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# Geological Relationships Between the Intrusions, Country Rocks, and Ni-Cu-PGE Sulfides of the Kharaelakh Intrusion, Noril′sk Region: Implications for the Roles of Sulfide Differentiation and Metasomatism in Their Genesis

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**Abstract**: The Ni-Cu-platinum group element sulfide ore deposits of the Kharaelakh Intrusion, Noril′sk Region, Siberia, represent a large concentration of sulfides associated with a small differentiated intrusion formed at the edge of the Siberian Craton in the roots of the Siberian Trap flood basalt. The deposit is associated with an intrusion that occupies a flanking periclinal structure adjacent to the Noril′sk-Kharaelakh Fault. The intrusion is strongly differentiated and comprises taxitic gabbrodolerites, picritic gabbrodolerites, and gabbrodolerites within the main body which in turn forms a chonolith within a sheet-like intrusion that extends laterally to form extensive undifferentiated sills of gabbrodolerite. The intrusion substantially replaces the stratigraphy of the country rocks, and although it appears to have exploited the axis of structures developed in response to transtension, the intrusion has created space by both mechanical dilation of stratigraphy and magmatic replacement of pre-existing sedimentary rocks. The frontal lobes of the main intrusion have complex apophyses of gabrodolerite on a range of scales that demonstrate replacement of the sedimentary rocks and link to the development of an extensive metamorphic halo in the country rocks. This halo is much narrower over the main body of the intrusion, and these observations have implications for the thermal history of the intrusion. Mg-skarns and breccias are developed in the roof of the main body of the intrusion. Within the intrusion, the taxitic rocks contain vesicles and the blebby sulfides developed in the picritic and taxitic gabbrodolerites appear to have a linkage to volatile phases. Cuprous sulfide mineralization developed at the roof of the Kharaelakh Intrusion is associated with metamorphosed and skarn-bearing country rocks, and appears to have been generated by a combination of sulfide fractionation and associated metasomatism. The geological relationships appear consistent with a chonolith model for the development of the differentiated intrusion and mineralization, but the extent of metasmorphism of the country rocks appears to be related to the unusual thickness of gabbrodolerite apophyses at the flanks of the intrusion rather than metamorphism produced by the passage of mafic magma through the intrusion. Variations in disseminated sulfide compositions and metasomatic textures in the skarns are described, and a model is proposed which balances traditional views on the evolution of the magma conduits with the impact of magmatic fluids transported through the magma column (i. e. transmagmatic fluids). The importance of structures in controlling the nature of the conduit, and the resultant small intrusions with excess sulfide is a feature of many other Ni-Cu sulfide deposits including Voisey′s Bay, and it is suggested that the sulfides are more likely to have been

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transported from depth into their final resting place rather than developed by in-situ equilibration of sulfide with fresh magma in the chonolith.

**Key words**: mafic-ultramafic intrusion; Ni-Cu sulfide deposit; metasomatism; genesis; Kharaelakh; Noril′sk

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## 1 Introduction

The economic Ni-Cu-platinum group element (PGE) sulfide ores of the Talnakh ore junction appear to be spatially and genetically related to the Talnakh-type differentiated intrusions (Zolotukhin et al., 1975) and to the flanking periclinal and graben structures of the Noril′sk-Kharaelakh wrench fault (Mezhvilk, 1984, 1995; Smirnov et al., 1994). The locus of mineralization and the development of primitive lavas and differentiated intrusions is linked to the position of a Permian mantle plume at the northwestern margin of the Siberian Craton at ~250Ma (e. g. Lightfoot et al., 1990) and to the development of mantle-penetrating structures inboard of the craton margin (e. g. Rempel, 1994; Golightly, 1996, Pers. Comm.; Lightfoot et al, 2012B). The localized centers containing the mineralized intrusions are termed ore junctions, and the intrusions are characterized by several key features; viz: ①The mineralized intrusions are localized adjacent to a major fault zone and occur within rift blocks between faults and the fold axes of periclinal structures. ②The intrusions largely replace the stratigraphy of the sedimentary rocks and they are volumetrically small (<2.5 $km^3$) and thin (<150 m). ③The intrusions are well differentiated in to layers from picritic gabbrodolerite through olivine gabbrodolerite to an upper olivine-free gabbrodolerite. ④The lower and sometimes the upper margins of intrusions are composed by coarse-grained to pegmatoidal olivine gabbrodolerites with locally distributed inclusions (this unit is termed the "taxite"). ⑤The intrusions contain massive Ni-rich and disseminated Ni-Cu-PGE sulfide mineralization that shows primary magmatic textures with evidence of sulfide differentiation. ⑥The flanks of the intrusions comprise sills and apophyses that extend into the country rocks. ⑦Skarn mineralogies are developed in the upper and lower exocontacts in association with Cu-rich sulfide mineralization. The Kharaelakh Intrusion is the most important from an economic perspective and provides examples of these features.

There are five principal types of mineralization that are developed in the Talnakh and Kharaelakh Intrusions; these are: ①Interstitial disseminated sulfides within the taxite and blebby sulfide segregations in the olivine-and picritic-gabbrodolerite (e. g. Torgashin, 1994). ②Massive fractionated contact ores and veins comprised of pyrrhotite, chalcopyrite, pentlandite, chalcopyrite, cubanite, and pentlandite, and mooihoekite-talnakhite mineralization (e. g. Torgashin, 1994). ③Breccia-like ores rich in chalcopyrite developed in the upper exocontact (Kharaelakh) and lower exocontact (Talnakh). ④Streaky disseminated sulfides in metamorphic and metasomatic rocks of the exocontact (Zotov and Pertsev, 1978). ⑤Disseminated sulfides enriched in PGE are associated with thick taxites in the upper part of the intrusion (Distler, 1994; Sluzhenikin et al., 1994). The mineralisation that is hosted in the country rocks adjacent to the intrusions are locally termed "cuprous ore" because of the elevated Cu content. These ore bodies form a small but economically important part of the Noril′sk ore deposits; they are associated with the exocontacts of the Kharaelakh, and Talnakh Intrusions and comprise a compliant reserve plus resource of 85.3 million tones with average grades of 0.89%Ni, 3.77%Cu, and $10.8\times10^{-6}$ 6E (Noril′sk Nickel, 2011; www. nornik. ru/en/ourproducts/MineralReservesResourcesStatement/).

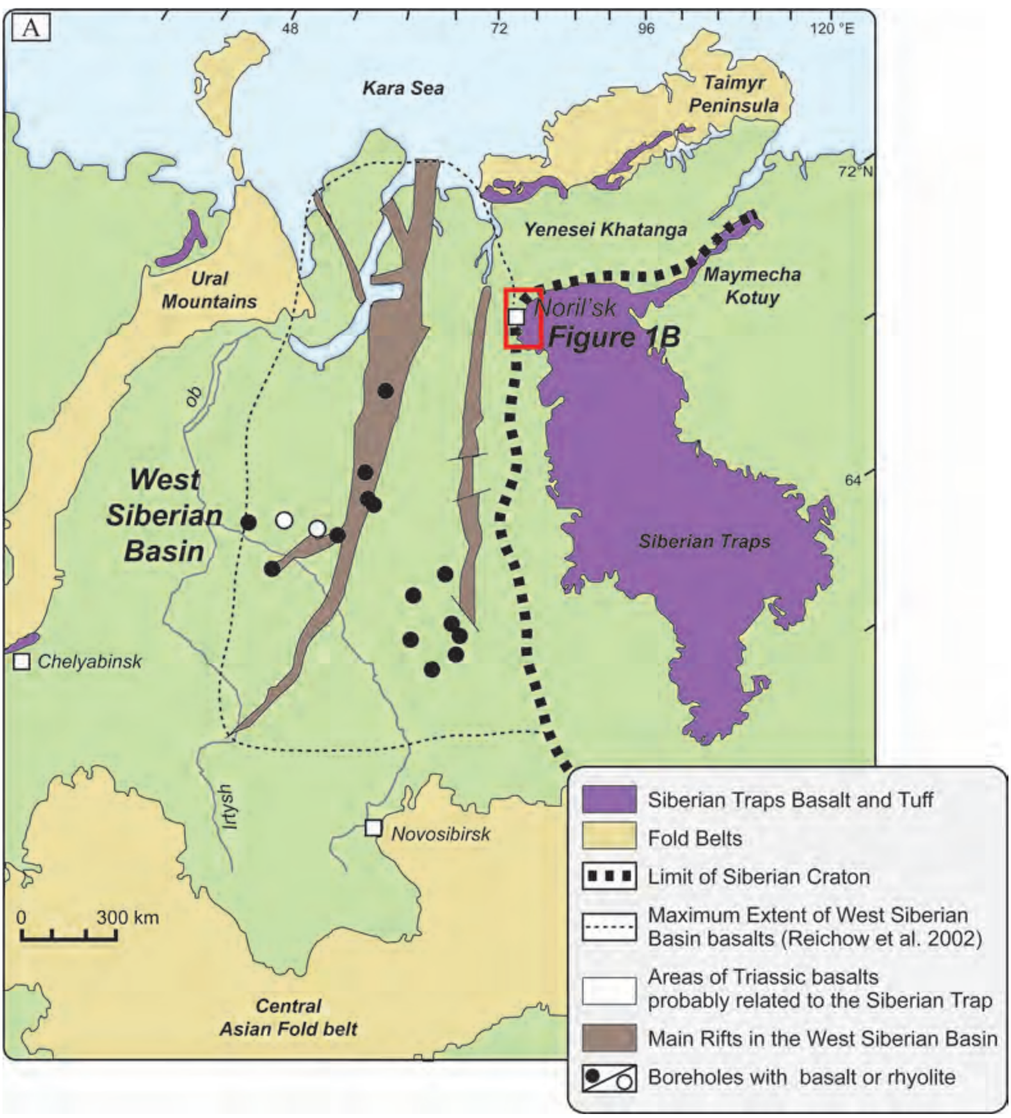
Most geologists now agree that the disseminated and massive sulfides were produced by equilibration of immiscible magmatic sulfide with silicate magma (e. g. Genkin et al., 1977; Distler et al., 1975; Naldrett et al., 1996; Keays, 1995). The volume of sulfide relative to silicate is very large within the heavily mineralized intrusions, so the formation of the ores requires an open system process where either the magma equilibrated with the sulfide within a chonolith (Naldrett et al., 1992, 1995, 1996, 1998) or where the emplacement of sulfide melts occurred through the conduits feeding the Siberian Trap in one or more episodes (Korzhinskii et al. 1984; Naldrett et al., 1992, 1995; Lightfoot and Zotov, 2007; Czamanskee, 2002). These conduits have been termed "chonoliths" to reflect their open system geometry; the rocks developed in the chonolith can comprise multiple pulses of melts and fluids, and the cumulates can have a bulk composition that is in equilibrium with a parental magma that is no longer represented by the bulk composition of the material in the intrusion. The chonolith is also an open system with respect to the equilibration of sulfide with magma (Naldrett and Lightfoot, 1996) as well as a pathway for the emplacement of dense magmatic sulfides which may be transported as weak disseminations within the magma (Bremond d'Ars et al., 2001), as dense massive sulfide liquid moved by tectonic pumping (Lightfoot and Evans-Lamswood, 2013A, B), and/or in association with transmagmatic fluids (Zotov, 1989; Korzhinsky et al., 1984; Luo et al., 2007). Equilibration of the magma with crustal sulfide appears to be a principal control on ore genesis at Noril'sk (e. g. Grinenko, 1985A, B, 1986; Godlevsky and Grinenko (1963); Gorbachev and Grinenko, 1973; Keays and Lightfoot, 2009 and references therein).

The formation of the exocontact breccia and disseminated Cuprous ores is less well understood. This paper examines the geological relationships in the exocontact domains using information from Zotov (1974, 1979, 1989), and attempts to constrain the timing and mechanism by which the hornfels, magnesian skarns, mafic apophyses, and mineralisation were formed. We show evidence for both primary magmatic processes as well as metasomatism that may have involved the physical and chemical transfer of fluids through the magma conduits which gave rise to the mineralized intrusions (Zotov, 1989).

## 2 Geological setting of the Noril'sk region

The world-class Noril'sk-Talnakh Ni-Cu-PGE sulfide deposits in Russia are associated with intrusions that have been extensively studied by a generation of Russian experts who mapped and logged drill core from the Noril'sk Region (e. g. Kunilov, 1994, and references therein). The Noril'sk Ni-Cu-PGE sulfide deposits are located at the northwestern margin of the Siberian Shield, and inboard to the east of the margin of the Siberian Craton (Fig. 1A). The Noril'sk Deposits are juxtaposed close to the Noril'sk-Kharaelakh wrench fault beneath or within the basal flows of the 250 Ma Siberian Trap basalts (Fig. 1B). The geology of the Noril'sk Region comprises a sequence of unexposed basement rocks that form the Siberian Craton, overlain by Proterozoic-aged metasedimentary rocks, and then a sequence of, Devonian and Permian-aged shallow marine and sabkha stratigraphy with intermittent packages of deeper water marls and shales (e. g. the Lower Devonian Razvedochninsky Formation and the Middle Carboniferous to Lower Permian Tungusskaya Series) and evaporates throughout the sequence, and Carboniferous coal-measures and shales (Fig. 2). These rocks are overlain by the Siberian Trap flood basalts and tuffs which comprise an almost continuous stratigraphy of nine different formations in the Noril'sk Region (e. g. Lightfoot et al., 1990, 1993; Wooden et al., 1993; Fedorenko et al., 1996). The entire package of sedimentary and volcanic rocks are cut by a complex network of faults, and folded on a regional basis to form basins and arches. The faults comprise a major group of NNE-SSW structures including the Noril′sk-Kharaelakh and Imangda Faults; these have both a strike-slip and a reverse sense of motion with development of periclinal fold structures and fault blocks (rifts) within the tectonic zone (Mezhvilk, 1984, 1995; Yakubchuk and Nikishin, 2004). The kinematics of displacement varies along the length of the Noril′sk-Kharaelakh fault (Mezhvilk, 1984, 1995; Fig. 3).

The dominant center of accumulation (depo-center) of metal-depleted basaltic rocks of the Nadezhdinsky Formation of the Siberian Trap is localized along the axis of the Noril′sk-Kharaelakh Fault, and this volcanic edifice has a volume of 5 000-10 000 km$^3$ (Fig. 3), from which up to ~99% of the precious metals and up to ~80% of the Ni, Cu, and Co has been removed as a response to equilibration of the parental magma with magmatic sulfide (Naldrett et al., 1995; Lightfoot and Keays, 2005; Monteiro and Lightfoot, 2006). This volcanic edifice is underlain by sedimentary rocks which contain intrusions that are more primitive than the basaltic rocks, but have similar ages and trace element ratios which indicate that they belong to a magma series that is temporally and



