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IRON OXIDE (±COPPER, GOLD) AND ASSOCIATED DEPOSITS OF THE ALTAI-SAYAN OROGENIC SYSTEM, SOUTH-WESTERN SIBERIA, RUSSIA

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Abstract - The Altai-Sayan orogenic system, located in the core of the Altaid orogenic collage of central Asia, hosts numerous iron oxide deposits, many of which contain substantial gold, copper, apatite, fluorite, barite, REE and uranium concentrations. These deposits represent several styles of mineralisation that belong the broad IOCG association, namely, (1) proximal to distal metasomatic (skarn) and more distal scapolite-albite to chlorite-amphibole replacement; (2) stratabound magnetite-apatite occurring within volcanic sequences (Kiruna-type); and (3) carbonatites. Each of these styles corresponds to a different tectonic terrane and metallogenic epoch.

The skarn and other replacement-type iron oxide (±copper, gold) deposits are especially numerous in the Caledonian orogenic terranes of the Middle to Late Cambro-Ordovician, and occasionally Silurian, with minor mineralisation re-deposited(?) in the Devonian. They include deposits associated with (1) proximal contact skarns, localised in the immediate vicinity of related intrusives; (2) proximal to distal skarns, frequently well above large plutons, but occurring in zones where intrusive apophyses, small stocks and dyke swarms are present, in some cases related to breccia pipes or diatremes, or as flat-lying skarns and orebodies in shallow-dipping host lithologies; (3) proximal to distal albite-scapolite-rich alteration in fault zones, with only minor skarn; and (4) distal chlorite-amphibole-dominated accumulations, also within fault zones. Deposits of the two latter sub-types host the largest iron oxide concentrations, often containing as much as 500 to 700 Mt of iron ore.

Stratabound magnetite (-hematite) and magnetite-apatite deposits are mostly found in Hercynian orogenic terranes, although older concentrations may locally occur in Caledonian domains. Devonian volcanic sequences exert a distinct stratigraphic control on these deposits, with gradual transitions from iron oxide-enriched alkalic volcanics (trachytes, etc.) to semi-massive and massive iron oxide mineralisation. Multi-stage formation of these deposits appears to be the most plausible explanation of their occurrence, with local re-deposition and enrichment of mineralisation related to the emplacement of younger plutons.

Mesozoic (Cretaceous?) iron oxide-rich carbonatites emplaced in Caledonian and older terranes are of particular interest due to their possible relationships with potassic granites and strong enrichment in hematite, REE (bastnaesite, monazite, etc.), uranium (uraninite), barite, fluorite, apatite, locally magnetite and chalcopyrite.

Introduction

The Altai-Sayan region of southwestern Siberia encompasses in excess of 100 significant iron deposits and thousands of lesser occurrences. The large number of producing iron mines supplying the steel-making plants in that part of Siberia make it one of the most important mining regions in Russia. Iron has been actively mined in the region since the 19th century, culminating in the 1980s. Some 20 large deposits have been, or are currently being exploited, with Evraz Group C.A. being the largest mining enterprise in the region. Gold mining has also become increasingly active in the same part of Siberia.

Many iron deposits in the Altai-Sayan region contain significant copper and particularly gold concentrations, and display other characteristics that stimulate their consideration in the IOCG context, as recognised by Williams *et al.* (2005). Previously, Pospelov (1959) and other researchers, had highlighted that these deposits showed a lack of direct spatial relationships with plutons, but a common structural control of iron oxide mineralisation, i.e., one of the common characteristics of IOCG deposits. In addition, Kassandrov and Ivanov (1979), Kalugin *et al.* (1981), Dunayev (1997) and other authors suggested similarities between some stratabound magnetite and magnetite-apatite deposits found in the Altai-Sayan region and the Kiruna (Sweden) and El Laco (Chile) iron oxide deposits. Gusev *et al.* (2006) first classified these deposits as IOCG-style and distinguished skarn, volcanic-hosted (Kiruna-type), carbonatite and other iron oxide deposit types.

The large number of iron oxide deposits found in the Altai-Sayan region and their broad variability allows the characterisation of various deposit types, their geological settings and important petrologic/mineralogical features, together with their spatial/temporal evolution.

Regional Geology

The Altai-Sayan orogenic system is part of the Altaid orogenic collage, bounded to the east and northeast by the Siberian craton, and passing into Kazakhstan, China and Mongolia to the west and south (Fig. 1). It is in turn, part of the greater Altaid-Transbaikal-Mongolian orogenic collage, which wraps around the western and southern margins of the Siberian craton, as distinguished by Sengor *et al.* (1993), Yakubchuk *et al.* (2005) and others, and is one of the most significant and extensive of the Earth's Palaeozoic tectonic systems. The Altai-Sayan region is located in the internal, or core part of the Altaid orogenic collage (Fig. 1), immediately adjacent to the Siberian craton. It has an extremely complex geological and tectonic structure caused by the presence of variably-oriented and

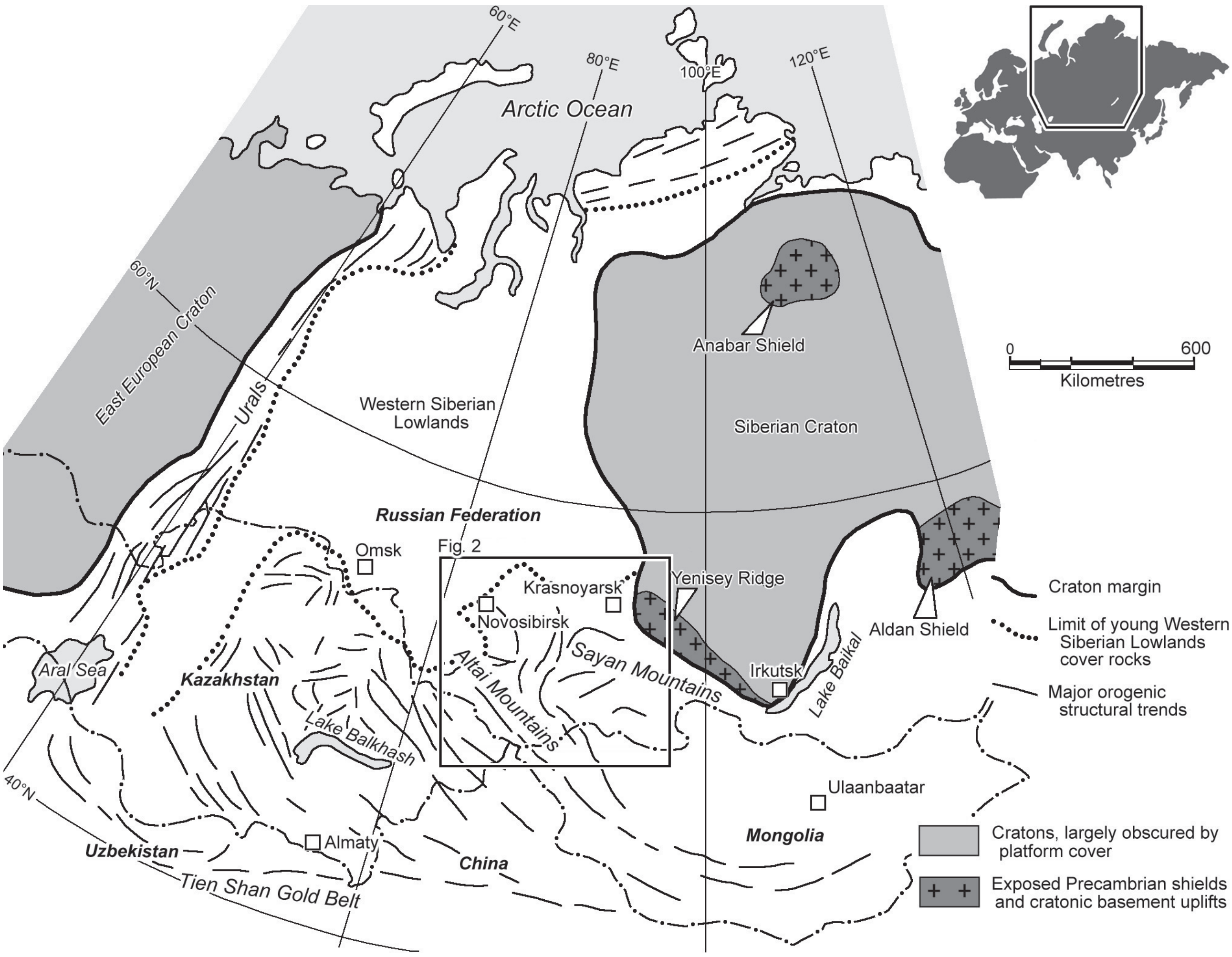


Figure 1: Location of the Altai-Sayan orogenic system in the Altaid orogenic collage (tectonic framework after Sengor *et al.*, 1993; Yakubchuk *et al.*, 2005).

variously-aged (Baikalian, Early and Late Caledonian, and Hercynian) orogens which incorporate a series of microcontinents (fragments of the Siberian craton) such as the Khakassian and Tuva-Mongolian blocks (Fig. 2). In general, the orogens become progressively younger with increasing distance from Siberian craton, while the number and size of the microcontinents decreases in the same direction (e.g., Kontorovich and Surkov, 2000). Correspondingly, the ancient basement outcropping locally in the microcontinents is represented by Archaean to Palaeoproterozoic metamorphic rocks similar to those of the Siberian craton.

In the Khakassian and Tuva-Mongolian microcontinents, ancient basement is overlain by Meso- to Neoproterozoic (Riphean-Vendian) and Lower to Middle Cambrian carbonates, or Riphean-Vendian carbonate-clastic-cherty sequences, with some volcanic rocks which increase in significance towards the Early-Middle Cambrian. These sequences were tectonised during the Early Caledonian orogenic event that included the intrusion of numerous gabbro-monzonite-granite, gabbro-syenite-granite, gabbro-diorite-granite and similar multiphase plutons. Another intense magmatic event occurred in the Devonian, which included intrusion of large granitoid plutons.

The large orogens of the Altai-Sayan region include the Baikalian Eastern Sayan, the Early Caledonian Salair, Sizim-Kazyr, and Eastern Tuva, the Late Caledonian Western Sayan, and the Early to Late Hercynian Altai (Fig. 2). These orogens are characterised as follows: (1) the Eastern Sayan orogen incorporates Archaean to Palaeoproterozoic basement overlain by Meso- to Neoproterozoic (Riphean) clastic and carbonate sequences; (2) the Salair, Sizim-Kazyr, and Eastern Tuva orogens comprise Late Neoproterozoic (Vendian) to Lower Cambrian volcano-sedimentary sequences intruded by Late Cambrian tonalite-granodiorite plutons; (3) the Western Sayan orogen is composed of Upper Cambrian to Silurian flysch-like clastic and carbonate sequences, with minor volcanic rocks; and (4) the Altai orogen incorporates Upper Cambrian to Lower Ordovician flysch-like sequences overlain by Ordovician to Silurian clastic-carbonate and carbonate formations and then by Devonian volcano-sedimentary sequences (e.g., Pluschev *et al.*, 2001). The majority of iron oxide deposits are located within the area covered by the Khakassian (or Kuznetsk Alatau) microcontinent and the Salair orogen, while some lie within the Sizim-Kazyr, Eastern Tuva and Altai orogens, and a few are found in the Western Sayan (Fig. 2). They consistently vary in age from Middle to Late Cambro-Ordovician and Silurian (Khakassia, Sizim-Kazyr, Eastern Tuva) to Devonian (Altai) (e.g., Pospelov, 1959; Indukaev, 1981; Alabin, 1983).

The iron oxide deposits of the Altai-Sayan region were emplaced contemporaneously with periods of maximum magmatic activity, when the respective tectonic environments most closely resembled Andean type active continental margins. However, in some terranes (most notably in the Khakassia domain), magmatic activity was extremely intense and lasted for a much longer period, resulting in the multiple occurrence of iron oxide mineralisation, persisting from the Cambrian to Ordovician to Silurian and into the Devonian. This intense endogenous activity, resembling a "hot spot" environment, is attributed to the presence of a large Early Palaeozoic mantle diapir underlying the Kuznetsk Alatau (Khakassia) and adjacent regions (Korobeinikov *et al.*, 1980). However, in some terranes, magmatic complexes distinctly correspond to the evolution from island arc to collisional environments, with the occurrence of various low-K tholeiitic/calc-alkaline and alkalic (shoshonitic) igneous suites. While some researchers argued for differences in magmatic suites producing iron oxide mineralisation (distinguishing deposits related to suites composed of mafic-intermediate, syenite to granosyenite, and granite, with some exhibiting a shoshonitic affinity; e.g., Vakhrushev, 1965, 1972), others suggested a general unity of these suites, thus, distinguishing a multiphase gabbro-diorite-monzonite-syenite-granosyenite-granite supersuite (e.g., Khomichev, 1988). Remarkably, the related intrusives are often coeval, and possibly comagmatic with, alkaline (trachytic) volcanics, in total forming complex volcanic-plutonic suites and respective local volcanic-tectonic structures. Interestingly, the respective trachytic volcanics are also accompanied by magnetite- and hematite-magnetite-bearing sandstones and tuffs, thus, possibly also suggesting intense formation of iron oxides during the volcanic stage (Mazurov, 1985; Kontorovich and Surkov, 2000).

In general, iron oxide mineralisation is most typical of the Early Palaeozoic (Cambrian to Ordovician, locally Silurian) igneous (plutonic, locally volcano-plutonic) suites (e.g., Vakhrushev, 1965, 1972), especially those dominated by relatively mafic (gabbro to diorite and monzonite) rocks. It has been observed that in many multiphase intrusives, iron oxide mineralisation is intersected by the late granitic phases. However, granite-dominated multiphase intrusives of this age are commonly accompanied by intense gold (±copper) mineralisation, rather than by iron oxides. In contrast, Devonian intrusives are accompanied by mostly copper (often copper-molybdenum; e.g., the Sorskoe deposit) mineralisation and likely by another pulse of gold mineralisation (e.g., Milman, 2004), although some of the Early Palaeozoic iron oxide mineralisation appears to have been remobilised and re-deposited in association with these younger plutons. Overall, the Early Palaeozoic iron oxide deposits form several clusters, some of which are coincident with metallogenic belts of gold, copper and gold-copper deposits (Fig. 2).

The most recent episode of tectonic and magmatic activity resulting in the formation of iron oxide deposits in the Altai-Sayan region is dated as Mesozoic. This age was obtained from iron oxide-rich carbonatites found in Tuva (Nikiforov *et al.*, 2006), associated with the formation of rift troughs and grabens, fault-controlled depressions, and the emplacement of numerous igneous suites, including alkaline complexes. This pulse of anorogenic activity corresponds to the Late Palaeozoic to Mesozoic (Permian to Cretaceous; ca. 260 to 100 Ma) mantle plume event recognised in Central Asia, and correlated with the Permo-Triassic mantle superplume below the Siberian craton (Borisenko *et al.*, 2006).

