6 Relationship Between the Lavas and the Ore-Bearing Massifs

The geologic relationships between the basalts and ore-bearing intrusions are described based on the example of the Southern Maslovsky massif, which intruded basalts of the Nadezhdinsky Formation. Therefore, these rocks were formed in post-Nadezhdinsky time. The ore-bearing intrusions are similar to the volcanic rocks of the Morongovsky Formation in terms of their rare elements and isotopic compositions (Sr, ε_{Nd}), but they contain higher MgO concentrations (10–12 wt % on average) and a heavier S isotope composition (up to 18‰ compared with 6–7‰ in the basalts).

The possibility of comagmatic relationships between intrusive and volcanic rocks has long been a matter of discussion and is not yet settled. Some researchers continue to distinguish volcano-plutonic associations (Rad'ko 1991; Dyuzhikov et al. 1992; Naldrett 2009; Li et al. 2009; Lightfoot and Zotov 2014), whereas others believe that massifs in the Noril'sk Complex were produced from derivatives of other magmas (Likhachev 1994, 2006; Latypov 2002, 2007; Malitch et al. 2010, 2014; Krivolutskaya et al. 2012a).

The principal candidates for comagmatic rocks of the ore-bearing intrusions were first thought to be the picrites of the Gudchikhinsky Formation because all of the rocks are highly magnesian. However, later data on the distribution of trace elements in the rocks demonstrated the differences between the Gudchikhinsky picrites and rocks of the Nori'lsk Complex. Gudchikhinsky rocks are the most primitive melts in the Noril'sk area. They show almost no evidence of their crustal contamination (Sobolev et al. 2009), which was suggested for other volcanites. These rocks have no negative Ta–Nb anomalies, which are typical of all of the trap rocks, and exhibit negative, but not positive, Pb anomalies. Therefore, the Gudchikhinsky melts are principally different from the melts that gave rise to the ore-bearing massifs: their trace element patterns are not as enriched, including that these rocks are depleted in HREE and show no negative Ta–Nb anomalies. Volcanic rocks of the Gudchikhinsky Formation and ore-bearing picritic gabbro-dolerites strongly differ in isotope composition, especially ε_{Nd} and $^{87}Sr/^{86}Sr$ (+5.5; 0,703 and +1; 0,706 consequently). Another remarkable feature is the extremely high Ni concentration in the olivine, which is almost twice as high in olivine as the ore-bearing units and has elevated Ca concentrations (0.40 and 0.22 wt % NiO; 0.30 and 0.12 wt % CaO for Fo_{82}, respectively). This result indicates that the picrite basalts and picrite gabbro-dolerites in intrusions of the Noril'sk Complex could not be derivatives of a single parental melt, as was previously hypothesized.

In their models of the ore-forming processes, A. Naldrett and P. Lightfoot (Naldrett and Lightfoot 1994; Naldrett et al. 1992; Lightfoot et al. 1994; Keays and Lightfoot 2007) attached much importance to the rocks in the Tuklonsky Formation as possible crystallization products of the parental magma of the ore-bearing intrusions. This conclusion is based on the elevated Mg# of the Tuklonsky rocks and their geochemical similarities with the gabbro-dolerites of the intrusions of the Noril'sk Complex. However, the vertical section of the Tuklonsky Formation was so far examined only in the eastern portion of the area, within the Sunduk paleovolcanic structure (in the vicinity of Lake Glubokoe, Fig. 6.1—section 1 F (Lightfoot et al. 1994)). The rocks were added as an important constituent to the vertical section constructed based on data from the Kharaelakh depression (Boreholes SG-9 and SG-32) (Lightfoot et al. 1990, 1993; Brügman et al. 1993) and assumed to be the reference for the area. This combination resulted in the "occurrence" of a thick (240 m) unit of magnesian rocks. However, the Tuklonsky high-Mg lavas (from 8–9 to 16 wt % MgO) were found only within a small (10 by 3 km) paleovolcanic structure at Mount Sunduk (Lightfoot et al. 1994). The possible analogues of these rocks were thought (Fedorenko et al. 1996) to be picrite basalts exposed in the Mikchangdinsky flow. However, we proved (Krivolutskaya et al. 2012b) that these rocks are cumulates of the Nadezhdinsky Formation.

