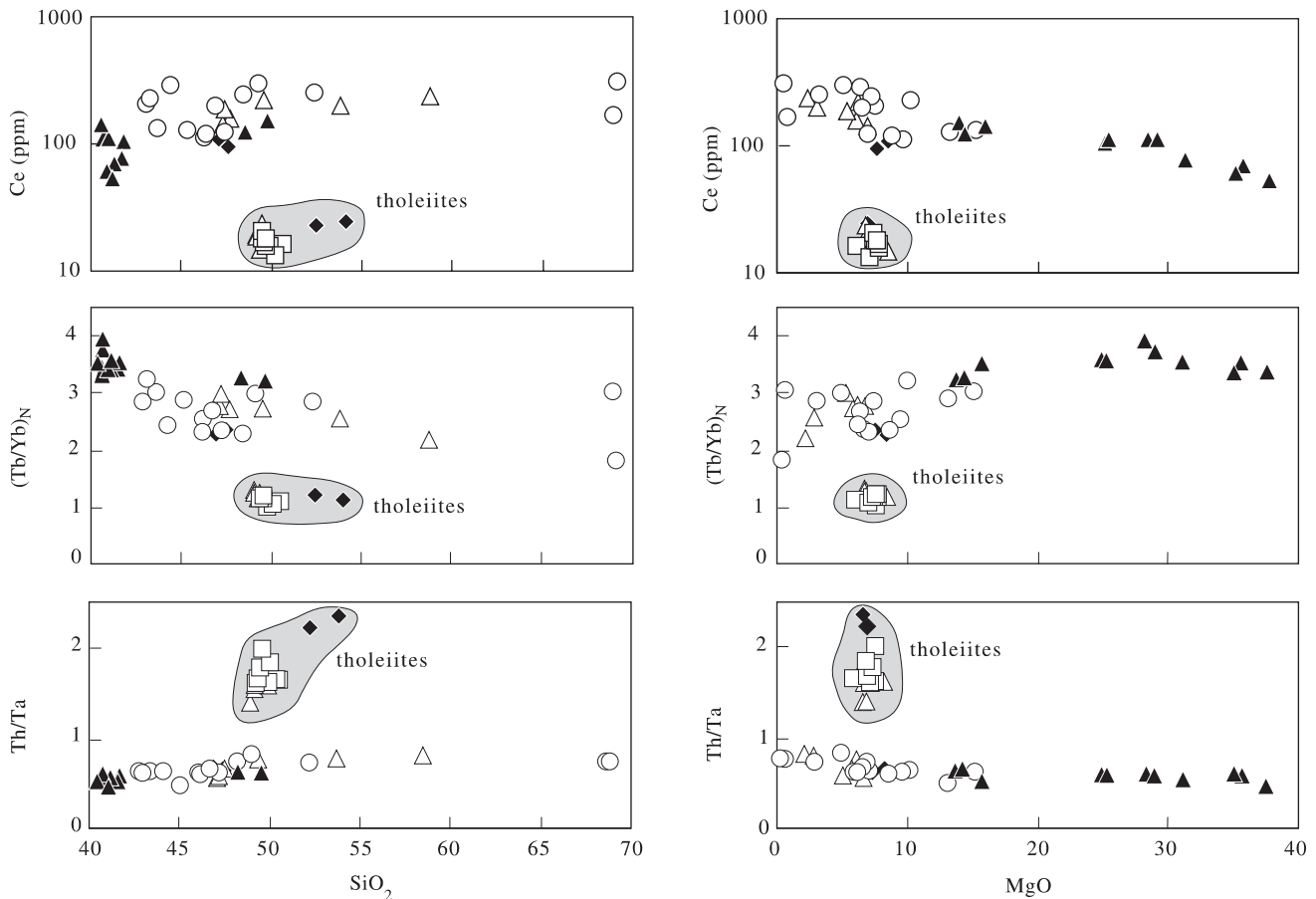
Fig. 9 Trace-element concentrations and ratios versus MgO and SiO₂ contents, emphasizing the contrast between the relative homogeneity of the tholeiites and the diverse compositions of the alkaline rocks

1. Their highly evolved and relatively uniform compositions
2. Evidence of crystallization at low pressures
3. Indications of significant crustal contamination.

