The Conduits of Magmatic Ore Deposits

Nicholas T. Arndt
LGCA, UMR 5025 CNRS,
BP 53
38400 Grenoble cedex
France
arndt@ujf-grenoble.fr

Abstract

The magmatic plumbing system plays a crucial role in the formation of ore deposits such as the Ni-Cu-PGE deposits of the Noril'sk-Talnakh region and the chromite-PGE deposits in the Bushveld Complex. The Noril'sk-Talnakh deposits are hosted by small intrusions with an unusual form; they contain central thickened segments, differentiated into gabbroic and olivine-rich cumulates, and flanked by thinner apophyses. The central segments are only 100-380 m thick but individual intrusions have been traced along strike for up to 17km. In the model developed by Naldrett and co-workers, (Naldrett, 2004 and references therein) these intrusions are interpreted as conduits that linked deeper staging chambers to overlying volcanic sequences. The ore sulfides formed when the magma assimilated granitoid and/or anhydrite-bearing sediments; these sulfides then accumulated from rapidly flowing magma that passed through the conduits to feed lava flows at the surface.

This model has been criticized on three grounds: (1) Latypov (2002) has argued the intrusions and the lava flows are not comagmatic, because the former are olivine normative and the latter Si-saturated. (2) Czamanske *et al.* (1995) maintain that differences in trace element and isotope compositions indicate distinct origins for the intrusions and lava flows. (3) Ripley *et al.* (2003) have shown that the volcanic rocks lack the heavy S-isotope signature acquired by the ores during anhydrite assimilation.

These criticisms can be countered as follows. The difference in the extent of Si-saturation between intrusions and lavas is due largely to the presence of olivine cumulates in the intrusions: their bulk compositions are olivine enriched and not those of magmatic liquids. The sulfur-isotope and trace-element compositions of the lavas have been affected by magma-rock interaction after the magmas left the ore-bearing intrusions, as these magmas flowed laterally in extensive sills within the sedimentary and volcanic strata. This interaction effaced part of the geochemical signature of ore formation. Finally, because of the complexity of the plumbing systems, individual magmas followed independent paths to the surface. On these paths, the extent and type of wall-rock interaction differed considerably and upon intrusion or eruption, the magmas had contrasting compositions reflecting the particular path that they followed.

Geochemical data provide evidence that the first tholeiitic magmas to enter the system assimilated granitic crust in a deep magma chamber. Although sulfide segregated as a result of this interaction, this sulfide may have been left in the deep chamber and may not form part of the ore deposits. The ores themselves formed when other, less contaminated, magmas assimilated anhydrite-rich sedimentary rocks as they flowed through a near-surface sill complex in the upper levels of the sediment pile. The specific stratigraphic location of deposits such as Noril'sk-Talnakh, Raglan and Penchega is related to the dynamics of magma flow in this near-surface sedimentary setting, which influenced how magma interacted with sedimentary rocks.

Complex magmatic plumbing also influenced the formation of the deposits in the Bushveld Complex. This intrusion was fed by plume-derived magmas (not boninite or partial melt of lithospheric mantle) that had assimilated crustal material in lower to mid-crustal magma chambers. The ore minerals segregated, at least in part, in the lower chambers and were transported by flowing magma into the main Bushveld Chamber.

Introduction

Through the work of Naldrett *et al.* (1992, 1995, 1996), Naldrett (1999), Brügmann *et al.* (1993), Lightfoot *et al.* (1990), Czamanske *et al.* (1994, 1995, 2002) and Fedorenko *et al.* (1996), we know that the magmas parental to magmatic ore deposits such as the Ni-Cu-PGE deposits of Noril'sk-Talnakh, or the chromite-PGE deposits in the Bushveld Complex, form through melting deep in the mantle. Because the solubility of sulfur depends inversely on pressure (Wendlandt, 1982; Keays, 1995; Mavrogenes and O'Neil, 1999), these magmas are strongly undersaturated in sulfur when they arrive at crustal levels. If they are to segregate an immiscible sulfide liquid, a process crucial to the formation of most base-metal and many PGE deposits, the magma must reach sulfur saturation. A common trigger is interaction between the magma and crustal wall rocks, which either changes the temperature and composition of the magma so as to decrease the sulfur solubility, or adds sulfur to the magma.

Once the sulfide liquid has formed, normally as droplets of immiscible liquid dispersed within the silicate magma, these droplets must accumulate if a commercially viable deposit is to form. In addition, if the deposit is to be rich, the tenor in ore metals must be high. This requires that the sulfide interacts with, and extracts chalcophile elements from, a large volume of magma. The extent of interaction between magma and crust depends in part on the structure and petrological makeup of the crust and in part on the physical and dynamic characteristics of the magmas themselves.

Magma dynamics: the passage of magma through the crust

Of the physical properties that influence how magma interacts with crustal rocks, the following are the most important:

- *Density*: Magma ascends because its density is less that that of surrounding rocks. All magmas are less dense than mantle peridotite and more magnesian varieties like komatiite and picrite are denser than lower-crustal granulites. These magmas often are trapped at the crust-mantle boundary where they differentiate into less dense and more evolved magmas (Cox, 1980). The evolved magma ascends farther but becomes trapped higher in the crust at junctures where the crustal density drops. Magma chambers of various forms and dimensions result, and in these chambers, or in the conduits between them, the magma interacts with crustal rocks
- *Viscosity*: Low-viscosity magmas flow rapidly and turbulently, if the conduit is sufficiently large. Under these conditions, the magma can thermally erode and rapidly assimilate its wall rocks (Huppert and Sparks, 1985)
- *Temperature*: High temperatures enhance the extent of crustal interaction in two ways: 1) high-temperature magmas have low viscosities, which causes them to flow rapidly and in some cases turbulently, and 2) high-temperature magmas are more capable of melting or reacting with their wall rocks.

- *Magma flux*: If the magma flux is very high and if the flow regime is turbulent, thermal erosion will result in rapid assimilation of wall rocks. If the flux is high, but insufficient to cause turbulent flow, the extent of assimilation of wall rocks will be minimal because the magma spends relatively little time in contact with fusible rocks. If the flux is still lower and the magma accumulates and crystallizes slowly in large magma chambers, then there again is opportunity for massive assimilation of wall rocks.

The crustal composition and lithology are also important. Typical continental crust is made up of a lower layer of dense granulite-facies rocks, an intermediate layer of lower density granitoids and metamorphic rocks, and in many areas an upper layer of still less dense sedimentary rocks. At shallow levels, porosity increases and open fractures become abundant, and the density drops further. Ascending magma tends to become trapped and to form magma chambers at each density discontinuity.

The upward migration of magma is also guided by the structure and state of stress of the crust. In zones of extension, steeply dipping faults provide passageways to the surface. When magma reaches horizontally bedded sedimentary strata, horizontal intrusions or sills form. Images of rifting sedimentary margins (Fig. 1; Planke *et al.* 2004) and maps of intrusions beneath flood basalt provinces show series of upward-stepping sills that form complexes of stacked, saucer-shaped intrusions. Near the surface, where lithostatic pressure is low and non-isotropic (far less vertical than horizontal pressure), the form and size of intrusions will depend on distance to the surface, as discussed by Planke *et al.* (2004). Magma passing through sill complexes flows near-horizontally for much of its passage. The complex pathway augments the period of interaction between magma and wall rocks and increases the extent contamination.

Finally, intrusion of magma into a compressive regime should produce abundant dykes and fewer sills. Compression of magma chambers may squeeze liquids and crystal mushes to higher crustal levels, providing a mechanism for transporting upward dense mixtures of silicate magma, crystals and sulfide liquid (Czamanske *et al.*, 1995; Tornos *et al.*, 2001).

The nature of the interaction between magma and wall rocks should therefore change from base to top of the crust. At the base, both magma (primitive and undifferentiated) and crust (granulite facies) are hot and the two should interact. However, because primitive and hot magmas form deep in the mantle, they are strongly S-undersaturated when they reach the crust, and moderate contamination will not cause the separation of a sulfide liquid. Furthermore, the extent of assimilation of crustal material in the magma will be mitigated if the granulite had become depleted in low-temperature components during earlier melting events, making it refractory and difficult to melt. At mid-crustal levels, temperatures of both magma and crust are lower but the wall rocks are more fusible. Magmas in large chambers may assimilate large amounts of granitoid or metamorphic wall rocks. Finally, at shallow levels in a sedimentary sequence, temperatures of magma and wall rocks are still lower, but if the magma flows horizontally along sills within poorly consolidated, easily fusible strata, the amount of assimilation can be large. It is probably in this setting, where magma encounters S-rich rocks, that most magmatic sulfide deposits form.

Noril'sk-Talnakh Cu-Ni-PGE sulfide deposits

The tectonic setting and geologic environment of these deposits have been described in numerous publications; e.g; (Naldrett *et al.*, 1992; Lightfoot *et al.*, 1997; Zen'ko and Czamanske, 1994; Czamanske *et al.*, 1995; Fedorenko *et al.*, 1996; Diakov *et al.*, 2002; Yakubchuk and Nikishin, 2004) and will only be summarized here. The Noril'sk-Talnakh region is located at the stratigraphic base of the Siberian flood volcanic province, at the rifted margin between the East Siberian craton and the West Siberian sedimentary basin (Fig. 2). The volcanic rocks erupted onto the Paleozoic to upper Mesozoic sedimentary rocks that fill the basin, as shown in the stratigraphic sections in Figures 3 and 4. A thick sequence of intensely deformed upper Proterozoic molasse is overlain by ~12 km of Vendian to Carboniferous marine to continental strata and in turn by 3-9 km of carbonates and evaporites. These are capped by the Tunguska series, 20-600m of Carboniferous to Permian terrestrial coal-bearing sedimentary rocks that directly underlie the Permo-Triassic flood volcanic formations.

The petrological and geochemical characteristics of the volcanic suites are summarized in Figure 3 and Table 2, using information from Lightfoot *et al.* (1990), Czamanske *et al.* (1995), Wooden *et al.* (1993), and Fedorenko *et al.* (1996). The sequence opens with a Lower Series (or assemblage) of alkaline volcanic rocks whose compositions range from picrite through basalt and basanite to trachybasalt. The Middle Series comprises the tholeiitic basalts and picrites of the Tuklonsky Suite and the crust-contaminated basalts of the lower part of the Nadezdhinsky Suite. The Upper Series consists of a monotonous series of moderately contaminated, moderately evolved tholeiitic basalts. For more detailed petrological and geochemical information, see Lightfoot *et al.* (1990), Naldrett *et al.* (1992), Wooden *et al.* (1993), Fedorenko *et al.* (1996 and references therein).

The ore deposits are located in mafic-ultramafic intrusions emplaced within a few hundred metres of the sediment-volcanic contact and largely confined to pronounced elliptical troughs or "volcanic-plutonic depressions". According to Fedorenko *et al.* *(*1996) and Diakov *et al.* (2002), these intrusions formed during compensated downwarping of the sedimentary sequences in a shallow-water environment. The downwarping is attributed to release of magma from deeper magma chambers that underlay the depressions. Many of the ore deposits are aligned along a major NNE-trending Noril'sk-Kharaelakh Fault, which, according to most, though not all, authors (see Yakubchuk and Nikishin, 2004), controlled the emplacement of the ore-forming magmas.

Numerous sills, dykes and irregular mafic and ultramafic bodies intruded the volcanic and sedimentary sequence. Estimates of their abundance in the upper part of the sedimentary pile range from 15-30% to as high as 80% (Czamanske *et al.*, 1995). Diakov *et al.* (2002) state that more than 300 intrusions have been mapped in the vicinity of the Noril'sk-Talnakh deposits. In geological maps these intrusions occur in clusters (Fig. 5), probably because the majority were emplaced just beneath the now-folded contact between sedimentary and volcanic sequences: most intrusions are found at places where this contact is close to the present erosion level.

The intrusions have been classified in various ways. On the basis of lithology, distribution, form and internal structure, Naldrett *et al.* (1992) recognized 5 broad types; Fedorenko *et al.* (1994, 1996) distinguished 15 to 21 types and Diakov *et al.* (2002) identified nine types. The situation is confused in part because these classifications represent a somewhat arbitrary subdivision of a highly complex and variable assemblage of igneous bodies, and in part because the terminology and names applied to individual intrusions is not well established but change from paper to paper. Here I adopt a broad classification along the lines proposed in the relatively recent article by Diakov *et al.* (2002) which summarizes information in earlier papers by Naldrett *et al.* (1992); Zen’ko and Czamanske (1994a,b); Czamanske *et al.* (1995); Likhachev (1994); Kunilov (1994), Fedorenko (1994) and Fedorenko *et al.* (1996).

A threefold subdivision is based on the age of the intrusions and their association with the volcanic suites; in the subdivision, intrusions synchronous with the main phase of tholeiitic flood volcanism are distinguished from those that intruded earlier or later (Table 1). Pre-tholeiite intrusions such as the Ergalakh complex (also written Yergalakh(sky)) and the North Kharaelakh intrusion are linked to the alkaline volcanism that preceded the tholeiites; another group including the Oganer and Daldykan mafic intrusions, as well as various more felsic bodies, were emplaced after the flood volcanism. All ore-bearing intrusions fall in the syn-tholeiite group. Three subgroups are identified: (1) differentiated mafic-ultramafic ore-bearing intrusions, referred to as the Talnakh intrusions by Naldrett *et al.* (1992) but called the Noril’sk or ore-bearing type in Czamanske *et al.* (1994), Federenko *et al.* (1996) and Diakov *et al.* (2002); (2) differentiated mafic-ultramafic, weakly mineralized intrusions called the Lower Talnakh type; and (3) a variety of other intrusions, some differentiated, others not, some containing disseminated mineralization, others without. The petrological and geochemical characteristics of the more important types are summarized in Table 1. Federenko *et al.* (1996) correlated the ore-bearing Noril’sk type intrusions with the Morongovsky-Mokulaevsky volcanic suites, which erupted midway through the volcanic pile. The rocks in these intrusions share certain geochemical characteristics with the volcanic rocks. The slightly older Lower Talnakh type intrusions are correlated with, and share many geochemical features with, the volcanic rocks of the Nadezdhinsky Suite.

