Mineralium Deposita (2004) 39: 125–142
DOI 10.1007/s00126-003-0373-0

ARTICLE

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Noril'sk–Talnakh Cu–Ni–PGE deposits: a revised tectonic model

Received: 19 June 2002 / Accepted: 3 June 2003 / Published online: 25 November 2003

Abstract The Noril'sk mining district is located at the northwest margin of the Tunguska basin, in the centre of the 3,000×4,000 km Siberian continental flood basalt (CFB) province. This CFB province was formed at the Permo-Triassic boundary from a superplume that ascended into the geometric centre of the Laurasian continent, which was surrounded by subducting slabs of oceanic crust. We suggest that these slabs could have reached the core–mantle boundary, and they may have controlled the geometric focus of the superplume. The resulting voluminous magma intruded and erupted in continental rifts and related extensive flood basalt events over a 2–4 Ma period. Cu–Ni–PGE sulfide mineralization is found in olivine-bearing differentiated mafic intrusions beneath the flood basalts at the northwestern margin of the Siberian craton and also in the Taimyr Peninsula, some 300 km east of a triple junction of continental rifts, now buried beneath the Mesozoic–Cenozoic sedimentary basin of western Siberia. The Noril'sk-I and Talnakh-Oktyabr'sky deposits occur in the Noril'sk–Kharaelakh trough of the Tunguska CFB basin. The Cu–Ni–PGE-bearing mineralized intrusions are 2–3 km-wide and 20 km-long differentiated chonoliths. Previous studies suggested that parts of the magma remained in intermediate-level crustal chambers where sulfide saturation and accumulation took place before emplacement. The 5–7-km-thick Neoproterozoic to Palaeozoic country rocks, containing sedimentary Cu mineralization and evaporites, may have contributed additional metal and sulfur to this magma. Classic tectonomagmatic models for these deposits proposed that subvertical crustal faults, such as the northeast-trending Noril'sk–Kharaelakh fault, were major trough-parallel conduits providing access for magmas to the final chambers. However, geological maps of the Noril'sk region show that the Noril'sk–Kharaelakh fault offsets the mineralization, which was deformed into folds and offset by related reverse faults, indicating compressional deformation after mineralization in the Late Triassic to Early Jurassic. In addition, most of the intrusions are sills, not dykes as should be expected if the vertical faults were major conduits. A revised tectonic model for the Noril'sk region takes into account the fold structure and sill morphology of the dominant intrusions, indicating a lateral rather than vertical emplacement direction for the magma into final chambers. Taking into account the fold structure of the country rocks, the present distribution of the differentiated intrusions hosting the Noril'sk-I and Talnakh–Oktyabr'sky deposits may represent the remnants of a single, > 60 km long, deformed and eroded palm-shaped cluster of mineralized intrusions, which are perceived as separate intrusions at the present erosional level. The original direction of sill emplacement may have been controlled by a northeast-trending paleo-rise, which we suggest is present at the southeastern border of the Noril'sk–Kharaelakh trough based on analysis of the unconformity at the base of the CFB. The mineralized intrusions extend along this rise, which we interpret as a structure that formed above the extensionally tilted block in the metamorphic basement. Geophysical data indicate the presence of an intermediate magma chamber that could be linked with the Talnakh intrusion. In turn, this T-shaped flat chamber may link with the Yenisei–Khatanga rift along the northwest-trending Pyasina transform fault, which may have served as the principal magma conduit to the intermediate chamber. It then produced the differentiated mineralized intrusions that melted through the

Editorial handling: P. Lightfoot

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evaporites with in situ precipitation of massive, disseminated, and copper sulfide ore. The Noril'sk–Kharaelakh crustal fault may not relate to mineralization and possibly formed in response to late Mesozoic spreading in the Arctic Ocean.

Keywords Noril'sk · Tectonics · Cu–Ni–PGE deposits · Superplume

Introduction

Noril'sk copper oxide ore may have been extracted by the Siberian Cossacks in the sixteenth to seventeenth centuries, but the first documented record on coal and copper mineralization in the Noril'sk district in northern Siberia was reported in 1866 by the Russian trader K.M. Sotnikov (Kunilov 1994). In 1915 his grandson staked the ground near to the future Noril'sk-I deposit and collected samples, which he passed to his friend N.N. Urvantsev who studied them at Tomsk University. Urvantsev identified nickel sulfides and recognized their similarity to the Sudbury ores. Due to the events of the 1917 Russian revolutions he managed to visit the area only in 1919 and discovered the Noril'sk-I sulfide-bearing intrusion. Subsequently, the economic Cu–Ni–PGE mineralization at Noril'sk was explored and developed during two episodes of state-funded exploration activity in the 1920–1930s and 1960–1970s (Kunilov 1994).

The Noril'sk–Talnakh group of deposits (Fig. 1) is one of the principal producers of copper, nickel and platinum group elements (PGE) in the world. In 2001, MMC Noril'sk Nickel, the company that mines these deposits, produced 20% of the world's Ni, $>10\%$ of Co, 3% of Cu, $\sim 60\%$ of Pd and 20% of Pt (Anonymous 2002). The deposits also have recoverable concentrations of Rh, Au, Te, Se, Ag and S. The published geological resource estimates for the massive sulfide ore vary from 555 Mt (Naldrett and Lightfoot 1994) to 1,500 Mt (see Diakov et al. 2002). These characteristics place the Noril'sk–Talnakh group of deposits alongside the world's largest and richest mining camps.

Several models for the Noril'sk–Talnakh deposits have been published in Russian and international publications since 1970. Tectonic aspects of the model were developed in the USSR in the 1970s after discovery of the giant Talnakh–Oktyabr'sky deposits (Sobolev 1978; Genkin et al. 1981; Zolotukhin et al. 1984, 1989; Duzhikov et al. 1992). They were further developed with excellent geological, geochemical and geophysical support in international publications, especially in the Proceedings of the Sudbury–Noril'sk symposium, a monograph edited by Lightfoot and Naldrett (1994). Despite some variations in details, these papers presented essentially similar models that can be collectively grouped as the "classic" model.

According to the classic model, the Cu–Ni–PGE mineralization is located in the Noril'sk–Kharaelakh trough (Genkin et al. 1981; Simonov et al. 1994), at the northwestern flank of the Tunguska flood basalt basin (Sobolev 1978; Lightfoot et al. 1990, 1993, 1994; Zolotukhin and Almukhamedov 1991; Duzhikov et al. 1992; Hawkesworth et al. 1995) (Fig. 2). The deposits are found in differentiated ultramafic–mafic intrusions (Fig. 3) located along the keels of local synclines, which are interpreted as deformational structures subdividing the original Noril'sk–Kharaelakh volcanogenic basin (Simonov et al. 1994), although some workers interpreted them as original volcano-tectonic depressions (Dodin et al. 2000; Diakov et al. 2002). However, the thickness of the related flood basalts (as published by Naldrett et al. 1992, Fedorenko 1994; Lightfoot et al. 1994) varies without any relation to the distribution of the synclines, and, therefore, the reconstructed tectonic pattern of the trough may be different to the observed structures.

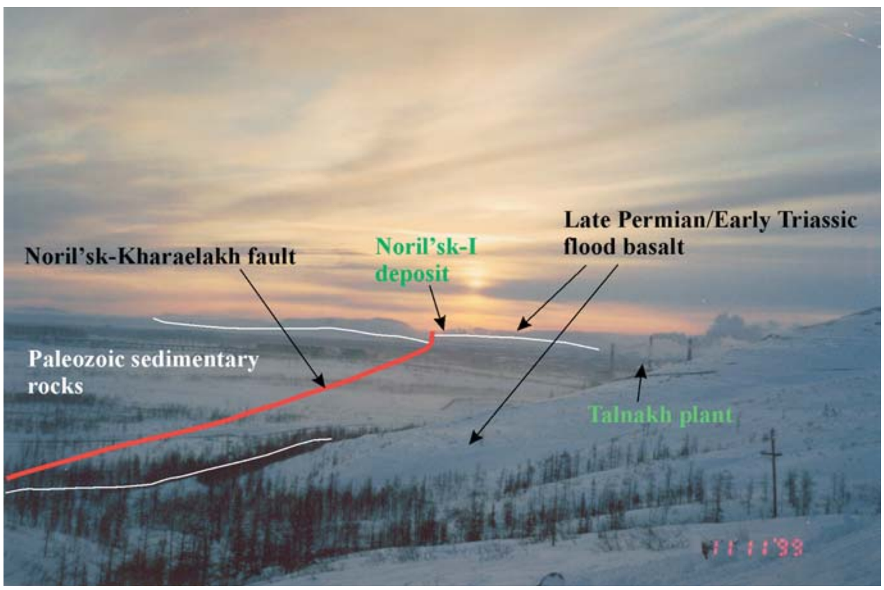


Fig. 1 Southwest-looking view from Talnakh across the Pyasina uplift to the Noril'sk-I deposit. The distance between the two deposits is approximately 20 km