The numerous iron oxide and related deposits found in the Altai-Sayan region can be conditionally subdivided into three major groups, namely, (1) skarn and related replacement-style iron oxide (±copper, gold); (2) stratabound iron oxide and iron oxide-apatite - possibly of volcanic-exhalative or combined volcanic-exhalative and replacement origin; and (3) iron oxide-rich REE-P-U-Ba-Sr carbonatites. Some more detailed subdivisions

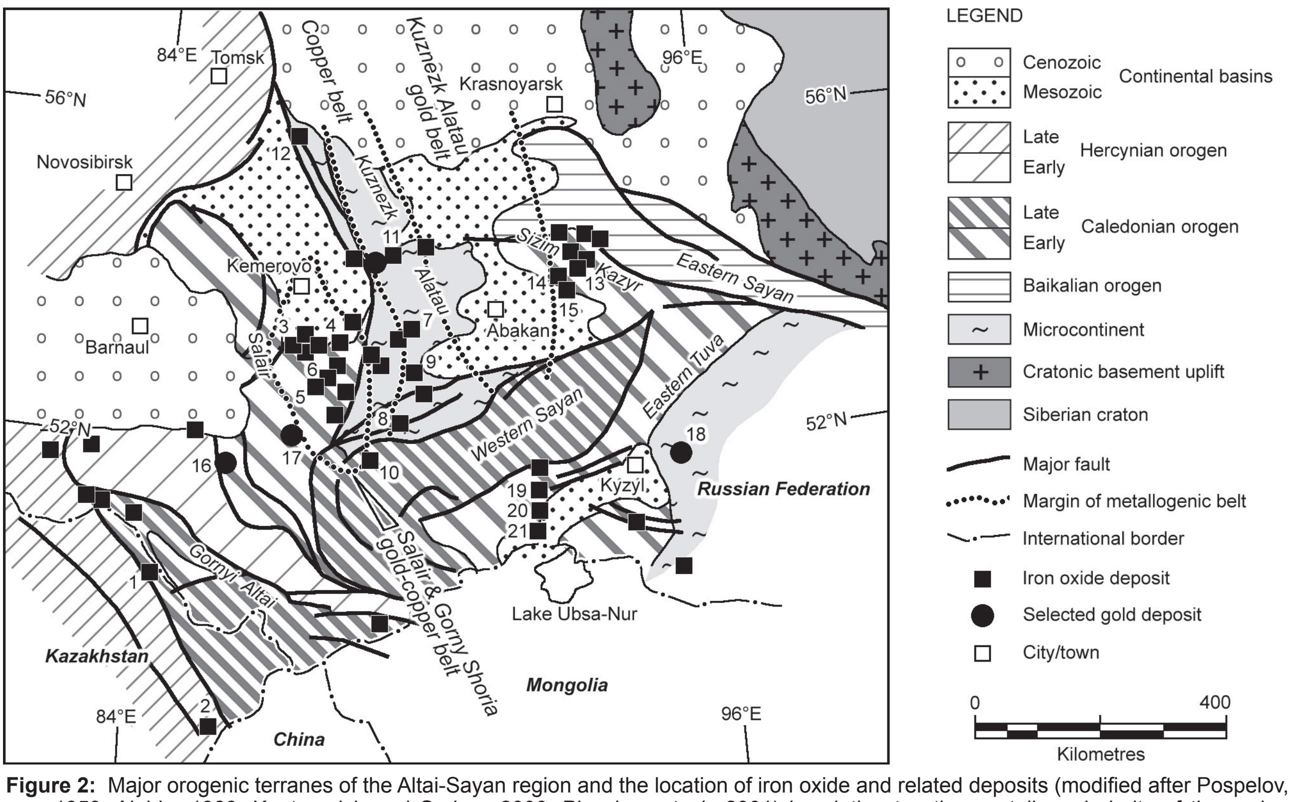


Figure 2: Major orogenic terranes of the Altai-Sayan region and the location of iron oxide and related deposits (modified after Pospelov, 1959; Alabin, 1983; Kontorovich and Surkov, 2000; Pluschev *et al.*, 2001) in relation to other metallogenic belts of the region (modified after Pospelov, 1959; Alabin, 1983). The Khakassian (Kuznetsk Alatau) and Tuva-Mongolian microcontinents are those in the central and eastern parts of the map respectively. Deposits (numbered on the map): **1** - Kholzunskoe; **2** - Markakulskoe; **3** - Temir-Tau; **4** - Kazskoe; **5** - Tashtagol; **6** - Sheregesh; **7** - Teiskoe and Abagasskoe; **8** - Anzass; **9** - Abakan; **10** - Volkovskoe; **11** - Kommunarovskoe; **12** - Ampalyk; **13** - Irbinskoe; **14** - Tabratskoe; **15** - Tayatskoe; **16** - Sinykhinskoe; **17** - Lebedskoe; **18** - Tardan; **19** - Karasug; **20** - Chaakhol; **21** - Ulatai-Choz.

within each group made on the basis of geological setting, mineral compositions, and other features are also possible. In addition, it is worth considering gold-copper deposits with only relatively minor associated iron oxide mineralisation.

Skarn and Related Replacement-style Iron Oxide (±Copper, Gold) Deposits

This group of deposits dominate in the Altai-Sayan region, hosting the vast majority of the known iron ore reserves and resources. Minor amounts of copper mineralisation (chalcopyrite, rarely bornite) are virtually consistently present in most deposits, becoming more significant in some. Gold mineralisation is also present in many although not recorded in resource estimates.

These deposits can be further subdivided into (1) proximal and (2) distal skarns, and (3) distal replacements (typically with no accompanying skarn alteration), corresponding to differences in their geological settings defined by the proximity to plutons, relation to fault zones, variations in host lithologies, as well as possible more fundamental differences in magmatic sources resulting from a variability in the associated plutons. In total, all this has influenced the styles developed and the relative abundances of accompanying hydrothermal-metasomatic alteration, iron oxide and associated mineralisation, etc., that generally determines the economic significance of deposits.

The skarn and related replacement-style iron oxide deposits found in the Altai-Sayan region have been studied by numerous researchers who have contributed to the understanding of the regional and local geological setting, deposit structures, compositions and formation conditions of various hydrothermal-metasomatic alteration assemblages and iron oxide and associated mineralisation (e.g., Pospelov, 1959; Vakhrushev, 1965, 1972; Korel, 1972; Sinyakov, 1975; Smirnov, 1977; Indukaev, 1981; Alabin, 1983; Mazurov, 1985).

Proximal (Contact Skarn) Iron Oxide Deposits

Iron oxide deposits of this type occur in the immediate proximity of related intrusives, most frequently represented by contact skarn alteration and mineralisation, often comprising groups of relatively small mineralised bodies, with a variety of skarn assemblages being abundant. These deposits typically constitute small to medium-sized iron reserves and resources, rarely exceeding 150 to 200 Mt of ore, and often containing less than 30 to 50 Mt.

The ***Kazskoe (Kaz) deposit*** (Fig. 3) - contained pre-production reserves of some 150 Mt of iron ore averaging 30 to 46 wt.% $Fe_{tot.}$, 1.0 to 8.1 wt.% $S_{tot.}$ and 0.05 to 0.25 wt.% P_2O_5 (Russian $B+C_1+C_2$ reserve categories; Kalugin *et al.*, 1981), containing up to 0.15 wt.% Cu. The deposit occurs in several segments, which overall form two subparallel strips approximately 1 km apart, each composed of mineralised bodies separated by barren intervals, that extend over a strike length of some 4 km. Individual orebodies may extend for up to 1 km along strike, with thicknesses of 4 to 126 m.

The deposit is hosted by a Lower Cambrian sequence made up of four units, comprising from the base, volcanic-carbonate, volcanic-chert, carbonate, and the uppermost volcanic-clastic. Mineralisation mostly occurs within the volcanic-chert and volcanic-clastic units. This sequence is overlain by Lower Ordovician rocks that incorporate conglomerates containing magnetite, martite and hematite fragments, and is intruded by three igneous suites including Early to Middle Cambrian gabbro, gabbro-diorite and syenite; Silurian diorite, monzonite, granodiorite, and granite; and Middle Devonian gabbro (Orlov *et al.*, 1998).

Magnetite ore occurs as lens-like, tabular and more complex bodies in skarn, often in the form of variously-sized roof pendants and remnants of host rocks wholly or partially enclosed within Early-Middle Cambrian and Silurian intrusive rocks. These orebodies are composed of magnetite, locally magnetite+pyrite, and occasionally hematite, with minor pyrrhotite, chalcopyrite and other sulphides. Mineralisation accompanies retrograde and hydrosilicate altered calcic skarn alteration. The formation of retrograde skarn is characterised by the re-crystallisation of pyroxene and garnet, particularly low-Fe skarn pyroxene (diopside and salite), which was converted into ferrosalite and hedenbergite, accompanied by magnetite mineralisation. Similarly, grossularite-andradite skarn garnet was re-crystallised producing more andradite-rich varieties. In some of the orebodies, magnetite mineralisation is closely associated with magnesian skarns containing spinel, clinohumite, phlogopite, serpentine, montichellite, brusite, boron minerals, etc. Magnetite-sulphide and sulphide-only mineralisation mostly occurs in the peripheries of the orebodies (Kalugin *et al.*, 1970, 1981; Sinyakov, 1975), with sulphides often forming up to 50 vol.% of the orebodies, locally as almost mono-minerallic accumulations. Pyrite and pyrrhotite predominate, while chalcopyrite and other sulphides are minor. According to Platonov and Sanin (1998), the deposit incorporates more than 30 significant intervals containing 1.3 to 19.3 g/t Au (average 2.64 g/t Au) over thickness of 1.5 to 27.5 m, and varying from a few tens to a few hundred metres along strike. The gold-bearing sulphide intervals have been traced for ~1000 m down plunge.

The ***Irbinskoe deposit*** (Fig. 4), which has been mined since the 18th century, has remaining reserves of around 100 Mt of iron ore averaging 39 wt.% $Fe_{tot.}$, 0.79 wt.% $S_{tot.}$ (Russian $B+C_1$ reserve categories; Kalugin *et al.*, 1981). The deposit and its extensions comprise a chain of

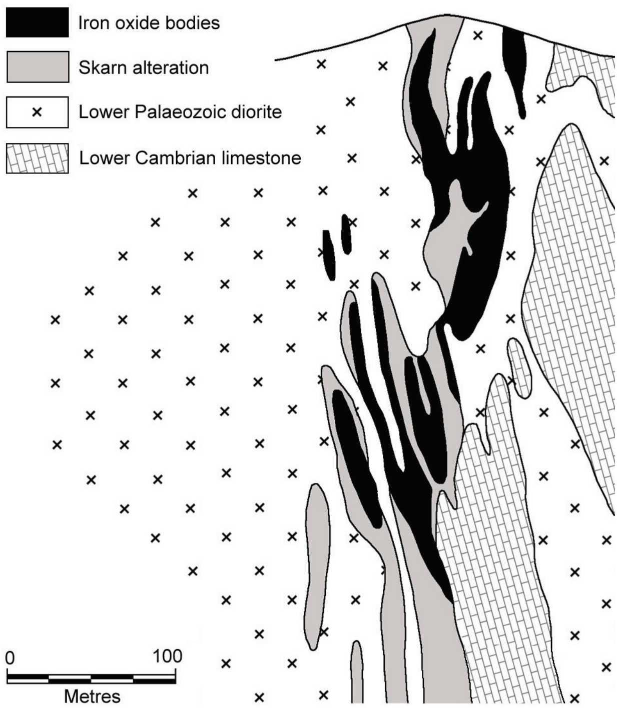


Figure 3: Geological cross section through part of the Kazskoe deposit (modified after Kalugin *et al.*, 1970).

separate bodies extending over a strike length of more than 12 km. These bodies largely occur in the contact zone of a composite Ordovician gabbro-diorite-monzonite-granosyenite-granodiorite pluton intruding a Lower to Middle Cambrian volcano-sedimentary sequence. The latter is composed of basalt, spilite, trachyte and rhyolite lava flows, progressively overlain by andesite and rhyolite tuffs, and by limestones, conglomerates, sandstones and siltstones. Ordovician diorites are partially overprinted by skarns, whereas the granosyenites as well as stocks and dykes of Devonian (?) granites and syenites, syenite-porphyry, trachytes, trachy-andesites and dolerite-porphyry postdate the mineralisation.

The main skarn-ore zone extends for 5 km along strike and is 300 to 400 m thick. It comprises garnet-pyroxene, garnet and plagioclase-pyroxene skarns, often overprinted by intense albite, epidote, and/or amphibole alteration (e.g., Dymkin *et al.*, 1975). These skarn alteration developments alternate with marble and hornfels, as well as diorite and syenite dykes and apophyses, and host several lens-shaped and tabular, massive to semi-massive magnetite orebodies, distributed in an *en echelon* pattern. They are characterised by steep (~80^o) dips. The orebodies are both proximal, confined to the contact zones of Ordovician diorite intrusives, and distal from contact zones, where they lie concordant to the bedding of the volcano-sedimentary sequence. A total of some 50 magnetite orebodies are known in the major skarn-ore zone, the largest of which persists for ~650 m along strike, 350 m down-dip, and over a thickness of up to 60 m. In some parts of the deposit, magnetite orebodies occur in large roof pendants partially or completely surrounded by intrusive rocks.

Magnetite and magnetite-mushketovite mineralisation predominates, with gangue minerals including pyroxene, garnet, chlorite, calcite, albite, less abundant epidote, quartz and serpentine. Large accumulations of sulphides are present in the hangingwall in some parts of the deposit, occurring as pyrite, pyrrhotite and chalcopyrite, together with magnetite, formed after an intense brecciation event which overprints the garnet skarns and magnetite mineralisation. The largest sulphide mass extends for 250 m along strike and is up to 50 m thick, with significant copper intersections, including 16.6 m @ 0.76 and 10.4 m @ 1.13 wt.% Cu (and 0.061 wt.% Co) (Kalugin *et al.*, 1970).

Mazurov (1985) described initial magnetite deposition accompanying the formation of retrograde skarns, particularly in assemblages where anisotropic andradite-grossularite garnet replaced essentially late prograde andraditic garnet. However, the majority of the magnetite was formed in assemblages which contained amphibole, probably indicating a transition to a younger hydrosilicate alteration stage. More specifically, the amphibole most closely associated with magnetite is hastingsite, which together with the magnetite, comprises the most abundant ores, replacing pyroxene and garnet, pyroxene and plagioclase in skarns, and forms veins and veinlets in altered igneous rocks, etc. However, assemblages of hastingsite (and magnetite) with retrograde garnet are also common. Hastingsite is subsequently substituted by actinolite in assemblages containing epidote, quartz, chalcopyrite and pyrite. Actinolite metasomatites are, in turn, essentially replaced by a chlorite-calcite-pyrite assemblage. Thus, there is a distinct evolution of amphibole composition corresponding to the transition from predominantly magnetite, to essentially sulphide (chalcopyrite, pyrite, etc.) mineralisation.

The ***Tabratskoe deposit*** (Fig. 5) contains some 240 Mt of iron ore averaging 28 to 29 wt.% $Fe_{tot.}$, 0.1 wt.% $S_{tot.}$ and 0.06 wt.% P_2O_5 (Russian B+C_1 reserve categories; Kalugin *et al.*, 1981). The deposit is localised on the contact of a Late Cambro-Ordovician composite gabbro, gabbro-diorite, diorite and quartz-diorite pluton intruding Lower Cambrian marbles and volcanics composed of andesite flows and tuffs. Mineralisation extends for 3.8 km and incorporates several separate bodies. The largest skarn and iron oxide orebody is lens-shaped, extending for 900 m along a diorite-marble contact at surface, and can be followed steeply down-plunge for 1300 m. This body is composed of veined and disseminated magnetite overprinting epidote-pyroxene, epidote-amphibole, and plagioclase-pyroxene skarns, altered gabbro, gabbro-diorite, and diorite. Younger dykes of diorite-porphyry and microdiorite cut the mineralisation.

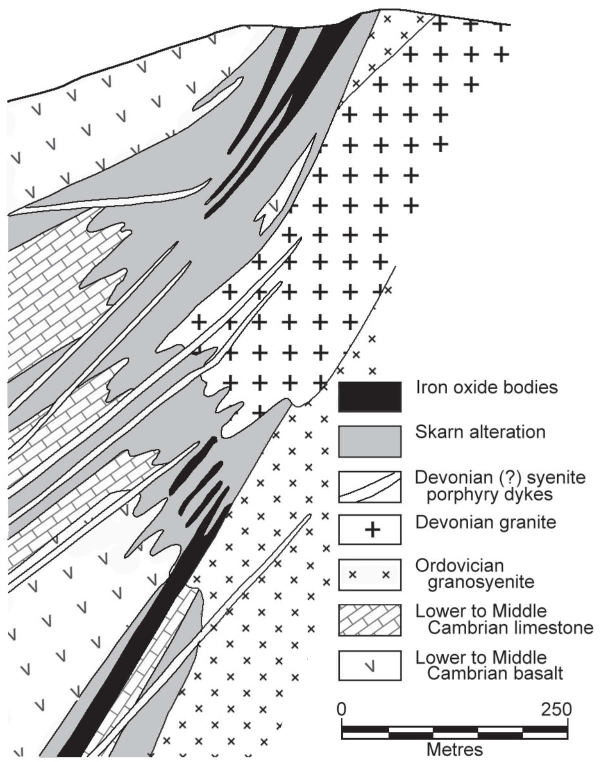


Figure 4: Geological cross section through part of the Irbinskoe deposit (modified after Kalugin *et al.*, 1970).