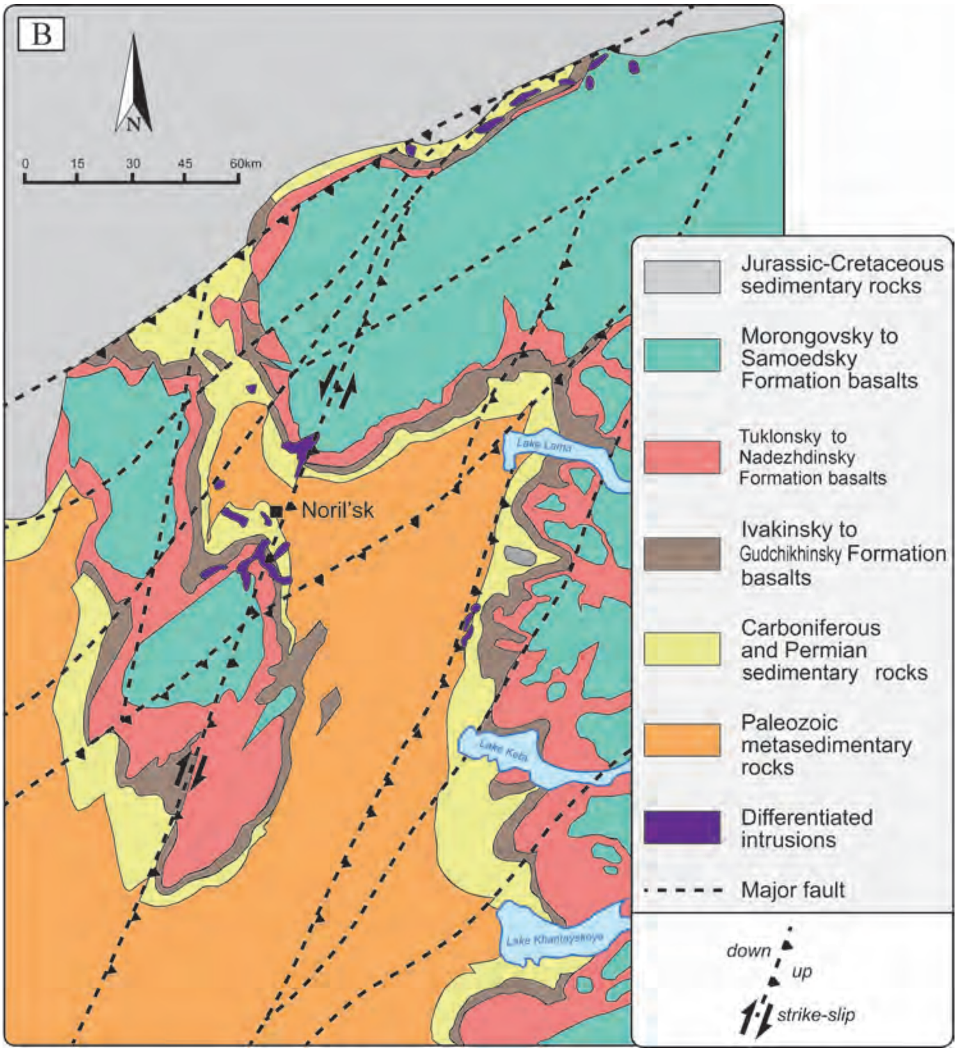



Fig. 1 A. Location of the Noril'sk Region at the northwestern margin of the Siberian Trap and the Siberian Craton. The location of the West Siberian Basin with associated rift-related flood basalts are shown after Saunders et al. (2005). B. Geological map of the Noril'sk region showing the principal groups of basalt formations, the major faults and their kinematics (Mezhvilk, 1984) and the location of differentiated Talnakh Type Intrusions (after Fedorenko, 1994; Fedorenko et al., 1996; Lightfoot et al., 1994)

spatially related (Naldrett et al., 1995; Hawkesworth et al., 1995). These include the strongly differentiated and weakly mineralized Ni-Cu-PGE-depleted Low Noril'sk and Low Talnakh Intrusions which underlie the footprint of the economically mineralized intrusions at Kharaelakh, Talnakh and Noril'sk Ⅰ (Fig. 4 and Lightfoot and Zotov, 2007). The Talnakh, Kharaelakh, and Noril'sk Ⅰ Intrusions are heavily mineralized and are positioned stratigraphically above the Low Talnakh and Low Noril'sk Intrusions and cross-cut the stratigraphy of the sedimentary rocks beneath the Siberian Trap (Figs. 2, 5), and in the case of the Noril'sk Ⅰ intrusion, the most basal Ivakinsky and Syverminsky Formation basalts of the Siberian Trap. The Talnakh and Kharaelakh Intrusions are located adjacent to the Noril'sk-Kharaelakh Fault, but appear not to be fed by a dyke along the main fault (Fig. 5). The Talnakh intrusion is at a higher stratigraphic level in Permian sedimentary rocks than the Kharaelakh Intrusion which is hosted in Devonian-aged sedimentary rocks (Fig. 2). The main part of the Kharaelakh intrusion rests largely within argillites of the Razvedochninsky Formation and the Tungusskaya series (Figs. 2 and 5), and these sedimentary rocks are typically missing or partially missing from the sequence along the axis of the widest part of the intrusion (Zotov, 1989).

The shape and form of the Low Talnakh Intrusion as described in Zenko and Czemanske (1994) includes both weakly differentiated sill-like domains, and thicker heavily differentiated channel-ways as shown in Figure 6. The channel-ways in the Low Talnakh Intrusion are distributed both

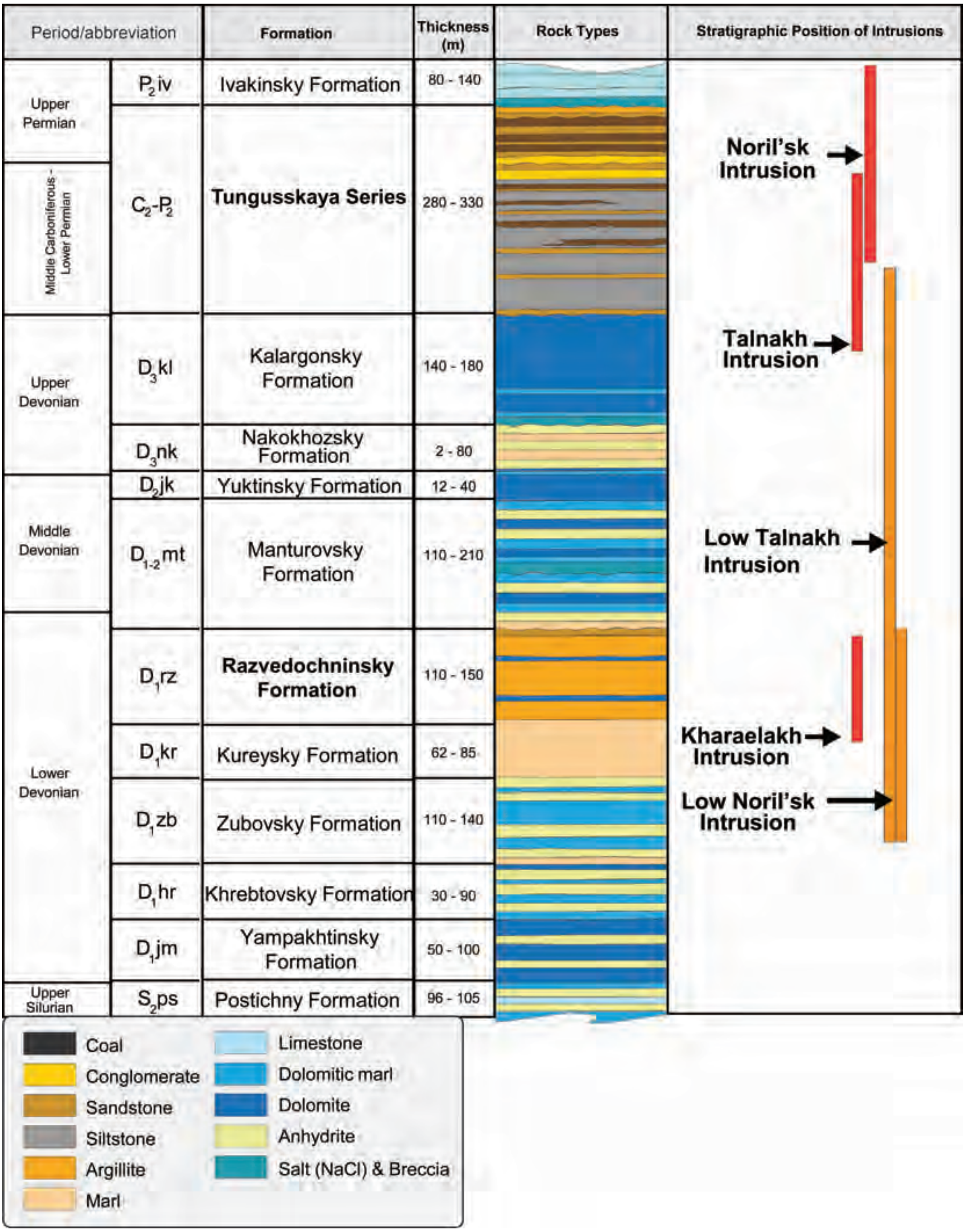



Fig. 2 Generalized stratigraphic column of the Silurian to Permian formations based on typical stratigraphic thickness in the area of the Talnakh Intrusion. The approximate stratigraphic positions of the intrusions are shown. Modified after Zenko and Czamanske (1994)

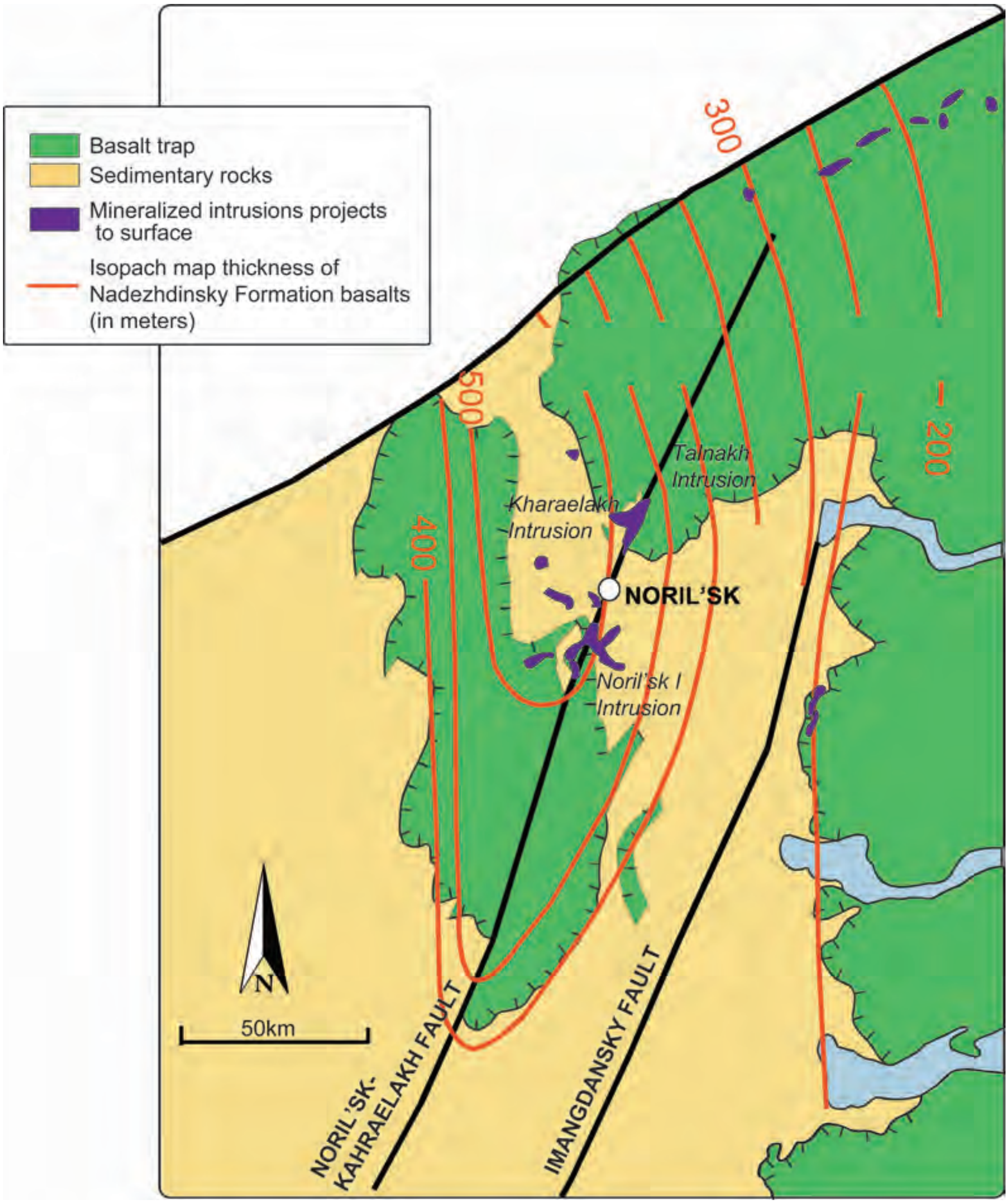



Fig. 3 General geology map of the Noril'sk Region showing the distribution of flood basalts and the location of the Ni-Cu-PGE-depleted Nadezhdinsky Formation of the Siberian Trap; the locus of maximum development of the Low Talnakh and Low Noril'sk type intrusions which are also Ni-Cu-PGE depleted is centered on the Noril'sk-Kharaelakh Fault and the center of the Nadezhdinsky depocenter as indicated by the isopachs. Note the localization of the intrusions proximal to the Noril'sk-Kharaelakh fault which is a wrench fault structure with both sinistral and dextral kinematics in different segments (Mezhvilk, 1984). After Lightfoot and Zotov (2007)

adjacent to the Noril'sk-Kharaelakh Fault and they extend away from the fault where they form a series of wider channels that spatially correspond to the anticlinal structures in the country rocks (Fig. 6). The bulk composition of the silicate rocks of the Low Talnakh Intrusion is very close to that of the Kharaelakh Intrusion (Zotov, 1989), but the two intrusions differ in the abundance of disseminated and massive sulfide mineralization, the development of less pronounced layering in the Kharaelakh Intrusion, and the extent of development of taxitic gabbrodolerites which is much greater in the Kharaelakh Intrusion. Although the Low Talnakh Intrusion is Ni-depleted and barren of sulfide

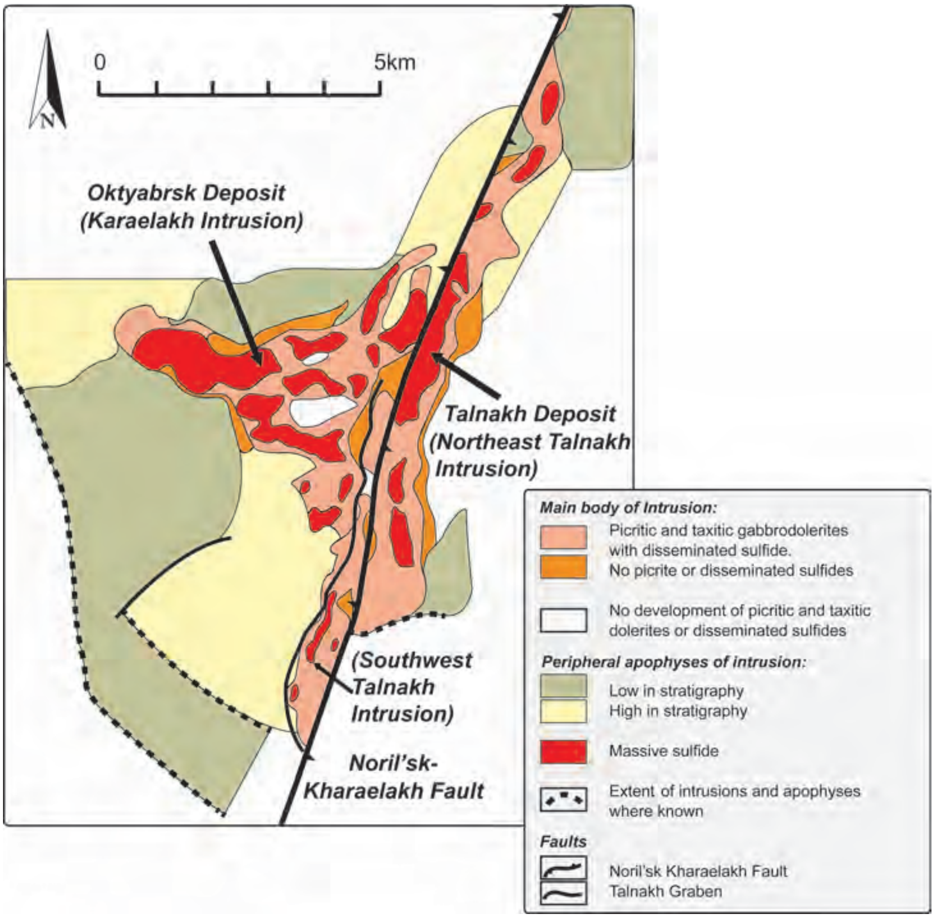



Fig. 4 Schematic geological map of the Kharaelakh-Talnakh mineral system (also called an "ore junction" or "ore knot" in the Russian literature) (after Zen′ko, 1986). The distribution of peripheral apophyses developed in the upper and lower portions of the stratigraphy adjacentto the main body of the intrusion is shown, and the Ni-rich massive sulfides are shown in relation to the distribution of the main bodies of the intrusions. The stratigraphy which contains picritic and taxitic gabbrodolerite of the main intrusion versus the flanking stratigraphy (apophyses) composed of olivine-and olivine-free gabbrodolerite is shown

mineralization, the rocks show a similar geometry and range of mafic-ultramafic rock types when compared to the economically mineralized Talnakh and Kharaelakh Intrusions (e. g. Naldrett et al., 1995; Hawkesworth et al., 1995). Although the Kharaelakh and Low Talnakh Intrusions have a contact relationship (Fig. 7A and Zenko and Czamanske, 1994), there is some ambiguity about the relative timing; the weight of geological evidence favors the emplacement of the Low Talnakh Intrusion before the Kharaelakh Intrusion. The geochemical evidence linking the differentiated Talnakh Intrusion to a more primitive Morongovsky magma type, and the Low Talnakh Intrusion to a more primitive variant of the Nadezhdinsky magma type is consistent with the relative order of eruption of maginas recorded in the basalt stratigraphy (Naldrett and Lightfoot, 2006).