Therefore, the vertical sections of the Tuklonsky rocks in the Noril'sk Trough and elsewhere in the area are dominated

N.A. Krivolutskaya, *Siberian Traps and Pt-Cu-Ni Deposits in the Noril'sk Area*,
DOI 10.1007/978-3-319-17205-7_6

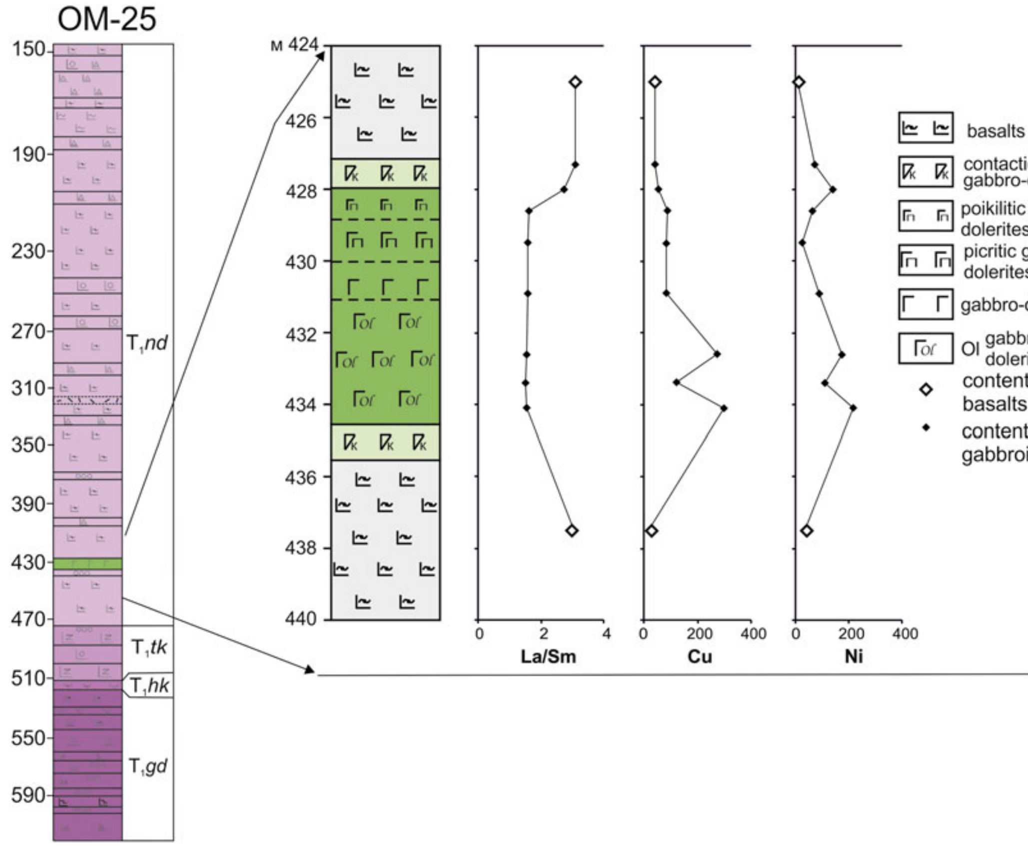

Fig. 6.1 Position of the Maslovsky sill inside tuff-lavas sequence After Krivolutskaya and Rudakova (2009)

by tholeiitic basalts (containing close to 7 wt % MgO), and locally occurring, thin bodies of picritic varieties are rare. The weighted mean composition of the rocks of the formation exposed over a length of >100 km is generally similar to the composition of the overlying tholeiite basalts. Comparing the geochemistry of the Tuklonsky rocks and gabbro-dolerites of the Noril'sk Complex, it is apparent that, because they have similar distributions of trace elements, the former rocks are depleted in U and enriched in Eu. Therefore, they have different isotopic compositions: for example, Tuklonsky basalts and picrobasalts have low $\varepsilon_{Nd} = -4, -5$, while in the intrusions, it varies approximately 0. Moreover, the olivine compositions in the hypothetical intrusive and volcanic varieties are notably different; the NiO concentrations are 0.11 and 0.21 wt % in the picrite basalts and picritic gabbro-dolerites, respectively, and the CaO concentrations are 0.21 and 0.12 wt % for Fo_{78} in these rocks. It follows that there is no justification to suggest that the Tuklonsky magma could be parental for the ore-bearing intrusions, as was hypothesized earlier based only on the elevated Mg# of the rocks.

