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A SHORT REVIEW OF PALAEOZOIC HYDROTHERMAL MAGNETITE IRON-OXIDE DEPOSITS OF THE SOUTH AND CENTRAL URALS AND THEIR GEOLOGICAL SETTING

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Abstract - The Urals orogen represents the site of Palaeozoic oceanic crust creation and subsequently a zone of arc development, arc-continent collision, continent-continent collision and post-orogenic collapse. The orogen is host to a number of world-class VMS deposits in the Silurian to Devonian arc sequences but in addition is host to highly significant iron oxide deposits of both hydrothermal and orthomagmatic origin. The hydrothermal ores are developed in Palaeozoic belts associated with rift-related, dominantly mafic, largely subaerial, alkaline volcanism intruded by comagmatic stocks of varying ages, from the Late Silurian to Early Carboniferous. Volcanism, sedimentation and mineralisation all seem to be controlled by major N to NNE trending structures. Much of the mafic volcanic sequence shows hematisation, which is evidence of early oxidation of the lava-tuff packages. Mineralisation comprises massive and disseminated magnetite bodies with elevated REE and ubiquitous accessory apatite. The deposits can be huge, as for example the giant Carboniferous Kachar deposit in Kazakhstan with reserves of over a billion tonnes of >45% Fe are defined. Some of the bodies are true contact skarns developed at the interface between intrusive bodies and volcano-sediments which include limestones. Other bodies, including Kachar, are distal to any possible related intrusions and are developed within regionally extensive scapolite alteration zones. A regionally consistent pattern of early feldspar ± biotite alteration followed by ore-stage pyroxene-garnet-scapolite followed by late hydrous silicate-carbonate alteration is repeated throughout the Urals. Regionally extensive scapolitisation is common in most of the belts. Base metals are generally present in the deposits, often appearing late in the paragenetic sequence, with some bodies having near economic copper grades (0.6% Cu) and significant precious metals.

Introduction

It is widely accepted that the Urals Orogen formed as a result of the closure of a Palaeozoic ocean, involving subduction, continent-island arc collision and finally continent-continent collision, and then later by orogenic collapse. Modern authors generally concur on the development of eastward dipping subduction during the closure of a Palaeozoic ocean attached to the passive margin of the East European craton (Seravkin et al. 1994, Ivanov 1998). The Main Uralian Fault (MUF) is generally agreed to represent the former location of the major subduction zone relating to the later stage of intra-oceanic subduction followed by collision between the East European Craton and the Magnitogorsk island-arc. Units to the West of this suture have been deposited or tectonically emplaced over Pre-Cambrian continental basement (the East European Craton), while those to the East are island arc related volcanic and sedimentary sequences (eg. Puchkov 1997, Brown et al., 1998, Zonenshain et al., 1984).

All the tectonic models concur on the existence of an ocean west of the Main Urals Fault (MUF) which formed in the Ordovician-Silurian and then began closing to produce an arc sequence on oceanic crust east of the MUF. In the north and central Urals, the arc-continent collision probably occurred in Late Silurian to Devonian times (Puchkov 1997). In the south, during the Devonian, the arc sequence developed east of the MUF with the MUF itself the site of obduction and accretion of material from the Urals ocean to the west. This progressive arc sequence is associated with over 60 VMS deposits which form the basis of the extensive copper mining and smelting industry of the south Urals (Herrington et al. 2001). The east European continent collided with the southern arcs in the Late Devonian (Brown et al. 1998) whilst volcanism continued in the east of the Urals through to the lower Carboniferous accompanied by comagmatic intrusive complexes. The major magnetite deposits here are related to this igneous activity. Overlying these are Late Carboniferous platform carbonates. The Lower Carboniferous igneous complexes are compared to those in continental rift settings (Fershtater 2000) and clearly post-date the onset of continent arc collision in the west (Brown et al. 1998). This would imply a change of magma source from subduction of an oceanic slab from the west and may be the result of deep mantle-sourced magmatism during some form of post-collision extension.

The Urals is also host to a number of iron oxide deposits which occur in a range of settings within the orogen (Smirnov & Dymkin 1989) (Table 1). The three main environments are: a) hosted within units of the continental margin of the East European Craton, b) contemporaneous with rocks of the Palaeozoic ocean-arc assemblage and c) deposits formed in syn to post collisional events within the orogen. These deposits form the basis for iron and steel production in the region which in 1998 amounted to 22 million tonnes of iron ore.

