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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

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Abstract. The sequence investigated of the Siberian Trap at Noril'sk, USSR, consists of at least 45 flows that have been divided into six lava suites. The lower three suites consist of alkalic to subalkalic basalts (the Ivakinsky suite), overlain by nonporphyritic basalts (the Syverminsky suite), and porphyritic and picritic basalts (the Gudchikhinsky suite). The upper three suites are tholeiitic. The uppermost 750 m of dominantly non-porphyritic basalt belong to the Mokulaevsky suite and are characterized by a nearly constant Mg number (0.54 – 0.56), SiO_2 (48.2–49.1 wt%), Ce (12–18 ppm), and Ce/Yb (5–8). The underlying 1100 m of dominantly porphyritic basalt belong to the Morongovsky and Nadezhdinsky suites. There is a continuous increase in SiO_2 (48.1–55.2 wt%), Ce (12–41 ppm), and Ce/Yb (5–18) from the top of the Mokulaevsky to the base of the Nadezhdinsky with little change in the Mg number (0.53–0.59). Mokulaevsky magmas have trace element signatures similar to slightly contaminated transitional type mid-ocean ridge basalts. The change in major and trace element geochemistry in the upper three suites is consistent with a decline in the degree of anatexis and assimilation of tonalitic upper crust by Mokulaevsky magma. The Nadezhdinsky and underlaying lavas thicken within and thus appear to be related to an elongate basin centred on the Noril'sk-Talnakh mining camp. The Mokulaevsky and Morongovsky lavas thicken to the east and appear to be related to a basin centred more than 100 km to the east of the Noril'sk region; these magmas may have risen up out of a different conduit system.

Introduction

The Siberian Trap arguably represents the largest known Mesozoic outpouring of continental flood basalt (CFB) magma, with an original area approaching 1 500 000 km^2 and an average thickness of 1 km (Basaltic Volcanism Study Project 1981). Eruption commenced in the late Permian and extended into the late Triassic.

Stratigraphic studies of such extensive CFB sequences represent an increasingly important source of information about the nature of the sub-continental mantle, and the petrogenetic processes responsible for temporal and spatial variations in basalt chemistry. Most of the rocks within CFB provinces have evolved from primary melt compositions by extensive degrees of fractional crystallization as they migrated from the mantle to the surface (Cox 1980). In some cases they have interacted with the crustal materials through which they have passed (e.g., Cox and Hawkesworth 1984). Stratigraphic variations in lavas reflect compositional diversity in successively erupted magmas and therefore provide a good spatial and temporal record of the changing magma composition, which in turn provides a basis for petrogenetic modelling.

In the Noril'sk region, the sequence of lavas is well developed in a basin and is associated with intrusions belonging to the same magmatic episode which are hosts to very important deposits of Ni-Cu sulfides. It has been proposed that these deposits are a consequence of the intrusions assimilating and reducing sulfate from early Devonian evaporites in the region (Godlevski and Grinenko 1963; Grinenko 1985). The chemical compositions of the basalts, their implications for the type of mantle from which they were derived, and the extent to which they have interacted with crustal rocks have an important bearing on this hypothesis. This, the first of a series of papers on the Siberian Trap, documents geochemical data from a 2200 m drill core (named core SG-9) located north of Noril'sk and examines:

1. The variations in geochemistry through the basalt stratigraphy and the subdivision of the stratigraphy into suites
2. The roles of fractional crystallisation and partial melting in explaining the variations within and between the suites
3. The evidence for the assimilation of crustal material by magma

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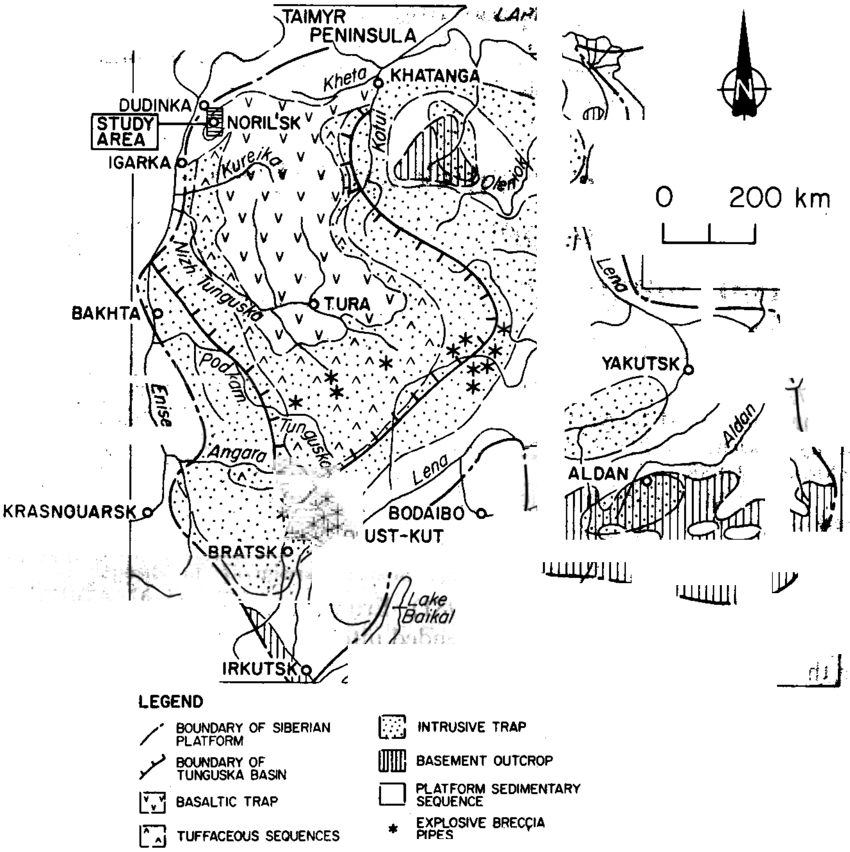


Fig. 1. Map of the Siberian Trap showing the location of the study area (after Zolotukhin and Al'mukhamedov)

Geology of the Noril'sk region

The area of the Siberian flood basalt investigated in this study is located on the extreme northwestern margin of the Siberian Platform (Fig. 1), which has been a stable craton since the end of the Precambrian. To the north, the platform is separated by the Khatanga trough from the second platform, the Taimyr Peninsula, which has been stable since the Proterozoic. To the west, the third craton, the East European-Urals Block, is separated from the Siberian Platform by the Enisei trough, known geographically as the West Siberian Lowlands. The East European-Urals Block has behaved as a craton since middle Permian time.

Within western Siberia, Lower Palaeozoic dolomites, limestones and agillites of marine origin are overlain by extensive Devonian calcareous and dolomitic marls, sulfate-rich evaporites, and Lower Carboniferous shallow-water limestones (Genkin et al. 1981). These are, in turn, unconformably overlain by Middle Carboniferous to Late Permian lagoonal and continental sediments, including gravels, conglomerates and coal measures (Smirnov 1966; Glazkovsky et al. 1977). The emergent sedimentary sequence is covered by late Permian and Triassic CFB (Bazunov 1976; Glazkovsky et al. 1977); these consist of alkalic, sub-alkalic, tholeiitic and picritic variants. Although the magmatic activity is very widespread, the lower formations of the investigated part of the sequence tend to be thickest in elongated north-south striking basins in the Noril'sk region (Fig. 2A), and individual sheets thin towards the flanks of the region. Sill-like tholeiitic intrusions, varying in composition from subalkaline dolerite to gabbro-dolerite (Glazkovsky et al. 1977), were largely emplaced contemporaneously with the lavas.

The lavas of the Noril'sk region are divided into 11 suites, the Ivakinsy, Syverminsky, Gudchikhinsky, Khakanchansky, Tuklonsky, Nadezhdinsky, Morongovsky, Mokulaevsky, Kharaelakhsky, Kumginsky, and Samoedsky. The total thickness of volcanic rocks exceeds 3700 m. The thickness of individual sequences varies greatly in a systematic manner, defining the basins referred to above, and Fedorenko (1979) and Zorin and Vladimirov (1989) have argued that these basins were produced syngenetically above sites of magma generation. Fedorenko (1979) shows that the Ivakinsky-Syverminsky-Gudchikhinsky and Nadezhdinsky sequences reach their maximum thickness in a basin centered on the Noril'sk-Talnakh mining camp and elongated in the direction of the Noril'sk-Kharaelakh fault (Figs. 2A, 3). The Tuklonsky includes picrites and is only developed in the eastern part of the Noril'sk region. The Morongovsky-Mokulaevsky sequence, though contributing to more than half of the total thickness of flood basalt in the Noril'sk region, thickens to the east and shows little relation to the Noril'sk-Talnakh basin (Fig. 2B).

Core SG-9 is located north of Talnakh (Fig. 4) and penetrates 2250 m of the trap close to the center of the Noril'sk basin.