The intrusions are elongate and irregular in plan view and sheet-like or U- or tube-shaped in cross section (Figs. 4, 5; Zen’ko and Czamanske, 1994). In general they are conformable with the sedimentary strata — sills are far more common than dykes. Most intrusions are less than a few hundred metres thick but tens of kilometers long. The Talnakh intrusion, for example, is on average only 120m thick but can be traced for 15-17 km (Zen'ko and Czamanske, 1994; Diakov, 2002).

The larger intrusions pinch and swell along strike, both in plan view and cross section. Many contain a thickened central portion (50 to 350m thick and several km long), flanked by thinner (10-50m) but more extensive (up to 15 km long) sill-like extensions or apophyses. The ore deposits are confined to basal parts of the thickened central sections. Figure 6 is a section through the ore-bearing Kharaelakh intrusion, based on Zen’ko and Czamanske’s (1994) diagram and description. The central portion, about 200 m thick in this intrusion, is differentiated into a lower series of olivine-rich cumulates and an upper series of gabbroic and leucogabbroic rocks. (These relatively fine- to medium-grained hypabyssal rocks are called gabbrodolerite in papers with Russian authors). The flanking apophyses, composed of relatively homogeneous gabbroic rocks, rise to higher stratigraphic levels as they pass outwards and away from the central differentiated bodies. In the volcanic sequence the intrusions are more steeply dipping.

Fedorenko *et al.* (1996), and Diakov *et al.* (2002) used a combination of geological mapping, drill-core logging and gravity, magnetic and seismic surveys to infer that the ore-bearing intrusions were the upper parts of a complex magmatic system that included several deeper staging chambers. The volcano-tectonic depressions that contain most of the ore-bearing intrusions are believed to be connected to a series of intermediate magma chambers located at upper- to mid-crustal depths at 12 to 17 km. According to Yakubchuk and Nikishin (2004), these chambers become broader and more abundant with depth and merge into a single large chamber located about 30-40 km to the north of the Noril'sk-Talnakh region. These intrusions, in turn, may be linked to still larger chambers near the base of the crust. Diakov *et al.* (2002) used deep seismic profiles to infer the presence of a Bushveld-sized intrusive complex (~5-12 km thick and ~150km long) just above the crust-mantle boundary, extending from immediately below the Noril'sk-Talnakh region to the SE and becoming thicker in that direction.

Models for the formation of Noril'sk-Talnakh deposits

Most authors accept that the intrusions that host the Noril'sk-Talnakh deposits are fossil conduits that originally linked deeper magma chambers to the volcanic pile at the surface. According to the ore-formation model proposed by Rad'ko (1991) and developed by Naldrett and co-workers (e.g. Naldrett, 1999, 2004; Naldrett *et al.,* 1992, 1995, 1996, 2004; Lightfoot and Hawkesworth, 1997), picritic magma first assimilated granitoid wall rocks in a mid-crustal magma chamber. The contamination led to the segregation of sulfides that were transported upward in the flowing magma. The droplets of dense sulfide were deposited as the upward velocity of the magma dropped when it entered a horizontal sill. More sulfide then segregated as the magma assimilated sedimentary rocks containing anhydrite (a source of sulfur) and coal (which reduced sulfate to sulfide). The accumulated sulfides interacted with magma flowing through the system, extracting Ni, Cu and PGE to produce high-grade ores. On exiting the conduits, the magmas flowed out onto the surface as flood basalts.

Some authors (e.g. Czamanske *et al.* 1994, 1995; Latypov, 2002) have questioned the model, arguing that the magmas that solidified in the ore-bearing intrusions were not directly related to the volcanic rocks. According to them, the intrusions were blind or formed as small-volume injections into the sedimentary sequence. Ore sulfides were injected into these intrusions either in pulses of sulfide-, phenocryst- and clast-charged magma or as sheets of sulfide magma. Arguments used to defend these interpretations depend partly on textural relations between ore-bearing and unmineralized parts of the intrusions (see Czamanske *et al.* 1995, for example), and partly on compositional differences between intrusive and volcanic rocks.

Differences between the compositions of lavas and intrusive rocks

1. *Phase equilibria constraints*. Latypov (2002) argued that the magma that formed the intrusions had a different crystallization history from the volcanic rocks. His estimated composition of the parental magma of the intrusions is silica-undersaturated and would have crystallized olivine whereas the lavas are silica-saturated and could not have crystallized olivine (Fig. 7).
2. *Sulfur isotope ratios*. Ripley *et al.* (2003) showed that δ^{34}S isotope values of all lavas fall in the range –5 to +8 with a peak around +2 (Fig. 8). This range is very similar to that of non-mineralized intrusions but very different from that of the ore-bearing and weakly mineralized intrusions, which have heavy S isotopic values in the range +5 to +16. These high values, attributed to the assimilation of evaporitic sediment, constitute one of the principal arguments

for the conduit model. Just why the high δ^{34}S values are missing from the lavas, if these represent magmas that passed through the ore-bearing intrusions, remains unexplained.

3. *Differences in trace-element ratios and isotopic compositions*. Figure 9 compares Rb/Sr ratios and Sr and Nd isotopic compositions of intrusive and volcanic rocks. Although the fields broadly overlap, and although there is an impressive match between the compositions of Lower Talnakh-type intrusions and Nadezdhinsky basalts on one hand, and between ore-bearing intrusions and overlying basalts on the other, some differences remain. The highest Sr isotopic compositions in the intrusive rocks are absent from the lavas, and a population of lavas has a combination of low Rb/Sr, low ^{87}Sr/^{86}Sr and low εNd that is absent from the intrusive rocks.

Many of these apparent inconsistencies can be explained if we take into account the paths followed by the magmas not only *before* they reached the ore-bearing intrusions but also *after* they left the intrusions and flowed onwards towards the surface. In the literature, almost all emphasis has been placed of the magmatic plumbing below or at the level of the ore deposits, for the very good reason that this is where the ores formed. However, the compositions of the volcanic rocks will also be influenced by how the magma interacted with rocks overlying, or along strike, from the ore deposits.

Sills are far more abundant than dykes in the Noril'sk-Talnakh region. Magmas passing through the sill complexes beneath the flood basalts flowed laterally far farther than vertically. The intrusions of the Noril'sk-Talnakh region are only a few hundreds of metres thick but tens of kilometers long, as shown in sections through the volcanic and sedimentary sequences such as Figure 4. This figure also shows numerous "undifferentiated intrusions of various types" (e.g. Zen'ko and Czamanske, 1994) that intrude the Tunguska series, the sequence of terrigenous sedimentary rocks that encloses or overlies the ore-bearing intrusions. At least in part, such intrusions represent a portion of the plumbing system that linked deeper intrusions with the surface. Magma flowing out of the ore-bearing intrusions interacted first with the Devonian marls, evaporates and carbonates deeper in the sequence, then with terrigenous sediments of the 20-600-m-thick Tunguska series, and finally with previously erupted volcanic rocks. These volcanic rocks include the entire Lower Series of alkaline volcanic rocks, a volcanic sequence whose thickness varies between 500 and 1000m in the area of the ore deposits. The magmas passed through many kilometers of sedimentary and volcanic rocks before reaching the surface, and as they did it they would have continued to crystallize and interact with these rocks. In so doing, the composition of erupted magma became different from that of the magma that solidified in the ore-bearing intrusions. In the light of these observations we can reconsider the three points listed above.

1. The mismatch between the compositions of rocks in the intrusions and the erupted lavas is related in part to the shallow-level processes and in part to the nature of the rocks in the intrusions themselves. As shown in Figure 6, the compositions of rocks in the intrusions vary widely, from the relatively evolved gabbroic and leucogabbroic rocks that form the uppermost layers in the differentiated intrusions, to the olivine-rich lower cumulates, which have highly mafic to ultramafic compositions. Czamanske *et al.* (1994, 1995) used the presence of abrupt jumps in major and trace element contents and isotope ratios at internal lithological contacts (e.g. MgO, FeO and Sr/Sm at the contact

between picritic gabbro and olivine gabbro in Figure 6, or ^{87}Sr/^{86}Sr at the contact between picritic gabbro and taxitic gabbro) to argue that these intrusions are not simple, internally differentiated bodies but instead were filled sequentially by a series of magma pulses. Many of the upper gabbroic rocks probably crystallized directly from gabbroic liquids and have compositions similar to these liquids. The lower olivine-rich rocks, on the other hand, formed from magmas charged with olivine phenocrysts, and their compositions are not those of silicate liquids. The compositions of these rocks, and therefore the average composition of an entire intrusion, are richer in olivine than any of the liquids that passed through the intrusion.

As seen from Figure 10, the main difference between the lavas and the intrusions is the presence of MgO- or olivine-enriched rocks in the intrusions. These rocks presumably are the solidification products of phenocryst-charged, relatively viscous magmas that entered, but did not exit, the chambers. The least mafic, gabbroic and leucogabbroic, rocks in both the ore-bearing intrusions and the Lower Talnakh-type intrusions have compositions broadly comparable to those of the erupted basalts. These probably represent more mobile magmas that transited the chambers on their way to the surface, leaving in the intrusions mafic to ultramafic cumulates deposited from phenocryst-charged magmas. The difference in the extent of silica saturation that troubled Latypov (2002) is therefore due mainly to the presence of the olivine cumulates in the intrusions.

There remain, however, some types of volcanic rocks whose compositions are unmatched in the intrusions. For example, certain basalts in the Nadezdhinsky Suite are more SiO_2-rich and MgO-poor, and more Si-saturated than any analyzed sample from the intrusions (Fig. 10). There are two possible explanations for these differences; (1) magmas with these compositions bypassed the intrusions, or if they did pass through them, they did not solidify to form part of the layered sequence; (2) as the magmas flowed onward through the sedimentary and volcanic strata overlying the chambers, they continued to crystallize olivine and assimilate their wall rocks, processes that enhanced the differences between the compositions of the intrusive and volcanic rocks.

2. The systematic differences in S isotope composition between lavas and rocks in the mineralized intrusions (Fig. 9) might also be explained by shallow-level magma-rock interaction. Although no S isotope data are available (to my knowledge) for the sedimentary rocks of the Tunguska suite, these terrigenous sediments should have had a wide range of compositions, including negative δ^{34}S values in pyrite-bearing sediments. Ripley et al's (2003) data show that the alkali volcanics of the Ivakinsky, Syverminsky and Gudchikhinsky Suites have a large range of δ^{34}S values, including many negative values, and that some of the lavas have very high S contents (up to 1393 ppm). During the movement of magma within horizontal sills in the sedimentary and volcanic strata, the incorporation of sulfur from sedimentary and volcanic wall rocks may have effaced the heavy S isotopic signature of evaporite assimilation.

3. The mismatches in Rb/Sr and radiogenic isotopes are more difficult to explain. Although compositions for Tunguska sedimentary rocks appear not to have been published, we can infer their likely characteristics. Like other Mesozoic continental sediments, they probably had relatively high ^{87}Sr/^{86}Sr (about 0.715), low εNd (around -10) and high Rb/Sr. From published analyses, we

> know that most of the overlying alkali volcanic rocks are more “isotopically depleted” with lower $^{87}Sr/^{86}Sr$ (0.7045-0.7065), higher εNd (0 to +5, but with several samples around –4) and relatively low Rb/Sr. Interaction between ascending magma and sedimentary or volcanic rocks would superimpose a range of compositions that fall on the dominant array in Fig. 9, eliminating or diluting the high $^{87}Sr/^{86}Sr$, moderate εNd signature acquired through interaction with evaporitic sediments.

Nonetheless, it remains unlikely that such interaction can explain the entire range of compositions of rocks in the flood volcanic sequence. The particular combinations of low $^{87}Sr/^{86}Sr$ at a given εNd, and low Rb/Sr in rocks with low $^{87}Sr/^{86}Sr$ (Fig. 9) are not readily explained by shallow-level interaction. One possible explanation for these characteristics, which are conspicuous in lavas of the upper volcanic series, is the assimilation of lower crustal granulites. Perhaps the magmas that erupted to form the Upper Series followed a path to the surface that bypassed shallow-level magma chambers. As with the highly silica-saturated Nadezdhinsky basalts, these flood basalts apparently followed different paths from those of the magmas that fed the ore-bearing intrusions.

Magmatic Plumbing of the Noril’sk-Talnakh System

On the basis of the observations and arguments given above, the following picture of the magmatic plumbing system of the Noril’sk-Talnakh region can be developed. As illustrated in Fig. 11, the magmas that formed the ore deposits and/or fed the flood volcanics followed a complex series of pathways as they moved from their mantle source to the surface. They transited a series of magma chambers of various sizes and forms: through some they passed rapidly, in others they stalled and crystallized and interacted with their wall rocks. Most of these magma chambers were sill-like, and, at least in the upper sedimentary series, most of the conduits between these sills were largely conformable. Magma rising through the system flowed far farther laterally than vertically.