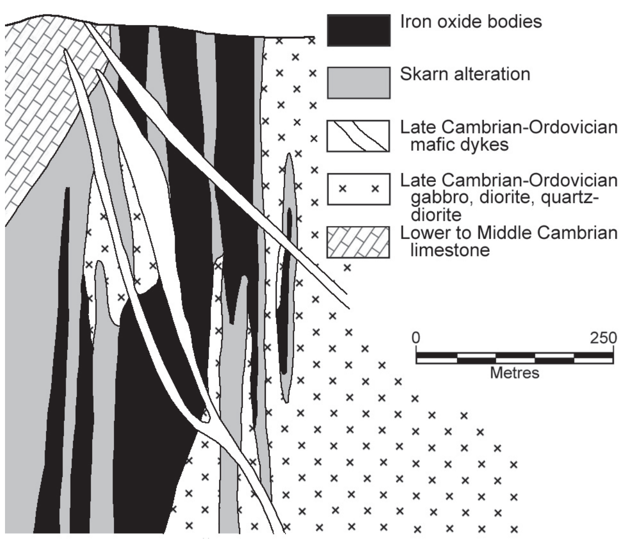


Figure 5: Geological cross section through the eastern part of the Tabratskoe deposit (modified after Kalugin *et al.*, 1981).

Pyrite (often cobalt-bearing), chalcopyrite and pyrrhotite are common in the iron oxide ores. In addition, the deposit incorporates two smaller pyrrhotite-pyrite-chalcopyrite bodies.

According to Mazurov (1985), the deposit is characterised by intense hydrosilicate (mostly amphibole) alteration occupying much wider areas than that of the magnetite mineralisation. Various amphiboles are constituents of the alteration assemblages pre-dating, coincident with, and postdating magnetite. In particular, hastingsite-albite, hastingsite-diopside-albite, hastingsite-clinozoisite, and garnet-epidote-hastingsite assemblages, together with diopside-albite and diopside-clinozoisite, represent an outer Ca-Na-Mg metasomatic halo surrounding pyroxene-garnet and essentially pyroxene skarns. The skarns and early amphibole-dominated assemblages are overprinted and replaced by magnetite-dashkesanite, dashkesanite, and dashkesanite-quartz-calcite assemblages corresponding to the major K-rich ore-forming stage. They, in turn, are overprinted by Ca-Mg rich actinolite-epidote-quartz (with calcite, scapolite and chlorite) assemblages.

Proximal to Distal Skarn Iron Oxide Deposits

These deposits generally occur in more distal settings, often well above larger plutons, i.e., in the areas where only intrusive apophyses, small stocks and dyke swarms are present. A distinct sub-type is associated with breccia pipes, which also occur at some distance from related plutons. A further, separate sub-type is represented by flat-lying skarn and related orebodies, well above associated plutons, hosted by shallow-dipping lithologies. No intrusive rocks have been encountered at all in association with some deposits, although large plutons are postulated at depth. Never-the-less, abundant skarn assemblages are still found in association with all of these deposits, while remarkably, the maximum iron ore reserves and resources are greater than those of the more proximal skarn deposits.

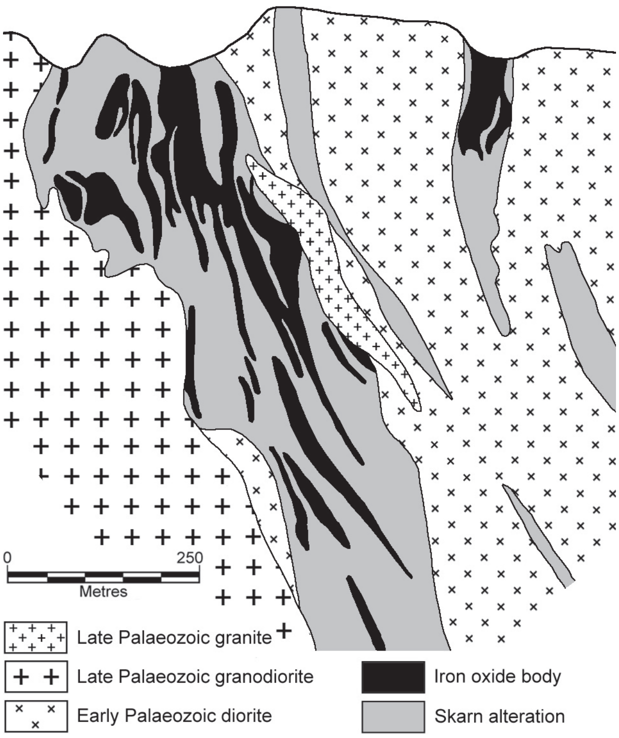


Figure 6: Geological cross section through part of the Temir-Tau deposit (modified after Kalugin *et al.*, 1970).

The ***Temir-Tau deposit*** (Fig. 6) has been mined out. It contained pre-production reserves of some 30 Mt of iron ore averaging 44 wt.% $Fe_{tot.}$, 1.9 wt.% $S_{tot.}$, and 0.15 wt.% P_2O_5 (Kalugin *et al.*, 1970). The deposit is localised in a roof pendant composed of a Cambrian sequence of essentially carbonate rocks, surrounded by an Early Palaeozoic pluton composed of diorite, granodiorite and granite. The carbonate rocks (mostly dolomites) were converted into magnesian skarns. Montichellite-forsterite-spinel magnesian skarn alteration is present at deeper levels, while upward there is partial to complete replacement by calcic pyroxene-garnet assemblages. Veined skarn bodies cutting diorite are locally present. These skarns were subsequently replaced by amphibole-dominated hydrosilicates and then by chlorite-calcite-serpentine metasomatites. Younger (Late Palaeozoic ?) granodiorite and granite intrusives cross-cut both the skarns and iron oxide mineralisation.

The deposit incorporated several orebodies found within a 200 to 300 m wide mineralised zone extending for 1000 m along strike and traced for 500 m downdip. To the east, this zone pinches out in diorites, whereas to the west it is cut by granites, where strong enrichment in magnetite is observed. Magnetite typically cements and replaces pyroxene and garnet and, is in turn replaced by pyrite, pyrrhotite, chalcopyrite and at higher levels by martite. Gangue minerals include epidote, green biotite, amphibole, ilvaite, calcite, chlorite, serpentine and apatite. Mazurov (1985) reported two major generations of magnetite, namely, (1) an early stage associated with an amphibole-dominated hydrosilicate assemblage, and (2) a late phase formed together with serpentine-dominated metasomatites. According to Platonov and Sanin (1998), magnetite-sulphide ores contained up to 0.25 wt.% Cu and 0.5 g/t Au, locally including intervals of as much as 0.8 to 1.0 wt.% Cu and 3 g/t Au. The deposit has remaining resources of some 19 tonnes of contained gold.

The ***Sheregeshevskoe (Sheregesh) deposit*** (Fig. 7) - contained pre-production reserves of some 320 Mt of iron ore averaging 35 wt.% $Fe_{tot.}$, 1.57 wt.% $S_{tot.}$, and 0.52 wt.% P_2O_5 (Russian $B+C_1+C_2$ reserve categories; Kalugin *et al.*, 1981). The deposit is localised on one limb of a Cambrian, cupola-like volcanic (or volcano-plutonic) structure, complicated by a local synclinal fold (alternatively interpreted as a caldera by Orlov, *et al.*,

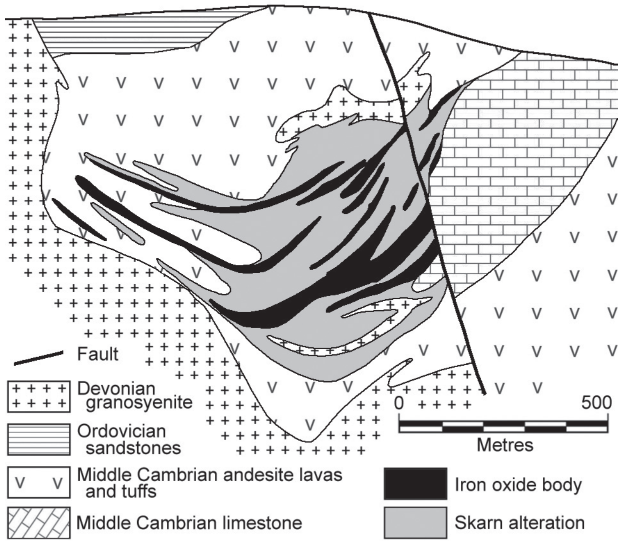
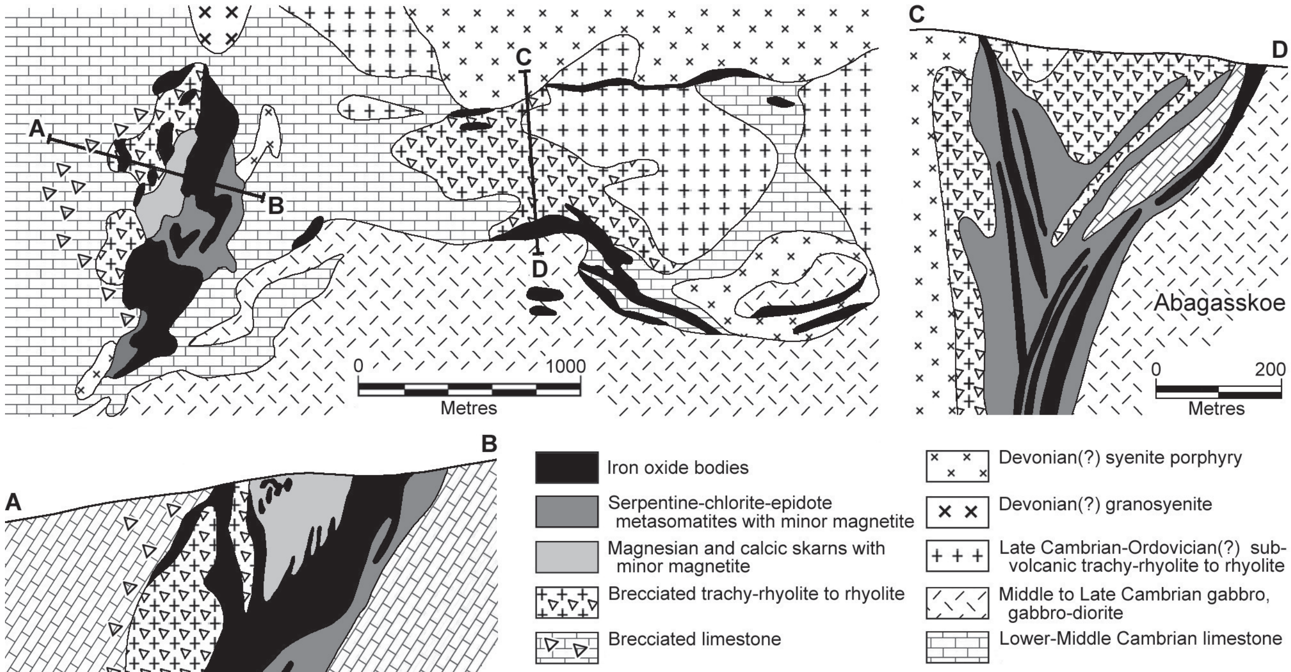


Figure 7: Geological cross section through part of the Sheregesh deposit (modified after Kalugin *et al.*, 1970). Note that the Devonian granosyenite crosscuts both the skarns and iron oxide bodies.



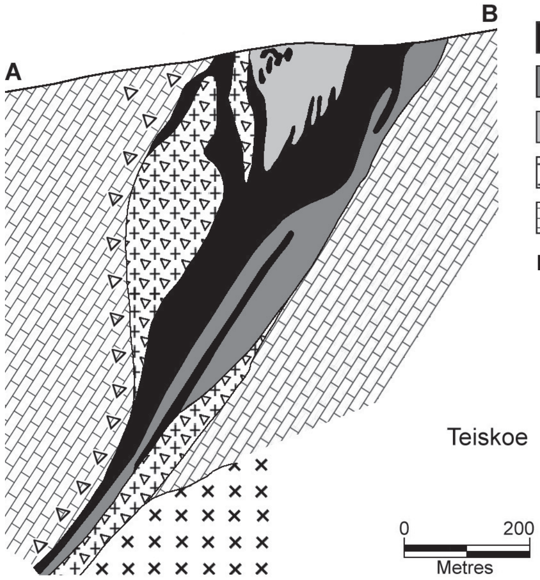


Figure 8: Geological plan and cross sections of the Teiskoe (section A-B) and Abagasskoe (section C-D) deposits (modified after Kalugin *et al.*, 1981).

1998). The mineralisation is hosted by a Middle Cambrian volcano-sedimentary sequence that includes: (1) a lower volcanic suite dominated by andesite-basalt flows and tuffs, with minor trachy-andesite volcanics, tuffaceous conglomerates and sandstones, (2) an intermediate unit that hosts the majority of the ore, composed of massive and fragmental limestones, trachytic tuffs, tuffaceous sandstones and siltstones, and (3) an upper succession of andesite-basalt tuffs and lava-breccias. This sequence is intruded by syenite stocks and dykes that are the apophyses of a larger, concealed syenite pluton, the roof of which is at a depth of 500 to 1000 m below the surface. Stocks and sills of melanogabbro and gabbro-diorite are also present. All of these volcano-sedimentary and plutonic rocks are discordantly overlain by Ordovician sandstones, siltstones and conglomerates containing magnetite grains and clasts. All are in turn intruded by Devonian granitoids. The deposit occurs as a series of flat-lying ore bodies enveloped by skarn, localised in a sub-horizontal to shallow-dipping volcano-sedimentary sequence, with no distinct spatial relationship to plutons, and has a geological setting somewhat resembling that of the Candelaria IOCG deposit in Chile (e.g., Marschik and Fontbote, 2001).

Two generations of skarn formation and corresponding assemblages are distinguished (Korel, 1972; Kalugin *et al.*, 1981). The earliest of these skarns were formed near syenite contacts, where they occur as thick (as much as 200 to 500 m) bodies composed mostly of intermediate andradite-grossularite garnet and pyroxene (diopside) that are replaced by epidote and Mg-amphibole. The syenites are also overprinted and fringed by intense potassic (K feldspar) and sodic (albite) alteration as well as by magnesian skarns (pyroxene-phlogopite-spinel). The second skarn generation forms veins and stockworks near the granite pluton, composed of diopside, andradite and wollastonite.

Massive to semi-massive iron oxide mineralisation forms complex-shaped bodies (lenses, stocks, pipes, etc.) overprinting skarns, and evolving into subeconomic stockworks on a depth of 500 to 700 m. At least two generations of iron oxides are recognised, namely: (1) fine-grained, often banded magnetite, and (2) a younger generation which includes coarsely-crystalline magnetite. Hematite and mushketovite are locally present as well as pyrite and pyrrhotite (up to 10 vol.%), and minor chalcopyrite. The distal parts of magnetite orebodies are especially enriched in Cu sulphides, where they contain on average 0.59 wt.% Cu, 0.087 wt.% Co, and 0.1 g/t Au. Some sectors are also enriched in sphalerite containing >0.4 wt.% Zn. According to Platonov and Sanin (1998), several local sections of the deposits carry 0.2 to 0.7 g/t Au over intervals as wide as 28 m across in these sulphide-enriched peripheries of the magnetite orebodies.

The ***Teiskoe and Abagasskoe deposits*** (Fig. 8), which are situated in close proximity to each other, contained pre-production reserves of some 210 Mt (*Teiskoe*) and 100 Mt (*Abagasskoe*) of iron ore, averaging 39 and 31 wt.% Fe_{tot}, respectively, and 1.76 wt.% $S_{tot.}$ (Russian $B+C_1+C_2$ reserve categories; Kalugin *et al.*, 1981; Orlov, *et al.*, 1998). These deposits are both related to explosive breccia pipes or diatremes (e.g., Dolgushin *et al.*, 1979).

Teiskoe is localised at a district-scale fault intersection within a sequence of Lower to Middle Cambrian limestones and dolomites. Several Middle to Late Cambrian stocks of gabbro-diorite and diorite are present in the deposit area. These have been subjected to intense epidote and amphibole alteration and are in turn intruded by Late Cambrian to Ordovician(?) granitoids. In addition, there are a number of small, likely Late Cambrian to Ordovician, sub-volcanic trachyte, trachy-rhyolite and rhyolite bodies in the same area. Younger granosyenites and syenite porphyries, accompanied by intense sodic (albite) and potassic (K feldspar) alteration, and silicification are found on the deposit flanks and at depth.