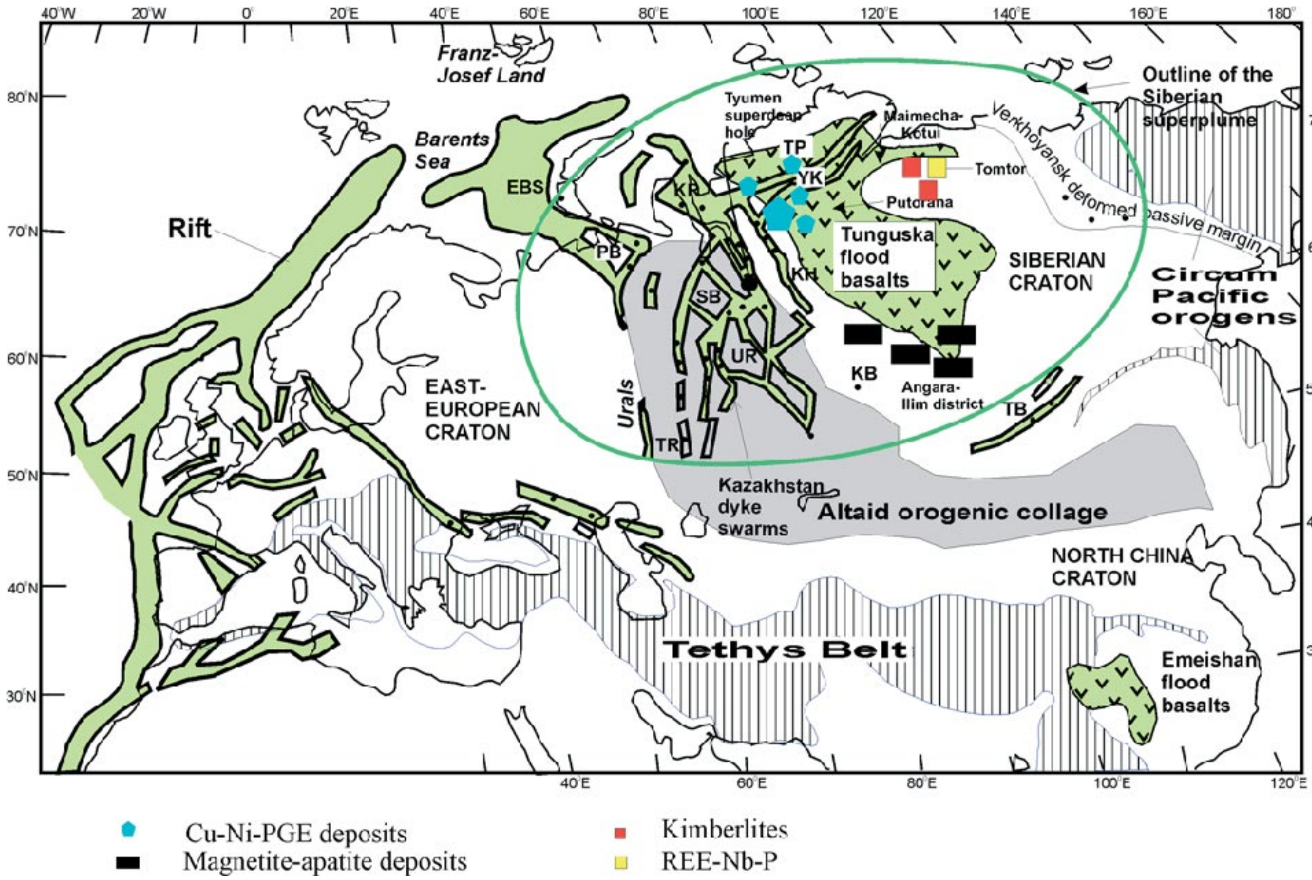


Fig. 2 Late Permian to Middle Triassic continental rifts, flood basalt basins (*in green*), and related mineral deposit types in the Siberian superplume province (modified after Nikishin et al. 2002). Mesozoic–Cenozoic sedimentary basins are not shown. *EBS* East Barents Sea rift system, *KH* Khudosei rift, *KR* South Kara rift, *SB* Surgut flood basalt, *TB* Transbaikal backarc rifts, *TR* Turgai rift, *UR* Urengoi rift, *YK* Yenisei–Khatanga rift; *KB* Kuznetsk flood basalt, *PB* Pechora flood basalt, *TP* Taimyr flood basalt

In the classic model, the Noril'sk–Kharaelakh trough hosts a 3,500-m-thick sequence of tholeiitic and subalkaline basalt and picrite lavas with tuffs. Although tholeiitic basalts are dominant, the presence of picritic basalts is believed to be an important factor for Cu–Ni–PGE mineralization (Simonov et al. 1994). The volcanic sequence of the Noril'sk–Kharaelakh trough can be subdivided into three assemblages (Fedorenko 1981). Variations in their chemical composition are interpreted to reflect melting associated with a deep mantle plume with differing contributions of asthenospheric and lithospheric material and continental crust at different stages (Lightfoot et al. 1990, 1993, 1994; Czamanske et al. 1994; Fedorenko 1994). These magmas produced the observed volcanic sequence and numerous sill-like intrusions; but picritic basalts are known only in the lower part of the volcanic assemblage. Due to high metal content, which is disproportionally large compared to the observed magma volume in the sills, the petrological studies suggested that portions of this magma remained in intermediate crustal-level magma chambers where separation into silicate and metal-rich sulfide liquids took place (Naldrett et al. 1992, 1998). The 5–7-km-thick Neoproterozoic–Palaeozoic country rocks, containing sedimentary Cu mineralization and evaporites (Dodin et al. 2000), may have contributed additional metal and sulfur to this magma (Lightfoot and Hawkesworth 1997).

Tectonic models for the Noril'sk-type deposits require that subvertical transcrustal faults, such as the Noril'sk–Kharaelakh fault, were major conduits, through which mineralized magma passed and entered into the final chambers (Sobolev 1978; Genkin et al. 1981; Duzhikov et al. 1992; Likhachev 1994; Simonov et al. 1994). This model is based largely on the apparent alignment of the Noril'sk, Talnakh and Talma deposits along the northeast-trending Noril'sk–Kharaelakh fault, but no steeply dipping magmatic feeders have been recorded within the fault zone or in any of the mines (Diakov et al. 2002). In contrast, geological maps of Noril'sk (Sherman 1991) show the dominance of sills, indicating that transcrustal faults were not major magma conduits. However, it was suggested (Duzhikov et al. 1992; Diakov et al. 2002) that the Noril'sk–Kharaelakh fault may still represent a feeder structure that was reactivated after magmatism (Diakov et al. 2002). Geological maps (Sherman 1991) show rotational kinematics on this fault, with the rotational centre in the core of the Pyasina uplift, between the Noril'sk-I and Talnakh–Oktyabr'sky

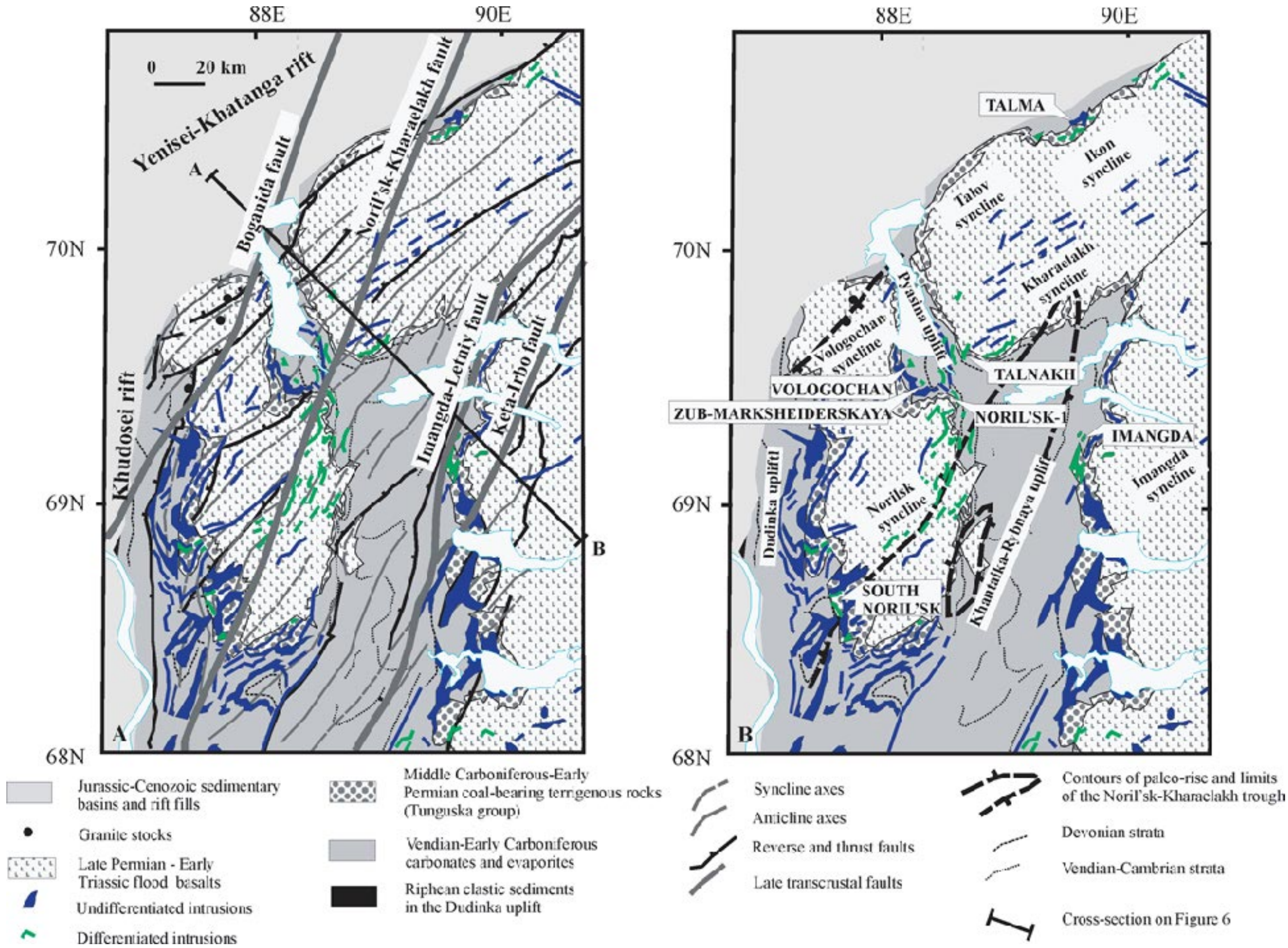


Fig. 3 Geologic map of the Noril'sk–Kharaelakh trough (compiled using Sherman 1991). **A** Post-mineralization compressional structures, **B** syn-mineralization pre-compressional structures

deposits. In addition, this and other subparallel faults, such as Boganida, Imangda–Letniya, and Keta–Irbo, offset not only the intrusions, but also the fold structures and related reverse faults. This indicates post-deformational movement along these faults, which has been interpreted as reactivation of the older faults (Diakov et al. 2002). The idea of reactivation is based on the general increase of the thicknesses and facies in Palaeozoic rocks of the Noril'sk–Kharaelakh trough in comparison with the adjacent parts of the Siberian craton (Milanovskiy 1996), but no evidence exists for early formation of the Noril'sk–Kharaelakh and other faults. In addition, the Noril'sk–Kharaelakh fault can be traced as far as the Arctic Ocean coast (Dodin et al. 2000), indicating its superimposed nature.

These inconsistencies require a refinement of the tectonic models for the Noril'sk district, to take into account the fold structure and the dominance of sills over dykes. We will also consider the regional tectonics of the Tunguska flood basalt basin and its continent-scale setting.

The Siberian superplume province

The term superplume was introduced by Larson (1991) to describe a Cretaceous igneous province of the Southwest Pacific, much larger than other plume provinces, which normally have diametres of 1,000–2,000 km (White and McKenzie 1989). Dobretsov (1997), Nikishin and Ziegler (1999), Dobretsov and Vernikovsky (2001) and Nikishin et al. (2002) described the Tunguska continental flood basalt basin and related rift systems as part of a Siberian superplume province. This province extends from the Polar Urals in the west to the Verkhoyansk fold belt in the east and from the Taimyr Peninsula in the north to central Kazakhstan in the south, thus encompassing a 3,000×4,000 km area (Fig. 2). The province includes the Tunguska, Taimyr, Kuznetsk and Pechora continental flood basalt basins (Lozovskiy and Esaulova 1998), the West Siberian continental rift system, volcanic rocks of the Verkhoyansk belt (Yapaskurt 1992; Kazakov 1995), and dyke swarms of Kazakhstan, all of which have similar ages (Nikishin et al. 2002).

Lightfoot et al. (1990), Naldrett et al. (1992), Schissel and Smail (2001) and Diakov et al. (2002) suggested that the Noril'sk mineral district and its flood basalts occur near a triple junction of continental rifts, now largely buried under the Mesozoic–Cenozoic sedimentary basin of West Siberia, but easily identifiable using magnetic data (Surkov and Zhero 1981; Zonenshain et al. 1990; Surkov 1995; Schissel and Smail 2001; Diakov et al. 2002). Rifting and continental flood basalt magmatism on the rift flanks were synchronous.