Some magma passed rapidly through the system and interacted little with the wall rocks. This was the case for the alkali magmas (meimechites, picrites, basalts) of the Kotui River region whose high volatile contents reduced their densities and drove them quickly to the surface (Arndt *et al.*, 1998, 2003). In this region, magmas of the alkali and tholeiitic series erupted synchronously, indicating that the two types of magma, which formed under very different conditions in the mantle, followed independent pathways to the surface.

In the Noril’sk-Talnakh region, the alkali magmas of the Lower Series (Fig. 3) erupted rapidly with little interaction with the crust. Tholeiitic magmatism started with the picrites and basalts of the Tuklonsky suite. These magmas stalled in a mid-crustal magma chamber where they assimilated granitoid wall rocks and acquired their distinctive chemical signatures, and where they segregated sulfides. Although many authors believe that these sulfides were subsequently transported to shallower levels to form part of the ore deposits, it is equally possible that, as shown in Figure 11, they remained where they formed, at deep levels inaccessible to mining. Magmas escaping the mid-crustal chambers ascended to the surface, forming Lower Talnakh-type intrusions and erupting as lavas of the Nadezdhinsky Suite.

Other picritic magmas bypassed the mid-crustal chambers and arrived at the level of evaporitic sediments with their full complement of ore metals. As they flowed through sills within the sedimentary strata, they assimilated anhydrite and segregated sulfide, as in the Naldrett-Lightfoot model. Although Naldrett (2004) suggested that assimilated coal reduced sulfate to sulfide, the ore-bearing Kharaelakh is emplaced stratigraphically below the coal-bearing Tunguskaya series (Fig. 3 and Czamanske et al, 1995). It is more probable, therefore, that the reductant was organic matter in the Devonian carbonates (which correlate with source rocks of the giant west Siberian oil and gas fields). Following interaction with these sedimentary rocks, the evolved magma continued to the surface, crystallizing more olivine and reacting with terrigenous sediments and previously erupted lavas, a process that effaced some of the geochemical signatures of ore formation. Subsequent magmas followed separate paths to the surface and erupted as the Upper Series of flood basalts.

Ore Deposits of the Bushveld Complex

The chromite, magnetite and arguably the PGE deposits of the Bushveld Complex are type examples of magmatic deposits. The overall characteristics of these deposits and their host intrusion are very different from the Noril'sk-Talnakh deposits. Descriptions of the Bushveld deposits are found in every text on economic geology and in numerous papers (e.g. Campbell *et al.* 1983; Eales and Cawthorn, 1996; Mathez *et al.* 1997; Wilson *et al.* 1999; Barnes and Maier, 2002) and I will not repeat this information. Instead, I will compare what we know of the magmatic plumbing of the Bushveld Complex with that inferred for the Noril'sk-Talnakh deposits.

The Bushveld Complex is much larger than the intrusions that host the Noril'sk-Talnakh deposits. As presently exposed (Fig. 12), it is over 200 km long, 150 km wide, and up to 9 km thick; it occupies nearly a quarter of the total thickness of the crust. The ore deposits occur as magmatic strata, albeit of unusual composition, and in terms of their overall form and origin, they constitute an integral part of the magmatic architecture of the complex. Unlike the Noril'sk-Talnakh ores, in which sulfide ores make up a disproportionately large part of the total mass of their host intrusions, the Bushveld ores represent only a minute fraction of the total mass of the complex.

Despite these differences, the processes that led to the formation of the deposits may not have been very different. The rocks of the Bushveld Complex have mineralogical and chemical compositions that are very different from those of mafic-ultramafic rocks from oceanic settings. Most of the ultramafic cumulates in the lower part of the intrusion contain orthopyroxene and not olivine as the dominant phase. Phlogopite and hydrous minerals are present in small but variable amounts throughout the complex. In most samples, SiO_2 and K_2O contents are higher than in ultramafic or mafic rocks from intrusions in other settings. Trace-element patterns are distinctive: in mantle-normalized diagrams (Fig. 13), the more incompatible elements are strongly enriched and there are pronounced negative Nb-Ta and positive Pb anomalies (e.g. Maier *et al.* 2000). Also distinctive are the Sr-, Nd and Os isotopic compositions (Kruger, 1994; Maier *et al.*, 2000; McCandless and Ruiz, 1991). As shown in Figure 12, rocks from the Bushveld complex have very low, but relatively uniform εNd values, and high but variable ^{87}Sr/^{86}Sr. Finally, the oxygen isotope ratios of Bushveld rocks are significantly higher than those of uncontaminated mantle-derived magma (Harris *et al.* 2004). These characteristics correspond to those of a "continental crustal component" which can be acquired either through the assimilation of crustal wall rocks or through partial melting of a source contaminated with crustal material.

Certain authors have suggested that the magmas parental to the Bushveld Complex were boninitic (see discussion by Barnes, 1989), having been derived through partial melting of lithosphere that had been metasomatized during subduction. Figure 14 shows, however, that the isotopic compositions of Bushveld rocks are very different from those of boninites and are more like those of the crust-contaminated Nadezdhinsky suite from Siberia. Maier *et al.* (2000) attributed the combination of low but constant εNd values, and high but variable ^{87}Sr/^{86}Sr, to assimilation of crustal rocks. Rocks from the lower continental crust have lower Rb/Sr than rocks of the upper crust, but their Sm/Nd ratios are similar. Because the half-life of ^{147}Sm is far longer than that of ^{87}Rb, the Sm-Nd system evolves more slowly than the Rb-Sr system. At the time of intrusion of Bushveld lavas (2.1 Ga), continental crust of the 3.0-3.5 Ga Kaapvaal Craton, which encloses the Bushveld Complex, would have had a wide range of ^{87}Sr/^{86}Sr (low in the lower crust and high in the upper crust) and a more restricted range of ^{143}Nd/^{144}Nd. Many magmas in ocean basins and subduction zones form in the presence of garnet, a mineral that strongly fractionates Sm/Nd. Old reservoirs in the convecting mantle have wide ranges in both ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd, the so-called mantle array. As seen in Figure 14, boninites fall on this array; but rocks from the Bushveld Complex do not. Instead, they form a trend oblique to the mantle array, a trend of variable ^{87}Sr/^{86}Sr at near-constant ^{143}Nd/^{144}Nd that is consistent with assimilation of rocks from old continental crust.

In general, therefore, the unusual compositions of rocks in the Bushveld can attributed to high levels of crustal contamination. To explain εNd values around –7, Maier *et al.* proposed that the magma assimilated between 20-40% of material from the lower and upper crust, a figure confirmed by Harris et al's (2004) oxygen isotope data. The crustal signature persists from base to top of the Complex, suggesting that the magmas became contaminated before they entered the Bushveld magma chamber. The amount of chromite in massive seams in the lower part of the complex is enormous. Eales and Cawthorn (1996) have calculated that the chromite in each seam must have been extracted from many times its mass of silicate magma. It appears that this chromite was extracted from a large volume of magma that flowed through, then out of the Bushveld Chamber. The picture emerges of a dynamic system comprising a lower chamber or chambers in which mantle-derived magma became contaminated with crustal rocks, and of a Bushveld intrusion that acted as a conduit between a deeper staging chamber and the surface. Although mafic volcanic rocks of Bushveld age are known in the Rooiberg Formation, their volume is small compared with that of the Bushveld Complex. Evidently most of the erupted products of the Bushveld system have been lost. Part could simply have flowed away and off the continent (like the large volumes of flood basalt off shore from the Deccan Traps in India), and part could have been removed by erosion.

The role of crustal structure in ore formation and a new classification of

The two examples considered above represent ore deposits that formed at different levels in the crust. The Noril'sk-Talnakh deposits are an example of mineralization that developed at very shallow levels in the crust, near the top of a sedimentary pile and just below, or at the very base, of the volcanic sequence. Other examples of this type include the Raglan deposits in northern Quebec (Lesher *et al.* 1999; Lesher and Keays, 2002), and the Pechenga deposit in the Kola Peninsular of Russia (Barnes *et al.* 2001, Naldrett, 2004). In all these deposits, ore formation is believed to have been triggered by the assimilation of sedimentary rock by magma flowing through shallow-level, concordant, highly elongate sills. At Bushveld and in other deposits such as Voisey's Bay, ore formation took place at deeper levels in the crust. The assimilated material was metasediment or granitoid, and the magmas flowed upwards through steeply dipping conduits before irrupting into magma chambers where the sulfides were deposited (Li and Naldrett, 1999). The status of the Jinchuan deposit in China is uncertain: if the host intrusion is a near-vertical,, discordant, trumpet-shaped body as in the models of Tang (1995) and Chai *et al.* (1992), it could be classed with Bushveld and Voisey's Bay; if it is a near-horizontal sill, as proposed by de Waal *et al.* (2004), it could be classed together with the Noril'sk deposits. Distinction between the two alternatives awaits more detailed study of contact relations between the intrusion and its wall rocks.

The subdivision into shallow- and deep-level deposits provides clues as to the manner in which magma flows through and interacts with its wall rocks. Magma ascending through a steeply dipping dyke may or may not interact with its wall rocks, depending on the width of the dyke, the flow rate and the physical and chemical characteristics of magma and wall rock. In a deep crustal setting, much of the interaction probably takes places in large, relatively static magma chambers, particularly at the top of the chamber where the rocks melt or are stoped into the magma reservoir. If this contamination leads to sulfide segregation, sulfides accumulate at the floor of the chamber. They may then be remobilized by the influx of new magma into the chamber, or unconsolidated sulfide-crystal mushes might be squeezed from the chamber during deformation. Or they may stay where they formed, at depths inaccessible to mining.

In the near-surface setting, the controls on magma dynamics are very different. Flowage through a sill complex in the sediment strata beneath the volcanic pile is largely horizontal. The form and dimensions of the intrusions are strongly influenced by the heterogeneous stress regime, by horizontal planes of weakness between the sedimentary units and the elastic strength of the sedimentary rocks. These parameters change dramatically with increasing depth in the sediment pile as lithostatic pressure increases and becomes more homogeneous and as the rocks become more consolidated. The similar stratigraphic position of the Noril'sk-Talnakh, Raglan and Pechenga deposits — in the uppermost part of the sediment pile — probably is related to the local environment in the sediment pile. The process of sulfide segregation, upgrading and accumulation that gives rise to an ore deposit may well be linked to the manner in which magma flows through the sill complexes and interacts with the enclosing sedimentary rocks.

Planke *et al.* (2004) observed changes in the form and dimensions of intrusions in sedimentary strata beneath flood basalts and in volcanic rifted margins, from layer-parallel, sheet-like intrusions deep in the sequence and in unconsolidated sediments near the surface, to smaller, saucer-shaped or irregular intrusions at intermediate depths. They describe how the form, size and abundance of intrusions are strongly influenced by structures and heterogeneities such as fault zones, layering and deformed strata. The rate of magma flow is linked to the thickness and continuity of the intrusions, which change with distance to the surface (Planke *et al.* 2000, 2004). In layer-parallel sills, flow will be rapid and perhaps turbulent; and turbulent flow results in thermo-mechanical erosion and enhanced assimilation of wall rocks that leads the formation of a sulfide liquid. In thicker parts of sills, which may result from disturbed flow in regions of weaker rocks in fault zones, the flow rate decreases, resulting in sedimentation of transported sulfide (and crystals and rock fragments). Magma might erode, assimilate and segregate sulfide liquid as it flows near-horizontally through sills a moderate depths, then deposit the sulfides when it steps up to shallower stratigraphic levels or when it encounters weaker rocks in fault zones. Pulsed flow of magma through the sills could result in remobilization and re-deposition of sulfide-crystal mixtures. Such a process provides explanations for the specific stratigraphic level of deposits such as Noril'sk-Talnakh, Raglan and Pechenga, and the spatial association between the Noril'sk-Talnakh deposits and the Noril'sk-Karaelakh fault.

These ideas have evident application to the exploration for Noril'sk-Talnakh-type deposits. Rather than basing such exploration solely on lithology and chemistry of the magmatic rocks and on the present structure of the region (which normally is controlled by post-ore deformation), consideration should be given to the dynamics of flow in the sub-surface sedimentary environment.

Conclusions

- The magmas that formed the Noril'sk-Talnakh deposits passed through a complex plumbing system before reaching the surface. Volatile-rich, low-density alkali magmas passed rapidly to the surface, interacting little with wall rocks. Dense, volatile poor tholeiitic picritic magmas interacted with wall rocks, and sulfides segregated because of this interaction.
- The host intrusions were broadly co-magmatic with the lava series; the conduit model is broadly correct. However, each batch of magma followed a separate path to the surface and had a different history of contamination and sulfide segregation. Shallow-level partial crystallization and wall-rock interaction influenced the compositions of erupted lavas and produced some differences between the composition of rocks in ore-bearing intrusions and those of erupted lavas. Magmas of the Lower Talnakh-type intrusions and the Nadezdhinsky suite assimilated granitic crust in a deep magma chamber. Although sulfide segregated as a result of this interaction, it is possible that this sulfide remained where it formed and does not constitute part of the ore deposits.
- Ore formation took place as magma assimilated anhydrite-rich sedimentary rocks in the near-surface sill complex in the upper levels of the sediment pile. The stratigraphic position of deposits such as Noril'sk-Talnakh, Raglan and Pechenga may be related to the dynamics of magma flow in this sub-surface sedimentary setting.
- The Bushveld Complex formed as a large, open-system magma chamber in the middle to upper crust. The compositions of magmas entering the chamber were strongly influenced by crustal contamination in deeper staging chambers. The formation of ore deposits may be related to this deep-level contamination and not to processes within the Bushveld chamber itself.