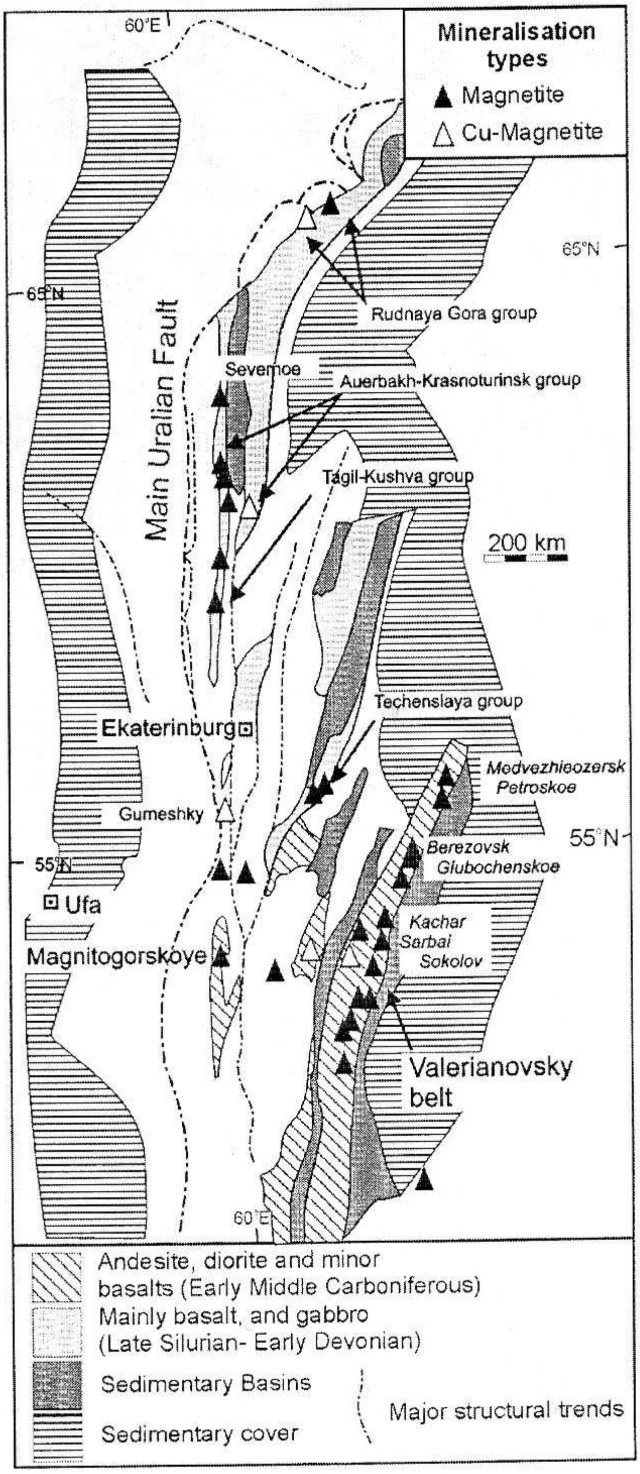

Figure 1: Hydrothermal magnetite deposits of the Urals (modified after Koroteev et al., 1997)

Table 1: Key iron oxide deposits of the Urals and their genetic associations

Genetic association	Petrological association	Deposit name (Age)	Relationship to intrusives
Orthomagmatic	Low-Ti magnetite-bearing intrusives of dunite-pyroxenite association	Kachkanar (Silurian)	Hosted within intrusion
	Titanomagnetite-ilmenite-bearing gabbroic intrusives	Kusinsk, Kopansk (Proterozoic)	Hosted within intrusion
Hydrothermal-(magmatic)	Magnetite calcic-skarn	Magnitogorsk, Vysokogorsk, Goroblagodat (Devonian)	Contact skarn Contact skarn Contact skarn
	Scapolite-albite-magnetite skarn	Kachar,	Stratified replacement
		Sarbai,	Contact skarn + stratified replacement
		Sokolovsk,	Contact skarn + stratified replacement
		Glubochensk (Carboniferous)	Contact skarn + stratified replacement

Orthomagmatic Oxide Deposits

The former two groups of deposits, a) and b) above, are related to layered mafic intrusive complexes in Proterozoic rift-related sequences of the East European craton margin and Alpine-type chromite deposits of Palaeozoic oceanic rocks. Examples of the former are the Kusinskaya ilmenite-titanomagnetite occurrences whilst examples of the latter include the world-class Kempirsai chromite deposits in Kazakhstan and the large Kachkanar deposits in the Middle Urals. These deposits are clearly orthomagmatic and are not discussed here (Koroteev et al. 1997).

Hydrothermal Magnetite Deposits

Magnetite dominated iron-oxide deposits that have formerly been grouped together and classified as 'skarns' (Smirnov & Dymkin 1989) include the Palaeozoic deposits of the Auerbakh-Krasnoturinsk, Magnitogorsk and Valerianovsky belts (see Figure 1). These groups of deposits are discussed in the text which follows.

Hydrothermal Magnetite Mineralisation

Auerbakh-Krasnoturinsk

This region hosts a number of 'skarn' magnetite deposits which are notable for their elevated gold and copper values (Sazonov et al. 1998). In this region which is a rather complex tectonic zone between the Tagil volcanic arc and the Precambrian Saldinsk massif in the east (Puchkov 1997), there are numerous porphyry copper prospects and what is described as a Carboniferous-age 'Carlin-type' replacement and vein deposit in limestones and volcanics (Sazonov et al. 1998).

One of the major magnetite bodies in this region is the Peschansk deposit. Peschansk had reserves of 173 million tonnes of magnetite ore in 1977, grading 48.5 to 54% Fe, in four sectors. Significantly, the western sector of the deposit contained on average, 0.61% Cu (Sokolov & Grigor'ev 1977).

The Peschansk deposit occurs at the margins of a large diorite complex which intrudes Lower Devonian sediments and volcano-sediments. The sediment package includes limestones and andesitic tuffites. The deposits appear to be classic skarns developed directly at the contact between the intrusive and flanking volcanics and sediments. Flanking the zones of massive magnetite are aureoles of metasomatically altered rocks. The skarns are dominated by garnet-pyroxene and garnet assemblages which finger out from the massive magnetite zones. Pervasive epidote alteration of the volcanic rocks occurs outside this.

Massive magnetite, magnetite-sulphide and magnetite skarn ores are recognised with a distinctive sulphide-rich facies in part of the deposit. The deposit carries around 3% S on average throughout.

Tagil-Kushva Group

The Goroblagodat deposit or series of deposits near Kushva is similarly associated with a diorite-syenite porphyry of Upper Silurian to Lower Devonian age which cuts Ludlovian (late Silurian) volcanics and sediments. Reserves were quoted as 140 million tonnes @ 35.5% Fe in 13 stratabound lenses of magnetite. Contact metamorphic zones are characterised by garnet and pyroxene-garnet skarns, magnetite skarns and zones of scapolite alteration. Brecciated magnetite ores are common and pyrite and chalcopyrite are noted disseminated in the magnetite ores (Sokolov & Grigor'ev 1977).

Other deposits in this group are Evstuninskoe, Lebyazhinskoe, Valuevskoe, Osokino and Visokogorskoe. Gold and silver are noted along with enhanced base metals at Visokogorskoe. Rare earth rich apatite is common at Lebyazhinskoe.

