KIRUNA-TYPE IRON OXIDE-APATITE ORES AND "APATITITES" OF THE BAFQ DISTRICT, IRAN, WITH AN EMPHASIS ON THE REE GEOCHEMISTRY OF THEIR APATITES

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Abstract - The Bafq metallogenic province in Iran contains world class Kiruna-type apatite-iron oxide ores, apatite-rich magmatic rocks called "apatitites", REE, Th-U, Pb-Zn and recently reported Cu(-Au?) mineralisation. The metallogenesis is related to magmatic events that accompanied a major late Precambrian rifting event within Gondwanaland. The magmatic activity is subvolcanic to volcanic, is characterised by the bimodal association of rhyolites and spilitic basalts and is accompanied by a regional alkali metasomatism.

The iron deposits are commonly hosted by hydrothermally altered and metasomatised rhyolitic rocks, which are either interstratified with volcano-sedimentary sequences, or form large subvolcanic and volcanic masses. The iron ore is dominantly a Ti-V-poor massive magnetite with subordinate hematite, and is commonly accompanied by apatite. Apatite also occurs within the magmatic "apatitites" which are spatially and temporally closely associated with the iron ores.

The behaviour of trace elements in the Bafq apatites from both associations is identical. Both apatites are enriched in REE up to 2 weight% REE oxides, and have a REE distribution pattern marked by a strong LREE/HREE fractionation, pronounced negative Eu and slightly positive Ce anomalies. They are also characterised by depletion in Sr (to 300-400 ppm) and Th (to 100 ppm) and are practically devoid of U and Pb.

The REE geochemistry of the apatites from the Bafq region is similar to other global apatite-magnetite ores, including those of Kiruna in Sweden, but also in part to both nelsonites and to the carbonatite association. However, they differ fundamentally from the sedimentary phosphorites, thus excluding a marine source.

The identical chemistry of apatites from both the iron ores and "apatitites" in the Bafq district reflects the composition of a homogeneous source reservoir and confirms the geological, mineralogical, and petrographic evidence that apatites of both associations are cogenetic. These observations strongly imply that fluids have played a crucial role in the formation of the iron ores and the "apatitites", putting the previously proposed iron-phosphorous liquid magma source into question. The fluid model also explains the large spectrum of modes of emplacement, from submarine hydrothermal to hydrothermal and metasomatic. The source of the mineralising fluids is assumed to be an evolved magmatic fluid rich in volatiles and incompatible elements, that was generated during late Precambrian intra-continental rifting within the Bafq district.

Introduction

The town of Bafq is located 115 km south-east of the city of Yazd, in central Iran. It has given its name to the Bafq district, a large metallogenic province containing world class iron ore, magmatic phosphate, Th-U and Pb-Zn deposits and recently discovered Cu (Au?) mineralisation.

Editors note: The Iranian location 'Bafq' may be translated into the Roman alphabet as either 'Bafq' or 'Bafg'. The former has been used in the text of this paper throughout, although the latter may appear on some plans and in citations in the reference list.

The district comprises a narrow rift zone extending from south of the town Bafq to Sagand and Robat-Posht-Badam in the north. The reserves of mostly high grade (65% Fe) iron ores, which are estimated at 1500 million tonnes, are distributed over 34 zones of aeromagnetic anomalies (Fig. 1). Iron ore is currently being mined to supply local steel works. In addition, economic apatite deposits, ignored for many years, have recently become attractive. The first phosphate plant was established at the Esfordy deposit, which has an estimated reserve of 17 million tonnes of apatite with 2-3% REE (Phosphate Mines Development Co., 1999).

In the Bafq district, apatite is associated with both magnetite (-hematite) ore and with apatite-bearing silicate-phosphate-magnetite-carbonate rocks ("apatitites"). The iron ore deposits are classified as Kiruna-type (Williams & Hushmandzadeh, 1966; Borumandi, 1973; Daliran, 1990, 1991; Daliran et. al., 1994; Förster & Jafarzadeh, 1994; Mücke & Younessi, 1994). Kiruna-type iron ores are low-Ti, low-V, magnetite(-hematite)-apatite mineralisation associated with near surface to surface felsic to intermediate magmatic systems (Daliran, 1990). The genesis of the Kiruna-type ores has been controversial for several decades. A wide spectrum of ore genesis models from liquid magmatic (Geijer, 1910; Geijer & Ödeman, 1974; Frietsch, 1984; Wright, 1986; Lyons, 1988; Nyström & Henriquez, 1994) to sedimentary (Parak, 1975) have been proposed for Kiruna-type ores worldwide. Recently volatile and hydrothermal ore forming processes have gained more prominence (Hildebrand, 1986; Oreskes & Einaudi, 1990; Hiztman et al., 1992; Oreskes et al., 1994; Bookstrom, 1995; Treloar & Colley, 1996; Rhodes & Oreskes, 1999; Rhodes et al., 1999) and their generation within a continental rift tectonic environment has been stressed. Broadly, the origin of the Iranian iron ores has been attributed to liquid magmatic processes, in analogy to that proposed for the Kiruna deposits in Sweden (Williams & Hushmandzadeh, 1966; Borumandi, 1973; Förster & Jafarzadeh, 1994; Mücke & Younessi, 1994).

A re-evaluation of the available data and recent fieldwork, demonstrates a close spatial and temporal association between the iron ores and "apatitite" rocks in the Bafq region. Field geological relationships, mineralogy and petrological studies support a common origin for the apatite-iron ores and the "apatitites" with varying modes of emplacement, which can not be explained by a liquid ore magma alone (Daliran, 1990; Daliran & Amstutz, 1991). This association thus offers an appropriate opportunity to approach the problem of the genesis of Kiruna-type ores by means of a comparative study of the geochemistry of apatites of both affiliations in the Bafq district.

Geological Setting

Regional Setting

The Precambrian basement of Iran was consolidated with the neighbouring Arabian Shield, to become part of Gondwanaland during the Upper-Precambrian Assyntic orogenesis (Stöcklin, 1968, Haghipour, 1994). Davoudzadeh et al. (1986) proposed that this event should be termed "Katangan/Pan-African" on the basis of the geodynamic linkage of the structural history of Iran with that of the African-Arabian plate.

During the post-Assyntic, Iran continued to be part of this larger craton within Gondwanaland until the Late Triassic when disruptions, such as that along the Zagros Line, developed an oceanic trough (Stöcklin 1968). Recent studies have indicated however, that there are deep seated faults and rift zones observed in the Bafq district that date from the end of the Precambrian (Haghipour, 1974, Daliran, 1990, Samani, 1993). This rifting took place as a part of

the Pan-African tectono-thermal event from 750 Ma to 550 Ma (Illin, 1991, Samani et al., 1994). The geology of the Bafq region was studied in detail by Haghipour (1974) and NISCO (eg., 1980) and was reviewed recently by Hushmandzadeh (1989) and Samani (1993, 1994, 1998).

The orogenesis of the Upper-Precambrian is responsible for the earliest preserved structural patterns observed in Iran with a quasi north-south trend in eastern Central Iran that was reactivated during subsequent rifting. The Bafq district coincides with a narrow north-south striking rift zone from Chogart in the south to Sagand and Robat-Posht-Badam to the north (Fig. 1). Samani (1998) distinguished a southern sector (the Chogart-Esfordy domain) and an 80 Ma younger northern sector (the Sagand-Khoshumi domain). The Chador Malu deposit lies on the dividing line between the two sectors, which corresponds to an east-west trending deep crustal fault. The rift sediments are overlain by platformal Cambrian formations, signifying the termination of the rifting event.

According to Samani (1998), rift-related tectono-magmatic activity in the Bafq district began with mantle doming, alkaline ultrabasic magmatism, and intrusion of late K-syenites in the southern sector. In the northern sector, rifting was associated with carbonatitic metasomatism and by intrusion of granitic masses of metasomatic origin that were accompanied by a regional Na metasomatism. The first rifting stage was accompanied by bimodal volcanic rocks (alkali-feldspar rhyolite and spilitic basalt), whereas the second stage was dominated by K-rich acid volcanism. These two rifting stages have been dated at 750-583 Ma and 583-550 Ma respectively, and are locally separated by a disconformity and a basal conglomerate (Samani et al., 1994). Large volumes of magmatic rocks in the Bafq district are represented by the Zarigan- or Narigan-type subvolcanic granites and by rhyolites, which are the most common host to the apatite-magnetite and "apatitites". Haghipour (1974) and Samani et al. (1994) attributed the formation of these granites to metasomatism of the rhyolites.

Host Sequences

The iron-apatite ores, the "apatitites", REE-, Th-U, Pb-Zn and recently discovered Cu, Co, U (Au?) mineralisation all occur within a series of volcanic and volcano-sedimentary rocks of rhyolitic composition, subordinate spilitic basalts, carbonates and detrital sediments with local evaporites. Syenite sills (albitites) and diabase dykes intrude these rift-related formations, which overly the older Precambrian basement above an angular unconformity. The basement comprises calc-alkaline magmatic and green-schist facies metamorphic rocks. The mineralised rift sequences are dis-conformably overlain by Cambrian platform sediments. The basal conglomerate of the Cambrian units contains reworked fragments of the iron ore and of metasomatic rocks marking the limit of the mineralising epoch.