The West Siberian Permo-Triassic rift system is inferred from geophysical data. It is superimposed onto the Altaid orogenic collage, otherwise known as the Ural–Mongolian fold belt (Surkov and Zhero 1981; Surkov 1995; Nikishin et al. 2002). This rift system has several branches, e.g. Turgai, Urengoi and Khudosei in the south, South Kara in the north, and Yenisei–Khatanga in the northeast (Fig. 2). The Turgai and Urengoi rifts form the southern, largest branch of the rift system (Surkov and Zhero 1981; Kontorovich 1994; Surkov 1995). The Tyumen superdeep hole, drilled in the Urengoi rift (Fig. 2), reached Permo-Triassic basalt at a depth of 7,502 m (Khakhaev and Kaplun 1995). The submerged Surgut flood basalt plateau on the western flank of the rift (Fig. 2) may have formed synchronously with this rifting (Surkov 1995). The southwestern flank of this structure is exposed in the southern Urals. Drillholes in the Turgai depression intersected Early Triassic grabens. The Khudosei rift, also hosting Permo-Triassic volcanic rocks, extends along the western flanks of the Siberian craton (Surkov 1995).

The South Kara rift, forming the northern branch of the rift system, is totally buried under more than 8 km of Mesozoic–Cenozoic sedimentary rocks (Shipilov and Tarasov 1998). Seismic data indicate that the main rifting phase took place at the Permo-Triassic boundary, and the continental crust was significantly stretched (Bogdanov et al. 1998; Shipilov and Tarasov 1998).

The Yenisei–Khatanga rift, forming an eastern branch of the triple junction, occurs between the Siberian craton and the Early Mesozoic Taimyr orogen. Its identification as a rift is largely based on its linear extent and the elevated thickness, up to 2.5 km, of Permo-Triassic basalts in its axial part compared to the adjacent Tunguska and Taimyr flood basalts, according to the seismic data (Bogdanov et al. 1998).

The age of the plume magmatism in the different parts of the Siberian province is constrained by a variety of methods. In the Pechora, Taimyr and Kuznetsk basins paleontological data indicate that volcanism started at the very end of the Permian and terminated in the Early Triassic (Olenekian) (Lozovskiy and Esaulova 1998). An $^{40}Ar/^{39}Ar$ age of 245.5 ± 1.2 Ma was reported for biotite from a meimechite flow in the Meimecha–Kotui area (Czamanske et al. 1993). A U–Pb zircon age of 248 ± 4 Ma was obtained for the Tunguska flood basalt (Campbell et al. 1992; Renne et al. 1995). Magneto-stratigraphic studies indicate that there was only one magnetic inversion during magmatism, suggesting that its duration was less than 1 Ma, although other evidence indicates that it has continued for as much as 2–4 Ma (Westphal et al. 1997; Courtillot et al. 1999).

Sedimentary rocks accumulated after the Middle Triassic, indicating that post-rift subsidence replaced rifting (Nikishin et al. 2002). Cretaceous flood basalts are known in Franz-Josef Land, far to the northwest of the Siberian province. They can be linked with the presently active North Atlantic plume province. Some geologists suggest that they were connected with the Siberian superplume province (Shipilov and Tarasov 1998), but there is a significant time gap with no plume magmatism in the Middle Triassic to Jurassic. This break with the presently active hotspots indicates that the Siberian superplume was a voluminous, but short-lived magmatic event at the Permo-Triassic boundary (Nikishin et al. 2002; Nikishin and Yakubchuk 2002).

Tunguska flood basalt basin

Regional tectonics

Permo-Triassic flood basalts are exposed along the southern (Tunguska basin) and northern (Taimyr) flanks of the Yenisei–Khatanga rift. In the south of the Taimyr orogen these basalts are deformed into linear folds thrust southward together with overlying Middle–Late Triassic and underlying Ordovician–Permian sedimentary rocks. The latter sequence is very similar to that exposed in the Siberian craton under the Tunguska flood basalts, but distinct from the northern zones of the Taimyr orogen (Milanovskiy 1996). Geological maps (Sherman 1991) show that the Permo-Triassic volcanic rocks of the Noril'sk–Kharaelakh trough are also compressionally deformed, but not as intensely as in the Taimyr orogen. Seismic data (Bogdanov et al. 1998) show folded Permo-Triassic basalts in the Yenisei–Khatanga trough. The lithological similarity and style of deformation suggest that the southern zones of the Taimyr orogen represent a strongly deformed margin of the Siberian craton. Jurassic clastic sedimentary rocks overlap unconformably these deformed sequences and, therefore, indicate the Late Triassic age of the compressional deformation (Milanovskiy 1996). The Jurassic sedimentary rocks of the Yenisei–Khatanga trough show low angle folds, which are also unconformably overlapped by undeformed Cretaceous sediments (Milanovskiy 1996). Therefore, the structural style of the Yenisei–Khatanga branch is very different to the other two branches of the West Siberian rift system (Bogdanov et al. 1998), which remained undeformed (Surkov 1995; Nikishin et al. 2002). The deformations of the Yenisei–Khatanga rift could be explained through the northward movement of Siberia towards Taimyr in the end of the Triassic, which was subparallel with the orientation of the West Siberian rift branches and, therefore, did not deform them. On this basis the Yenisei–Khatanga trough can be interpreted as a failed rift, which was transformed into a foredeep-like structure in front of the Taimyr orogen after the major deformational event in the Late Triassic.

Internal structure

The Tunguska flood basalt basin constitutes the world's largest continental flood basalt basin (Fig. 2), extending over 675,000 km^2 with a preserved volume of mafic rocks in excess of 2 million km^3 (Milanovskiy 1996). The central part of the basin consists mainly of basalts, whereas tuffs dominate on the periphery (Zolotukhin and Almukhamedov 1991). The thickness of the volcanic sequences varies from hundreds of metres on the periphery to 2–2.4 km on the Putorana plateau, 3 km in the Noril'sk–Kharaelakh trough, and 3.5 km in the Meimecha–Kotui region (Zolotukhin and Almukhamedov 1991; Milanovskiy 1996). This maximum thickness is based on seismic data (Rempel 1994). The composition of the volcanic rocks changes from tholeiitic basalts in the largest part of the basin in the southeast (Zolotukhin and Almukhamedov 1991) to dominantly high-MgO alkalic and picritic lavas in the Meimecha–Kotui area (Arndt et al. 1995), and picrites, subalkaline and tholeiitic basalts in the Noril'sk–Kharaelakh trough (Lightfoot et al. 1994).

The dominant form of the intrusions is sill-like. They tend to intrude the underlying Palaeozoic sedimentary rocks, but rarely penetrate into the flood basalt sequence. The most voluminous intrusions occur on the northern and northwestern periphery of the Siberian craton, but they also occur in large areas in its southeastern part where there is a deeper level of erosion. Kimberlites, commonly diamondiferous, reveal a wide age spectrum ranging from Ordovician to Cretaceous. Middle Triassic kimberlites are known in the river Kotui region, located almost 1,000 km to the east from the Noril'sk–Kharaelakh trough, at the eastern flank of the Tunguska flood basalt basin (Milanovskiy 1996). One of the world's largest REE deposits, the Tomtor carbonatite deposit (Fig. 2), also relates to this magmatic event (Khain and Kravchenko 1999). At the western and southern periphery of the Tunguska basin are Early Triassic magnetite-bearing explosive pipes and related Fe-skarn bodies (Fig. 2) of the Angara–Ilim district (Milanovskiy 1996), some of them are producing mines (Yakubchuk et al. 2002). Geochemical data indicate that this magmatism originated from a mantle plume with some contamination and melting of the lower lithosphere (Lightfoot et al. 1990, 1993, 1994; Hawkesworth et al. 1995).

Noril'sk–Kharaelakh trough

The Noril'sk–Kharaelakh trough occurs on the northwestern flank of the Tunguska basin (Fig. 3 a, b). The trough contains most of the Cu–Ni–PGE sulfide mineralization, but similar occurrences, which will not be considered here, are also known at Imangda to the southeast.

Structure

The West Siberian sedimentary basin and the Yenisei–Khatanga rift bound the Noril'sk–Kharaelakh trough to the west and north respectively. To the southeast is the Khantaika–Rybnaya uplift. The trough is filled with tholeiitic basalts and subordinate picrites (Fedorenko 1994; Lightfoot et al. 1994).

Within the trough from west to east are the Dudinka uplift, the Noril'sk and Vologochan synclines, the Pyasina uplift, and the Talov and Kharaelakh synclines (Fig. 3b). The synclines are filled with Late Permian–Early Triassic basalts, whereas Palaeozoic sedimentary sequences and mafic–ultramafic sills are exposed in their periphery. The fold axes in synclines and anticlines as well as numerous reverse and thrust faults strike northeast (Sherman 1991), roughly parallel with the fold axes in the Taimyr orogen. This fold structure is intersected by the northeast-trending Boganida, Noril'sk–Kharaelakh, Imangda–Letniya and Keta–Irbo faults (Fig. 3a). Seismic data indicate that they are transcrustal faults (Rempel 1994). Regional geological data (Dodin et al. 2000) and geophysical maps (Schissel and Smail 2001) show that some of these faults can be traced as far as the Arctic shelf, for a total distance of 1,000 km. The relationships between these transcrustal faults and fold structures indicate that these faults were active after the Late Triassic deformations, possibly during Jurassic–Cretaceous time. They were most likely formed as a result of ocean-floor spreading in the Canadian basin of the Arctic Ocean, and may represent a continental continuation of transform faults.

Stratigraphy

The Noril'sk–Kharaelakh trough coincides with an 8–10-km-deep depression in the basement of the craton (Simonov et al. 1994). The stratigraphic sequence starts from folded Riphean (Middle–Late Proterozoic) flood basalts and overlying clastic rocks that host medium-size sedimentary-Cu deposits at the western flank of the Siberian craton. A 3–8-km-thick sequence of Yudomian (Eocambrian) to Early Carboniferous carbonate and terrigenous sedimentary rocks unconformably overlies the folded Riphean rocks (Simonov et al. 1994). Devonian clastic rocks and shales host evaporites, including salt, anhydrite and gypsum.

The Middle Carboniferous to Permian Tunguska group (this group should not be mixed with the overlying Tunguska flood basalt basin) is 40–600 m thick and consists of continental coal-bearing clastic rocks that lie unconformably on the older stratigraphic units (Simonov et al. 1994). We structurally analysed this unconformity and found that its configuration outlines a trough-parallel northeast-trending rise (Fig. 3b) that existed before and/or during accumulation of the Tunguska group. This rise may correspond to a tilted basement block. It corresponds to the southern part of the Noril'sk syncline and most of the Khantaika–Rybnaya uplift that separates the Noril'sk–Kharaelakh and Imangda troughs. This analysis also allows us to restore the northwestern flanks of the trough at the Vologochan syncline.