Severnaya

This small group of magnetite deposits forms stratabound lenses at the boundaries between Silurian-age limestones and basalts. The main minerals are magnetite with subordinate pyrite, pyrrhotite and often abundant apatite. Skarn assemblages are developed very erratically and comprise magnetite, hematite, mushketovite, pyrite, chalcopyrite, quartz, epidote, chlorite, pyroxene and amphibole. Garnet, titanite and apatite are also found.

Magnitogorsk Region

The magnetite deposits of the Magnitogorsk region was the basis of the large iron and steel complex developed in the city in the 1930s which formed the backbone of Russian production during the second world war. The main deposits of the region are Magnitogorsk (2 main bodies), Maliy Kuibas, Berezky and Dimitrovskoye. In addition the district holds another 30 smaller deposits. The Magnitogorsk resource of some 500 million tonnes of ore is practically exhausted and the only major mine in the region now is the open-pit exploiting the ca. 60 million tonne Kuibas deposit.

The geological structure of the region is dominated by the Devonian to lower Carboniferous volcano-sedimentary rocks, the major part of which comprise subduction related volcanics which are host to major volcanic-hosted massive sulphide deposits (Herrington et al. 2001). The structural grain of the region is dominated by a sequence of parasitic anticlines and synclines aligned sub-parallel to the main N-S trend, with granitic bodies intruded into the cores the fold cores.

These granitoids form two series. The older Devonian suite is comagmatic with the Devonian arc rocks, while the second series is associated with the magnetite skarn-like deposits which are of early Carboniferous age. These younger intrusive massifs are comagmatic with the early Carboniferous volcanics which they intrude. The intrusives show an evolution from gabbro (first stage) to amphibole sub-alkaline granites and syenites (later stage). The ore bodies are located: (a) at the contacts between granites and meta-volcanites (eg. Maliy Kuibas), (b) within granites (eg. Beresky) and (c) along the exocontacts (eg. Magnitogorskoye, Dmitrovskoye etc.). The sequence has been dated at between 333 and 330 Ma (Ronkin 1989). Emplacement of these intrusives is controlled by a major NNE trending structure, indicated on Figure 2. The intrusive igneous suite shows clear evidence of fractionating gabbro to diorite from a common source, with the latest granitic intrusions developed as thin sheets marginal to the gabbros (Fershtater et al. 1997, Fershtater 2000). The main pluton is also zoned from the base, from a lower gabbro to a transitional gabbro-granite breccia to an upper granite. The composition of the plutonic rocks is typical for moderately alkaline continental rift series, comparable to igneous suites from the Afar Rift (Fershtater 2000).

The magnetite bodies at Magnitogorsk itself occur as exoskarns, formed largely at the expense of Tournaisian and Lower Visean (lower Carboniferous) limestones (Figure 3) located on the southern contact of the Magnitogorsk intrusion. The host limestone unit is shown as being underlain by Late Devonian basalts. The footwall is intensely albite-altered close to the limestone unit and the magnetite body, while the overlying Carboniferous volcanics are albitised and overprinted with skarn alteration. The ore-bearing skarn comprises andradite-grossular-garnet, diopside, epidote, calcite and apatite.

The ores are largely magnetite with minor pyrite (carrying up to 5% Co), pyrrhotite and chalcopyrite. Sulphides often form inter-granular aggregates within the magnetite as well as more discrete sulphide-rich lenses.

The Maliy Kuibas orebody is situated 14 km to the NNE of the Magnitogorsk deposit, along the northern flank of the Kuibas granite intrusive. From a structural perspective, as at Magnitogorsk, the deposit lies within the core of a branched anticline of folded volcanic and volcano-sedimentary rocks. The structure is intruded and metamorphosed by the granitoid massif. The deposit itself is clearly related to a tectonic zone within the anticlinal structure (Figure 4). The wall rocks comprise mafic volcanic units, including metamorphosed diabases