The rift-related sequences that were previously known as the Rizu, Dezu, Esfordy and Sagand formations and were attributed to the Infracambrian, are now assigned to two
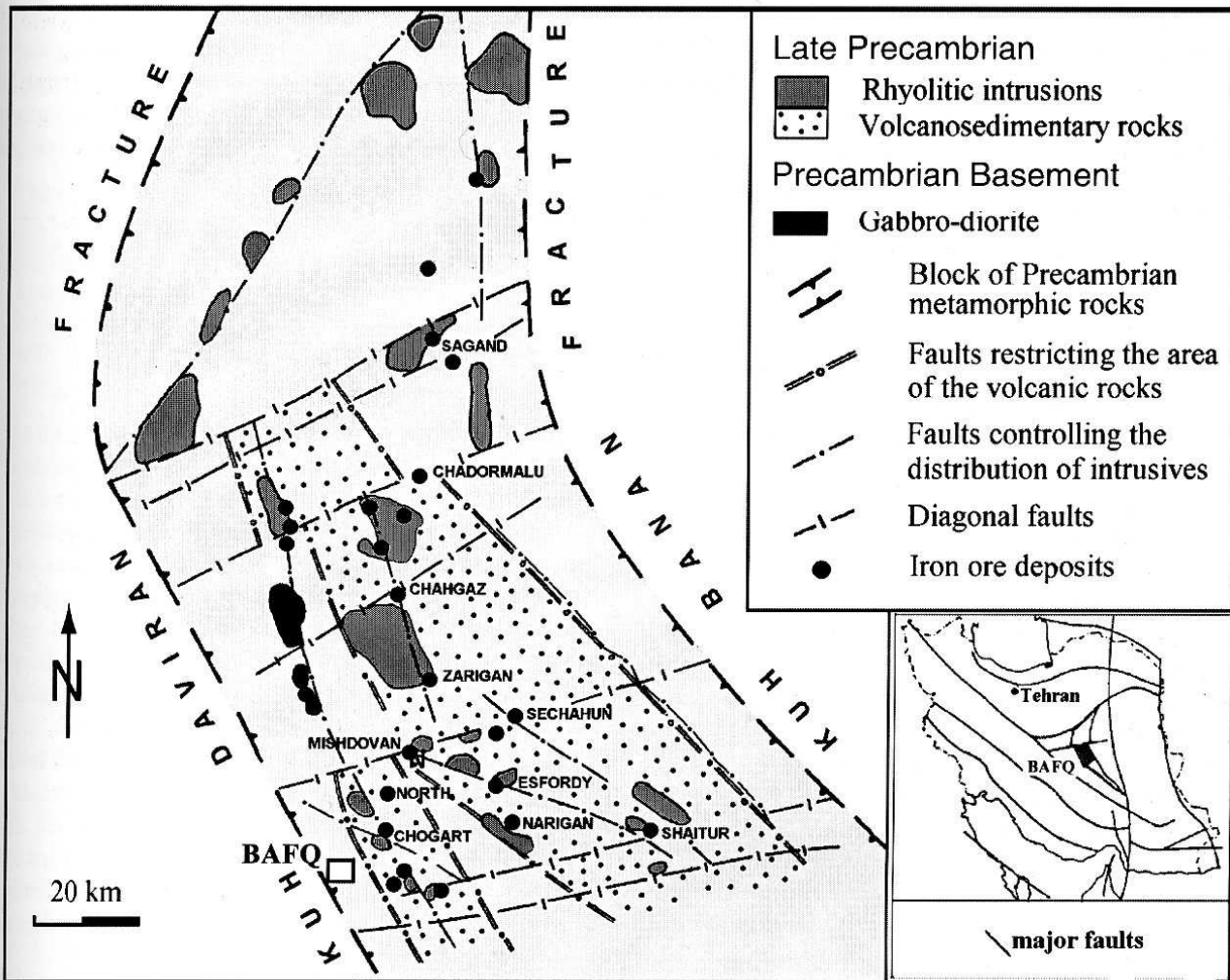
Figure 1: Structural map of the Bafq zone with location of the studied deposits (modified after NISCO, 1980).

new stratigraphic units (Fig. 2). The lower unit, which is now referred to as the Sagand Formation, formed during the major late Precambrian rifting, while the upper unit has been defined as the Rizu-Dezu Series and is related to the later subsidiary stage (Samani, 1998).

The *Sagand Formation* is a 1200-1500 m thick sequence that commences with a basal conglomerate, overlain by bimodal volcanics (rhyolite-basalt), volcanic-exhalites, and then by submarine volcanic rocks with intercalated carbonate beds at the top. The upper volcanic member progresses up-section from mainly basic rocks into more acid varieties. This unit that is strongly metasomatised and is the major host to the iron-apatite ore, "apatitites" and U-Th mineralisation of the region. Thick-bedded recrystallised limestones with intercalations of clastic-volcaniclastic rocks and evaporites form the end member of this mineralised volcanic unit.

The *Rizu-Dezu Series* comprise a sequence of high-K acid volcanic rocks with carbonates at the top, minor basic volcanics, carbonatic shales and evaporites. The basal conglomerate that overlies the angular unconformity with the Sagand Formation, contains pebbles of metasomatised Sagand Formation, marking the upper limit of metasomatism. The Rizu-Dezu Series is host to sulphide

mineralisation (Pb-Zn ore at the Kushk mine) and to the Fe-Mn ores of the region (eg., the Narigan deposit).

Mineralisation

The iron ores of the Bafq district are estimated to total approximately 1500 million tonnes and are distributed over 34 zones of aeromagnetic anomalism, from the Chogart mine in the south, to Sagand and Robat-Posht-Badam in the north. The ore reserves of the individual deposits vary from low tonnage examples (eg., Mishdovan, 20 mt) to larger bodies of several hundred (up to 300-400) million tonnes (eg., the Chogart, Chador Malu, and Seh Chahun deposits). Most are high grade (65% Fe) with some low grade mineralisation (20-30% Fe) that is a function of the ore mineralogy.

Systematic investigation of the iron ore resources of the Bafq district began in 1968 with exploration by the former NISCO, National Iranian Steel Corporation) assisted by Soviet geologists. The results of this work were compiled in a series of internal reports by NISCO between 1969 and 1980. Despite this extensive body of geological and exploration data, the fundamental questions regarding the genesis of the iron ores remains open.

AGE	ROCK Units	Lithology	DESCRIPTION	Alteration & Deformation		Geological Setting
UPPER PRECAMBRIAN — Uppermost Vendian	Equivalent to: Rizu Series or Banestan Formation		Alternation of High K Volcanics and Carbonate with Minor Clastics, Evaporites Mn-Fe-Pb-Zn Hosted.	No Deformation	Locally K-Metasomatism	Subsidary Rift ended to Platform
UPPER PRECAMBRIAN VENDIAN	SAGHAND FORMATION — Member-5 ~150-200m		Mostly Carbonate, Evaporatea with Intracalations of Tuff, and Lava, Some Fe-Ore, (Rift Salt-Lake Facies.)	METASOMATIC GRANITOID MAGMATISM LOCALLY CONTACT METAMORPHISM	EXTENSIVE ALKALI METASOMATISM	MAJOR INTRACONTINENTAL RIFT
	Member-4 >400m		Main Ore Bearing Member, Mostly Volcanogenic Consisting of Agglomerate, Breccia, with Intracalations of Carbonate in Upper Part, Extensively Metasomatized, Transformed into Different Metasomatic Rocks, Hosting Fe, U-Th-REE and Apatite Ores (Main Eruptive Volcanic Facies).			
	Member-3 ~150-200m		Rhythmic Clastic - Hydrothermal Albitic Sandston and "Slate" (Exhalative Sediment Facies)			
	Member-2 ~200-300m		Alternation of Acidic - Intermediate Lava, Lower Part More Acidic, and Upper Part Mainly Basic (Bimodal Continental Lava Facies)			
	Mb. 1 ~0-40m		Basal Conglomerate (Debries Flow Acc. Facies)			
Upper RIPHEAN	NATK FORMATION		Greenschist Metamorphosed F. Grained Flyschoid Clastics Minor Intracalations of Carbonate and Basic Volcanic Lava, Locally Metasomatized.	METAMORPHISM Greenschist Facies	Locally No Metasomatism	Continental-Slope

Figure 2: Stratigraphic column of Sagand Formation and Rizu Series (after Samani, 1993)

The iron deposits of the Bafq district exhibit a wide variation in their geology, relationship with host rocks, geometry, and their ore and gangue mineralogy, particularly the REE-bearing species. On the basis of current knowledge, these deposits may be grouped into two main styles:

1. The first is interpreted to have been generated by the discharge of ore fluids onto sedimentary basin floors to precipitate and form **syngenetic submarine hydrothermal** deposits. The ore bodies are bedded to lenticular, concordant, and have gradational boundaries with the enclosing host rocks (eg., Mishdovan and Narigan).

2. In the second style, which includes the majority of the ore deposits, the ore fluids penetrated sub-volcanic and volcanic rhyolitic rocks. The passage of the ore fluids resulted in strong metasomatic and hydrothermal alteration of the host rocks, producing **epigenetic replacement** deposits (eg. Chogart, Chador-Malu and the North anomaly). This type of iron ore passes gradationally into "apatitites" in some deposits, as is observed at Esfordy and Chogart.

Each of these two mineralisation styles may be further sub-divided on the basis of their ore and gangue assemblages. With few exceptions however, (one being Mishdovan, Daliran, 1990), no systematic studies have been undertaken to allow the assignment of many of the deposits to specific sub-types.