## 3 Geological relationships between the Talnakh and Kharaelakh intrusions and the country rocks

The heavily mineralized and differentiated Talnakh and Noril′sk intrusions differ from the weakly mineralized and unmineralized differentiated Low Talnakh and Low Noril′sk type intrusions in the abundance of flanking apophyses and the large scale of the metamorphic haloes (Zotov, 1979; Korzhinskii et al., 1984). The widest parts of the Kharaelakh Intrusion are located where the

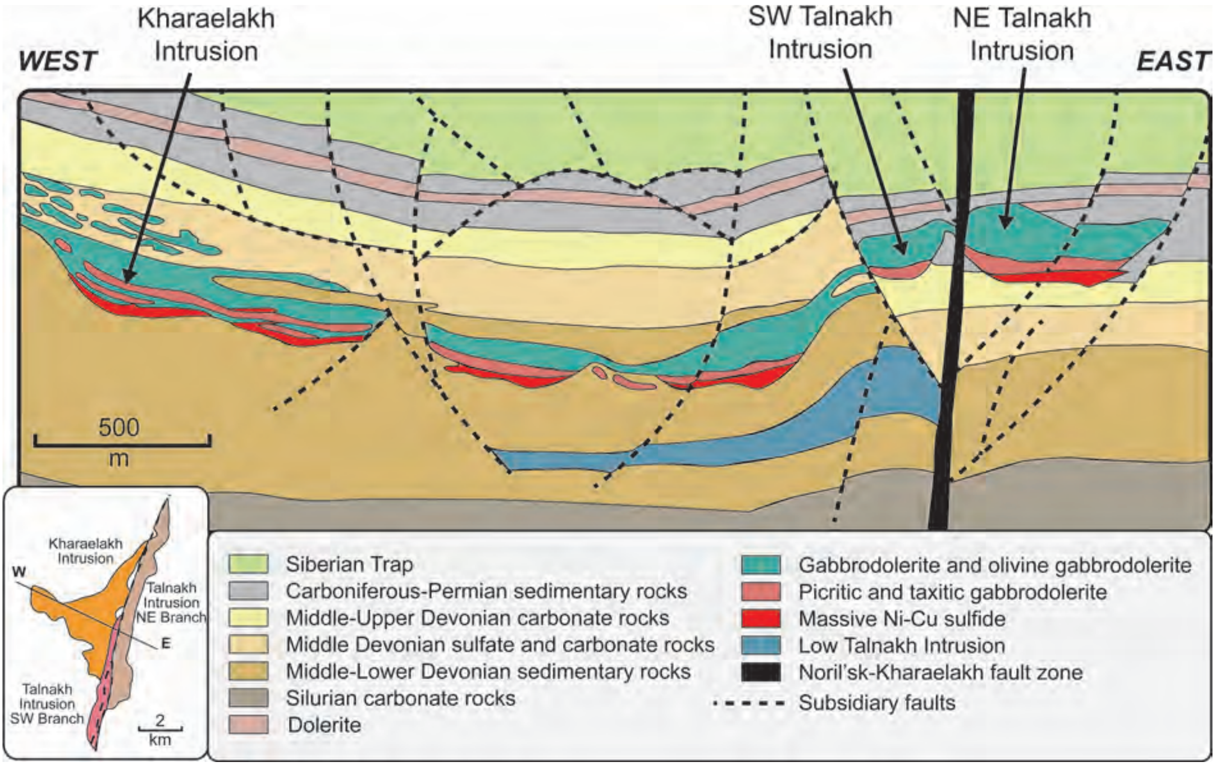



Fig. 5　Cross section showing the geology and structure of the Kharaelakh and Talnakh Intrusions, and the positions of the intrusions in the country rock stratigraphy (based on Zenko and Czamanske, 1994). Note the location of the major Noril'sk-Kharaelakh Fault Zone and the subsidiary fault structures developed along the flanks; these fault structures are related to the development of peripheral synclinal structures which are occupied by the intrusions

country rocks have a periclinal structure in the flanking areas of the Noril'sk-Kharaelakh wrench fault (Zenko and Czemanske, 1994; Fig. 7A). The main zones of basal Ni-rich massive sulfide mineralization are either located at the base of the base of the intrusion or within ~20 m of the intrusion in the underlying sedimentary rocks, and broadly follow the axis of the channels (Fig. 7B after Zenko and Czemanske, 1994). In cross section view, at the northern end of the Kharaelakh and Talnakh Intrusions, the chambers resemble oval conduits within more laterally extensive narrow sheets (Fig. 5), and the base of these conduits contain the deposits of the Skalisty and Gluboky Mine Areas. The geometry of the Noril'sk I Intrusion is very similar to the Talnakh and Kharaelakh conduits (e. g. Lightfoot and Zotov, 2007), and although the association is with disseminated sulfides, the same channel-ways control both styles of mineralization (Lightfoot and Evans-Lamswood, 2013A, B).

The main conduits of the Kharaelakh Intrusion have a form similar to the Low Talnakh Intrusion. The intrusions generally slope at angles of <=10°, and form tabular bodies <300 m thick but with a length of several kilometers. Both bodies are sub-conformable with the stratigraphy of the host rocks at various levels in the Devonian, Permian and Triassic formations of sedimentary rocks and basalts. Both intrusions comprise a series of branches which appear to trend along the flanks of the Noril'sk-Kharaelakh Fault. The main parts of both intrusions have a simple structure with an upper 1/3-2/3rds of the intrusion comprising: ①Layered medium-grained olivine-free gabbrodolerites at the upper contact. ② Coarse-grained olivine-free gabbrodolerites through olivine-bearing and olivine gabbrodolerites, and ③ Olivine-rich (40%-60%)

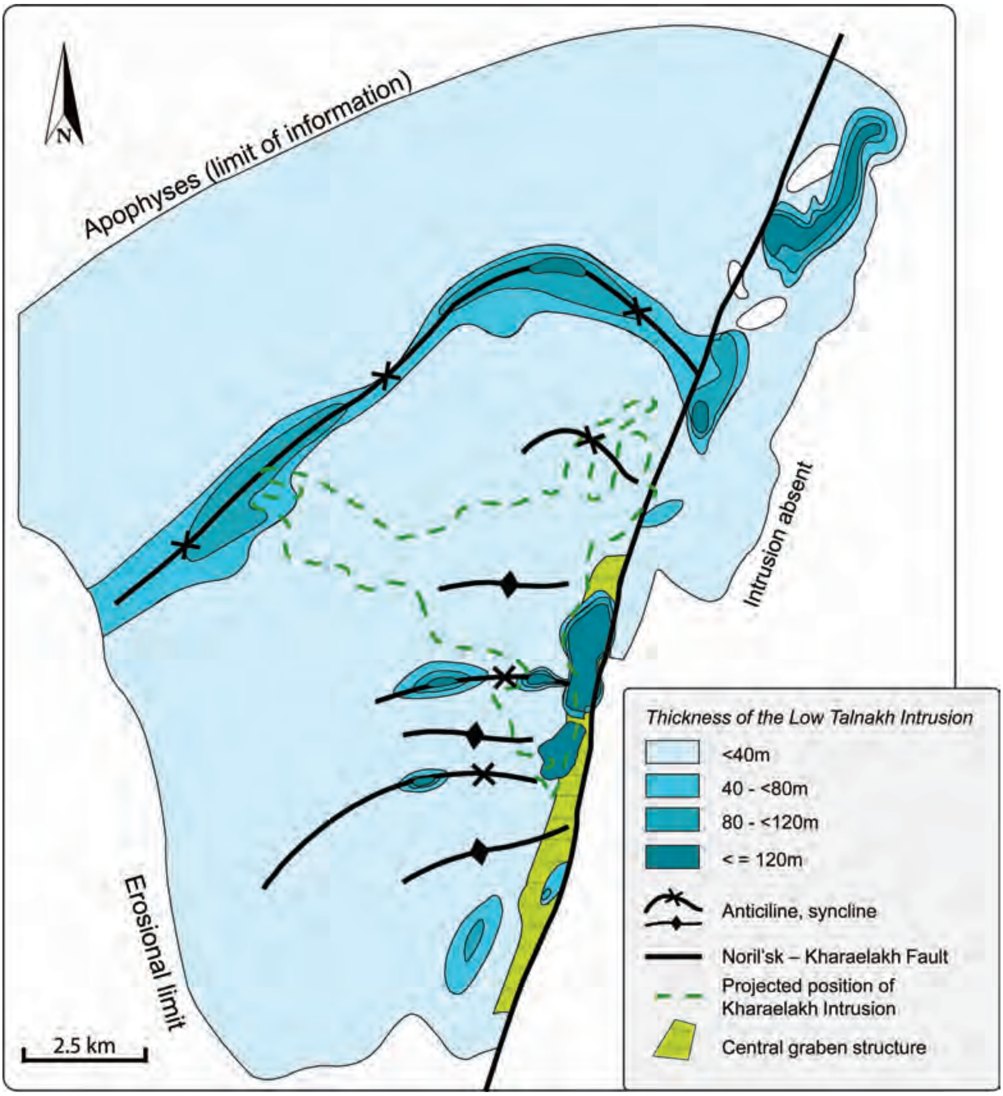



Fig. 6 Contour map showing the thickness of the Low Talnakh Intrusion located beneath the Talnakh and Kharaelakh Intrusions. Note how the intrusion conduits follow synforms and rift structures linked to the Noril′sk-Kharaelakh Fault (Lightfoot and Evans Lamswood, 2013 modified after Zenko and Czamanske (1994). The distribution of apophyses of the Low Talnakh Intrusion is also shown, and in this respect, the morphology of the intrusion is similar to that of the Kharaelakh Intrusion

gabbrodolerite. This layered series is underlain by coarse-grained taxitic gabbrodolerite which often contain fragments of host rocks. The proportion of olivine gabbrodolerite declines towards the edge of the intrusion, and the taxitic gabbrodolerites become finer-grained and more homogeneous.

The margin of the Kharaelakh Intrusion consists of a flanking domain where the intrusion has complex relationships with the surrounding sedimentary rocks at a range of scales, viz:

(1) Sheet-like apophyses of weakly differentiated gabbrodolerite sills (termed ‘the sills of the Kharaelakh Intrusion′ and shown in Figure 8 after Zotov, 1989). The apophyses are laterally discontinuous extending for up to ~5 km from the main intrusion and they occur on the western and eastern flanks of the Kharalekah Intrusion (Zotov, 1989).

(2) Apophyses which are described in Zotov (1989) as 1-10 m thick sills within a wide domain

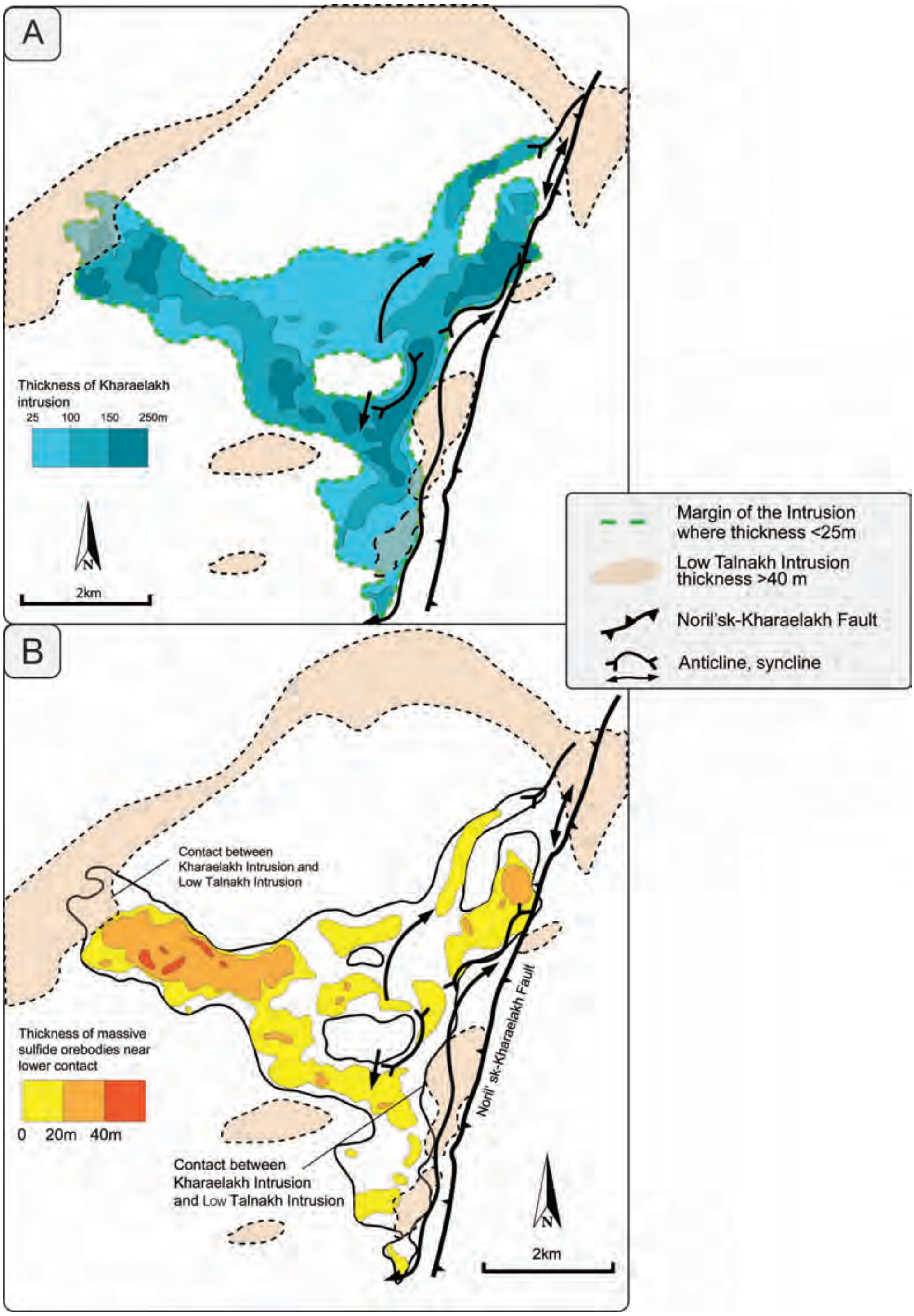



Fig. 7　Contour maps showing the thickness of the Kharaleakh Intrusion, and the thickness of massive Ni-rich ores at the lower contact of the Kharaelakh Intrusion. The boundary of the intrusion is marked where the differentiated intrusion thins below 25m. A. Thickness of the intrusion in meters showing the development of distinct channel-ways parallel to the Noil'sk-Kharaelakh Fault and at right angles to the fault. The location of these conduits is approximately coincidental with the development of a synformal structure to the west of the Noril'sk-Kharaleakh Fault, and a graben-like structure between subsidiary faults of the Noril'sk-Kharaelakh Fault Zone. B. Thickness of massive Ni-rich sulfides developed proximal to the basal contact of the Intrusion; the localization of mineralization in the apparently blind western segment of the Kharaleakh Intrusion is not readily explained unless the pulse of magma took place into a failed conduit previously exploited by the Low Talnakh Intrusion. Modified after Zenko and Czamanske (1994)

of metamorphosed metasedimentary rocks adjacent to the Kharaelakh Intrusion (these apophyses are termed "the horns of the Kharaelakh Intrusion"; Zotov, 1989; Fig. 8, 9A, B). The extensive development of the sill-like apophyses is interpreted in cross-section in Fig. 8 and 9A. The apophyses are seemingly not connected in two dimensional space, but Zotov (1989) showed that they connect back to the main body of the intrusion beyond the plane of the section.

(3) Local apophyses of gabbroic magma that were rapidly cooled where they are in direct contact with the surrounding hornfelsed sedimentary rocks to form lobes on the scale of 10-50cm which have fine-grained aphanitic margins and fine-grained dolerite interiors (these apophyses are termed "the ears of the Kharaelakh Intrusion"; Zotov, 1989; Lightfoot and Zotov, 2007; Figs. 10A-D). These lobes are more typically developed on the upper contact of the apophyses of the Kharaelakh Intrusion. Although many of the lobes appear to be connected to the main apophyses, there are reported examples where rounded bodies of dolerite appear to have no connection to the main intrusion (Fig. 10B-C). The sample in Fig. 10A shows that the emplacement of the gabbrodolerite apophyses does not appear to disturb the conformable stratigraphy of the sedimentary rocks.