In the Noril'sk–Kharaelakh trough, the Late Permian – Early Triassic flood basalts occur almost everywhere above the Tunguska group, but they directly overlie the Early Palaeozoic rocks in the Khantaika–Rybnaya uplift. As mentioned above, the 3-km-thick flood basalt sequence consists of picrites and alkaline basalts at the base, forming the lower 5% of the sequence, and tholeiitic basalts, constituting the remaining 95% of the sequence (Fedorenko 1994; Lightfoot et al. 1994). The presence of picrites indicates that the magma formed at very high temperatures of 1,700 °C (Diakov et al. 2002). The thickness of individual volcanic formations typically increases across the present configuration of the mapped synclines and uplifts (Naldrett et al. 1992; Fedorenko 1994; Lightfoot et al. 1994). The structural pattern of the paleoisopachs in the lowermost picrite-bearing assemblage is most informative for understanding the paleostructure (Fedorenko 1994; Fig. 15.3a). The isopachs show that the maximum thickness of the volcanic formations is elongated to the northeast along the trough, emphasizing its keel, which correlates with the distribution of mineralized sills (Fig. 7a).

Intrusion types

Intrusions with mafic–ultramafic compositions dominate, but there are also several small granite bodies in the northwestern portion of the Vologochan syncline (Sherman 1991). Diakov et al. (2002) mentioned that more than 300 mafic–ultramafic intrusions have been mapped in the region, but only 33 contain elevated sulfide concentrations. Sixteen intrusions have relatively rich disseminated ore, but only four host massive sulfide orebodies (Diakov et al. 2002). These magmatic bodies have been subdivided into five groups, each including several types of barren undifferentiated intrusions (Naldrett et al. 1992), which were emplaced before and after mineralized intrusions. Cu–Ni–PGE mineralization is associated exclusively with the differentiated intrusions of two types, typified by the Noril'sk and Lower Talnakh types (Naldrett et al. 1992).

The undifferentiated intrusions form two major clusters in the Imangda syncline and in the Dudinka uplift (Fig. 3b). The undifferentiated intrusions are mostly sills of mafic composition, but they are linked to northwest and northeast- striking dykes. The intrusions occupy large areas and occur throughout the Palaeozoic sedimentary to Triassic volcanic formations.

The differentiated intrusions that host the Cu–Ni–PGE mineralization occur mostly in the upper parts of the pre-flood basalt stratigraphic sequence. They were emplaced in the Devonian evaporites and Carboniferous–Permian clastic rocks at the Talnakh–Oktyabr'sky deposit, and they occur near to the base of the volcanic sequence in the Noril'sk-I deposit. The differentiated intrusions form four major clusters, whose extent is much smaller than that of undifferentiated intrusions. The largest cluster, containing the Noril'sk and Talnakh–Oktyabr'sky deposits, strikes northeast from the central part of the Noril'sk syncline to the southwestern closure of the Kharaelakh syncline; it has a strike length of 60 km and a width of 20 km. Many intrusions in this cluster occur far from the Noril'sk–Kharaelakh fault. One small cluster is known in the South Noril'sk area, and the Talma cluster occurs on the northwestern flank of the Ikon syncline. A fourth cluster is known at Imangda. There are no differentiated intrusions in the Khantaika–Rybnaya uplift. This distribution is not a result of the level of erosion as basalts overlap its northwestern limb and northern closure and are not associated with intrusions in those locations. Economic mineralization is presently known in the Noril'sk-I and Talnakh- Kharaelakh intrusions, but at higher palladium prices the presently subeconomic mineralization of the Imangda, Chernaya Gora, and Noril'sk-II intrusions may be reconsidered for mining (Dodin et al. 2000).

The mafic–ultramafic intrusions are almost exclusively sills, but the mineralized sills are tongue-shaped and must be called chonoliths. In addition, they do not "inflate" stratigraphy, but rather replace it (Zen'ko and Czamanske 1994). The presence of sills and chonoliths indicates significant lateral rather than vertical injection of magma, at least in the upper crustal levels.

Noril'sk and Talnakh–Oktyabr'sky mineral clusters

Geological setting

The Talnakh and Oktyabr'sky deposits are associated with two intrusive bodies, Talnakh and Kharaelakh (Fig. 4a). A poorly differentiated Lower Talnakh intrusion (Fig. 4a) was emplaced before the fully differentiated mineralized intrusions (Simonov et al. 1994; Zen'ko and Czamanske 1994). The Talnakh and Kharaelakh intrusions plunge northeastward (Kunilov 1994). The Talnakh intrusion occurs within the terrigenous rocks of the Tunguska group, whereas the Kharaelakh intrusion was emplaced into a Devonian evaporite-bearing sequence. These complex 250-m-thick intrusions have been traced by drilling and seismic data for at least 20 km in a northeastern direction. The width of the intrusions is 3–5 km. Based on drilling, the intrusions occur at variable depths up to 3 km. The intrusions are mostly hidden under volcanic rocks, but the edge of the Talnakh intrusion crops out east of the town of Talnakh.

The Noril'sk-I deposit occurs 20 km southwest of the Talnakh and Oktyabr'sky deposits (Fig. 1). The differentiated intrusion hosting the Noril'sk-I deposit forms a 2–3-km-wide sickle-shaped body extending north–south for 15 km (Fig. 4b). The Noril'sk-I intrusion has been emplaced along the contact of the flood basalts and the underlying Tunguska group. It is exposed only on the northeastern flank of the Noril'sk syncline; elsewhere the bulk of the intrusion is hidden under volcanic rocks.

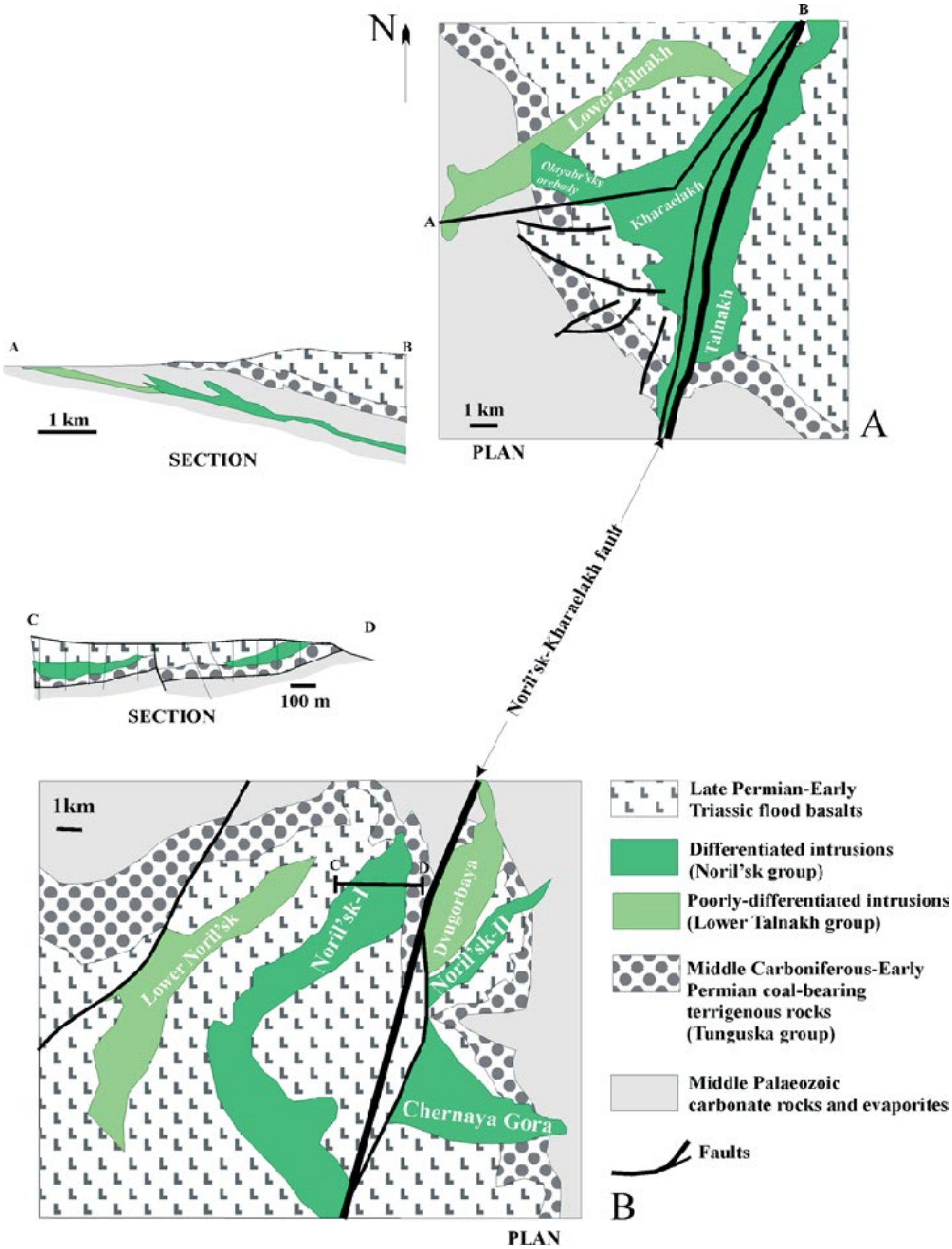


Fig. 4 Geologic maps and cross sections of the Talnakh–Oktyabr'sky (**A**), Noril'sk-I and related deposits and intrusions (**B**). Intrusions at depth have been projected to surface as they are largely hidden under flood basalts. Note that Noril'sk-I is a rootless intrusion, whereas the Talnakh–Kharaelakh intrusion plunges to the northeast towards its possible source

Geophysical and drilling data show that it is a rootless intrusion at the present level of erosion. Several intrusions that host subeconomic mineralization are known near the Noril'sk-I intrusion, e.g. Chernaya Gora and Noril'sk-II (Fig. 4b). The Zub-Marksheiderskaya and Vologochan intrusions are more distant (Fig. 3b). The poorly differentiated Lower Noril'sk and Dvugorbaya intrusions are known stratigraphically below the Noril'sk-I intrusion (Fig. 4b).