The main mineralised zone is represented by magmatic breccias, cemented by trachy-rhyolite, and subsequently metasomatically altered and enriched in magnetite. These breccias are composed of large, un-sorted, clasts of trachyte, limestone, granite, etc. A strip of brecciated limestones and dolomites containing magnetite fragments follows the hanging wall of the breccia. At the surface, the breccia pipe has plan dimensions of some 600 × 1250 m, decreasing downward to a diameter of 150 to 300 m at a depth of 1000 m. It hosts 12 steeply dipping lens-like magnetite orebodies, with the largest found towards its footwall. This main magnetite orebody extends for more than 1500 m along strike and for 1300 m down-dip, with a maximum thickness of 300 m.

The deposit is associated with both magnesian and calcic skarns which are distinctly related to the Middle to Late Cambrian gabbro-diorite-granite suite and are accompanied by retrograde and hydrosilicate alteration, and by early iron oxide (magnetite) mineralisation (cf. Mazurov, 1985). Magnesian skarns contain olivine, hondrodite, clinohumite, diopside, and spinel, while the calcic skarns are composed of garnet and pyroxene. The breccia pipe was subsequently formed during the emplacement of trachy-rhyolite and rhyolite subvolcanic intrusions, essentially as the result of magmatic eruption and explosive hydrothermal processes. This caused intense and possibly multiple brecciation of the early skarns and associated magnetite, and was accompanied by albitic alteration. Further hydrothermal activity produced magnetite, magnetite-serpentine, magnetite-chlorite-serpentine and magnetite-serpentine-phlogopite mineralisation that overprinted and replaced breccias and early skarns clasts. Multiple re-crystallisation and re-deposition of the mineralisation, numerous generations of magnetite, serpentine and other minerals are typical of the breccia pipe. A distinct variety of iron oxide mineralisation is represented by hematite overprinting early magnetite ores and locally forming coarsely-crystalline specularite aggregates. Minor pyrite, pyrrhotite, chalcopyrite, nickeline, safflorite and sphalerite are locally present.

The *Abagasskoe* deposit adjoins Teiskoe to the east, and is also associated with a distinct ovoid pipe-like structure. The mineralised zone is represented by arc-like branches which dip toward the centre of this structure, corresponding to the north and south sides of this breccia pipe or diatreme. The internal part of this generally concentric structure is composed of intensely fractured and brecciated Middle Cambrian limestone and dolomite as well as Late Cambrian (?) trachytes, rhyolite-porphyries and their breccias. This east-west elongated ovoid structure has surface dimensions of approximately 700 × 2500 m. To the south, it is bounded by Middle to Late Cambrian gabbro and gabbro-diorite intrusives and to the north by a Devonian (?) syenite-porphyry pluton. Both the gabbros outside the structure and limestones within it are cut by an intense swarm of small trachyte dykes and veins and their associated breccias. The latter have sharp contacts with both the limestones and gabbros, but are overprinted by intense serpentine, chlorite, amphibolite, carbonate, epidote and hematite alteration and accompanying magnetite mineralisation. Boron minerals (ilvaite, ludwigite, asharite, etc.) are locally present. Serpentine-chlorite-epidote metasomatites dominate the breccia pipe, with garnet and pyroxene-garnet skarns remaining on its flanks and at lower levels. In addition to magnetite, the mineralisation includes hematite, mushketovite, pyrrhotite and minor to locally abundant pyrite and chalcopyrite.

Proximal to Distal Albite-scapolite-rich Iron Oxide Deposits

These deposits are characterised by abundant albite-scapolite-dominated alteration that is younger than the skarns and replace them. In addition, the skarns are generally of relatively minor importance or are almost totally absent from many of these deposits. Correspondingly, the albite-scapolite metasomatites, and related iron oxide mineralisation, mostly occur as sub-vertical bodies, often distinctly related to fault zones that follow steeply dipping, pre-existing, lithological contacts, rather than being confined to intrusive contacts of related plutons. These deposits are often large, containing as much as 300 Mt of iron ore.

The ***Tayatskoe deposit*** (Fig. 9), which is relatively small, is located approximately 20 km from Sheregesh (described above) and contains 30 Mt of iron ore averaging 27 to 37 wt.% $Fe_{tot.}$, 1.44 wt.% $S_{tot.}$, and 0.11 wt.% P_2O_5

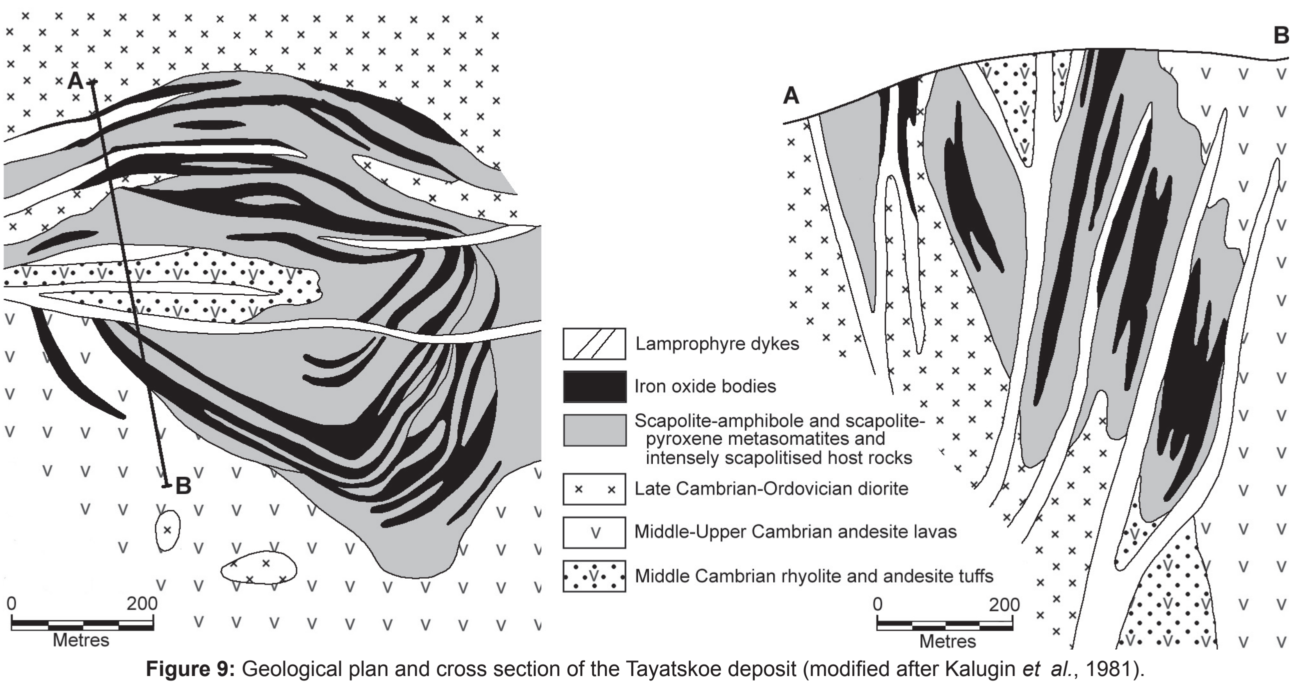


Figure 9: Geological plan and cross section of the Tayatskoe deposit (modified after Kalugin *et al.*, 1981).

(Russian B+C_1+C_2 reserve categories; Kalugin *et al.*, 1981). It is also some 15 km from the Tabratskoe deposit (described above), within the same linear volcanic trough filled by Lower Cambrian mafic volcanic-pyroclastic sequences, which have been metamorphosed to green schist facies, and intruded by multiphase Late Cambro-Ordovician gabbro-diorite-granodiorite plutons. The deposit is hosted by intercalated tuffaceous sandstones, siltstones and conglomerates overlain by mafic volcanics. The plutons are multiphase, composed of gabbro-diorite and gabbro (1st phase), diorite, quartz diorite (2nd phase), and plagiogranite-porphyry (3rd phase). The rocks of the 1st and 2nd phases form large, irregularly-shaped stocks and are subjected to endocontact metasomatic alteration. In contrast, the 3rd phase rocks occur as dykes intersecting all older intrusive rocks as well as all metasomatised and mineralised rocks. Late lamprophyre dykes are also present.

The deposit has as a generally downward tapering conical shape, with surface dimensions of some 600 × 700 m, and incorporates numerous lensoid bodies of massive magnetite which dip steeply (70 to 80^o) toward the cone axis. It is unclear whether this shape reflects a local syncline within a large roof pendant hosting the mineralisation, or alternatively, if it represents the upper section of a pipe- or diatreme-like structure. Individual massive magnetite bodies persist for up to 700 m along strike, 650 m downdip, and are 10 to 50 m in thickness. According to Kalugin *et al.* (1981), some steeply dipping magnetite bodies apparently merge at depth. Several styles of magnetite mineralisation are present, including early fine-grained banded magnetite, late higher-grade veined magnetite-amphibole, disseminated and brecciated low-grade scapolite-pyroxene-magnetite, and minor magnetite-chlorite-biotite varieties. Minor sulphides (pyrrhotite, chalcopyrite and pyrite) occur as local disseminations. The host tuffaceous sandstones, siltstones and conglomerates found in the immediate deposit area are now essentially to wholly converted into scapolite-pyroxene and scapolite-amphibole metasomatites.

Mazurov (1985) described abundant scapolite overprinting and replacing early magnetite-bearing skarn assemblages. This resulted in the transformation of early banded magnetite into “spotty” scapolite-magnetite aggregates (with the re-crystallisation of magnetite) or into an almost mono-minerallic scapolite metasomatites. The pervasive, massive scapolite alteration of early skarns is coincident with veined scapolitisation of gabbro-diorite and gabbro to form scapolite-diopside metasomatites, and immediately pre-dated massive post-skarn magnetite deposition. The latter was accompanied by the substitution of early low-Fe pyroxene (diopside) and amphibole by actinolite and hastingsite. Magnetite replaces scapolite, incorporating poikilitic pyroxene grains, and actinolite replaces this pyroxene. This magnetite-amphibole mineralisation overprints skarns which previously replaced both intrusive and volcano-sedimentary rocks, and follows crosscutting and bedding-parallel fractured zones. The magnetite-amphibole assemblage was subsequently partially replaced by a younger albite-actinolite-epidote mineralogy which was coincident with the deposition of sulphides (pyrrhotite, pyrite, and chalcopyrite). Mazurov (1985) also described younger (?) pegmatite-like pyroxene-apatite veins found in intrusive rocks.

The ***Anzasskoe (Anzass) deposit*** (Fig. 10) contained pre-production reserves of some 260 Mt of iron ore averaging 29 to 38 wt.% $Fe_{tot.}$, 0.97 to 2.88 wt.% $S_{tot.}$, and 0.09 to 0.18 wt.% P_2O_5 (Russian B+C_1+C_2 reserve categories; Kalugin *et al.*, 1981). It is localised in an intensely tectonised Lower Cambrian volcano-sedimentary sequence that includes cherty and clayey shales, basalts and limestones, which are intruded by a gabbroic suite considered to be either Cambrian or Ordovician-Silurian in age (Kalugin *et al.*, 1981). It is represented by trachytic gabbro and gabbro-dolerite, and at deeper levels by olivine gabbro. Younger phases include Na-syenite, and dykes and stocks of strongly albitised felsic(?) rocks locally containing magnetite. This intrusive suite is accompanied by magmatic and explosive hydrothermal breccias, often enriched in magnetite, both in the clasts and matrix. The gabbroic rocks, together with the host volcanics, were subjected to intense albitic alteration. Pavlov (1983) described strongly albitised felsic(?) rocks containing magnetite at the Anzass deposit as “ore porphyry”. These are composed essentially of magnetite and albite, with larger albite “porphyrocrysts”. The magnetite content varies from 5 to 40 vol.%, averaging 20 to 25 vol.%. Locally, these “porphyries” have a breccia-like appearance, with clasts composed of the same “ore porphyry”, Na-syenite, and albitised granite-porphyry.

Hydrothermal alteration assemblages are characterised by a predominance of albite, scapolite, epidote, amphibole, and phlogopite, with abundant mono-minerallic albite and

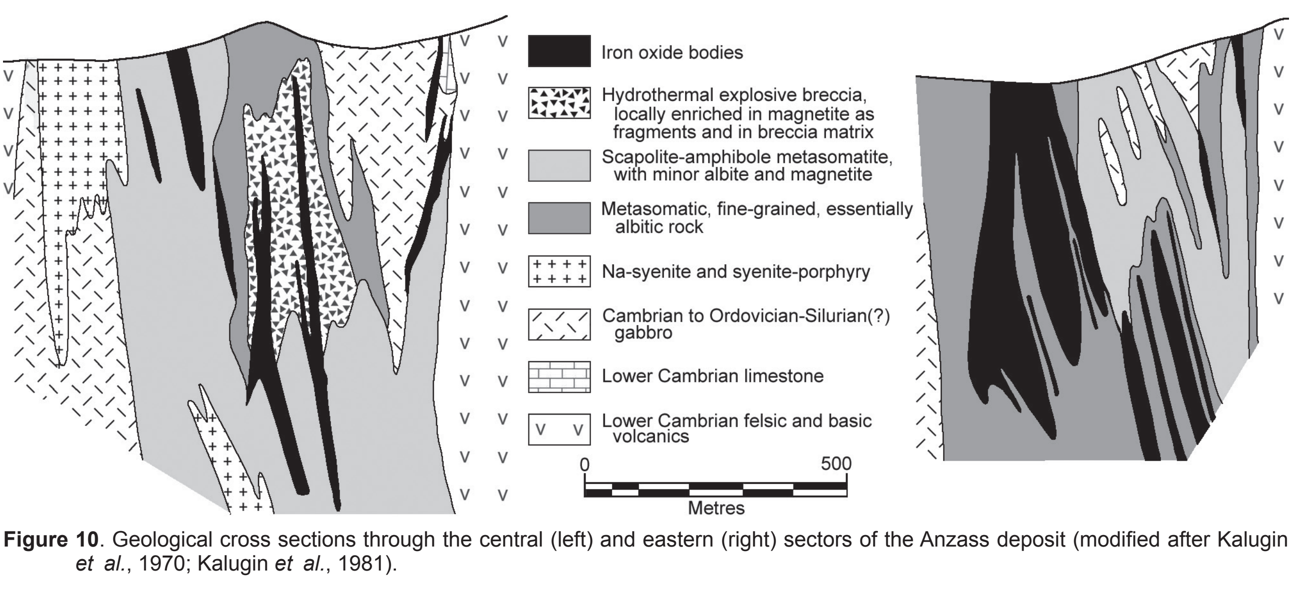


Figure 10. Geological cross sections through the central (left) and eastern (right) sectors of the Anzass deposit (modified after Kalugin *et al.*, 1970; Kalugin *et al.*, 1981).

albite-scapolite replacing igneous and sedimentary rocks. According to Kalugin *et al.* (1970), there were at least two stages of intense sodic alteration. The most intense scapolitisation slightly pre-dates the late, and similarly strong albitisation. The strongest magnetite mineralisation was formed later by the replacement of essentially albitic rocks, together with the formation of phlogopite, amphibole and apatite. Corresponding magnetite-albite, magnetite-amphibole-albite, magnetite-amphibole, and rare magnetite-apatite ores are recognised. As a result, the largest magnetite orebodies occur in zones of intense albitisation and brecciation within the gabbroic intrusives. Three subparallel mineralised zones are distinguished, the largest of which extends for 1700 along strike and is up to 200 m (averaging 50 m) in thickness. The magnetite ores are predominantly brecciated, ranging from weakly in the lower deposit levels, to strongly in the upper parts of the system. Magnetite is accompanied by albite, amphibole (Fe-actinolite, hastingsite-dashkesanite), scapolite, phlogopite and minor apatite, cobaltian-pyrite, pyrrhotite, chalcopyrite, etc.