Examples of the variation and sub-types recognised from the *syngenetic submarine hydrothermal* style include: apatite-magnetite±hematite (eg., Mishdovan) and Fe-Mn-jaspilite (eg., Narigan) deposits. Barite is a common mineral in the Fe-Mn-jaspilites which are characterised by very low Ti and V (< 0.01%), low P (0.05-0.17%), relatively higher S (0.01 to 1.94%) and up to 10% Mn. Apatite while rare, is reported from Narigan (NISCO, 1980), although it's distribution within other ore deposits of this type is unclear.

The *epigenetic replacement* style deposits are commonly massive bodies of apatite-magnetite±hematite. The principal ore mineral is a low Ti-V (2-3%) magnetite that is commonly martitised with subordinate amounts of primary hematite. This basic mineralogy may however be accompanied by a variety of temperature dependant assemblages of silicates, REE minerals, carbonates and quartz, which permits two sub-types to be distinguished. The first of these is a *low-temperature hydrothermal* type which is characterised by the presence of hydro-silicates. An example of this type is the North Anomaly where the iron ore is hosted by rhyolites which form large masses of volcanic (perlites) to subvolcanic rocks. The mineralisation is accompanied by albitisation and actinolitisation of the rhyolites. Magnetite ore is intergrown with quartz, albite and actinolite and is paragenetically associated with chlorite, epidote, allanite, sphene, zircon, calcite, tourmaline and leucoxene. Only minor apatite is present, resulting in low P type deposits. In contrast, the *high-temperature metasomatic* types (eg., Chogart and Esfordy) are commonly accompanied by "apatitites" on a deposit scale

containing high temperature minerals such as pyroxenes and garnets, and are enriched in REE-bearing apatite and REE minerals (silicates and phosphates).

In some aspects, this classification supports the observations of the Soviet geologists (NISCO, 1980) who recognised four types of deposits: (a) Red banded, ferruginous quartzite (jasper) with hematite ±siderite and mangano-siderite, (b) Mn-rich ores with siderite and mangano-siderite, (c) Pyrolusite-limonite±hematite ore, and (d) "Contact metasomatic" ore, the grouping into which the Soviet geologists classified the majority of the Bafq district iron ores. This latter group of deposits were defined as having formed at the „crushed and metasomatised" contact zone between granite porphyry intrusions and the Infracambrian (late Precambrian) sequences. The composition of the majority of the metasomatic rocks is given as albite±chlorite±actinolite, grading into a monominerallic albitite with 4-10% magnetite. Other less common metasomatites contain biotite, microcline, carbonate, and actinolite, while those characterised by talc and skarn garnet-diopside carbonate-bearing varieties are rare. In many deposits classified in this group however (eg., Mishdovan), no contact metasomatic zone can be revealed between the volcano-sedimentary sequences and the subvolcanic granites. The "contact metasomatic" ores of the Soviet geologists, correlates in many respects with the *"epigenetic replacement"* style of mineralisation described in the present work.

The spatial and temporal distribution of the different styles of mineralisation in the Bafq region was described by Daliran (1990) who observed that the Pb-Zn ores were deposited in a separate environment to that in which the apatite-iron formed. Samani (1993, 1998) recognised two stages of mineralisation. The first was developed in association with the early rifting accompanied by alkali magmatism, Na-metasomatism, apatite-iron ores and the mineralisation of incompatible elements REE, U and Th. He related the formation of Pb-Zn and Fe-Mn and Cu, Co, U(-Au?) deposits to the later subsidiary rifting stage.

Iron ore deposits

The most systematically studied of the many iron-apatite deposits of the Bafq district is Mishdovan (Daliran, 1990), which is described in more detail below as an example of one of the main styles of ore found in the region.

Mishdovan Deposit

The Mishdovan iron deposit is located some 30 km to the north of the town of Bafq in the southern segment of the rift that defines the Bafq district. It is a high-grade, low tonnage deposit of 20 mt at around 65% Fe, whose morphology is illustrated by the geological map and section of Fig. 3. The orebody is made up of more than 20 individual lenses that are interstratified within, and are clearly concordant with, the host volcano-sedimentary sequence which comprises rhyolitic tuffs with intercalated carbonate lenses in its lower sections. These volcanics and sediments
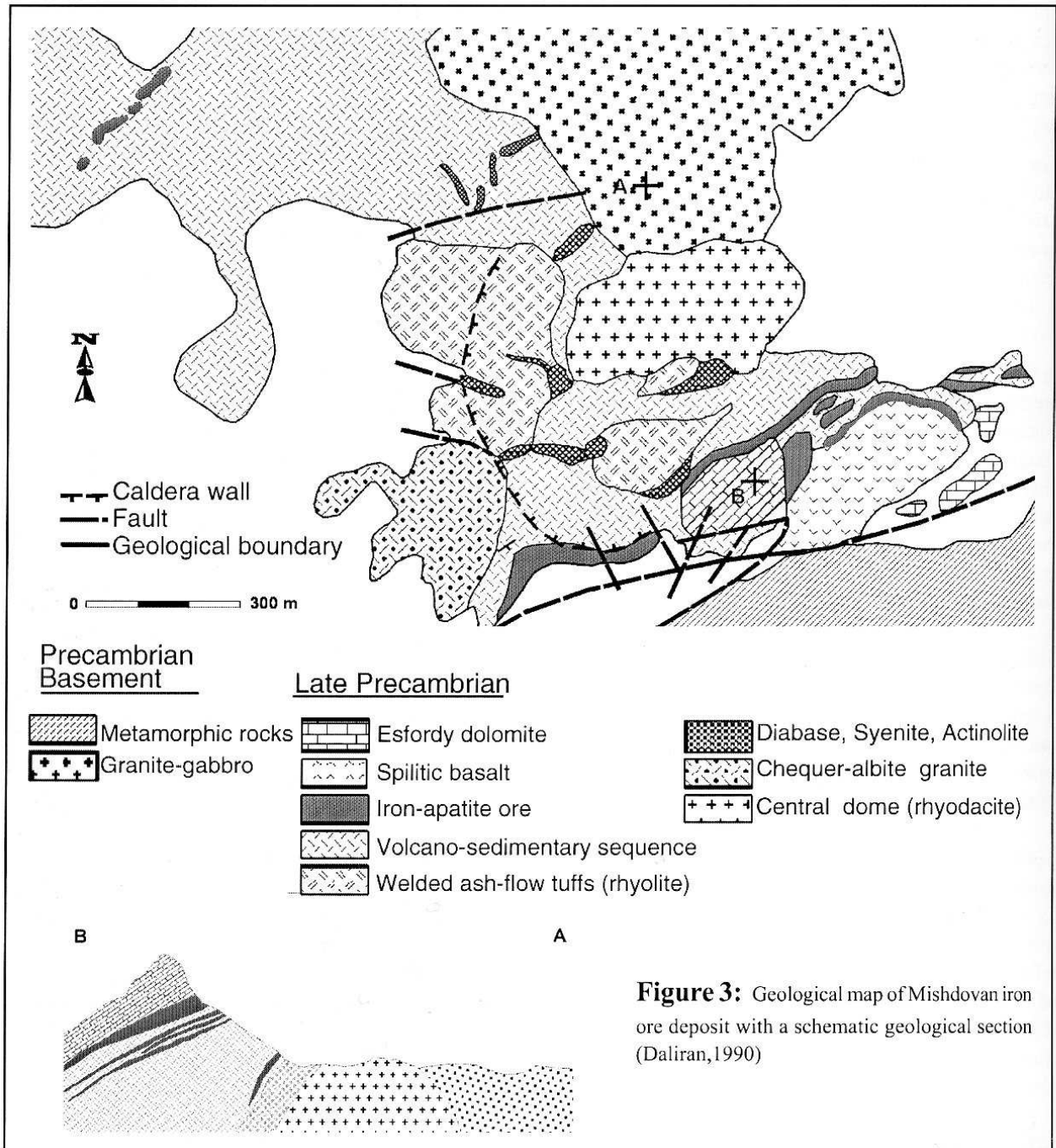
Figure 3: Geological map of Mishdovan iron ore deposit with a schematic geological section (Daliran, 1990)

are unconformably overlain by the massive cherty dolomites of the Esfordy Formation. The dolomites have a sharp contact with the underlying ore body, which is in the uppermost member of the volcano-sedimentary sequence. A small outcrop of spilitic basalt outcrops on the southern flank and may be intercalated within the dolomites. Welded ash flow tuffs are found on the western margin of the deposit, while a central dome of rhyodacitic composition has intruded the host rocks. Syenitic sills (albitites) and diabase (dolerite) dykes cross cut the host rocks and represent the latest magmatic activity at the deposit. The granite-gabbro-diorite massif to the north of the deposit and the metamorphic rocks to the south represent the Precambrian basement and are pre-mineralisation.

Hematite lenses predominate in the lower stratigraphic levels of the ore zone (Fig. 4A). These grade upwards to an interval of intercalated hematite laminae within rhyolitic

tuffs, which in turn pass into the overlying main massive magnetite ore body in the uppermost member of the host volcano-sedimentary sequence. Syn-sedimentary deformation features such as interbedding and slumped beds, and the local admixture of the rhyolitic agglomerates with the ore minerals suggest synsedimentary precipitation of the iron ore minerals. The hematite-tuff strata grade laterally into hydrothermally altered chloritic tuffs-magnetite to the east beneath the massive ore body zone (Fig. 4B). The hematite ore is accompanied by a number of minerals that show some local and partly stratigraphic control. These minerals include authigenic quartz and feldspar, micro pockets of barite, tourmaline, chlorite, talc?, carbonates and late rutile, pyrite and goethite. Pockets of actinolite have been locally formed.