Petrography

Many of the tholeiitic non-prophyritic basalts have subophitic textures where pyroxene crystals partially enclose plagioclase laths. Intergranular textures are also common, with interstices between laths of plagioclase occupied by granular pyroxene and opaques. With the appearance of glass and chloritic alteration products the texture becomes intersertal. Flow orientation of the plagioclase laths is rare. Porphyritic textures ($<10\%$ phenocrysts) are common in the lower tholeiites (Fig. 5); plagioclase is the dominant phenocryst and occurs as small (<2 mm) glomeroporthyriths with pyroxene and pseudomorphed olivine. Augite is the dominant pyroxene in both the phenocrysts and ground-mass. Fresh olivine phenocrysts are found in the picritic basalts (up to 50 modal percent). In the sub-alkalic basalts, plagioclase and augite phenocrysts occur in a ratio of 65:35, and the ground mass is composed of plagioclase

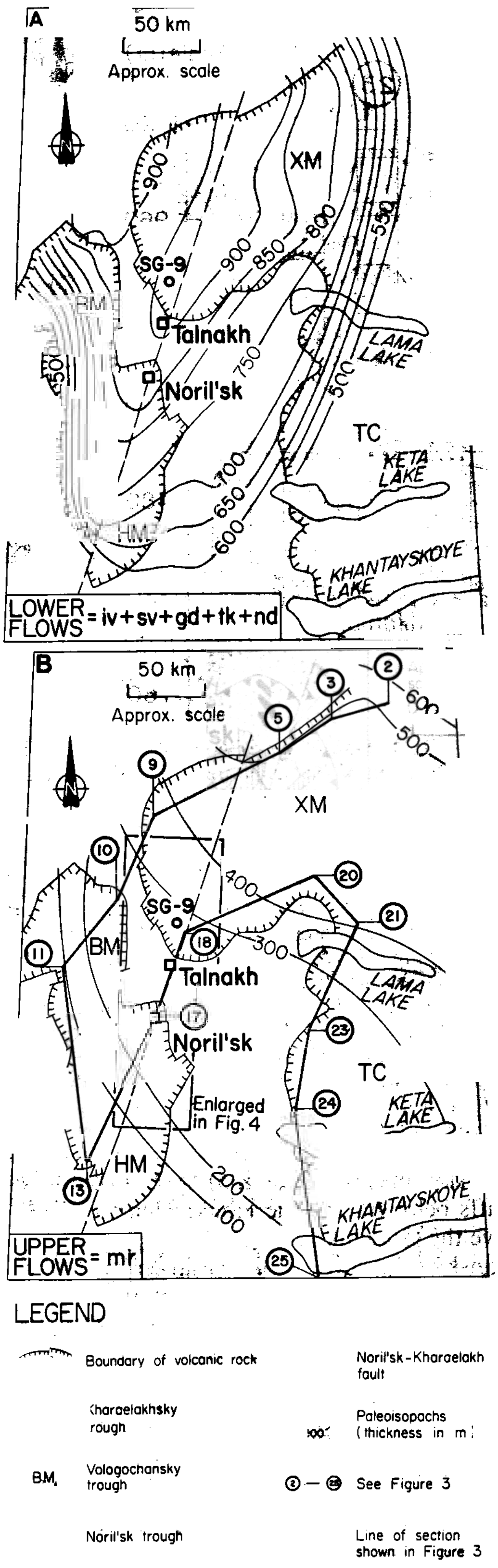


Fig. 2A, B. Map showing isopachs for the lower flows (**A** – *iv, sv; gd, tk,* and *nd*) and upper flows (**B** – *mr*). Also shown are the location of core SG-9, the major basins, and the line and section shown in Fig. 3 (based on Fedorenko and Djuzhikov 1981)

augite, and opaques. Glass is abundant in many of the flows and may be fresh and colorless to dark brown. Zeolite-filled cavities are common. A complete mineralogical and mineral chemical study of the flows is in progress (Naldrett et al., in preparation).

Sample preparation and analytical techniques

Samples (25–100 g) cut from segments of drill core by us (V.A.F. and N.S.G.) were hand-crushed using a Rocklabs D3 steel anvil smasher and ground to <200 mesh in a 99.8% pure alumina Fritsch laboratory planetary mill. The Al_2O_3 data are considered qualitative as the mills can introduce <0.25% Al_2O_3 during grinding.

Major elements were determined on fused glass discs by X-ray fluorescence (XRF) spectrometry. Trace elements were determined by inductively coupled plasma mass spectrometry (REE, Th, U, Nb, Ta, Hf, Zr, Y, Rb, Sr) (Doherty 1989), inductively coupled plasma emission spectrometry (Sc, V), and atomic absorption (Ba, Ni, Cr, Cu, Zn, Co) at the Geoscience Laboratories, Ontario Geological Survey (Geoscience Laboratories Manual, in preparation). BHVO-1, in-house reference materials, the University of Toronto basalt standard (UTB-1) and blind duplicates were used for quality control purposes (see Table 1). Minimum observed concentrations in the suite of samples were well in excess of analytical detection limits. Results are presented in Table 1.

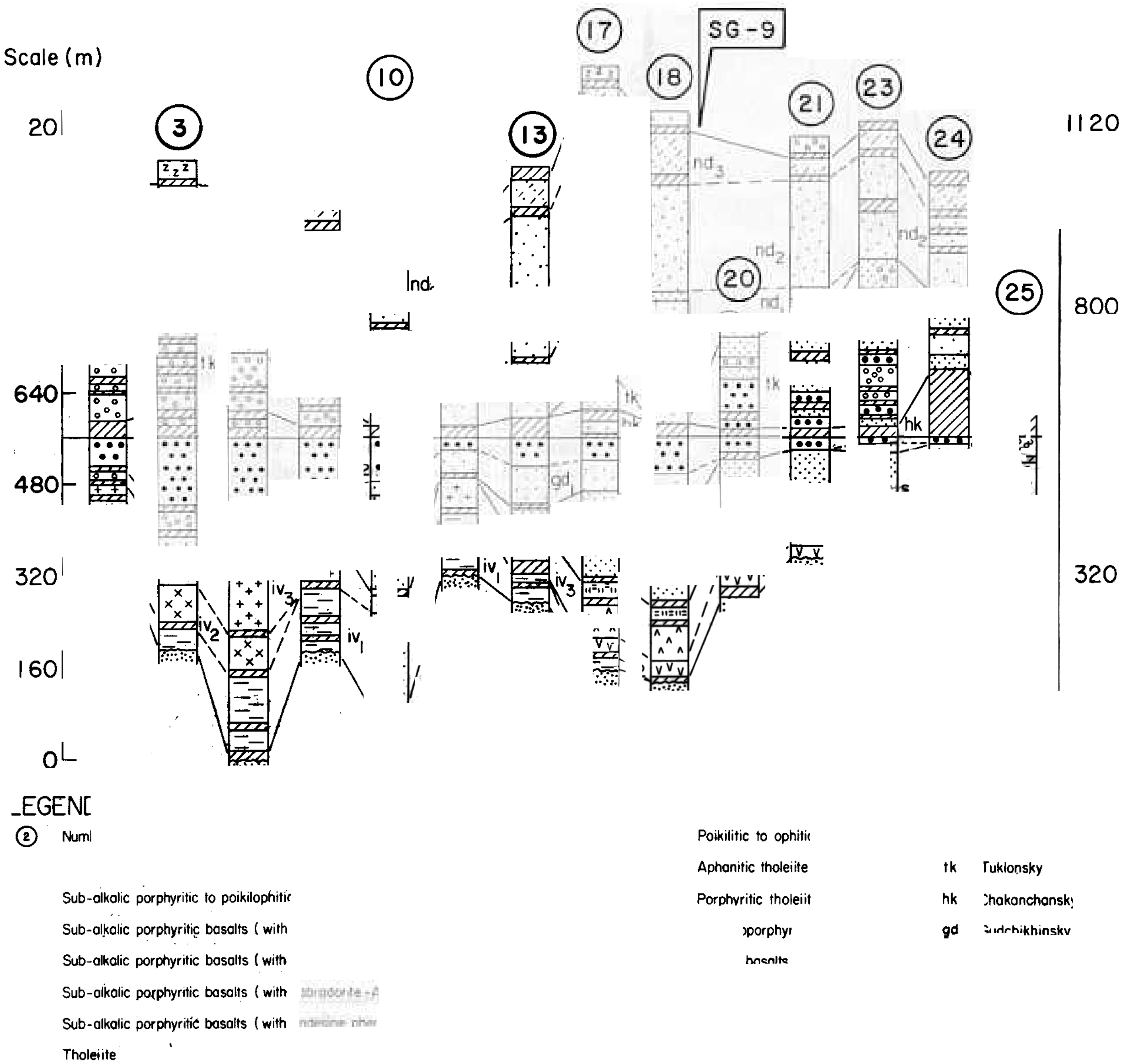
As the original samples were small in size, it was considered necessary to ensure that they were representative. A 40-g sample of basalt (SG-9, 864.0) was split in half, and the two sub-samples were then prepared by conventional techniques. The results shown for the two splits in Table 1 indicate, with exception of Al_2O_3 (introduced during grinding), that the two sub-samples are analytically indistinguishable.

Alteration and flow homogeneity

Two styles of alteration appear to be represented in the samples. Amygdales tend to be filled with secondary zeolites, and some samples contain pervasive bifurcating veins of micaceous material. Amygdales exceeding 5 mm diameter were removed from samples during preparation. It is presumed that the removal of amygdaloidal material from the samples is an effective technique of minimizing secondary enrichment or depletion of Ba and Sr, which are remobilized during zeolite facies metamorphism (Wood et al. 1976; Lightfoot 1985; Jolly 1987).

Alteration is therefore largely limited to bifurcating veins containing micaceous material in otherwise fresh basalt. It is possible that these veins are a consequence of hydrothermal circulation around the major intrusive magma bodies related to the Trap. Rb, Sr, and K_2O (see later) show greater scatter than the other incompatible elements. We are confident that this is not an analytical problem because of the quality-control measures. Instead, the variation in Rb, Sr, and K_2O may be an inherent feature of the magma, or it may reflect the remobilisation of the large-ion lithophile elements (LILE). We also note that in a general sense the variations in Rb and K_2O are similar to Ba and Th and that the detailed variations may have been blurred by selective remobilization.

The possibility that local flow heterogeneities may be present in CFB has been suggested by many workers. Although Lightfoot (1985) confirms that chemical char-



acteristics are constant within a single non-amygdaloidal flow throughout an area of 200 km^2 along the southern margin of the Deccan Trap, Mahoney et al. (1985) show substantial heterogeneity through a vertical section in a non-amygdaloidal Deccan Trap flow. It has not yet been possible to carry out more widespread studies of variations within single flows of Siberian Trap lava.

Stratigraphic variation and subdivision of the basalts

The basalt samples from core SG-9, Noril'sk district, belong to six stratigraphic units, termed (from the base to the top) the Ivakinsky (iv), Syverminsky (sv), Gudchikhinsky (gd), Nadezhdinsky (nd), Morongovsky (mr), and Mokulaevsky (mk) suites (Fig. 5). A 20-m-thick sequence of tuffs belonging to the Khakanchansky is developed above the Gudchikhinsky.