In the models of A. Naldrett and his followers (Lightfoot et al. 1993; Brügman et al. 1993), the rocks composing the lower portion of the Nadezhdinsky Formation should be genetically related to the Tuklonsky basalts, and their depletion in base metals was predetermined by the crystallization of sulfides from the parental Tuklonsky melt contaminated with the host rocks. If the suggested mechanism had operated, the fields of ore-bearing intrusions should not have included any rocks of the Tuklonsky Formation because massifs of the Noril'sk Complex and the basalts of the Nadezhdinsky Formation are the interaction products of the Tuklonsky magma and terrigenous-carbonate sediments. Consequently, the picritic gabbro-dolerites of the ore-bearing massifs should have been identical to picritic basalts of the Nadezhdinsky Formation. However, their mineralogy and geochemistry are remarkably in contrast to the hypothetical intrusive comagmatic rocks, which were not saturated with sulfur (Likhachev 2006); the examined vertical section also includes (along with intrusions of the Noril'sk Complex) rocks from all of the aforementioned formations, which casts doubt onto the plausibility of the mechanism suggested for the origin of the ores.

Later this model was transformed into a two-stage model (Li et al. 2009). It was suggested that "early sulfide segregation took place in a deep staging chamber due to contamination with granitic crustal materials in the lower parts of the upper crust", as suggested previously by other researchers (Naldrett et al. 1992; Naldrett and Lightfoot 1994; Arndt et al. 2003). The magma then rose to form the weakly mineralized intrusions and erupted to the surface to form the Nd_{1-2} lavas, leaving a sulfide liquid with relatively low tenors of Ni, Cu, and PGE in the staging chamber. The PGE-poor sulfide liquid in the chamber was then upgraded in chalcophile elements (PGE, Ni, and Cu) by the Morongovsky magma forming a PGE-rich sulfide liquid. The PGE-rich sulfide liquid remained in the staging chamber while the Morongovsky magma erupted to form the Morongovsky lavas. New, S-unsaturated magma from the mantle continued to enter the chamber and progressively dissolved the PGE-rich sulfide liquid in the chamber to form a PGE-enriched magma. The PGE-enriched magma then rose to the upper parts of the upper crust where it reacted with anhydrite-bearing evaporite country rocks and became sulfide saturated, thereby producing immiscible sulfide liquid with high PGE concentrations as well as high $\delta^{34}S$ values. The sulfide liquid became lodged in the hydraulic traps of the plumbing system at Kharaelakh.

This hypothesis explains the differences between the sulfur isotopes, PGE, Cu, and Ni tenors in weakly mineralized and ore-bearing intrusions, i.e., Low Talnakh and Kharaelakh. However, it does not account for the large difference between the Re-Os compositions of the sulfides from these intrusions.

6.1 Geologic Relationships Between the Lavas and the Intrusions of the Noril'sk Complex

The possible comagmatic relationships between the ore-bearing intrusions and lavas were examined within the Noril'sk Trough, where intrusive rocks with disseminated or massive ores (at the Noril'sk 1, Maslovsky, Chernogorsky, and Noril'sk 2 deposits) are hosted in the uppermost units of the volcanic rocks, i.e., in the middle portion of the tuff–lava unit. In other regional folded structures, these massifs are hosted mostly in the Devonian sedimentary rocks underlying the volcanics (the Kharaelakh and Talnakh intrusions in the Kharaelakh Trough and the Vologochansky intrusion in the Vologochansky Trough), and hence, it is more difficult to correlate them. An important fact is that the Noril'sk Trough hosts rocks of all formations used in the models of various researchers (Gudchikhinsky, Tuklonsky, Nadezhdinsky, and Morongovsky); thus, it is possible to obtain insight into their role in the genesis of the ores.

We selected the geologic sections penetrated by boreholes OM-6 and OM-25 as references. The latter borehole penetrated a sill of the Noril'sk Complex, which is hosted in volcanic rock, is a tongue of the Maslovsky intrusion, and contains high-grade stringer-disseminated Cu–Ni ore mineralization. Despite its relatively insignificant thickness (12 m), this sill is clearly differentiated from the olivine gabbro-dolerite to leucogabbro. It was attributed to the Noril'sk Complex based on detailed data about the composition of its rocks, which were proven to be identical to rocks in the Noril'sk 1 Massif (Krivolutskaya and Rudakova 2009).

