Ferride Geochemistry of Swedish Precambrian Iron Ores

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Chemical analysis for major and trace elements have been performed on 30 Swedish Precambrian iron ores and on some from Iran and Chile. The Swedish ores consist of apatite iron ores, quartz-banded iron ores, skarn and limestone iron ores from the two main ore districts of Sweden, the Bergslagen and the Norrbotten province. Some Swedish titaniferous iron ores were also included in the investigation. The trace element data show that the Swedish ores can be subdivided into two major groups: 1. orthomagmatic and exhalative, 2. sedimentary. Within group 1 the titaniferous iron ores are distinguished by their high Ti-contents. From the ferride contents of the Kiruna apatite iron ores, the ores are considered to be mobilization products of skarn iron ores from the Norbotten province.

1. INTRODUCTION

The Precambrian iron ores constitute one of the more complex problems regarding ore genesis. In this context, for example, the composition of the atmosphere, in addition to the geophysical properties of the earth's crust prevalent during the Archean and also the Proterozoic, are markedly different from present day conditions. It would nevertheless appear possible that there are Precambrian iron ores of sedimentary, volcano-sedimentary and pure orthomagmatic types.

To what extent is it possible to genetically characterize the Swedish Precambrian iron ores by applying trace element geochemistry? Earlier attempts to use geochemistry (e.g. Landergren, 1948; Hegemann and Albrecht, 1954; Frietsch 1970) have been restricted by analytical drawbacks regarding the determination of the trace element contents. However during the last ten years, analytical methods and instrumental accuracy and precision have improved considerably, thus allowing a high degree of reproducibility for low levels of trace element concentrations. In this respect, it is felt that a renewed geochemical investigation is worthwhile.

In this present contribution the authors, in common with earlier workers in the field (e.g. Landergren, op.cit.; Hegemann and Albrecht, op.cit.; Frietsch, op.cit.; Parak, 1975a), have used the ferride elements Ti, V, Cr, Mn, Fe and Ni present in magnetite and hematite.

2. GEOLOGICAL SETTING AND NATURE OF THE
IRON ORES

The Swedish iron ore deposits are main-
ly restricted to the Bergslagen and Norr-
botten provinces (Fig.1).

   The Bergslagen province, which appears
to have been part of a Proterozoic island
arc (Löfgren, 1979; Loberg, 1980), is
dominated by an arcuate area with gra-
nitoid intrusives. The older rock types
consist predominantly of metavolcanics
together with different varieties of

metasediments (argillaceous schists;
arenites/graywackes/ and limestone)
dated to between 2000 and 2500 My
(Lundquist, 1979). Associated with the
metavolcanics are iron ores which in-
clude apatite iron ores, quartz banded
iron ores and skarn iron ores (Lund-
quist, op.cit.; Magnusson, 1973).

   The apatite iron ores, at their
richest levels contain 56-63 % Fe. The
phosphorus content varies from 0.06 to
1.30 % P with an average of about 1.0%
P. The dominant mineral constituent is
magnetite with subordinate amounts of
hematite. Apart from the ore minerals
and apatite, there also exists quartz
and skarn minerals of which actinolite
dominates (Magnusson, 1973).

   According to Magnusson (op.cit.),
the apatite iron ores are magmatic in
origin. They exhibit features charac-
teristic of a volatile-charged magma
which has been injected into the sur-
rounding volcanics (leptites) forming
lens-shaped bodies orientated parallel
to the layering in the volcanic suite.
However, the iron ores also appear to
have cut across contacts, especially
where the ores are lensing out, where-
upon small penetrating dykes brecciate
the country rocks. In addition, parts
of the country rock are completely en-
closed by the ore. Components trans-
ported by volatiles accompanying the
magma have formed hematite and skarn
impregnations within the adjacent vol-
canic country rocks.

   The quartz iron ores of the Bergs-
lagen province contain, in general,
less than 55% Fe with a phosphorus con-
tent which ranges from 0.01 and 0.02% P
(Magnusson, op.cit.). The ores probab-
ly existed earlier as quartz banded he-
matite concentrations which have later
been metamorphosed to hematite and mag-
netite. The quartz banding seems origi-
nally to have been jaspilitic, but also
this material has been metamorphosed
resulting in recrystallised coarse
quartz with the finely disseminated
hematite altering to form dispersed
magnetite grains in the quartz fabric
(Magnusson, op.cit.).

   Even if the genetic conditions for
the formation of the quartz banded
iron ores in some respects remain an
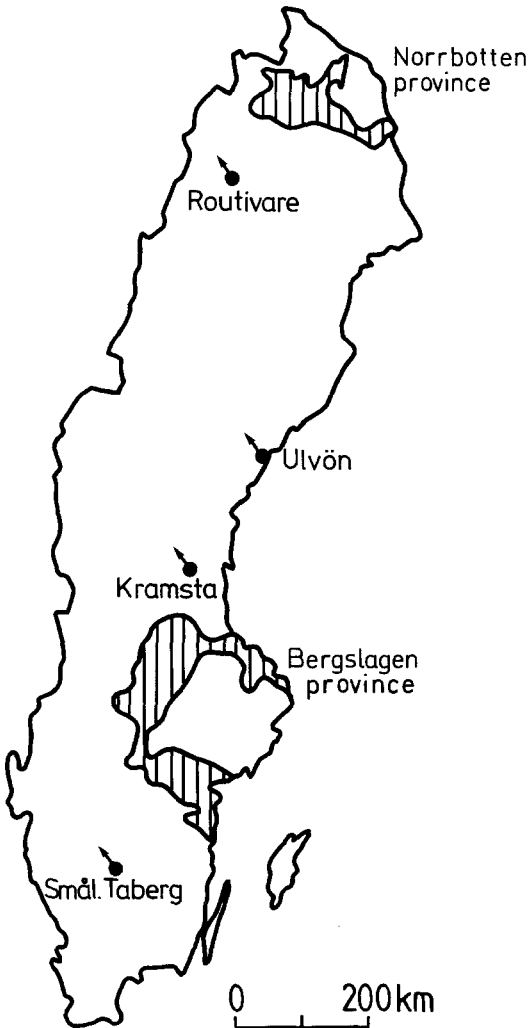enigma, the indications suggest sub-

Fig.1. Map of Sweden showing the loca-
tion of the Norrbotten and Bergslagen
iron ore districts (lined areas)

aquatic deposition (Geijer and Magnusson, 1952).

The skarn iron ores of the Bergslagen province, after Geijer and Magnusson (1944), have been subdivided into manganese-poor (< 1 % Mn) and manganese-rich (1-12 % Mn).

The manganese poor skarn iron ores are usually characterized by magnetite being irregularly distributed within the skarn rock fabric, which is comprised essentially of andradite, diopside and actinolite. Varying amounts of dolomitic limestone also occur within the skarn. There are also manganese-poor skarn iron ores which show all gradations between homogeneous and inhomogeneous magnetite distributions. It is also interesting to note that there exist transitions from skarn iron ores to lime-dolomite iron ores containing only subordinate skarn material (Magnusson, 1973). From a genetic aspect, it is noticeable that several deposits of skarn iron ores contain considerable quartz, and that one can observe in such cases transitions to quartz banded iron ores. According to Magnusson (op.cit.) the skarn iron ores, characterised by an inhomogeneous distribution of magnetite, have formed from the quartz banded ores which originally were deposited together with substantial quantities of lime and dolomitic sediments. This inhomogeneous distribution of ore minerals has thus resulted from a combination of later tectonic events and the processes eventually giving rise to the skarn development. It is clear that these skarn iron ores, together with the quartz banded iron ores, have originally been deposited as sediments (Magnusson, op.cit.).