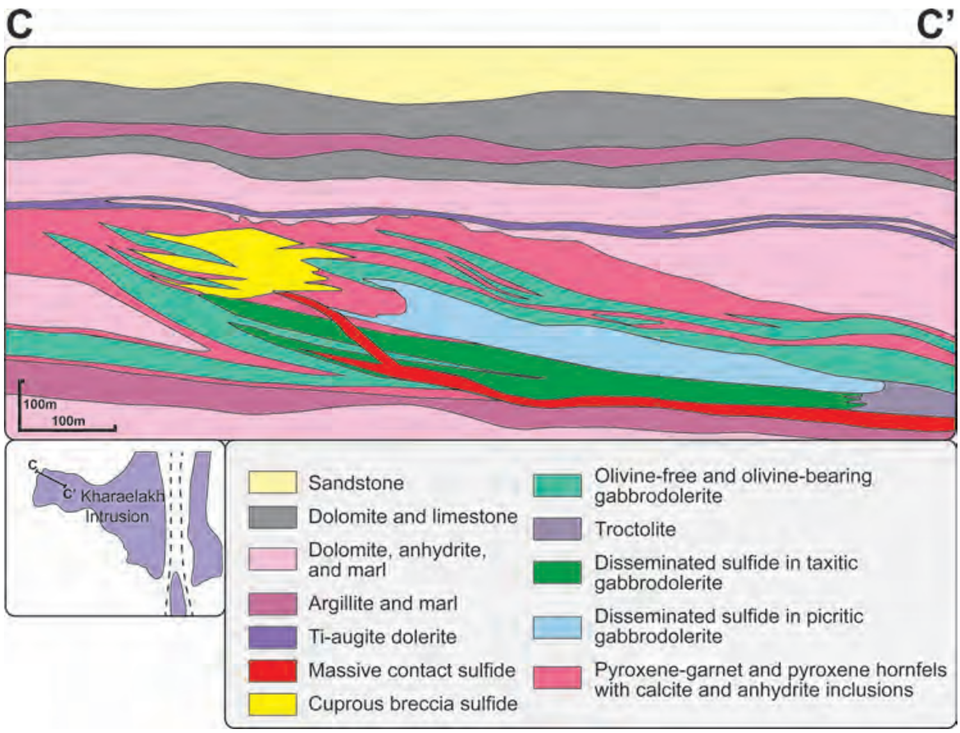



Fig. 8 Schematic vertical WNW-ESE section through the Kharaelakh branch of the Kharaelakh Intrusion hosted in the Kalargonsky, Nakakhozsky, Yuktichesy, Manturovsky, Razvedochninsky, Kureisky, and Zubovsky formations (Fig. 2). Diagram shows the main rock types of the differentiated intrusion, the distribution of massive and disseminated sulfides, and the relationship of the massive sulfides to the breccia-hosted sulfides at the upper exocontact. The apophyses of the Kharaelakh Intrusion are shown as sill-like horns of olivine-bearing and olivine-free gabbrodolerite and a continuous sill-like body which is termed the "sills of the Talnakh Intrusion". Note the scale of the metamorphic halo links to the development of the apophyses and lobes of the Kharaelakh Intrusion; the metamorphic halo is thin over the main intrusion towards the ESE. Note that Zotov (1989) documents variations in massive sulfide composition (transition from monoclinic through hexagonal pyrrhotite to troilite, and S isotope composition ($\delta^{34}S$ from 10. 1 to 13. 9) of these ores from west to east. After Korzhinskii et al. (1984), Zotov (1989) and modified by Lightfoot and Zotov (2006)

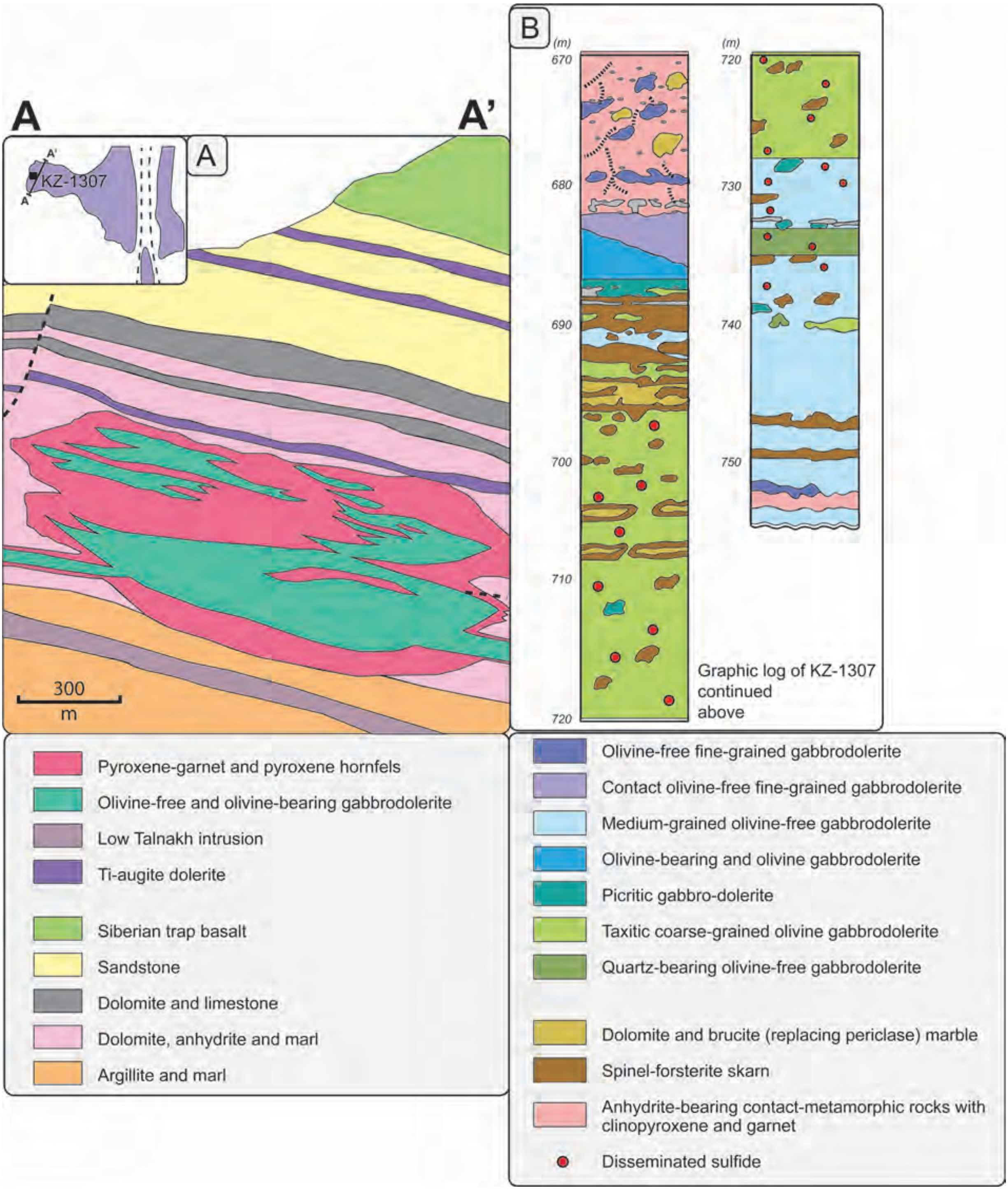



Fig. 9　A. N-S geological section through the western part of the Kharaelakh Intrusion, showing how the main intrusion breaks up into sills which are surrounded by a wide metamorphic halo in Devonian dolomites, anhydrites, and marls. The intrusion does not significantly disturb the stratigraphy of the sedimentary rocks. From Zotov (1989). B. Vertical section (continuous in the two logs) through vertical Borehole KZ-1307 that penetrates the frontal portion of the Kharaelakh branch of the Upper Talnakh Intrusion (based on detailed petrographic data); based on Zotov (1989)

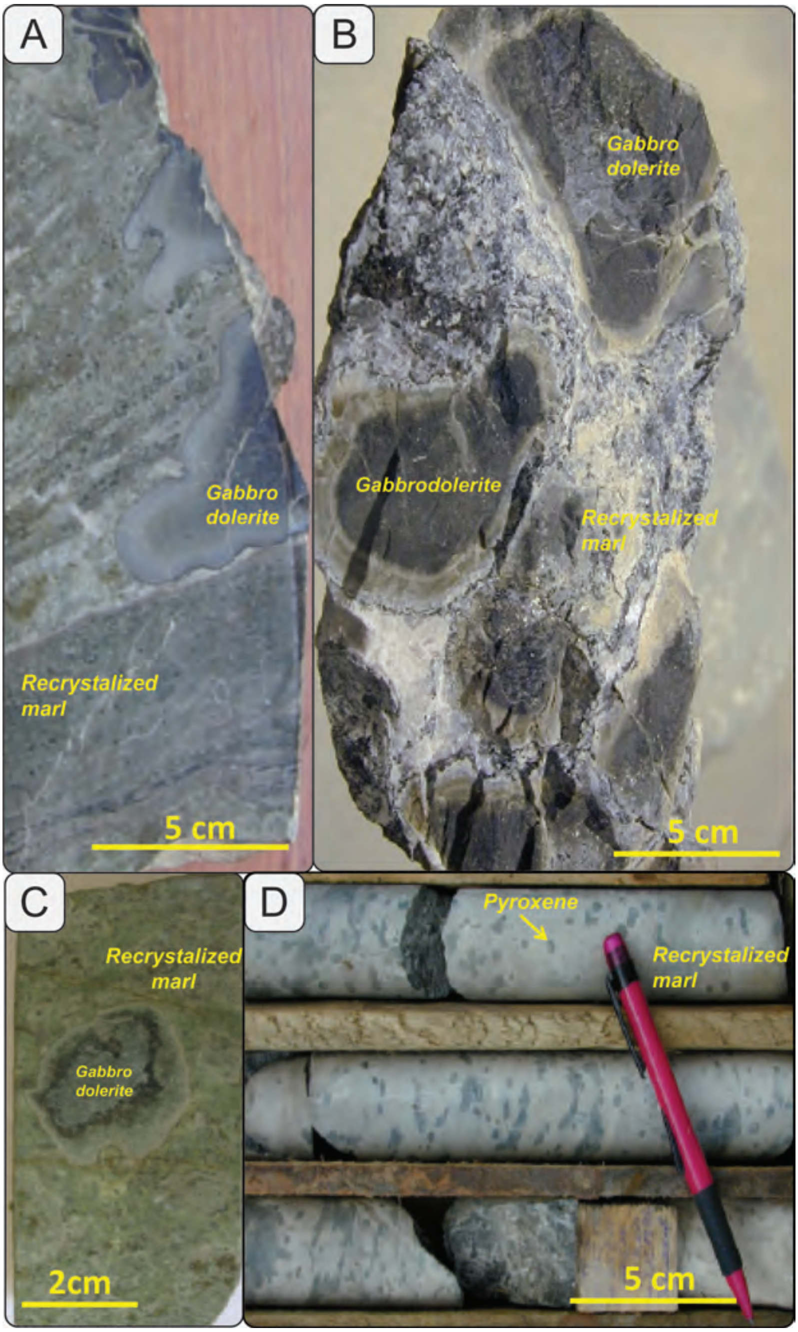



Fig. 10 A. A sample of drill core from the western boundary of the Kharaelakh Intrusion in the Oktyabrysk Mine area. The sample comprises marl and anhydrite of the Manturovsky Formation that is replaced by the frontal lobes of the Kharaelakh Intrusion. The lobes are composed of chilled gabbro-dolerite grading into aphyric gabbro-dolerite in the center. The lobes often develop into thin sheets along the bedding, and these sheets may blow out laterally into further ball-shaped lobes of gabbro-dolerite. Photograph was taken of a sample reported in Zotov (1989). B. A similar sample to A where the cross-section view of the gabbrodolerite lobes; Manturovsky Formation, Oktyabrysk Mine area (Lightfoot and Zotov, 2006). C. An example of a pipe-like lens of gabbrodolerite in Manturojvsky Formation anhydrite and carbonate marls, Oktyabrysk Mine. Photograph from sample reported in Zotov (1989). Core diameter 7.6cm. D. Typical pyroxene hornfels of the Razvedochininsky Formation, developed between 1-5m thick lateral sill-like apophyses of gabbrodolerite in the Oktyabrysk Mine area of the Kharaleakh Intrusion. The sample is from drill core TG21 at 952m depth (Lightfoot and Zotov, 2006)

A study by Zotov (1989) used drill core from the western branch of the Kharaelakh Intrusion. Zotov (1989) documented detailed logs for 13 cores from outside the Kharaelakh Intrusion through the frontal lobes and sills into the main body of the intrusion (Fig. 11A-B). Borehole sections 1 and 2 were located 2.5 and 1.0 km from the front of the main intrusion, and borehole 9 was located in the main intrusion. Boreholes 12 and 13 penetrated the SE flank of the Kharaelakh Intrusion. To illustrate the correlation between the different sections, the base of the Middle Devonian Manturovskaya subsuite ($D_2mt_2$) is used to anchor the relative positions of the different logs (Fig. 11A). The sections show the extent of the intrusion and associated mineralization within a stratigraphy comprised mostly of the Razvedochninskaya Formation terrigenous and chemical sedimentary rocks. The thickness of the Razvedochninskaya Formation appears to be almost constant, whereas the thickness of the Kharaelakh Intusion varies by an order of magnitude. In detail, the drill core sections with thin portions of the Kaharelakh Intrusion tend to be about 25% thinner than sections where the intrusion is thick.

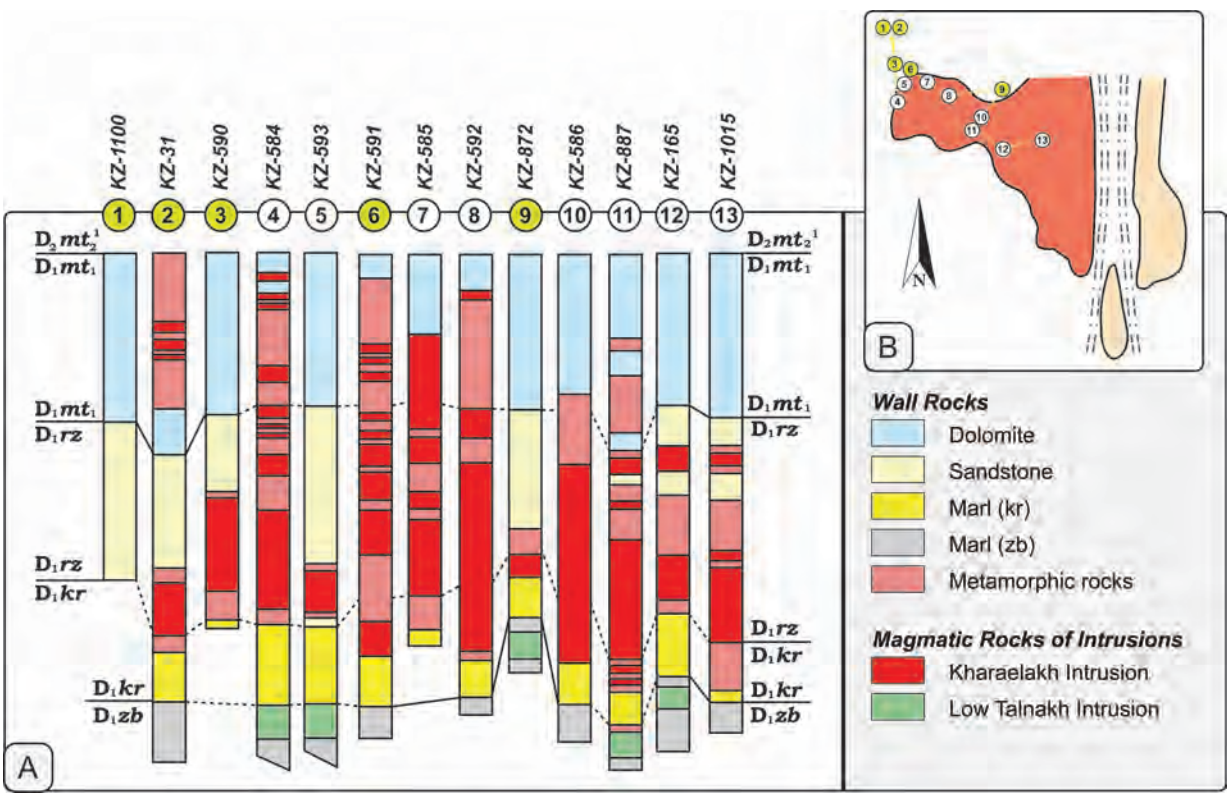



Fig. 11　A—B: Correlation of drill ore sections across the Kharaelakh Intrusion along the polyline shown in Fig. 11A, along the long axis of the Kharaelakh branch. Unmetamorphosed rocks include mainly dolomites of the Manturovskaya Formation (mt), shales and sandstones of the Razvedochninsky Formation (rz), marls of the Kureisky Formation (kr), and marls of the Zubovsky Formation (zb). The metamorphosed rocks are not broken out by protolith. The drill section numbers and cores examined in Zotov (1989) are located on Fig 11A based on Zotov (1989). Map shows the location of holes logged through the Kharaelakh Intrusion. The boundaries of the Kharaelakh, NW Talnakh, NE Talnakh Intrusions are shown where the total thickness of the intrusion exceeds 30m. The location of the "graben" structure that follows the Noril'sk-Kharaelakh Fault corridor is shown. The locations of drill cores 1-13 are shown with those on the flanking margins highlighted in yellow circles

## 4 The metamorphic halo of the Kharaleakh Intrusion

The development of extensive metamorphism of the country rocks is illustrated in Fig. 8 and 9 from Zotov (1989). Unusually large exocontact haloes surround the frontal parts of the Kharaelakh Intrusion (Turovtsev, 2003), and they are very atypical of the scale of metamorphism found around other much larger intrusions. We note a number of detailed features of the metamorphic halo, viz:

(1) The thickness of the metamorphic halo beyond at the flanks of the Kharaelakh Intrusion is typically much larger than that developed around the main body of the intrusion (see Fig. 8). Zotov (1989) showed that the metamorphic halo can reach 500m in thickness and extend up to 1.5 km from main intrusion body at the western flank. Towards the rear part of the intrusion in the east, the thickness of metamorphic rocks decreases to 2-10 meters.

(2) The thickness of hangingwall metamorphic halo is larger by a factor of 2-2.5 than the footwall metamorphic halo.

(3) High temperature mineral metamorphic parageneses vary with position of the halo relative to the main conduits of the intrusion (Zotov, 1989). Monomineralic clinopyroxene hornfelses prevail between apophyses and at the rear of the intrusion (60%-70% vol. of the metamorphic rocks); the rocks have the spotted appearance of the pyroxene hornfels in drill core (Figure 10D). The rocks of the metamorphic halo also contain anhydrite, Mg-rich marbles, pelitic hornfels and forsterite skarns (e. g. Turovtsev, 2003; Zotov, 1989; Zotov and Pertsev, 1978). The high-temperature (800-900℃) forsterite + clinoproxene + calcite facies metamorphic rocks compose a larger proportion of the metamorphic rocks towards the front of the intrusion (up to 90%).