The volcanics hosting the sill were subdivided into eight suites, and the tongue appeared to cut through the rocks of the lower portion of the Nadezhdinsky Formation; these rocks were distinguished by the high La/Sm ratios and low Cu and Ni concentrations (Lightfoot et al. 1990; Fig. 6.1). To determine whether the sill is affiliated with the Noril'sk Complex, we compared its geochemistry with that of the Noril'sk 1 Massif (Tables 6.1 and 6.2). It follows that the Maslovsky intrusion and, hence, other comparable ore-bearing intrusions were emplaced after the eruption of the early flows of the Nadezhdinsky Formation, i.e., the ore-bearing intrusions cut across volcanic rocks that are thought to be comagmatic with the picrites of the Gudchikhinsky Formation and the basalts of the Tuklonsky and Nadezhdinsky formations.

This result suggests the hypothesis that the rocks can be comagmatic with rocks of the Morongovsky Formation (Li et al. 2009), whose geochemistry is the closest to that of the rocks of the Noril'sk Intrusive Complex.

However, we have found a barren dyke in Cape Kamenny in Lake Lama whose geochemistry (MgO concentration of 8.92 wt %, TiO_2 concentration of 0.81 wt %, and trace

Table 6.1 Concentrations of rare elements in intrusive rocks of the Noril'sk Trough (Noril'sk 1 intrusion), ppm

No	1	2	3	4	5	6	7	8	9
	Sample No								
Element	59	65.2	67.9	71.8	78	90	96.8	103.8	425
Rb	12.6	10.4	8.43	15.1	18.7	24.8	22.4	11.6	23.3
Ba	103	68.6	71.0	120	104	97.1	114	99.3	309
Th	0.44	0.60	1.05	0.95	1.08	0.95	1.24	0.57	4.16
U	0.17	0.23	0.44	0.36	0.41	0.35	0.45	0.21	1.03
Nb	1.79	2.56	4.13	3.77	4.30	3.55	4.78	2.37	10.5
Ta	0.13	0.25	0.25	0.22	0.95	0.21	0.27	0.14	0.68
La	2.89	2.94	4.74	5.25	5.74	5.00	6.82	3.46	20.9
Ce	6.86	7.06	11.3	12.4	13.5	11.9	16.5	8.11	43.5
Pr	0.93	0.94	1.46	1.67	1.74	1.64	2.20	1.08	5.19
Sr	213	128	124	226	257	295	460	150	301
Nd	4.44	4.40	6.72	7.84	8.11	7.46	10.15	4.96	20.7
Sm	1.28	1.27	1.83	2.16	2.30	2.14	2.86	1.31	4.35
Zr	33.5	39.0	67.4	62.5	65.8	57.5	77.6	38.3	150
Hf	0.92	1.02	1.76	1.63	1.72	1.54	2.08	1.01	3.54
Eu	0.59	0.42	0.58	0.76	0.82	0.74	0.91	0.49	1.16
Ti	2,930	2,555	3,630	4,660	4,565	4,730	5,390	2,830	6,035
Gd	1.53	1.49	2.20	2.58	2.66	2.51	3.30	1.51	4.30
Tb	0.26	0.25	0.37	0.45	0.46	0.43	0.58	0.26	0.69
Dy	1.87	1.74	2.54	3.02	3.15	2.91	3.83	1.79	4.37
Y	11.9	12.4	17.5	20.6	20.8	19.1	25.1	12.0	23.9
Ho	0.43	0.41	0.59	0.70	0.72	0.67	0.87	0.40	0.92
Er	1.13	1.12	1.60	1.89	1.90	1.76	2.36	1.09	2.56
Tm	0.17	0.17	0.24	0.27	0.29	0.26	0.35	0.16	0.37
Yb	1.11	1.05	1.50	1.76	1.84	1.69	2.15	1.06	2.31
Lu	0.16	0.16	0.22	0.25	0.27	0.25	0.32	0.16	0.35
Cu	7,940	2,180	2,590	132	277	81	91.4	643	43.7
Ni	7,487	2,743	2,875	556	295	210	164	1,239	14.1
Co	176	143	143	77.6	60.9	51.1	50.3	36.2	37.7