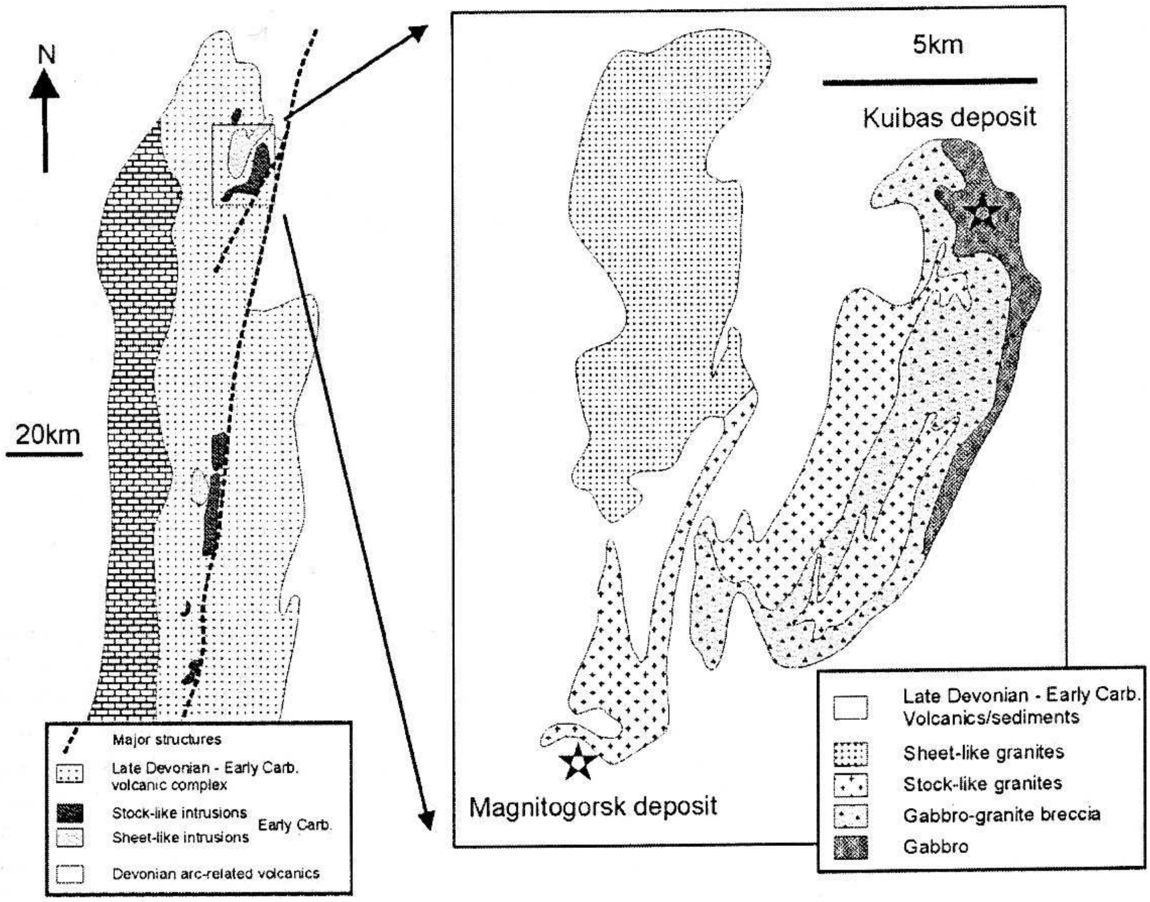

Figure 2: Simplified geology of the Magnitogorsk region (after Fershtater, 2000)

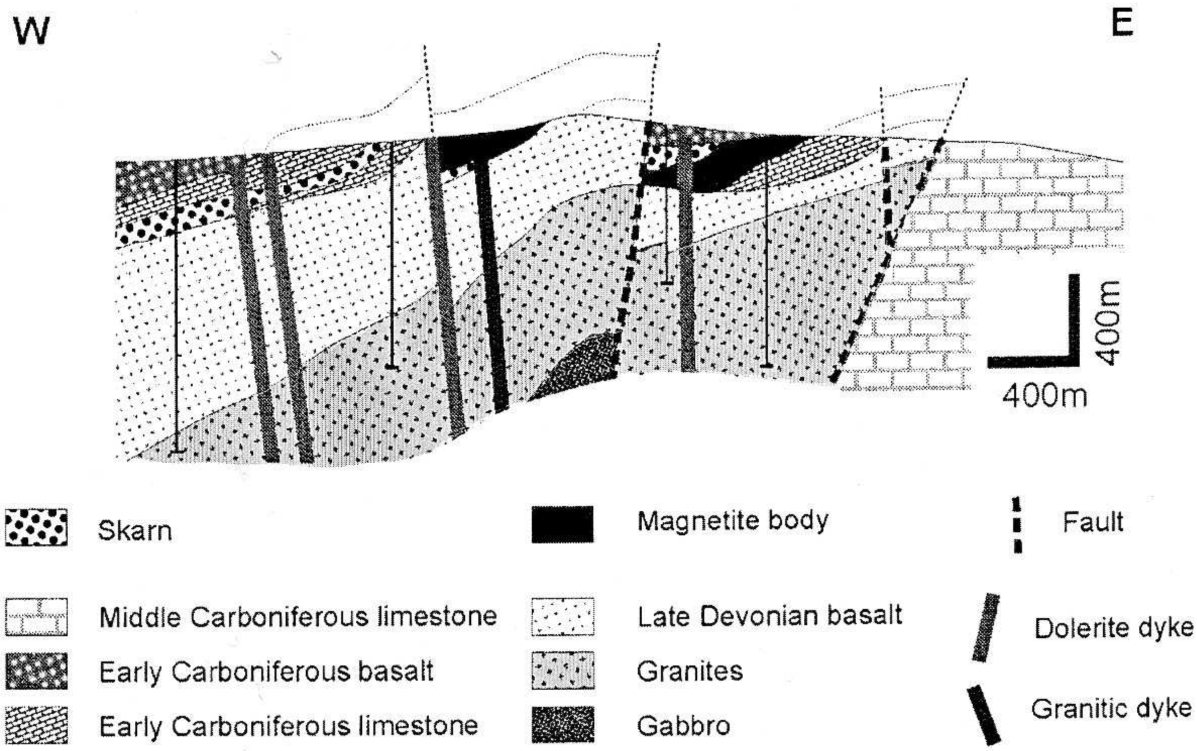

Figure 3: Geological section through the Magnitogorsk deposit (after Ya. Baklaev: unpublished)

(dolerites) and their tuffaceous equivalents, which are plagioclase and pyroxene phyric. In addition, there are granites, gabbros and various hornfels facies which are now represented by a fine-grained rock composed of quartz, plagioclase, hornblende and pyroxene with secondary and accessory leucoxene, epidote, chlorite and titanite.
In the central part of the deposit, pyroxene-feldspar and quartz-feldspar hornfels are developed with skarn and magnetite bodies. These form a zone measuring 200-600x2500 m in extent, elongated parallel to the NNE trend and dipping westwards at 70-85°. Many apophyses and metre wide veins of granite are injected into the ore-zone and separate ore blocks. In detail, there are actually more than 50 individual magnetite lenses in the deposit with sizes varying from 50x50 to 500x300 m, with thicknesses of between 2 and 50 m.

In the limits of the ore zones, granites have progressive transitional contacts with hornfels, tuffs and diabases. Skarns occurs as rims around magnetite ore bodies and veins, and as lens-like inclusions within the ores, granites and hornfels. The mineralogical composition of the skarns comprises: garnet (andradite-grossular, andradite), diopside-hedenbergite, calcite, tremolite, actinolite, bluish hornblende, vesuvianite, scapolite, albite, epidote, chlorites, hematite, pyrrhotite, pyrite, siderite, magnetite and apatite. There are many different mineralogical associations within the skarns, but usually they are dominated by a pyroxene-garnet-association. Skarns are coarse-grain and form zonal veins with cavities and druzy aggregates. The proposed sequence of mineralisation and alteration is summarised in Table 2.