"Sandy ore", which is composed of lithified sand and blocks of iron ore, is a conspicuous feature at Mishdovan. It
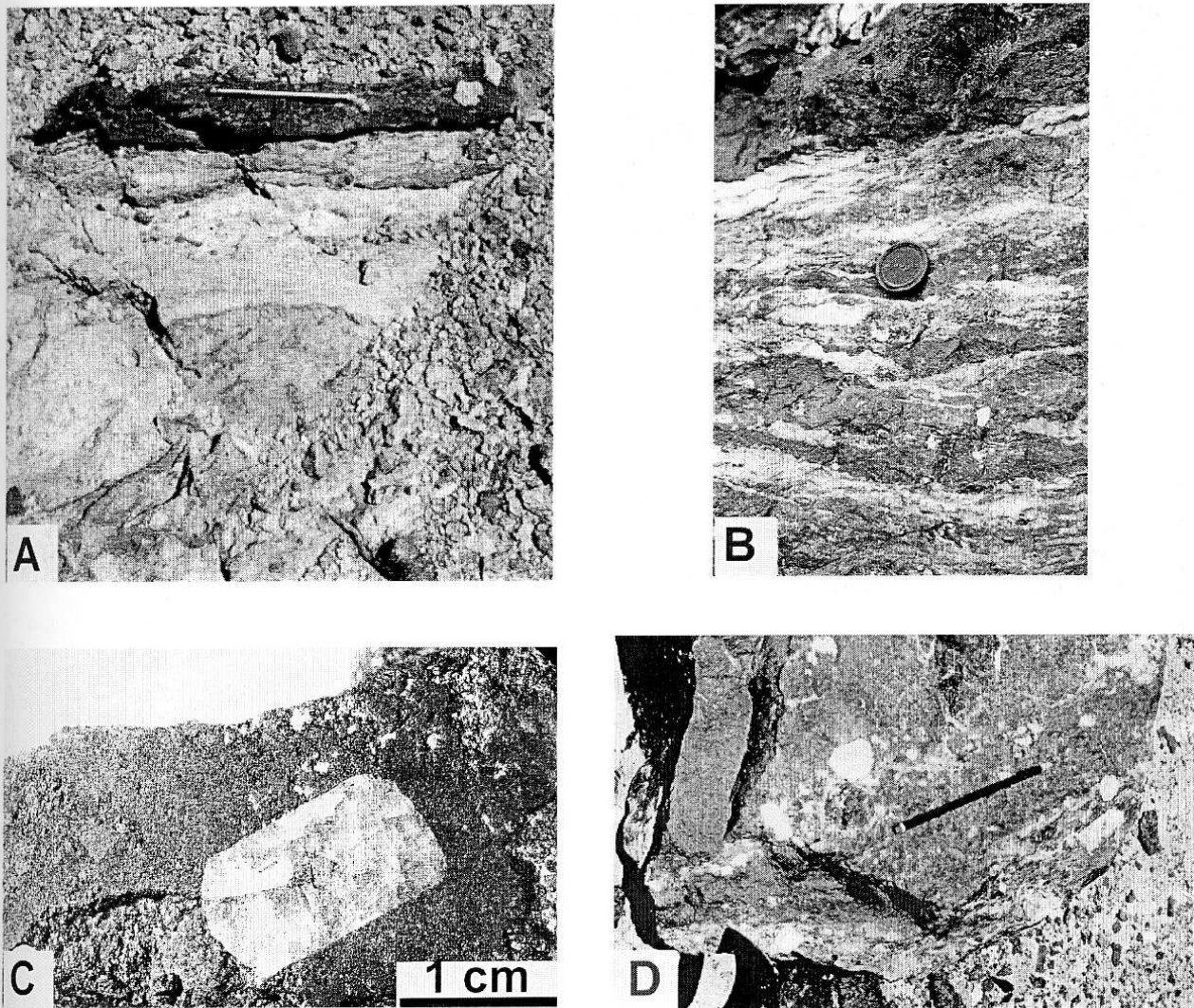
Figure 4: Field features and hand specimen from Mishdovan iron ore deposit.

(A) Lense of hematite ore interbedded within the rhyolitic tuffs.

(C) Hematite-apatite ore.

(B) Interbedding of the magnetite ore with hydrothermally altered (chloritised) tuffs at the base of the massive main ore body.

(D) Magnetite-apatite ore. Note the concentration of apatite crystals (and crystal mush) in a layer.

represents a localised "V"-shaped channel filling that was formed by the erosion and local deposition of the primary ore (Daliran, 1990). This channel which is cut into the volcano sedimentary sequence, indicates a period of erosional at the end of the ore-sedimentary cycle prior to the deposition of the cherty dolomites.

Apatite is virtually the only "gangue" mineral within the high grade ore and accompanies both the magnetite and hematite mineralisation. In the hematite ore it occurs as isolated crystals (Fig. 4C) and as tiny yellow "authigenic" crystals in the carbonate-rich hematite ore lenses. Apatite commonly forms accumulations of large yellow crystals and crystal fragments that are occasionally found in "schlieren" of calcite within the magnetite ore (Fig. 4D). Apatite crystals as well as the magnetite commonly exhibit a fragmented texture and crystal mush. In the so-called "banded ore" (Daliran, 1990), mush of apatite and of magnetite crystals are concentrated in distinct laminae and

are cemented by calcite with associated monazite (Fig. 5A, B). Some apatite crystals showed a pronounced oscillatory growth zoning filled with fluid inclusions.

The principal ore mineral within the Mishdovan deposit is magnetite. It is largely martitised (supergene) and contains up to 2-3% TiO_2 and <1% V_2O_3 in solid solution (Daliran, 1990). Discrete exsolutions of black spinel and ilmenite trellis (an oxidation exsolution) can occasionally be observed (Fig. 5C, D). Primary sulphides occur as rare submicroscopic inclusions of chalcopyrite in the magnetite. The hematite ore consists of densely packed xenomorphic grains or as specularite blades and contain occasionally inclusions of pyrite.

Single sheets within the welded ash flow tuffs contain submicroscopic hematite developed along the flow lineation. This hematite, which contains occasionally rutile, is associated with apatite, and tourmaline which is believed to have formed from fumaroles (Daliran, 1990).
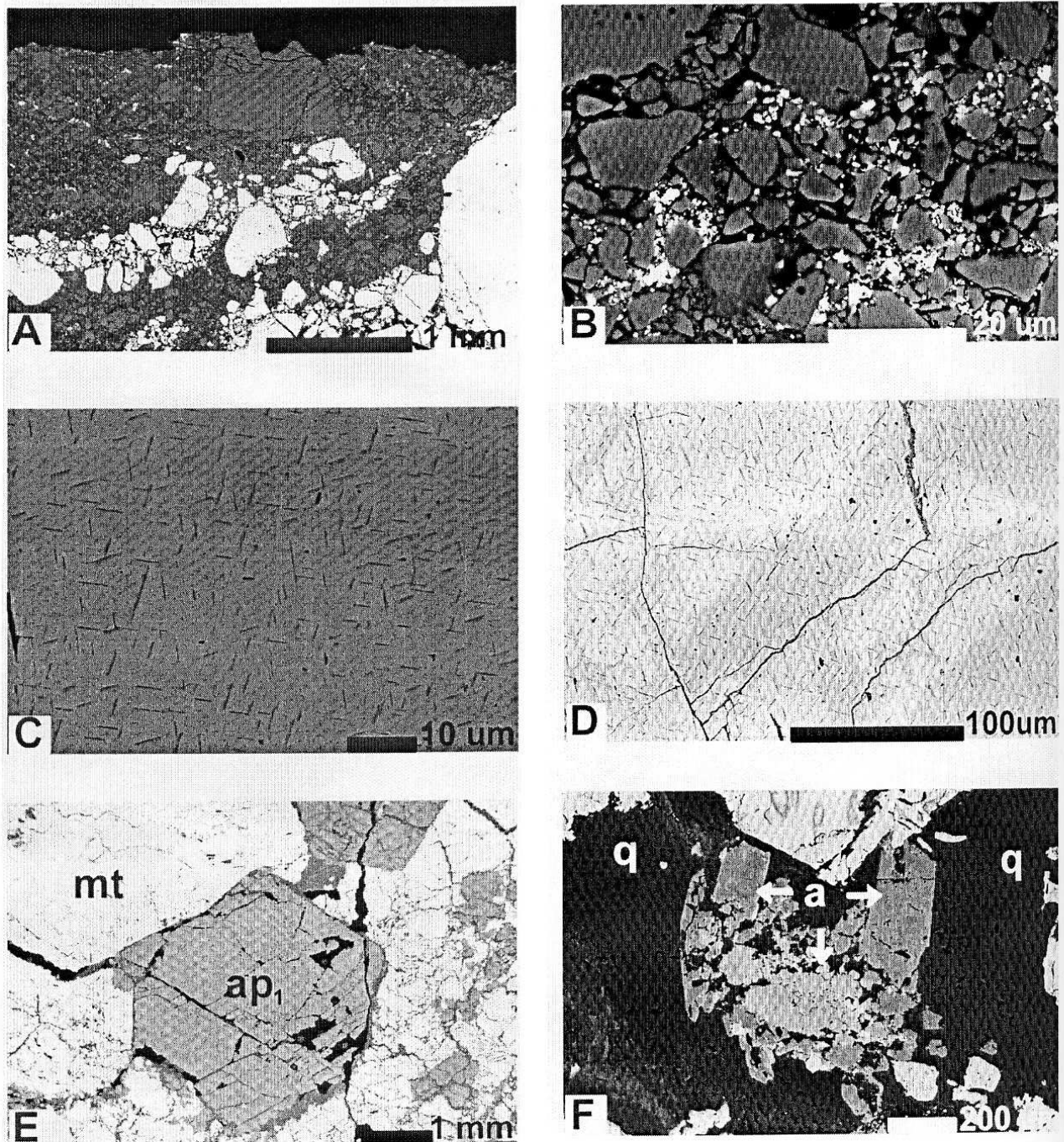
Figure 5: BSE images from the iron ores.