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Figure Captions

Fig. 1: Sill complexes in sedimentary sequences. (a) map of the Karoo flood basalts, sill complexes and underlying sedimentary basin, from Chevallier and Woodford (1990). From south to north the altitude increases and increasing shallower levels of the northward-dipping sequence are exposed. In the lowermost sediments the sill are planar; farther north they form ring-shaped bodies that are the surface expression of saucer-shaped intrusions. (b) Interpreted seismic profile through sediments at the rifted margin offshore from Norway, from Planke *et al.* (2004). The sedimentary strata are intruded by numerous conformable, sheet or saucer-shaped intrusions probably of doleritic composition. These intrusions provide an analogue for intrusions beneath many magmatic ore deposits.

Fig. 2: Map of the Noril'sk-Talnakh region showing the locations of the ore deposits and the principal geological features (from Czamanske *et al.* 1994).

Fig. 3: Simplified stratigraphic columns through the sedimentary units underlying the Noril'sk flood volcanic province (left) and through the flood volcanic units themselves (right). The vertical bars on the left show positions of the main ore-bearing and weakly mineralized intrusions. More detail is shown in Zen'ko and Czamanske (1994) and Czamanske *et al.* (1995), the sources of this diagram.

Fig. 4: Simplified sections through the sedimentary and volcanic units at Noril'sk-Talnakh (modified from more detailed diagrams in Zen'ko and Czamanske, 1994 and Naldrett, 2004). Note that the upper diagram is drawn with the vertical scale the same as the horizontal scale (unlike in the original diagram from Zen'ko and Czamanske) but that in the lower diagram, there is a ~2 times vertical exaggeration (as in the original diagram). The sections illustrate the extremely long but thin form of the ore-related intrusions and the abundant intrusions in the sedimentary and volcanic strata overlying the ore horizons.

Fig. 5: Map of the Noril'sk region showing clusters of intrusions near the contact between the sedimentary and volcanic sequences (redrawn from Yakubchuk and Nikishin, 2004).

Fig. 6: Section through the ore-bearing Kharaelakh intrusion (drill hole KZ-1879), showing variations in rock type, olivine content and composition, and in some geochemical parameters (data from Czamanske *et al.* 1994).

Fig. 7: Phase diagrams from Latypov (2003) showing that most samples from the intrusions related to ore deposits are silica undersaturated and plot in the olivine field whereas as the volcanic rocks are silica-saturated. Latypov (2003)

used these data to argue that the volcanic and intrusive rocks were not co-magmatic.

Fig. 8: Sulfur-isotope compositions, expressed as d^{34}S values, of various types of intrusive and volcanic rock from the Noril'sk region (from Grinenko 1985 and Ripley *et al.,* 2003). The lavas show a range of d^{34}S values centred on the mantle value of zero, like those of the unmineralized intrusions. All mineralized intrusions have higher values.

Fig. 9: Neodymium and strontium isotopic compositions of intrusive and volcanic rocks from the Noril'sk-Talnakh region (from Wooden *et al.* 1993 and Arndt *et al.* 2003). The fields broadly overlap, but the highest Sr isotopic compositions in the intrusive rocks (Fig. 9b) are absent from the lavas, and lavas from the upper part of the volcanic pile (Fig. 9c) have a combination of low Rb/Sr, low ^{87}Sr/^{86}Sr and low eNd that is absent from the intrusive rocks.

Fig. 10: Histograms showing the ranges of MgO and extent of silica saturation in intrusive and volcanic rocks. The intrusions have a wider range in compositions extending to more magnesian, olivine-normative compositions; these compositions are those of the olivine-enriched lower portions of the intrusions. The gabbroic and leucogabbroic upper portions of the intrusions have compositions broadly comparable to those of the volcanic rocks. The only exception is several basalts from the Nadezdhinsky suite, which are more silica-saturated than any of the intrusive rocks. (Data from Czamanske *et al.* 1994, 1995; Arndt *et al.* 2003, and unpublished).

Fig. 11: Sketch showing the possible plumbing of the Noril'sk intrusions and volcanic rocks. The diagram illustrates a four-stage model for the formation of the magmatic sequence. (1) Eruption of the Lower Series of alkali volcanics into a sedimentary basin. (2) Lower Talnakh-type magmas first entered deep staging chambers where they interacted with granitic rocks and separated sulfide liquid. The sulfide liquid remained in the chamber while the silicate liquid rose through a complex series of sills and conduits, forming the Lower Talnakh intrusion, then interacting with sedimentary and volcanic strata before erupting as the Nadezdhinsky basalts. (3) The magmas that formed the ore deposits followed a separate pathway, arriving only slightly contaminated at the level of evaporites. They assimilated these rocks, formed the ore deposits, then continued to the surface to erupt as the lower part of the Upper Series. (4) Later magmas bypassed these chambers to erupt as the main sequence of the upper volcanic series.

Fig. 12: Sketch map of the Bushveld Complex.

Fig. 13: Trace-element compositions, normalized to primitive mantle of Hofmann (1989) of the peripheral sills to the Bushveld complex.

Fig. 14: Neodymium- and strontium-isotopic compositions of boninites (data from the GEOROC data base http://georoc.mpch-mainz.gwdg.de/georoc/), of Siberian flood basalts (Wooden *et al.* 1993) and rocks from the Bushveld Complex (Maier *et al.* 2000).

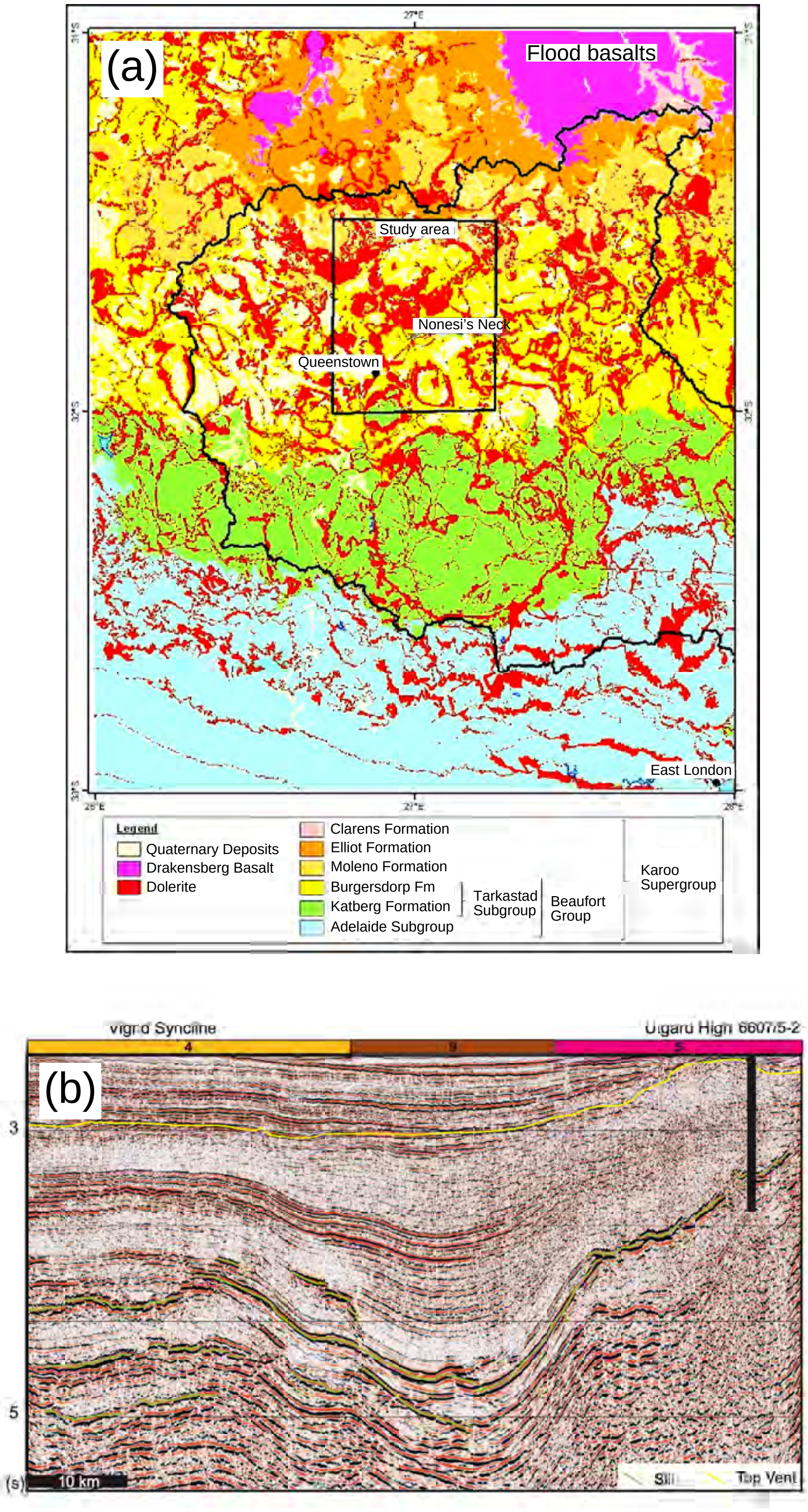
Table 1: Characteristics of Intrusions in the Noril'sk-Talnakh region

	Ore-bearing (Noril'sk type)			**Lower Talnakh type**
Example	Kharaelakh	Talnakh	Noril'sk 1	Lower Noril'sk, lower Talnakh
Position within stratigraphy	In the sedimentary pile, top of intrusion is ~300-600 m below the volcanic contact	In the sedimentary pile, top of intrusion is ~0-500 m below the volcanic contact	Extending from the sedimentary pile into flood volcanics; top of intrusion is ~200 m below to ~200 m above the volcanic contact	Upper 50-600 m of the sedimentary pile, but normally slightly below level of ore-bearing intrusions
Host rocks	Dolomite, marl, anhydrite, minor shale and sandstone	Mainly siltstone, sandstone, coals	Siltstone, sandstone, coals and alkali tuff and lava for the Noril'sk intrusion	Dolomite, marl, anhydrite, minor shale and sandstone
Lithology	Picritic - differentiated with olivine-cumulate or taxitic gabbroic lower parts and gabbro or leucogabbro upper portions	Picritic - differentiated with olivine-cumulate or taxitic gabbroic lower parts and gabbro or leucogabbro upper portions	Picritic - differentiated with olivine-cumulate or taxitic gabbroic lower parts and gabbro or leucogabbro upper portions	Picritic - differentiated with olivine-cumulate lower parts and gabbro or leucogabbro upper portions
Size and shape	Three sheet-like branches with subparallel upper and lower contacts; thickness = 260m max, 109m av; 8 km long	Finger-like, straight; upper contact flat, lower contact curves downward; thickness ~220 m max, 120 m av; 100-1000 m wide; 14.5 km long	Finger-like, curved; upper contact concave downward; thickness = 350m max, 147m av; 20 km long	Sheetlike but with pinches and swells; ~□ km wide, 30-130 m thick; > 40 km long
Peripheral sills	olivine gabbro, extending >6.5 km from main intrusion	olivine gabbro, extending 15 km from main intrusion	olivine gabbro, extending 3□km from main intrusion	>40 km

The information in this table is taken from the text and the diagrams in the following papers: Naldrett et al. (1992), Zen'ko and Czamanske (1994a,b); Czamanske et al. (1995); Likhachev (1994); Kunilov (1994); Fedorenko (1994), Fedorenko et al. (1996), Diakov et al. (2002)

Table 2 Lithological and geochemical characteristics of flood volcanics

	Suites	**Rock types**	**Geochemical characteristics**	**Origin**
Upper series	Samoed, Kumgin, Kharaelakh, Mokulaev, upper Morongov (Mr2)	Tholeiitic basalt of remarkably uniform composition	Evolved moderately siliceous basalt (SiO_2 = 48.5-50%; MgO = 6.3-8.1%). Moderate enrichment of incompatible trace elements; negative Nb-Ta anomalies; ε_{Nd} ~0.	Moderate crustal contamination of high-degree mantle melts
Middle series	lower Morongov (Mr1), Nadezhda	Lavas and tuffs of tholeiitic basalt	Siliceous basalt (SiO_2 = 52-55%; MgO = 6.3 to 8.1%). Moderate to strong enrichment of incompatible trace elements; large negative Nb-Ta anomalies; ε_{Nd} ~0 to -11	Highly contaminated tholeitic magma
	Tuklon	Basalt and picrite	Basalt (SiO_2 = 49-50%; MgO = 8-9%); picrite (SiO_2 = 47-49%; MgO = 10-17%). Moderate enrichment of incompatible trace elements; negative Nb-Ta anomalies; ε_{Nd} ~-1 to -4.5	Moderately contaminated more primitive magmas
Lower series	Gudchikhin	Lavas and tuffs of alkali picrite	Basalt (SiO_2 = 49-52%; MgO = 5.5-9%); picrite (SiO_2 = 46-51%; MgO = 10-21%). Moderate enrichment of incompatible trace elements; no Nb-Ta anomalies; ε_{Nd} ~-2 to +4.6	Relatively uncontaminated moderate-degree mantle melts
	Syvermin, Ivakin	Lavas and tuffs of alkali trachybasalt and basalt	Variable compositions (SiO_2 = 47-55%; MgO = 2.8-7.5%). Variable enrichment of incompatible trace elements; variable Nb-Ta anomalies; ε_{Nd} ~0 to -4.	Relatively uncontaminated low-degree mantle melts