No	10	11	12	13	14	15	16	17	18
	Sample No								
Element	427.3	428	428.6	429.5	430.9	432.6	433.4	434.1	437.5
Rb	48.5	37.1	4.30	27.3	3.51	6.81	3.85	2.57	63.5
Ba	459	355	91.1	196	74.7	163	100	117	495
Th	3.29	2.23	0.94	0.91	0.82	1.07	1.02	1.00	3.70
U	0.88	0.71	0.36	0.36	0.31	0.41	0.39	0.39	0.91
Nb	8.52	6.37	3.80	4.95	5.39	4.18	4.15	5.33	9.17
Ta	0.53	0.41	0.23	2.72	0.36	0.28	0.26	0.37	0.57
La	16.4	12.0	6.30	5.77	5.62	6.66	6.57	6.44	17.5
Ce	34.1	25.1	14.4	13.1	12.9	15.3	15.2	14.9	36.7
Pr	4.10	3.10	1.97	1.79	1.76	2.12	2.11	2.07	4.42
Sr	405	397	308	310	271	242	258	265	257
Nd	16.08	12.4	9.12	8.44	8.08	9.88	9.69	9.69	17.5
Sm	3.41	2.82	2.49	2.34	2.30	2.77	2.79	2.69	3.81
Zr	117	95.6	80.1	74.2	72.0	87.6	86.1	85.3	133
Hf	2.84	2.21	1.95	1.87	1.71	2.20	2.09	2.08	3.19
Eu	1.00	0.94	1.05	0.78	0.88	1.00	1.13	0.95	0.95
Ti	4,908	4,460	5,766	5,588	5,448	6,328	5,989	6,607	5,297
Gd	3.37	2.92	2.96	2.84	2.69	3.30	3.30	3.28	3.97
Tb	0.55	0.48	0.50	0.48	0.47	0.56	0.57	0.56	0.63

(continued)

Table 6.1 (continued)

No	10	11	12	13	14	15	16	17	18
	Sample No								
Element	427.3	428	428.6	429.5	430.9	432.6	433.4	434.1	437.5
Dy	3.50	3.08	3.29	3.16	3.06	3.76	3.70	3.62	4.01
Y	18.7	17.1	18.7	17.4	17.4	21.3	20.9	21.1	21.6
Ho	0.74	0.65	0.72	0.69	0.64	0.81	0.82	0.78	0.81
Er	2.00	1.79	2.00	1.88	1.80	2.26	2.25	2.19	2.31
Tm	0.29	0.27	0.31	0.29	0.27	0.34	0.34	0.33	0.35
Yb	1.87	1.67	1.96	1.78	1.75	2.19	2.13	2.08	2.18
Lu	0.28	0.26	0.29	0.27	0.26	0.33	0.32	0.32	0.34
Cu	41.7	53.0	90.4	83.1	82.1	273	123	299	29.1
Ni	72.4	139	63.7	26.1	88.4	173	112	215	43.5
Co	42.0	39.8	41.7	29.6	35.3	56.8	51.2	60.2	37.2

Note: Sample No is the depth in borehole G-22. After Krivolutskaya and Rudakova (2009)

Table 6.2 Average mean composition of the Noril'sk Complex intrusions and supposed comagmatic formations, wt %

Intrusion, formation	N	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Cr_2O_3
Noril'sk 1 borehole MS-31	25	47.75	0.89	15.93	11.46	0.14	11.67	9.28	1.91	0.5	0.15	0.32
Noril'sk 1 borehole G-22	14	47.16	0.79	15.36	12.17	0.2	12.04	10.6	0.97	0.39	0.09	0.23
Maslovsky borehole OM-4	21	47.36	0.89	15.27	11.98	0.26	12.25	10.28	1.17	0.43	0.1	0.02
mk	9	50.3	1.3	15.99	11.81	0.2	6.93	12.08	1.08	0.16	0.12	0.02
mr	12	49.72	1.19	15.9	11.98	0.21	7.29	11.93	1.26	0.37	0.14	0.02
nd	10	51.86	1.11	15.75	10.94	0.18	6.89	11.38	1.03	0.72	0.13	0.02
tk	4	50.75	1	15.78	9.34	0.21	6.74	14.61	1.04	0.38	0.1	0.04
gd_2*	5	46.76	1.06	7.72	14.13	0.19	22.41	6.24	0.74	0.48	0.1	0.17
mk*	8	49.34	1.22	16.65	11.68	0.19	6.92	11.57	2.03	0.3	0.1	–
mr*	6	50.01	1.11	16.49	11.31	0.18	6.99	11.43	1.97	0.38	0.11	–
nd*	2	50.97	1.02	16.69	10.43	0.18	6.64	11.11	1.95	0.85	0.15	–
tk*	9	50.18	0.89	15.88	10	0.17	9.09	11.24	2.12	0.34	0.08	–
gd_2*	5	48.64	1.63	10	13.59	0.2	16.69	7.61	0.98	0.53	0.12	–