The ore mineralogy is dominated by magnetite with minor pyrrhotite and pyrite, although cobalt is an important trace element. The ores are coarse grained, massive or banded, with breccias being present in places. In the northern part of deposit there is a titano-magnetite-bearing ore body with 16-25% TiO_2,. ulvospinel and herzinite. The deposit is capped by a 5 to 30 m thick supergene blanket.

The composition of typical ores from Maliy Kuibas is (in percent): Fe - 38.5; Co - 0.02; Ni - 0.01; Mn - 0.17; TiO_2 - 0.41; V_2O_3 - 0.05; S - 1.83; P - 0.06; SiO_2 - 16.0; Al_2O_3.- 5.9; CaO - 7.8; MgO - 1.42. For a comparison, the chemical and mineralogical composition of ores from the Magnitogorsk deposit are shown in Table 3.

Valerianov Trend

The 700 km long, NNE striking Valerianov trend (see Figure 1) is host to a major group of magnetite bodies which are described as skarns (Koroteev et al. 1997). This trend contains the major iron-ore producing area of Turgai which includes the Sarbai, Sokolovsk and Kachar deposits. Kachar has a reported resource of some 2 billion tonnes of ore at around 45% contained iron in magnetite. The trend contains two major districts of mineralisation to the south and the north respectively, the Turgai and Glubochensk regions.

Stages of Alteration	Sequence		Mineralogy
	Magmatic stage	Post-magmatic stage	
Telethermal contact hornfels			Labradorite, oligoclase, pyroxene, hornblende, magnetite
Alkaline metasomatism, (oligoclase stage).			Oligoclase, quartz, pyroxene, hornblende, magnetite.
Alkaline metasomatism, albite (albite-orthoclase) stage.			Albite, orthoclase, quartz, actinolite, magnetite, epidote, calcite, sericite.
Skarn-magnetite stage, skarn sub-stage			Pyroxene, garnet, epidote, vesuvianite, wollastonite, hornblende, magnetite, pyrrhotite, apatite.
Skarn-magnetite stage, magnetite sub-stage			Magnetite, garnet, hornblende, pyrite, chlorite, calcite.
Low temperature metasomatism and hydrothermal stage			Quartz, epidote, chlorite, sericite, pyrite, albite, calcite, apatite, siderite.

Table 2: Paragenetic sequence of alteration and mineralisation in the Magnitogorsk area (after Sidorenko, 1973)

Turgai Region

The Turgai region contains the major iron producers of Sarbai, Solovsk and Kachar which have supplied magnetite ore to the Magnitogorsk iron and steel complex since the depletion of virtually all of that complex's associated deposits, with the exception of Kuibas.

The region comprises a NNE trending fault-bounded linear corridor of Tournaisian to Namurian (Carboniferous) volcano-sedimentary rocks developed between large sedimentary basins (Figure 1). The Carboniferous units in the corridor are entirely covered by a 40 to 180 m thick sub-horizontal layer of Mesozoic to Cainozoic sediments. The magnetite bodies were discovered by airborne and ground geophysics in the 1940s, following reports of magnetic compasses being deflected when the area was overflown.

Sarbai

This deposit lies in the south of the belt, at the contact of the Sarbai dioritic intrusion, which comprises a pyroxene-quartz-diorite, accompanied by various dyke phases, culminating in post-ore granite porphyries (Dymkin 1966). The deposits lie above the Valerianov sub-zone of rocks, within andesitic porphyries and diverse volcaniclastic rocks, some of which show extensive early hematite alteration. This host unit defines the Sokolovsk-Sarbai anticline, with the deposits occurring on the western limb. Pre-, syn- and post-ore structure is important in the location of the various intrusive phases and the mineralisation.

Alteration comprises pre-ore hornfelsing and the development of biotite-k spar and albite alteration facies. This phase is followed by pyroxene-scapolite, pyroxene-garnet and epidote-actinolite alteration directly associated with the ore formation. Post ore alteration consists of chlorite-prehnite, calcite-silica and zeolite assemblages. Pervasive scapolite is a noted feature of the Sarbai deposit and of the Turgai province as a whole (Smirnov 1977). Alteration appears to be zoned outward from the Sarbai diorite pluton as follows: a) biotite-albite-scapolite, b) garnet-pyroxene 'skarn', c) 'skarn' ore (dominantly magnetite and scapolite), d) scapolite-pyroxene, and e) pyroxene skarns, passing out into f) hornfels and albitised host rocks.

Orebodies at Sarbai are interpreted as having replaced bituminous limestones, calcareous tuffs and tuffites (Chuguevskaya 1969). The ore layers are conformable and appear bedded, passing laterally into less altered tuffaceous units and calcareous sediments. Post-ore dykes complicate the present geometry. The dimensions of the ore lenses at Sarbai are impressive, with the three main lenses each measuring between 1000 m and 1700 m long, 800 to 1700 m down-dip and are up to 170 to 185 m in thickness. Around half of each of these bodies is present as a higher grade core of approximately 50% Fe, while the remainder is 20-50% Fe. The dominant ore mineral is magnetite, with significant accessory sulphide, mainly pyrite, pyrrhotite and chalcopyrite. Sulphides can form layers in the footwall of the magnetite bodies but are currently not of commercial interest. Other gangue minerals are scapolite, pyroxene, garnet, wollastonite, albite, epidote, actinolite, apatite, calcite and quartz. Quoted reserves in 1970 were 725 million tonnes of ore at a grade of 45.6% Fe, 4.05% S and 0.13% P.