The ***Ampalyk deposit*** (Fig. 11) contained pre-production reserves of some 300 Mt averaging 30 wt.% $Fe_{tot.}$, 2.37 to 3.24 wt.% $S_{tot.}$, and <0.06 wt.% P_2O_5 (Russian $B+C_1+C_2$ reserve categories; Kalugin *et al.*, 1981). The deposit is localised at the contact between a sequence of Middle Cambrian volcano-sedimentary rocks and an Early Palaeozoic diorite pluton. These older rocks are discordantly overlain by a Jurassic to Cretaceous coal-bearing continental sequence. The Middle Cambrian rocks comprise basalt and andesite flows, dolerite sills and limestones. The steeply dipping contact zone incorporates subparallel, alternating bands of magnetite mineralisation, pyroxene and garnet skarns, thin diorite dykes and apophyses, remnants of volcano-sedimentary rocks and hornfels.

The iron oxide ore occurs as a series of sub-vertical bodies that can be traced to a depth of 1200 m below the surface. The mineralisation is composed of magnetite (>40 vol.%) with minor pyrite, pyrrhotite, chalcopyrite, etc., accompanied by locally abundant scapolite and epidote, and by consistently intense amphibole, chlorite, K feldspar and biotite alteration. Thus, this deposit may represent the transition from albite-scapolite to a chlorite-amphibole-dominated iron oxide deposits. The most intense magnetite mineralisation is associated with amphibole-dominated hydrosilicate alteration of skarns, overprinting all previous hydrothermal products, including skarns, and scapolite and albite metasomatites. Late zones of quartz-sericite-carbonate alteration carry abundant sphalerite and galena (locally up to 4.2 wt.% Zn and 1.2 wt.% Pb). The deposit incorporates two zones with magnetite-sulphoarsenide mineralisation that includes magnetite (60 to 90 vol.%), arsenopyrite, loellingite, danaite, cobaltite, pyrite, pyrrhotite, bismuthite and native gold. According to Platonov and Sanin (1998), native gold forms fine intergrowths with sulphoarsenides. The ore contain 0.03 to 17.4 g/t Au (averaging 0.85 g/t Au), for a total of about 17 tonnes of gold within the deposit.

Distal Chlorite-amphibole-rich Iron Oxide Deposits

These deposits have a similar geological setting to the albite-scapolite-dominated deposits described above, and are also generally localised in sub-vertical fault zones that follow pre-existing lithological contacts. They are, however, characterised by only relatively minor albite and scapolite, dominated instead by chlorite-amphibole alteration assemblages. As such, they resemble the copper-iron skarn deposits in the central coast belt of Peru (e.g., Vidal *et al.*, 1990). This might reflect the respective differences in "fluid specialisation" and fluid regime of associated plutons, combined with variations in the local geological setting and host lithologies. As suggested by Mazurov (1985), those deposits that are essentially hydrosilicate-dominated (chlorite-amphibole), represent the most distal type of iron oxide (±copper, gold) deposits of the Altai-Sayan region. They are often large, with significant potential for down-dip extensions of mineralisation, and include the Volkovskoe, Abakan and Tashtagol deposits; the latter being the largest iron oxide deposit of the Altai-Sayan region.

The ***Volkovskoe deposit*** (Fig. 12) - contains some 500 Mt of iron ore averaging 36 wt.% $Fe_{tot.}$, 0.04 to 1.7 wt.% $S_{tot.}$, 0.02 to 0.20 wt.% P_2O_5, 0.01 to 0.22 wt.% Cu, and 0.01 to 0.04 wt.% Co (Russian C_1+C_2 reserve categories; Orlov, *et al.*, 1998). It is located within a district- to regional-scale fault zone which separates two structural domains, namely: (1) a western block, composed of Upper Cambrian to Lower Ordovician(?) gneisses, migmatites, crystalline biotite schists and trachy-rhyolite tuffs, and (2) an eastern block which includes Lower Silurian sandstones, siltstones,

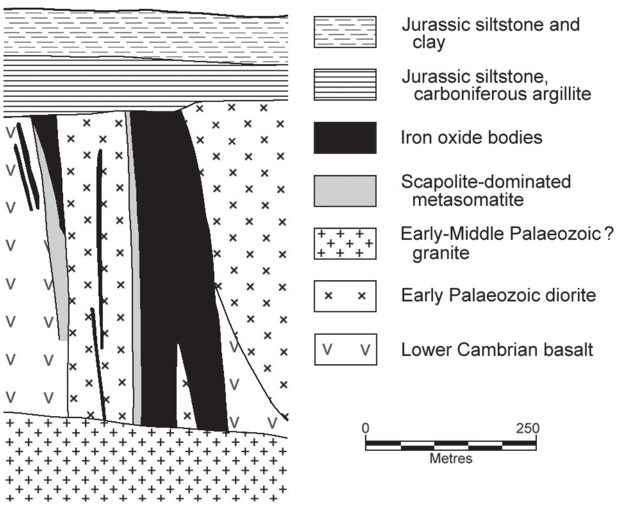


Figure 11: Geological cross section through part of the Ampalyk deposit (modified after Kalugin *et al.*, 1970).

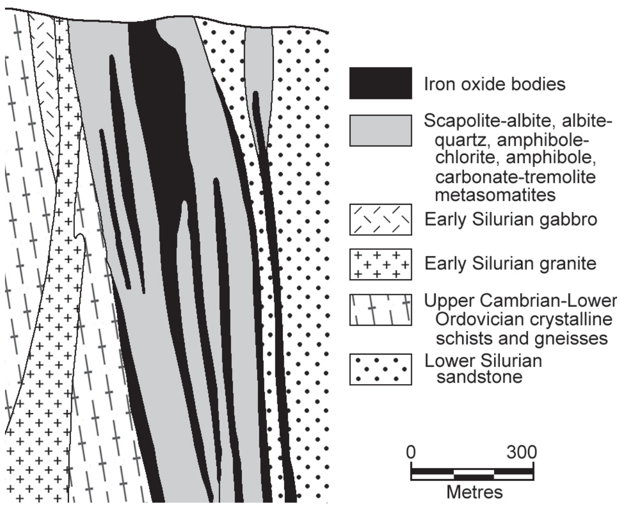


Figure 12: Geological cross section through part of the Volkovskoe deposit (modified after Orlov, *et al.*, 1998).

argillites, minor dolomites and limestones. These sequences are intruded by Early Silurian granitoids, the larger pluton of which outcrops some 1500 m from the deposit, and by Early Devonian gabbro-dolerites.

The deposit comprises several sub-vertical, lens-like and tabular iron oxide orebodies, together with a zone of intense hydrothermal alteration, localised by the fault zone dividing the two structural blocks. The mineralised zone persists over a total length of 3.5 km, with individual orebodies extending for 500 to 650 m along strike and over widths of up to 250 m. The alteration zone essentially includes amphibole, chlorite-amphibole, epidote, albite-quartz, carbonate-tremolite, scapolite-albite, assemblages. Mineralisation is represented by massive and stockwork magnetite, accompanied by minor hematite, pyrite, pyrrhotite, chalcopyrite, etc. Overall, magnetite-biotite-amphibole-chlorite ores predominate, with some intervals that include mushketovite-quartz ores with albite and biotite alteration, and magnetite-tremolite-talc mineralisation within brecciated dolomites. Magnetite-scapolite-amphibole, magnetite-carbonate, and magnetite-sulphide ores are only of minor importance.

The ***Abakan deposit*** (Fig. 13) - contained pre-production reserves of some 220 Mt of iron ore averaging 42 to 47 wt.% $Fe_{tot.}$, 2.3 to 2.4 wt.% $S_{tot.}$ and 0.19 to 0.70 wt.% P_2O_5 (Russian $B+C_1+C_2$ reserve categories; Kalugin *et al.*, 1981). There is also significant cobalt and gold mineralisation that is not extracted. The deposit is localised along an anticlinal limb occupied by a sequence of Lower to Middle Cambrian volcanic and tuffaceous-sedimentary rocks that are overlain by Lower Devonian(?) volcanics. The Lower Cambrian rocks include a lower basalt to rhyolite volcanic suite and an upper package of sandstones, siltstones and tuffaceous conglomerates. The mineralisation is found in the upper package, in the intervals containing limestone units. The deposit area incorporates small Cambrian stocks and dykes of diorite, monzonite and granite, often intensely albitised. The volcanic-sedimentary sequence is also intensely altered, mostly to albite, amphibole and chlorite.

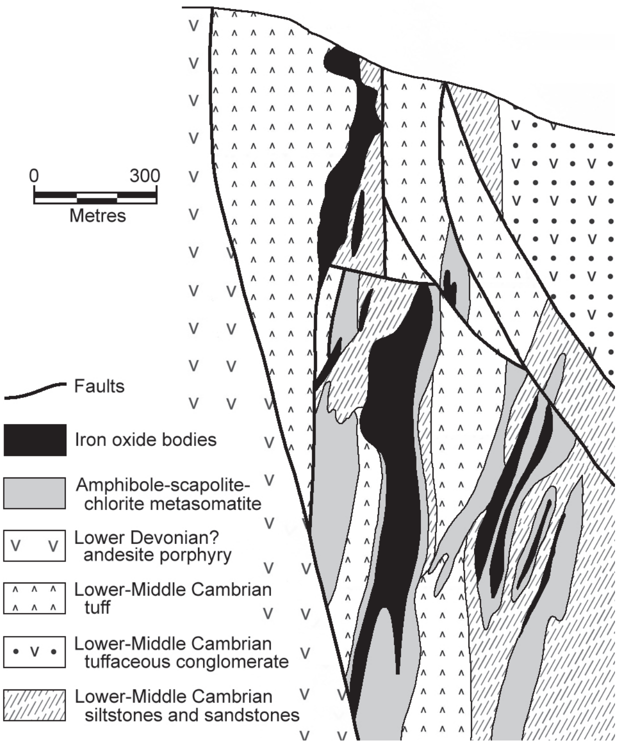


Figure 13: Geological cross section of the Abakan deposit (modified after Kalugin *et al.*, 1981).

Iron oxides are concentrated within a large mineralised zone that is some 300 to 400 m thick and extends for 1.3 km along strike, incorporating two large *en echelon* magnetite orebodies and several much smaller lenses. The two large orebodies respectively have strike lengths of 1130 and 350 m, down dip extents of 620 and 430 m and average thicknesses of 50 and 17 m. The mineralisation is essentially magnetite, accompanied by chlorite, calcite and pyrite, with minor minerals which include mushketovite, hematite, chalcopyrite and pyrrhotite, and a gangue of albite, scapolite, amphibole (actinolite, hastingsite), epidote, apatite, quartz, ankerite, siderite, etc. The bulk of the magnetite mineralisation is associated with scapolite, hastingsite and actinolite, while most chlorite post-dates the magnetite. As emphasised by Mazurov (1985), the typical skarn minerals of pyroxene and garnet are absent from most of the deposit. Pyroxene skarns and pyroxene-bearing albite-scapolite-amphibole assemblages are present at deeper levels only, suggesting a vertical mineral zonation, and demonstrates the distal character of the magnetite mineralisation. Platonov and Sanin (1998) reported consistently elevated gold contents in the iron oxide ores, varying from 0.2 to 2 g/t Au, with some higher-grade intervals of 3 to 4 g/t, and locally as much as 10 to 30 g/t Au. Shibistov and Ekhanin (2004) also recorded elevated gold levels in magnetite-bearing sulphide-quartz-carbonate ores averaging 0.6 to 0.8 g/t Au, and assays of as much as 1.2 g/t Au from the deposit dumps. Gold is closely associated with sulphides (pyrite, pyrrhotite, chalcopyrite, etc.). The deposit also contains some nickel-cobalt-arsenic and copper-cobalt mineralisation in late sulphoarsenide-sulphosalt veins (Tretiakova and Borisenko, 2006).

The ***Tashtagol deposit*** (Fig. 14) - contained pre-production reserves of some 700 Mt of iron ore averaging 40 to 45 wt.% $Fe_{tot.}$, 0.11 wt.% $S_{tot.}$ and 0.10 wt.% P_2O_5 (Russian $B+C_1+C_2$ reserve categories; Kalugin *et al.*, 1981). It is located within a 50 × 4 to 15 km volcano-tectonic depression occupied by a folded Middle Cambrian volcano-sedimentary sequence. This sequence comprises three units: (1) a lower suite of chlorite and carbonate altered andesite and andesite-basalt flows, hematitic lava-breccias and tuffs, with minor tuffaceous conglomerates, siltstones and sandstones, including magnetite-sandstones; (2) an overlying middle unit that hosts the magnetite ore and accompanying hydrothermal alteration, and is composed of trachytic tuffs, tuffaceous sandstones and siltstones, and limestones; and (3) an upper package of andesite-basalt flows, tuffs, tuffites, limestones, trachytic tuffs and ignimbrites.

These volcano-sedimentary rocks are intruded by Middle Cambrian gabbro-syenite and Middle Devonian granosyenite to granite suites. The Middle Cambrian intrusive suite is marginally younger than the Middle Cambrian trachytic volcanics. Where found at the contacts with syenite, the volcano-sedimentary rocks and earlier gabbros have been subjected to intense alteration, producing potassic (K feldspar), skarn, propylitic and other assemblages. The syenites themselves, where found in contact with magnetite ores, are also altered (chlorite, epidote and skarn) and are enriched with disseminated magnetite. In contrast, the Middle Devonian granosyenites crosscut pre-existing skarns and chlorite-calcite-magnetite-sulphide ores.

The magnetite ore forms steeply dipping lens-like bodies, which extend over 7.5 km along strike, reach a maximum thickness of 300 to 350 m, and have been traced

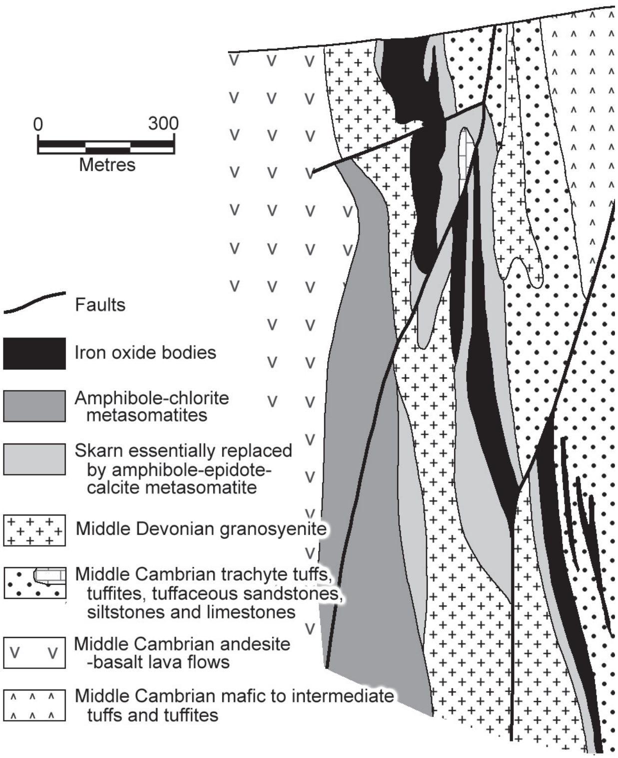


Figure 14: Geological cross section of the Tashtagol deposit (modified after Kalugin *et al.*, 1981).

down-dip for 1100 to 1500 m where they remain open at depth. In the central sections of the deposit, mineralisation is associated with skarn bodies, some of which are up to 280 m in thickness. These skarns are composed of garnet (grossularite-andradite) with minor pyroxene, and are overprinted by intense retrograde and hydrosilicate alteration, characterised by epidote, chlorite, amphibole, biotite, albite, calcite, quartz, etc. Both the skarns and subsequent alteration assemblages contain abundant magnetite and subordinate, but consistent hematite. In contrast, skarns are rare in the more distal parts of the deposit, where potassic, hydrosilicate and especially phyllic assemblages predominate, composed of albite, andesine, K feldspar, calcite, dolomite, ankerite (up to 20 vol.% in total), chlorite (up to 15 vol.%), amphibole (5 vol.%), epidote, sericite, quartz, etc. These assemblages include magnetite and martite, with minor pyrite, chalcopyrite and other sulphides. According to Platonov and Sanin (1998), some parts of the orebodies contain as much as 0.2 to 0.4 g/t Au.