The first two are relatively unambiguous and non-contentious. With 6–8 wt% MgO, Mg numbers < 60 and high-SiO₂ contents, the tholeiitic basalts are highly evolved compared with their primary magmas which, if formed at the base of the continental lithosphere, would have had picritic compositions (Cox 1980). The restricted composition of the basalts is a consequence of two processes: (1) the development of steady-state conditions in crustal magma chambers; (2) buffering of major-element compositions through equilibrium with olivine, pyroxene and plagioclase, the three crystallizing phases (Cox 1980; Wooden et al. 1993).

More contentious is the interpretation that the magmas acquired their crustal signature through interaction with wall rocks (Arndt and Christensen 1992; Wooden et al. 1993; Griselin and Arndt 1996). The alternative interpretation, defended by Lightfoot et al. (1994), Gallagher and Hawkesworth (1994), Hawkesworth et al.

(1995) and Lassiter and De Paolo (1997) is that this signature was acquired through melting of lithospheric mantle of appropriate composition.

The significance of the Maymecha volcanic rocks in this context stems from the virtual restriction of the "crustal signature" to magmas that were processed in crustal magma chambers. There appears to be a link between the degree of evolution of the magmas and the presence or absence of a crustal component: with few exceptions the highly evolved tholeiites have this signature and the more primitive alkaline magmas do not. Although it has been argued that contamination and fractional crystallization may have operated independently (Hawkesworth et al. 1995), it is difficult to accept that the tholeiitic magmas first acquired their peculiar crust-like characteristics by melting in the lithospheric mantle, then evolved in magma chambers without interacting with crustal wall rocks. If the lithosphere-melting model is accepted, we do not understand why only those magmas that formed in the lithosphere, and not those from deeper in the mantle, should have been trapped in crustal magma chambers. Other things being equal, melts from deeper sources should be richer in MgO and FeO, and their greater densities would increase their chance of being trapped at density discontinuities at the base of, or within, the continental crust.

Table 2 Summary of geochemical characteristics and inferred petrogeneses of the two magma series [*Mg number* mol MgO/(MgO + FeO)]

	Tholeiitic series	Meymechite-trachyte series
Rock types	Tholeiitic basalt	Trachybasalt, trachyandesite, rhyolite, nephelinite, picrite, meymechite
MgO (wt%)	5.8–8.3	0.3–37.6
Mg number	46–57	18–84
SiO$_2$ (wt%)	49–54	40–69
La (ppm)	6–12	26–170
(La/Sm)$_N$	1.2–2.3	2.5–5.7
(Sm/Yb)$_N$	1.3–1.7	3.6–11.9
(Ta/La)$_N$	0.6–0.8	1.0–2.1
ε_{Nd}	0 to +2	~0 to +6
$^{87}Sr/^{86}Sr$	0.7044 to 0.7055	0.7033 to 0.7049
Volatiles in primary magma	Anhydrous	Hydrous
Source of primary magma	Moderate degree of melting at relatively shallow depths	Low-degree melting at great depths in the mantle
Passage to the surface	Fractional crystallization and crust contamination in large, open-system magma chambers	Rapid ascent with minimal interaction with crustal rocks

Table 3 Origin of meymechite and picrite – summary of trace-element modelling

	Ta$_N$[a]	La$_N$	Sm$_N$	Yb$_N$	Ni (ppm)	(La/Sm)$_N$	(Sm/Yb)$_N$
Source A (25% MORB + 75% DM)	2.1	2.4	3.1	3.1	1913	0.8	1.0
Source B (40% MORB + 60% DM)	2.9	2.8	3.6	3.5	1795	0.8	1.0
Meymechite							
2% melting of source A at high pressure	107	69	20	2.4	1000	3.5	8.3
Primary meymechite liquid (25% MgO)	100	77	21	2.4	1031	3.7	8.8
Picrite							
2% melting of source B at moderate pressure	152	121	29	3.4	815	4.2	8.5
After 30% fractional crystallization	200	157	38	4.4	110	4.2	8.5
Average picrite	200	156	35	4.7	107	4.5	7.4
Partition coefficients – olivine	0	0.001	0.001	0.01	5		
- opx	0	0.002	0.002	0.02	1		
- cpx	0.01	0.05	0.35	0.60	1		
- garnet	0.01	0.02	0.13	2.50	0		