Sokolovsk

This deposit is adjacent to Sarbai and was also discovered in the late 1940s. Like Sarbai, Sokolovsk is similarly located at the margin of a dioritic pluton, and has extensive scapolite alteration accompanying the margins of the mineralisation, forming a hanging-wall blanket to the ore. The deposit has reserves of 967 million tonnes at a grade of 41% Fe, and carries significant sulphide with contents of between 2.5 and 3.3% S in the bulk ore (Sokolov & Grigor'ev 1977).

Element	Content in weight %			Host Minerals
	From	To	Average	
Fe	27	69,8	48,6	Magnetite, pyrite, pyrrhotite, garnet, hornblende
S	0,01	8,6	1,98	Pyrite and others sulphides
P	0,001	0,4	0,04	Apatite
SiO_2	0,3	36,2	8,3	Silicates
CaO	0,02	26,1	1 2,8	Calcite, garnets, epidote, diopside
MgO	-	3,18	1,02	Chlorite, diopside
MnO	0,01	0,26	0,08	Garnets, psilomelane
TiO_2	0,02	0,63	0,21	Titanite, titano-magnetite.
V_2O_5	-	0,12	0,03	Magnetite
Zn	-	0,21	0,03	Sphalerite.
Pb	-	0,1	0,05	Galena
As	-	0,36	0,015	Arsenopyrite.
Cu	-	0,6	0,07	Chalcopyrite
Co	-	-	0,018	Pyrite, magnetite, pyrrhotite.

Table 3: Chemical and mineral composition of ores from the Magnitogorsk deposit (from Sidorenko, 1973)

Kachar

Kachar is the largest of the Turgai region deposits with published ore reserves of 1 billion tonnes of @ 44.9% Fe (Figure 5). More recent press reports indicate that the tonnages may be at least double that figure. As with the other deposits of the district, it was discovered in 1943 by aeromagnetics.

Two supergroups have been recognised in the Carboniferous volcano-sedimentary series in the Kachar region. The older, Lower Carboniferous Valerianovo supergroup comprises approximately 1 km of andesitic volcanics and pyroclastics with interbeds of sediments and carbonates. Anhydrite layers with clay are intercalated with the limestones. The overlying Middle-Late Carboniferous Kachar supergroup contains more than 800m of polymict conglomerates, tuffs and sediments, and andesitic volcanics, basalt and andesite flows and tuff equivalents.
Scapolite-altered granite porphyry bodies cut the host sequence, while the orebody is associated with nearby gabbro-diorite intrusives. Deep geophysics suggests a buried gabbro could also be present, some 2 to 2.5 km below the deposit.

In contrast to the other deposits of the region, Kachar is distinguished by the absence of intrusive bodies immediately proximal to the ore. The high-temperature alteration in and adjacent to the deposit appears to have developed in the absence of a proximal intrusion, with scapolite forming a halo that extends for several hundred metres outward from the ore. In addition, there are broad zones of sulphide alteration accompanied by anhydrite within the deposit, which is enveloped by peripheral alunite (Sledzyuk & Shiryaev 1958).

Extensive scapolite alteration, accompanied by pyroxene, post-dates all the intrusives. Associated phases are actinolite, tourmaline, apatite, chlorite, albite, zeolite and calcite. Pyroxene-albite and pyroxene-garnet suites replace the scapolite alteration in places. Anhydrite occurs as discrete bodies in the limestone and as a replacement phase in the intrusives which are common in the magnetite ores. Belyashov & Plekhova (1965) considered the anhydrite to have originally been syngenetic, and to have been remobilised into the ore, although it only occurs close to ore and appears to be an epigenetic feature.

The ores at Kachar are closely associated in particular with scapolite and albite, in addition to other phases (see Table 4). Sulphides are common accessories although lower than at other deposits. Ores vary from 0.5 up to 3%S, 0.15-0.33% P and 0.02-0.03% Zn with significant vanadium.

Dacite porphyry, interpreted to be extrusive equivalents of the igneous complex in the Kachar ore field, have been dated by Rb/Sr at 315±24 Ma (Sokolov & Grigor'ev 1977).

Glubochensk Region

This region is defined by a group of deposits on the northeastern segment of the Valerianov trend as it enters Russia. The four main deposits of Glubochensk, Berezovsk, Medvezh'yeozersk and Petrovo are currently undeveloped but are similar to those exploited in the Turgai region, although higher grade (>50% Fe) ores are only recorded in the latter two of the group.

Again mineralisation relates to a northeast trending structural zone in the form of a fault-bounded syncline. Volcanic structures of Lower Carboniferous age are an acknowledged feature of the zone and the association of mineralisation with the early Carboniferous volcanism was recognised by Galkin (1963) and Dymkin et al. (1982). The Lower Carboniferous volcano-sedimentary host package has been dated as middle Visean and is subdivided into a lower Valerianovo and upper Kachar supergroup as