Sulfide mineralization

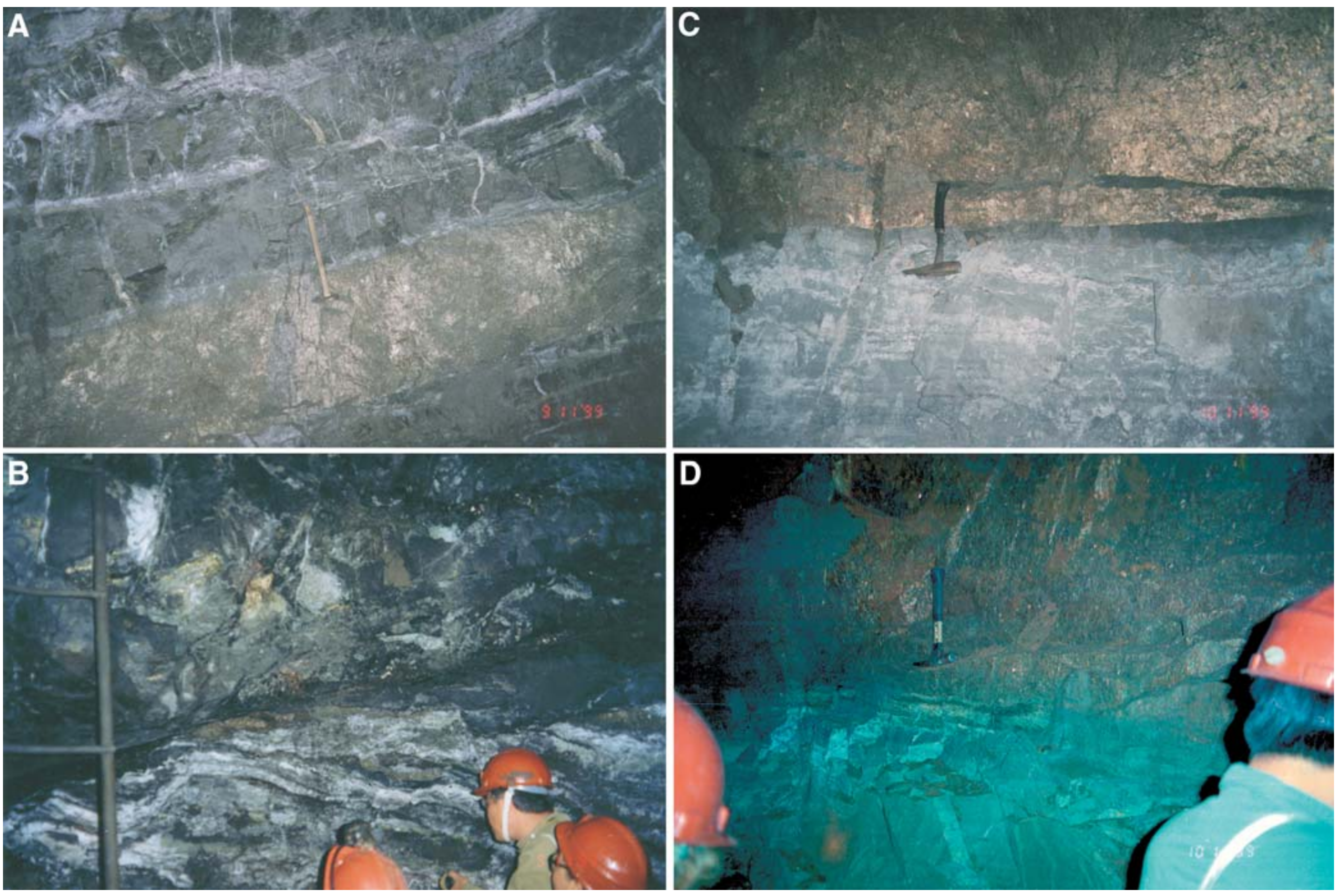
The differentiated intrusions host three principal types of Cu–Ni–PGE sulfide mineralization, viz. disseminated, massive and so-called copper sulfides. Detailed descriptions of these ore types and their mineralogy were published by Sobolev (1978), Genkin et al. (1981), Duzhikov et al. (1992) and in several papers in the Proceedings of the Sudbury–Noril'sk Symposium (in Lightfoot and Naldrett 1994). This paper focuses on the structural relationships between the mineralization types and the intrusions. All three types of mineralization are known in the Talnakh, Kharaelakh and Noril'sk-I intrusions; disseminated mineralization is found in many differentiated intrusions.

Disseminated sulfides constitute the most voluminous sulfide type. They occur at two levels within the differentiated intrusions. The basal portions of the 150–250-m-thick differentiated intrusions host disseminated sulfides immediately above the massive sulfides. The disseminated sulfides are most consistent along the strike of the intrusions. This type of mineralization constitutes the largest Cu–Ni–PGE resource in the area, but the grade is low. In the olivine-bearing rocks, the sulfides form blebs up to 2 cm across, commonly containing chalcopyrite, pyrrhotite and pentlandite. The average thickness of the units with disseminated sulfide is 40–60 m, reaching a maximum of 150 m. There is a relationship between the thickness of the differentiated intrusions, and the thickness of the disseminated sulfide ore and the underlying massive sulfide ore (Likhachev 1996; Diakov et al. 2002). Naldrett et al. (1994) showed that disseminated ore crystallized as a closed system. Additional study of the disseminated ore by Naldrett et al. (1996) has revealed that it has not fractionated to a great degree and that adequate sampling gives an average composition close to that of the primary sulfide liquid. The second type of disseminated ore occurs at the top of the intrusions (Distler 1994; Sluzhenikin et al. 1994). It is low-sulfide material that has low Ni and Cu concentrations, but proportionally higher PGE grades.

The differentiated sills that host disseminated sulfide ore are cryptically layered with olivine-rich picritic gabbro at the bottom, olivine-free gabbro in the middle, and gabbro–diorite at the top of the intrusions (Ryabov and Zolotukhin 1977; Sobolev 1978; Genkin et al. 1981; Duzhikov et al. 1992). This indicates that portions of the magma were emplaced in the relatively thin (250–300 m), but very long (> 20×3 km) final chambers and differentiated in them without development of layered structures. Taxitic horizons may have formed near the margins of these intrusions.

Massive sulfides are the richest ores of the Noril'sk district. They form impressive lens-shaped orebodies. The largest lens, known as the Oktyabr'sky deposit, covers an area 3×1 km with an average thickness of 30 m. The massive ore lenses strike for up to 20 km under the Talnakh–Kharaelakh and Noril'sk-I differentiated intrusions (Czamanske et al. 1994; Kunilov 1994; Likhachev 1994; Naldrett et al. 1994; Stekhin 1994; Diakov et al. 2002), but massive sulfides commonly form orebodies entirely separated from intrusions (Fig. 5a), being surrounded by hornfelsed host sedimentary rocks (Naldrett et al. 1994; Diakov et al. 2002), but they always occur below differentiated intrusions (Fig. 5b). Kunilov (1994) demonstrated that massive sulfides also

Fig. 5 Relationships between massive sulfides and host rocks. **A** 80-cm-thick bedding parallel massive sulfide lens in the hornfelsed siltstone, Komsomolsky mine, Talnakh intrusion; **B** oblique intrusive contact between the differentiated intrusion (*above*) and limestone (*below*) with sulfide lenses along the contact, Komsomolsky mine, Talnakh intrusion; **C** hornfelsed contact of massive pyrrhotite–chalcopyrite ore and evaporite, Oktyabr'sky mine, Kharaelakh intrusion; **D** massive mooihoekite–cubanite ore and evaporite, Oktyabr'sky mine, Kharaelakh intrusion



intrude into the overlying differentiated intrusions, indicating that sulfide liquid was emplaced or remobilized after emplacement of the sills. The massive sulfide orebodies are internally zoned, with Cu-rich sulfides in the core rimmed by pentlandite and pyrrhotite (Duzhikov et al. 1992). Stekhin (1994) attempted to constrain the direction of sulfide liquid injection by studying the mineralogy and geochemistry of the ores. The massive ore of the Kharaelakh (Oktyabr'sky) orebody fractionated as injection proceeded from east to west, with the fractionated liquid moving progressively to the west (Stekhin 1994; Naldrett et al. 1998). This liquid leaked into the overlying hornfels to produce breccias and copper sulfide ore mantles. The Cu enrichment is most pronounced above the western part of the Kharaelakh orebody (Fig. 5 c, d), affecting the lower part of the disseminated ore zones within the intrusion (Naldrett et al. 1996). Stekhin (1994) identified several streams showing that sulfide liquid migrated from the thickest parts of the Talnakh and Kharaelakh intrusions to the west-northwest in the Oktyabr'sky deposit and to the south-southeast in the southeastern part of the Talnakh deposit. He also interpreted the northeastward injection of the sulfide liquid into the deep parts of the Talnakh–Oktyabr'sky deposit in the Gluboky mine area (Stekhin 1994; Fig. 18.9).

Copper sulfide ores occur in the endo- and exocontacts of the differentiated intrusions (Torgashin 1994) and also in the country rocks (Stekhin 1994). Economically, they represent the second most important ore type in the Noril'sk mining district (Diakov et al. 2002). They occur in the bottom and upper parts of the differentiated intrusions, forming irregular orebodies with breccia textures (Naldrett et al. 1994). The copper ore is multilayered, containing numerous barren or weakly mineralized layers (Torgashin 1994), and its thickness is 60 to 70 m. Torgashin (1994) notes that the location and shape of the copper ore depends on local pre-ore structures such as downfaulted blocks of the intrusion. He also demonstrated that the massive sulfide lenses link upwards with the copper ore (Torgashin 1994; Fig. 19.2). Stekhin (1994) showed that copper ore sulfides tend to occur along the outer rim of differentiated intrusions and massive sulfide bodies. In many cases this ore is associated with the taxitic gabbro. These relationships led Naldrett et al. (1994) to conclude that the copper sulfide ore is genetically linked with the emplacement of the massive sulfide ore and represents a fractionated sulfide liquid that escaped from the massive ore as it crystallized.

Relationships between sulfide types and intrusions

The three sulfide types and their relationships to differentiated intrusions and each other led Naldrett et al. (1992) to suggest that separation of magma into immiscible sulfide and silicate liquids might have taken place in unexposed hypothetical intermediate chambers prior to emplacement. Although no direct relationships were identified, on the basis of geochemical data Lightfoot et al. (1990, 1993, 1994) and Naldrett et al. (1992) interpreted the final chambers as feeder channels for Permo-Triassic continental flood basalts that merge with an extensive system of peripheral sills, through which part of the magma is thought to have continued to the surface. These workers also recognised that some formations (e.g. Nadezhda formation) in the lower volcanic assemblage show depleted concentrations of Cu, Ni and platinoids, in contrast to the rest of the sequence. Therefore it was suggested that during this particular stage of magmatism these metals accumulated in the intermediate chambers.

On this basis we speculate that injections of the hot sulfide-bearing magma created the thermal aureoles and reacted with evaporites, causing in situ precipitation of massive sulfides and possibly melting of anhydrite. As mentioned above the picritic magma had a temperature of 1,700 °C at the plume head, and, therefore could be hot enough to melt anhydrite, which has a melting temperature of 1,360 °C. Once dense sulfide melt collected at the bottom of the chamber in contact with the evaporites its high temperature and high thermal conductivity would rapidly transfer more heat to the evaporites, possibly making more melting available, but also possibly preventing reaction between anhydrite and iron in the magma. Melted anhydrite would float up through the sulfide melt and magma, providing ideal conditions for further reaction. This mechanism is in agreement with the observation that the differentiated intrusions and massive sulfide lenses do not inflate the stratigraphy by silling, but rather replace (melt?) the evaporite layers (Torgashin 1994, Fig. 19.1; Zen'ko and Czamanske 1994).