The Ivakinsky suite consists of a basal series of alkalic to sub-alkalic basalts, of which one of the samples comes from a comagmatic intrusion (SG-9, 2200). The Syverminsky suite consists dominantly of tholeiitic basalts. The Gudchikhinsky suite consist of a basal series of porphyritic tholeiitic basalts overlain by a series of progressively more olivine-rich picritic basalts. Although not developed in core SG-9, the Tuklonsky includes picritic basalts (Fedorenko 1981; Fedorenko and Djuzhikov 1981; Fedorenko et al. 1984). The entire sequence of Nadezhdinsky suite basalts are porphyritic tholeiitic basalts. The overlying Morongovsky and Mokulaevsky consist of tholeiitic porphyritic to non-porphyritic basalts. Generally, the phenocryst content of the tholeiitic basalts decreases up through the sequence. The uppermost suites (Kharaelakhsky, Kumginsky, and Samoedsky) are not present in SG-9.

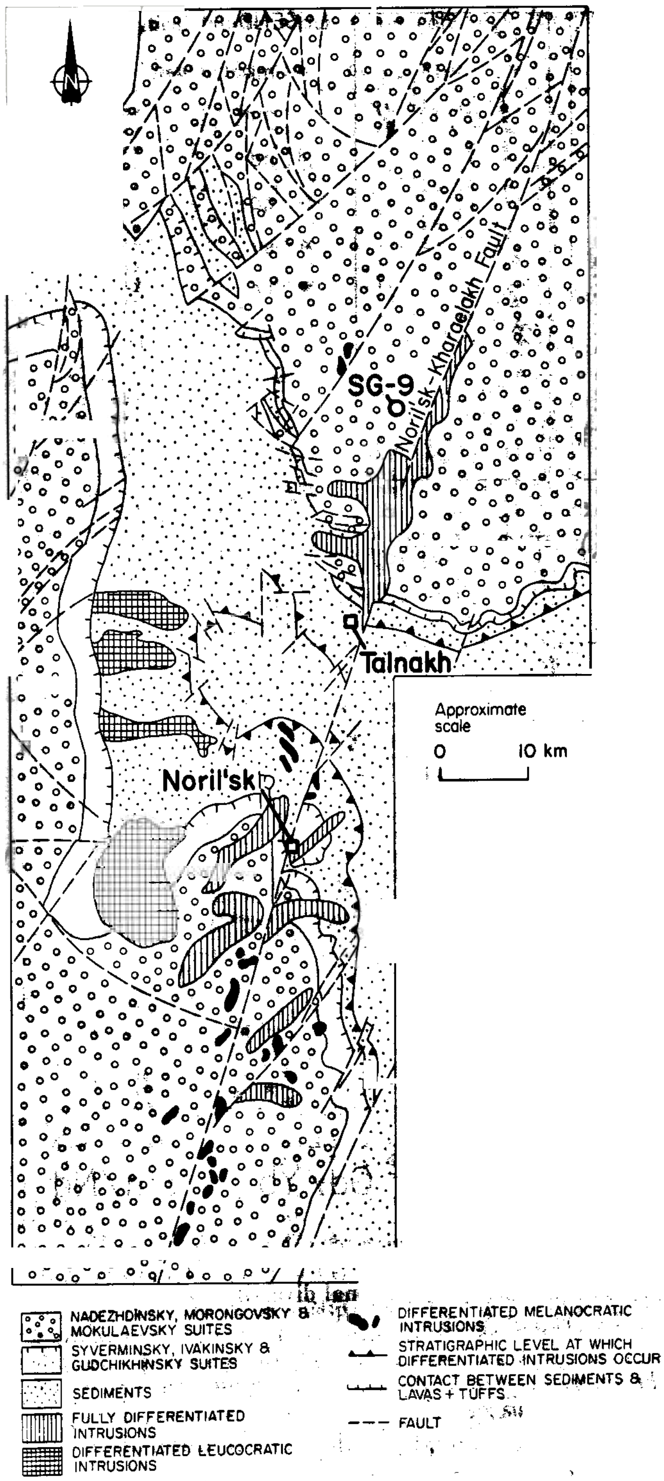


Fig. 4. Geological map of the Noril'sk-Talnakh district, showing the location of the sampled lava formations and differentiated intrusions, and the location of core SG-9

Several petrological and geochemical features have been established as characteristic of the magmas comprising each suite (Table 2); these include Mg number, TiO_2, and Ce, which act as monitors of fractional crystallization, and the ratios Ce/Yb, Sm/Nd, La/Sm, and Gd/Yb, which help to identify different magmatic and crustal components, the extent to which they have interacted, and the nature of the processes responsible for these interactions. Data for selected oxides, elements, and element ratios are plotted against depth in core SG-9 in Fig. 5.

Although some of the stratigraphic horizons can be identified as picritic basalts (gd) and trachybasalts (iv), the majority of the flows are porphyritic to non-porphyritic tholeiites, which are best grouped according to their major and trace element compositions. The subdivisions of Fedorenko (1981) and Fedorenko et al. (1989) into suites are based on both petrographic variations and some geochemical data; our data for samples from core SG-9 support this subdivision and refine the characteristic features of each suite. With the exception of the upper boundary of the Gudchikhinsky, the boundaries between the suites are gradational and, to some extent, arbitrary in the sense that a subjective decision has been made about the levels at which a particular magma type becomes dominant (cf. Cox and Hawkesworth 1985). A small number of the samples analyzed show transitional characteristics such as SG-9-1862.0, which is geochemically similar to the Syverminsky.

Several points are evident from the geochemical stratigraphy shown in Fig. 5. These will be described from the base upwards:

1. The Ivakinsky suite (including SG-9, 2200) shows a wide range of Ce and Yb concentrations (73–132 ppm Ce and 3.2–4.7 ppm Yb), but a narrow range in Ce/Yb (22.8–30.3). Both the overall abundances of the incompatible elements and the ratios of large-ion lithophile elements to high field strength elements (LILE/HFSE) are higher than in most of the tholeiitic and picritic basalts. The overlying Syverminsky is not well represented in core SG-9, but apparently has slightly lower overall incompatible trace element abundances than the underlying Ivakinsky, but similar Ce/Yb.
2. The Gudchikhinsky consists largely of picritic basalts and, consequently, the overall incompatible element abundances are relatively low. The uppermost flows are more olivine-rich than the lower flows. Although these basalts show quite strong heavy rare-earth element (HREE) depletion (Yb = 1.0–2.2 ppm), the profile of the heavy rare-earth elements (HREE) is steeper (Gd/Yb > 2.6) than most of the other rocks in core SG-9.
3. The Nadezhdinsky basalts have higher Ce concentrations than the Morongovsky basalts, but similar Yb; the SiO_2 content is much higher and more variable. Ce/Yb systematically declines upwards through these suites between 1750–750 m in core SG-9.
4. The Mokulaevsky and Morongovsky suites are compositionally similar, but not identical. With the exception of the lowermost Morongovsky basalts between 1250–1000 m depth, which are compositionally transitional into the Nadezhdinsky, the stratigraphy consists of almost 1000 m of geochemically homogeneous tholeiitic basalt, which can be referred to as the Mokulaevsky magma type. The Mokulaevsky magma type is characterized by: constant Mg number (0.54–0.58), Ce (14–18 ppm), Yb (2.2–2.7 ppm), and Ce/Yb (5.4–7.4).

Distinctions and similarities among the six suites are best illustrated using the criteria outlined in the classifi-