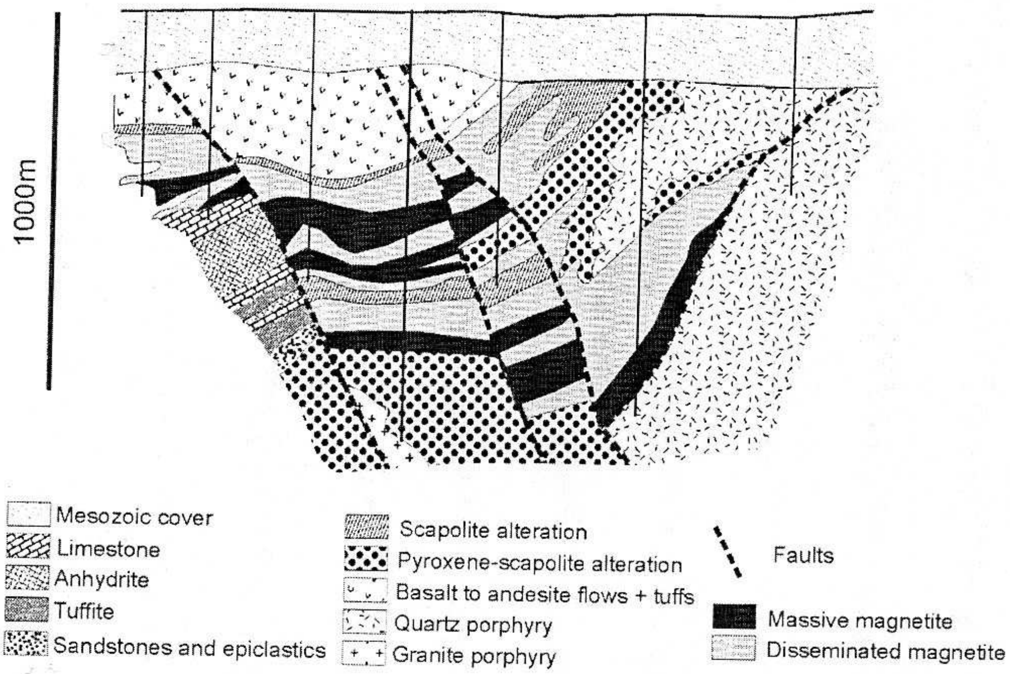

Figure 4: Section through the Kachar deposit (modified from Smimov 1977)

Deposit	Ore Mineralogy	Alteration Mineralogy
SW Valerianovsk Turgai region		
Sarbai	Mag, pyx, scap, gar, woll, alb, epi, act, apat, py, calc, qtz Sulphide ore: py, po, cpy, sphal	Pre-ore: Biotite, kspar, albite Syn-ore: Pyroxene-scapolite, pyroxene, garnet, pyroxene-scapolite-garnet Post-ore: Chlorite-prehnite, calcite-quartz, zeolite Regional: Scapolite
Sokolovsk	Mag, scap, alb, pyx, gar, act, epi, ido, hem, chl, apat, preh, calc, py, po, ms, cpy, sphal	Pre-ore: Plagioclase-biotite, pyroxene-kspar Syn-ore: Pyroxene-scapolite, pyroxene-garnet Post-ore: Albite-actinolite, epidote, prehnite, calcite, quartz
Kachar	Mag, mat, scap, alb, pyx, gar, epi, act, chl, anhy, apat, titanite, zois, preh, ser, calc, py, po, sphal, cpy, gal, bn, cc	Regional: Scapolite, pyroxene, actinolite, tourmaline, apatite, chlorite, albite, zeolite, calcite Marginal to ore: Pyroxene-albite, pyroxene-garnet, garnet Syngenetic/replacement: Anhydrite
NE Valerianovsk		
Glubochensk	Mag, mart, magh, hem, mush, titano, il (cpy, sphal, gal, py, po, cc, moly, cov, bn, val	Early pervasive: Scapolite, pyroxene-scapolite Skarn: Calcic-garnet, pyroxene-scapolite, epidote-garnet Flanking skarn: Epidote, actinolite, chlorite Late: Calcite, silica, sulphides, anhydrite, gypsum
Sverdlovsk / Ekaterinburg region		
Goroblagodat	Mag, gar, pyx, ortho, scap, py, cpy, calc, epi, chl, alb, preh, zeo (traces: sphal, hem, po, gal, bn, mar, apat, titanite, fluor	Skarn: garnet-magnetite; garnet-epidote-magnetite 'Variolitic': orthoclase-pyroxene-scapolite-magnetite
Peschan'sk	Oxide: Mag, pyx, gar, Sulphide: Mag-cpy, pyx, gar	Distal: Albite, epidote, chlorite, carbonate Proximal: Garnet, garnet-pyroxene
Magnitogorsk region		
Magnitogorsk	Mag, py, po, cpy	Skarn: Garnet(and-gross), diopside, epidote, calcite, apatite
Kuibas	Mag, hem, po, py, apat, cpy	Skarn: Garnet, pyroxene (diopside-hedenbergite), calcite, tremolite, actinolite, vesuvianite, hornblende, scapolite, albite, epidote, chlorite

Table 4 - Summary of key ore and alteration mineralogies for key Urals magnetite deposits

described for Kachar above. In the Glubochensk region, mineralisation is largely confined to the Valerianovo supergroup which comprises mafic to intermediate lavas, tuffs and associated sediments, which include limestones. Limestones are erratically distributed through the supergroup but generally form less than 10% of the sequence.

The Kachar supergroup, which hosts magnetite bodies farther to the southwest, overlies this and comprises dominantly mafic to intermediate volcanics. In the Glubochensk region this supergroup only contains minor magnetite bodies. The volcanics of the Kachar supergroup are alkalic basalts to andesites with trachytes. Flow facies are common and there is a widespread development of mafic tuffs, commonly hematite altered, evidence for an early, probably subaerial, oxidation.

The two supergroups are considered to part of the same mega-volcanic event, although the volcanics of the Kachar supergroup are recognised as having been erupted in a largely subaerial environment (Pumpyanskiy et al. 1985). These volcanics are considered to be co-magmatic with the Sokolovsk-Sarbay intrusive complex, dated as Early to Middle Carboniferous (Ksenofontov & Ivlev 1971).

The chemistry of the igneous suites ranges from basalt to dacite in a continuous series indicating a common igneous source, but also that the Glubochensk rocks are directly comparable to those of the Turgai region. The suites have been compared to continental alkaline basalts formed in a rifted platform environment (Samarkin & Pumpyanskiy 1983).

The orebodies are located where the main NNE trending structures intersect easterly striking faults, with the main mineralised centres seemingly regularly spaced at 30 to 35 km intervals, a similar pattern to that noted in the Turgai district (Teterev 1970). All the orebodies occur as conformable to sub-conformable layers, with the main differences being between those hosted in volcano-sedimentary packages (Glubochensk and Berezovsk) and those in dominantly volcanic host rocks (Medvezh'yeozersk and Petrovo).