(4) The Low Talnakh Intrusion has a main body with similar thickness to the Kkaraelakh Intrusion, but the metamorphic halo is 2-10 times narrower (Turovtsev, 2003).

The localization of the metamorphism at the intrusion flank as opposed to the main chonolith conflicts with the model that the larger metamorphic halo of intrusion reflects the greater volume of magma that has travelled through the system conduit (Naldrett et al., 1995); in such a model, the metamorphic halo should be wider where the chonolith is thickest.

Metamorphic rocks in the upper exocontact of the Kharaelakh Intrusion comprise 10%-30% of the metamorphic aureole, and consist of monticelite, merwinite, larnite and spurrite which signifies a higher-T metamorphism than the forsterite skarn. Some of the metamorphic minerals were formed late in the evolution of the intrusion as evidence by spinel + monticellite veinlets which cross into the upper gabbrodolerites (Zotov, 1979).

## 5 Magmatic stage metasomatic rocks

The stratigraphy of drill hole KZ 1 307 shown in Fig. 9B depicts the detailed relationships at the front of the Kharaelakh Intrusion; it is evident that the taxitic gabbrodolerite replaced the dolomitic marble, with the development of magnesian skarns adjacent to the mafic magma. Skarn xenoliths with relics of brucite marble (where brucite replaces periclase) can be found inside the intrusion.

An important group of samples is described in Zotov (1989). The rocks show the development of skarn assemblage mineralogies directly adjacent to fresh unaltered gabbrodolerites of the Kharaelakh Intrusion. Mg-skarns replace dolomite marble which is in contact with gabbrodolerite. Skarn fragments are sometimes enclosed in taxitic gabbrodolerites (Fig. 12A), or partially resorbed in taxitic gabbrodolerite (Fig. 12B). Flame-like dolerite protuberances sometimes cut into the skarn and result in break-down and assimilation of fragments into the magma. The details of these relationships are described in Zotov (1979; 1989), and the geological relationships underpin a paragenetic sequence from high temperature to low temperature mineral associations; viz:

(1) Magmatic stage magnesian skarns (spinel-forsterite skarns), formed before the final crystallization of Talnakh magma type.

(2) Post-magmatic magnesian skarns (spinel-clinopyroxene, spinel-montichellite).

(3) Magnesian scarns with phlogopite.

(4) Garnet-clinopyroxene calc-skarns.

(5) Vesuvianite-wollastonite calc-skarns.

(6) Albitised metasomatic rocks.

(7) Development of prehnite, epidote, tremolite and carbonate and anhydrite veins with xonotlite and apophyllite.

(8) Carbonate and anhydrite veins with galena and Co-Ni arsenide mineralization.

(9) Brucite, serpentine, hydro-garnet-serpentine and chlorite rocks.

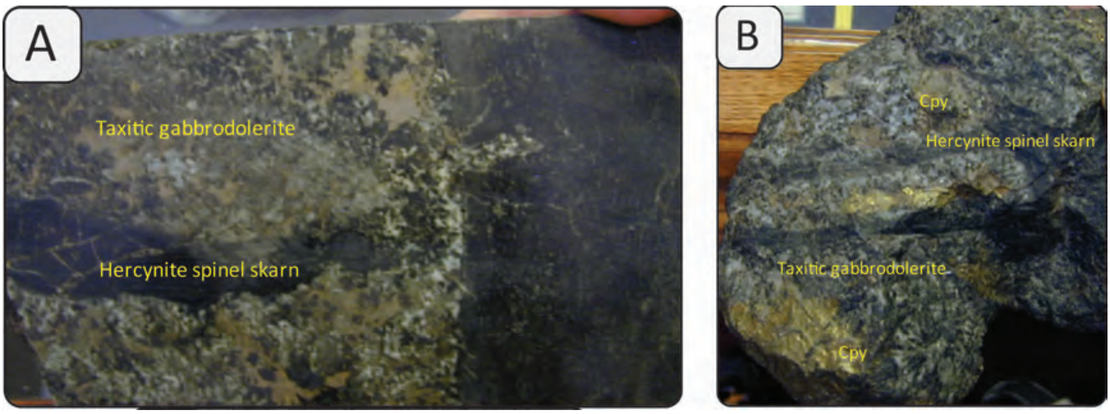



Fig. 12 A. Contact of sulfide-bearing taxitic gabbrodolerite (left) with spinel-forsterite skarn (right). Note that the orientation of the corroded skarn xenolith in the dolerite is perpendicular to the contact. Another noteworthy feature is the protrusion of taxitic gabbrodolerite into the skarn that appears to indicate replacement. The sample was taken from the lower contact zone of the Upper Kharaelakh Intrusion. Field of view is 10cm. B. Loop-shaped relict xenolith of spinel-forsterite skarn in taxitic gabbrodolerite, with taxitic gabbro-dolerite replacing the central part of the xenolith. Field of view is 5cm. From the Kaharaelakh Intrusion (sample from Zotov, 1989 where details are presented)

The high-temperature metasomatic rocks represented by the magnesian skarns are restricted to intrusive contacts. They are developed near to the exocontact zone of intrusion or within the intrusion. At some distance from the intrusive contact the high-temperature magnesian skarns are replaced by lower temperature skarns as well as other metamorphic rocks (e. g. the garnet-pyroxene hornfels). The transformation of high-temperature metasomatic rocks into low-temperature metasomatic rocks is very widespread. Some magnesian skarns are present in places where the intrusion is in contact with dolomite-bearing country rocks.

## 6 Disseminated sulfides of the Kharaelakh and Noril'sk 1 intrusions

The taxitic olivine gabbrodolerites are characterized by variations in texture, grain size, sulfide and inclusion content. In many ways they resemble the variable-textured olivine gabbros and troctolites of the Voisey's Bay Intrusion in Labrador, Canada (Lightfoot et al., 2012A, B) and the mineralized inclusion-laden gabbronorites of the Sublayer of the Sudbury Igneous Complex, Ontario, Canada (Lightfoot et al., 1997A, B). The taxite is highly variable on the scale of both outcrop and mine opening. Fig. 13A shows a taxite in a mine opening from the Talnakh Intrusion; the rock comprises interstitial to irregular segregations of sulfide separated by olivine gabbronorite which contains fragments of skarn material (containing hercynite spinel) and vesicles with quartz-carbonate in-filling. The variability in texture within a single hand samples in Fig. 13B shows that the rock is broadly pegmatoidal in parts and a fine-grained olivine gabbrodolerite in other parts. In thin section, the scale of these primary magmatic variations is less than 1cm (Fig. 13C).

Disseminated sulfides are concentrated in the lower portions of the piicritic gabbrodolerite. The sulfides occur as droplet-shaped segregations; sulfides also occur in the lower and upper taxitic gabbrodolerites, and these sulfides have an interstitial texture. The contact domains and apophyses typically have no sulfides. The boundary between picritic and taxitic gabbrodolerite is typically un-even and shows embayments and protrubrances and there are widespread veins of taxitic gabbrodolerite that penetrate into the picritic gabbrodolerite for 0.5-5m. Locally taxitic gabbrodolerite occurs as vein-like enclaves in the picritic gabbrodolerite, but there is general agreement that the taxitic gabbrodolerites formed after substantial crystallization of the picritic gabbrodolerites (Zotov, 1989).

The disseminated sulfides typically do not grade into massive sulfides with increased sulfide content. The massive Ni-rich sulfides are often depicted as concentrations at the base of the Talnakh and Kharaelakh Intrusions, but their distribution is now widely understood to be controlled by the lower contact and the immediate footwall where veins cross-cut the sedimentary sequence (Fig. 13D).

The picritic gabbrodolerites frequently show the development of blebby sulfide textures, where the sulfides are zoned from pyrrhotite-pentlandite-rich bases to chalcopyrite-rich tops (Fig. 14A).

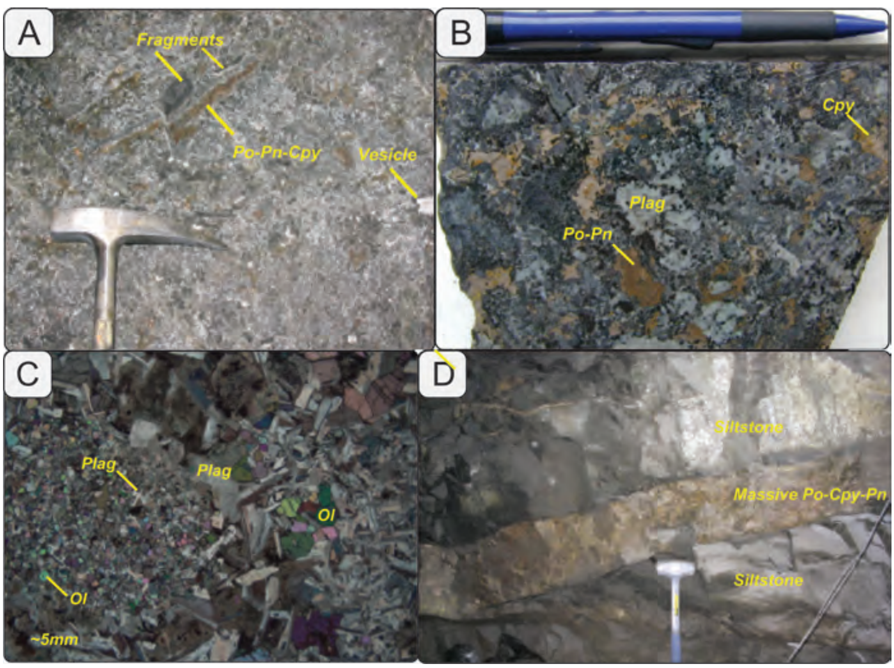



Fig. 13 A. Taxitic gabbrodolerite from the Talnakh Intrusion at Komsomolsk Mine showing irregular sulfide segregations within a taxitic olivine gabbro-dolerite which contains fragments of Mg-rich skarn (see Zotov, 1989); these fragments resemble to paragneiss inclusions from the Voisey's Bay Deposit as described in Li and Naldrett (2000), Ripley and Shin (2002), and Lightfoot and Naldrett (1999). The country rocks nearby are principally dolomite marbles which have been metamorphosed to form brucite (after periclase); the black skarn material comprises of hercynitic spinel and forsterite. The reaction relationships described in Zotov (1989) are consistent with transfer of Si and Al into the magma to leave a Mg-rich skarn assemblage. The same black skarn fragments areoften developed in the taxite (see Fig. 12A-B). B. Taxitic olivine gabbro-dolerite sample from Oktyabrysk Mine. C. Sample of taxitic olivine gabbro-dolerite in polished thin section (xp) from core KZ997 at 958. 4 m depth (from N. S. Gorbachev). Note the diversity in textures and grain size of olivine on the scale of the thin section. D. Massive sulfide vein cutting through footwall siltstone beneath the NE Talnakh Intrusion (Skalisty Mine)

The sense of fractionation of the sulfide blebs is systematic in samples from different locations at Noril'sk (Fig. 14B-D), and polished samples reveal a zonation with development of magnetite at the base (Fig. 14E). Fig. 14B-C show that the blebs of sulfide are associated with cryptocrystalline quartz, and it is possible that these blebs occupy primary gas-laden vesicles in the magma. Fig. 14F shows vesicles in the Syverminsky Formation basalts adjacent to the Noril'sk Ⅰ Intrusion where vesicles in the country rock basalts are replaced by pyrrhotite, pentlandite and chalcopyrite.

In a study of the development of taxities in the Kharaelakh Intrusion, Zotov (1989) used the work of Genkin et al (1977) to show that the irregular development of a taxite (within an envelope of picritic gabbrodolerite above and an olivine gabbrodolerite beneath) is not clearly linked to the distribution of disseminated sulfide mineralization (Fig. 15). The mineralization zone appears to cross-cut through taxitic gabbrodolerites and picritic gabbrodolerites of the Khararaelakh Intrusion.

Another key relationship documented by Zotov (1989) is the zonation in mineralogy of the disseminated sulfides in the Kharaelakh Intrusion. Fig. 16A-B shows two sections through the Kharaelakh Intrusion. In Fig. 16A, the host lithology is shown, and in Fig. 16B the same section is used to show the mineralogy of the disseminated sulfides. This diagram shows that the sulfide assemblage varies across the Kharaelakh Intrusion and becomes more metal-rich towards the center of the intrusion and more metal-poor towards the flanks. There is a superimposed trend towards metal-rich sulfides towards the core of the disseminated sulfide domain. These trends appear to

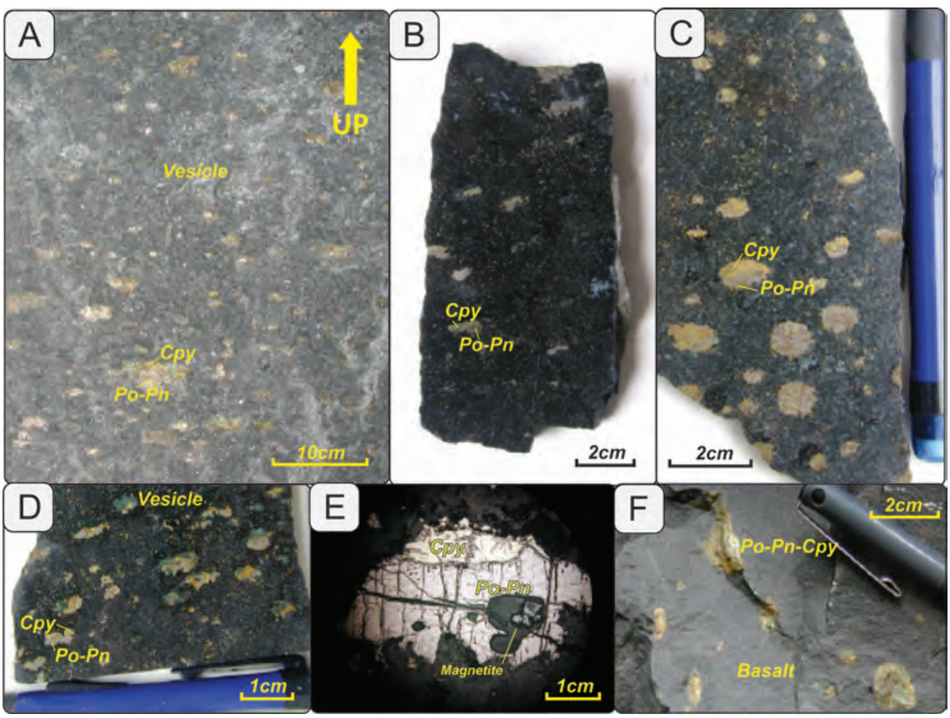



Fig. 14 A. Picritic gabbro-dolerite with 0.5-1cm fractionated blebs of Po-Cpy-Pn sulfide, Komsomolsk Mine, NW Talnakh Intrusion. B. Picritic gabbro-dolerite with flattened blebs comprising fractionated Po-Pn (lower part) and Cpy (upper part). C. Fractionated blebby sulfide from the taxitic gabbro-dolerite at Oktyabrysk Mine in the Kharaelakh Intrusion. Note the presence of green cryptocrystalline silica around the upper part of the belbs-these are possibly vesicle infillings. D. Picritic gabbro-dolerite with blebby sulfide from the Kharaelakh Intrusion-in this case there is no clear evidence of a mineralogy that might indicate vesicle infillings. E. Polished sample from Oktyabrsk Mine Area, Kharaelakh Intrusion. This zoned globule of sulfide has a chalcopyrite-rich upper domain and a pyrrhotite-pentlandite-rich base. The globule is ～4 mm across, and is slightly flattened. F. Replacement of vesicles in Syverminsky Formation basalt, roof region, Noril'sk 1 Intrusion, Medvezhy Ruchey Open Pit Mine