(A-D Mishdovan deposit).

(A) "Fragmented" texture of the banded ore showing a heterogeneous mush of magnetite (white) and of apatite crystals (gray) concentrated along distictinct layers.

(B) Mush of apatite cemented by calcite associated with submicron monazite (white).

(C) Spinel exsolution in magnetite ore.

(D) Ilmenite exsolution trellis in magnetite ore.

(E-F Chahgas deposit).

(E) Apatite (ap)-magnetite (mt) ore.

(F) Idiomorphic allanite crystals (a) associated with late quartz (q) infiltrating the early crystallised magnetite. Lighter allanite grains are richer in REE.

Chahgas Deposit

Magnetite ore from the Chahgas deposit which consists of hypidiomorphic granular magnetite with rare pyrite inclusions, is infiltrated by a network of apatite, which are in turn infiltrated by later fluids that formed talc, chlorite, calcite and quartz with sporadic idiomorphic allanite crystals (Fig. 5E, F). Minor hematite was also deposited in this late stage. This mineral assemblage indicates a metasomatic origin for the deposit.

"Apatitites"

The informal term "apatitite" refers, in a broad sense, to rocks consisting essentially of apatite accompanied by silicates, iron oxides, phosphates and silicates of REE,

titanite, calcite, quartz, talc, scapolite and (phlogopite?). To date, these rocks are only poorly studied, and their relationship to the iron ores is not well documented.

Most of the "apatitite" occurrences are closely associated with iron ore deposits as at Esfordy and Chogart. In these deposits, there is a transition from apatite-magnetite ore to the "apatitite" rocks by the addition of other minerals at the expense of magnetite. At the Chogart iron mine, which is hosted by subvolcanic rhyolites the "apatitites" are mainly confined to the crushed wall-zones between the orebody and the host rhyolite, or as veins, veinlets, and pockets cutting cross the orebody (Fig. 6). The dyke-like body at the Zarigan deposit (Fig. 7A) consists of extraordinarily large apatite crystals (>20 cm) that are crushed or show torsional deformation (Fig. 7B), and are cemented by large laths of calcite (Fig. 8A). Information from an unpublished manuscript of the GSI, appears to indicate that the different rock types at the Esfordy deposit have a concentric configuration.

The "apatitites" have undergone a complex multi-stage history of crystallisation and alteration that has resulted in a heterogeneous pegmatoidal texture with an extensive mineralogical variation and partly in the total destruction of the primary minerals and textures. The heterogeneous pegmatoidal texture has resulted from a two stage crystallisation. In the first stage, the megacrysts of yellow apatite (locally >20 cm across), pyroxene and occasionally garnet grains with magnetite have crystallised. The early crystals are commonly crushed and/or "cataclased", apparently as a result of the filter-pressure exerted by the rest fluid, and sometimes occur as a crystal mush (Fig. 8B, C). Occasional torsion of the early crystals (see Fig. 7B) may indicate a kind of plastic deformation due to a large scale flow movement of the rest fluids that entrained the early crystals at shallower levels. The rest fluids were

Figure 6: Sketch geological map of Chogart deposit showing the relationship between the magnetite-apatite ore body and the "apatitites" (modified after NISCO, 1980).

enriched in carbonates and the incompatible REE elements and were crystallised into a "non-fragmented" matrix consisting of a second generation of apatite (ap_2), REE minerals (allanite, monazite), hornblende, calcite, quartz, talc, (phlogopite?) and later veins (third stage) of calcite, scapolite and talc. Ap_2 with allanite and monazite form submicroscopic stubby crystals that are intimately associated with late calcite, quartz and other matrix minerals (Fig. 8C, D). In "carbonate-apatitites" (eg., Esfordy, Chogart and Zarigan) calcite is the main matrix component and forms large laths (Fig. 8A, B). Apatite is commonly rich in fluid and solid inclusions.

The samples investigated from the Chogart mine comprise crystal fragments of (ap_1) in a calcite matrix "carbonate-apatitite" (Fig. 8B). The (ap_2) and minor monazite are intimately associated with the carbonate matrix. Quartz and scapolite cross cut the early-formed minerals.

In the samples investigated from the Esfordy deposit, large apatite crystals and crystal fragments (ap_1) occur together with pyroxene crystals and garnet grains in a highly altered matrix of amphiboles, late calcite, quartz and the second apatite generation (ap_2), with allanite and monazite. Amphiboles were in part formed by the alteration of early pyroxenes. The new-formed hornblende is commonly smaller and idiomorphic. Pyroxene crystals are strongly "cataclased" and are infiltrated by an assemblage of calcite and scapolite. Magnetite is an accessory component, while quartz is later than the calcite, and is filled with carbonate inclusions (Fig. 8 C, D).

Geochemistry

For the geochemical studies, apatite samples from two apatite-magnetite deposits (Mishdovan and Chahgaz) and from four "apatitite" occurrences (Chogart, Esfordy, Zarigan and Chahgaz) were considered. In addition, analytical data of apatites from six occurrences (Mishdovan, Chogart, Chadormalu, Anomaly 14A, Chahgaz, Anomaly 13A) were used for comparison (NISCO, 1980).

Analytical Methods

Microprobe analyses of the apatites were performed at the Max-Plank Institute in Heidelberg using an ARL-SEMQ wavelength-dispersive microprobe at a 20 KV accelerating voltage and 20 nA beam current for 30 seconds per element. Semi-quantitative analyses of other minerals were done with a Cameca SX50 at the University of Karlsruhe. Proton-induced X-ray emission data (PIXE) were obtained with the proton microprobe at the Max-Plank Institute in Heidelberg at a proton energy of 2.2-MeV. The analyses were carried out with a beam current of 70 -110 pA for 4000-6000 seconds (Traxel et al., 1995). Apatite samples were analysed in addition for REE with inductively coupled plasma-mass spectrometry (ICP-MS) using a Fions VG-Plasma Quad PQ2 in the University of Karlsruhe. For determination of the cell parameters of the apatites X-ray powder diffraction analysis was applied with a Huber Guinier Diffractometer with Cu Kα1 at the University of Karlsruhe.
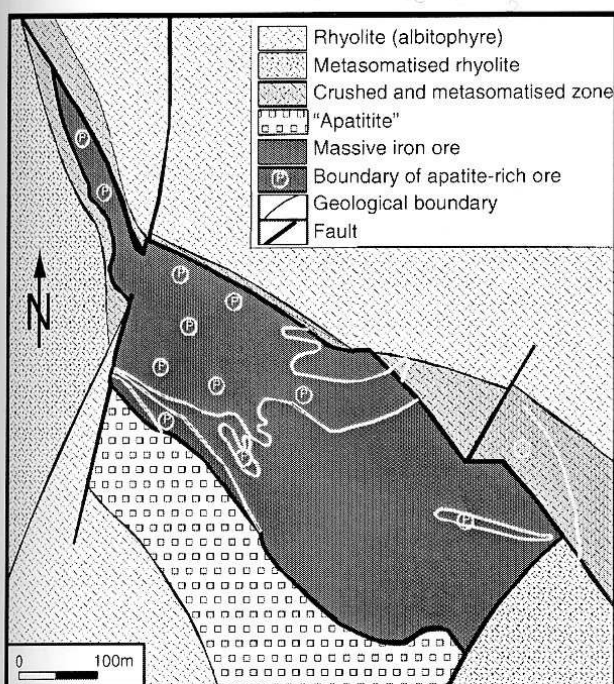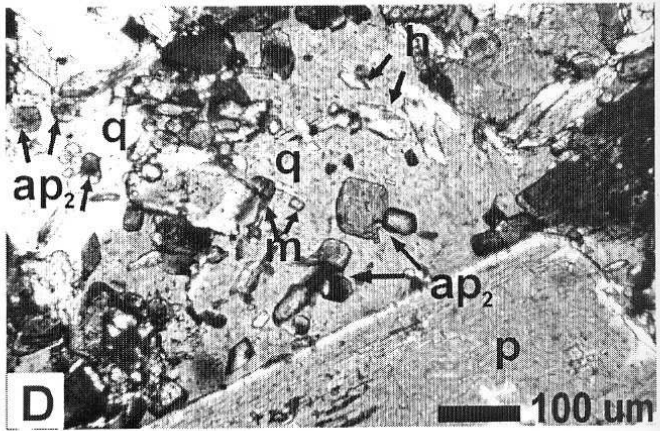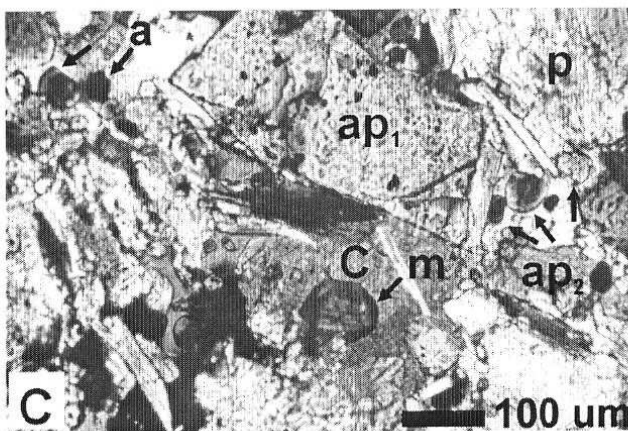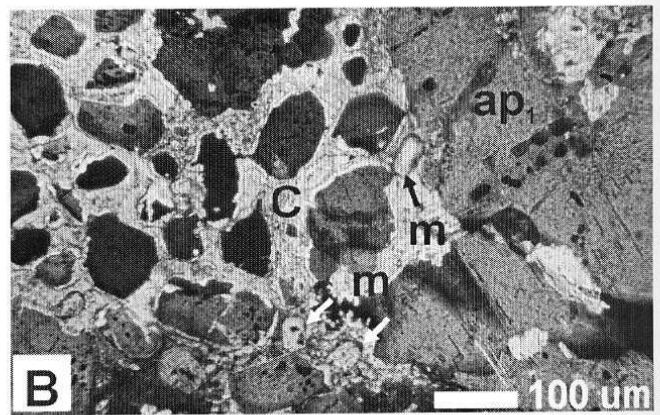
Figure 7:

(A) A dyke-like body of "apatitites" penetrating the Sagand Formation at Zarigan.

(B) Hand specimen from (A) showing splinter of "distorted" megacrytals of apatite (some with a dark core), magnetite (black grains) and pyroxene (not visible here) with interstitial amphibole, carbonate, quartz and REE minerals.
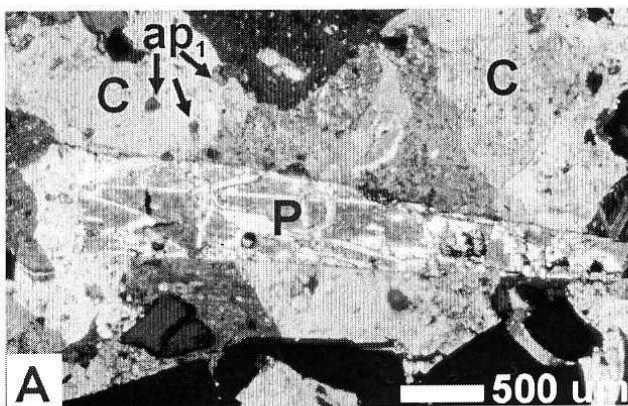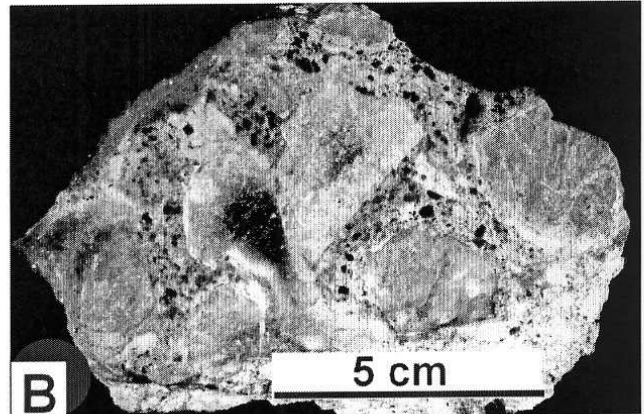
Figure 8: Microphotographs from "apatitites".

(A) Zarigan deposit. Fragments of early pyroxene (p) and apatite crystals (ap_1) in a matrix of large calcite laths (c).

(B) Chogart deposit. Crystal fragments of early apatite (ap_1) in a matrix of calcite associated with monazite (m).

(C-D) Esfordy deposit. Fragments of early apatite (ap_1) and partly altered pyroxene crystals (p) in a matrix composed largely of calcite with minor quartz, hornblende (h) associated with stubby crystals of REE minerals, the second apatite generation (ap_2), monazite (m), and allanite (a).

Results and Discussion

Apatite Chemistry

Apatites of the first generation (ap$_1$) were analysed for almost all elements, but not for carbon dioxide or water. The results are listed in Tables 1 to 3.

To provide a basis of comparison with other Kiruna-type ores, apatites from Kirunavaara (Sweden) and Durango (Mexico) were also analysed (Tables 2, 3). The ICP-MS results of this study, closely match the data published by Frietsch & Predhal (1995) and Dill & Kantor (1997) for the Kiruna apatite and the data from the Durango apatites (Roeder et al., 1987).

One apatite crystal from the iron ore deposit on Hormoz Island in the Persian Gulf, which seems to belong to the same mineralising event as of the Bafq iron ores (Daliran, 1990), was also analysed for REE (Table 2).

REE Chemistry and Distribution

Apatites from both the apatite-magnetite ores and in the "apatitites" in the Bafq district have similar compositions. Both are enriched in REE, in equal amounts, while the content of the other trace elements is not significant.

Apatites from the Mishdovan iron ores have the highest REE concentrations (1.75 wt% REE), while those from the Chahgaz ore contain the lowest (0.76 wt% REE). A line-scan of an optically zoned apatite crystal from Mishdovan also showed REE chemical zoning.

Bafq apatites have approximately equal concentrations of La and Nd, the former being slightly enriched, while La concentrations are 3 times those of Y. The degree of LREE enrichment relative to HREE, represented by the Ce/Y ratio, varies between 5.5 to 8.5 and indicates the relative compositional homogeneity of the Bafq apatites. There is a positive correlation between the total content of REE and the Ce/Y ratio. La/Nd is even more uniform and fluctuates around 1.

The chondrite-normalised REE patterns of the Bafq apatites (ICPM data) are represented in Figure 9. The patterns evidently all follow the same path, which is marked by a steep slope with LREE enrichment and a pronounced negative Eu anomaly. A slight positive Ce anomaly can also be seen in all of the analysed Bafq apatites. Figure 10 shows an identical pattern obtained for the Bafq apatites using the analytic data of NISCO (1980).

Other Elements

The content of other trace elements is typically low. The apatites contain consistently low amounts of Sr, averaging 300-400 ppm, and only a few ppm Rb. Th concentrations are around 100 ppm, and U is close to the limit of detection. Pb could not be detected. Significant amounts of As (110-345 ppm) were measured in all samples, and may be indicative of their source.

The fluorine content of most analysed apatites is around 1.8 wt %, while chlorine is around 0.6 wt %. Carbon dioxide and water were not determined by EMPA, although the infra-red spectrographic examination of the apatite from the hematite ore of Mishdovan, showed OH-F absorption bands. The lattice constants for the Bafq apatites and the fluor-apatite samples from Durango (Mexico) were calculated and are listed together with ICDD data for F-, Cl- and (OH)-apatites in Table 4 for comparison. It is emphasised that it has not been possible to distinguish between a F- or a Cl- variety of the REE-bearing apatites, because of the composite substitutions, which cause incalculable changes in the X-ray data of the end-member apatites.

Chemistry of Associated Minerals

The EMPA survey of associated minerals showed that apart from the typical REE minerals, monazite and allanite, no REE could be detected. Other relevant trace elements, such as Th, U, Sr or F and Cl, could not be detected either.

Monazite and allanite exhibit a strong LREE enrichment, similar to the apatites, with Ce, La, Nd selectivity, and Y deficiency. A zoned allanite crystal displayed REE zoning with Ce-La enrichment from the core to the rim, controlled by Ca depletion.

The pyroxene is a Ca-rich diopside. Diopside grains contain almost 1 to 2 wt% Na, whereas the amphiboles, particularly the obviously newly formed hornblendes, contain no Na. Actinolite formed from the alteration of pyroxene is impoverished in Ca and enriched in Mg, whereas its Fe remains almost constant. Garnet is a Ca- and Fe-rich andradite variety, and is Al poor. The carbonate matrix was identified as calcite with minor amounts of Fe, Mg and Mn, but without the conspicuous chemistry that characterises carbonatite calcites.

Genetic Discussion

The long-standing debate on the genesis of the Kiruna-type apatite-magnetite ores was based primarily on the ore liquid magma model introduced by Geijer, who published several manuscripts on the Swedish Kiruna ores. This genetic concept, which was applied to the majority of the Kiruna-type ores (Geijer & Ödeman, 1974, Frietsch, 1984; Wright, 1986; Lyons, 1988; Nyström & Henriquez, 1994) was challenged by Parak (eg., 1973, 1975) who contended they were not magmatic, but rather exhalative-sedimentary.