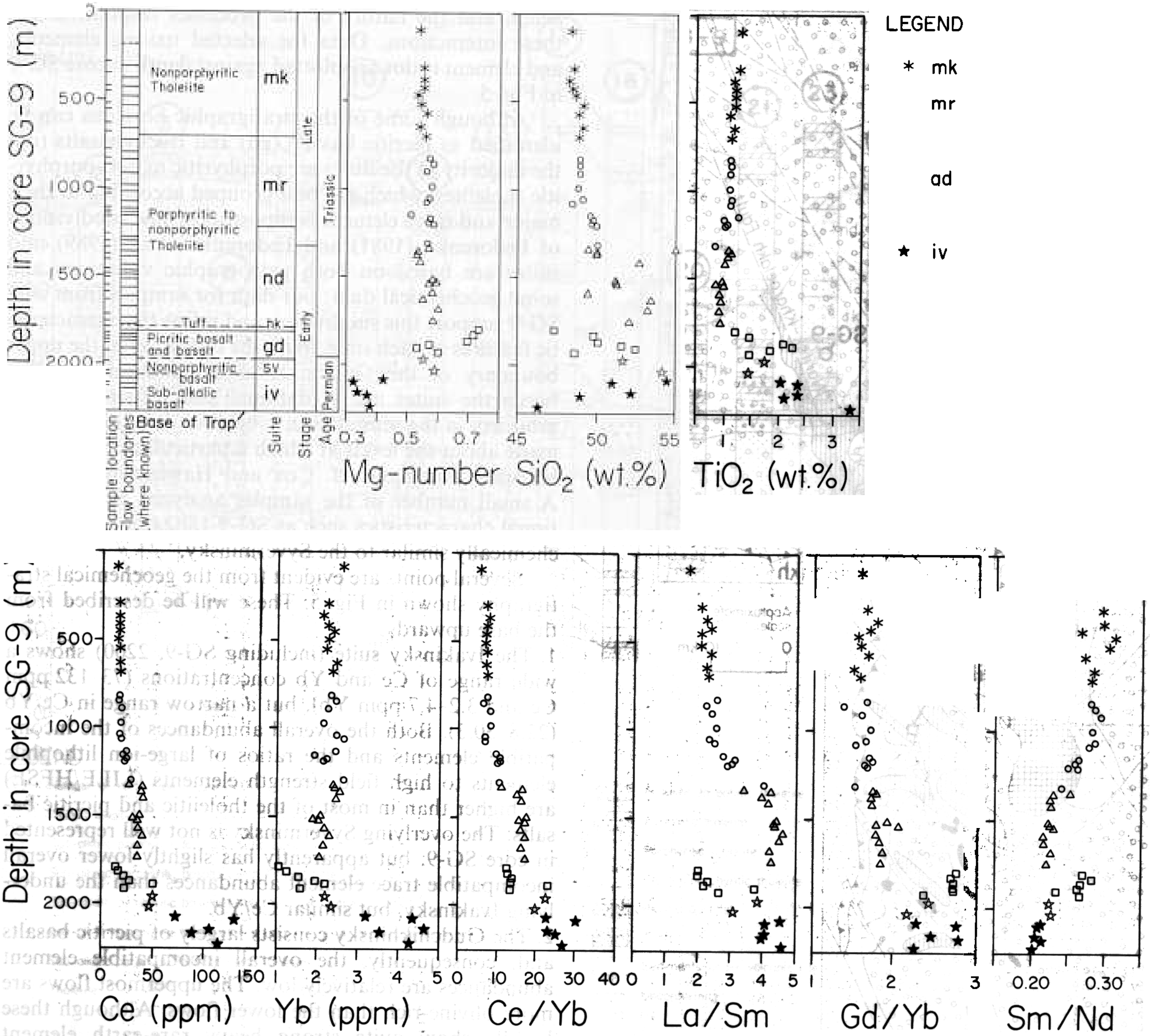


Fig. 5. Petrological and geochemical stratigraphy of core SG-9

cation scheme (Table 2). Figure 6 a illustrates these distinctions in terms of Gd/Yb versus La/Sm, and shows the clear compositional clustering within each suite. The Ivakinsky, Gudchikhinsky, Nadezhdinsky, and Mokulaevsky are separated into quadrants by lines with Gd/Yb = 2 and La/Sm = 3. There is a general sense of increasing La/Sm and Gd/Yb from the Mokulaevsky, through the Morongovsky, into the Nadezhdinsky, and this variation is coupled with a systematic change in the stratigraphic position of the sampled flows; the samples with lowest La/Sm occur at the top of the trap, whereas those with higher La/Sm are found at the base of the Nadezhdinsky (Fig. 5). The Ivakinsky and Syverminsky are compositionally similar, but are quite distinct compared to the Gudchikhinsky, and all three of these suites fall above Gd/Yb = 2 and are therefore quite different compared to the upper 1750 m of trap stratigraphy (nd, mr, and mk suites).

Reasons for the compositional diversity of the Trap at Noril'sk

Fractional crystallization and partial melting

Petrographic data indicate that the evolution of the Siberian Trap tholeiites is controlled by plagioclase, augite, and/or olivine (see above). Since most of the Siberian Trap tholeiites contain <10% phenocrysts, they can essentially be treated as liquid compositions. The variation in the major and trace elements, with special reference to the REE (Figs. 5, 6), provide important information about the role of fractional crystallization.

Ivakinsky and Syverminsky basalts show a progressive decrease in overall REE abundance upwards through the two suites (Fig. 5), with little change in La/Sm (3.2–4.5) and Gd/Yb (2.2–2.8) (Fig. 6a), accompanied by an upward increase in Mg number, Ni, and

Table Analytical data for samples from core SG-9, Noril'sk district, USSR

Suite	Depth (m)	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5		Mg#
Mokulaevsky	85.6	48.3	1.33	16.42	13.36	6.83	0.18	11.02	2.17	0.23	0.10	1.40	0.543
Mokulaevsky	294.5	48.5	1.29	15.59	13.52	7.28	0.21	11.04	2.06	0.37	0.12	3.00	0.556
Mokulaevsky	367.0	48.2	1.19	17.51	12.49	6.78	0.20	11.37	1.95	0.17	0.11	1.60	0.558
Mokulaevsky	414.0	48.5	1.22	17.21	12.66	6.81	0.18	10.65	1.97	0.75	0.09	1.40	0.556
Mokulaevsky	449.0	48.7	1.22	16.08	13.22	6.64	0.20	11.68	1.99	0.22	0.09	2.20	0.539
Mokulaevsky	502.0	49.1	1.21	16.24	12.71	6.63	0.19	11.60	2.02	0.20	0.10	0.80	0.548
Mokulaevsky	557.0	48.9	1.11	16.59	12.54	7.03	0.19	11.03	2.18	0.36	0.10	1.20	0.566
Mokulaevsky	636.5	49.1	1.19	15.78	12.79	6.56	0.18	12.17	1.96	0.18	0.10	3.00	0.544
Mokulaevsky	683.0	48.9	1.15	16.46	12.49	6.89	0.19	11.78	1.90	0.17	0.11	1.40	0.562
Morongovsky	788.0	48.9	1.12	16.73	12.27	7.15	0.19	11.35	1.98	0.25	0.10	0.80	0.576
Morongovsky	819.0	48.9	1.14	17.07	11.79	7.18	0.17	11.48	1.92	0.24	0.11	1.60	0.586
Morongovsky	864.0	48.9	1.12	16.21	12.94	7.19	0.20	10.91	1.93	0.46	0.12	1.80	0.564
Morongovsky	947.0	48.8	1.11	17.00	12.22	7.25	0.18	11.10	1.88	0.36	0.12	1.60	0.580
Morongovsky	1012	49.1	1.14	16.29	12.50	7.22	0.19	11.16	2.05	0.28	0.11	1.60	0.574
Morongovsky	1036	48.4	1.12	17.33	12.64	6.98	0.19	11.01	1.98	0.20	0.10	1.80	0.562
Morongovsky	1109	49.6	1.27	16.32	12.75	5.79	0.18	11.33	2.02	0.62	0.13	1.00	0.514
Morongovsky	1129	49.7	1.00	15.83	12.54	7.31	0.17	11.20	1.80	0.33	0.09	2.40	0.576
Morongovsky	1151	49.7	1.05	15.51	12.45	7.07	0.18	11.53	1.92	0.51	0.11	1.80	0.569
Morongovsky	1160	49.9	1.03	16.44	11.51	7.05	0.16	11.51	1.95	0.32	0.10	2.60	0.588
Morongovsky	1271	50.1	0.84	17.84	10.91	6.15	0.17	10.91	2.08	0.92	0.14	1.90	0.567
Nadezhdinsky	1300	49.5	1.09	17.28	11.79	6.75	0.17	10.78	2.01	0.50	0.12	1.60	0.571
Nadezhdinsky	1312	50.0	1.14	16.43	12.50	6.28	0.19	11.16	1.76	0.44	0.11	3.00	0.539
Nadezhdinsky	1337	55.2	1.07	15.33	10.66	5.25	0.16	8.52	2.54	1.16	0.11	1.40	0.534
Nadezhdinsky	1373	52.7	1.01	15.61	11.25	5.82	0.16	9.98	2.13	1.22	0.10	1.00	0.546
Nadezhdinsky	1476	51.2	0.96	17.49	10.47	6.35	0.15	10.07	2.05	1.21	0.09	1.00	0.585
Nadezhdinsky	1491	51.2	0.83	16.37	10.43	6.60	0.14	11.57	2.66	0.14	0.08	4.00	0.596
Nadezhdinsky	1498	51.2	1.00	16.62	10.35	5.91	0.15	11.89	2.64	0.12	0.08	4.60	0.571
Nadezhdinsky	1546	49.4	0.91	20.86	9.91	5.93	0.14	9.79	2.01	0.96	0.07	1.20	0.582
Nadezhdinsky	1591	53.4	0.95	15.93	10.11	5.44	0.15	8.77	3.18	1.92	0.10	2.80	0.556
Nadezhdinsky	1644	53.3	0.92	15.99	9.96	6.57	0.16	10.18	2.48	0.40	0.07	4.00	0.606
Nadezhdinsky	1709	52.1	0.93	16.23	10.31	6.29	0.16	10.82	2.05	1.04	0.09	1.00	0.587
Gudchikhinsky	1761	47.3	1.21	9.67	15.30	18.29	0.20	6.91	0.64	0.41	0.09	6.60	0.736
Gudchikhinsky	1790	49.8	1.47	11.58	12.52	13.68	0.19	8.25	1.96	0.47	0.09	4.60	0.718
Gudchikhinsky	1821	50.1	2.10	11.05	13.47	13.36	0.19	7.05	0.94	1.64	0.12	4.20	0.698
Gudchikhinsky	1841	51.6	2.27	13.85	13.12	7.53	0.20	6.24	3.97	1.07	0.19	2.80	0.572
Gudchikhinsky	1862	52.4	1.86	15.59	11.56	5.68	0.15	9.09	2.63	0.76	0.23	2.60	0.533
Gudchikhinsky	1887	48.7	1.47	19.51	10.02	6.44	0.13	10.37	2.60	0.66	0.13	2.60	0.599
Syverminsky	1931	51.7	1.76	15.94	11.90	6.36	0.16	7.80	2.95	1.12	0.28	2.80	0.554
Syverminsky	1991	54.2	1.46	17.06	10.38	6.46	0.14	5.09	3.75	1.28	0.20	3.60	0.591
Ivakinsky	2045	54.5	2.07	15.70	11.15	3.54	0.17	8.25	2.91	1.37	0.32	2.80	0.425
Ivakinsky	2059	51.0	2.38	14.91	15.22	3.13	0.24	6.72	3.17	2.12	1.12	2.80	0.323
Ivakinsky	2117	52.2	2.38	15.13	13.51	2.95	0.18	6.88	3.47	2.48	0.83	1.40	0.337
Ivakinsky	2136	48.9	2.13	15.45	15.56	3.91	0.21	8.36	3.30	1.37	0.78	3.60	0.369
Ivakinsky	2200	46.2	3.35	16.43	15.31	4.04	0.21	8.00	3.09	2.22	1.13	1.40	0.380
Precision (1σ)[1]		0.3	0.03	0.14	0.20	0.09	0.01	0.09	0.19	0.03	0.02	0.40	
Observed UTB-1[2]		49.7	3.09	13.5	15.30	3.95	0.22	8.70	2.69	1.32	0.68	0.20	
Expected UTB-1		49.6	3.09	13.5	15.20	4.50	0.21	8.50	2.83	1.30	0.74	n.a.	
SG-9, 864.0 Split 1[3]		47.8	1.06	16.7	12.1	7.01	0.19	10.4	1.90	0.42	0.10	20	
SG-9, 864.0 Split 2		47.8	1.09	15.8	12.6	7.16	0.19	10.6	1.88	0.45	0.12	80	
Averages of suites[4]:													
iv (n=5)		51.83	2.16	15.36	13.40	3.84	0.20	7.85	3.09	1.62	0.65	2.64	-
sv (n=2)		52.97	1.61	16.50	11.14	6.41	0.15	6.44	3.35	1.20	0.24	3.20	-
gd (n=5)		49.48	1.70	13.13	12.88	10.86	0.18	7.76	2.02	0.85	0.12	4.16	-
nd (n=11)		51.75	0.98	16.74	10.70	6.11	0.16	10.32	2.31	0.83	0.09	2.33	-
mr (n=11)		49.20	1.11	16.47	12.36	7.02	0.18	11.25	1.94	0.36	0.11	1.54	-
mk (n=9)		48.68	1.21	16.43	12.87	6.83	0.19	11.37	2.02	0.30	0.10	1.78	-
mk (1σ)		0.32	0.07	0.62	0.40	0.22	0.01	0.47	0.10	0.18	0.01	0.78	-