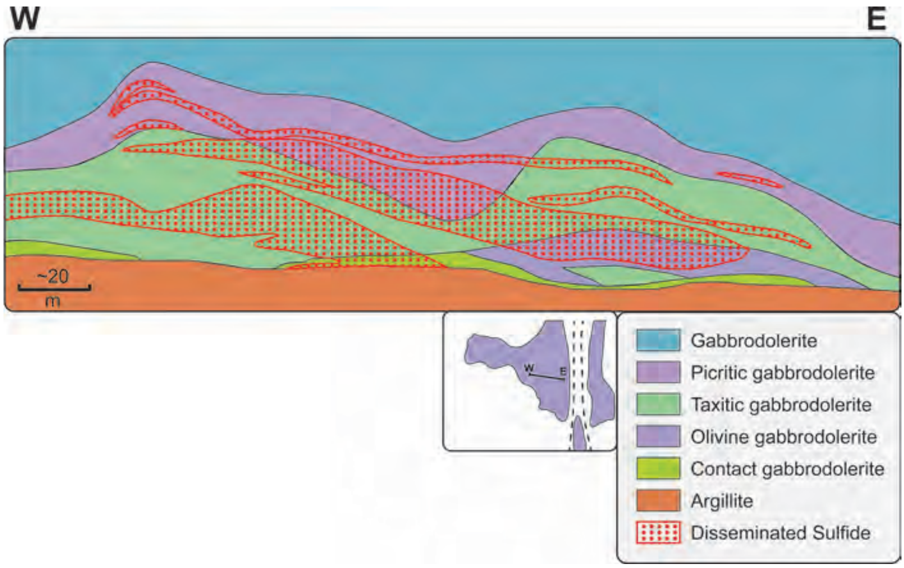



Fig. 15 Cross section through the southwestern part of the Kharaelakh Intrusion showing the distribution of the olivine gabbro-dolerites, taxitic gabbro-dolerites, picritic gabbro-dolerites, and gabbro-dolerites, with the superimposed position of disseminated sulfides (from Zotov, 1989 and after Genkin et al. (1971). This diagram shows that the disseminated sulfide envelope cross-cuts the sequence of silicate rocks that form the stratigraphy of the differentiated intrusion. The lack of correlation between the silicate host lithologies and the distribution of disseminated sulfides is not easily explained by simple in-situ accumulation of the sulfide from a single magma

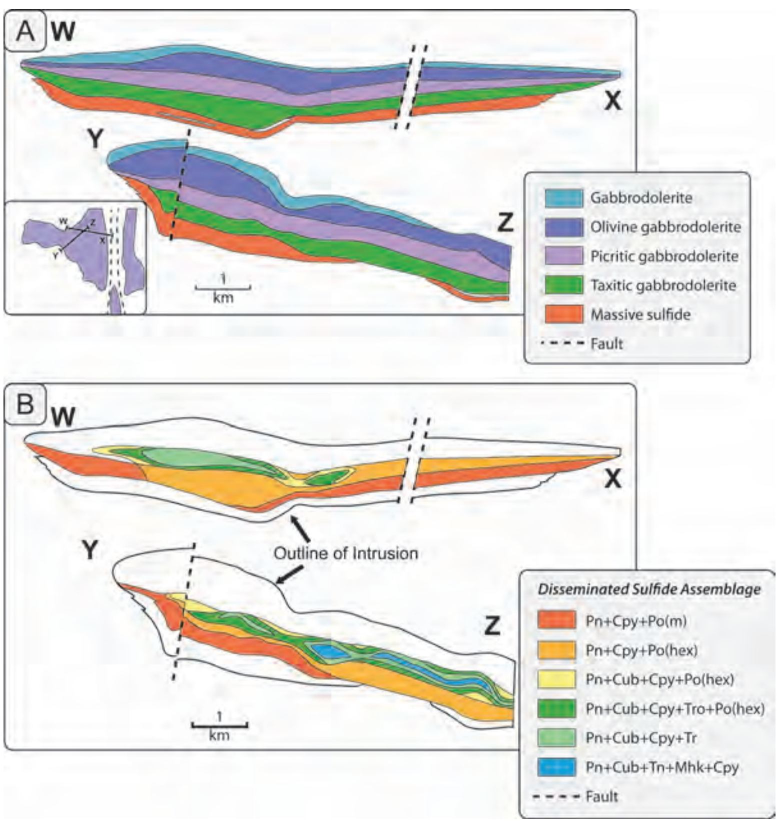



Fig. 16 Cross sections through the Kharaelakh Intrusion, showing the sequence of rocks types and the distribution of sulfide assemblages (based on Zotov, 1989). A. Major rock types. B. The mineral assemblages are documented based on detailed petrography completed by Genkin et al. (1977). The diversity in sulfide mineralogy and chemistry is therefore not immediately related to the host rock composition. Pn-pentlandite; Cpy-chalcopyrite; Po (m) -monoclinic pyrrhotite; Po (hex) -hexagonal pyrrhotite; Cub-cubanite; Tr-troilite; Mhk-mooihoekite; Tn-talnakhite

broadly link to the distribution of metal-rich sulfides developed close to the lower contact in the variably fractionated Ni-rich ore deposits (e. g. Stekhin, 1994; Distler, 1994), but the halos of disseminated sulfide and the diversity in mineralization within the halo cross-cut the boundaries between the main rock types developed within the intrusion.

Zolotukhin et al. (1975) also brought attention to the fact that the spatial distribution of disseminated sulfides within the Noril'sk 1 intrusion did not relate directly to the petrology of the rocks developed in the sequence of rocks. They noted various features, but the following stand out as especially important, viz: ①There is no correlation between the thickness of the intrusion, individual layers within the intrusion, and the scale of mineralization. ②There is an increase in Ni/ (Ni+Cu) down-plunge towards the south of the intrusion, and ③ The sulfides are un-evenly distributed and not obviously related to the composition of the host rocks. These observations are similar to those made by Zotov (1989) for the Kharaelakh Intrusion.

## 7 Geology and mineralogy of the Cuprous ore zones

Sulfide mineralization in metamorphic and metasomatic rocks occur throughout the Talnakh Ore Junction both in the footwall, and in the hangingwall of the sub-horizontal Talnakh and Kharaelakh intrusions (Fig. 17A). The economically important ores are concentrated in the floor of Talnakh Intrusion and in the roof of the south and western parts of Kharaelakh Intrusion (Fig. 17A). Some of the mineralization is associated with metasomatically altered magmatic rocks of the intrusions, but the economic mineralisation is represented by the sulfides lying in the contact-metamorphic aureole of the Talnakh and Kharaelakh intrusions (Fig. 17B). These ores have a layer-like geometry and are distributed parallel to the contacts of the intrusions.

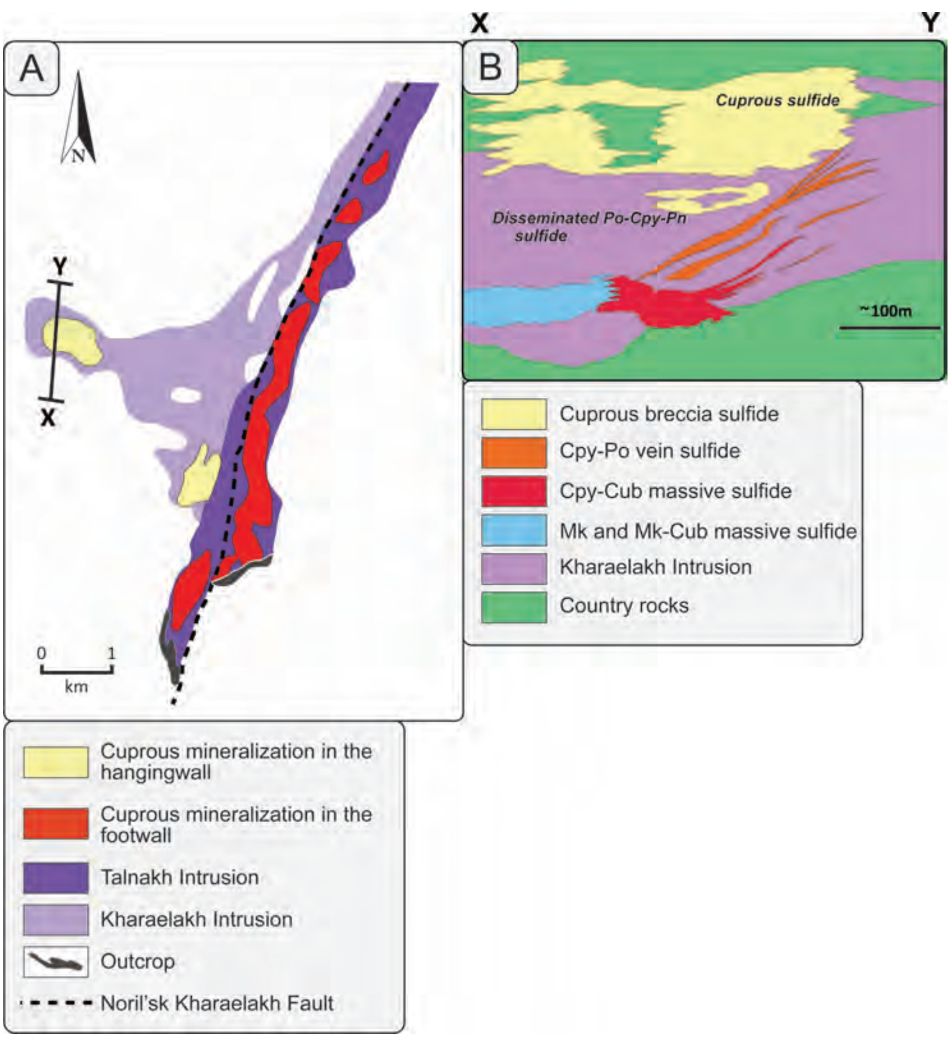
The textural features of the disseminated exocontact ores are complex and there are no published reports on their detailed geology of the mineralization or the host rocks. Broadly the host rocks break-out into lower and upper exocontact mineral domains. The lower exocontact mineralisation is developed in association with the Talnakh Intrusion in the dolomite marls and shales of the Kalargorsky Formation. The upper exocontact mineral zones are developed in association with the Kureysky Formation below the Kharaelakh Intrusion.

Within the hangingwall exocontact mineralisation there is a broad zonation of the sulfide mineralogy (Figs. 17C-D). The zonation pattern broadly consists of a transition from mainly pyrrhotite with minor chalcopyrite ores near to the upper contact of the intrusion in to predominantly chalcopyrite ores at some distance from it; in detail, there is a transition through five principal sulfide associations as shown in Figure 17C (Zotov and Pertsev, 1978). Such zonation of the sulfides is commonly observed in mineralisation of upper exocontact aureole of the Southwest branch of Talnakh intrusion. Mineralisation consisting of mainly pyrrhotite with minor chalcopyrite extends along the hangingwall of the intrusion at the contact, and is characterized by a gradual transition from pyrrhotite-chalcopyrite to millerite-bornite-chalcopyrite associations in the more distal western portions of the ore body. The millerite-bornite-chalcopyrite mineralisation is typically lens-shaped, and these lenses represent the western termination of the mineralization. The veins and lenses of mineralisation are typically 30-40 cm wide, and extend along strike for >100 m into the hornfels.

Fig. 17C shows the composition of the country rocks that are associated with the mineralisation (depicted in the drill logs). Primary sedimentary layering provides a broad control on the location of the mineralisation, with some mineralisation restricted to bedding surfaces or lithological contacts; the vast majority of the ores follow this pattern, but the bornite ores cross-cut the fabric of the country rocks and the other sulfide associations. Layers of anhydrite inside the pyrrhotite association are locally enriched in chalcopyrite.

Fig. 18A-F show examples of lower exocontact mineralization from the NE Branch of the Talnakh Intrusion and the NW Branch of the Talnakh Intrusion. The samples illustrate a range of textures including replacement of metasedimentary rock where the banding is produced by alternation of mm-scaled layers of metamorphosed country rocks that are enriched and impoverished in sulfide content. The contents of sulfides in the mineralized bands varies from a few percent to reach 40%; they occur within layers of semi-monomineralic pyroxene hornfels (Fig. 18A-D). Lower exocontact mineralization also includes breccia ores at Skalisty and Komsomolsk Mines (Fig. 18E-H).

Fig. 19A-I show examples of upper exocontact mineralization from the Kharaelakh Intrusion. The massive ore veins are often emplaced into country rocks that consist of anhydrite and marble, and more rarely chlorite, vesuvianite, wollastonite, epidote and others minerals; the veins often contain fragments of these materials, with little evidence of reaction with the sulfide (Zotov, 1979; Zolotukhin et al., 1975). In some cases, anhydrite crystals are enclosed in chalcopyrite, and locally the anhydrite-sulfide intergrowth (Fig. 19A) contains inclusions of mineralized gabbro that is variably corroded (Figs. 19B-E). Another style of



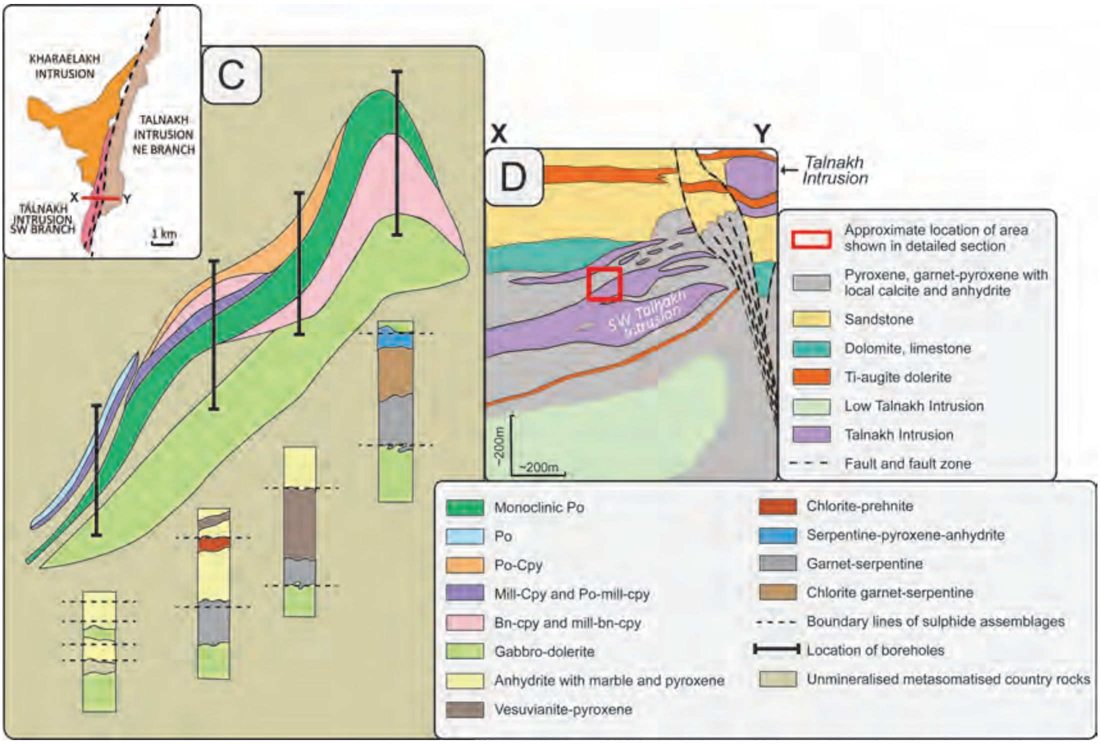
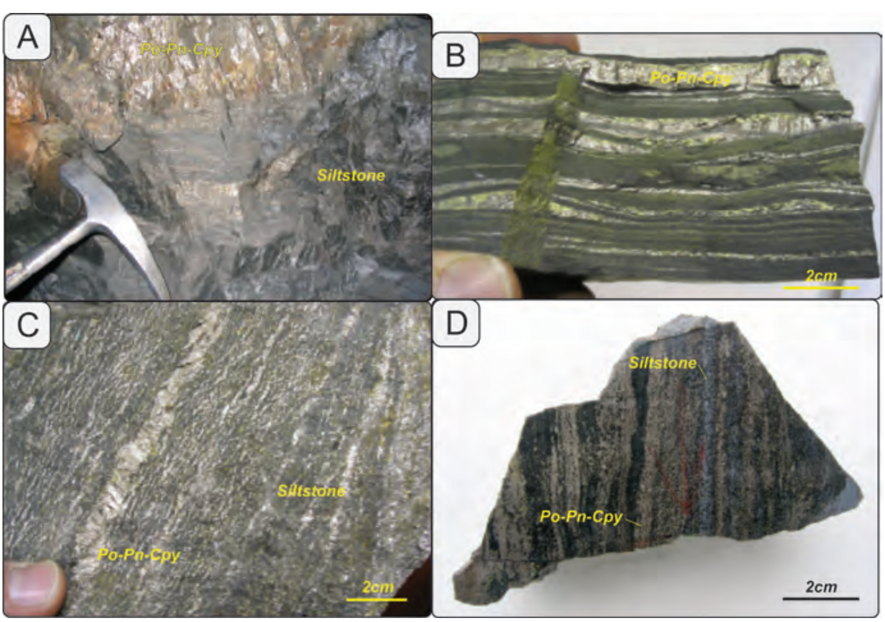



Fig. 17　A. Map of the Kharaelakh and Talnakh Intrusions showing the distribution of the upper and lower exocontact styles of mineralization. B. A simplified cross section through the Kharaelakh Intrusion showing a possible relationship between the Ni-rich contact ores and the cuprous mineralisation at the roof of the Kharaelakh Intrusion. C. A geological section through the mineral zones in the metamorphic aureole in the roof of the SW branch of the Talnakh Intrusion (from Zotov and Perstev, 1978). The section shows the borehole locations, the host rocks, and the style of mineralization. The mineral zone is broadly concordant with the roof of the intrusion. D. Geological section showing the approximate location of the mineralization depicted in Fig. 17C