Note: 1—element was not determined; 2—all compositions were recalculated in 100 %; 3—formations (*mk* Mokulaevsky, *mr* Morongovsky, *nd* Nadezhdinsky, *tk* Tuklonsky (author's data)); 4—gd* Gudchikhinsky (after) (Lightfoot et al. 1993); 5—Noril'sk 1, hole G-22 (average mean composition of rocks based on borehole G-22). N – analyses number. After Krivolutskaya et al. (2012a)

element patterns) is closely similar to that of the rocks in the Noril'sk Complex and cuts across the basalts of the Morongovsky Formation (Fig. 6.2); several similar dykes at the contact of the Nadezhdinsky Formation are mapped below (Fig. 6.3).

It is thus highly probable that intrusions of the Noril'sk Complex were emplaced in post-Morongovsky time, but the absence of disseminated sulfides provides no conclusive arguments in support of this hypothesis.

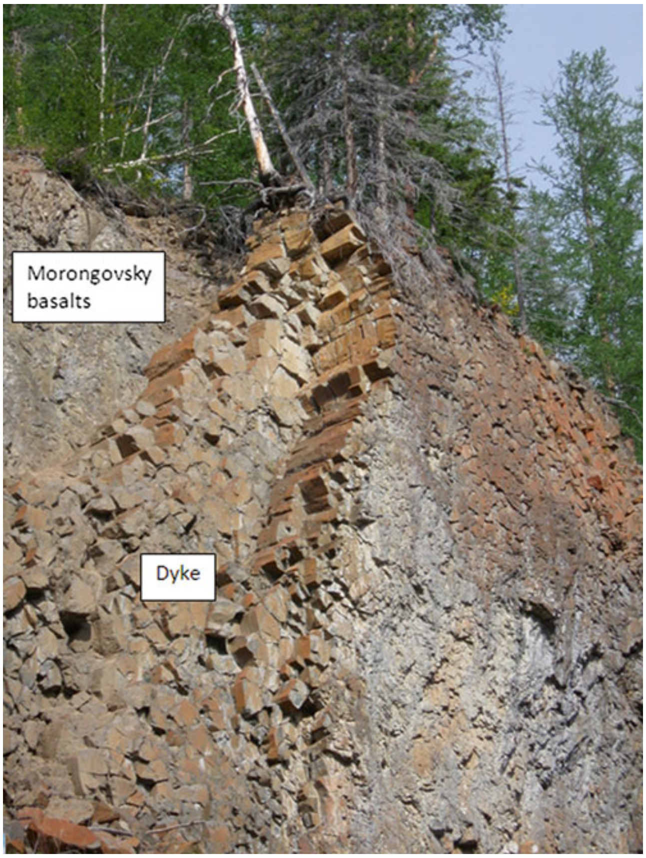

Fig. 6.2 Dyke of the Noril'sk Complex in basalts of the Morongovsky formation

6.2 Comparison of the Geochemistry of the Lavas and Intrusive Rocks of the Noril'sk Complex

The aforementioned data on the inner structure and composition of tuff–lava and intrusive rocks recovered from boreholes in the northern and eastern portions of the Noril'sk depression were demonstrated (see above) to show that the ore-bearing massifs and rocks of the Gudchikhinsky, Tuklonsky, and Nadezhdinsky formations are not comagmatic. This unambiguously follows from the fact that the sill of the Maslovsky intrusion cuts the volcanic rocks of these formations and from the differences between the trace element and mineralogical compositions of the rocks.