Gold-copper-magnetite, Gold-magnetite and Gold-copper Skarn Deposits

There is a large and economically important group of deposits in the Altai-Sayan region that are characterised by relatively minor amount of iron oxides but, instead, by strong gold (and locally copper) mineralisation. These deposits usually have features more characteristic of gold skarn deposits and are generally described as such. However, a close genetic relationship, and possibly a transition between these and skarn iron oxide deposits is suggested by their common association with the same igneous suites, spatial coincidence in the same mineralised districts, and by the presence of some, usually minor, iron oxide concentrations within the skarn gold assemblage. Many authors consider skarn iron oxide deposits, and both gold and gold-copper deposits with minor accompanying iron oxide skarn, as belonging to the single, regional-scale, Early Palaeozoic magmatic-hydrothermal system of the Altai-Sayan region (e.g., Indukaev, 1981; Bulynnikov and Rabinovitch, 1990). However, some authors (e.g., Vakhrushev, 1972) have suggested a negative correlation between the grades of gold and iron oxide in the mineralisation at individual deposits.

The more significant examples of superimposed iron oxide and economically dominant gold (with some copper) mineralisation include the *Lebedskoe, Kommunar, Kaliostrovskoe* and *Tardanskoe* deposits (e.g., Alabin and Kalinin, 1999).

The ***Lebedskoe deposit,*** which was originally discovered as a consequence of its magnetite content, contains a marginally sub-economic resource of 4 Mt of iron oxide mineralisation. It is hosted by a Lower Cambrian volcano-sedimentary sequence composed of basalts and their tuffs, with minor limestones, that was deposited within a volcanic basin. These rocks are intruded by a Middle to Late Cambrian multi-phase pluton composed of quartz-diorite, monzonite and granodiorite. Vakhrushev (1972) noted that regionally, this intrusive suite is accompanied by both magnetite-skarn and gold-quartz vein mineralisation. At the Lebedskoe deposit, gold mineralisation is found in skarn and magnetite lenses which occur as disconnected strips along the granodiorite contact with the volcano-sedimentary rocks. The skarns are composed of garnet (andradite) and pyroxene, with the subsequently formed magnetite most often associated with the garnet skarns. Chalcopyrite and the other sulphides, in turn, postdate the magnetite. Gold mineralisation is localised in retrograde and hydrosilicate altered andradite and magnetite skarns, and is accompanied by very minor sulphides (pyrite, chalcopyrite, sphalerite, and galena) and tellurides.

The ***Tardanskoe (Tardan) deposit*** is also hosted by a Lower Cambrian volcano-sedimentary sequence composed of rhyolite flows and tuffs, with minor dolomite and limestone, often silicified and hematitised, especially along tectonic zones. These rocks are intruded by diorite stocks that likely represent the outer part of a multi-phase pluton incorporating gabbro-diorite, quartz-diorite and plagiogranite. Magnesian and calcic skarns, which are developed on the diorite contacts, are accompanied by thin lenses of massive and disseminated magnetite, while magnetite veins and stockworks also overprint the carbonate rocks. Sulphides occupy between 5 and 8 vol.%, and locally more, with abundant chalcopyrite in both the skarns and diorite, often at a distance of as much as 100 m from the skarns. Three styles of gold mineralisation are distinguished, namely: (1) gold-copper-sulphide stockworks in magnetite lenses and garnet skarns, (2) similar mineralisation in chlorite-amphibole-magnetite and phlogopite-serpentine metasomatites, partially overprinting garnet and pyroxene skarns, and (3) gold-bearing quartz veins and stockworks in granodiorite. Gold is free, with a fineness of 870 to 910. The deposit contains some 60 tonnes of gold, with an average grade of 10 g/t Au.

The ***Kommunarovskoe (Kommunar) deposit*** is hosted by a Lower Cambrian sequence that includes a lower volcanic suite (dolerite, spilite, lava-breccias and conglomerates, intercalated with thin units of shale, tuffaceous sandstone, limestone, and rhyolite), overlain by an upper suite of limestones, carbonaceous-cherty and cherty shales, tuffaceous siltstones, tuffites and rhyolite tuffs. These rocks are intruded by diorite stocks, dykes and sills. Ore grade mineralisation mostly occurs along the stratigraphic contact between the lower and upper suites and occurs as several styles. These include gold mineralisation within magnetite skarn bodies (localised along diorite contacts), gold-bearing sulphide lenses, gold-bearing quartz stockworks and quartz veins. Gold is free, with a fineness of 900 to 970. The deposit has been mined for over 100 years, with >100 tonnes of gold recovered, and some 11 tonnes remaining, at an average grade of 2 to 3 g/t Au.

Minor magnetite mineralisation is also present at the ***Sinyukhinskoe (Sinyukha) deposit*** (northeastern Altai) (e.g., Ettlinger and Meinert, 1990; Gusev, 2006) which is localised at the contact of an Ordovician to Early Silurian (or Early to Middle Devonian?) pluton intruding a Cambrian volcano-sedimentary sequence. This sequence includes basalt flows, tuffs, tuffaceous sandstones, limestones, etc. The pluton incorporates gabbro-diorite, diorite, tonalite, biotite-amphibole and biotite granodiorite and granite. The deposit is composed of both relatively small zones of structurally controlled skarn alteration and mineralisation, and large flat-lying tabular skarn bodies hosted by a section of alternating volcanic and carbonate rocks. Wollastonite and wollastonite-garnet skarns predominate over pyroxene-garnet and pyroxene varieties. In addition, small lenses of massive and disseminated magnetite are also present, with magnetite replacing pyroxene-garnet skarns (Vakhrushev, 1972). Sulphides are locally abundant, including bornite, chalcocite, chalcopyrite, pyrite and pyrrhotite. Gold-sulphide mineralisation occurs in the skarns, and to a lesser degree in magnetite bodies. Gold-chalcocite-bornite mineralisation predominates on the upper parts of the deposit, while gold-chalcopyrite is more common in deeper levels. The deposit originally contained approximately 60 tonnes of gold, with some 37 tonnes remaining at grades of 8 to 35 g/t Au.

Stratabound Magnetite-apatite Deposits

In contrast to the iron oxide deposits described above, these are situated in a separate terrane, the Altai Mountains, localised within a marginal strip between the Caledonian orogen of the Gorny Altai (in Russia) and the Hercynian orogen of the Rudny Altai (in Kazakhstan). They also differ in that they are mostly hosted by Devonian sequences, suggesting a generally younger age. Stratabound iron oxide deposits occur within an up to several kilometres thick Devonian sequence of cherty and carbonate rocks intercalated with significant amounts of trachy-andesites, trachytes, dolerites and dolerite porphyries. Granitoids occupy some 30% of the terrane, producing quite intense contact metamorphism and metasomatism of the host volcano-sedimentary sequences, including the development of a range of skarns. These skarns have an important influence on the form and mineralogy of the iron oxide deposits and raise the question of whether the iron oxide mineralisation is a metamorphosed primary volcanic and/or exhalative accumulation, or the product of metasomatic skarn replacement processes. Nevertheless, the location of the deposits within a volcanic sequence and their common apatite enrichment invites a comparison with the Kiruna deposit in Sweden (e.g., Carlon, 2000) that was noted by many of the Russian authors who have studied these deposits (e.g., Kassandrov and Ivanov, 1979; Dunayev, 1997).

The ***Kholzunskoe deposit*** (Fig. 15), which contains some 680 Mt of iron ore averaging 30 wt.% $Fe_{tot.}$, up to 2.0 wt.% $S_{tot.}$ and 0.5 to 0.8 wt.% P_2O_5 (Russian C_1+C_2 reserve categories; Orlov, *et al.*, 1998), is hosted by a Middle Devonian volcano-sedimentary sequence that comprises three stratigraphic units.

The lower of the three units is composed of trachyte, trachyte-porphyry, trachy-rhyolite-porphyry, trachy-andesite-porphyry, rhyolite-porphyry, their tuffaceous

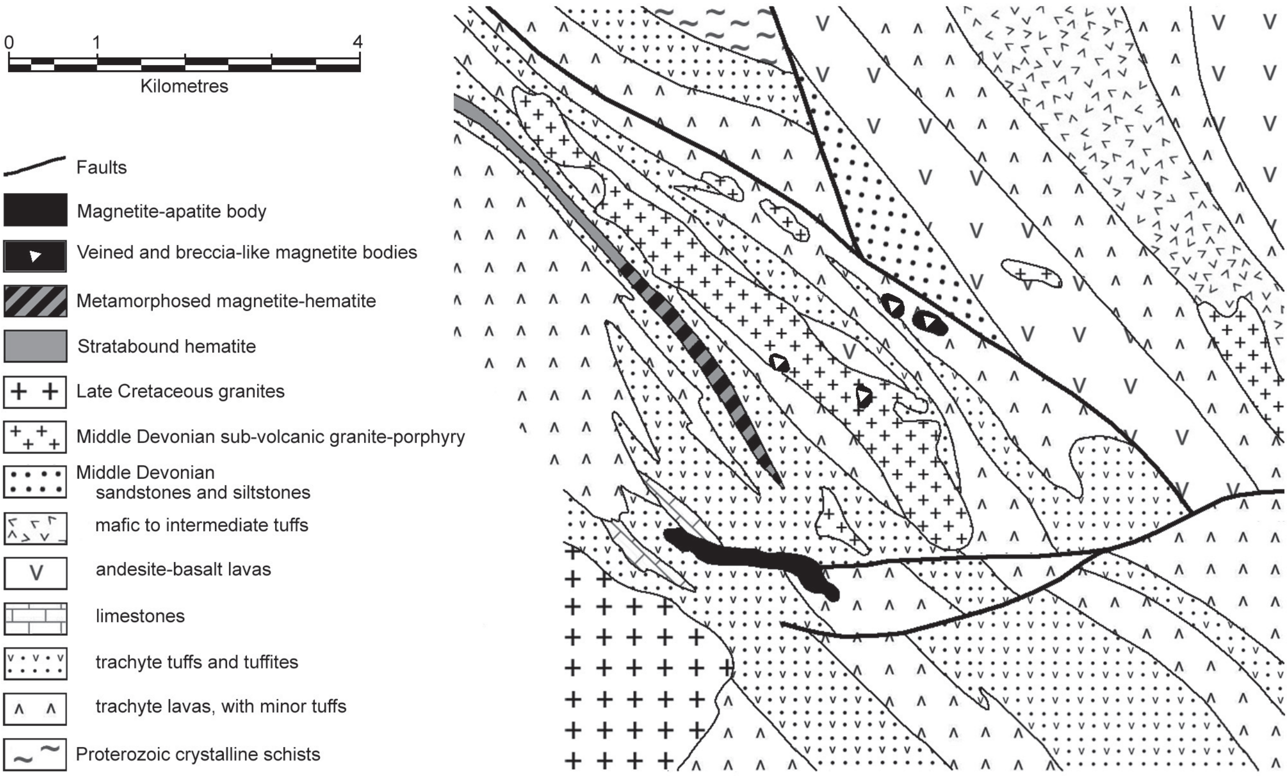


Figure 15: Geological map of the Kholzunskoe deposit (modified after Popov, 1991).

flows and tuffs, local tuffites, and minor lenses of carbonate and tuffaceous-carbonate rocks. This sequence is often enriched in disseminated hematite and locally contains veined-metasomatic cherty-hematite formations as well as quartz-hematite layers. Kalugin *et al.* (1981) reported fragments of these hematite-rich lithologies occurring in tuffaceous conglomerates of the same stratigraphic unit. The hematitic rocks have also been subjected to potassic, phyllic (sericite), silica, and less frequently to sodic (albite) alteration. Fracture zones also contain veins of K feldspar, quartz, epidote and amphibole, and locally garnet, with minor pyroxene, hematite, magnetite and apatite. Kassandrov and Ivanov (1979) reported the presence of hematite and magnetite in the groundmass of trachy-andesite-, trachyte- and trachy-rhyolite-porphyries, emphasising their porphyritic texture. Iron oxides, together with quartz and apatite, also often infill vugs. These iron oxide-enriched rocks exhibit a gradual transition to massive fine-grained ores.

The overlying stratigraphic unit, mainly composed of mafic to intermediate tuffs, hosts the majority of the magnetite mineralisation. It varies from 70 to 300 m in thickness, with magnetite ores occupying >25 vol.% of the unit. Other lithologies include albite-biotite-amphibole and amphibole-epidote schists, altered trachytes and rhyolites, and essentially albite rocks ("albitites"). A thick development of albitites occurs in the hangingwall of the deposit. Some individual bands of magnetite and wall rocks, with a combined thickness of up to 20 m, are strongly enriched in apatite, with an average P_2O_5 content up to 6 wt.% and locally to a maximum of 25 to 27 vol.%.

The upper stratigraphic unit is composed of rhyolites, intercalated with tuffaceous shale-carbonate-sandstone packages. The sequence was intruded by small stocks of rhyolite-porphyry, trachy-rhyolite, and plagio-granite-porphyry, often subjected to intense albite alteration. Permian granitoid intrusives are also present.

Magnetite forms lens-like, tabular, and locally veined bodies. The main mineralised band has been traced for

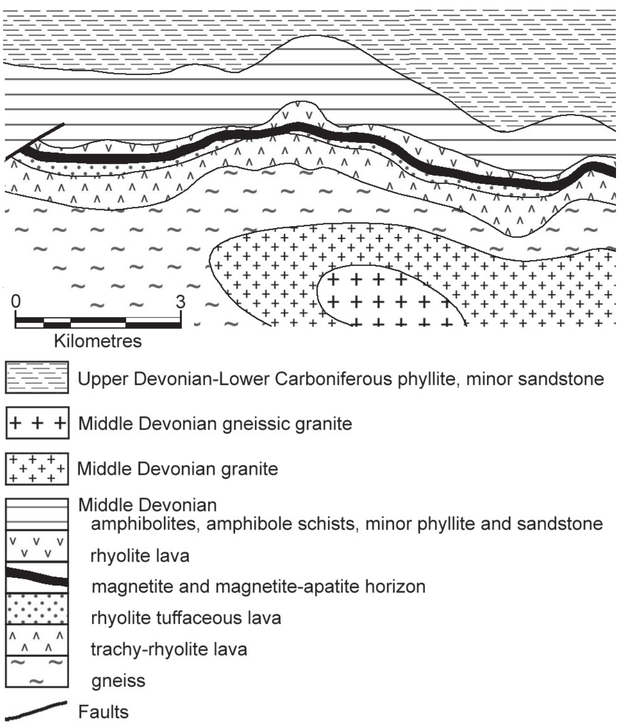


Figure 16: Geological map of the Markakulskoe deposit (modified after Kalugin *et al.*, 1970).

8 km along strike and is 100 to 150 m thick. It incorporates bodies of massive magnetite up to 300 m in strike length and from 2 to 30 m thick. In total, the entire mineralised stratigraphic package can be traced for almost 25 km along strike. Magnetite is associated with an assemblage of biotite, albite, amphibole, chlorite, quartz, apatite and epidote. Minor minerals include pyrite, phlogopite, pyroxene, garnet, hematite and chalcopyrite. Barren layers separating the magnetite bands contain abundant sericite, dolomite, ankerite, K feldspar, barite and tourmaline. Magnetite ores gradually evolve into 'ironstone-like' hematite mineralisation along strike.

It has been suggested (Kalugin *et al.*, 1981; Pavlov, 1983; Popov, 1991) that the deposit was formed during several mineralising events including, (1) an early volcanic-exhalative event, (2) transformation of the mineralisation in association with regional fault zones and coeval alkaline metasomatism, (3) a possible contact-metasomatic event involving re-mobilisation and partial re-deposition of the ores by Devonian sub-volcanic and Permian hypabyssal intrusives. Part of the mineralisation was re-deposited as coarse-grained magnetite forming concordant and discordant bodies. Some authors (e.g., Kassandrov and Ivanov, 1979; Dunayev, 1997) suggest similarities between the initial magnetite mineralisation and interpreted magnetite lava flows at e.g., El Laco in Chile (Starostin and Kudryavtseva, 1973; Frutos and Oyrzun, 1975; Naslund *et al.*, 2002).