The manganese-poor skarn – and lime dolomitic iron ores contain on average 30 % Fe with a phosphorus content varying between 0.004 and 0.08 % P (Magnusson, op.cit.).

The manganese-rich skarn ores (> 1% Mn) always occur in limestone or dolomite mainly as layered concentrations frequently exhibiting a marked schistosity. The ore mineral is magnetite with a small content of manganese. This element is mainly present within the silicate phases i.e. the skarn minerals. The most important include knebelite $(Mn,Fe)_2SiO_4$, dannemorite (Mn-rich grunerite) and ferruginous rhodonite. The carbonate gangue associated with the ore itself has often a high Mn content. For example the $MnCO_3$ content can be as high as 64 % (Magnusson op.cit.).

The iron content of the manganese-rich skarn iron ores varies between 50 % and 30 % Fe whilst the manganese content lies between 2 % and 10 % Mn within the mined ores. The phorphorus content ranges from 0.005 % to 0.01%P. There is no doubt that the manganese-rich skarn iron ores are sedimentary in origin, a fact which is further supported by the general geological environment and the layered attitude of the ores.

The Norrbotten province's Precambrian bedrock shares many similarities to the Bergslagen province, consisting of a series of supracrustal rocks and granitoid plutons (Lundqvist, op.cit.). The older supracrustal formational group (2000-2500 My) comprises a basal conglomerate overlayen by the so-called greenstone group which is composed of partly spillitised, metamorphosed basaltic pillow lavas. The greenstones are associated with subordinate amounts of tuffs as well as crystalline limestones, graphite schists and chert in addition to skarn-type iron ores and layered quartz-rich iron ores (Grip and Frietsch, 1973; Frietsch, 1980 a, b). Stratigraphically overlying this sequence are conglomerates and quartzitic layers with intercalated metaarkoses and mica schists.

To judge from radiometric measurements, there is a younger supracrustal series consisting of folded and metamorphosed rhyolitic and trachytic lavas which are spatially associated with the province's apatite rich iron ores (Lundqvist, 1979).

The apatite iron ores of the Norrbotten province have much in common with the Bergslagen province. They are comprised mainly of magnetite with subordinate hematite which is mostly a product of magnetite martitization. The apatite, mainly as fluor-apatite, can occur in such high concentrations that analysis of the ore shows 1 % to 5 % P. The main accessory minerals with-

in the ores are amphibole (tremolite-actinolite) and diopsidic pyroxene.

The apatite iron ores in the Kiruna region can be mineralogically subdivided into three groups (Frietsch, 1978).

The Kiruna ore type "sensu stricto" consists of magnetite (hematite), apatite and actinolite. The phosphorus content is less than 2 % P. Only local alteration of the contact country rock (sericitisation and silicification) occurs.

The phosphorus rich ore type is characterised by hematite (magnetite), apatite, quartz and calcite. The phosphorus content is 2 % to 5 % P and alteration of the contact country rock is common.

The Hauki ore type comprises hematite, quartz (sericite, calcite, barytes) and has formed as impregnations as well as minor dyke-like features. The contact country rocks are extensively altered.

Regarding the genetic relationships of the Kiruna ores, there have been conflicting theories for more than 100 years since the State Commission first visited the Kiruna region in 1875 (Geijer, 1910). The Commission considered that the ores where sedimentary in origin occurring as layers within a sedimentary-derived country rock. The genetical interpretations which have been advanced during the last 100 years have concentrated around two main alternatives, namely an orthomagmatic (ore magma) and a sedimentary exhalative origin.

The orthomagmatic interpretation has been upheld by Geijer (1910; 1931; 1935), Vogt (1927), Asklund (1949), Bateman (1951) and Frietsch (1966; 1973; 1978; 1980) whilst the sedimentary exhalative process has found support from, amongst others, Bäckström (1904), Hegemann and Albrecht (1954), Oelsner (1961) and Parak (1975 a, b). In contrast Landergren (1948) chose a compromise position, preferring to explain the ores as the products of an ore magma which formed through the melting of iron concentrations of sedimentary origin.

The skarn iron ores within the Norrbotten province, in contrast to the apatite iron ores are associated with sedimentary products i.e. clastic and chemical sediments of the greenstone group and believed to be of volcanosedimentary origin (Grip and Frietsch,1973). The skarn iron ores form tabular-shaped bodies which laterally merge with the layering in the surrounding sedimentary rocks. Furthermore the ores are often associated with carbonate and marlstones or found within the same stratigraphic position. It is very probable that the skarn iron ores have originally been in the form of sediments rich in iron, silica and carbonate which, through metamorphic processes, have achieved their present mineralogical composition (Frietsch, 1973; 1980).

The dominant ore phase is magnetite with subordinate amounts of hematite. The iron content varies between 30 % – 40 % Fe and the sulphide content, due to significant amounts of pyrite and pyrrhotite, commonly exceeds 1 % S, a feature which distinguishes these ores from the Bergslagen skarn iron ores. The phosphorus content is usually below 0.1 % P whilst the manganese content is normally less than 0.2 % Mn. The ore is usually accompanied by large amounts of skarn minerals such as tremolite-actinolite, diopside, hornblende, phlogopite-biotite, olivine, serpentine, talc and chlorite (Frietsch, 1980).

The layered quartz-rich iron ores within the Norrbotten province are similar to the skarn iron ores in that they belong to rocks of the greenstone group. They can be regarded as a type of quartzite in which magnetite and the skarn minerals occur distributed in such a way that it gives the quartzite a more or less distinct layering. Because of the ores occurrence and close association with basaltic eruptives (the greenstones), a volcano-sedimentary origin has also been assumed for the layered quartz-rich ores (Frietsch, 1977). These, which through their stratiform character have a considerable planar extension, are never-the-less small, reaching only some tens of metres in thickness. The iron content is low, mostly less than 20 % Fe. The most common skarn minerals are cummingtonite-grunerite, clinoenstatite, hypersthene, hornblende and almandine garnet. Minor amounts of sulphide minerals (pyrite and pyrrhotite) also occur resulting in a sulphur content of a few percent.

The phosphorus content is less than
0.1 % P and even the manganese content
is low although this can increase to
a couple of percent in certain deposits
(Frietsch, 1973; 1980).

The titaniferous iron ores in Sweden
are not confined to any particular pro-
vince. Not many deposits exist (Fig.1)
and those which do tend to be relative-
ly small and are associated with mag-
matically-formed rocks such as gabbro,
norite or anorthosite. The ore minerals
consist of magnetite and ilmenite which
usually exhibit intimate intergrowth
textures. The iron content of the ores
varies between 25 % - 40 % Fe whilst
the titanium content (5 % - 10 % Ti) and
vanadium (0.1 % - 0.3 % V) are relative-
ly low (Frietsch, 1975).