[a] Concentrations expressed as enrichment factors relative to Hofmann's (1988) primitive mantle; partition coefficients from Green (1994); mineral proportions: ol = 0.3; opx = 0.25; cpx = 0.15; garnet = 0.3

A key question is whether the lithosphere has the appropriate physical properties to produce large volumes of high-degree melts such as those that erupt during continental flood volcanism. McKenzie and Bickle (1988) and Arndt and Christensen (1992) showed, using petrological arguments and thermomechanical modelling, that the lithosphere, if dry, would contribute only minimal amounts of melt and that most magma would come from the asthenosphere or plume. Gallagher and Hawkesworth (1994) countered by proposing that the melting temperature of the lithosphere may have been reduced by the presence of volatile phases, in which case this part of the mantle would melt more readily than a volatile-poor plume. An implication of this model is that the tholeiitic basalts should be hydrous, and magmas from the deeper mantle essentially anhydrous. This is opposite to what we see in the Maymecha River basin, where the tholeiites show little evidence for the presence of primary volatiles (the amygdules in the lavas and the presence of abundant tuffs can be interpreted as the result of assimilation of water-, carbonate- or sul-fate-bearing sediments; Naldrett 1992; Naldrett et al. 1995), whereas magmas parental to the alkaline series appear to have been hydrous.

Comparison of primary magmas and sites of fractional crystallization for the two magma series

The two principal magma series of the Maymecha River basin appear to have formed in different parts of the mantle and, more importantly, seem to have behaved differently during their passage from source to surface. The tholeiites were derived from picritic primary melts that were processed in large, open-system magma chambers where they acquired both their restricted compositions and their crustal signature. Magmas parental to the alkaline series, on the other hand, came from deeper sources and passed relatively unscathed to the surface. Why the difference in behaviour? A possible explanation lies in the volatile-rich nature of the more alkaline magmas. The presence of volatiles would have

had two effects: (1) when dissolved in the magma the volatiles would decrease both density and viscosity, allowing the magma to pass through density barriers at the Moho and within the crust; (2) exsolution of volatiles would drastically reduce the density, propelling bubble-bearing magmas towards the surface, and allowing them to bypass the large open-system magma chambers.

Note added in proof There is some confusion surrounding the spelling of the rock name "meymechite". In other publications (e.g. Arndt et al. 1995), and in dictionaries of geological terms, "meimechite" is found, but we believe that "meymechite" is a more accurate transliteration of the Russian term. The name of the river is "Maymecha", hence the stratigraphic unit "Maymechinsky" Suite.

Summary and conclusions

On the basis of the data from the Noril'sk section, it has been proposed that the magmas parental to the Siberian flood-volcanic sequence formed through melting of the mantle beneath the continental lithosphere, either in a mantle plume (e.g. Sharma et al. 1991, 1992; Lightfoot et al. 1993; Wooden et al. 1993; Arndt et al. 1993) or in convecting normal mantle (Czamanske et al. 1998). Initial melting beneath relatively thick lithosphere, in the garnet field, at depths of at least 100 km, produced the early alkaline series. A major period of tholeiitic volcanism followed ascent of the site of melting. A combination of decreasing pressure and increasing degree of melting eliminated garnet from the source and produced parental magmas that assimilated continental crust in large magma chambers before reaching the surface.

The volcanic sequence in the Maymecha River basin formed during a third, chemically and geographically distinct, magmatic episode. Magmas of the alkaline series formed through melting deep in the mantle and ascended to the surface along conduits that bypassed the large, open-system, crustal magma chambers. The interlayering of lavas from the two magma series in the three lowermost rock suites in the Maymecha River basin (Figs. 2 and 3) provides evidence that two independent crustal plumbing systems operated contemporaneously.