In the Bafq district, the field relationships between the iron ores and the "apatitite" rocks, combined with their petrographic and mineralogical characteristics, provide strong evidence for a common source for both types of occurrence. The mode of emplacement of the iron ore deposits, however, is varied. Fundamental aspects such as syn-sedimentary structures within the ore which are in continuity with the host rock in one group of deposits (eg., Mishdovan), provide sufficient evidence to suggest that iron ore was deposited in a sedimentary environment. Growth of the megacrysts of apatite in this same group of deposits by sedimentary processes however is still ambiguous. Conversely however, there is a lack of sedimentary features in the other group of deposits, which have been assigned a metasomatic origin. A model must therefore be defined that

Table 1: Average composition (wt%) of Bafq apatites (EMPA)

Deposit	Esfordy		Chahgas	Chogart	Mishdovan	
			Apatite-Pyroxenite	Apatite-Carbonate		
Sample	Apatite-Pyroxenite				Apatite-Magnetite	
Na_2O	0.31	0.34	0.38	0.37	0.60	0.61
MgO	0.05	0.05	0.05	0.07	0.06	0.06
SiO_2	0.25	0.26	0.21	0.29	0.27	0.25
P_2O_5	41.51	41.65	41.76	41.63	41.25	41.11
CaO	53.07	53.10	52.98	52.75	52.10	51.80
MnO	0.03	0.05	0.04	0.04	0.03	0.04
Fe_2O_3	0.08	0.09	0.05	0.07	0.05	0.07
La_2O_3	0.50	0.52	0.32	0.62	0.55	0.56
Ce_2O_3	0.95	1.16	0.84	1.26	1.21	1.32
Pr_2O_3	0.25	0.22	0.19	0.20	0.22	0.23
Nd_2O_3	0.46	0.47	0.41	0.51	0.50	0.62
Sm_2O_3	0.08	0.12	0.07	0.07	0.11	0.16
Eu_2O_3	0.00	0.08	0.03	0.00	0.07	0.07
F	1.84	1.87	1.85	1.85	1.80	1.82
Cl	0.67	0.63	0.76	0.54	0.68	0.67
Total	100.05	100.61	99.94	100.27	99.50	99.39

H_2O and CO_2 were not analysed

Table 2: REE analyses (ppm) of apatites (ICP-MS)

Deposit	Mishdovan	Chahgaz		Hormoz	Durango		Kiruna
	Apatite-Magnetite	Apatite-Magnetite	Apatite-Pyroxenite	Apatite-Hematite			
Sample					1	2	R17493
La	3175	1310	2400	2050	2995	3460	681
Ce	8570	3590	6770	3825	3825	4180	1740
Pr	934	417	769	415	304	334	220
Nd	3285	1470	2840	1520	945	1010	873
Sm	459	241	406	277	117	122	161
Eu	32	16	27	24	14	14	24
Gd	492	253	432	311	143	160	178
Tb	52	29	49	42	13	16	22
Dy	266	136	245	235	65	70	121
Ho	48	25	44	48	12	14	24
Er	138	66	127	138	34	37	67
Tm	17	7	16	18	4	5	8
Yb	100	39	93	97	24	26	49
Lu	13	5	12	12	3	4	7
Σ REE	*17581*	*7604*	*14230*	*9012*	*8498*	*9452*	*4175*

Table 3: Trace element analyses (ppm) of apatites (PIXE)

Deposit	Mishdovan			Esfordy		Chahgaz	Chogart	Zarigan	Durango
						Apatite-Pyroxenite	Apatite-Carbonate	Apatite-Carbonate-Pyroxenite	Apatite-Magnetite
Sample	Apatite-Magnetite			Apatite-Pyroxenite					
Mn	79	86	122	112	94	239	115	135	85
Fe	690	757	730	758	742	755	684	586	298
Ni	nd	nd	nd	nd	nd	nd	nd	nd	nd
Cu	nd	nd	nd	nd	nd	nd	nd	nd	nd
Zn	7	10	9	11	6	16	8	15	4
As	345	310	325	340	112	244	213	126	517
Rb	3	1	3	5	nd	3	3	3	6
Sr	363	385	275	360	420	315	349	283	332
Y	1590	1589	1113	1224	1570	1164	1315	1210	292
La	4380	4130	3934	3930	4170	2420	4150	2080	2969
Ce	11390	10575	9740	9030	9470	6680	9630	5800	3580
Pr	1080	958	802	767	933	645	859	638	230
Nd	4290	4020	3560	3240	3585	2850	3670	2640	889
Sm	735	706	463	577	684	558	584	385	100
Eu*									
Gd	512	472	279	424	522	420	368	273	nd
Tb*									
Dy	263	262	230	256	255	231	245	203	nd
Ho	nd	nd	nd	nd	nd	nd	nd	nd	14
Er	149	149	108	141	155	119	138	119	30
Tm	nd	nd	nd	nd	nd	nd	nd	nd	nd
Yb	103	109	65	91	100	70	79	80	15
Lu	nd	nd	nd	nd	7	nd	nd	nd	10
Pb	nd	nd	nd	nd	nd	nd	nd	nd	nd
Th	88	83	63	111	130	51	83	44	115
U	nd	nd	11	11	8	nd	nd	nd	nd
Σ La-Lu	22902	21381	19181	18456	19881	13993	19723	12218	7837

nd = not detected, * = values not reliable due to interferences
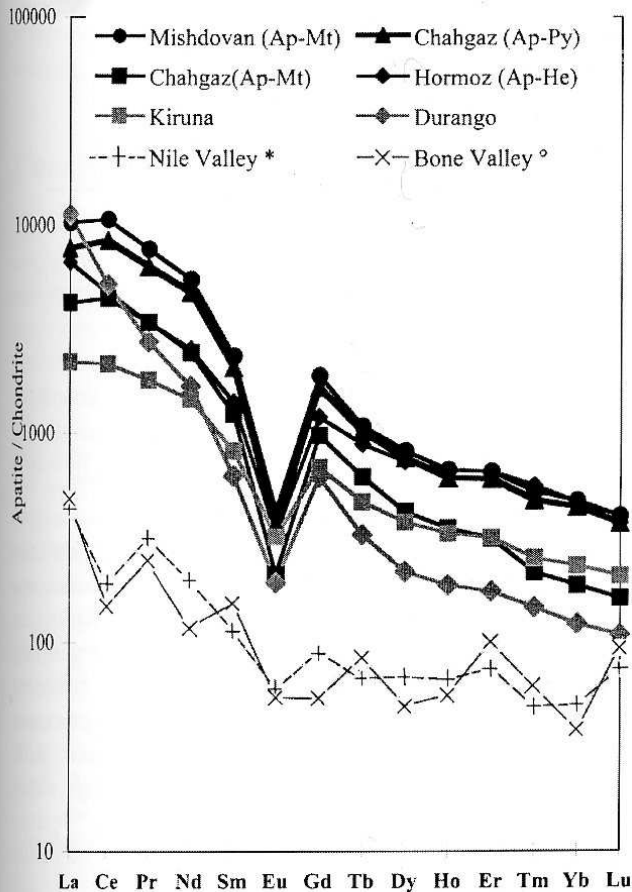
Figure 9: Chondrite-normalised REE patterns of Bafq apatites compared to apatites from Kiruna and Durango (Table 2) and sedimentary phosphorites (* El Kammer et al., 1979; ° Altschuler et al., 1976).

Figure 10: Chondrite-normalised REE patterns of Bafq apatites after analytic data of NISCO (1980).

is able to explain the mode of emplacement of these two different style of mineralisation in the Bafq district.

Comparative Occurrences

REE concentrations and their pattern of distribution can be used as petrological tracers for the classification of the apatites. Roeder et al. (1987) showed that apatites of carbonatitic affinity, commonly exhibit high total REE contents, strong LREE enrichment, and low Y/REE ratios. A similar behaviour was revealed by the study of several other occurrences as compiled in Fleischer & Altschuler (1986), who stated that apatites associated with iron ores resemble those of carbonatites, alkalic ultramafic, and ultramafic rocks. Differing REE patterns are rarely noted. For example Campbell and Henderson (1997), reported a flat, MREE (Mid Rare Earth Element)-enriched chondrite-normalised pattern in apatites with a probable, carbonatitic origin.

For a genetic classification of the Bafq apatites three classes of apatite occurrences can be considered:

1 Iron Ores

Apatite-iron ores comprising both the low-Ti Kiruna-type and the high-Ti iron ores (nelsonites) commonly have REE contents ranging from some tenths of a percent, up to 10
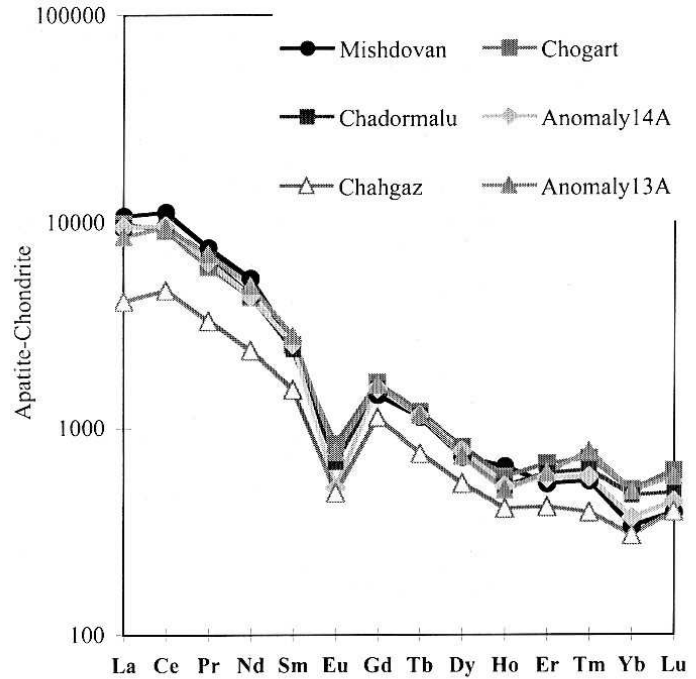
wt%. The chondrite-normalised distribution patterns for the apatites associated with these two groups of iron ores are similar and show enrichment in LREE and a negative Eu anomaly (Kolker, 1982; Landa et al., 1983; Van Marcke de Lummen, 1985; Roeder et al., 1987; Barker, 1995; Frietsch & Perdhal, 1995), as in the Bafq apatites. Frietsch & Perdhal (1995) reported an exception within the Kiruna-type iron ores from the Avnik apatite-magnetite deposit in Turkey, which differs in that it lacks LREE fractionation.