The ***Markakulskoe deposit*** (Fig. 16) is also, in some parts, strongly enriched in apatite. It contains at least 70 Mt of iron ore (inferred resource) and possibly much more, averaging 63 wt.% $Fe_{tot.}$, 0.001 wt.% $S_{tot.}$, and 1.8 wt.% P_2O_5 (Kalugin *et al.*, 1981). The deposit is hosted by a Middle Devonian volcano-sedimentary sequence composed essentially of altered rhyolites and possibly trachytes, with minor mafic volcanic rocks. The mineralisation has been traced as an 18 km long strip, with individual lenticular ore bodies extending for 3 to 6 km and being 10 to 200 m thick. The mineralised zone is concordantly with the host rocks and dips at 20 to 30^o. Some sections contain high-grade magnetite and magnetite-apatite mineralisation, the latter characterised by a "porphyry-like" appearance resulting from large apatite crystals developed within a fine-grained magnetite groundmass. Locally, apatite forms up to 30 vol.% of the ores. Minor minerals include amphibole, biotite, muscovite, allanite, and locally hematite.

Iron Oxide-rich Carbonatites

The Central Tuva region (southern Altai-Sayan orogenic system, north of Lake Ubsa Nur; Fig. 2) encompasses a number of carbonatite deposits and occurrences with similar Late Mesozoic ages of emplacement, and many comparable mineralogical and geochemical features. They also have signatures suggesting they belong to the IOCG family of deposits, or are at least, IOCG related deposits (e.g., Gusev *et al.*, 2006).

The Central Tuva area is underlain by Ordovician and Silurian clastic sequences, with minor late Neoproterozoic (Vendian) to Lower Cambrian domains exposed in anticline cores. This sequence is overlain by Devonian to Lower Carboniferous volcano-sedimentary units and by Jurassic continental coal-bearing units, with the latter only preserved in small depressions. These Lower to Middle Palaeozoic sequences are intruded by Late Devonian to Early Carboniferous mafic (gabbro, gabbro-diorite, dolerite, etc.) to granitic stocks and dykes. Many of the granitic

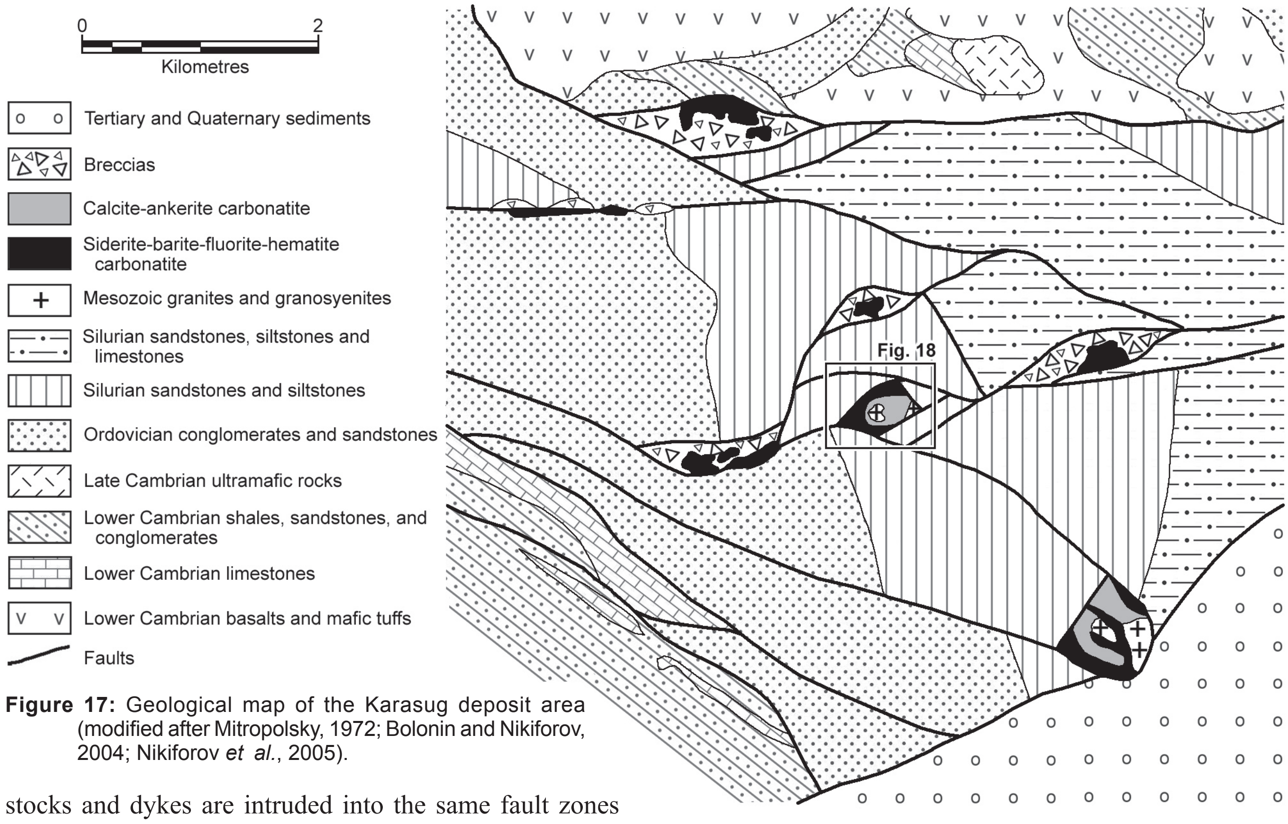


Figure 17: Geological map of the Karasug deposit area (modified after Mitropolsky, 1972; Bolonin and Nikiforov, 2004; Nikiforov *et al.*, 2005).

stocks and dykes are intruded into the same fault zones that host carbonatite occurrences, while some carbonatite breccias contain granitic clasts. The Tuva carbonatites are spread over an area of >1000 km^2, and define a north-south-trending corridor, likely controlled by a deep-seated basement lineament crosscutting the major orogenic structures of the region. As noted by Nikiforov *et al.* (2005), carbonatites further to the south in Mongolia, where carbonate-fluorite-magnetite-apatite occurrences are known, may be controlled by the same basement structure.

Significant carbonatite deposits and occurrences found in the Tuva region were described in detail by Mitropolsky (1959, 1963, 1972), Puzanov (1975), Ontoev (1984), Bolonin and Nikiforov (2004), Nikiforov *et al.* (2005, 2006) and other authors. The descriptions given below are based on the data published by these researchers.

The ***Karasug deposit*** (Figs. 17 and 18) is the largest carbonatite known in the Tuva region. It contains a complex mineralogy, including iron oxides, carbonates, F, Ba, Sr, REE, U, Mo, etc. The deposit area encompasses eight ore-bearing carbonatite bodies that are localised in fault zones and their intersections, and intrude locally brecciated and altered Ordovician to Silurian sandstones and siltstones.

The two largest carbonatite bodies are pipe-like and concentrically-zoned, with dimensions of 400 × 550 m and 670 × 750 m, while the others are dyke-like with lengths of 300 to 1300 m, and thicknesses of up to 160 m. They have been traced to depths of 300 to 550 m, with no indication of pinching out. The large pipe-like carbonatites are composed of early calcite-ankerite intruded by a late siderite-barite-fluorite assemblage. In contrast, the smaller bodies are composed of siderite-barite-fluorite carbonatite only. They contain numerous fragments, clasts and large blocks of the host sandstone, siltstone and granite, cemented by either more finely-dispersed material of the same composition, or by siderite. Where the two carbonatite assemblages are present, fragments of the first occur within the second. Thus, the carbonatite pipes represent multiphase breccias.

The close association between the carbonatites and granitoids (granosyenite and granite) is inferred by both occurring in the same fault zones, and by fragments of the latter being included within carbonatite breccias. The granitoids appear to immediately pre-date the carbonatites. Mitropolsky (1972) noted that small granosyenites and granites intrusives are also found within the mineralised carbonatite breccias, although these intrusives have been divided into separate, partially brecciated blocks, and subjected to intense hydrothermal alteration, with especially

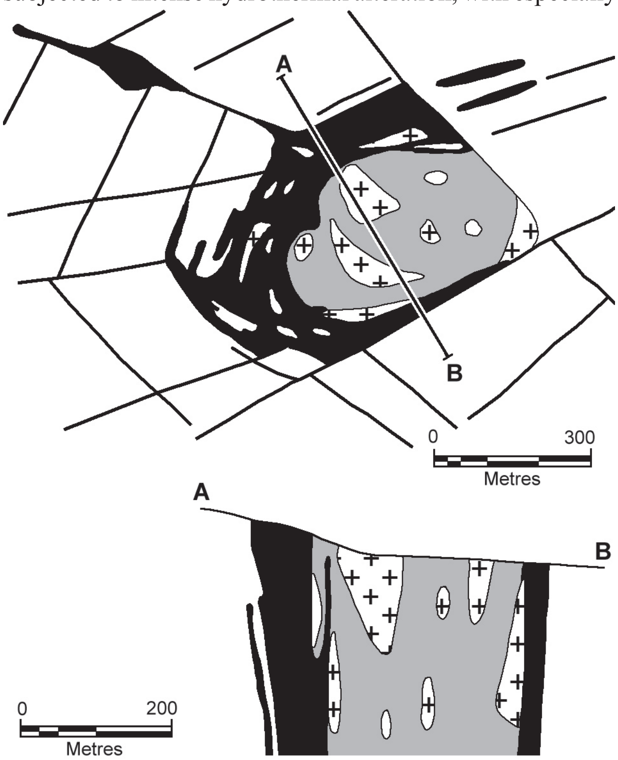


Figure 18: Geological plan and cross section of part of the Karasug deposit (modified after Bolonin and Nikiforov, 2004; Nikiforov *et al.*, 2005). For legend and location see Fig. 17.

intense replacement by phyllic (muscovite- and sericite-dominated) assemblages. The granitoids are dated at 112 to 122 Ma, i.e., Cretaceous (K-Ar method; Mitropolsky, 1972), and the carbonatites at 118±9 Ma (Rb-Sr method; Nikiforov *et al.*, 2006).

The deposit contains both hypogene and supergene iron ores, with the former being essentially siderite-hematite and containing 26 wt.% $Fe_{tot.}$, with reserves of some 150 Mt (Russian C_1+C_2 reserve categories), and the latter being oxidised hydrohematite and hoetite-hydrohematite in composition and containing 30 to 33 wt.% $Fe_{tot.}$, with reserves of some 125 Mt (Russian A+B+C_1 reserve categories; Kalugin *et al.*, 1981). Frolov *et al.* (2003) reported resources totalling 50 Mt of barite, 4 Mt of REE, and 4.5 Mt of Sr, with the grades of 0.7 to 1.62 wt.% REE_2O_3, 0.016 wt.% Y, 0.17 wt.% U and 0.18 wt.% Sr.

The calcite-ankerite carbonatite comprises calcite (45 to 60 vol.%), ankerite (35 to 50 vol.%), minor apatite, pyrite, quartz, monazite and parisite, and sporadic thorite, magnetite, muscovite, siderite, dolomite, chalcopyrite and molybdenite. In contrast, the siderite-barite-fluorite carbonatite is composed of siderite (av. 61 vol.%), barite (av. 20 vol.%), fluorite (av.12 vol.%), minor pyrite, bastnaesite, quartz, apatite, molybdenite, uraninite, magnetite, chalcopyrite, muscovite, etc. These rocks are characterised by a porphyritic texture, with large siderite, fluorite, barite, pyrite and quartz phenocrysts scattered in a fine-grained groundmass. The siderite-barite-fluorite carbonatite has been subjected to intense post-magmatic mineralisation, in the form of hematite and associated bastnaesite. As a result, hematite becomes one of the major rock-forming minerals, averaging 10 to 20 vol.%, but locally comprising up to 65 vol.% of the carbonatite, accompanied by average grades of 9 vol.% fluorite, 12 to 13 vol.% barite and lesser celestite, strontianite and apatite. In addition, this carbonatite has been subjected to the formation of siderite-quartz and celestite veinlets, and to local silicification, while barite is locally replaced by late barium and strontium sulphates. Purple fluorite predominates, accompanied by minor amounts of its green variety. Hematite replaces siderite and occurs as disseminations of platy crystals, often concentrated into veinlets and patches. Bastnaesite is present in two forms, an early magmatic and a late hydrothermal variety, replacing fluorite. Uraninite forms fine dissemination within the carbonatite matrix, while molybdenite is a constant accessory admixture also found in the matrix. The apatite content locally reaches 4 wt.%. Chalcopyrite was related to late processes, forming together with barite, celestite, silica and siderite-quartz veining.

The ***Chaakhol deposit*** (Fig. 19A) is located 15 km south of Karasug. It comprises five separate carbonatite bodies localised in a large fault zone where the host terrigenous sandstones and siltstones are intensely brecciated to form tectonic breccias. As at Karasug, the carbonatites occur as both calcite-ankerite and siderite-barite-fluorite assemblages, with the latter saturated in hematite and carrying disseminated barite and fluorite. Some of the bodies comprise lens-like tectonic breccia zones of around 50 to 150 × 500 m, which are cemented by calcite-ankerite carbonatite, with well-pronounced central cores of siderite-barite-fluorite containing only minimal (<35 vol.%) fragments. Hematite saturates both the host sandstone-siltstone sequence locally outside of the carbonatite, and the finely-dispersed matrix of tectonic breccias where it occurs as fine crystals. Hematite has been partially replaced by magnetite. Supergene oxidised carbonatites contain 40 to 70 vol.% iron hydroxides (after siderite and pyrite), 20 to 50 vol.% hematite, 1 to 15 vol.% barite and 1 to 10 vol.% fluorite, with minor quartz and bastnaesite.

The *Southern* and *Northern Choz, Ulatai*, and *Teeli-Orgudid* carbonatites and related occurrences form a cluster situated some 30 km further south of Chaakhol. Together, the Ulatai and Choz deposits account for 200 to 250 Mt of iron ore containing 30 to 60 wt.% $Fe_{tot.}$ (Kalugin *et al.*, 1981).

The ***Ulatai carbonatite deposit*** (Fig. 19B) is distributed over an area of some 20 km², and is controlled by the same east-west-trending district-scale fault zone as Chaakhol. The area surrounding the deposit has been intruded by a variety of pre-carbonatite bodies ranging in composition from gabbro to granites. Many of these Late Devonian to Early Carboniferous gabbroic intrusives include both calc-alkaline and alkalic gabbroids, some of which have been subjected to intense hydrothermal alteration including by scapolite, amphibolite and biotite. There are also leucocratic biotite granites which crosscut the gabbroic rocks, and have been subjected to intense greisenisation.

Numerous exposures of calcite-ankerite and siderite-barite-fluorite carbonatites are found within the deposit area. Calcite-ankerite carbonatites predominate, forming numerous dykes and veins up to 10 to 25 m thick, some of which persist for more than 1 km along strike. These carbonatites are composed of calcite with subordinate ankerite, 1 to 25 vol.% hematite, and minor pyrite, magnetite, quartz, muscovite, monazite, molybdenite, chalcopyrite, etc. The largest siderite-barite-fluorite body, which is strongly enriched in iron oxides, has been evaluated and is referred to as the Ulatai iron deposit.

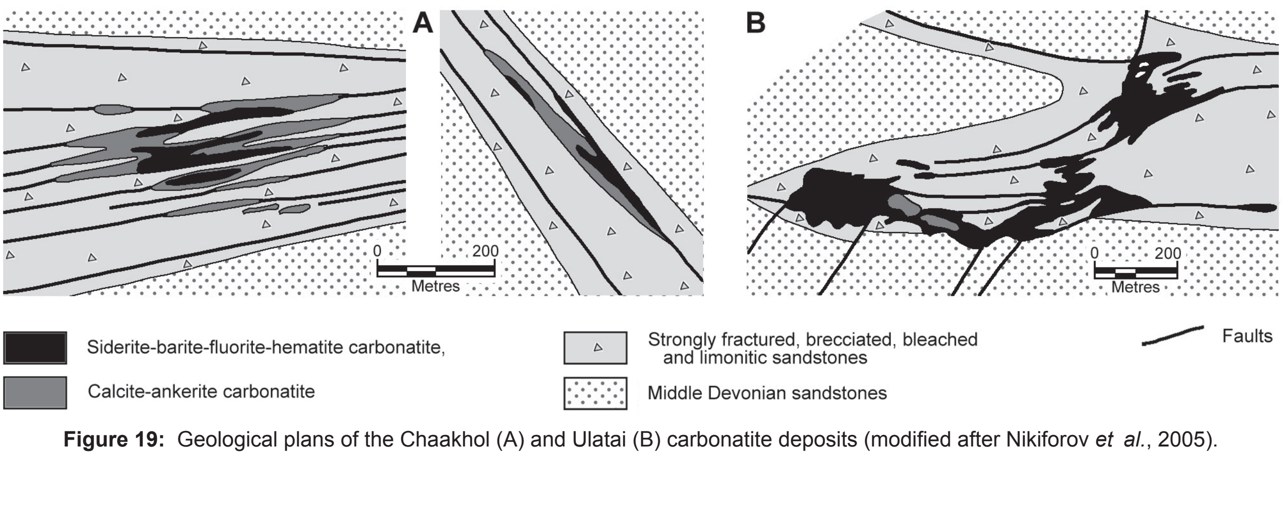


Figure 19: Geological plans of the Chaakhol (A) and Ulatai (B) carbonatite deposits (modified after Nikiforov *et al.*, 2005).