3. THE FERRIDE CONTENT OF MAGNETITE AND HEMATITE

The ferride elements are present both
in magnetite and hematite (Hegemann
and Albrecht, 1954; Frietsch, 1970;
Annersten and Ekström, 1971; Parak,
1975a). They belong to the transition
elements in the fourth period. Because
of similarities in chemical character
and atomic radii, these elements are
capable of substituting for each other
within the crystal structure of mag-
netite and hematite.

Another consequence of the ferrides
mutual chemical compatibility is that
they, during the mineral forming pro-
cesses here under discussion, do not
preferentially undergo any chemical
separation (Kisvarsanyi and Proctor,
1967), with the exception of manganese
which is more mobile due to its vari-
able valency state. Nevertheless, mag-
netite and hematite belonging to ores
of different genetic origins reflect
different ferride distributions (Hege-
mann and Albrecht, 1954). There has
also been shown to be different ferrid
distributions in magnetite and hema-
tite from the same ore (Annersten and
Ekström, 1971; Parak, 1975 a).

4. SAMPLE PREPARATION AND ANALYTICAL PROCEDURE

The analysed material has involved
iron ores from the Bergslagen and Nor-

botten provinces and also from Smålands
Taberg. Additional samples have been
analysed from El Laco (Chile) and the
Bafq province in Iran. Samples have
included both handspecimens collected
in the field and portions of drillcores.
Details of the Swedish deposits examin-
ed are presented in tables I and II.

The samples were crushed using a
plattner mortar, secondly the contamin-
ating fragments were removed under the
binocular microscope, and finally the
rest was finely crushed using an agate
mortar. An attempt has been made to
separate the magnetite and hematite
from the ore by means of magnete and
heavy liquids. However, the results
have only been successful in a few
cases (see Table 3) and therefore the
investigation has been wholly based
on the total analysis of the ores.

Treatment of the crushed material
for chemical analysis has involved
fusion with lithium metaborate for Si
analysis and dissolution using HF and
$HClO_4$ for the remaining elements. The
ore material has been analysed for the
major elements Si, Ti, Al, Fe, Mn, Mg,
Ca, K and Na in addition to the trace
elements V, Cr and Ni. Co has not been
included because of instrumental inter-
ference.

The analyses have been carried out
using an optical emission spectrograph
(ARL 33 000) fitted with an inductive
coupled plasma (Burman et al.,1977).
Precision lies around 1-2 % relative
error for the major elements and about
10 % for V, Ni and Cr (Burman, et al.,
1978; Burman et al., 1979). These re-
lative errors are commonly less than
those obtained with the XRF which is
often used for trace element analysis.
Comparison with standard rocks includ-
ed during analysis shows that the ab-
solute values obtained are of good
quality (Burman et al.,op.cit.).

5. RESULTS OF THE ANALYSIS

The ferride trace element contents of
the ores (Table 1) have initially been
correlated in pairs, thus the distri-
bution relationships between Ni-Cr,
V-Cr, V-Ni, V-Ti, Ni-Ti and Cr-Ti have

Table 1. Chemical analyses of Swedish iron ores

No	Mine	Ore type (ore minerals)	% SiO2	% Al	% Ti	% Fe	% Mn	% Na	% K	% Ca	% Mg	% P	ppm Cr	ppm Ni	ppm V
2	Svappavaara	aio (hem)	1.4	0.06	0.05	60.1	<0.02	<0.03	<0.01	1.62	<0.09	1.32	12	38	312
3	Leveäniemi	aio (mag)	1.8	0.57	0.24	68.3	0.08	<0.03	0.02	<0.02	0.16	0.04	13	262	2230
4	Tuolluvaara	aio (mag)	0.5	0.09	0.09	70.7	0.06	<0.03	0.03	0.05	0.26	0.04	14	234	470
5	Kiirunavaara	aio (mag)	0.8	0.13	0.04	21.0	0.05	0.07	<0.01	25.5	<0.09	18.5	71	93	481
7	Malmberget	aio (mag)	30.8	2.40	0.22	34.4	0.05	1.80	0.64	3.32	3.00	0.20	18	90	496
17	Vintjärn	lio+sio (mag)	28.0	0.44	0.06	54.5	0.85	0.03	0.27	0.29	2.28	0.07	18	24	35
23	Lernbo (Norberg)	lio+sio (hem)	38.9	0.47	<0.03	18.7	0.04	0.17	<0.01	7.82	7.43	0.04	21	20	25
25	Grängesberg	aio (mag)	10.3	0.74	0.31	22.0	0.10	0.04	0.02	19.2	0.60	12.8	183	89	1170
26	Lönnfallet	aio (mag)	4.3	0.41	0.07	56.9	0.03	0.06	0.22	2.70	0.51	1.06	24	88	2310
30	Nordmark	lio+sio (mag)	9.5	0.35	0.05	57.3	0.30	0.03	0.01	1.52	1.87	0.02	12	22	33
31	Persberg	lio+sio (mag)	2.0	0.83	0.05	64.0	0.04	0.05	0.12	0.02	0.98	0.03	14	29	42
32	Herrgårdshagen	lio+qio (hem)	8.4	0.35	<0.03	28.2	0.33	0.04	0.18	17.6	0.11	0.09	39	26	45
34	Stripa	qio (hem)	11.0	0.08	0.03	54.0	0.03	<0.03	<0.01	0.27	<0.09	0.04	11	21	37
35	Striberg	qio (hem)	50.4	0.14	<0.03	27.4	<0.02	0.07	0.02	0.02	<0.09	0.03	9	14	20
38	Utö	qio (hem)	20.9	0.20	0.03	47.1	0.17	0.04	0.05	1.93	0.55	0.03	22	22	37
77	Smålands Taberg	tio (mag)	21.5	1.85	4.80	31.5	0.25	0.28	0.07	0.35	9.53	0.04	36	254	2110
78	Smålands Taberg	tio (mag)	30.9	3.01	4.03	28.0	0.24	0.69	0.12	1.34	8.68	0.04	20	157	1630
79	Långvik (Garpenberg)	Mn-sio (mag)	12.6	0.17	0.04	39.8	1.94	<0.03	0.03	1.16	0.82	0.03	7	16	22
80	Långvik (Garpenberg)	Mn-sio (mag)	6.3	0.12	<0.03	32.3	5.51	<0.03	0.02	6.64	2.41	0.07	10	13	22

aio = apatite iron ore   hem = hematite

lio = limestone iron ore   mag = magnetite

qio = quartz-banded iron ore

sio = skarn iron ore

tio = titaniferous iron ore

Mn-sio = Mn-rich skarn iron ore

been investigated. A distinct separation of the different ore type groupings has been obtained using the V-Ti ratios. For example Fig.2 shows that the higher V content of the apatite iron ores (V > 100 ppm) clearly distinguishes this group from the banded iron ores (BIF) together with the other related sedimentary-derived ore types. In contrast, the titaniferous ores differ because of their high titanium contents (Ti > 10 000 ppm) which is distinct from the other two groups.

The V-Ni ratios indicate a less convincing subdivision of the ore types (Fig.3) in that the apatite iron ores and the titaniferous iron ores plot within the same field. However, if one also takes into consideration the Ti-content, which is plotted in Fig.4, similar groupings to those shown in Fig.2 are obtained although not so distinct.