(a)
27°E
31°S
32°S
33°S
26°E
28°E
Flood basalts
Study area
Nonesi's Neck
Queenstown
East London
Legend
Quaternary Deposits
Drakensberg Basalt
Dolerite
Clarens Formation
Elliot Formation
Moleno Formation
Burgersdorp Fm
Katberg Formation
Adelaide Subgroup
Tarkastad Subgroup
Beaufort Group
Karoo Supergroup
(b)
Vigrid Syncline
Utgard High 6607/5-2
4
9
5
3
5
(s)
10 km
Sill
Top Vent

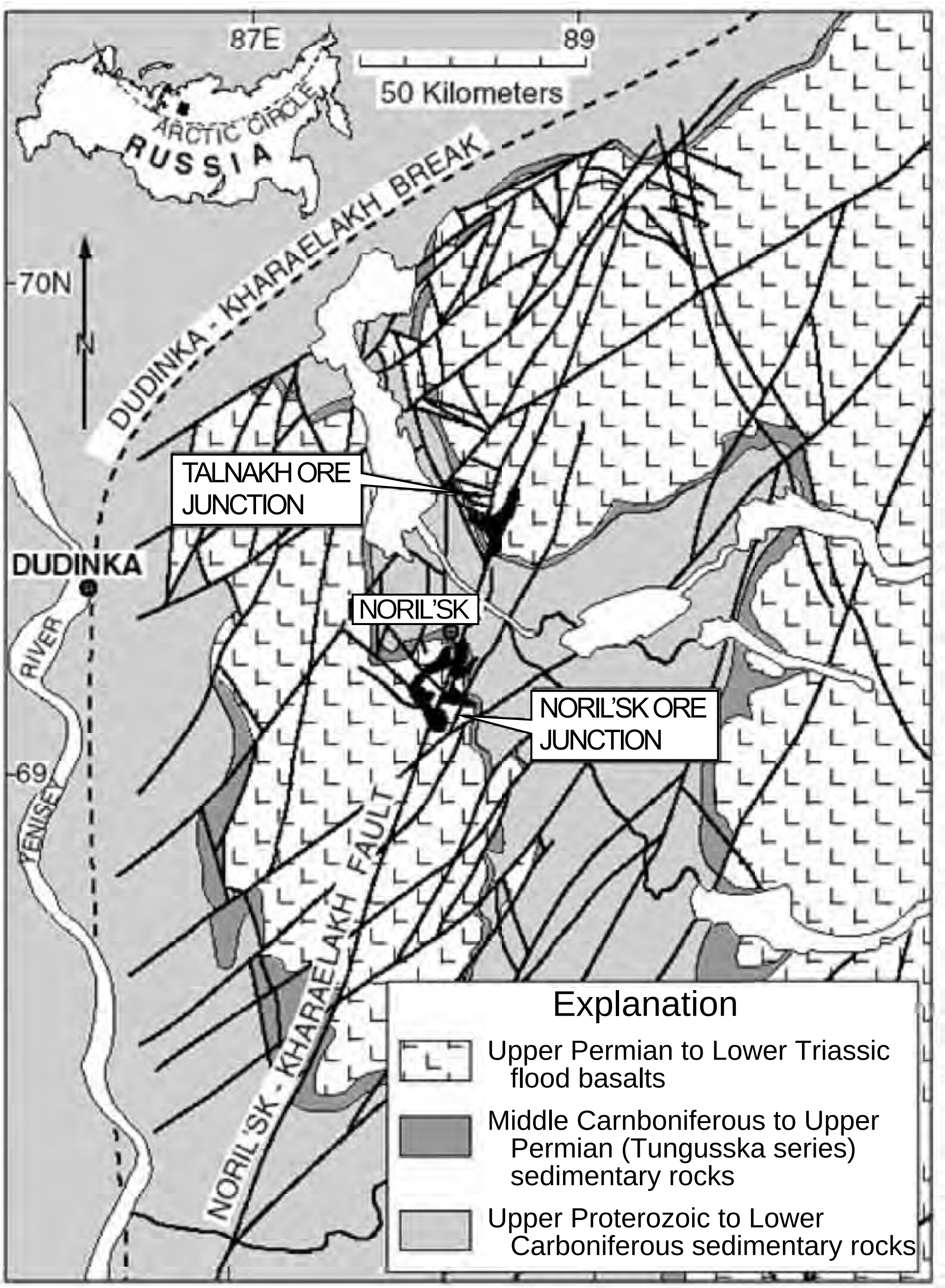

87E
89
50 Kilometers
ARCTIC CIRCLE
RUSSIA
DUDINKA - KHARAELAKH BREAK
70N
N
TALNAKH ORE JUNCTION
DUDINKA
NORIL'SK
NORIL'SK ORE JUNCTION
69
YENISEY RIVER
NORIL'SK - KHARAELAKH FAULT
Explanation
Upper Permian to Lower Triassic flood basalts
Middle Carnboniferous to Upper Permian (Tungusska series) sedimentary rocks
Upper Proterozoic to Lower Carboniferous sedimentary rocks

Fig 2

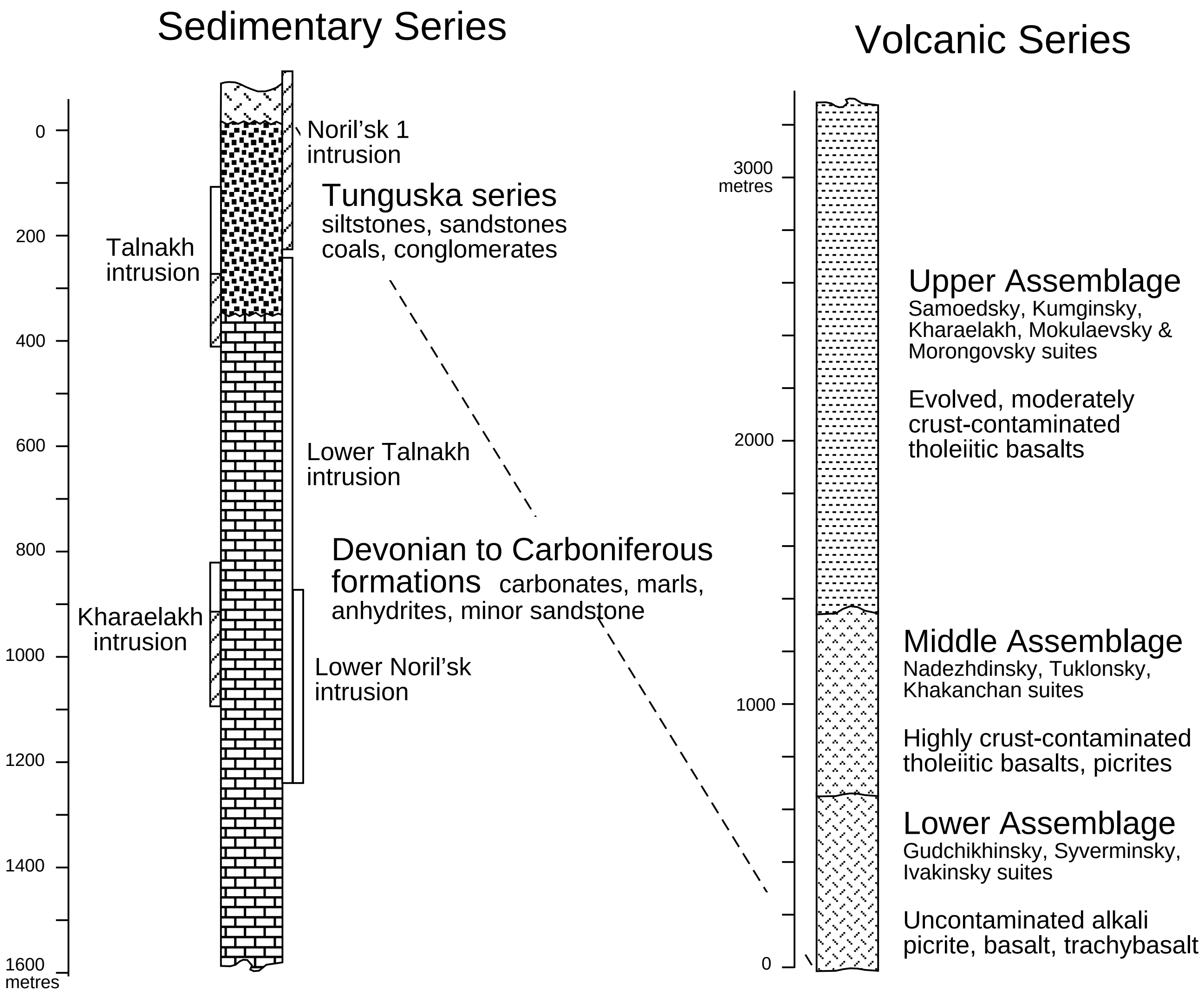

Sedimentary Series
Volcanic Series
0
200
400
600
800
1000
1200
1400
1600
metres
Noril'sk 1
intrusion
Tunguska series
siltstones, sandstones
coals, conglomerates
Talnakh
intrusion
Lower Talnakh
intrusion
Devonian to Carboniferous
formations carbonates, marls,
anhydrites, minor sandstone
Kharaelakh
intrusion
Lower Noril'sk
intrusion
3000
metres
2000
1000
0
Upper Assemblage
Samoedsky, Kumginsky,
Kharaelakh, Mokulaevsky &
Morongovsky suites
Evolved, moderately
crust-contaminated
tholeiitic basalts
Middle Assemblage
Nadezhdinsky, Tuklonsky,
Khakanchan suites
Highly crust-contaminated
tholeiitic basalts, picrites
Lower Assemblage
Gudchikhinsky, Syverminsky,
Ivakinsky suites
Uncontaminated alkali
picrite, basalt, trachybasalt

Fig 3

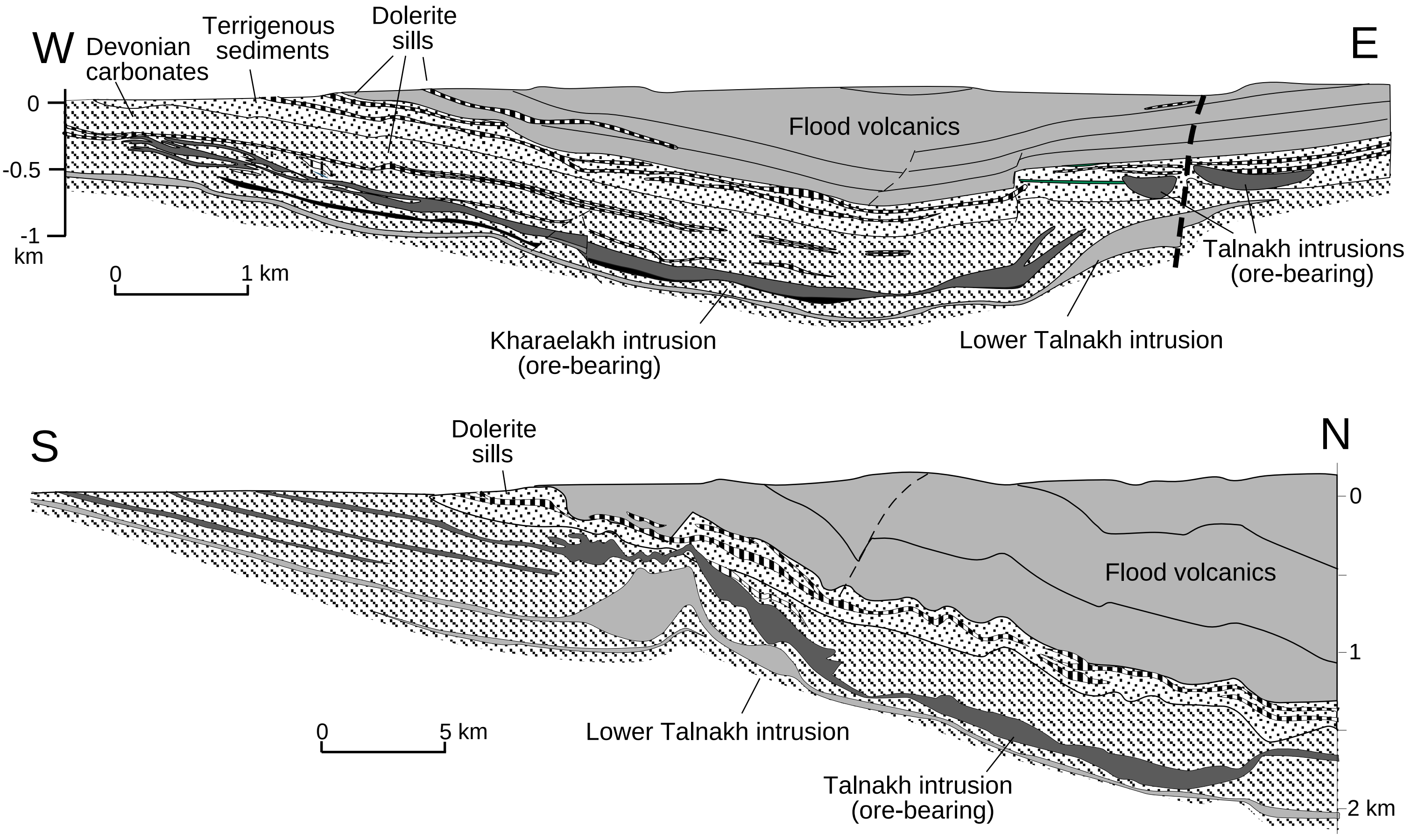

W
Devonian carbonates
Terrigenous sediments
Dolerite sills
E
0
-0.5
-1
km
Flood volcanics
0
1 km
Talnakh intrusions (ore-bearing)
Kharaelakh intrusion (ore-bearing)
Lower Talnakh intrusion
S
Dolerite sills
N
0
Flood volcanics
1
2 km
0
5 km
Lower Talnakh intrusion
Talnakh intrusion (ore-bearing)