In this way we can explain the correlation between the thickness of differentiated intrusions, disseminated and massive sulfides, e.g. the thickest parts of intrusions must have created the strongest thermal effect on country rocks. The model also allows generation of massive sulfides in more than one in situ centre accumulating metals from the magmatic liquid under intrusions and explains why massive sulfides form isolated and semi-isolated lenses. However, we do not exclude some lateral migration of massive sulfide liquid to the area where evaporites are absent underneath the differentiated intrusions. At the same time the differentiated intrusions could be conduits to effusive flows of the Noril'sk–Kharaelakh trough. Lightfoot et al (1994) and Lightfoot and Hawkesworth (1997) analysed the chemistry of flood basalt formations and found that one of them (Nadezhda formation) is depleted in ore components in comparison with the others indicating that those metals could be accumulated in the intrusions.

One possible reason for lateral migration could be the lithostatic pressure of the thick overlapping volcanics and extensional faulting during melt injection, resulting in escape of the sulfide liquids from under intrusions and formation of the metasomatic halo of copper ore near the massive sulfide lenses. Extensional block faulting and related tilting of the solidifying intrusion would favour the escape of sulfide liquid into its roof and accumulation of the upper contact copper ore.

We understand that our in situ model explaining the varieties of ore types requires isotopic evidence to support it. Indeed, isotopic studies (Grinenko 1986) showed a mixture of heavy and light sulfur isotopes of sedimentary and mantle origin in massive sulfide. Therefore, our model does not require intermediate chambers to explain the massive sulfide ore, but they are necessary in explaining the disseminated sulfides. In the following section we review the geophysical data and test the tectonic model.

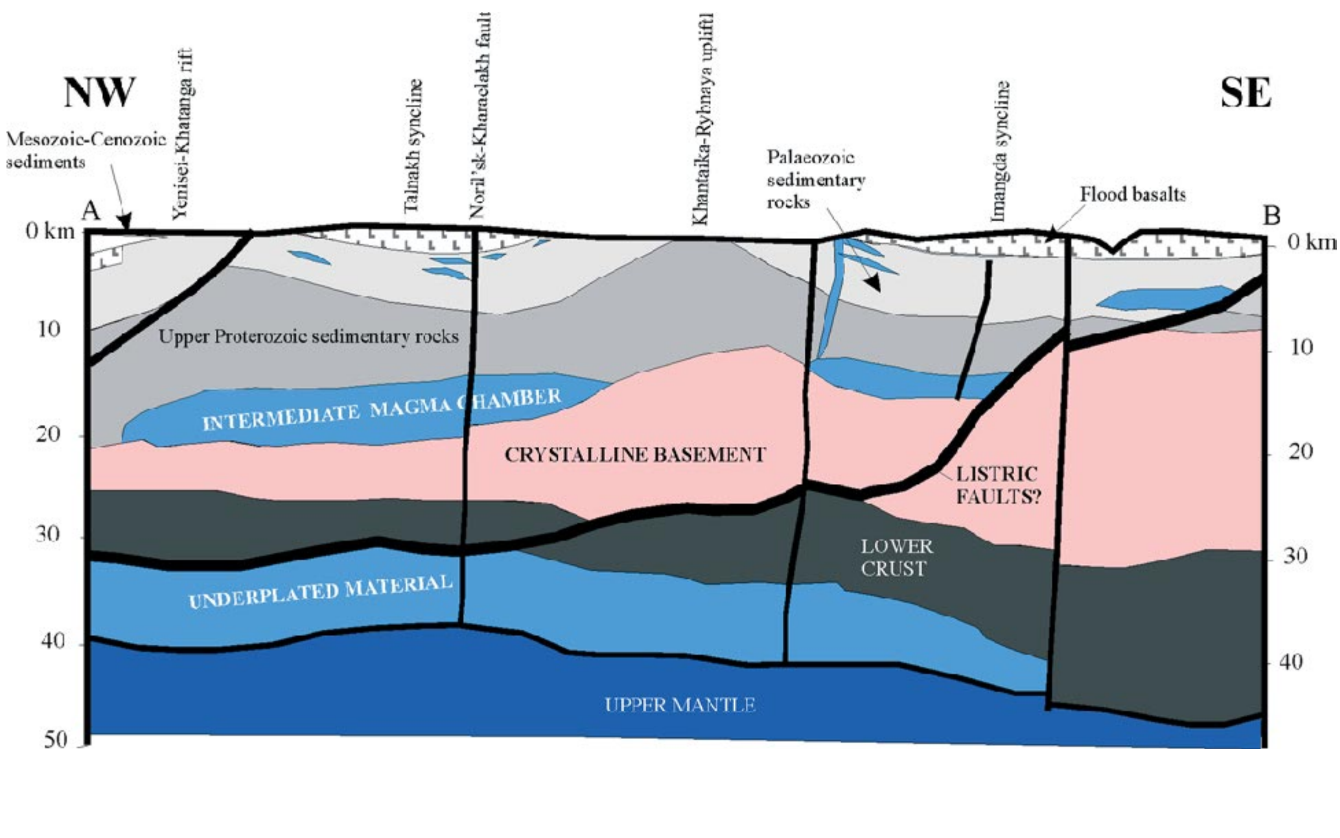
Geophysical data

Hot mantle plume material is thought to be responsible for generation of the Mg-rich picritic magma that was emplaced in the Noril'sk–Kharaelakh trough (Schissel and Smail 2001; Diakov et al. 2002). On the basis of petrological studies Naldrett et al. (1992, 1998) suggested that, during migration from the mantle to the upper crustal levels, portions of this magma remained in intermediate crustal-level magma chambers where separation into silicate and metal-rich sulfide liquids took place.

Fig. 6 Interpreted cross section of the Noril'sk–Kharaelakh trough and adjacent structures (modified after Sherman 1991) demonstrate presence of magma chambers at several levels in the northwestern part of the Siberian craton. Position of the cross section is shown on Fig. 3A

Published geophysical data (Sherman 1991; Rempel 1994; Diakov et al. 2002) show evidence for magnetic bodies, interpreted as intermediate magma chambers (Sherman 1991; Rempel 1994), at several levels within the stratigraphic sequence of the Noril'sk–Kharaelakh trough (Fig. 6). The "crust–mantle mixture" at the Moho beneath the trough (Sherman 1991) should be excluded from further interpretation as it can be interpreted as underplated plume material.

At the intermediate and upper crustal levels, our analysis of the distribution of all types of sills and geophysically identified magma chambers in plan (Fig. 7a, b) shows that the differentiated sills are restricted to shallow levels of the Noril'sk–Kharaelakh trough. The undifferentiated intrusions correlate with the peripheral parts of most chambers occurring at the depth of 12–17 km (Figs. 6 and 7b; Sherman 1991; Diakov et al. 2002), which may be correlated with the intermediate magma chambers (Rempel 1994). The differentiated intrusions and these chambers overlap only in three areas (Fig. 7a, b), viz. Noril'sk–Talnakh, Talma and Imangda. The best correlation is in the case of Talnakh and possibly Talma. At these locations, the chambers seem to be linked to the Yenisei–Khatanga rift, whereas in all other cases the intermediate chambers occur as isolated anomalies, coinciding with undifferentiated sills in the Dudinka uplift (Fig. 7b). Therefore, we suggest that these geophysically identified chambers may be of different nature, e.g. some may reflect an accumulation of undifferentiated sills in the Palaeozoic sequence, such as the Dudinka uplift, whereas others may represent intermediate chambers where differentiation of magma took place, such as Pyasina uplift.



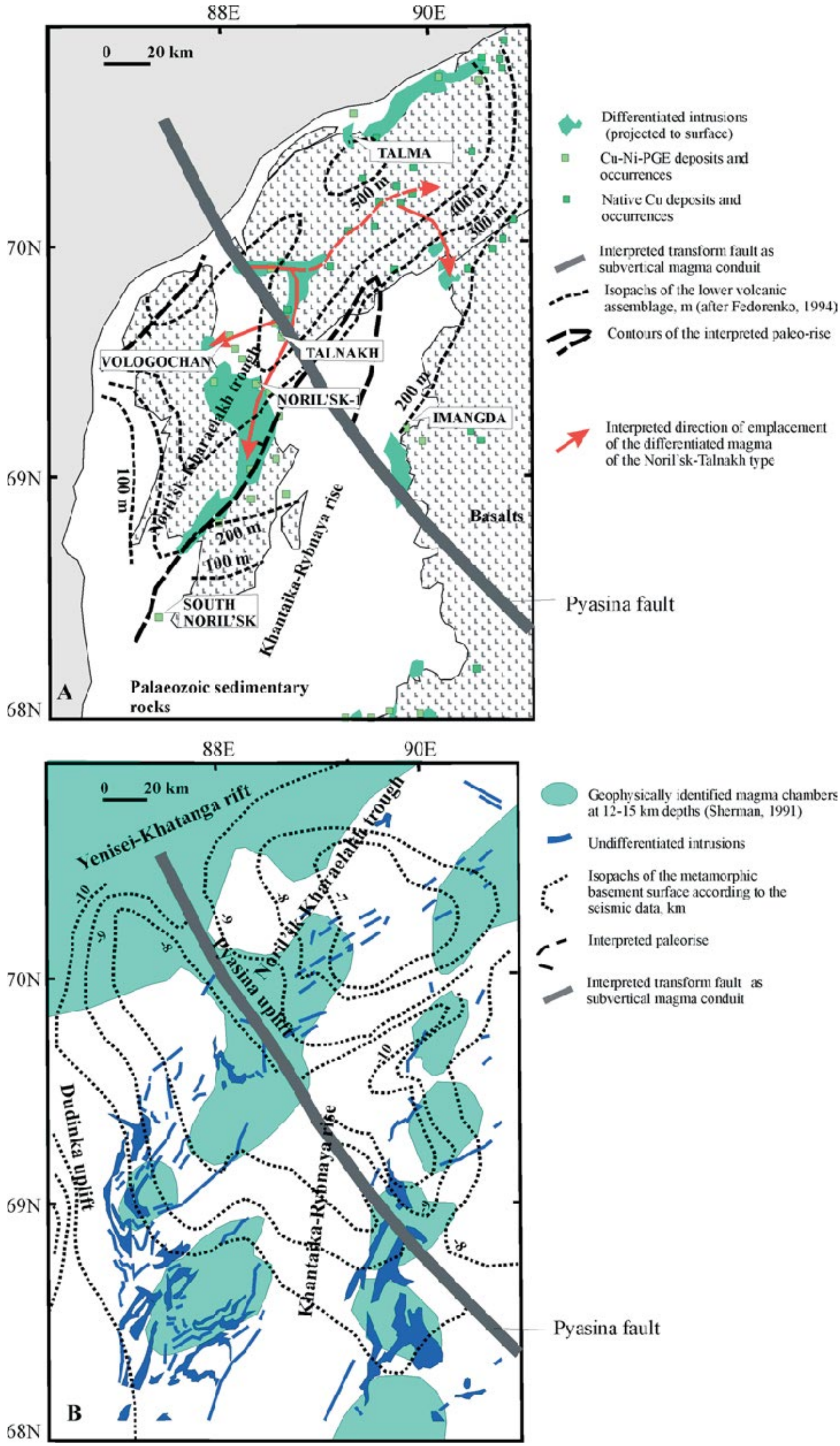


Fig. 7 Geological–geophysical interpretation of the Noril'sk–Kharaelakh trough and adjacent structures (modified after Sherman 1991). **A** Shallow structures; **B** metamorphic basement surface. Note that interpreted transform fault separates areas with different structural pattern

The Talnakh–Oktyabr'sky deposit seems to occur on the southern periphery of the intermediate chamber near the Pyasina uplift (Fig. 7b). It is worth mentioning again that the Talnakh and Kharaelakh differentiated intrusions plunge to the northeast towards this geophysically identified magma chamber. The geophysical data indicate this flat chamber is T-shaped in plan. Its northwest-trending branch strikes towards the Yenisei–Khatanga rift (Fig. 7b).