Unfortunately there are no analysis available for the skarn iron ores and the quartz-rich iron ores from the Norrbotten province area. To compensate for this discrepancy the published results of Frietsch (1970) have been used. From these results (Fig.5, 6) it can be seen that the V-Ti ratios are dispersed within both the fields of the apatite iron ores and the BIF ores.

With reference to the continuing debate on the genetical background of the Kiruna iron ores, several samples from the Kiruna region have also
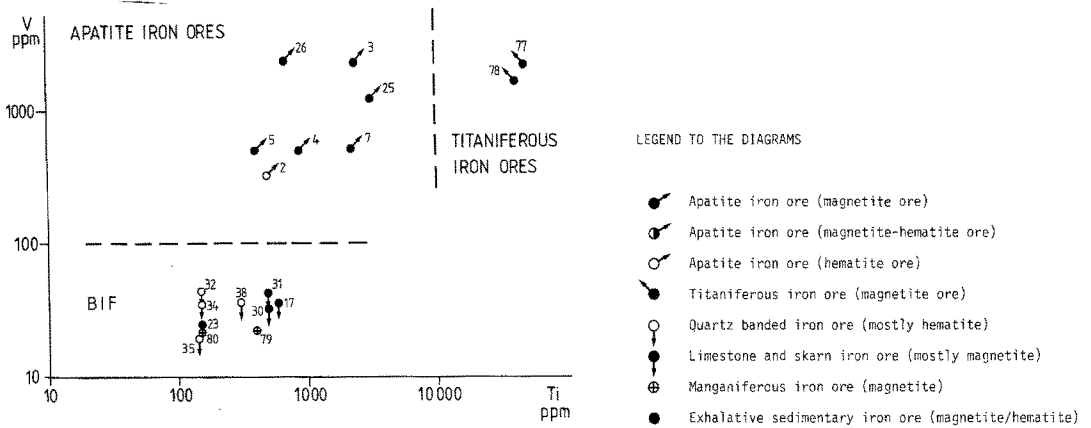
Fig.2. The V/Ti ratio distributions within the Swedish iron ores. The numbers in the figure correspond to the following deposits: 2 Svappavaara, 3 Leveäniemi, 4 Tuolluvaara, 5 Kiirunavaara, 7 Malmberget, 17 Vintjärn, 23 Lernbo (Norberg), 25 Grängesberg, 26 Lönnfallet, 30 Nordmark, 31 Persberg, 32 Herrgårdshagen, 34 Stripa, 35 Striberg, 38 Utö, 77 Små lands Taberg, 78 Smålands Taberg, 79 Långvik (Garpenberg), 80 Långvik (Garpenberg): Numbers 2-7 are from the Norrbotten province; 17-38 from the Bergslagen province; 77-80 from southern Sweden excluding the Bergslagen iron ore province sensu stricto
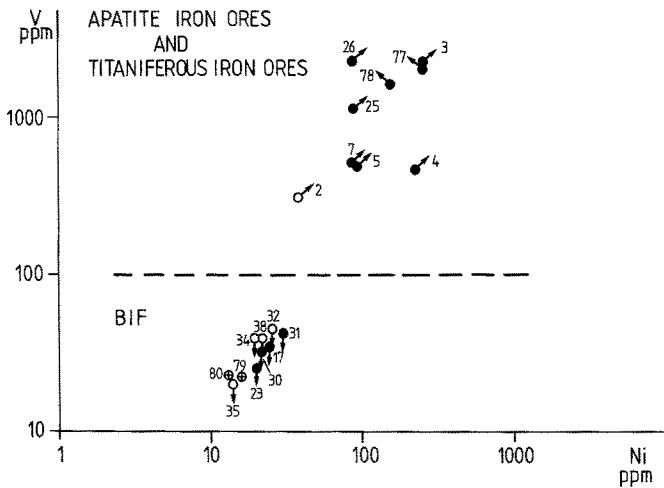
Fig.3. The V/Ni ratio distribution within the Swedish iron ores. For sample number locations see Fig.2

been analysed (Table 2) with the possibility in mind of using the ferride contents to help elucidate the question of genesis of these special ore types. Fig.7 shows that all ore samples from the Kiruna region, regard-less to being magnetite or hematite ores, plot within the field for apatite iron ores (compare Fig.2).

One complicating factor encountered during sample preparation has been the incomplete separation of the iron oxide
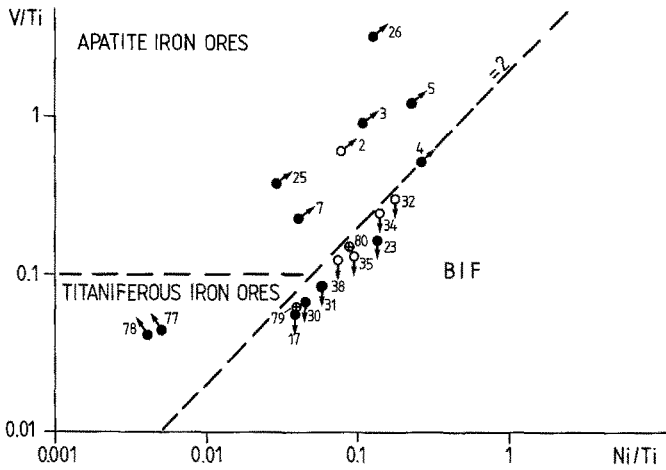
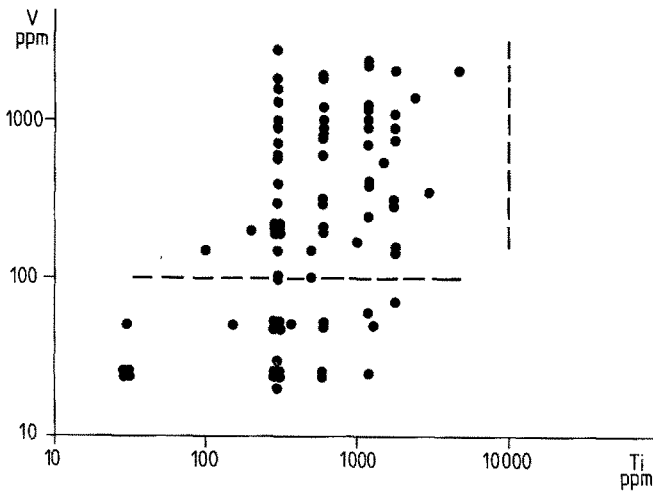Fig.4. The V/Ti-Ni/Ti ratio distributions within the Swedish iron ores. For sample number locations see Fig.2

Fig.5. The V/Ti ratio distribution within the skarn iron ores from the Norbotten province. Analytical values are from Frietsch (1970). Diagram subdivisions as for Fig.2

phases from the silicate phases. One has therefore to be aware of the possible diluting effect of the trace element (ferride) analysis due to the introduction of contaminating silicates. For this reason the distribution ratios V/Fe and Ti/Fe have been studied, as the ferrides for the most part are concentrated within magnetite and hematite. The corresponding diagram (Fig.8) essentially shows the same distinction between the three different ore types as illustrated by Fig.2.