The nature of these plumbing systems is a matter for speculation. One possibility is that the centre of tholeiitic activity was in the Putorana or Noril'sk regions in the central and northwestern parts of the province, and that lavas from this centre flowed as far as the Maymecha-Kotuy region, where they alternated with flows erupting from alkaline conduits. A problem with this idea arises from the petrological and chemical data of Fedorenko and Czamanske (1997) which demonstrate that the same two types of magma are also present in intrusive dykes and sills of the Maymecha River basin. If the sole source

of tholeiitic magma was to the west, then magma must have flowed laterally along dykes away from this centre, in much the same way as magma flowed outward from Muskox-Coppermine magmatic centre along the radial McKenzie dyke swarm in Canada (Ernst and Baragar 1992). Alternatively, there may have been multiple exits from a large magma chamber, or multiple chambers, each of which supplied magma of similar chemical and petrologic character. The similarity of low-Ti continental flood basalts worldwide provides support for the latter interpretation (e.g. Carlson 1991; Hergt et al. 1991).

The site of melting for the alkaline magmas was far deeper in the mantle than for the tholeiites. If dry, the meymechites formed at a pressure up to 8 GPa which corresponds to a depth of about 240 km; the tholeiites were produced at a depth sufficiently shallow, or at a degree of melting sufficiently high, that garnet was eliminated from the residue. This diversity indicates that the mantle source of Siberian flood volcanic province was strongly heterogeneous, both in temperature and composition, and was capable of producing magmas over a wide range of depths and degrees of partial melting. It is a matter of substantial debate whether such a source is most consistent with current ideas that attribute such flood volcanism to melting in the head of a mantle plume, or to a convecting mantle undergoing partial melting (King and Anderson 1995, in press).

References

Arndt NT, Christensen U (1992) Role of lithospheric mantle in continental volcanism: thermal and geochemical constraints. J Geophys Res 97: 10967–10981
Arndt NT, Czamanske GK, Wooden JL, Fedorenko VA (1993) Mantle and crustal contributions to continental flood volcanism. Tectonophysics 223: 39–52
Arndt NT, Lehnert K, Vasil'ev Y (1995) Meimechites: highly magnesian alkaline magmas from the subcontinental lithosphere? Lithos 34: 41–59
Carlson RW (1991) Physical and chemical evidence on the cause and source characteristics of flood basalt volcanism. Aust J Earth Sci 38: 525–544
Chauvel C, Hofmann AW, Vidal P (1992) HIMU-EM: the French Polynesian connection. Earth Planet Sci Lett 110: 99–119
Cox KG (1980) A model for continental flood volcanism. J Petrol 21: 629–650
Cox KG (1988) The Karoo Province. In: Macdougall JD (ed) Continental flood basalts. Kluwer, Dordrecht, pp 239–272
Czamanske GK, Wooden JL, Zientek ML, Fedorenko VA, Zen'ko TE, Kent J, King BS, Knight RL, Siems DF (1994). Geochemical and isotopic constraints on the petrogenesis of the Noril'sk-Talnakh ore-forming system. In: Lightfoot PC, Naldrett AJ (eds) Proc Sudbury-Noril'sk Symp. Ont Geol Surv Spec Vol 5, pp 313–342

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Dalrymple BG, Czamanske GK, Fedorenko VA, Simonov ON, Lanphere MA, Likhachev AP (1995) A reconnaissance 40Ar/ 39Ar geochronological study of ore-bearing and related rocks, Siberian Russia. Geochim Cosmochim Acta 59: 2071–2083

Erlank AJ (1984) Petrogenesis of the volcanic rocks of the Karoo Province. Geol Soc S Afr Spec Publ 13: 395 pages

Ernst RE, Baragar WRA (1992) Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Nature 356: 511–513

Fedorenko V, Czamanske GK (1997) Results of new field and geochemical studies of the volcanic and intrusive rocks of the Maymecha-Kotuy area, Siberian flood-basalt province, Russia. Int Geol Rev 39: 479–531