[1] Precision (1σ) is based on multiple analysis of an in-house basaltic reference standard during the course of this work

[2] Expected and observed values for appropriate reference standards (the USGS standard BHVO-1 and the University of Toronto basalt standard UTB-1) are shown. Expected values for UTB-1 from Lightfoot (1985)

[3] Analyses of two splits of sample 864.0 (splits 1 and 2)

[4] Also given are the averages of each of the six suites (*n* = number of analyses) and for the Mokulaevsky, the standard deviation (1σ) is given as a measure of the variation in this suite, which is considered a magma type (see text)

[5] Concentrations of major element oxides are expressed in weight percent, and trace elements in ppm. All major elements are calculated free of loss on ignition (L.O.I.), but L.O.I. values are shown for completeness

Cr (Table 1). These variations, together with those of the other major and trace elements, are broadly consistent with the eruption of progressively less fractionated magmas through time.

Gudchikhinsky picritic basalts show a progressive decrease in overall REE abundances upwards through the sequence, accompanied by an increase in Mg number (Fig. 5), Ni, and Cr (Table 1). The stratigraphically higher picritic basalts are more mafic. The most primitive (SG-9-1760.7) and evolved (SG-9-1841.0) members appear to be linked by olivine control. For example, a picritic basalt containing 800 ppm Ni can be generated by the combination of olivine (containing 1500 ppm Ni) with a low-Mg tholeiitic liquid (containing 100 ppm Ni) in the ratio 50:50. Progressive accumulation of olivine in the magma chamber with periodic eruption of progressively more olivine-rich magma is consistent with the development of a replenished, tapped, and fraction-

Table 1 (continued)

Depth	Ni	Cu	Cr	Co	Sc	V	Zn	Rb	Sr	Y	Zr	Nb	Th		Ta	Hf
85.6	123	215	206	44	36	262	108	2.8	165	24.9	93	4.3	0.75	0.25	0.24	2.47
294.5	109	76	194	44	35	251	105	4.3	183	23.9	84	4.3	0.90	0.34	0.24	2.36
367.0	110	137	192	45	36	260	103	3.7	223	21.7	92	4.5	0.93	0.35	0.26	2.46
414.0	134	146	216	46	39	280	97	1.4	240	22.2	87	4.4	1.01	0.35	0.26	2.42
449.0	80	151	180	46	36	267	98	2.3	208	23.9	92	4.6	0.91	0.34	0.25	2.47
502.0	85	143	196	41	38	277	99	3.2	216	23.1	88	4.4	0.97	0.38	0.30	2.41
557.0	107	141	144	42	38	268	99	6.2	206	21.8	85	4.3	1.07	0.41	0.25	2.28
636.5	101	129	146	43	35	251	99	5.4	224	22.5	102	4.7	1.02	0.38	0.24	2.68
683.0	98	134	156	46	37	270	115	5.0	221	22.8	86	4.8	1.08	0.44	0.27	2.35
788.0	97	125	175	41	38	270	96	9.1	230	21.9	90	5.1	1.10	0.43	0.35	2.42
819.0	115	110	225	40	37	261	91	1.9	198	21.4	82	4.7	1.00	0.43	0.34	2.31
864.0	113	134	153	47	35	248	104	9.5	197	23.4	97	5.4	1.12	0.47	0.30	2.61
947.0	104	121	130	42	31	219	96	3.7	204	22.5	88	5.1	1.07	0.46	0.28	2.37
1012	108	154	207	42	38	285	99	2.2	203	22.6	91	4.9	1.02	0.38	0.28	2.45
1036	96	100	192	42	38	275	99	1.6	214	23.7	102	5.5	1.22	0.46	0.33	2.75
1109	51	126	172	40	41	297	103	9.8	198	25.4	110	6.7	1.93	0.71	0.40	2.90
1129	91	92	100	45	37	253	94	3.5	194	20.4	83	4.9	1.31	0.48	0.26	2.23
1151	80	124	148	41	37	254	96	6.8	212	23.4	109	6.1	1.64	0.55	0.33	2.81
1160	93	81	115	42	38	256	92	2.1	222	23.1	95	5.9	1.78	0.63	0.34	2.64
1271	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	20.7	301	24.0	104	7.6	1.87	0.96	0.43	2.65
1300	79	113	153	39	35	251	98	7.7	239	22.3	107	7.0	1.98	0.69	0.41	2.91
1312	47	100	38	37	30	209	93	4.8	321	25.3	143	10.7	2.88	0.86	0.57	3.81
1337	45	115	38	40	30	212	121	28.5	405	25.5	139	10.3	3.56	0.97	0.61	3.60
1373	54	88	62	37	33	224	103	28.0	262	23.8	140	10.3	3.46	0.92	0.54	3.77
1476	38	69	142	37	32	213	92	35.5	234	22.0	127	8.9	3.04	0.83	0.51	3.26
1491	22	27	86	35	31	225	77	3.7	52	18.5	103	7.1	2.51	0.74	0.40	2.71
1498	15	47	74	36	30	212	80	2.4	49	21.3	114	8.1	2.70	0.78	0.43	3.19
1546	24	27	116	34	30	207	81	19.3	273	20.9	115	9.1	3.72	1.04	0.63	3.11
1591	33	46	121	33	33	218	94	52.4	435	23.0	134	10.4	3.68	0.97	0.60	3.69
1644	23	53	244	33	32	215	85	9.2	113	20.1	118	9.3	3.73	0.88	0.52	3.26
1709	38	46	194	39	32	211	94	29.9	264	20.9	124	8.4	2.64	0.68	0.46	3.36
1761	775	72	850	79	26	211	145	7.1	218	12.4	66	5.0	0.87	0.32	0.30	1.91
1790	490	106	800	52	28	253	112	9.3	181	14.8	81	6.4	0.96	0.38	0.40	2.41
1821	490	64	475	58	27	275	100	22.4	395	16.7	104	8.9	1.17	0.44	0.57	2.90
1841	126	139	322	44	32	326	116	23.2	196	21.9	138	11.8	1.58	0.44	0.68	3.88
1862	42	21	211	33	28	215	84	13.8	378	24.4	200	17.3	1.90	0.43	0.82	5.00
1887	76	62	270	36	25	176	77	12.9	445	17.5	94	7.6	0.76	0.19	0.41	2.47
1931	43	38	196	36	28	209	107	24.7	400	25.2	177	14.8	2.08	0.46	0.78	4.66
1991	68	34	242	32	22	167	90	33.5	440	25.1	194	17.3	3.49	0.88	0.91	5.08
2045	36	33	92	28	25	204	150	18.5	411	33.2	279	25.6	5.74	1.49	1.39	7.00
2059	6	26	n.a.	19	26	109	173	19.9	426	54.3	383	34.8	6.64	1.71	1.67	9.00
2117	16	22	29	24	25	142	163	48.7	384	50.1	377	31.2	4.82	1.22	1.46	9.10
2136	22	20	30	24	21	114	155	47.2	453	42.1	252	24.5	4.22	0.91	1.23	6.16
2200	36	39	31	31	24	180	173	55.3	465	43.7	346	40.8	6.82	3.24	2.04	7.61
Precision[1]	4.4	1.4	6.6	1.4	5	10	5.8	0.8	4	0.8	3.5	0.5	0.05	0.05	0.05	0.12
Obs. UTB-1[2]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	33.5	329	44.6	207	18.6	4.0	0.6	1.01	5.31
Exp. UTB-1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	35	311	41.0	200	15.3	4.4	1.0	1.03	5.1
SG-9, 864.0[3]																
Split 1	113	134	153		35	248	104			23.4	97					
Split 2	112	140	152		39	262	100			23.0	n.a.					
Averages of suites:																
iv	24	24	91	26	25	157	145	38	428	41.0	327	31.4	4.7	1.3	1.56	7.77
sv	55	36	219	34	25	188	99	25	420	25.0	186	16.1	2.8	0.7	0.85	4.87
gd	391	89	543	54	28	248	110	15	302	17.0	114	9.5	1.1	0.4	0.53	3.10
nd	38	66	115	36	32	218	93	20	240	22.0	125	9.1	3.1	0.9	0.52	3.33
mr	95	117	162	42	37	262	97	5	210	23.0	95	5.5	1.4	0.5	0.32	2.55
mk	105	141	181	44	37	265	103	4	206	23.0	90	4.5	1.0	0.4	0.26	2.43
mk (1σ)	17	35	26	2		10	6	3	24	1.0	6	0.2	0.1	0.1	0.04	0.22

ated (RTF) magma chamber, as described by O'Hara and Mathews (1981). Similar models have been proposed for the Ivakinsky, Syverminsky, and Gudchikhinsky basalts by Godlevski (1959) and Fedorenko (1981).