Fig 4

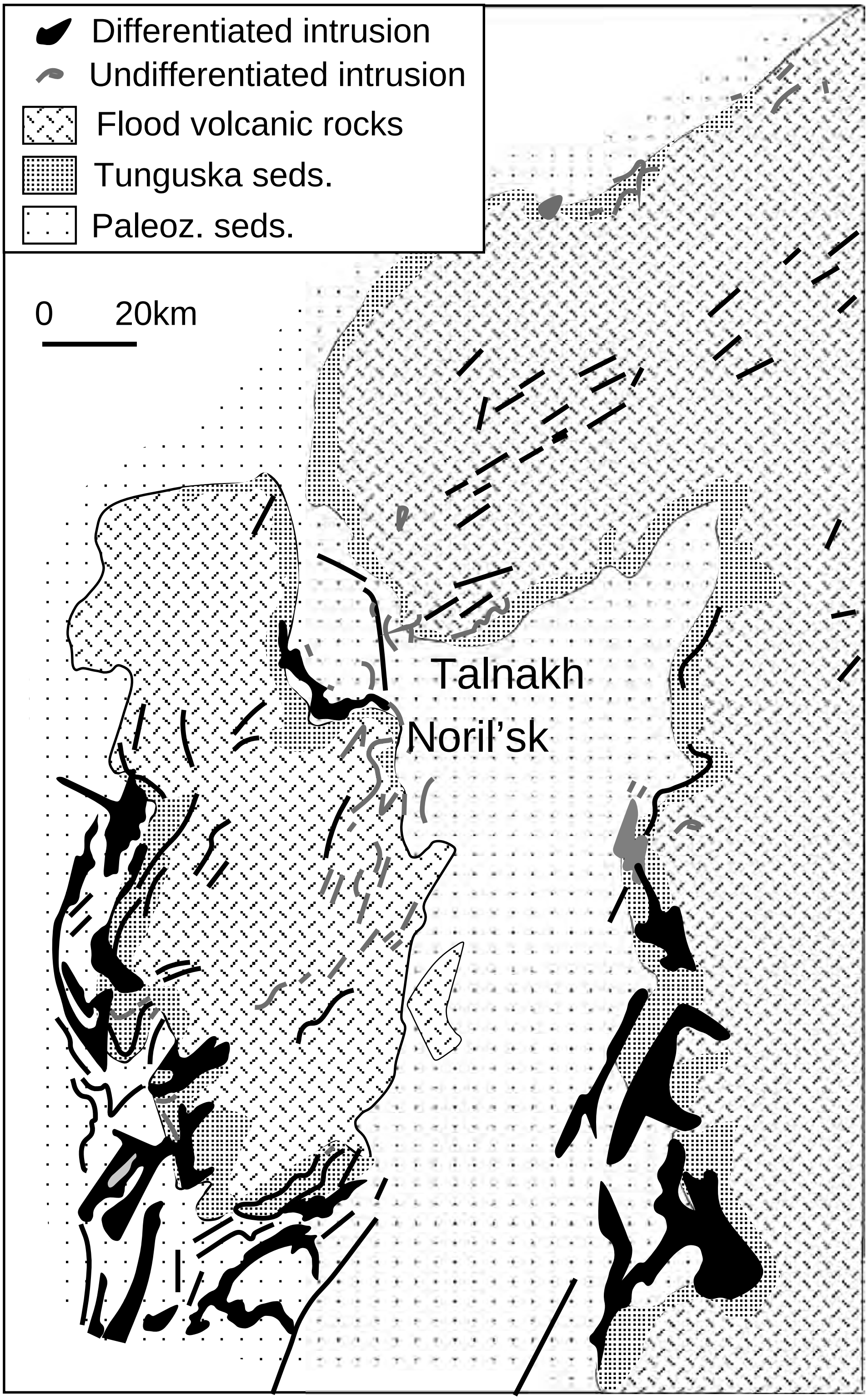

Differentiated intrusion
Undifferentiated intrusion
Flood volcanic rocks
Tunguska seds.
Paleoz. seds.
0
20km
Talnakh
Noril'sk

Fig 5

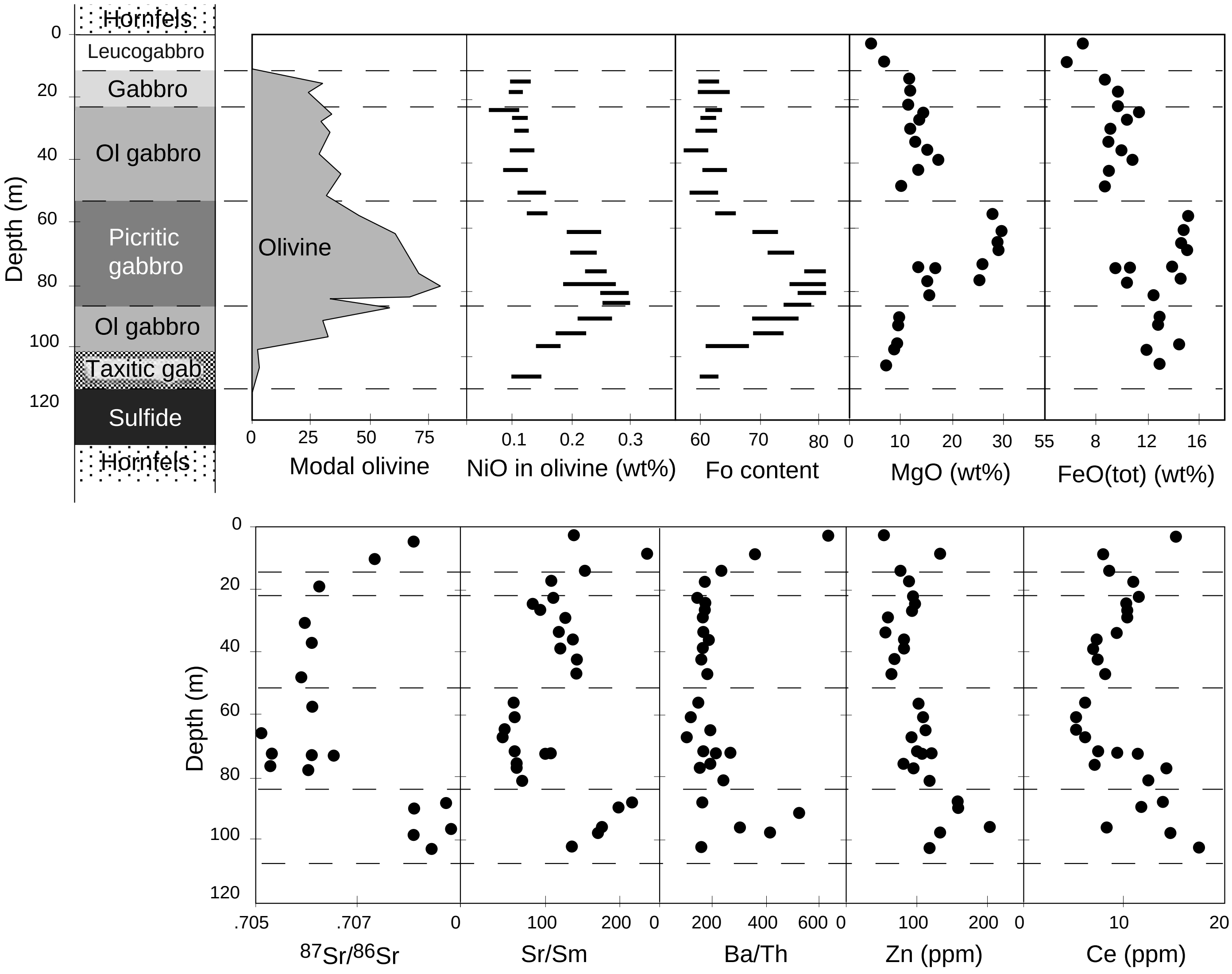

Hornfels
Leucogabbro
Gabbro
Ol gabbro
Picritic gabbro
Ol gabbro
Taxitic gab
Sulfide
Hornfels
Depth (m)
0
20
40
60
80
100
120
Olivine
0
25
50
75
Modal olivine
0.1
0.2
0.3
NiO in olivine (wt%)
60
70
80
Fo content
0
10
20
30
MgO (wt%)
55
8
12
16
FeO(tot) (wt%)
Depth (m)
0
20
40
60
80
100
120
.705
.707
0
$^{87}Sr/^{86}Sr$
100
200
Sr/Sm
0
200
400
600
Ba/Th
0
100
200
Zn (ppm)
0
10
20
Ce (ppm)

Fig 6

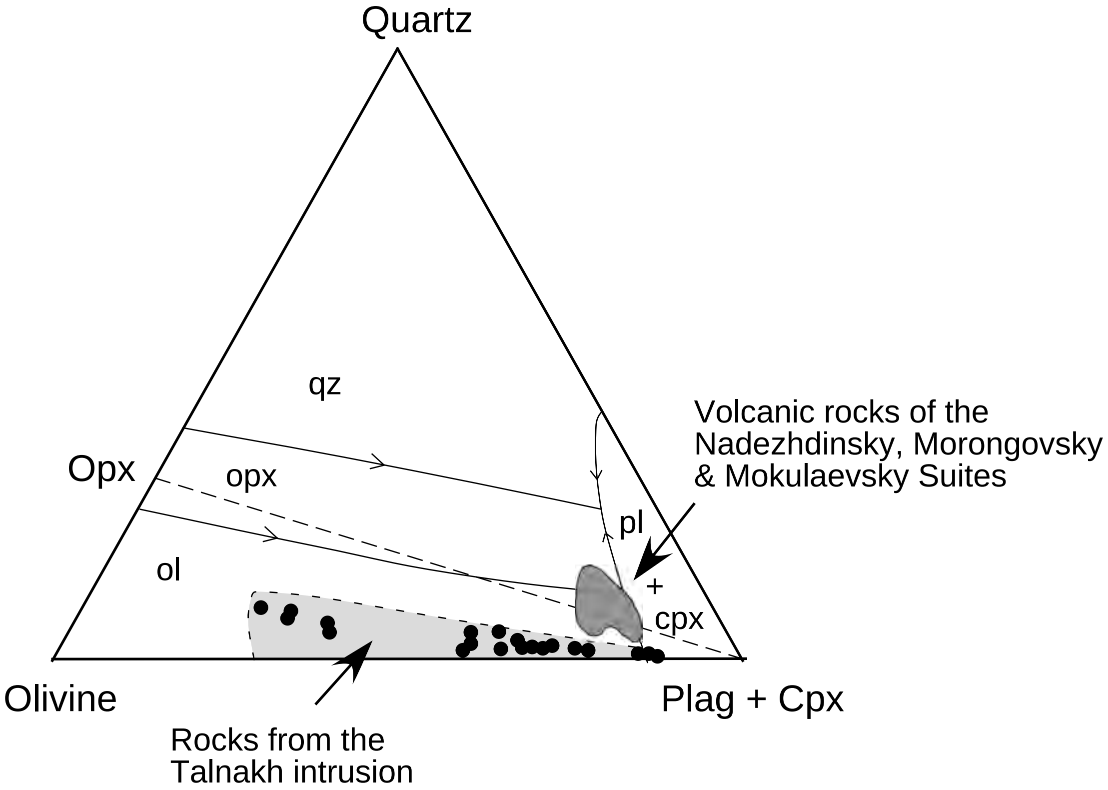

Quartz
qz
Volcanic rocks of the
Nadezhdinsky, Morongovsky
& Mokulaevsky Suites
Opx
opx
pl
ol
+
cpx
Olivine
Plag + Cpx
Rocks from the
Talnakh intrusion