Another approach to test the consequences of silicate contamination is that if the separation of the iron oxide phases has been successful, then it should be possible to compare the ferride contents of the iron oxides with those of the corresponding ore. This is illustrated in Table 3 and Fig.9 which show, with one exception,
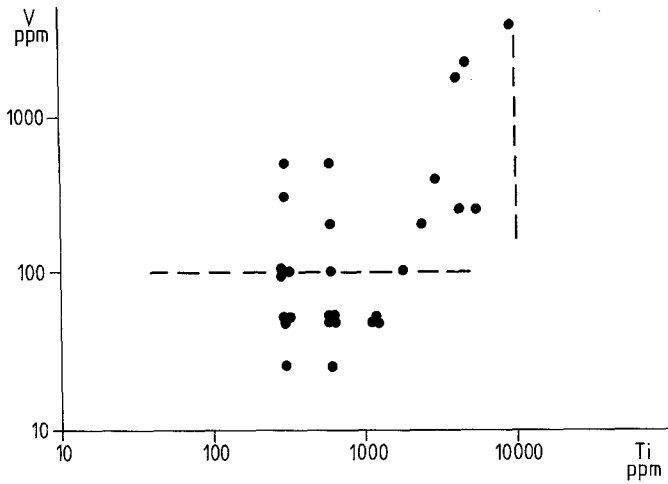
Fig.6. The V/Ti ratio distribution within the quartz iron ores from the Norbotten province. Analytical values are from Frietsch (1970). Diagram subdivisions as for Fig.2
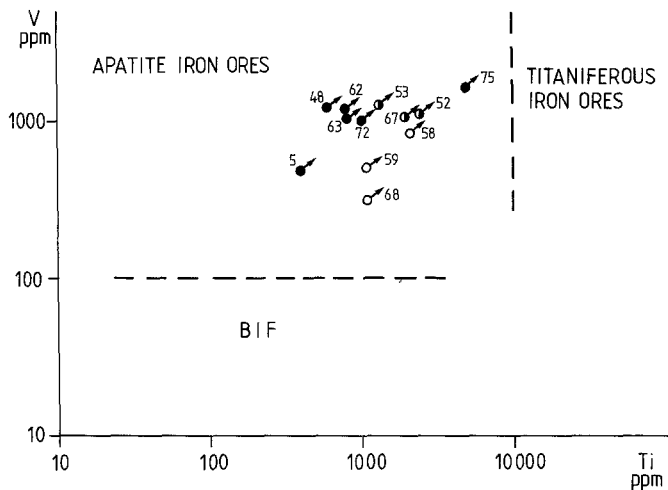

Fig.7. The V/Ti ratio distribution within the apatite iron ores from the Kiruna district. Diagram subdivision as for Fig.2; the sample numbers refer to the following deposits: 5 Kiirunavaara, 48 Kiirunavaara, 52 Rektorn, 53 Rektorn, 58 Haukivaara, 59 Lappmalmen, 62 Kiirunavaara, 63 Kiirunavaara, 67 Nukutusvaara, 68 Nukutusvaara, 72 Kiirunavaara, 75 Kiirunavaara

that the iron oxide concentrate has a higher vanadium content than the corresponding ore, which can be considered due to a diluting effect of the ore by the non-iron oxide minerals.

Regarding the titanium contents of the ores and the corresponding iron oxide concentrates, two of the six ores investigated have a lower titanium content than the concentrate. This means that a percentage of the titanium present in some ores is contained within phases other than those of the iron oxides. However, Fig.9 shows

Table 2. Chemical analyses of apatite iron ores from the Kiruna District

No	Mine	Ore minerals	SiO$_2$ %	Al %	Ti %	Fe %	Mn %	Na %	K %	Ca %	Mg %	P %	Cr ppm	Ni ppm	V ppm
48	Kiirunavaara	mag	6.4	0.1	0.06	52.6	0.11	<0.04	0.07	4.6	1.6	2.90	30	195	1230
52	Rektorn	mag/hem	5.0	0.9	0.24	47.0	0.03	0.20	0.66	6.4	0.5	5.05	42	147	1010
53	Rektorn	mag/hem	1.8	0.1	0.13	56.1	0.03	0.05	0.07	4.7	<0.09	3.25	53	216	1270
58	Haukivaara	hem	1.8	0.5	0.21	51.3	0.02	<0.05	0.36	6.3	<0.09	5.05	39	41	853
59	Lappmalmen	hem	2.4	0.4	0.11	61.6	0.03	<0.05	0.34	0.7	<0.09	1.10	23	54	500
62	Kiirunavaara	mag	1.1	0.1	0.08	63.1	0.08	<0.05	0.17	0.1	0.2	0.02	14	186	1140
63	Kiirunavaara	mag	2.1	0.1	0.08	61.2	0.10	<0.05	0.02	2.5	0.3	0.70	17	177	1080
67	Nukutus	hem/mag	<0.5	0.2	0.19	51.5	0.03	0.4	0.06	6.4	0.2	5.70	27	130	1050
68	Nukutus	hem	5.5	1.3	0.11	17.0	<0.02	0.4	1.16	20.4	1.2	14.1	46	137	317
72	Kiirunavaara	mag	6.4	0.6	0.10	50.6	0.05	0.2	0.75	4.8	0.8	3.40	34	160	1010
75	Kiirunavaara	mag	1.2	0.1	0.50	64.0	0.06	0.06	0.14	0.2	n.d.	0.03	15	52	1650

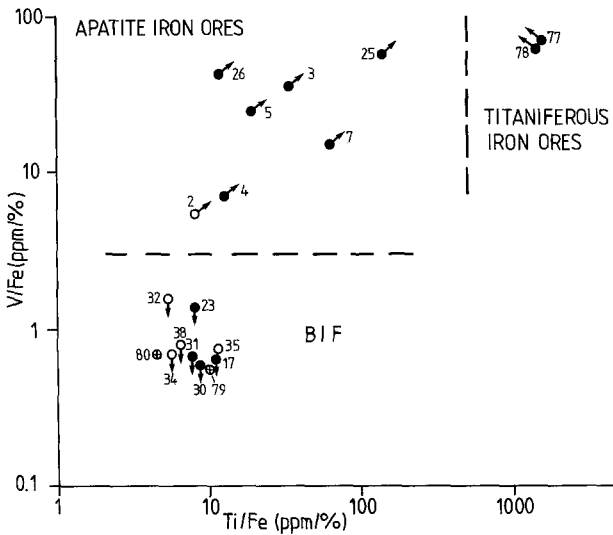hem = hematite

mag = magnetite

Fig.8. The V/Fe-Ti/Fe ratio distributions within the Swedish iron ores. For sample number locations see Fig.2