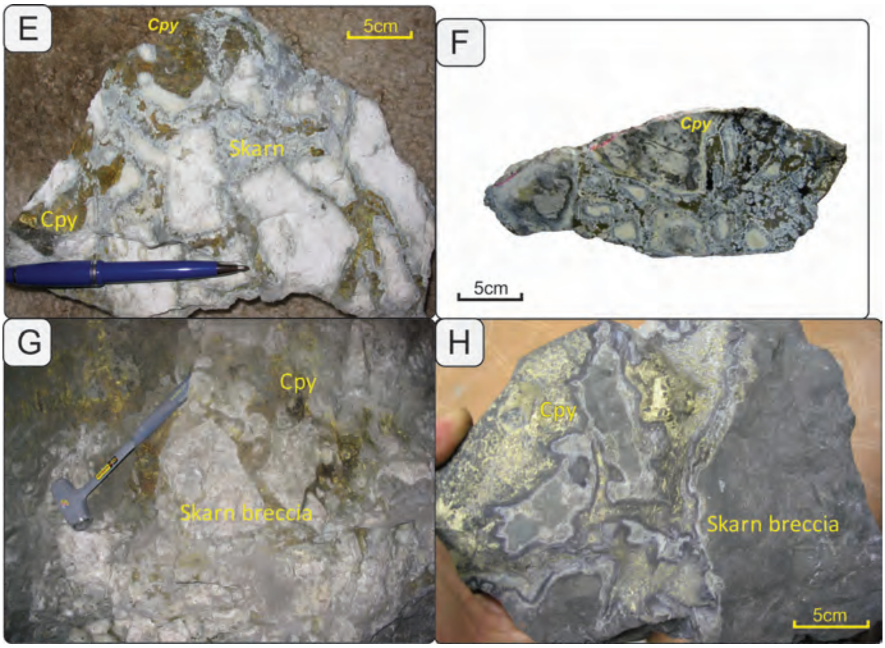
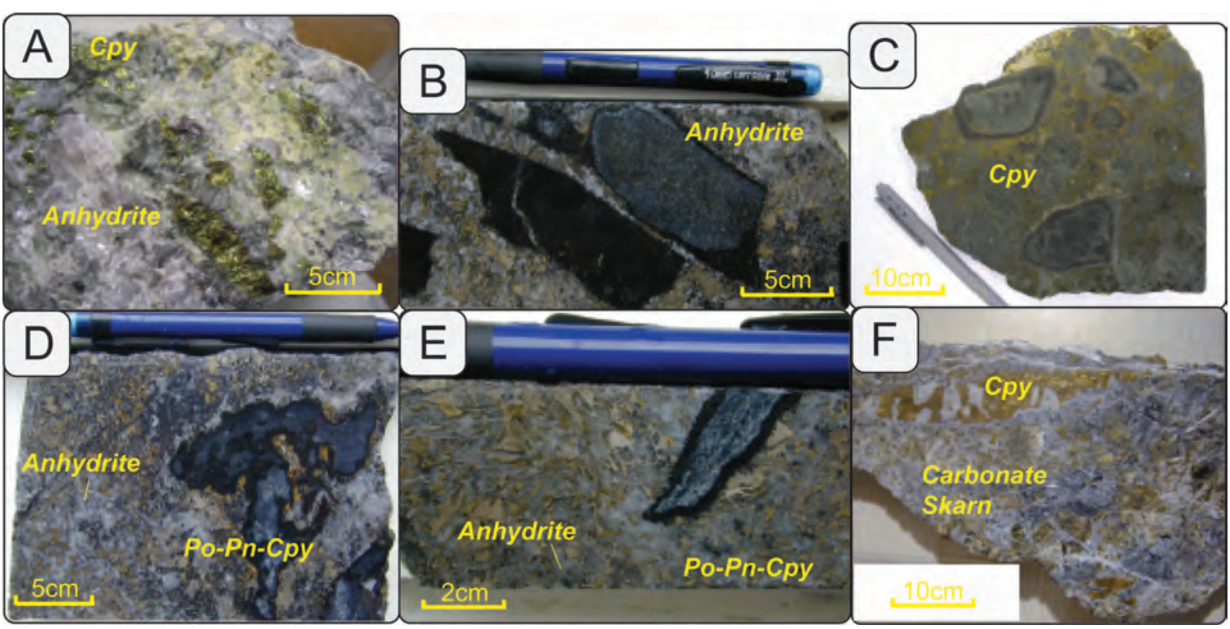



Fig. 18 A. Photograph of basal part of nickel-rich mineralization (the veins cut though the footwall parallel to the base of the intrusion) hosted in the contact zone between the intrusion and the Upper Devonian Kalargonsky Formation marls at the base of the NE Talnakh Intrusion in Skalisty Mine. Note the penetration of mineralization along bedding. B. More detailed view of sulfides cut through the fine-grained argillite parallel to bedding. C. Replacement of meta-silstone in the lower exo-contact of the SW Talnakh Intrusion. D. Replacement of meta-siltstone in the footwall of the NE Talnakh Intrusion at Skalisty Mine by contact style mineralization. E. Cuprous mineralization developed in carbonate-rich skarn and breccia at the base of the NE Talnakh Intrusion at Skalisty Mine. F. Detailed photograph of a slab showing the relationships between mineralization, fragments and metasomatised carbonate assemblage rocks. G. Cuprous mineralization from the lower exo-contact of the SE Talnakh Intrusion, Komsomolsk Mine; note the extensive brecciation of skarn assemblage rocks developed after Kalargonsky Formation carbonate rocks. H. Sample of cuprous mineralization from Komsomolsk Mine showing the extensive brecciation and re-crystallisation of the marl and silstone into skarn assemblage



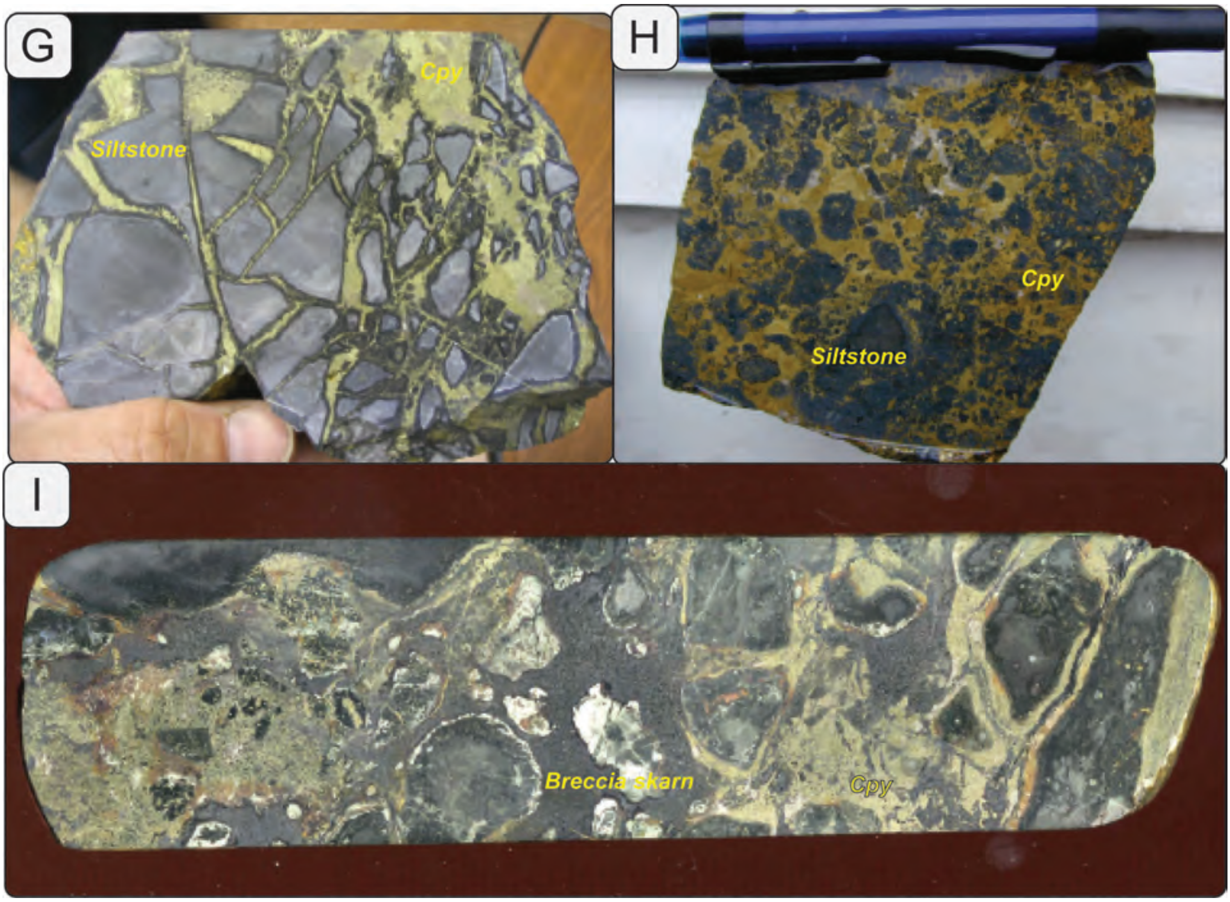



Fig. 19　A. Upper exocontact cuprous mineralization hosted in anhydrite, Oktyabsrysk Mine, Kharaelakh Intrusion. B. Fragment of country rock in heavily mineralised coarse-grained anhydrite from upper exocontact of the Kharaelakh Intrusion, Oktyabrysk Mine. C. Fragments of meta-sedimentary rock that are heavily recystallised in a matrix of anhydrite with interstitial chalcopyrite; from the upper exocontact of the Kharaelakh Intrusion, Oktyabrys Mine. D. Fragments of meta-sedimentary rock that are heavily recystallised in a matrix of anhydrite with interstitial chalcopyrite; from the upper exocontact of the Kharaelakh Intrusion, Oktyabrysk Mine. E. Semi-massive chalcopyrite with fragments of meta-sedimentary rock, upper exocontact breccia ores from the Kharaelakh Intrusion, Oktyabrysk Mine. F. Association of chalcopyrite with skarn in the upper exocontact of the Kharaelakh Intrusion. G. Cuprous breccia from the lower exocontact, Komsomolsk Mine. H. Semi-massive chalcopyrite with fragments of metasedimentary rock, upper exocontact breccia ores from the Kharaelakh Intrusion, Oktyabrysk Mine. I. Chalcopyrite-rich breccia from upper exocontact of the Kharaelakh Intrusion (photographs are taken from Lightfoot and Zotov, 2006)

upper exocontact mineralization consists of chalcopyrite replacement of monticelite skarn (Fig. 19F) and examples of partially brecciated country rocks through fragmental cuprous ore from the roof of the Kharaelakh Intrusion at Oktyabrysk Mine (Figs. 19G-I).

The sulfide minerals of the Cuprous Ore zones are dominantly chalcopyrite with lesser pyrrhotite, cubanite, pentlandite, magnetite, millerite, polydymite, bornite, pyrrhite, valeriite, djerfisherite, and/or galena (Genkin et al., 1977). Some of the ore minerals form common associations that comprise individual domains of the ore bodies. The following sulfide paragenetic associations are volumetrically important:

(1) pentlandite + chalcopyrite + monoclinic pyrrhotite and pentlandite + monoclinic pyrrhotite.

(2) pentlandite + monoclinic pyrrhotite + chalcopyrite.

(3) pentlandite+ cubanite+ chalcopyrite.

(4) pentlandite+ chalcopyrite.

(5) millerite+ chalcopyrite.

(6) millerite + bornite + chalcopyrite and bornite+chalcopyrite.

Magnetite occurs within the sulfide minerals as both crystals enclosed within sulfides and as a reaction rim. Bornite frequently cross-cuts other sulfide minerals and occurs at the boundary between sulfides and silicates, so it is considered to be late in the paragenetic sequence (Zotov and Pertsev, 1978).

Primary sulfide minerals are often replaced by secondary sulfides; examples of replacement include pyrrhotite + magnetite-II, pyrrhotite + millerite; pyrrhotite + millerite + polydymite; valeriite; and djerfisherite. The primary sulfide associations comprise the largest proportion of the metasomatic ores. There tends to be a broad zonation of the associations, but with gradational boundaries (Genkin et al., 1977).

There is a broad correlation between the facies of the metasomatic rocks and the type of sulfide mineral association. For example, magnesian skarns are essentially associated with pyrrhotite mineralization and are localized near to the intrusion. At some distance from intrusion, garnet-pyroxene skarns and hornfelsed country rocks are associated with chalcopyrite-rich mineralization. Petrographic examination of the metasomatic sulfides reveals that pyrrhotite-rich sulfides are accompanied by recrystallization of the forsterite and montichellite (e. g. Fig. 19F and Zotov and Pertsev, 1978). Chalcopyrite-rich mineralization isoften associated with re crystallisation of the calc-skarn, hornfels, and garnet. Wollastonite-vesuvianite calc-skarns and the low-temperature metasomatic rocks appear to originate later than the primary sulfide associations. Zotov and Pertsev (1978) describe the replacement of primary sulfides by vesuvianite. Prehnite is also found as worm-like intergrowths in the sulfides. These features are associated with the development of a second generation of magnetite associated with pyrrhotite and they also show a linkage to the development of serpentinized magnesian scarns in brucite and brucite-serpentine-carbonate rocks; these rocks also contain valeriite and the potassium-rich sulfide, djerfisherite (Zotov and Pertsev, 1978). Chalcopyrite is the most resistant sulfide of the primary sulfide associations; it is less liable to decomposition and replacement during low-temperature metasomatic processes.

## 8 Physical and chemical conditions of formation of exocontact mineralization

The exocontact mineralisation of the Talnakh and Kharaelakh Intrusions has many features that are atypical of the more classic magmatic-textured massive and disseminated sulfide that has formed by more traditional models of silicate liquid-sulfide liquid immiscibility, and gravitational accumulation and concentration (e. g. Barnes and Lightfoot, 2005, Naldrett, 2004). The following observations are important in underpinning a model for the formation of this style of mineralization:

(1) In most cases the strongest development of footwall and hangingwall cuprous ores are located above and below the thickest parts of the intrusion that develop the largest concentrations of massive Ni-rich sulfide.

(2) The ratios of Cu/ (Cu + Ni) and chalcopyrite concentrations of the exocontact Cuprous ores are typically much higher than the massive ores at the lower contact.

(3) Much of the mineralization is located along bedding planes within the exocontact hornfelsed sedimentary rocks (Figs. 18A-D). Chalcopyrite-rich mineralisation also occurs as interstitial sulfides which surround prismatic grains of anhydrite in the anhydrite-sulfide association (Figs. 19A-D).

(4) The hangingwall cuprous ores at Oktyabrysk Mine consist of breccia stockworks which break up and incorporate what appear to be both fragments of mineralized Kharaelakh Intrusion, fragments of pyroxene hornfels as well as fragments of previously metasomatised country rocks (Figs. 19G-I). In some cases there is a superimposed growth of later minerals at the margins of the mineralization.

These features all indicate that the formation and emplacement of the cuprous mineralization was late, but related to the terminal phase of a major episode of metasomatism. The location of the mineralization at the margins of the intrusion-hosted deposits, and the presence of physical connections of vein-like massive sulfide as recorded at Oktyabrysk are features that must also be reconciled with a genetic model. Two competing hypothesis compete as possible explanations for these genetic associations, viz:

(1) Metasomatic formation of the Cuprous ores: There is a clear association of finely disseminated sulfide mineralization within the hornfelsed country rocks and metasomatic rocks; this mineralisation stretches for on tens to hundreds of meters into the country rock, and is often conformable with the bedding, but also occurs as major cross-cutting veins. There is an especially close association of economic ores with calc-skarn mineralogies, and these assemblages are typically stable at temperatures of < 500-600℃ (excluding ores in spinel-forsterite magnesian skarns) which is typically below the temperatures of a sulfide melt (Zotov and Pertsev, 1978). There is a regular distribution of sulfide assemblages in mineral zones of both the footwall and hangingwall exocontacts of the intrusions, and the changes in sulfide mineralogy link to distance from the contact. Pyrrhotite-rich sulfides occur close to intrusion and this is consistent with their formation at higher temperatures than the more chalcopyrite-rich ones. There was a broad temperature gradient in the exocontact of the intrusion that is reflected in the thermal metamorphic aureole; it is in this zone that metasomatism and the development of skarn assemblages took place, and although the thermal aureole was presumably due to intrusion, the superimposed metasomatism presumably resulted from the introduction and remobilisation of large amounts of fluid into the adjacent country rocks. The transition from magnesian to calc-skarns is generally interpreted to reflect an increase in the amount of acid component activity with falling temperature (Zharikov, 1959; Korzhinskii, 1953; Pertsev, 1973). This model would link the formation of the Cuprous ores to the formation of the various skarns at the margins of the intrusion, and Zotov (1989) suggests that the metals were carried into the sediments in association with the fluids. The fluid capacity of the silicate magma was presumably insufficient for a ~10-15 $km^3$ magma chamber to generate this volume of mineralization, so models have developed that require the magma columns and sheets to represent passageways through which metal-rich fluids passed, and flushed into the surrounding country rocks.