The continuous compositional variation from the base of the Nadezhdinsky to the top of the Mokulaevsky is not related to fractional crystallization because the Mg number of the basalt sequence does not change and there are systematic changes in the ratios of the REE (Figs. 5, 6) and Sr- and Nd-isotope ratios (unpublished data from Hawkesworth et al., in preparation).

In Fig. 6a–c, we model the effects of fractionally crystallizing a Mokulaevsky magma (represented by the average of this suite – the Mokulaevsky magma-type from Table 1), using distribution coefficient data from the compilation of Henderson (1984) and assuming a bulk crystal extract containing 60% plagioclase, 30% augite, and 10% olivine. The calculated trends shown in Fig. 6 fail to reproduce the trend of the Morongovsky and Nadezhdinsky. This is confirmed by the major and other trace element data, which are not consistent with a fractionation lineage between the tholeiitic suites.

The role of garnet and amphibole crystallization is not considered to be important, as there is no petrographic evidence for the participation of these phases. Furthermore, the participation of garnet would be identified by not only strong depletion of the HREE, but also a fall in Tb/Yb. As the Tb/Yb ratios of the tholeiitic suites are similar, it is considered unlikely that high-pressure garnet fractionation is responsible for the compositional variation in these rocks. Unpublished Sr- and Nd-isotope data (Hawkesworth et al., in preparation) confirm that garnet control is unlikely. Amphibole is capable of fractionating the HREE/LREE in a similar way to clinopyroxene, but these phases would be required to make up close to 100% of the crystal phase extract for the observed REE fractionation to be generated by this mechanism, which is unreasonable on petrographic grounds.

The relationship of the picritic basalts of the Gudchikhinsky to the rest of the trap is even less straightfor-

Table 1 (continued)

Depth	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
85.6	5.54	14.39	1.91	10.47	3.34	1.07	4.17	0.68	4.72	1.01	2.95	0.43	2.65	0.38
294.5	6.68	16.57	1.89	11.06	3.25	1.13	3.76	0.64	3.99	0.86	2.36	0.34	2.29	0.34
367.0	7.13	16.88	1.91	10.84	3.20	1.09	3.80	0.63	3.92	0.84	2.46	0.36	2.15	0.35
414.0	6.96	16.56	2.18	11.15	2.95	1.11	3.86	0.65	4.22	0.90	2.61	0.39	2.29	0.36
449.0	7.15	17.00	2.00	11.14	3.46	1.15	3.72	0.64	3.98	0.88	2.46	0.38	2.42	0.37
502.0	6.63	15.69	1.86	10.69	3.24	1.10	3.61	0.64	3.96	0.86	2.46	0.37	2.30	0.35
557.0	7.22	16.54	2.18	11.26	3.04	1.11	3.74	0.66	4.21	0.89	2.62	0.37	2.25	0.38
636.5	7.27	17.30	2.28	11.55	3.26	1.12	3.70	0.66	4.34	0.95	2.72	0.38	2.49	0.38
683.0	7.26	17.84	2.06	11.35	3.17	1.13	3.76	0.61	3.87	0.87	2.45	0.36	2.40	0.36
788.0	7.62	16.94	2.20	10.75	2.99	1.07	3.88	0.65	4.25	0.85	2.58	0.35	2.35	0.34
819.0	6.66	15.51	2.04	10.51	2.99	1.05	3.36	0.63	4.18	0.91	2.60	0.35	2.47	0.37
864.0	7.64	18.34	1.97	10.89	3.18	1.03	3.62	0.65	4.10	0.90	2.53	0.37	2.28	0.34
947.0	7.38	17.74	1.90	10.33	2.90	1.04	3.68	0.63	3.79	0.87	2.44	0.35	2.17	0.34
1012	7.17	16.71	2.26	10.83	3.08	1.13	4.08	0.68	4.36	0.92	2.81	0.38	2.49	0.39
1036	8.09	18.08	2.41	11.74	3.24	1.08	4.02	0.70	4.31	0.94	2.73	0.40	2.67	0.41
1109	10.19	23.63	2.62	14.08	3.69	1.18	4.14	0.68	4.25	0.94	2.53	0.40	2.46	0.38
1129	8.78	20.30	2.13	10.97	2.82	0.90	3.32	0.59	3.57	0.76	2.16	0.32	1.93	0.32
1151	10.25	23.54	2.42	13.66	3.39	1.14	3.65	0.63	4.11	0.85	2.51	0.34	2.24	0.37
1160	9.92	22.24	2.47	13.06	3.41	1.01	3.60	0.61	3.88	0.83	2.43	0.33	2.17	0.32
1271	13.28	28.22	3.21	13.80	3.30	1.07	4.02	0.70	4.23	0.93	2.86	0.44	2.67	0.43
1300	12.03	26.57	3.15	13.96	3.51	1.03	4.19	0.71	4.40	0.92	2.71	0.38	2.42	0.36
1312	18.93	40.17	4.03	19.54	4.46	1.29	4.33	0.75	4.52	0.95	2.64	0.41	2.44	0.38
1337	17.01	38.76	3.86	19.10	4.28	1.16	4.40	0.74	4.25	0.98	2.56	0.39	2.57	0.38
1373	18.58	40.73	4.49	19.78	4.46	1.23	4.29	0.74	4.68	0.98	2.72	0.38	2.49	0.38
1476	16.91	36.50	3.56	17.25	3.82	1.11	3.97	0.68	3.96	0.83	2.36	0.35	2.08	0.31
1491	14.04	29.93	3.35	14.43	3.23	1.02	3.38	0.58	3.44	0.73	2.05	0.29	1.90	0.27
1498	16.88	34.71	3.89	16.80	3.85	1.11	4.17	0.66	3.85	0.84	2.41	0.33	2.03	0.30
1546	17.15	35.19	4.09	17.23	3.70	1.02	3.88	0.63	3.92	0.84	2.38	0.34	2.19	0.32
1591	19.18	39.98	4.58	19.67	4.24	1.17	4.22	0.73	4.37	0.92	2.57	0.36	2.32	0.35
1644	15.47	35.05	3.96	16.30	3.67	0.98	4.01	0.64	3.67	0.84	2.30	0.33	2.16	0.33
1709	16.30	35.53	3.46	17.37	3.81	1.17	3.77	0.62	3.80	0.83	2.23	0.34	2.06	0.29
1761	4.97	13.02	1.81	9.07	2.44	0.87	2.88	0.45	2.63	0.50	1.37	0.17	1.04	0.12
1790	6.11	15.99	2.10	10.74	3.02	1.10	3.38	0.53	2.99	0.61	1.59	0.19	1.25	0.17
1821	8.94	21.56	2.83	14.52	3.86	1.30	4.26	0.67	3.58	0.71	1.91	0.23	1.56	0.23
1841	10.86	26.84	3.66	18.79	4.91	1.65	5.36	0.86	4.94	0.93	2.45	0.31	1.97	0.26
1862	23.63	50.80	5.95	26.90	6.26	1.92	5.99	0.90	4.76	0.98	2.54	0.36	2.20	0.33
1887	9.31	21.68	2.70	13.10	3.47	1.39	3.78	0.61	3.45	0.70	1.81	0.26	1.59	0.24
1931	22.64	50.37	5.80	26.04	5.84	1.95	5.40	0.83	4.62	0.95	2.56	0.34	2.22	0.30
1991	18.71	46.79	5.20	26.16	5.94	1.72	5.13	0.80	5.02	0.99	2.68	0.35	2.36	0.34
2045	34.86	73.48	8.32	35.97	7.65	2.18	7.40	1.22	6.82	1.32	3.61	0.50	3.22	0.41
2059	59.13	132.1	13.69	69.10	14.40	4.04	12.14	1.79	9.72	1.99	4.96	0.69	4.36	0.64
2117	48.67	107.9	12.28	57.90	11.84	3.49	11.46	1.76	10.06	2.06	5.31	0.70	4.65	0.63
2136	40.69	90.05	10.47	47.18	10.08	2.72	10.05	1.52	8.52	1.66	4.65	0.63	3.57	0.54
2200	51.95	115.5	12.64	56.01	11.23	2.87	9.74	1.56	8.54	1.77	4.66	0.66	4.30	0.68
Precision[1]	0.36	0.8	0.16	0.8	0.21	0.10	0.17	0.04	0.20	0.03	0.11	0.02	0.06	0.01
Obs.BHVO-1	15.5	38.8	5.88	25.3	6.38	2.15	6.39	0.98	5.43	1.03	2.64	0.33	2.02	0.29
Exs.BHVO-1	15.8	39	5.7	25.2	6.2	2.06	6.4	0.96	5.2	0.99	2.4	0.33	2.02	0.29
SG-9, 864.0[3]														
Split 1	7.64	18.3	1.97	10.9	3.13	1.03	3.62	0.65	4.10	0.90	2.53	0.37	2.28	0.34
Split 2	8.50	19.0	n.a.	12.0	3.20	1.10	3.70	0.66	4.20	0.92	2.50	0.38	2.40	0.37
Averages of suites[4]:														
iv	41.4	90.8	11.4	47.4	10.0	2.87	9.41	1.44	7.97	1.60	4.21	0.88	3.60	0.51
sv	20.7	48.6	5.5	26.1	5.89	1.84	5.27	0.82	4.82	0.97	2.62	0.35	2.29	0.32
gd	8.4	19.8	3.4	13.2	3.50	1.26	3.93	0.62	3.51	0.69	1.83	0.23	1.48	0.20
nd	16.6	35.7	3.7	17.4	3.91	1.12	4.06	0.68	4.08	0.88	2.45	0.36	2.24	0.33
mr	8.8	20.1	2.3	11.9	3.18	1.06	3.76	0.65	4.09	0.88	2.56	0.37	2.35	0.37
mk	6.9	16.5	2.0	11.2	3.21	1.11	3.79	0.65	4.13	0.90	2.57	0.38	2.36	0.36
mk (1σ)	0.6	1.0	0.2	0.3	0.15	0.02	0.16	0.02	0.27	0.05	0.18	0.03	0.15	0.02

ward. Any fractionation model must explain not only the flatter LREE patterns, but also the steeper HREE trends relative to the tholeiites. It is inappropriate to model these variations by the removal of plagioclase, pyroxene, amphibole, or olivine, for the reasons outlined above. Rather, garnet involvement would be required to produce the steep HREE depletion of the picritic basalts. The picritic basalts have low Ca/Al and relatively high TiO_2, which is consistent with garnet control, but it would appear more logical to us if garnet were a control in the source region of these magmas during melting rather than a fractionating phase at high pressure [see also Fedorenko et al. (1989)].