Fig 7

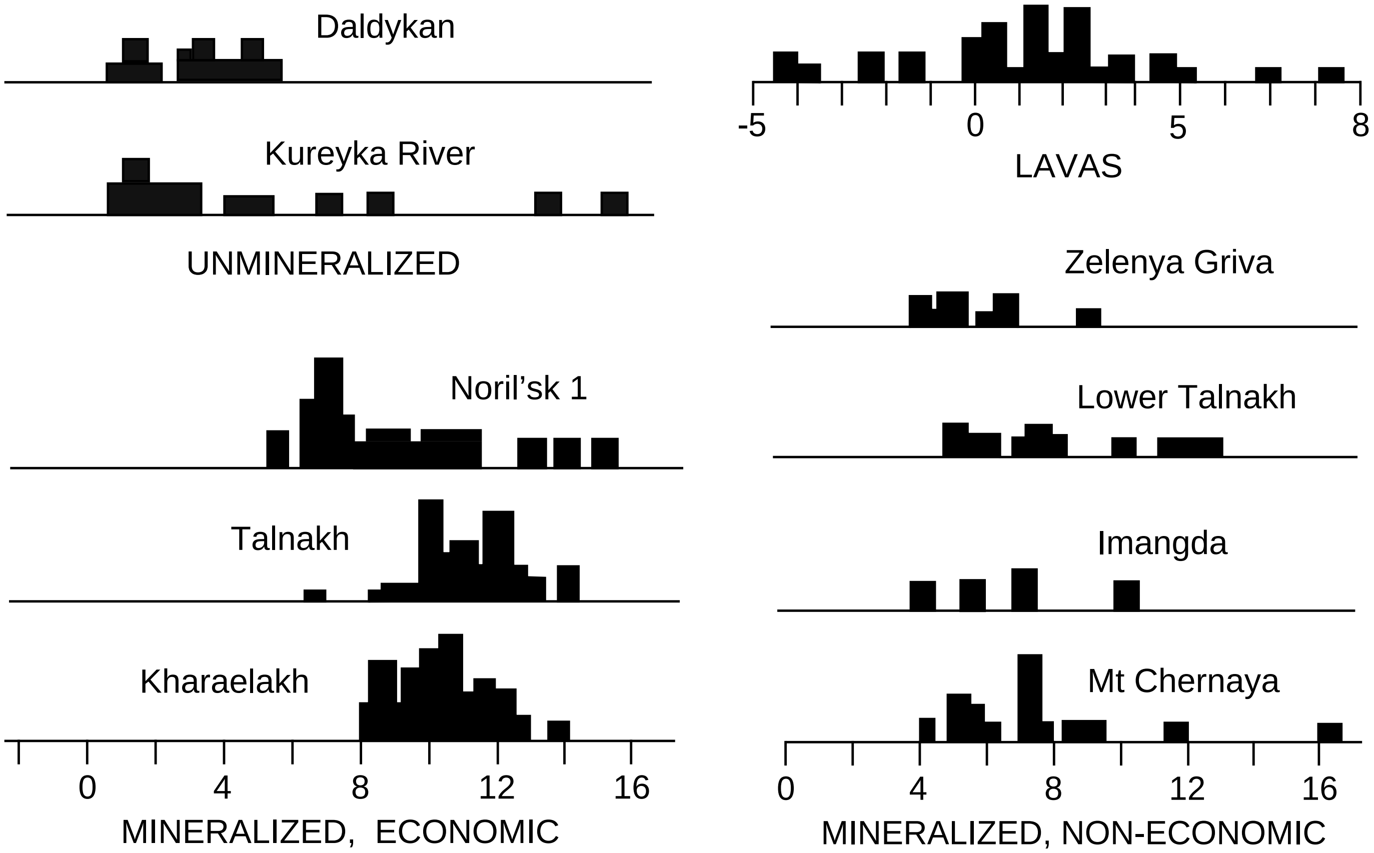

Daldykan
Kureyka River
UNMINERALIZED
Noril'sk 1
Talnakh
Kharaelakh
0
4
8
12
16
MINERALIZED, ECONOMIC
-5
0
5
8
LAVAS
Zelenya Griva
Lower Talnakh
Imangda
Mt Chernaya
0
4
8
12
16
MINERALIZED, NON-ECONOMIC

Fig 8

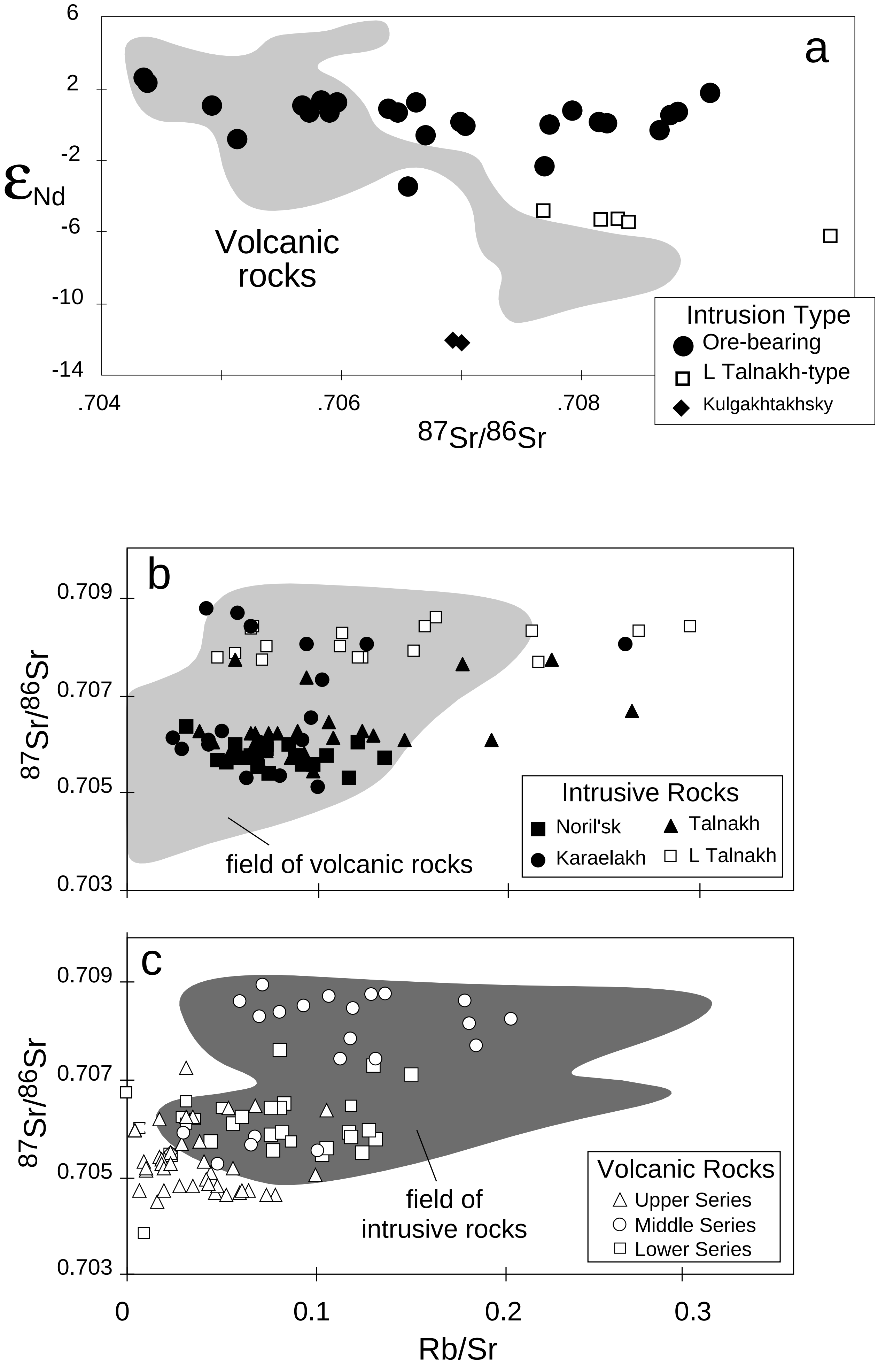

a
6
2
-2
-6
-10
-14
εNd
.704
.706
.708
87Sr/86Sr
Volcanic rocks
Intrusion Type
Ore-bearing
L Talnakh-type
Kulgakhtakhsky
b
0.709
0.707
0.705
0.703
87Sr/86Sr
field of volcanic rocks
Intrusive Rocks
Noril'sk
Talnakh
Karaelakh
L Talnakh
c
0.709
0.707
0.705
0.703
87Sr/86Sr
field of intrusive rocks
Volcanic Rocks
Upper Series
Middle Series
Lower Series
0
0.1
0.2
0.3
Rb/Sr

Fig 9

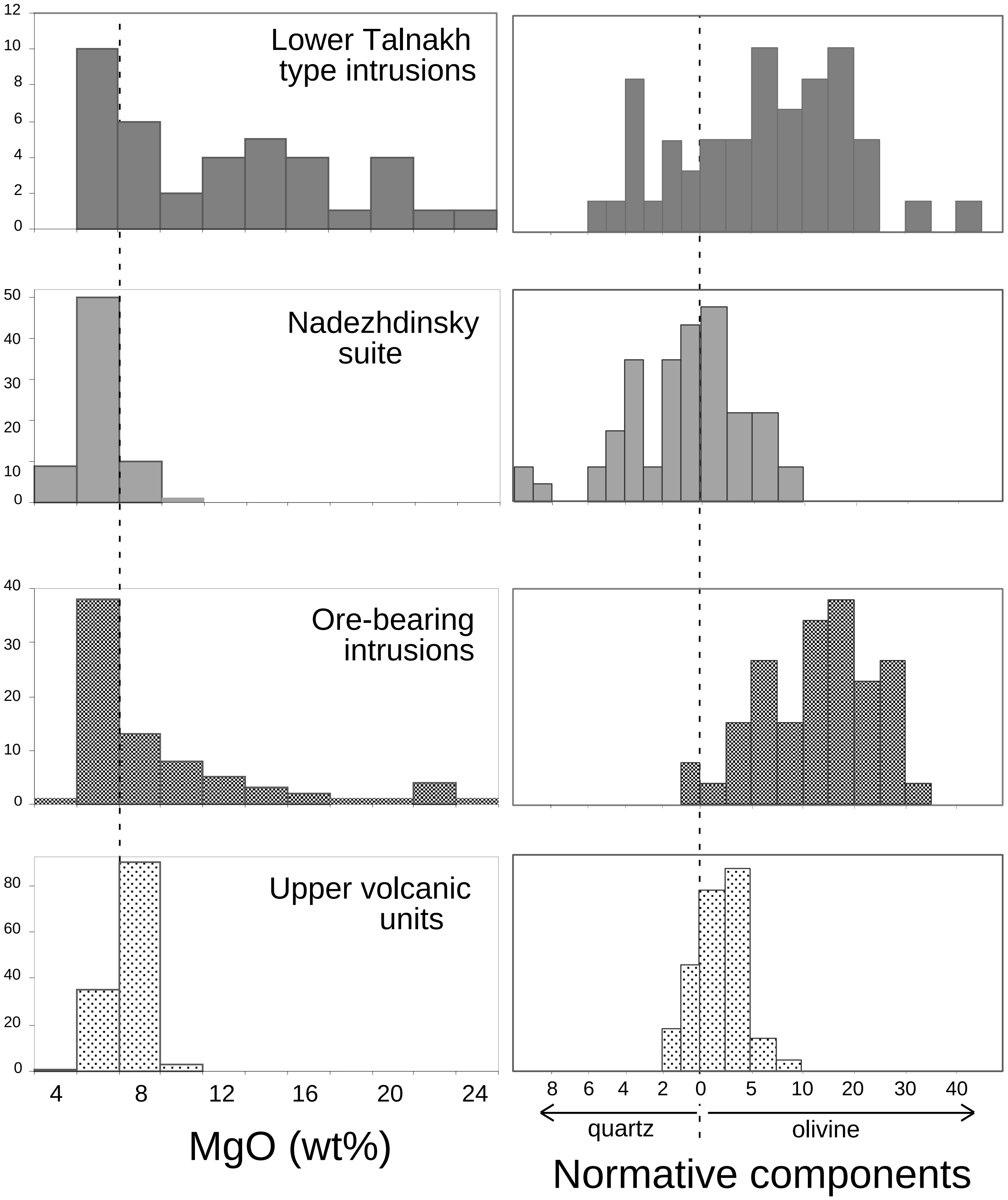

Lower Talnakh type intrusions
Nadezhdinsky suite
Ore-bearing intrusions
Upper volcanic units
12
10
8
6
4
2
0
50
40
30
20
10
0
40
30
20
10
0
80
60
40
20
0
4
8
12
16
20
24
MgO (wt%)
8
6
4
2
0
5
10
20
30
40
quartz
olivine
Normative components

Fig 10

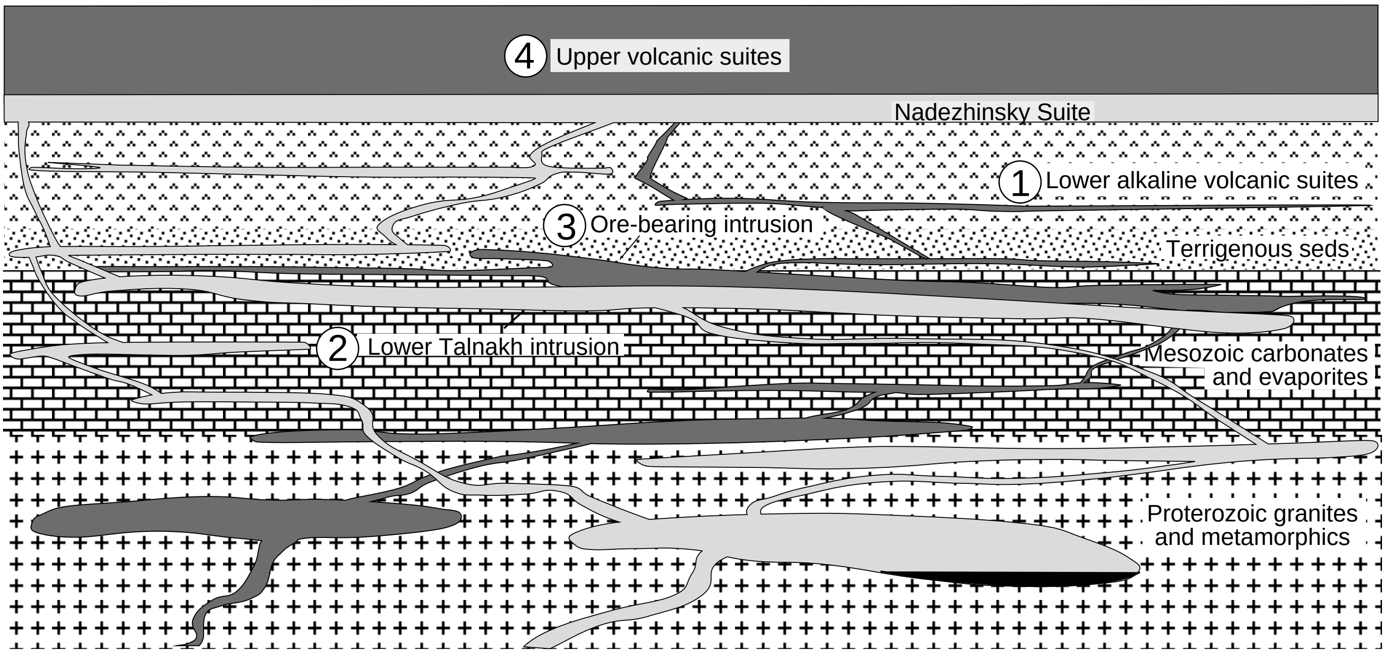

④ Upper volcanic suites
Nadezhinsky Suite
① Lower alkaline volcanic suites
③ Ore-bearing intrusion
Terrigenous seds
② Lower Talnakh intrusion
Mesozoic carbonates and evaporites
Proterozoic granites and metamorphics