(2) Sulfide liquid differentiation: This model would link the Cuprous ores to the contact massive ores; it would require that the cuprous mineralization represents a Cu-rich liquid that separated from the contact ores and migrated into the footwall and hangingwall of the intrusion into spaces generated due to tectonic disturbances or separation along bedding surfaces. The unusual exocontact Cu-PGE ores are possibly the product of sulfide melt differentiation, but their emplacement is probably controlled by space available within the evolving conduit system. Some of this space was available at the base of the intrusion to the east of the Noril′sk-Kharaelakh Fault, but to the west it appears to have been generated in response to the collapse of roof rocks over the partially crystallized rocks within the chonolith along minor structures parallel to the Noril′sk-Kharaealakh Fault (Lightfoot

and Zotov, 2007). The model is widely applied to explain the linkages between monosulfide solid solution and cuprous ores (examples include the Noril′sk and Sudbury ores; e. g. Naldrett et al., 1994, 1996 and Keays and Crockett, 1973), but the geological relationships in the Talnakh and Kharaelakh ore bodies require a careful re-examination of the paragenetic associations of sulfide minerals with the products of metasomatism (Zotov, 1989).

## 9 A model for magmatism in the Noril′sk-Talnakh region

We propose that melting in the mantle was initiated in response to the effect of a deep mantle hot spot which triggered melting at ~250 Ma (Kamo et al., 2003 Campbell et al., 1992); the early manifestations of this activity was flood basalts volcanism (the Ivakinsky through Gudshinkhinsky Formation basalts and Gudchikhinsky picritic basalts) (Lightfoot et al., 1990, 1993) and emplacement of the Irgalakksky and Fokinsky type sills (Fedorenko et al., 1996). Subsequent magmas giving rise to the Tuklonsky Formation basalts and picritic basalts were centered east and south-east of Noril′sk (Fedorenko, 1979). The development of the Noril′sk differentiated intrusions began close in time and space to the eruption of the Nadezhdinsky Formation basalts and the emplacement of a more primitive version of this magma to form the Low Talnakh type intrusions (Naldrett et al., 1995) which are centered beneath the Talnakh type intrusions and along the Noril′sk-Kharaelakh Fault Structure (Figs. 1B and 4). These intrusions and basalts were Ni-Cu-PGE-depleted (e. g. Lightfoot et al., 1994; Naldrett et al., 1995; Lightfoot, 2007), and the sulfide mineralization which presumably accompanied this event was retained at depth within the conduit system. Subsequent migration of the volcanic edifice to the northeast (Fedorenko, 1979, 1981) is represented by the eruption of thick sequences of Morongovsky through Samoedsky Formation lavas. The Noril′sk-Kharaelakh Fault Zone acted as a major locus for emplacement of magmas along chonoliths which occupied transtensional openings in the wrench fault system (Mezhvilk, 1984; Lightfoot and Evans Lamswood, 2013A, B) from the end of the Tuklonsky to the start of the Mokulaesky which was likely a time period of less than 1Ma, and correlated with the development of basalt depocenters linked to the development of regional basins (Monteiro and Lightfoot, 2006).

The mechanism of emplacement of the intrusions appears to be controlled by periclinal folds and rifts developed in response to compression and transtension along the Noril′sk-Kharaelakh Fault. This is illustrated by the clay model in Fig. 20A and simple block model in Fig. 20B. The effect of transpression on the surface manifestation of faulting is shown to develop positive and negative flower structures. The chonoliths which are now represented by the Talnakh, Noril′sk 1, and Kharaelakh Intrusions appear to replace the country rocks along the flanks of the fault, and as they do not significantly expand the stratigraphy.

Although there appears to be a structural primary control on the location of the main bodies of the mineralized intrusions, there is evidence to suggest that a significant part of the intrusion replaced the country rocks. The emplacement of the Kharaelakh intrusion appears to have proceeded without significant disruption of the stratigraphy of surrounding rocks and without expansion of the stratigraphy (Godlevskii, 1959; Smirnov, 1966; Zotov, 1989; Figs. 8, 9A-B). The intrusions were referred to as "castings that filled voids of uncertain origin" (Godlevskii, 1959). Korovyakov et al. (1963) suggested that the intrusions were formed by magma which "plowed through the stratigraphy", but no signs of the displaced material were found. Zolotukhin et al. (1975) attached importance to the production of the magma chambers by

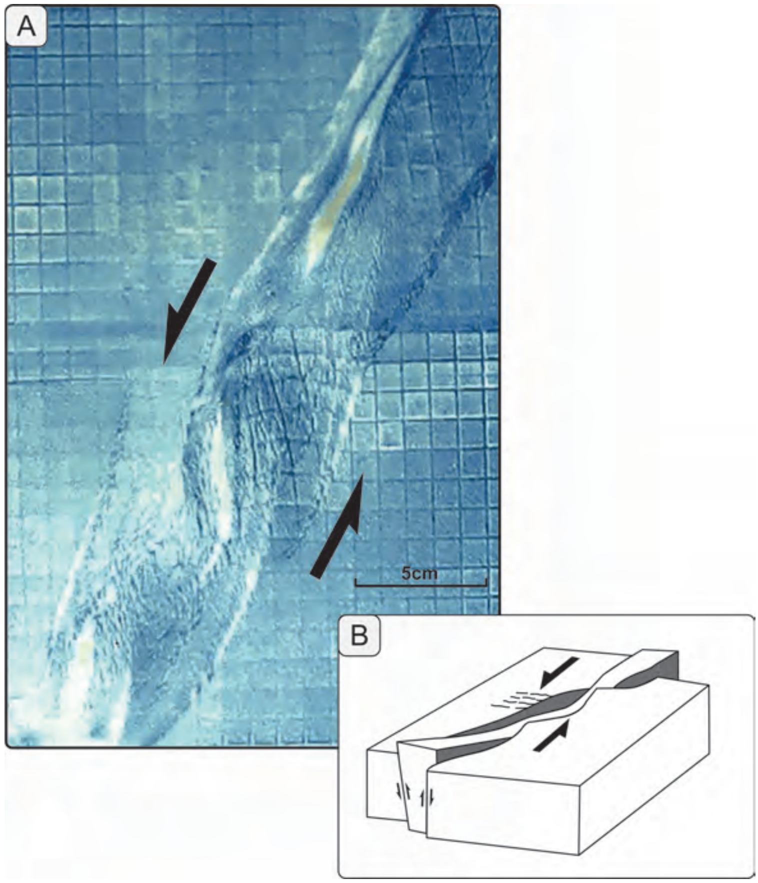



Fig. 20　A. A clay model illustrates in map view the evolution of a transtensional graben striking obliquely to the direction of regional extension using analogue modelling designed to reflect the structuire controlling possible intrusions piercing through sedimentary units adjacent to the main structure. In the model case, the deformation culminates with intrusives (white material) emerging locally along the graben (Monteiro and Lightfoot, 2006). The extrusion loci are structurally controlled by the graben boundary and internal faults, particularly at their intersections and bridges along boundary fault relay. After Monteiro and Lightfoot (2006). B. Block model shows the broad structure and kinematics in the area of this section where smaller faults and local synformal structures develop in the stratigraphy adjacent to the fault. It is these graben structures and folds which help localize the position of the Kharaelakh, NW Talnakh, NE Talnakh and Noril'sk I Intrusions along the fault zone at shallow levels in the crust

uplifting of blocks of roof rock, compaction of the exocontact rocks, and hornfelsing and degassing of the carbonate and sulfate rocks during metamorphism. It appears that the stratigraphy of the Razvedochninskaya Formation is replaced by the intrusion. A thicker package of contorted Razvedochininskaya Formation rocks is not developed at the periphery of the intrusion, so Korovyakov's suggestion of displacement of the country rocks appears unlikely. It appears more likely that 45%-75% of the intrusion occupied space that was created by replacement of the stratigraphy by magma.

On the scale of the smallest apophyses, Zotov (1989) showed that a more likely explanation for the apophyses is related to the development of magmatic branches which permeate through thin-banded clinopyroxene-garnet hornfels with anhydrite layers and connect the rounded dolerite bodies.

The development of the magma chamber now represented by the Kharaelakh Intrusion attests to magma emplacement coeval with the development of the Noril′sk-Kharaelakh Fault; and Zotov (1989) agrees some of the space occupied by this magma was created by the development of rifts and synforms adjacent to the main fault.

The high temperature metamorphic assemblages in the halo around the intrusion is evidence for the migration of supercritical fluids. The greater thickness of the upper metamorphic halo when compared to the footwall halo is independent of the lithology of the host rocks, and demonstrates that the magmas served as main sources of metamorphic fluids.

The main chonoliths have flanking zones where the magmas have formed sheets and apophyses. These sheets and apophyses explain the wide metamorphic halo in the frontal parts of the sheet relative to the narrow halo over the wide part of the conduit.

The sequence of events responsible for the formation of the mineralized intrusions involved the production of a range of geological features that require a magmatic fluid contribution (Zotov, 1989). The most important rock type that provides evidence of a significant fluid content is the taxite where the variations in texture and grain size, coupled with the presence of vesicles points to the importance of magmatic fluids (Zotov, 1989). Moreover, the development of blebby sulfides with cryptocrystalline silica at the tops of the blebs points to the presence of fluid/gas vesicles in the magma that gave rise to the picritic and taxitic olivine gabbrodolerite (Lightfoot and Zotov, 2006). The presence of abundant skarns in the upper and lower exocontacts of the intrusions points to the role of fluids in metasomatising the rocks, and also point to a role for fluids in the introduction of more Cu-rich sulfide melts into the upper exocontacts of the Kharaelakh and the lower exocontact of the Talnakh Intrusions.

The origin of the fluids likely rests with melt generation in the mantle. Up to 1% fluid in the mantle might accumulate during moderate degrees of melting within enclaves of magma that migrated into structural pathways at the base of the crust. These magmas were able to migrate from mantle to surface along a network of conduits within transtensional structures like the Noril′sk-Kharaelakh fault zone. The magma conduits would also act as pathways for the migration of volatiles through the melt-the transmagmatic fluids described by Korzhiskii et al (1984) —are a key ingredient in the development of the mineralized intrusions as described in Zotov (1989). Adiabatic melting in the mantle was presumably a response to uplift, and the thinning of the lithospheric mantle produce conditions critical for the eruption of vast volumes of flood basalt magma (Lightfoot et al., 1990, 1993, 1994). This process is shown in Figure 21A-D after Zotov (1989). This diagram shows the effect of continual uplift throughout the process, and the localization of magma transport pathways by deep structures. The uplifted mantle likely contains of the order of 1% volatiles, and these volatiles would be removed from the mantle into the melt to generate a fluid-oversaturated magma which would likely contain gas bubbles. The concentration of these fluid bubbles and selective partitioning of elements into these fluids is discussed by Zotov (1989), and he shows that the fluids likely explain the development of metasomatic features at the edges of the mineralized intrusions, and may also play a role in metal transportation from depth to surface. The transportation pathways of magmas likely followed the transtensional spaces created adjacent to the main structures created-by or modified-by far-field plate tectonic processes. Figure 20E shows how the magma column would serve to localize fluid transport over a large vertical length. Fluid release from the magma would likely occur only above 10km depth (Zotov, 1989).

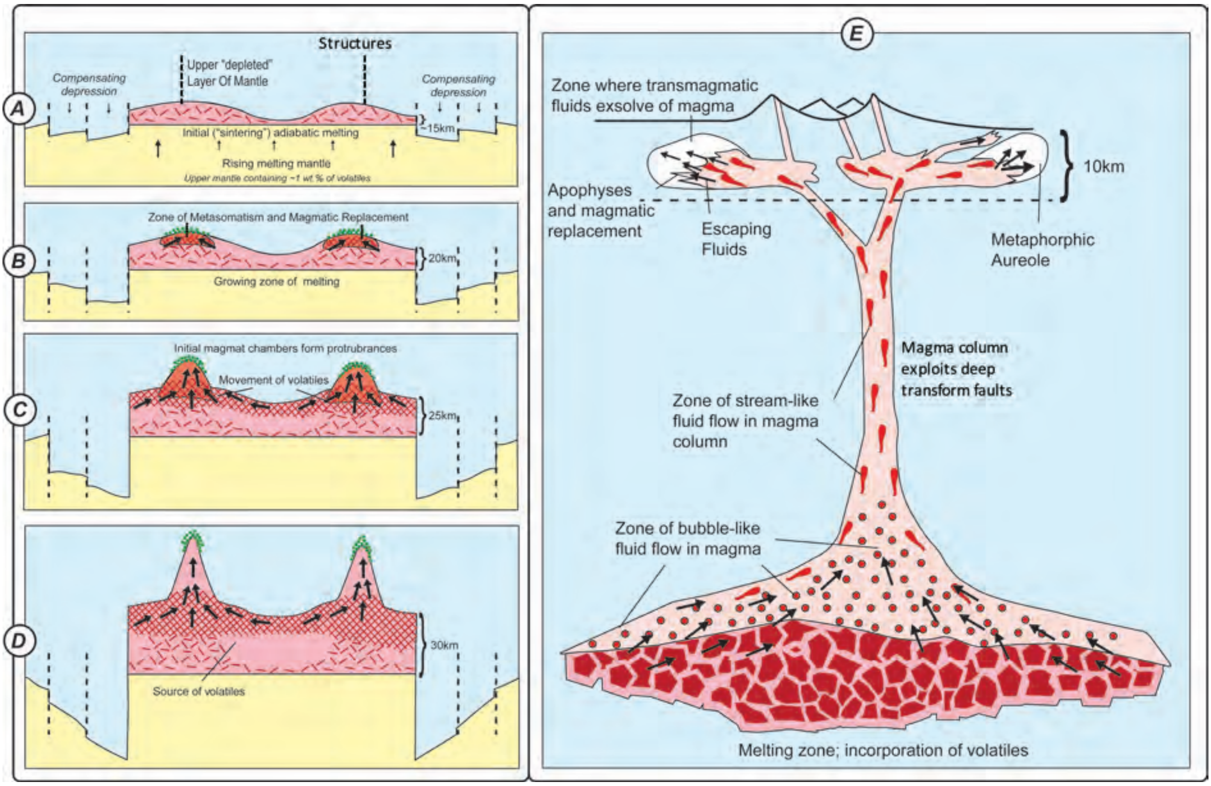



Fig. 21 A-D: Diagram shows evolution of magmas generated by mantle melting, mobilization of fluids, and metasomatism in an uplifted block of primitive mantle material. E: Schematic cross section showing the structure of a magma conduit system developed along major crustal faults; these conduits may have acted as not only magma pathways, but also control the movement of fluids from the mantle to the surface (termed transmagmatic fluid flows by Korzhinskii et al (1984)). After Zotov (1989) where the details of the model are presented

## 10 Summary and conclusions

(1) The Noril'sk – Talnakh ores are associated with small differentiated intrusions flanking the Noril'sk-Kharaelakh wrench fault zone. The intrusions were emplaced close to surface beneath an extensive package of Ni-Cu-PGE depleted basaltic rocks, and within a corridor that contains a series of Ni-Cu-PGE-depleted intrusions of the differentiated Low Talnakh and Low Noril'sk types.

(2) Tectonic controls on the development of the Noril'sk chonoliths are incompletely understood, but there is clear evidence that local periclinal structures adjacent to the N-K wrench fault have localized the distribution of the magma channel-ways in the sedimentary rocks (e. g. Lightfoot and Evans-Lamswood, 2013A, B). The tectonics that controls the development of the intrusion may also have contributed to the localization of the breccias and exocontact cuprous mineralisation.

(3) The detailed geology of the Kharaelakh Intrusion is described, and it is clear that the frontal part of the intrusion comprised many sills and apophyses which penetrated into and replaced the country rocks, generating a wide metamorphic halo in association with the apophyses, but a narrow metamorphic halo where the intrusion has no apophyses.

(4) It appears that 45%-75% of the intrusion occupied space that was created by replacement of the stratigraphy by magma that was introduced from a mantle source.

(5) The geology of the country rocks above the Kharaelakh Intrusion comprise a range of skarns and breccias which are developed in response to the migration of fluids into the country rocks. These skarns are closely associated with Cu-rich sulfide mineralization at the roof of the Kharaelakh Intrusion.

(6) The disseminated sulfides within the Kharaelakh Intrusion are blebby in picritic gabbrodolerites and irregular in taxitic gabbrodolerites. The distribution of zones of disseminated sulfide cross-cut the internal stratigraphy of the intrusion. These variations are not immediately consistent with a magmatic origin. Zotov (1989) proposed that these features could be produced if the sulfides were introduced together with fluids through the conduit prior to crystallization of the silicate rocks. In this model, the variation in sulfide composition is related to fluid chemistry rather than fractionation of the sulfide or mobilization of sulfide from massive pools of sulfide melt into the overlying silicate magma.

(7) The exocontact styles of mineralization typically have elevated Cu (Cu/Ni～5) and PGE, but they are low in Ni which contrasts with the differentiated Cu-rich mineralization at the lower contact of the intrusions in the pyrrhotite-pentlandite-chalcopyrite style of Ni-rich ores (Cu/Ni～15) as described in Naldrett et al. (1992, 1995) and Stekhin et al. (1994).

(8) We show evidence that the nickel-rich ores are emplaced into or beneath the contact of the intrusion, and so they appear to represent individual discrete pulses of massive magmatic sulfide that were injected into the chonolith much like the ores at Voisey's Bay (Lightfoot et al., 2012A, B).

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