Fedorenko VA, Lightfoot PC, Naldrett AJ, Czamanske GK, Hawkesworth CJ, Wooden JL, Ebel DS (1996) Petrogenesis of the Siberian Flood Basalt sequence at Noril'sk. Int Geol Rev 38: 99–135

Gallagher K, Hawkesworth CJ (1992) Dehydration melting and the generation of continental flood basalts. Nature 258: 57–59

Gasparik T (1993) The role of volatiles in the transition zone. J Geophys Res 98: 4287–4299

Ghiorso MS, Sack RO (1995) Chemical mass transfer in magmatic processes. IV. A revised and internally consistent model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures. Contrib Mineral Petrol 119: 197–212

Green TH (1994) Experimental studies of trace-element partitioning applicable to igneous petrogenesis – Sedona 16 years later. Chem Geol 117: 1–36

Griselin M, Arndt NT (1996) Plume-lithosphere interaction and crustal contamination during formation of Coppermine River basalts, Northwest Territories, Canada. Can J Earth Sci 34: 958–975

Gusev BV (1970) Paleomagnetic correlation and age interpretation of mamatic formations of the Maymecha-Kotuy province (in Russian). In: Egorov LS (ed), Carbonatites and alkaline rocks of northern Siberia, Leningrad, NIIGA, pp 15–28

Hawkesworth CJ, Lightfoot PC, Fedorenko VA, Blake S, Naldrett AJ, Doherty W, Gorbachev NS (1995) Magma differentiation and mineralisation in the Siberian flood basalts. Lithos 34: 61–88

Hergt JM, Peate DW, Hawkesworth CJ (1991) The petrogenesis of Mesozoic Gondwana low-Ti flood basalts. Earth Planet Sci Lett 105: 134–148

Herzberg C, Zhang J (1996) Melting experiments on anhydrous peridotite KLB-1: compositions of magmas in the upper mantle and transition zone. J Geophys Res 101: 8271–8295

Hofmann AW (1988) Chemical differentiation of the Earth: the relationship between mantle, continental crust, and oceanic crust. Earth Planet Sci Lett 90: 297–314

Hofmann AW, White WM (1982) Mantle plumes from ancient oceanic crust. Earth Planet Sci Lett 57: 421–436

Horan MF, Walker RJ, Fedorenko VA, Czamanske GK (1995) Osmium and neodymium isotopic constraints on the temporal and spatial evolution of Siberian flood basalt sources. Geochim Cosmochim Acta 59: 5159–5168

Inoue T (1994) Effect of water on melting phase relations and melt composition in the system Mg_2SiO_4-$MgSiO_3$-H_2O up to 15 GPa. Phys Earth Planet Inter 85: 237–263

Inoue T, Sawamoto H (1992) High pressure melting of pyrolite under hydrous condition and its geophysical implications. In: Syono Y, Manghnani MH (eds) High-pressure research: application to Earth and planetary sciences. Terra Publ Co, Washington, DC, pp 323–331

Kamo SL, Czamanske GK, Krogh TE (1996) A minimum U-Pb age for Siberian flood-basalt volcanism. Geochim Cosmochim Acta 60: 3505–3511

Khabin AG, Surina NP (1970) Petrology of dikes, sills, and explosive pipes in the Maymecha-Kotuy province (in Russian), Nauka Press, Moscow 204 p

King SD, Anderson DL (1995) An alternative mechanism of flood basalt formation. Earth Planet Sci Lett 136: 269–279

King SD, Anderson DL (1998) Edge driven convection. Earth Planet Sci Lett (in press)

Lassiter JC, DePaolo DJ (1997) Plume/lithosphere interaction in the generation of continental and oceanic flood basalts: chemical and isotopic constraints. In: Mahoney JJ, Coffin MF (eds) Large igneous provinces: continental, oceanic and planetary flood volcanism. Am Geophys Union, Washington, DC, pp 335–356

Lightfoot P, Hawkesworth C (1988) Origin of Deccan Trap lavas: evidence from combined trace element and Sr-, Nd- and Pb-isotope studies. Earth Planet Sci Lett 91: 89–104

