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A VOLCANOGENIC EXHALATIVE IRON FORMATION IN THE SOUTHERN MARGIN ZONE OF THE DAMARA OROGEN

by

J.H. Breitkopf and K.J. Maiden
Department of Geology
University of the Witwatersrand
1 Jan Smuts Avenue
JOHANNESBURG
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ABSTRACT

An iron formation of late Proterozoic age is developed as a narrow band in a succession of metasediments and metavolcanic rocks in the Southern Margin Zone of the Damara Orogen south of Windhoek. The succession has undergone low- to medium-grade metamorphism. Two primary metamorphic assemblages are distinguished containing a) magnetite, hematite, quartz, apatite with no or minor ilmenite, minnesotaite, stilpnomelane, chlorite, amphiboles and carbonate, and b) magnetite, quartz, plagioclase, amphiboles, chlorite, minnesotaite, stilpnomelane, biotite, carbonate and apatite. Bulk compositions in the two rock types are highly variable with respect to their concentrations in Ti, AI, Mg, Na, Zr, and Nb. A volcanogenic exhalative origin is indicated by its high apatite content, the formation of plagioclase and actinolite in layers within the iron formation, from possible metamorphosed volcanogenic detritus, and its close association with mafic metavolcanic rocks.

1. INTRODUCTION

Iron formation (BIF, itabirite) occurring in the mountainlands south and east of Windhoek has been recorded by numerous workers (e.g. Burg, 1943; Telfair, 1954; Hälbich, 1970; Beukes, 1973; Martin, 1975; Hoffmann, 1983; Miller, 1983 a, b). The iron formation is developed in an area that is part of the Southern Margin Zone (Martin, 1975) or Southern Margin Thrust Belt (Hoffmann, 1983) of the late Proterozoic Damara Orogen (Fig. 1). The iron formation occurs within the Chuos Formation and is interpreted by Hoffmann (*op. cit.*) to form part of the Lichtenstein-Auas Nappe Complex (LANC). Similar occurrences of iron formation are found in the Chuos Formation in the Southern Margin Zone (e.g. between the Bismarckberge and Dordabis to the east and south-east of Windhoek). The lithotypes contained in the Chuos Formation and its position within the stratigraphic succession of the Southern Margin Zone are documented in Table 1. Thrusting in a south-easterly direction accompanied the development of overturned to recumbent F_1 and F_2 fold structures in the Southern Margin Zone (Miller, 1983 b). Only one schistosity (s_1) was observed throughout the extent of the iron formation.

As part of a research project on the origin of the iron formations in the Southern Margin Zone and their economic potential, an area to the south of Windhoek was selected for detailed study. Within this area (Fig. 2) the iron formation forms an almost continuous unit over 25 km on the farms Regenstein 32, Krumhuk 30, Windhoek Townlands 31 (Morester) and Klein Windhoek Townlands 70 (Schalk and Hoffmann, in prep.).

To document variations in the lithology, mineralogy and geochemistry of the iron formation, 50 profiles, spaced approximately 500 m apart, were measured across the iron-rich unit and its wall rocks. Six representative stratigraphic columns are shown in Fig. 3; their positions are given in Fig. 2. Approximately 500 samples of the iron formation and its wall rocks were collected from surface outcrops. A study of thin sections and polished thin sections was complemented by whole-rock chemical analyses of major, minor and trace elements using X-ray fluorescence spectroscopy.

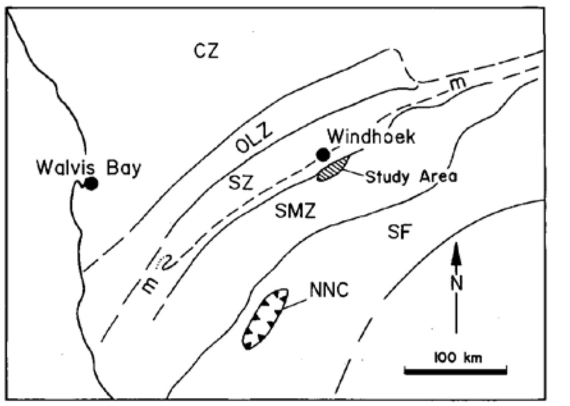


Fig. 1: Main structural zones of the Damara Orogen (after Miller, 1983b) and location of the study area. CZ: Central Zone - OLZ: Okahandja Lineament Zone - SZ: Southern Zone - SMZ: Southern Margin Zone - SF: Southern Foreland - NNC: Naukluft Nappe Complex - M: Matchless Member.