Another possible candidate for a volcanic analogue of the Noril'sk intrusions is the Morongovsky Formation (Rad'ko 1991; Arndt et al. 2003). The ore-bearing massifs are localized below their basalts and are similar to them in several geochemical parameters, such as the concentrations of trace elements and their distribution (Lightfoot et al. 1993; Brügman et al. 1993). At the same time, the concentrations of the major oxides, primarily MgO, in these rocks are principally different from those in rocks of the Noril'sk Complex (Fig. 6.4). Throughout its entire field, the Morongovsky Formation comprises exclusively tholeiitic basalts (6–7 wt % MgO), and no rocks with elevated Mg# have been found either in this formation or in the overlying formations. Conversely, practically all rocks of the ore-bearing massifs contain olivine. It is hard to visualize the complete settling and removal of olivine and sulfides from a melt volume of 50,000 km^3 in intrusive chambers that make up less than 10 % by volume. Indeed, in addition to bent magma feeders where these phases could accumulate, there could be numerous magmatic conduits of other geometries that did not facilitate this process. These could be vertical channels and fissures, whose presence at that time follows from the occurrence of Morongovsky-age central-type volcanoes that were mapped in the valley of the Mikchangda River (geological survey conducted by Noril'skgeologia and the author) and documented by several researchers (Petrology and Ore Potential 1978). Volcanic edifices in the fields of the Morongovsky Formation should then have contained magnesian rocks with elevated contents of sulfides. Neither these rocks nor sulfides have been found anywhere in the rocks of the formation, which are exposed over hundreds of kilometers along their strikes.

Finally, the geochemical parameters of the Morongovsky and all overlying formations such as ε_{Nd} (Fedorenko et al. 1996; Lightfoot et al. 1993; Wooden et al. 1993) and, particularly, S isotopic composition (Grinenko 1985; Ripley et al. 2003, 2010: $\delta^{34}S = 1–5‰$ in the basalts and 18‰ in the intrusive rocks) are remarkably different from those in the ore-bearing intrusions. The ore-bearing intrusions could have conceivably been emplaced even after all of the tuff–lava rocks were formed because some zircons from the Kharaelakh Massif were dated at 220 Ma (Malitch et al. 2010), which is generally consistent with the geological data.

6.3 Conclusions

The data presented above show that the ore-bearing intrusions are not directly genetically related to the lavas but were produced during a separate pulse of magmatic activity in post-Nadezhdinsky time. It is important to emphasize that if there was an open system (with a long flowing melt along the chamber), we could not observe such quenched rocks in endocontacts intrusions that have been found in the Maslovsky and Mikchangdinsky intrusions – with the presence of glass and the contrast-zoned rock-forming minerals.