At Glubochensk there are three layers of magnetite mineralisation hosted within a volcano-sedimentary package. The mineralised system extends over a strike length of around 4.5 km, with lenses of magnetite which have dimensions of up to 1300x750 m and may be as thick as 300 m. In its southern sections, sulphides are common, dominated by pyrite, pyrrhotite and chalcopyrite.

The Berezovsk body extends over a strike of 2.8 km and as much as 1.3 km down-dip. The mineralisation takes the form of up to 10 lenses of magnetite, often with abundant disseminated pyrite.

Medvezh'yeozersk is poorly defined, being masked by 400 m of Mesozoic cover, although it is known to comprise a lens of disseminated magnetite some 200 m thick within pyroxene-scapolite and garnet alteration.

Petrovo is almost entirely hosted by volcanics, which are highly altered mafic to intermediate tuffs. These rocks are strongly altered to albite, amphibole, chlorite 'skarns' with common associated garnet-pyroxene skarn and scapolitisation. Magnetite zones are up to 40 m thick with common accessory pyrite, chalcopyrite, pyrrhotite, galena and sphalerite, resulting in a sulphur content within the mineralisation of between 1.5 and 5 weight%.

In summary, the orebodies are characterised by alternating layers of magnetite-bearing and magnetite-poor material. The magnetite-poor zones are generally altered while ore horizons can be massive, disseminated, patchy or veinlet-swarms. The principal ore minerals are magnetite, martite, maghemite, hematite and mushketovite, with minor Ti-bearing spinels. Sulphide mineralisation is widespread, with copper elevated at Glubchensk and Berezovsk whilst zinc and lead are enhanced at Petrovo. Minor molybdenite is recorded.

Alteration is ubiquitous in the host rocks (Pumyanskiy et al. 1985). An early scapolitisation is recorded, accompanied by either pyroxene or epidote-albite, and surrounded by a halo of albitisation. This pattern is observed in both volcanic and intrusive host rocks, indicating the timing to be post volcanism and intrusion. Scapolitisation zones may reach thicknesses of several hundreds of metres, often enclosing small pods of mineralisation. Skarn assemblages in limestone, volcano-sedimentary or volcanic units are common, and are associated directly with magnetite bodies. They comprise calc-silicate assemblages of garnet, pyroxene-garnet and epidote-garnet in the case of Glubochensk. These are also developed in intrusive rocks at Berezovsk. The scapolite alteration is over printed by hydrous silicate assemblages of epidote, actinolite and chlorite; often associated with albite and carbonate. The latest stage alteration identified is carbonate, associated with silicification and accompanied by sulphides and gypsum or anhydrite.

Discussion

The hydrothermal magnetite bodies of the Urals span a period from the Late Silurian to Lower Carboniferous, but all appear to show consistent feature of an association with centres of basalt-dominated alkaline volcanism, likely to be related to post-collisional rifting as it migrates from the north southwards along the Urals. The rifts are manifested in the form of sub-parallel, N to NNE striking graben features, now often defined by fold axes. On closer inspection, the classification of the magnetite deposits as simple contact skarns is not so evident and many of these deposits have poorly defined relationships with intrusive rocks. Less than 20% of the magnetite bodies actually form in contact with igneous bodies. The largest body in the Turgai district, Kachar, lies some 18 km laterally and probably more than 2 km vertically (based on geophysical modelling) from the contact zone of any prospective intrusive body of sufficient size to have provided adequate heat-flow. Furthermore, the presence of uniform zones of pyroxene-scapolite alteration many kilometres from the intrusive contact has also been pointed out as incompatible with a simple skarn origin (Belevtsev et al. 1982), although these authors propose a metamorphosed syngenetic origin for the ores. There is also a general lack of spatial association between the extensive zones of scapolitisation and the intrusive bodies, suggesting that the scapolite alteration may not be directly controlled by the presence of igneous bodies. Structure is a key component to deposit formation, both in controlling the large intrusive complexes and for focusing hydrothermal systems.

Table 4 summarises the alteration and mineralisation for key magnetite deposits of the region. Much of the alteration is of a regional nature, developed well beyond the aureole of any of the related intrusive bodies. Evidence for the high chloride activity in the alteration fluids is manifested by the large regional scapolite alteration halos. The fluids were highly oxidised from the bulk mineralogical evidence (magnetite, often anhydrite). Apatite is a ubiquitous associated phase in the deposits.

Undoubtedly contact metasomatic zones (s.s.) are recognised at Magnitogorsk where a classic high-temperature assemblage of plagioclase + pyroxene + hornblende + quartz + magnetite is developed, reflecting an almost isochemical change at the margin of the large Magnitogorsk gabbro-granite pluton. Nevertheless, in the Turgai district and at Goroblagodat, scapolite metasomatism is developed on a regional scale, evidence for major regional fluid flow linked to favourable structural trends rather than simple contact alteration skarn development.

Many of the deposits have base metal sulphides, dominated by copper, as a late phase associated with hydrous silicates and carbonate, similar to many of the Cu-Au bearing iron-oxide camps. In the Auerbakh-Krasnoturinsk camp, the margins of the magnetite bodies are noted to have more sulphide-rich bodies where grades of up to 1.6% Cu are not uncommon. Gold values of up to 6 ppm and silver values of 37 ppm are reported in the sulphides.

Exploration in the Urals for major Cu-Au bodies related to the iron-oxide systems has not been carried out systematically, as these belts have been targeted simply for magnetic iron-ore deposits. There must be potential for large tonnage base metal discoveries, given the scale of alteration shown by the systems. Existing bodies show significant copper and gold values and currently these are not being recovered.

A further feature to note is the dominance of subaerial mafic volcanic suites in the volcanic sequences of the Urals belts. Previous Russian authors have also noted the presence of early hematisation of these volcanics, another positive indicator for the generation of oxidised, copper and gold bearing fluids in regional hydrothermal systems (Hitzman 2000).

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