Rare earth concentrations within apatites from Kiruna and Durango (see Tables 2 & 3) are one half to a quarter of that of most of the Bafq apatites. Their chondrite-normalised pattern, however, is similar to the Bafq apatites. The slightly positive, higher Ce anomaly of the Bafq apatites exists also in Kiruna apatite, but is absent in those from Durango(see Fig. 9).

There are many factors which influence the distribution of REE in a mineral. These include ionic radius, ionic charge, temperature, pressure and composition of a system and the fO_2 (Henderson, 1996; Roeder, et. al., 1987). The oxidation states of the Eu and Ce also effect their geochemical behaviour. A common explanation for the negative Eu anomaly in many igneous rocks is its removal by the partitioning of Eu^{2+} in early fractionated plagioclase, as has been assumed for the negative Eu-anomaly associated with Kiruna-type apatites eg., Oyarzun (1985) and Frietsch & Perdhal (1995). Since the genetic relationship between the apatite-bearing rocks and the host rhyolites in the Bafq district is not documented, the explanation for the negative Eu-anomaly within the Bafq apatites remains unclear.

The Bafq apatites crystallised in two stages (ap_1 and ap_2), both of which are enriched in LREE. In addition, the presence of the Ce-rich minerals monazite and allanite, rather than any other HREE mineral, obviously indicates

Table 4: Cell parameters of Bafq apatites, compared to the apatites of different compositions

Cell Parameter	Mishdovan	Esfordy	Chahgaz	Durango	F-Apatite (ICDD)	Cl-Apatite (ICDD)	OH-Apatite (ICDD)
a	9.413	9.410	9.412	9.437	9.358	9.641	9.418
c	6.876	6.880	6.875	6.879	6.884	6.771	6.884

the availability of a Ce-rich source reservoir, rather than any fractionation process occurring during crystallisation. Gerasimovskiy & Mineyev (1981) noticed that, in the presence of other REE minerals, apatite had lower REE concentrations. There is some doubt over this statement however, since the bulk of the apatite (ap_1) crystallised prior to the other REE minerals allanite and monazite. Consequently, it's chemistry could not be influenced by the incorporation of one or another element into these minerals. Furthermore, even in the presence of abundant monazite and allanite the apatites of these samples were among the most REE-rich encountered. Differences in the REE content of the apatites from various localities seems to be unrelated to the type of provenance (apatite-iron oxide ore or "apatitites"), and reflect the REE concentration of the local reservoirs.

2 Carbonatites

The apatite-bearing rocks of Bafq show some striking geological, mineralogical, petrographic and geochemical similarities with carbonatite occurrences worldwide (Anderson, 1986; 1987; Woolley & Kempe, 1989; Bailey, 1993; Morteani & Preinfalk, 1996; Wall & Mariano, 1996; Nothholt, 1997). The apatite-carbonatites containing monazite at Kangankunde, Malawi, described by Wall & Mariano (1996), show some striking similarities in their petrographic features to the Chogart "apatitites". Pecora (1956) recognised the apatite-magnetite ores as one of the carbonatite varieties. These apatite-magnetite occurrences have been variously termed phoscorite (foskorite) or camphorite, particularly by geologists of the Soviet school (Russel et al., 1954; Borodin et al., 1973; Zhuravleva et al., 1976; Landa et al., 1983; Sokolov, 1983).
In carbonatite systems, apatites are generally enriched in REE and may contain up to several per cent. As apatite can crystallise at different stages in the development of a carbonatite system, its REE content may be variable within the same occurrence (Anderson, 1986, 1987; Roeder et al., 1987; Hogarth, 1989; Morteani & Preinfalk, 1996; Wall & Mariano, 1996). Apatite that occurs in carbonatite rocks is commonly enriched in LREE. However, where the complete REE spectrum was available (Anderson, 1986, 1987; Roeder et al., 1987; Hogarth, 1989; Mariano, 1989; Morteani & Preinfalk, 1996; Wall & Mariano, 1996; Wu et al., 1996), they do not reveal the same negative Eu anomaly observed in Bafq apatites.

Carbonates of carbonatitic affinity also generally contain variable concentrations of REE (Anderson, 1986, Morteani & Preinfalk, 1996). The calcite from the "apatitite" rocks

of Bafq region however, did not reveal any REE concentrations. This might be due to their incorporation in the earlier formed REE-bearing minerals apatite, monazite and allanite.

The tendency for the REE minerals of the Bafq district to form in the final stages of the paragenetic sequence has also been noted in these carbonatite occurrences. Hydrothermal or volatile fluid systems which generate carbonatites have been documented from different examples around the world and confirm that such processes are predominantly responsible for the formation of REE minerals (Anderson, 1986, 1987; Bailey, 1993; Gieré, 1996; Wall & Mariano, 1996). A kind of "filter-press" texture observed in the Bafq "apatitites" may be explained by the observation of Bailey (1993) who described similar features from carbonatite intrusions that he assumes to have been formed by the emplacement of a near-solidus "mush", with interstitial fluid metasomatising the country rocks. Oscillatory growth zoning of apatite samples observed from Mishdovan most probably reflect fluctuations in the composition of the fluids as argued by Gieré (1996) and not by crystallisation from a melt.

The Mishdovan deposit exhibits apparent sedimentary features, but also some mineralogical and geochemical affinities with the carbonatite-related apatite-magnetite and REE mineralisation described at Bayan Obo (Wu et al., 1996; Campbell & Henderson, 1997) and Olympic Dam (Oreskes & Enaudi, 1990; Hitzman et al., 1992).

The evolutionary history of the Bafq district and the timing of the different styles of mineralisation developed in the district (Fe-REE, Th-U, Pb-Zn, Cu-(Au?)) are obviously complex and have not yet been systematically studied. A rift-related mineralising system is nevertheless accepted by some workers (eg., Haghipour, 1974; NISCO, 1980; Daliran, 1990) and by Samani (1993, 1998), who postulated the generation of carbonatite magma in relation to the rifting.

3 Marine Apatites

Parak (1973) postulated that the distribution of the REE in the apatites of the Kiruna ores is similar to that found in sedimentary rocks. This statement of Parak's possibly arose from inaccurate analytical results of apatites. Marine apatites or phosphorites have REE contents which are an order of magnitude lower than Bafq apatites and their REE pattern is marked by an enrichment in Y and a Ce deficiency (see Fig. 9), which reflects the composition of the sea water (Altschuler, 1980). These geochemical particulars exclude

a marine source for both the Kiruna ores and the Bafq apatites.

Conclusions

The consistent spatial and temporal association of apatite-magnetite ores and the "apatitite" rocks in the Bafq region provides conclusive evidence that these two assemblages are cogenetic. The result of the present geochemical study, particularly the REE geochemistry of the apatites, leaves no doubt of a common source for the apatites.

At present, the author can find no conclusive evidence that the apatite-magnetite orebodies of the Bafq region were emplaced as a liquid ore magma. The apatite-iron ores of the Bafq district that were studied most likely formed from a source with a fluid-rich component. In some cases, these super-critical fluids carried early crystallised minerals (mega-crystals) to shallow levels of emplacement. The continental rift tectonic setting of the district, with its associated crustal fractures probably provided pathways from deep magmas and for the volatiles and ore fluids to reach higher crustal levels.

The deposition of the mineralising fluids within the Bafq district took place in a variety of different environments, which would explain the diversity of the mode of occurrence of the deposits:

- Fluids released into a lithified environment, mainly rhyolites and subvolcanic granites, pervasively metasomatised the host and resulted in the formation of the replacement type ores with local formation of the "apatitites". Based on the physio-chemical characteristics of a given deposit, two replacement ore types can be distinguished, namely, (1). A *high-temperature metasomatic type,* which appears to be characterised by non-hydrous silicates and enrichment in "apatitites" (eg., Chogart and Esfordy). (2). A relatively *low-temperature hydrothermal type* with extensive albitisation and hydrosilicates (actinolitisation), which is not apparently associated with "apatitites" (eg., North anomaly).

- Fluids discharged onto the basin floor during sedimentation resulted in the development of synsedimentary stratiform ore bodies. This group comprises two subtypes based on mineral assemblages. (1). *Apatite-magnetite-hematite* type (eg., Mishdovan), and (2). The *Mn-Fe-jaspilite* type (eg., Narigan).

The consistent LREE enrichment on a regional scale in the Bafq district implies a primary LREE-rich reservoir. The homogeneous source chemistry has also played a crucial role in the distribution pattern of REE in the apatites. Small differences in the REE contents of the apatites in individual deposits may have been influenced by local conditions.

The enrichment of REE in the Bafq apatites reflects some affinity with alkaline complexes and carbonatites and is similar to the global Kiruna-type ores, which implies a common genesis.

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