Lightfoot P, Hawkesworth CJ, Devey CW, Rogers NW, Van Calsteren PWC (1990a) Source and differentiation of Deccan Trap lavas: implications of geochemical and mineral chemical variations. J Petrol 31: 1165–1200

Lightfoot PC, Naldrett AJ, Gorbachev NS, Fedorenko VA (1990b) Geochemistry of the Siberian trap of the Noril'sk area, USSR, with implications for the relative contributions of crust and mantle to flood basalt magmatism. Contrib Mineral Petrol 104: 631–644

Lightfoot PC, Hawkesworth CJ, Hergt J, Naldrett AJ, Gorbachev NS, Fedorenko VA, Doherty W (1993) Remobilization of the continental lithosphere by mantle plumes: major-, trace-element and Sr-, Nd-, and Pb-isotope evidence from picritic and tholeiitic lavas of the Noril'sk district Siberian Trap, Russia. Contrib Mineral Petrol 114: 171–188

Lightfoot PC, Naldrett AJ, Gorbachev NS, Fedorenko VA, Hawkesworth CJ, Hergt J, Doherty W (1994) Chemostratigraphy of Siberian Trap lavas, Noril'sk District, Russia: implications for the source of flood basalt magmas and their associated Ni-Cu mineralization. In: Naldrett AJ, Lightfoot PC (eds) Proc Sudbury-Noril'sk Symp. Ont Geol Surv Spec Vol 5, pp 283–312

Makarenko GF (1976) The epoch of Triassic trap magmatism in Siberia. Int Geol Rev 19: 1089–1100

McKenzie D, Bickle MJ (1988) The volume and composition of melt generated by extension of the lithosphere. J Petrol 29: 625–679

Naldrett AJ (1992) A model for the Ni-Cu-PGE ores of the Noril'sk region and its application to other areas of flood basalt. Econ Geol 87: 1945–1962

Naldrett AJ, Fedorenko VA, Lightfoot PC, Kunilov VE, Gorbachev NS, Doherty W, Johan Z (1995) Ni-Cu-PGE deposits of the Noril'sk region, Siberia: their formation in conduits for flood basalt volcanism. Trans Inst Min Metall London 104: B18-B36

Ohtani E, Mibe K, Kato T (1996) Origin of cratonic peridotite and komatiite: evidence for melting in the wet Archean mantle. Proc Jpn Acad 72: 113–117

Peng ZX, Mahoney J, Hooper P, Harris C, Beane J (1993) A role of lower continental crust in flood basalt genesis? Isotopic and incompatible element study of the lower six formations of the western Deccan Traps. Geochim Cosmochim Acta 58: 267–288

Sharma M, Basu AR, Nesterenko GV (1991) Nd-Sr isotopes, petrochemistry, and origin of the Siberian flood basalts, USSR. Geochim Cosmochim Acta 55: 1183–1192

Sharma M, Basu AR, Nesterenko GV (1992) Temporal Sr-, Nd-and Pb-isotopic variations in the Siberian flood basalts: implications for the plume-source characteristics. Earth Planet Sci Lett 113: 365–381

Shikhorina KM (1970) Volcanic formations of the Maymecha-Kotuy province (in Russian). In: Egorov LS (ed), Carbonatites and alkaline rocks of northern Siberia, Leningrad, NIIGA, pp 5–14

Sobolev AV, Kamenetskiy S, Kononkova NN (1991) New data on Siberian meymechite petrology. Geochem Int 29:10–20

Wooden JL, Czamanske GK, Fedorenko VA, Arndt NT, Chauvel C, Bouse RM, King BW, Knight RJ, Siems DF (1993) Isotopic and trace-element constraints on mantle and crustal contributions to Siberian continental flood basalts, Noril'sk area, Siberia. Geochim Cosmochim Acta 57: 3677–3704

Zhuralev EG (1986) The trap formation of the Western Siberia plate (in Russian). Izv Akad Nawk SSSR Ser Geol 7: 26–32

Zolotukhin VV, Al'mukhamedov AI (1988) Traps of the Siberian Platform. In: Macdougall JD (ed) Continental flood basalts. Kluwer, Dordrecht, pp 273–310