The Ulatai iron deposit occurs as a large, dyke-like body of strongly oxidised siderite carbonatite, localised at the intersection of district-scale faults. It can be traced for 1400 m along strike, and with pinch and swell variations, reaches a maximum thickness of 150 m. Locally, the ores also contain abundant magnetite (up to 50 vol.%). The ores consistently contain angular fragments of the host sandstones and siltstones, as well as fragments of the early calcite-ankerite carbonatites, dolerite, metamorphic rocks, etc. Some fragments of calcite-ankerite carbonatites also contain magnetite (up to 50 vol.%) and fluorite. At the surface, the deposit is represented by iron-hydroxide ores which can be traced for tens of metres down-dip as porous hoetite-hydrohoetite aggregates saturated in hematite. These ores contain some fluorite (4 vol.%), barite (4 vol.%) and REE minerals (bastnaesite and parisite). Assaying of some samples returned 3.78 wt.% REE_2O_3 (Nikiforov *et al.*, 2005).

The ***Southern Choz deposit*** (Fig. 20) is located some 12 km from Ulatai, and is represented by a single multiphase carbonatite body with surface dimensions of some 375 × 500 m, composed of calcite-ankerite and siderite carbonatites. It is localised in a district-scale fault zone which contains intervals of intense brecciation and hydrothermal alteration of the host sandstones. The internal structure of the carbonatite body is defined by a series of alternating linear zones of calcite-ankerite and siderite carbonatites divided by brecciated sandstones. The carbonatites contain 20 to 35 vol.% (on average) angular clasts and fragments of sandstones, sericite-quartz schist, granite-porphyry and amphibolite which are locally cemented by the carbonatite. Hematite is present in the calcite-ankerite carbonatites in minor (0 to 20 vol.%) amounts, but in contrast, is abundant (20 to 60 vol.%) in the siderite phase, together with minor disseminated fluorite, quartz, muscovite and pyrite. Other minor minerals include apatite, bastnaesite, magnetite and chalcopyrite.

The ***Teeli-Orgudid mineralised area*** also embraces numerous carbonatite occurrences represented by both calcite-ankerite and siderite carbonatites, some of which carry lens-like bodies of iron oxides with dimensions of from 3 × 30 m to 75 × 300 m. These bodies are mostly composed of hematite, with local magnetite, minor barite (up to 2 vol.%), fluorite (up to 5 vol.%), bastnaesite, apatite, quartz and fragments of host rocks. Assays of some samples returned 0.63 wt.% REE_2O_3 (Nikiforov *et al.*, 2005). Elsewhere in the same area, carbonatite bodies include explosive breccias, with fragments of host rocks as well as exotic clasts of greisens and amphibolites, most likely transported from greater depth. These explosive breccias are often cemented by carbonatite and are found on the peripheries of larger carbonatite masses. The carbonatites themselves also contain fragments of the host rocks.

The ***Northern Choz area*** includes two small siderite-barite-fluorite carbonatites in close proximity to a large sub-volcanic granosyenite-porphyry dyke. This dyke is accompanied by a potassic alteration halo within the host sandstones and gravel-conglomerates, and in which these rocks are locally completely converted into a K feldspar-quartz metasomatite. In addition, zones of intense chlorite and sericite alteration are present within the same halo, as well as breccias cemented by quartz-calcite-chlorite carrying fluorite and sulphides. One such zones hosts the occurrence of uranium (nasturane-sulphide) mineralisation. The carbonatites themselves are siderite-dominated, with abundant hematite altered to porous hematite-hydrohoetite, and contain disseminated fluorite (1 to 20 vol.%), barite (up to 5 vol.%), apatite, quartz, pyrite, bastnaesite, etc. They are surrounded by a wide hematite stockwork and halo of metasomatic hematitic replacement and silicification, with locally disseminated fluorite, barite, calcite, apatite, basnaesite, pyrite, mushketovite, etc. (Nikiforov *et al.*, 2005).

Discussion and Conclusions

The exceptional abundance, concentration and size of the iron oxide (±copper, gold) deposits of the Altai-Sayan region, and their characteristic associated alteration, allow it to be considered as a distinct, large, IOCG metallogenic province, although to date no large IOCG *sensu stricto* deposits are known. These deposits span a range of ages, with the majority being Middle to Late Cambrian to Ordovician and occasionally Silurian, i.e., Caledonian, while others were formed in the Devonian and Mesozoic. These deposits represent several types distinguished within, or related to, the IOCG continuum, namely, (1) proximal to distal metasomatic/skarn, (2) distal replacement, (3) metamorphosed volcanic-exhalative, and (4) carbonatite types (cf. Williams *et al.*, 2005; Corriveau, 2007).

The proximal to distal metasomatic/skarn and distal scapolite-albite to chlorite-amphibole replacement deposits are the most abundant styles in the Altai-Sayan region, and are essentially characterised by a distinct temporal relationship with plutonic (locally volcano-plutonic)

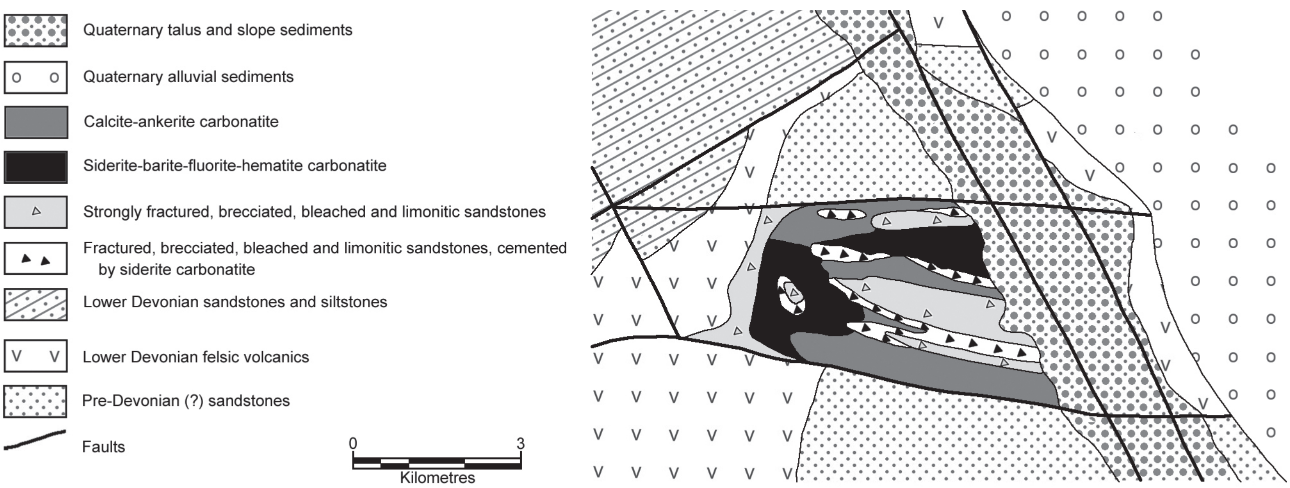


Figure 20: Geological plan of the Southern Choz carbonatite deposit (modified after Nikiforov *et al.*, 2005).

suites varying from tholeiitic/calc-alkaline to alkalic in composition. Similar occurrence of near-contemporaneous calc-alkaline and alkalic (shoshonitic) suites is reported in many large IOCG metallogenic provinces, including those in Australia (e.g., Mark *et al.*, 2006) and the Andes (e.g., Sillitoe, 2003). This may be attributed to near-simultaneous tholeiitic/calc-alkaline and shoshonitic magmatism occurring in an island arc or rift environment, with the possible mutual influence and interaction of the different magmas. Moreover, the occurrence of both tholeiitic/calc-alkaline and shoshonitic phases may be a more typical signature of IOCG deposits than is currently recognised (e.g., Pollard, 2006). In general, the Caledonian skarn and other replacement-type iron oxide deposits of the Altai-Sayan orogenic system are similar to the Carboniferous iron oxide (±copper, gold) deposits of the Urals (e.g., Herrington *et al.*, 2002; Hawkins *et al.*, this volume) and Mesozoic iron oxide-copper-gold deposits of Chile (e.g., Sillitoe, 2003) and Peru (e.g., Vidal *et al.*, 1990).

The Altai-Sayan skarn and other replacement-type iron oxide (±copper, gold) deposits define an evolutionary trend reflected through the change in their structural settings from proximal contact skarns, to more distal veined skarns and breccia pipes, to distal albite-scapolite- and chlorite-amphibole-dominated metasomatites hosted by steeply dipping fault zones. The occurrence of breccia pipes or diatremes at some of these iron oxide deposits is of special interest, in that it may indicate a structural evolution toward other deposit styles within the IOCG deposit continuum. These, and other distal iron oxide deposits that have no apparent direct association with intrusives, most closely correspond to the more typical IOCG-style mineralisation (e.g., Williams *et al.*, 2005).

The spatial and temporal distribution of alteration and mineralisation assemblages in the region may be summarised as follows. In the proximal to distal contact skarns, pyroxene is more common deeper in the system, while garnet predominates at higher levels. Proximal to distal sodic and sodic+calcic alteration, characterised by albite-scapolite assemblages, may be seen to have occurred at least twice, both pre- and post-dating skarn development, the latter more often coinciding with intense magnetite mineralisation. The chlorite-amphibole-dominated alteration assemblages appear to be more distal than those characterised by albite-scapolite. Significantly, iron oxide mineralisation occurs at several times, corresponding to different hydrothermal stages. These include during the retrograde skarn stage, associated with contact metasomatism, and later, accompanying overprinting proximal to distal albite-scapolite or distal chlorite-amphibole related replacement. In contrast, copper mineralisation is generally restricted to a later stage and occurs in the marginal/distal parts of iron oxide orebodies and systems as a whole, where sulphides may occur in significant concentrations. Gold appears to be less directly related to either the iron oxide or copper mineralisation. While some gold is often associated with copper concentrations, in many locations the gold occurs in late mineralised zones overprinting and crosscutting mineralised skarns and iron oxides.

The proximal to distal skarn and replacement deposits of the Altai-Sayan region include both magnetite-bearing contact skarns, which are not generally accepted as members of the IOCG continuum (e.g., Williams *et al.*, 2005), and 'distal' iron oxide-rich scapolite-albite to chlorite-amphibole dominated replacement assemblages which are included as part of that continuum (e.g., Corriveau, 2007), or at least as related deposits (e.g., Williams *et al.*, 2005). This apparent conflict may be avoided, if a model is considered implying the formation of proximal skarns and distal replacement assemblages in different spatial positions (i.e., structural settings) relative to the associated pluton (possibly, also at different depths), and the differences in both the timing and thermodynamic conditions of their formation. As noted previously, the proximal (prograde and retrograde) skarns are characterised by sharp predominance of magnetite, with relatively minor sulphides (including chalcopyrite) and gold. In contrast, more distal albite-scapolite- and then amphibole-chlorite-dominated replacement assemblages are characterised by younger generations of magnetite and by more abundant hematite and chalcopyrite that replace the early skarn magnetite and, more importantly, further expand the mineralisation into more distal settings. The latter exhibit more compositional and structural similarities to the "classic" IOCG deposits. This evolution is consistent with a change from conductive to convective thermodynamic models (cf. Norton and Cathles, 1979), with the latter largely the product of large fluid circulation cells, a distinct feature on many IOCG deposits, which are the product of large scale, circulating, hypersaline, oxidised fluid systems, which have no clear spatial association with intrusions (Williams *et al.*, 2005). As emphasized by Johnson and Norton (1985), similar changes from conductive to convective thermodynamic conditions also occur at different stages of intrusive emplacement (intrusion and crystallisation), i.e., these conditions evolve both in space and time. This evolution may include the involvement of meteoric waters, as well as buried evaporite-related saline brines, as is interpreted to have occurred in many IOCG deposits (cf. Barton and Johnson, 2000). This implies a common link between the generation of the intrusions and the circulation of the fluid cells, but that the intrusive is not necessarily the sole, or in some cases even the dominant, contributor to the chemistry of the mineralising fluid which scavenges metals and ligands from the country rock through which it passes.

It therefore follows, that while a major IOCG-style (oxidised and hypersaline) fluid circulation system prevailed in the Altai-Sayan region during the Palaeozoic, as evidenced by the extensive iron oxide-rich scapolite-albite to chlorite-amphibole replacement assemblages, the contemporaneous intrusives related to the same thermal event, initially only altered country rock carbonates to produce localised magnetite-rich prograde and retrograde contact skarns. It is also likely that any iron-oxides produced as part of the contact skarn development, would then be available to react with fluids of the larger scale IOCG system, resulting in the late stage formation of copper and/or gold mineralisation. Contact skarn development would also produce a brittle rock susceptible to fracturing, thus facilitating the ingress of the late stage IOCG system copper-gold mineralising fluids (cf Candelaria in Chile).

The iron oxide±apatite accumulations of the Gorny Altai orogen represent further examples of IOCG related mineralisation within the region. Some of these appear to resemble the Kiruna deposit in Sweden (e.g., Carlon, 2000), based on their localisation in volcanic sequences, distinct stratigraphic control, reported gradual transition from iron oxide-enriched volcanic hosts (trachytes, etc.) to semi-massive and massive magnetite/hematite mineralisation, the common presence of apatite, etc. The most plausible explanation for the formation of these deposits appears to be a multistage process involving deposition contemporaneously with the host volcanic suite, followed by transformation during the emplacement of younger plutons which caused local re-mobilisation and enrichment of the pre-existing mineralisation.

The Tuva carbonatites represent yet another variety of iron oxide-rich deposits. They share many common characteristics, including their significant enrichment in hematite and often in magnetite, as well as fluorite, barite, quartz, REE, uranium, apatite, and locally molybdenite and chalcopyrite. These features clearly differentiate the Tuva carbonatites (from e.g., those that are Nb-Ta-bearing, etc.), and places them in the group regarded as end-members of (e.g., Corriveau, 2007), or related deposits to (e.g., Williams *et al.*, 2005), the IOCG continuum. An additional characteristic is their well developed brecciation, which many authors have suggested to be of tectonic origin, although demonstrated by Nikiforov *et al.* (2005) to be explosive in nature, in at least some of the carbonatite occurrences. The close spatial relationship between the Tuva carbonatites and pene-contemporaneous granitoid rocks, in many cases with a pronounced potassic character, is also of special interest. Many authors (e.g., Mitropolsky, 1962; Ontoev, 1984) have suggested genetic link between the granitoids and carbonatites. Nikiforov *et al.* (2005) also emphasised these spatial relationships while noting the lack of convincing data necessary to constrain a genetic model. Nevertheless, it is interesting to compare the gross similarities in the mineral associations, brecciation and relationship to potassic granites with IOCG deposits such as Olympic Dam (e.g., Reynolds, 2000). Comparisons can also be suggested between the Tuva carbonatites and the Bayan Obo deposit in China (e.g., Smith and Chengyu, 2000), mainly on the basis of significant iron oxides, REE mineralisation (bastnaesite, etc.) and fluorite. However, in contrast to Bayan Obo, the Tuva carbonatites, are characterised by the predominance of hematite over magnetite, presence of uranium, and by the total absence of niobium mineralisation, alkali amphiboles and pyroxenes. The basement structure controlling the localisation of carbonatites in the Tuva region continues south, across the Russian-Mongolian border, to where similar carbonatite occurrences are known in Mongolia (Nikiforov *et al.*, 2005).

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