In Fig. 6a–c we illustrate the effects of batch melting on a garnet lherzolite source with chondritic trace element abundances (Nakamura 1974), consisting of 50% olivine, 30% orthopyroxene, 10% clinopyroxene and 10% garnet. All phases are assumed to contribute equally to the melt, so that garnet and clinopyroxene are eliminated from the residue simultaneously when 40% of the source rock has melted. Calculations have been carried out on the assumption of equilibrium batch melting, using distribution coefficient data from the compilation of Henderson (1984). The trends shown in Fig. 6a–c reflect the difference in the degree of melting required to relate the Gudchikhinsky and Mokulaevsky by partial melting of a garnet lherzolite. As fractional crystallization of the picritic parental magmas will produce some variation in the REE ratios, the models must be treated with caution. However, in principle it would appear possible that these two suites are related by different degrees of melting of a common mantle source. The degree of melting required to generate the Gudchikhinsky would be significantly less (by about 20%) than that required to generate the Mokulaevsky. It is clear that the compositional variation within the tholeiitic suites does not

Table 2. Characteristic geochemical features of the six Siberian trap suites exposed in core SG-9

Suite	iv	sv	gd	nd	mr	mk
Thickness (m)	300	100	150	500	550	700
Mg-number	<0.45	>0.55	>0.50			
TiO_2 (wt %)	>2.0	>1.5	<2.2	<1.4	<1.4	<1.4
Ce (ppm)	>70	>45	<50	<35	<30	<25
Yb (ppm)	>3.2	>2.2	<2.2			
La/Sm	>3.2	>3	<3.2	>3.2	–	<3.2
Gd/Yb	>2.0	<2.5	>2.0	<2.0	–	<2.0
Ce/Yb	>22	>19	<22	>15	<10	<10
Sm/Nd	<0.22	<2.2	>0.23	<0.25	>0.23	>0.23

reflect the effects of variable amounts of partial melting, as the observed data trends diverge away from the batch melting vectors (Fig. 6a–c). Although changing degrees of partial melting of the mantle could give rise to magmas of significantly different compositions, possibly as variable as we have documented, we cannot see why successive melts should show such a wide variation in incompatible element ratios unless the style of melting is dynamic (Langmuir et al. 1978), and this may not be appropriate for the degrees of melting (up to 30%) appropriate to CFB. Sr-, Nd-, and Pb-isotope studies are currently in progress to further evaluate this problem.

The data therefore indicate that low-pressure fractional crystallization has not played a major role in controlling the compositional variation in the tholeiitic magmas, but has played a part in controlling the evolution of the Ivakinsky and Syverminsky.

Contamination

It has been argued above that the progressive compositional change observed from the base of the Nadezhdinsky to the top of the Mokulaevsky cannot be due to fractionation of a single magma type or different degrees of partial melting of a homogenous mantle source. Rather, the data support the successive eruption of flows representing a continuum of different magmas, which might have been formed by: (1) melting of a heterogeneous mantle source (cf. Fedorenko et al. 1989); (2) mixing of a magma from a single source with decreasing amounts of a contaminated magma; (3) progressively declining crustal contamination of a uniform source magma with time. We are impressed by progressive nature of all compositional changes within and above the Nadezhdinsky and the extreme range in LILE/HFSE ratios (Fig. 6d): we feel that although the source regions of these magmas may be heterogeneous, it is unlikely that such systematic trends can be produced by successively melting a heterogeneous mantle source. It is also difficult to envisage a process which would explain the continuous changes in chemistry through the stratigraphy by mixing of magmas; for this reason we do not favor magma mixing in deep crustal magma chambers, and concentrate on process (3), the progressive decrease in the degree of contamination of the Mokulaevsky magma-type. The feasibility of this process is the subject of this section. An explanation as to how progressively less contaminated magmas can be produced is the subject of the next section.

Criteria established in other studies of CFB magmatism (e.g. Najafi et al. 1981; Mahoney et al. 1982; Cox and Hawkesworth 1984, 1985; Lightfoot 1985; Lightfoot and Hawkesworth 1988) indicate that crustally contaminated magmas have higher SiO_2, K_2O, Rb, Ba, and Th compared to uncontaminated magmas and are likely to be depleted in TiO_2. Lightfoot (1985), among others, suggested that the effects of crustal contamination versus those produced within the mantle source regions may be identified using not only isotopic data, but also the ratios of the LILE/HFSE. Crustal materials tend to have high Th/Yb and low Ta/Yb ratios (Pearce 1983; Pearce et al. 1984), whereas mantle-derived magmas from oceanic settings and mantle xenoliths tend to be characterized by high Th/Yb and moderate Ta/Yb.

Figure 6d shows the variation in Th/Yb versus Ta/Yb for Siberian Trap basalts. The range of Th/Yb and Ta/Yb found within all of the Siberian Trap basalts falls above the field of within-plate basalts (WPB) and mid-ocean ridge basalt (MORB).

The most straightforward interpretation of the trace element data from the upper 2000 m of stratigraphy at Noril'sk is that LIL-depleted (Th/Yb = 0.4, Ta/Yb = 0.15), moderate Mg number (0.55) mantle-derived magmas of the Mokulaevsky type have been variably contaminated by LIL-enriched, high Th/Yb (>2), and moderate Ta/Yb (>0.25) material, probably continental crust. This contamination has been slight to produce the Morongovsky and more extreme to produce the Nadezhdinsky (Fig. 6d). The contaminant required to form this trend may be derived from ancient amphibolite from the underlying Siberian shield, which would suggest deep-level contamination, or Phanerozoic sediments, which would suggest high-level contamination rather than granulite (which would be long bereft of mobile LILEs). The close juxtaposition of diverse Precambrian tonalitic terrains and Phanerozoic sediments cropping out around the borders of the Siberian Trap, and the vertically complex nature of the underlying shield (Kulikov et al. 1972), indicate that more than one crustal contaminant is possible. Furthermore, the contaminant may not be represented at the surface. Unfortunately, we have no rock samples, and it is only possible to test this hypothesis in a general fashion using average tonalitic compositions typical of the shield. Nevertheless, we can attempt to quantify the contamination process using a least-squares mixing model for the major element variations (Wright and Doherty 1970).

In Table 3, a least squares mixing model is shown where the composition of the average Nadezhdinsky magma is produced by contamination of the Mokulaevsky magma; we include the effects of fractional crystallization to demonstrate the lack of major element evi-