Fig 11

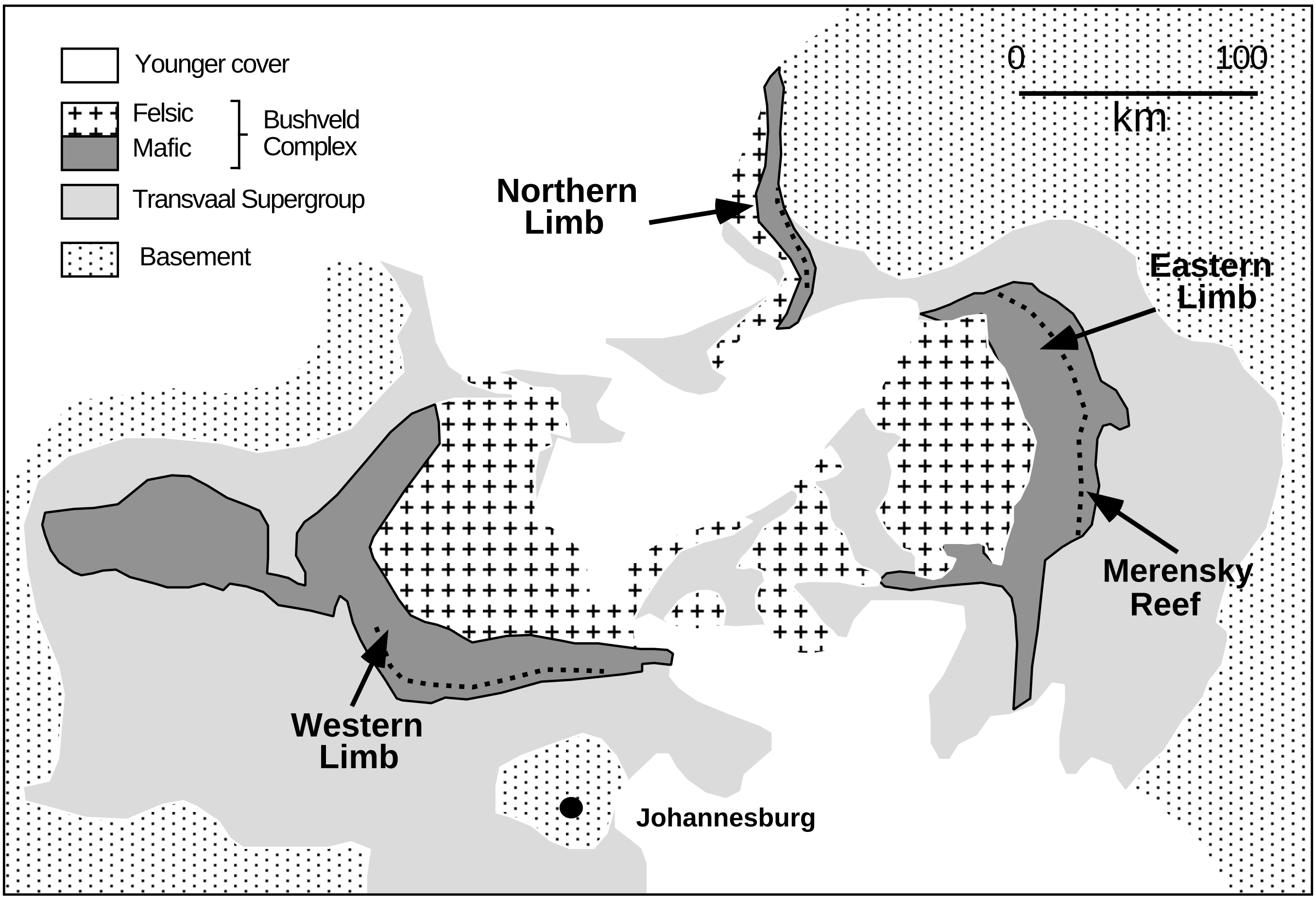

Younger cover
Felsic
Mafic
Bushveld Complex
Transvaal Supergroup
Basement
0
100
km
Northern Limb
Eastern Limb
Merensky Reef
Western Limb
Johannesburg

Fig 12

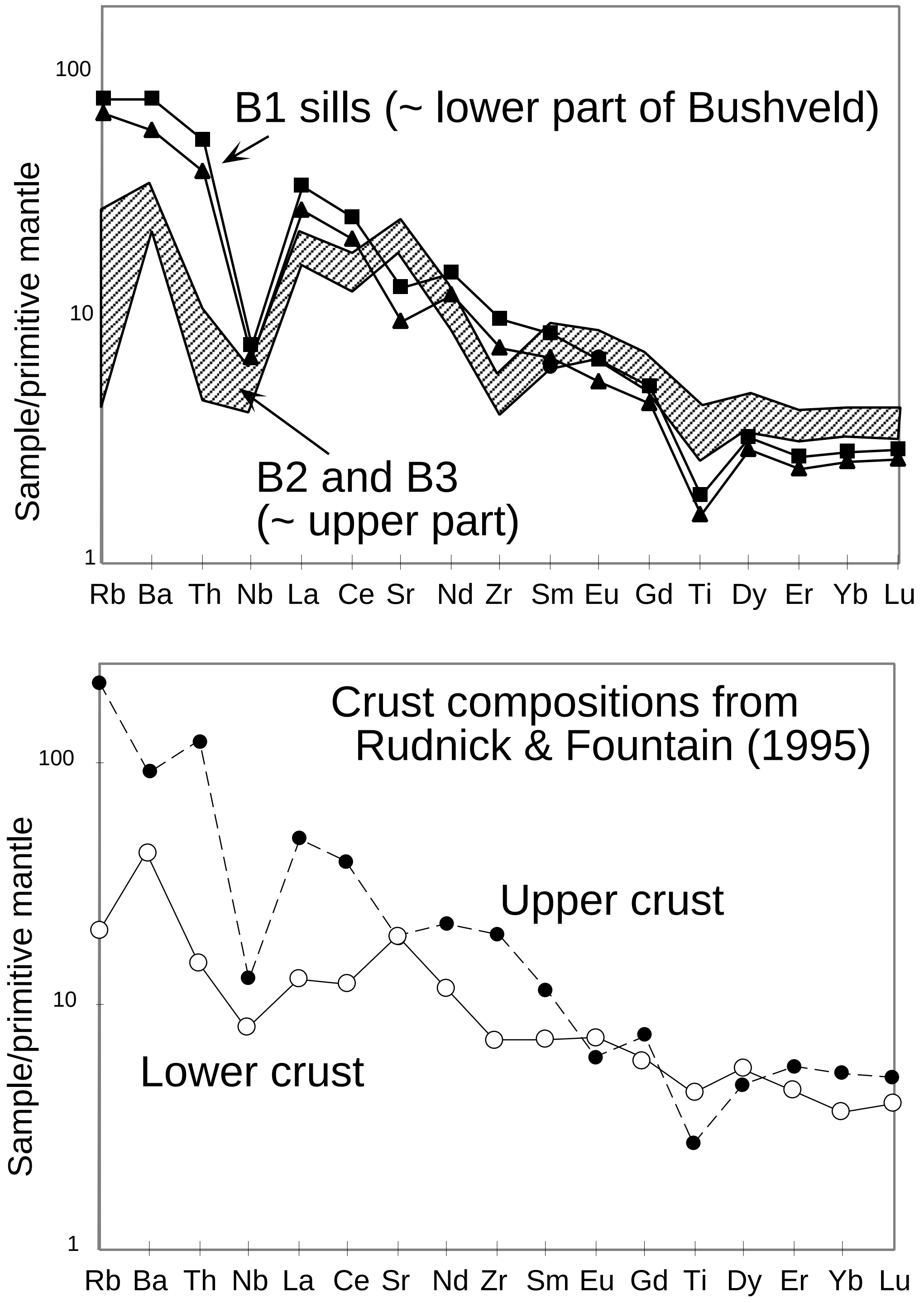

100
10
1
Sample/primitive mantle
B1 sills (~ lower part of Bushveld)
B2 and B3
(~ upper part)
Rb Ba Th Nb La Ce Sr Nd Zr Sm Eu Gd Ti Dy Er Yb Lu
100
10
1
Sample/primitive mantle
Crust compositions from
Rudnick & Fountain (1995)
Upper crust
Lower crust
Rb Ba Th Nb La Ce Sr Nd Zr Sm Eu Gd Ti Dy Er Yb Lu

Fig 13

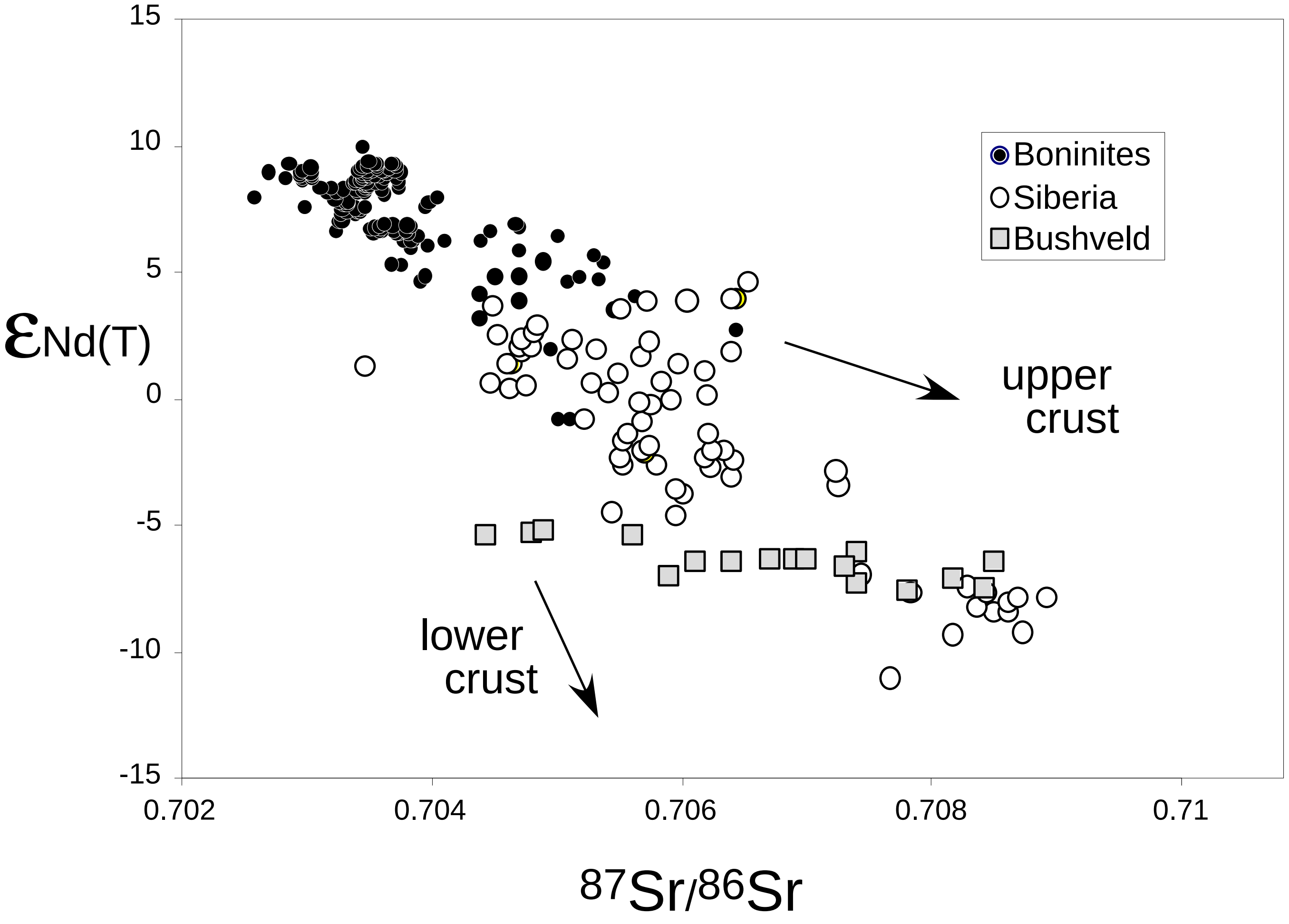

15
10
5
0
-5
-10
-15
εNd(T)
0.702
0.704
0.706
0.708
0.71
87Sr/86Sr
● Boninites
○ Siberia
▨ Bushveld
upper crust
lower crust

Fig 14