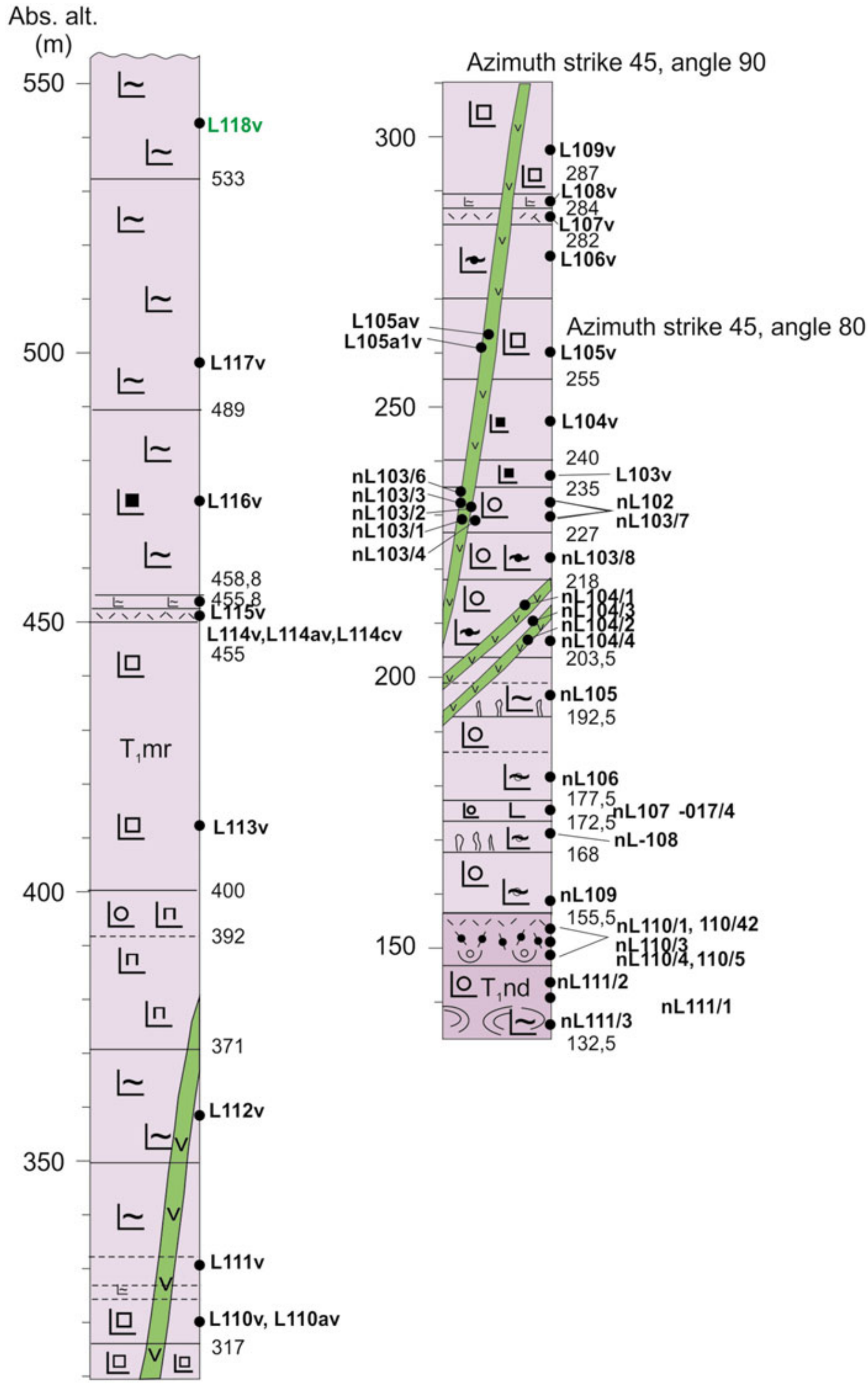

Fig. 6.3 Structure of volcanic rocks of the Morongovsky formation with dykes of the Noril'sk Complex (Section was studied with A. Rudakova) L118v – sample number and its location

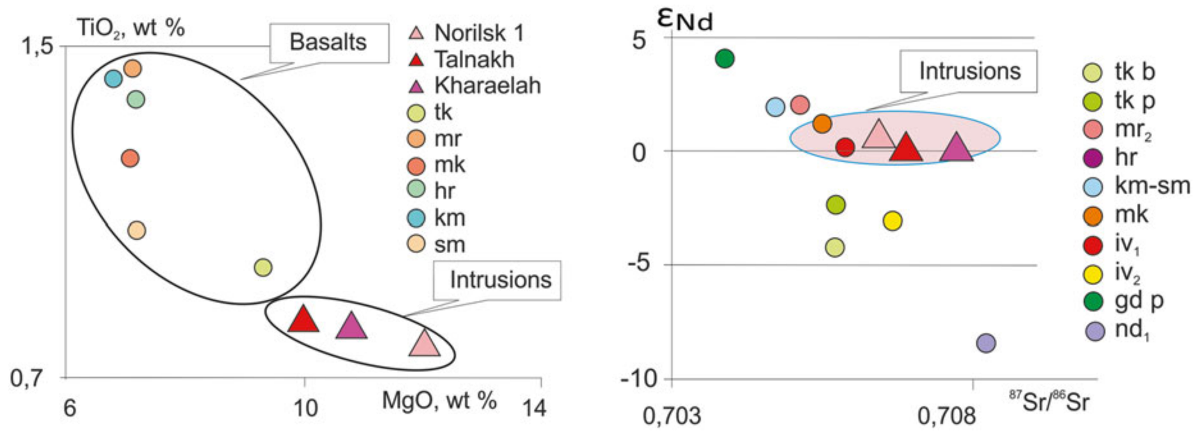

Fig. 6.4 TiO_2–MgO and $\mathcal{E}_{Nd}$–$^{86}Sr/8^{7}Sr$ for magmatic rocks of the Noril'sk area

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