The configuration of the isopachs of the metamorphic basement (Fig. 7b) shows the "break" corresponding to the northwest-trending branch of the intermediate magma chamber, which we interpret as its possible feeder. This suggests that it may be controlled by the northwest-trending crustal fault, which we suggest to call the Pyasina transform fault, coinciding broadly with the northeastern flank of the Pyasina uplift. This fault has a transverse position with respect to the Yenisei–Khatanga rift and Noril'sk–Kharaelakh trough. A seismic cross section along the northwestern flank of the Noril'sk–Kharaelakh trough (see Fig. 9 in Diakov et al. 2002) suggests that interpreted mafic rocks may form a subvertical body rising from the Moho. Its orientation corresponds exactly to the northeastern flank of the Pyasina uplift. This suggests that the principal crustal conduits for magma ascent are reconstructed northwest-striking faults, rather than the traditionally proposed northeast-striking crustal faults, such as the Noril'sk–Kharaelakh fault.

Along the Dudinka uplift, where mostly undifferentiated intrusions are known, there is no definite break in isopachs (Fig. 7b). Most of the intrusions are sills, but some of them are related to the WNW- and NE-striking dykes penetrating into deeper levels of the stratigraphic sequence, indicating narrow feeder channels for these sills that might be emplaced into Palaeozoic sedimentary rocks along trough-parallel normal faults without intermediate chambers. If that is the case, then it might explain the difference in distribution of differentiated and undifferentiated intrusions in the Noril'sk–Kharaelakh trough.

Structural analysis of the Noril'sk–Kharaelakh trough

The geophysical data are consistent with a complex system of magmatic conduits, which link the mantle source and the mineral deposits. They also show that both the Noril'sk and Talnakh intrusions may occur in the same chonolith. We can test this model by structural analysis, using variations of volcanic thickness recorded by Fedorenko (1994) and Lightfoot et al. (1994).

Taking into account that the Noril'sk–Kharaelakh trough has a folded structure we suggest that the presently isolated Noril'sk–Vologochan and Talov–Kharaelakh synclines (Fig. 3b) may represent a formerly single volcanic area whose centre was located 30–40 km north-northeast of the present Talnakh–Kharaelakh intrusion, as can be deduced from the data by Fedorenko (1994) and Lightfoot et al. (1994). Their data also show that the thickness of the lower volcanic assemblage gradually increases in northeastern direction that does not match the present configuration of the synclines (Fig. 7a).

The mineralized intrusions occur along the zones with maximum thickness in the lower volcanic assemblage and on this basis we suggest that the intrusions that host the Talnakh–Oktyabr'sky, Noril'sk-I, Noril'sk-II, Chernaya Gora, Zub–Marksheiderskaya and even Vologochan deposits may represent an originally single palm-shaped intrusion or system of intrusions that were injected southwestward from the T-shaped intermediate chamber to the north of Talnakh. In other words, the Talnakh–Oktyabr'sky and Noril'sk-I deposits may constitute an originally single, approximately 60-km-long, but now deformed and eroded intrusion. This explains why Noril'sk-I is hosted by a rootless intrusion, whereas a root can be inferred for the Talnakh–Kharaelakh intrusion.

We suggest that extension occurred throughout the Permo-Triassic flood basalt magmatism. The Khantaika–Rybnaya paleo-rise developed above the extensionally tilted block that served as a natural barrier and influenced magma to penetrate along its ridge rather than propagate in all directions, especially across the tilted block (Fig. 8a). This explains why the host intrusions are so narrow and thin in comparison to their length, and why only disseminated mineralization is known to the southwest of the Noril'sk deposits, whereas massive, copper and disseminated sulfide ores occur at Noril'sk-I in the middle, and the richest ores occur at Talnakh, closest to the proposed intermediate magma chamber.

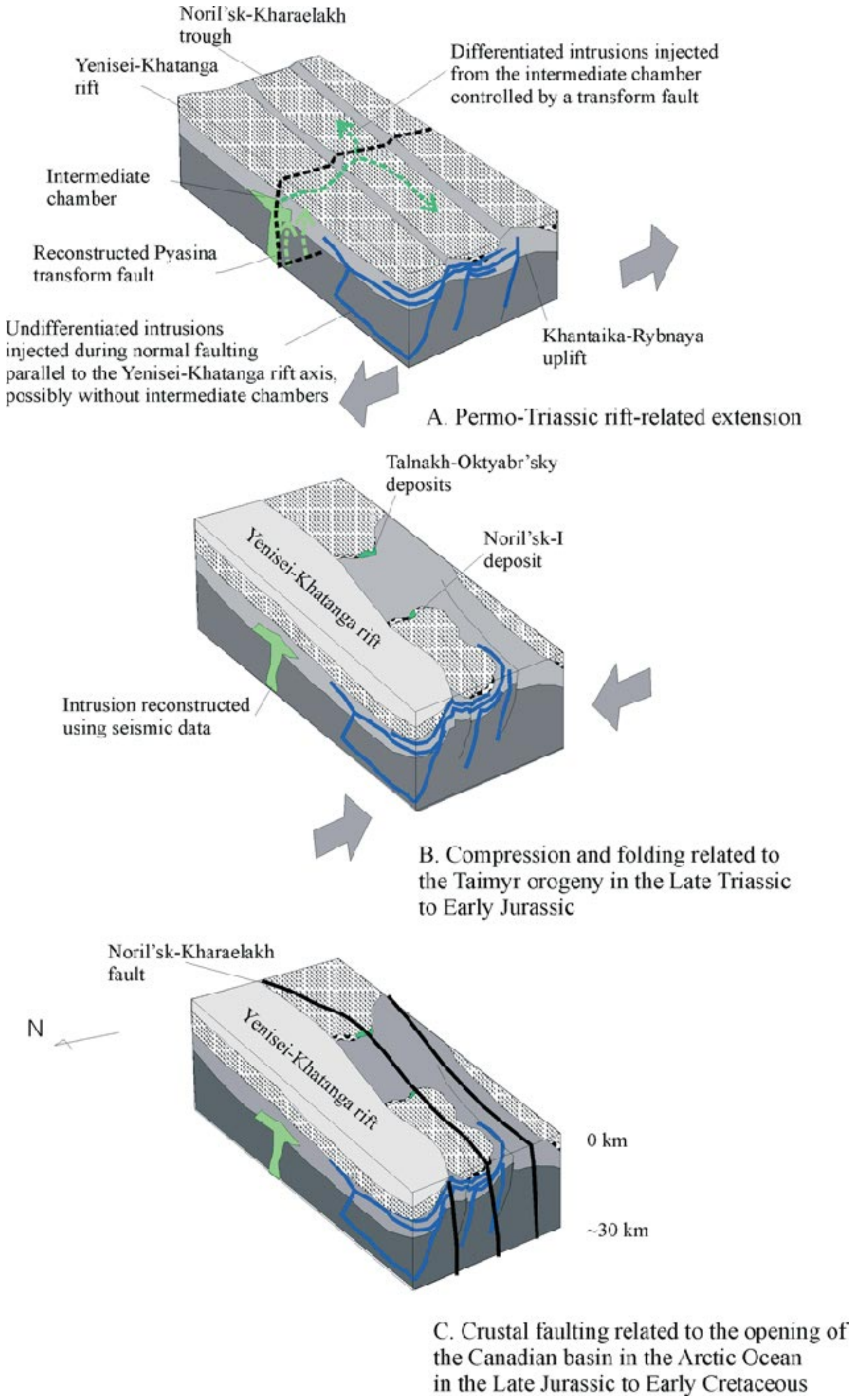
The Late Triassic orogeny in Taimyr was the reason of folding and reverse faulting in the Noril'sk–Kharaelakh trough (Fig. 8b), whereas major crustal faults, such as the Noril'sk–Kharaelakh fault, intersect all structures (Fig. 8c) and therefore must be considered as superimposed fractures.

Continent-scale tectonic setting of the Siberian superplume province at the Permo-Triassic transition

Previous sections analysed the regional and local factors that contributed to the uniqueness of the Noril'sk–Talnakh group of deposits. Here we investigate whether there are global factors that might explain the extensive mineralization in the Noril'sk mining camp and adjacent areas.

The plume and rifting events affected the Laurasian continent from the North Atlantic to the former Verkhoyansk passive margin, and from the South Kara rift in the north to Central Asia in the south (Nikishin et al. 2002). This event did not form a new ocean: instead, the Permo-Triassic Siberian continental flood basalts occupied a huge area over 4,000 km in diameter.

Fig. 8 A proposed model of the Permo-Triassic to Late Jurassic–Early Cretaceous tectonic evolution of the Noril'sk–Kharaelakh trough and related structures. See Fig. 3 for rock symbols



Scotese and McKerrow (1990), Ziegler (1990), Veevers (1995) and Veevers and Tewari (1995) discussed the global tectonic environment at the Permo-Triassic transition. They showed that in Permian times, Pangea consisted of the continents of Laurasia and Gondwana. Laurasia was surrounded by subduction zones (Fig. 9). We do not have isotopic evidence from the Siberian plume, but if the subducting slabs were able to penetrate as deep as the core–mantle boundary, as is the case for some presently active subduction zones (Su et al. 1994), they may have formed a funnel to the mantle under this continent (Fig. 10).