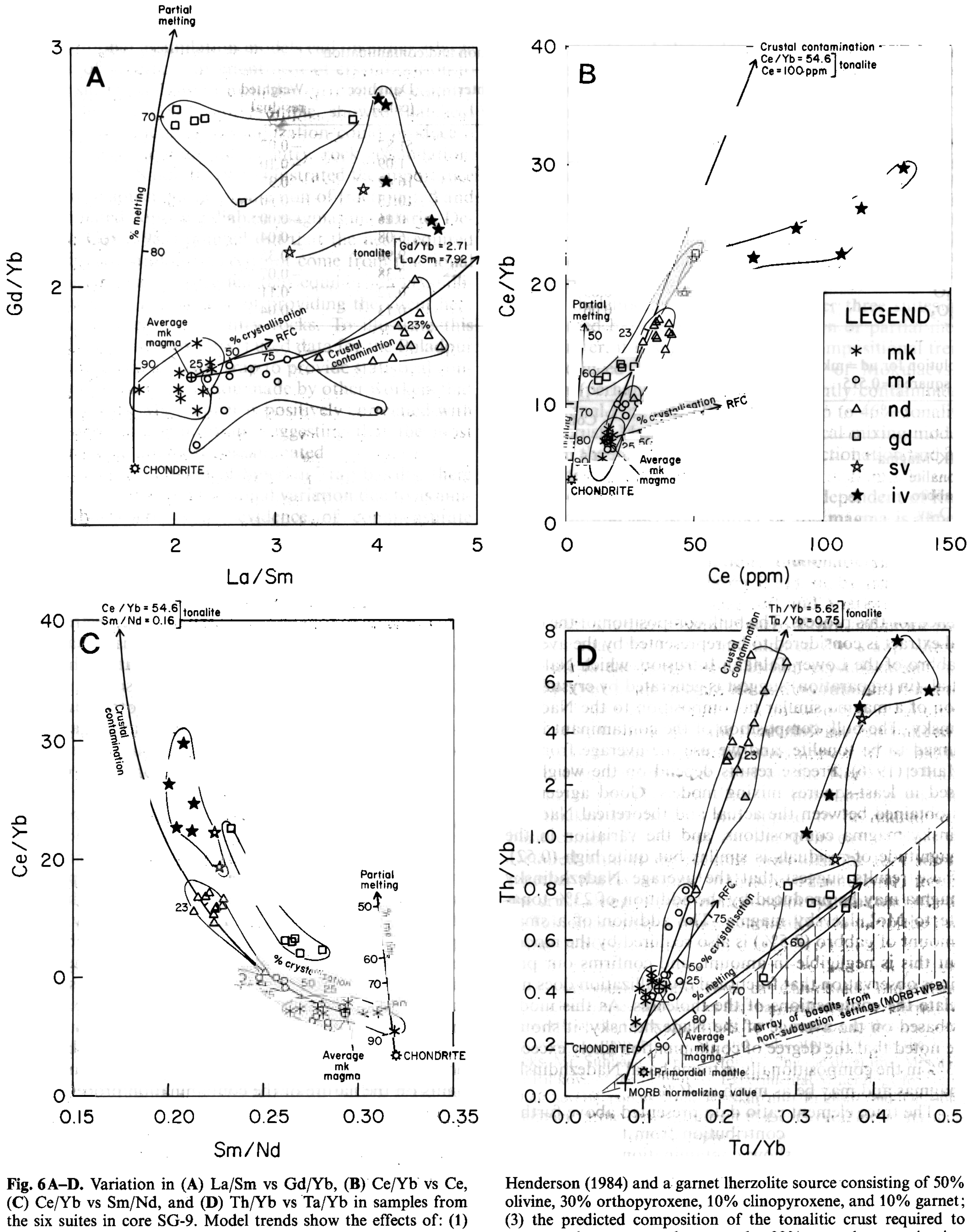


Fig. 6A–D. Variation in (**A**) La/Sm vs Gd/Yb, (**B**) Ce/Yb vs Ce, (**C**) Ce/Yb vs Sm/Nd, and (**D**) Th/Yb vs Ta/Yb in samples from the six suites in core SG-9. Model trends show the effects of: (1) Rayleigh fractional crystallization (*RFC*) on the average mk magma-type, assuming distribution coefficients from Henderson (1984) and a phase extract consisting of 60% plagioclase, 30% clinopyroxene, and 10% olivine; (2) batch partial melting of a chondritic source (Nakamura 1974), assuming distribution coefficients from Henderson (1984) and a garnet lherzolite source consisting of 50% olivine, 30% orthopyroxene, 10% clinopyroxene, and 10% garnet; (3) the predicted composition of the tonalitic crust required to generate the average nd magma by 23% crustal contamination of the average mk magma-type. Also shown is the field of within plate basalts from Pearce (1983). *Tick marks* on model trajectories correspond to the percentage fractionation and the percentage partial melting

Table 3. Petrological mixing model illustrating the effects of fractionation and contamination

Oxide (wt %)	Parent (mk type)	Tonalite (av.)	Gabbro (av.)	Daughter (nd av.)	Daughter (calc.)	Weighted residual
SiO_2	48.82	62.49	49.84	51.79	51.87	−0.07
TiO_2	1.21	0.74	0.56	0.98	1.09	−0.10
Al_2O_3	16.48	16.74	13.69	16.75	16.42	0.33
FeO	11.61	5.55	9.45	9.64	10.13	−0.50
MnO	0.19	0.08	0.18	0.16	0.16	−0.00
MgO	6.85	2.84	13.43	6.11	6.08	0.04
CaO	11.40	5.51	9.96	10.33	9.98	0.35
Na_2O	2.03	3.69	1.19	2.31	2.38	−0.07
K_2O	0.30	2.10	0.63	0.83	0.72	0.11
P_2O_5	0.10	0.25	0.06	0.09	0.13	−0.04

Solution for nd = mk + gabbro + tonalite
R squared = 0.515

	Solution	% Contribution
MK-Magma	1.000	74.5
Tonalite	0.309	23.0
Gabbro	0.034	2.5
ND-av.	1.343	100.0

Abbreviations: Av., average; *Calc.*, calculated. All Fe is expressed as Fe^{2+}

dence for this process. The bulk composition of the crystal extract is considered to be represented by the average gabbro of the Lower Talnakh Intrusion, which Naldrett et al. (in preparation) suggest is generated by crystallization of a magma similar in composition to the Nadezhdinsky. The bulk composition of the contaminant is assumed to be tonalite, and we use the average from Le Maitre (1976). Precise results depend on the weighting used in least-squares mixing models. Good agreement is obtained between the actual and theoretical Nadezhdinsky magma compositions, and the variation in the magnitude of residuals is similar but quite high (0.52). These results suggest that the average Nadezhdinsky magma may be produced by the addition of 23% tonalite to Mokulaevsky magma. The addition of a small amount of gabbro (2.5%) is also required by the model, but this is negligible in amount, and confirms our previous observation that fractional crystallization does not relate the compositions of the tholeiites. As this model is based on the average of the Nadezhdinsky, it should be noted that the degree of contamination likely exceeds 23% in the compositionally extreme basal Nadezhdinsky magmas and may be as much as 46%.

The trace element ratio data presented above further support a significant contribution from tonalitic upper crust. In Fig. 6, we show contamination trends where the average Nadezhdinsky magma is modelled by contamination of the Mokulaevsky magma by 23% tonalitic upper crust. The ratios of the trace elements required in the crustal end member (see Fig. 6) are comparable to those found in tonalitic crust from throughout the world (e.g., Taylor and McLennan 1981).

Presently, we favor a model involving contamination of Mokulaevsky magma by upper crustal material of granodioritic to tonalitic composition, but we are uncertain whether the contamination mechanism was more likely to have involved wholesale assimilation than partial anatexis; we shall be better able to resolve this question when a complete Sr-, Nd-, and Pb-isotope data base is available to complement these data, and analyses of Tuklonsky suite samples.

Discussion and conclusions

In the upper 1700 m of Siberian Trap stratigraphy, Mg number, Y, and Yb change very little, whereas the ratios of LILE/HFSE and LREE/HREE continually decline upwards with falling SiO_2. It was suggested above that the variations are consistent with a decline in the degree of contamination of mantle-derived Mokulaevsky-type magmas by either wholesale or partial anatexis. This information, when combined with the important observation that the Nadezhdinsky flows tend to be more phenocryst-rich than the Mokulaevsky, places important limits on the nature of the contamination process. First, as there is little change in Mg number and the concentration of the HFSE and HREE up through the upper 1700 m of the sequence, there is no suggestion that gabbro fractionation has played a role in the contamination process. This is confirmed by the petrological mixing models (see above).

The key variations through the sequence must therefore reflect open-system processes, where magma, presumably of Mokulaevsky-type, has interacted with a progressively declining amount of material, presumably derived from the upper crust.

Traditional assimilation models call on either a large amount of superheat or latent heat of crystallization to impart sufficient heat to melt the surrounding country rocks. DePaolo (1981), for example, showed that heat produced by fractional crystallization could produce a commensurate amount of country rock assimilation. Lightfoot and Naldrett (1989) illustrated the importance of this mechanism in the production of fractionated and contaminated Nipissing diabase magmas in Ontario. Devey and Cox (1987) pointed out that the heat required for assimilation of crust need not come from fractional crystallization and suggested that equilibrium crystallization was equally capable of providing the latent heat required to melt the country rocks. To illustrate this point, Devey and Cox (1987) used data for the Poladpur formation of the Deccan Trap to provide statistical confirmation of the observation made by other workers that the whole-rock Mg number is positively correlated with the Sr-isotopic composition, suggesting that the most mafic magmas are most contaminated.

In the upper 1700 m of Siberian Trap basalts, there is a wide range in compositional variation due to assimilation, but there is no evidence of commensurate amounts of fractionation. As none of the lavas are primitive, a substantial amount of fractionation must have happened prior to assimilation, and perhaps in deep magma chambers where the composition of the magma was buffered by the fractionating phases (e.g., Cox 1980). The decrease in phenocryst proportions upwards through the stratigraphy indicates that the amount of crystallization occurring in the magma conduit decreased through time, perhaps reflecting an increasing rate of magma supply. The generation of significantly more latent heat of crystallization in the earlier tholeiites may have promoted assimilation of the crust, whereas the later magmas may have migrated to the surface up their conduits without crystallizing. Perhaps the plating of the conduit walls with chilled basic magma (Patchett 1980) may have promoted the isolation of the later magmas from the crustal system, as has been previously proposed for the Deccan (Mahoney et al. 1982). This may also have contributed to the upward variation within the Nadezhdinsky, although in this case the initial magma may have imparted sufficient heat to the country rocks to remove the more mobile components, leaving a restite around the conduit (cf. Patchett 1980).

The dominant Mokulajevsky type magma is compositionally similar to some transitional type MORBs, although the ratios of LILE/HFSE (e.g., Th/Yb in Fig. 6d) are higher than MORB and within-plate basalts. This may be explained by very small amounts of crustal contamination; unpublished Sr- and Nd-isotope data are consistent with this explanation.

In summary, the following main conclusions can be drawn:

1. The trap stratigraphy in core SG-9 can be subdivided into six lava suites, of which the lower three are compositionally diverse. Within the Ivakinsky and Syverminsky flows, there is some evidence suggesting that individual flows have compositions linked by fractional crystallization of augite and plagioclase, but these flows are apparently compositionally unrelated by similar lineages to the main package of tholeiites. The Gudchikhinsky picrites are also unambiguously different in composition than the tholeiites, although individual flows within this suite appear to be related by olivine control. The upper three suites constitute well over 50% of the sequence and show a transition from incompatible-element-enriched Nadezhdinsky magmas through the Morongovsky to the Mokulaevsky. Mokulaevsky magmas are extremely uniform in composition and are considered a magma type.
2. The tholeiitic members of the upper three suites are not related by fractional crystallization or partial melting. Rather, it is suggested that the compositional trend are produced by the contamination of Mokulaevsky magma (perhaps derived from a slightly contaminated transitional-type MORB source) by up to 46% tonalitic upper crust. Major element petrological mixing models confirm the limited role of gabbro fractionation and are supported by the trace element data.
3. As contamination appears to be independent of fractionation and the Mg number of the magma is almost constant, it is considered unlikely that assimilation was controlled by an assimilation, fractional crystallization (AFC) mechanism (DePaolo 1981), or by temperature-controlled assimilation (Huppert and Sparks 1985). We note that the most contaminated flows are more porphyritic than the least contaminated flows and suggest that the latent heat of equilibrium crystallization may have played a role in controlling the contamination process.
4. Finally, we note that the Nadezhdinsky and underlying lavas thicken within and thus appear to be related to an elongate basin centered on the Noril'sk-Talnakh mining camp. The Mokulaevsky and Morongovsky lavas thicken to the east and appear to be related to a basin centered more than 100 km to the east of Noril'sk. Detailed studies in progress will attempt to evaluate whether the lavas found in these two basins rose through the crust along two or more conduit systems and whether Tuklonsky magmas are genetically related to the tholeiites in SG-9.

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