Table 3. Ti and V concentrations (ppm) of some iron ores and of their mutual iron oxide concentrates

| No	Mine	Ore type	Ore minerals	Ore Ti	Ore V	Iron oxide concentrate Ti	Iron oxide concentrate V
7	Malmberget	apatite iron ore	magnetite	2200	496	2800	1130
23	Norberg (Lernbo)	limestone skarn ore	hematite	150	25	500	53
25	Grängesberg	apatite iron ore	magnetite	3100	1170	600	2450
31	Persberg	limestone skarn ore	magnetite	500	42	300	45
34	Stripa	quartz banded iron ore	hematite	300	37	1000	26
35	Striberg	quartz banded iron ore	hematite	150	20	1000	31
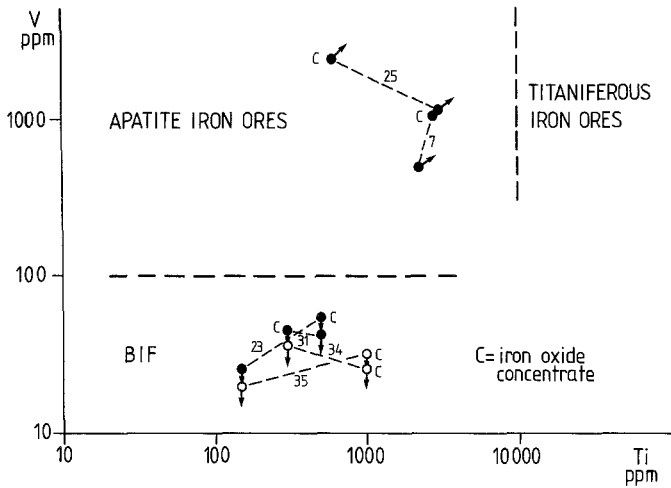
Fig.9. Comparison between the V/Ti ratio distribution within the ore and within the corresponding iron oxide concentrates from different iron ore types. For sample number locations see Fig.2. The iron oxide concentrate is denoted by C

6. DISCUSSION

that the V-Ti distributions within the iron oxide ore concentrates are in all cases within the field for the corresponding ore types. As a consequence only the total analysis of the ores have been used in this present investigation.

The banded iron ores (BIF) from the Bergslagen province, which in Fig.2 comprise a distinctive group, include (as described above) the quartz banded iron ores and the closely associated calcareous and skarn iron ores. From a genetic point of view these ore types are regarded as sedimentary in origin (Magnusson, 1973). Fig.10 illustrates the V/Ti ratio distributions of ore types from several world-wide deposits inclusive of average values for two itabirite types from S.America (Dorr, 1973). These latter types plot within the same field as the Swedish BIF ores thus indicating some similarities in genesis.

The Swedish BIF ores are only sporadically associated with metasomatically altered country rocks, which argues against an exhalative origin.

Where the banded iron ores and their host rocks have been metasomatically altered, it is the result of granitoid intrusions affecting the older rocks causing localized metasomatic alteration. This process seems to have developed from a convection geothermal water system driven by heat from the magmas.

Where the country rocks in contact with the iron ore are altered to cordierite quartzites, cordierite mica schists and Mg-rich skarns, it is obvious that younger sulphide impregnations have formed relative to the iron oxide concentrations. Magnusson (1975) emphasized that this metasomatic alteration of the country rocks gave rise to major mineralogical similarities to the central Swedish sulphide ores of the Falun type, whose character is similar to that of the Kuroko ores (Schermerhorn, 1978).

The investigations carried out on Fe-Mn-rich sediments of exhalative origin within active ocean-floor spreading centres (Boström, 1974) show that the V-Ti distribution ratios deviate markedly from the BIF ores but coincide convincingly with the apatite iron ores. According to Boström (1981) there is good agreement of the Fe-P-Ti-V and Ni distributions between the
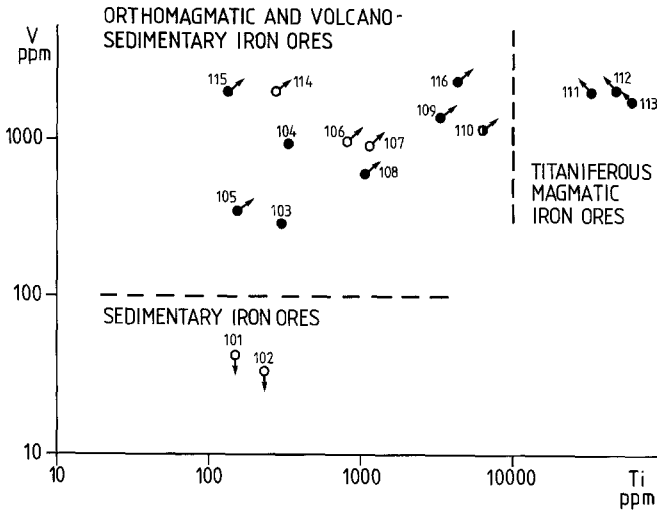
Fig.10. The V/Ti ratio distribution within several worldwide iron deposits to-
gether with three Swedish titaniferous magnetite deposits. The sample numbers
correspond to the following deposits: 101 Dolomitic itabirite. Minas Gerais,
Brazil. Average of 6 analyses (Dorr, 1973). 102 Itabirite. Minas Gerais, Brazil.
Average of 8 analyses (Dorr, 1973). 103 Magnetites. Lahn-Dill, West Germany.
Average of 3 analyses (Frietsch, 1970). 104 Fe, Mn-rich sediment. East Pacific
Rise. Average of 15 analyses (Boström, 1974). 105 Magnetites. El Laco, Chile.
(Fruto and Oyarzun, 1975). 106 Hematite. El Laco, Chile. (Parak, 1975). 107 He-
matite. El Laco, Chile. (Parak, 1975). 108 Apatite-magnetite ore. Pea Ridge,
Missouri, USA. Average of 4 analyses (Kisvarsanyi and Proctor, 1967). 109 Apa-
tite-magnetite ore. Bourbon, Missouri, USA. Average of 14 analyses (Kisvarsanyi
and Proctor, 1967). 110 Apatite-hematite-magnetite ore, Iron Mountain, Missouri,
USA. Average of 8 analyses (Kisvarsanyi and Proctor, 1967). 111 Titaniferous
magnetite. Kramsta, Sweden (Frietsch, 1975). 112 Titaniferous magnetite. Ulvön,
Sweden (Frietsch, 1975). 113 Titaniferous magnetite. Routivare, Sweden (Frietsch,
1975). 114 Hematite. El Laco, Chile (Table 4, M3). 115 Apatite-iron ore. Chadur-
Malu, Bafq, Iran (Table 4, M4). 116 Apatite iron ore, Mishdovan, Bafq, Iran
(Table 4, M5)

oceanic sediments and the El Laco ores.
Thus the El Laco and other Circumpaci-
fic Fe-P-rich ores have been interpret-
ed by Boström as supporting evidence
of ores which have been formed from
metalliferous sediments by subduction
and metamorphism. During such processes
most of the manganese content disap-
pears.

Concerning the West German iron
ores from the Lahn-Dill region, which
are considered as exhalative sedimen-
tary in origin and associated with
basic volcanism (Borchert, 1960; Bau-
mann, 1976), the V/Ti ratio distribu-
tions (Frietsch, 1970) plotted in
Fig.10 fall within the field of the
apatite iron ores. Thus the restricted

field of the apatite iron ores (Fig.2),
also contains ores of exhalative origin
(Fig.10). Furthermore, it is clear that
orthomagmatic ores fall within the
same field, as shown by the analyses
(Table 4) of the ores from El Laco
(Chile) and Bafq (Iran) as well as the
ores from the Missouri province in the
USA (Kisvarsanyi and Proctor, 1976).
The El Laco ores of Quarternary age
comprise magnetite lava flows or near
surface magnetite intrusions in associ-
ation with rhyodacites and andesites
(Park, 1961; Frutos and Oyarzum, 1975;
Henriquez and Martin, 1978). The ores
from the Bafq province in Iraq are late
Precambrian in age. These ores, which
consist of magnetite lavas with fluid-

al textures and apatite-schlieren, are associated with rhyolitic volcanics. Several of the iron ores have the form of pyroclastic layers consisting of magnetite lapilli. In addition, there occur magnetite bombs embedded in rhyolites rich in disseminated magnetite dustings (Förster et al., 1973); Förster and Knittel, 1979). Finally, regarding the Missouri province, these Precambrian magnetite-hematite ores compare favourably to those from Iran and also occur associated with rhyolitic lava flows (Kisvarsanyi and Proctor, op. cit.). The shape of the ore bodies vary from tabular to irregular and contacts with the host country rocks range from sharp to transitional (via an ore breccia). The general character of the ores suggests an infilled fracture zone.