We suggest that these slabs could determine the geometry of the superplume, restricting it to ascending in the centre of the Laurasia continent. The resulting voluminous magma erupted during a short period of 2–4 Ma in continental rifts and related extensive flood basalt basins. Cu–Ni–PGE mineralization is found

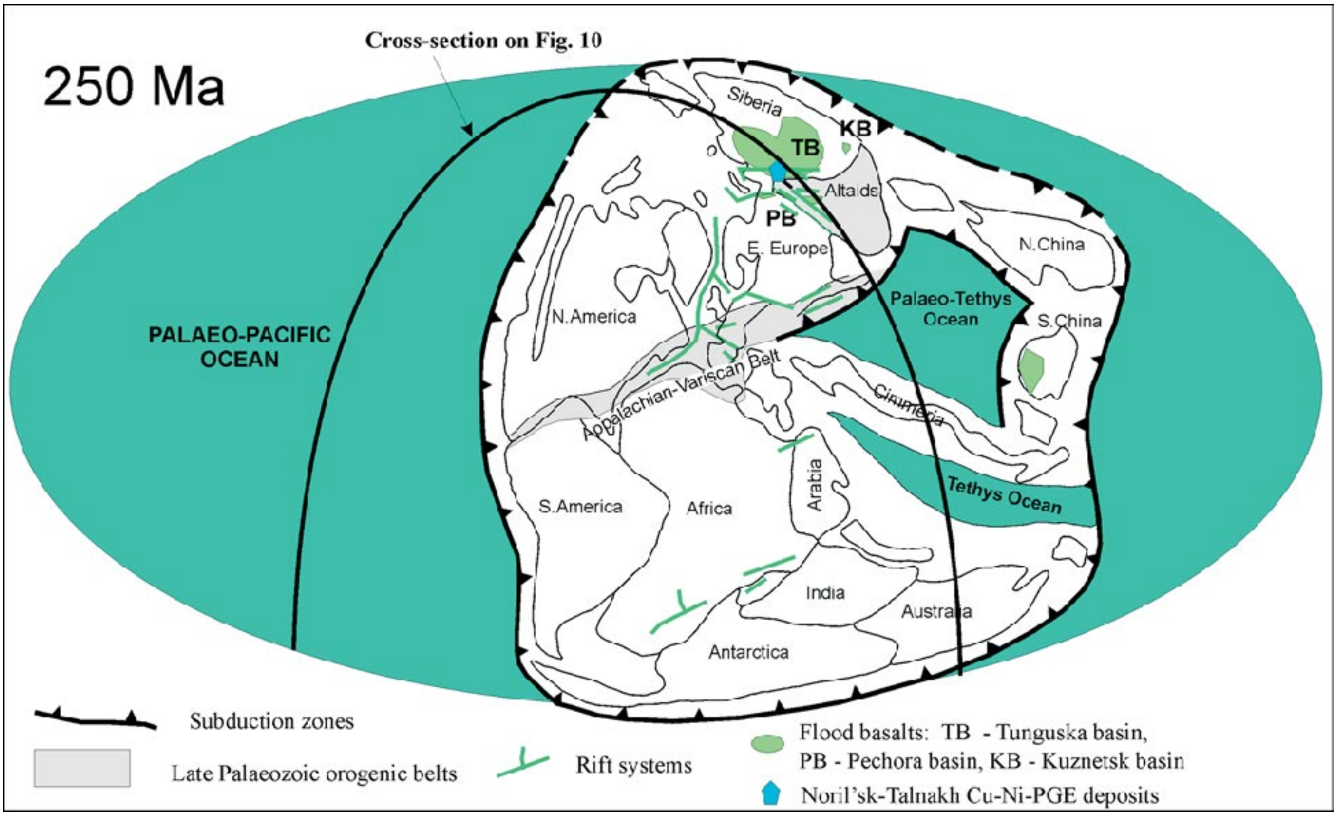


Fig. 9 Permo-Triassic (250 Ma) reconstruction (simplified after Scotese and McKerrow (1990)) showing location of major continental rifts, flood basalt provinces and related Cu–Ni–PGE mineralization

300 km east of a triple junction of continental rifts, which is located in the geometric centre of both the superplume and the continent.

It is possible that the plume material was enriched in Fe, Ni, Cu, PGE, Au, Se, Te and possibly S derived from the metal-rich core. If so, this may explain numerous Ni–Cu occurrences in various parts of the Tunguska and Taimyr flood basalt basins (Dodin et al. 2000) as well as anomalous concentrations of these components in the Noril'sk district. In addition, some Cu and S may have been derived from the host sedimentary rocks in the intermediate chambers of the Noril'sk–Kharaelakh trough (Czamanske et al. 1994) and, as we showed above, from the host rock in situ under differentiated intrusions.

Paleomagnetic data suggest that the Siberian craton experienced clockwise rotation during the Palaeozoic (Smethurst et al. 1998). This rotation culminated in the Late Palaeozoic in amalgamation of the Altaid orogenic collage between the Siberian and East European cratons followed by emplacement of the Siberian superplume. The final episodes of this rotation may have been responsible for the Late Triassic deformation in the Taimyr fold belt and the adjacent part of the Tunguska flood basalt province. This compressional regime may explain why the plume activity ceased in the Siberian province and spreading and formation of a new ocean did not take place.

In the Late Jurassic oceanic spreading started in the Arctic Ocean and continued until the Early Cretaceous and a new spreading episode started in the Arctic Ocean in the Oligocene (Scotese and McKerrow 1990). It is possible that the Noril'sk–Kharaelakh fault and other northeast-trending transcrustal faults represent the transform faults on the flanks of the spreading Canadian and/or Arctic basins.

Conclusions

On a continent scale, the Cu–Ni–PGE deposits of the Noril'sk mining district occur in the Tunguska continental flood basalt basin, emplaced near a triple junction of continental rifts in the geometrical centre of the Siberian superplume province. The superplume may have ascended from the core–mantle boundary, possibly in response to funnel-shaped subduction surrounding the Laurasian continent at the Permo-Triassic transition. The superplume generated voluminous picritic magma that erupted during a short period of 2–4 Ma, and that was able to form a >2–3-km-thick volcanic sequence of subordinate subalkaline and picritic basalts and dominant tholeiitic basalts. Numerous intrusions were emplaced into country rocks during the associated extensional rifting event; however, Cu–Ni–PGE mineralization is known only within 400–500 km from a triple junction of continental rifts located at the proposed plume centre.

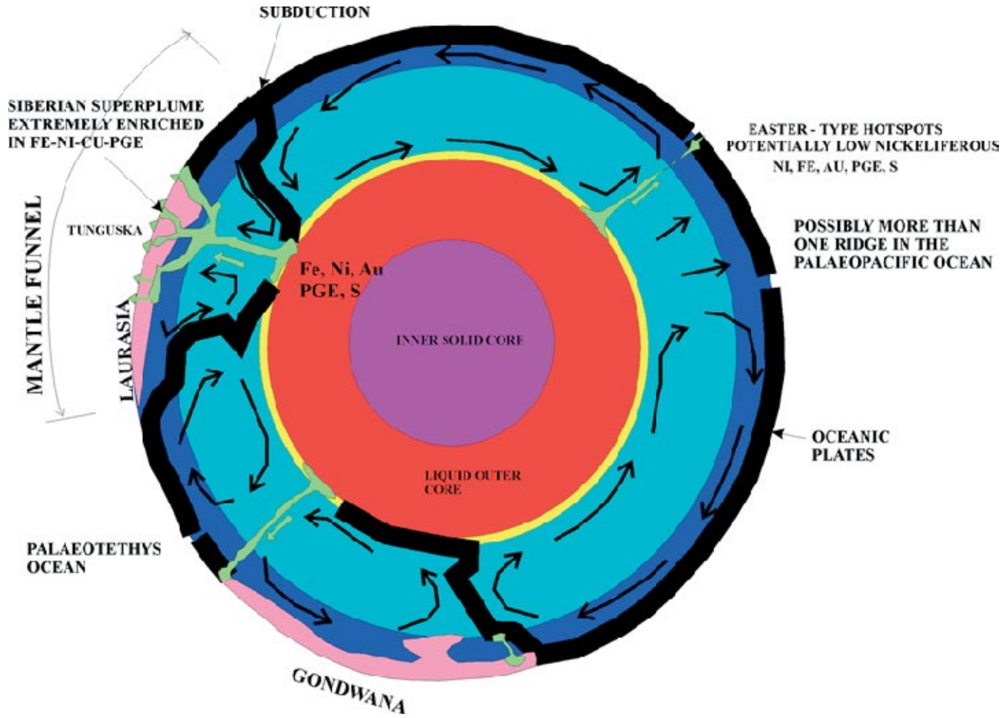


Fig. 10 Possible structure of the Earth at the Permian–Triassic transition. We suggest the presence of a whole-mantle subduction funnel under Laurasia, which might stimulate focused ascent of the Cu–Ni–PGE-rich mantle plume (*green*) in the geometric centre of the continent. *Black arrows* show possible convection in the mantle

On a regional scale, northwest-trending transcrustal faults are possible magma conduits from the mantle to the geophysically identifiable intermediate magma chambers. The presence of sills, and not dykes, as expected if the northeast-trending transcrustal vertical faults were major conduits, suggests a lateral, rather than vertical emplacement of magma from intermediate chambers. A reconstructed northeast-trending paleorise at the southeastern border of the Noril'sk–Kharaelakh trough controlled the direction of injection of the Cu–Ni–PGE-rich differentiated intrusions. It restricted their plan distribution along and not across its strike.

Regional maps show folds and reverse faults in the Noril'sk area, suggesting significant compression of the region after mineralization. In many cases, the variations of flood basalt thickness do not correlate with the configuration of the mapped synclines and anticlines. Because the Noril'sk-I deposit is hosted by a rootless intrusion, whereas the Talnakh–Kharaelakh intrusions can be traced to a possible source, which may be inferred 30–40 km to the north, we suggest that they may represent an originally single, at least 60-km-long, mineralized intrusive system emplaced southwestward from the interpreted intermediate magma chamber located north of the Talnakh–Oktyabr'sky deposits. This structure was then deformed and separated by erosion.

On a local scale, the differentiated ultramafic–mafic intrusions that host the Noril'sk-I and Talnakh–Oktyabr'sky deposits were injected into a 5–7-km-thick preflood basalt sedimentary sequence hosting sedimentary Cu mineralization and evaporites, which may have contributed additional metal and sulfur to metal-rich magma in the intermediate crustal chambers. The thick volcanic package would have resulted in a higher lithostatic pressure on the deep-seated intermediate chambers, causing lateral extrusion of differentiated material into structurally favourable final chambers.

On a deposit scale, this magma was emplaced into narrow 2–3-km-wide, but more than 20-km-long differentiated mineralized sills (high-level chambers). The sills reveal cryptic layering with disseminated sulfides accumulated in the olivine-rich bottom facies. Injection of hot magma into sulfur-bearing evaporites could be responsible for in situ formation and precipitation of lens-shaped massive sulfide orebodies underneath the intrusions. In turn, these massive sulfide lenses produced the metasomatic halo of copper ore that partly escaped and accumulated in the upper portions of the intrusions.

Acknowledgements We thank Sergei Diakov, Don Schissel, Peter Ziegler, Dallas Abbott and Chris Stanley for discussions. We specially thank Jeff Hedenquist for useful comments and Noel White for very helpful critical comments and arguments. Alexander Yakubchuk benefited from discussions with Alexander Stekhin and Oleg Oleshkevich, who worked extensively in Noril'sk and were excellent guides to its mines. We thank BHP-Billiton World Exploration Inc for permission to publish parts of the research results discussed in this paper. The reviews by Nick Arndt and Peter Lightfoot helped to improve and defend our arguments. We also thank Bernd Lehmann who encouraged us to write this paper.

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