The skarn iron ores and the quartz-rich iron ores of the Norbotten province show such a large spread of vanadium and titanium values (Figs 5 and 6) that they plot within the fields for both the BIF and the apatite iron ores (orthomagmatic and exhalative iron ores in Fig.10). There is thus the possibility that the skarn iron ores represent a genetically inhomogeneous group which include several exhalative-sedimentary types and the rest sedimentary without any exhalative association. This could also be pertinent for the corresponding quartz-rich iron ores (Fig.6).

The titaniferous iron ores, which differ from the remaining iron ores in terms of an extremely high Ti content, plot as a distinctive group in Fig.2. Some additional analyis of the Swedish titaniferous iron ores (Frietsch, 1975) serve to verify this (Fig.10). That these ores, commonly associated with gabbros and anorthosites, are orthomagmatic in origin, has long been accepted (e.g. Stanton, 1972).

The special interest involving the apatite iron ores from Kiruna and their genesis warrant, even in the context of this paper, careful interpretation. Comparison of Figs 2, 7 and 10 show that the Kiruna iron ores, together with the other Swedish apatite iron ores, plot within the same area of the diagram as the ortho-magmatic ores

from El Laco, Bafq and the Missouri province. However, this area also includes the ores of exhalative-sedimentary origin such as the iron- and manganese-rich sediments from the oceanic spreading centres (East Pacific Rise), the Lahn-Dill ores and the quartz and skarn iron ores from Norrbotten. We are, in other words, within the familiar sphere of debate as to whether the Kiruna iron ores are the products of a consolidated magnetite magma or have been formed through exhalative-sedimentary processes. It is clear that the V/Ti ratio does not discriminate between the two genetic groups.

Comparison of the ferride contents of the above-mentioned groups with those of the Kiruna apatite iron ores should provide a sound basis for judgement concerning the question of genesis (see plots Fig. 11a-i). Fig.11a shows a reasonable correlation with the apatite iron ores from Grängesberg; only Cr deviates significantly from the Kiruna ores. Even the apatite iron ores from the Missouri province (Figs 11b and c) indicate a clear correlation (Kisvarsanyi and Proctor, 1967), with the exception of the Pea Ridge ore which is considerably lower in Cr; this may be due to an analytical error.

The Late Precambrian phosphorus-rich magnetite-hematite ores from Mishdovan (Bafq) contain ferride contents (Table 4) which correlate closely to the Kiruna ore, apart from a somewhat higher vanadium content (Fig.11d). In contrast the Chadur Malu magnetite ores, also from the Bafq province, differ significantly from the Kiruna ore (Fig.11e) which indicates that there occurs an appreciable variation of ferride content within a group of ores from the same province and genetically of the same type.

The El Laco ore's ferride distribution (Fig.11f), based on one analysis of hematite (Table 4) and two from the published literature (Parak, 1975 a), deviates significantly from the Kiruna iron ores. The large discrepancies obtained for several elements may be due to hematite being a secondary alteration product of magnetite. According to Henriquez and Martin (1978) "magnetite is certainly the more important
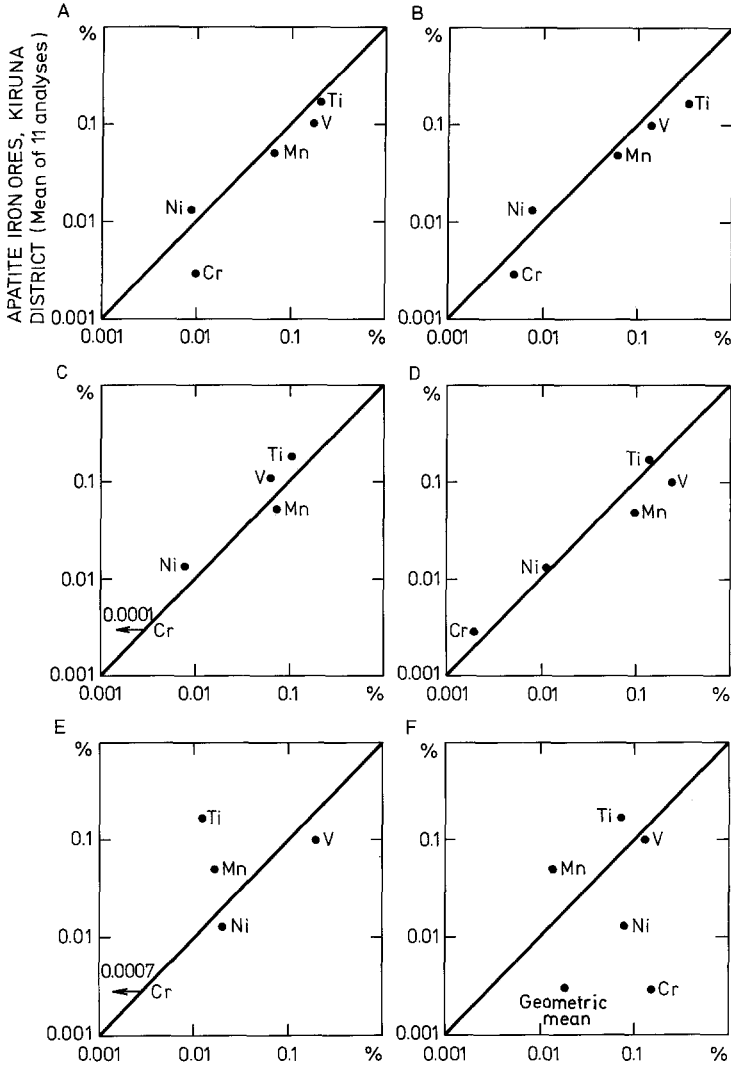
Fig.11. Diagram relates the ferride content of the Kiruna district's apatite
iron ores (comprising an average of 11 analysis; Table 2) to the contents with-
in the following iron deposits: a) Apatite iron ores (average of 2 analyses,
Table 1) Grängesberg and Lönnfallet, Sweden. b) Apatite iron ores (average of
14 analyses) Bourbon, Missouri, USA (Kisvarsanyi and Proctor, 1967). c) Apatite
iron ores (average of 4 analyses) Pea Ridge, Missouri, USA (Kisvarsanyi and
Proctor, 1967). d) Apatite iron ore (1 analysis, Table 4) Mishdovan, Bafq,Iran.
e) Apatite iron ore (1 analysis, Table 4) Chadur-Malu, Bafq, Iran. f) Hematites
(average of 3 analyses) El Laco, Chile (Parak, 1975 and Table 4 this study).
The Cr-value is presented as a geometrical average of 5400 and 4000 ppm. g) Mag-
netites (average of 3 analyses) Lahn-Dill, West Germany (Frietsch, 1970).
h) Iron-rich sediment (average of 15 analyses) East Pacific Rise (Boström, 1974).
Cr-value (personal comm., K.Boström). i) Skarn iron ores (average and standard
deviation for an average of 84 analyses) Norrbotten, Sweden (Frietsch, 1970)
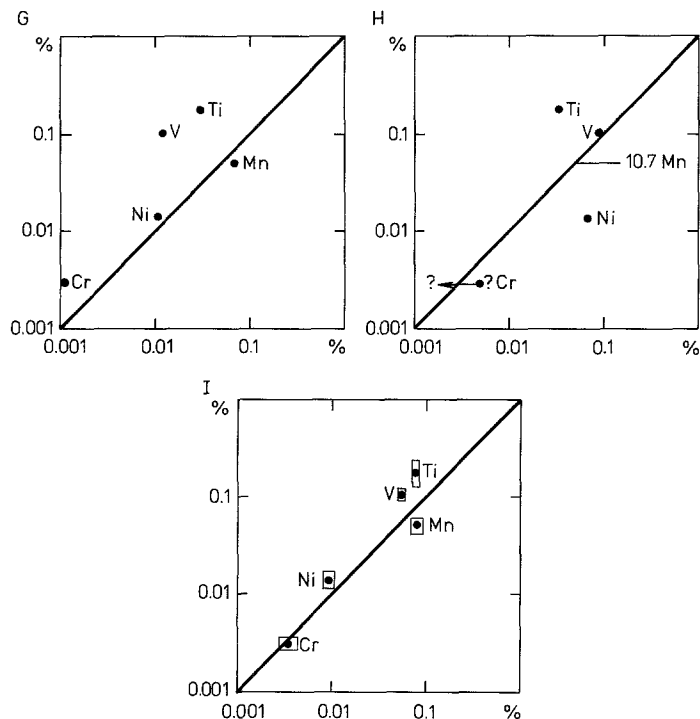
primary iron oxide; primary hematite is scarce. Secondary hematite and maghemite develop extensively as oxidation products of primary magnetite". Furthermore they emphasize that the whole El Laco complex (andesites, rhyodacites as well as intrusive and extrusive magnetite-rich rock units) "shows signs of important and pervasive hydrothermal alteration". Moreover, the established similarities between the El Laco ore and the East Pacific Rise sediments can also allude to a genetic connection (Boström, 1981).

The iron ores from Lahn Dill, supposed to be of exhalative-sedimentary origin, and the Fe-Mn-rich East Pacific Rise sediments, show a significant deviation in ferride content from the Kiruna iron ores (Fig. 11g and h). In contrast, the Norbotten skarn iron ores which are also considered to be exhalative-sedimentary in origin (Grip and Frietsch, 1973), exhibit a ferride distribution (Fig 11i) which is in very close agreement with the Kiruna iron ores.

In general, the ferride distribution within the iron ores does not appear to be genetically definitive. What can be established is that the ferride chemistry of the Kiruna iron

Table 4. Chemical analyses of magmatic apatite iron ores from Chile and Iran

No	Locality	Ore minerals	Ti ppm	V ppm	Mn ppm	Ni ppm	Cr ppm
114 (M3)	El Laco (Chile)	Hematite	280	2100	320	270	5
115 (M4)	Chadur-Malu (Bafq, Iran)	Magnetite	126	2000	720	200	7
116 (M5)	Mishdovan (Bafq, Iran)	Hematite/ magnetite	1440	2400	1000	120	20

ores is reflected most convincingly by the Grängesberg ores (Fig. 11a), the Missouri ores (Fig.11b and c), the Mishdovan ores (Fig. 11d) as well as the Norrbotten skarn iron ores (Fig. 11i). Of these ores, the first three are considered orthomagmatic in origin whilst the skarn ores, based on geological evidence, are thought to be exhalative-sedimentary. These apparently contradictory relationships need not, however, exclude a genetic connection.

Park (1972), having been engaged in a study of the Circum-Pacific apatite-magnetite-amphibole ores, suggested that their origin could be attributed in part to partial mobilization of iron from rocks at depth (e.g. Precambrian BIF and iron-rich quartzites). This mobilized material, which is assumed to have contained large quantities of volatiles (phosphorus, chlorine, fluorine, water etc.), was forced upwards towards the earth's surface with access provided by fault and fracture systems, either to form extrusives or near surface intrusives.

With reference to the El Laco iron ores, Frutos and Oyarzun (1975) essentially supported this concept. They showed that although the V-Cr-Ti distributions clearly distinguished the ores from the magnetites of the andesitic host rocks, a marked correlation existed between the ores and the underlying Precambrian "iron formations". They therefore considered that these old iron rich rocks were partially melted at depth thus producing, through differentiation, a magnetite magma. The possibility of a magnetite magma has been supported by the works of Fischer (1950) and Philpotts (1967) both of whom showed the existence of a broad miscibility gap in the system magnetite-apatite-silicate. Another already mentioned possibility (Boström, op.cit.) is that metal-rich oceanic sediments have been melted during subduction resulting in magnetite-apatite magmas.

The good agreement of the ferride geochemistry (Fig.11i) between the apatite iron ores of the Kiruna type and the skarn iron ores of Norbotten can also be interpreted in such a way to suggest that the apatite iron ores re- present the differentiated product of a magmatic melt which itself has formed partly from the digestion of skarn iron ore material. According to Smellie (1980) the apatite iron ore type has formed "from a magma which has assimilated iron-rich materials from depth". It just may be that such a source of iron-rich material could be represented by the skarn iron ores associated with the Norbotten greenstone groups. It is worth noting that the skarn iron ores have been shown to be older than the apatite iron ores (Lundqvist, 1979), even if the exact age differential is not yet finally established.

It has been convincingly shown by field relationships (Lundberg and Smellie, 1979) that some of the Kiruna-type iron ores in Norbotten are of orthomagmatic origin. This does not exclude the possibility that residual solutions from a magnetite magma could have given rise to ores of a hydrothermal (exhalative-sedimentary) character (Frietsch, 1978; Smellie, 1980). This hydrothermal relationship has been taken by, for example Parak (1973, 1975), to explain the Kiruna iron ores as being completely hydrothermal in origin.

7. CONCLUSIONS

The ferride distributions present within the Swedish Precambrian iron ores indicate two major groups:

1. Orthomagmatic and exhalative

2. Sedimentary BIF

Within group 1 the titaniferous iron ores are distinctive because of their high Ti-contents.

The apatite-rich Kiruna iron ores, according to their ferride contents, can be considered as the differentiated products from a magmatic melt, which has largely formed from the melting and assimilation of skarn iron ore material associated with the Norrbotten greenstone groups.

G-GU 4587-101). The authors are grateful to Professor K.Boström for valuable discussions and advice during the project, and to Dr. J.Zuber for his critical comments on the manuscript. Thanks are due also to Professors Förster (Aachen) and Frutos (Concepcion) for supplying iron ore samples from Iran and Chile respectively, to Drs L. Mauritzon and S. Liedberg for material from the LKAB mines and to Dr.H.Cristoffersson for material from the Garpenberg district.

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