TABLE 1: Lithostratigraphy of the Southern Damara Belt (after Hoffmann, 1983)

Group	Subgroup	Formation	Lithology
SWAKOP	(Khomas)	Kuiseb	schist, amphibolite (Matchless Member)
	VAALGRAS	Kleine Kuppe	quartzite, quartz schist, mica schist, amphibolite
		Gomab River	mafic schist, acid metavolcanics, minor mica schist and marble
		Mahonda	schist, quartzite, amphibolite, very minor marble
		Melrose	garnet-schist, minor calcareous quartzite and schist, marble
		Chuos	"pebbly schist"(mixtite), quartzite, amphibolite, iron formation
	KUDIS	Hakos, Auas, Blaukrans, Corona	Hakos: quartzite, graphite schist Auas: quartzite, graphite schist, minor conglomerate Corona: marble, minor phyllite Blaukrans: graphite schist, minor quartzite, conglomerate, marble
NOSIB		Kamtsas and Duruchaus	Duruchaus: pelitic to psammitic metasediments, meta-evaporite Kamtsas: quartzites, conglomerates

2. FIELD RELATIONSHIPS AND DISTRIBUTION

The iron formation in the area weathers out positively within the rock sequence, forming horizons that can be readily traced in the field. It strikes in a north-easterly direction, parallel to the general strike of the Damara Orogen, and dips at moderate angles towards the north-west. The iron formation occurs as an almost continuous unit within a limited stratigraphic interval in a sequence of mafic schist (metavolcanic rock; Miller, 1983 c) and quartz-mica schist (metapelite), minor interbedded quartzite and rare marble. On Regenstein and Morester, the unit is repeated to the west by displacement due to normal faulting (Fig. 2). The average thickness of the iron-rich metasediments is approximately 2,5 m with a maximum thickness of 10 m being developed on Klein Windhoek Townlands 70 in profile 13 AU (Figs. 2 and 3). On Regenstein, the unit thins laterally and pinches out at two localities (Fig. 2).

The iron formation as a mappable unit consists of one or more iron-rich horizons, or bands, representing various iron-rich lithosomes, which are interbedded with mafic schist, pelitic schist and quartzite. The bands appear in outcrop as strongly elongate lenticular bodies. Some bands extend over hundreds of metres, others pinch out laterally over distances of less than a metre. The rapid variation in thickness of the iron formation over short distances is related mainly to the number of iron-rich horizons developed, which may vary from 1 to 15. Fig. 3, for example, shows the iron formation at location 13 AU consisting of 15 iron-rich horizons, with a total thickness of 10 m, whereas at location 39 AU only one horizon is developed and the total thickness is 0,35 m. Repetition of bands due to folding or thrusting was not observed. However, intrafolial folding within the bands is common and has caused local thickening.

3. LITHOLOGY

The iron-rich horizons exposed in the area occur as a variety of macroscopically distinguishable lithologies. For the purpose of field mapping, the following varieties could be distinguished:

1. coarse-grained magnetite-quartz rock;
2. fine-grained magnetite-quartz rock;
3. hematite-(specularite-)quartz rock;
4. quartz-magnetite-mica-(plagioclase-carbonate) schist.

Magnetite- or hematite-(specularite-)quartz rocks are the most common types of iron formation. Quartz-magnetite-mica schist is mainly found west of the main road from Windhoek to Rehoboth on farms Regenstein and Krumhuk on the southern slopes of the Liebenstein and

Grossherzog Friedrich Berg (Fig. 2).

3.1 Coarse-grained Magnetite-quartz Rock

Magnetite-quartz rock is by far the most commonly occurring component of the iron formation. Being strongly resistant to weathering, it forms the most prominent iron-bearing rock type in outcrop. The rocks show a large range in grain size, with magnetite grains varying from about 0,1 up to 5 mm in size. Banding is generally not well developed. However, in a few localities (e.g. 9 AUα, Fig. 2) the coarser-grained varieties show alternating layers of blue-grey magnetite- and quartz-rich bands. The magnetite-rich laminae range in thickness from a few millimetres up to 20 mm and are commonly two to five times thicker than the alternating quartz bands. Rarely the laminae are of even thickness. A common occurrence within the iron formation is coarse-grained magnetite-quartz rock with only a little quartz disseminated throughout. Layers of pure magnetite may be present in this rock type. Weathered rocks show reddish-brown limonitic stains on outcrop surfaces. Coarse-grained magnetite rock with pores filled with powdery limonite is another variety that contains almost no quartz at all. This porosity is probably the result of supergene leaching of quartz. Coarse-grained layers of magnetite-rich rock with dis-seminated carbonate or layers of carbonate occur less commonly. Patches or radially orientated actinolite were observed in a coarse-grained magnetite-rich horizon on Windhoek Townlands 31 east of the Windhoek-Rehoboth road.

3.2 Fine-grained Magnetite-quartz Rock

Fine-grained magnetite-quartz rock represents banded iron formation (BIF) in the narrow sense defined by James (1954; see discussion below). It is generally well laminated with the magnetite-rich bands exceeding the quartz-rich bands in thickness (Fig. 4). However, millimetre-thick quartz bands commonly pinch out over distances of a few centimetres and represent fine lenticular layering. The rock is generally strongly magnetic and occurs in places as nearly pure magnetite rock with few disseminated grains of quartz. Quartz-rich varieties are compara-tively rare. In a few localities carbonate is developed in fine bands or as disseminated grains or patches forming magnetite-quartz-carbonate rock. The contacts of the magnetite-quartz horizons with adjacent rocks are generally sharp.

3.3 Hematite-(specularite)-quartz Rock

The hematite-rich horizons within the iron formation are generally quartz-poor. Specularite schist is mainly found along the northern slope of the Auas Mountains on Windhoek Townlands 31 (east of the Rehoboth road) and Klein Windhoek Townlands 70 (e.g. 12 AU, 13 AU, Fig. 3). The specularite schist is generally a hard, and less commonly a friable, rock. Both varieties have a

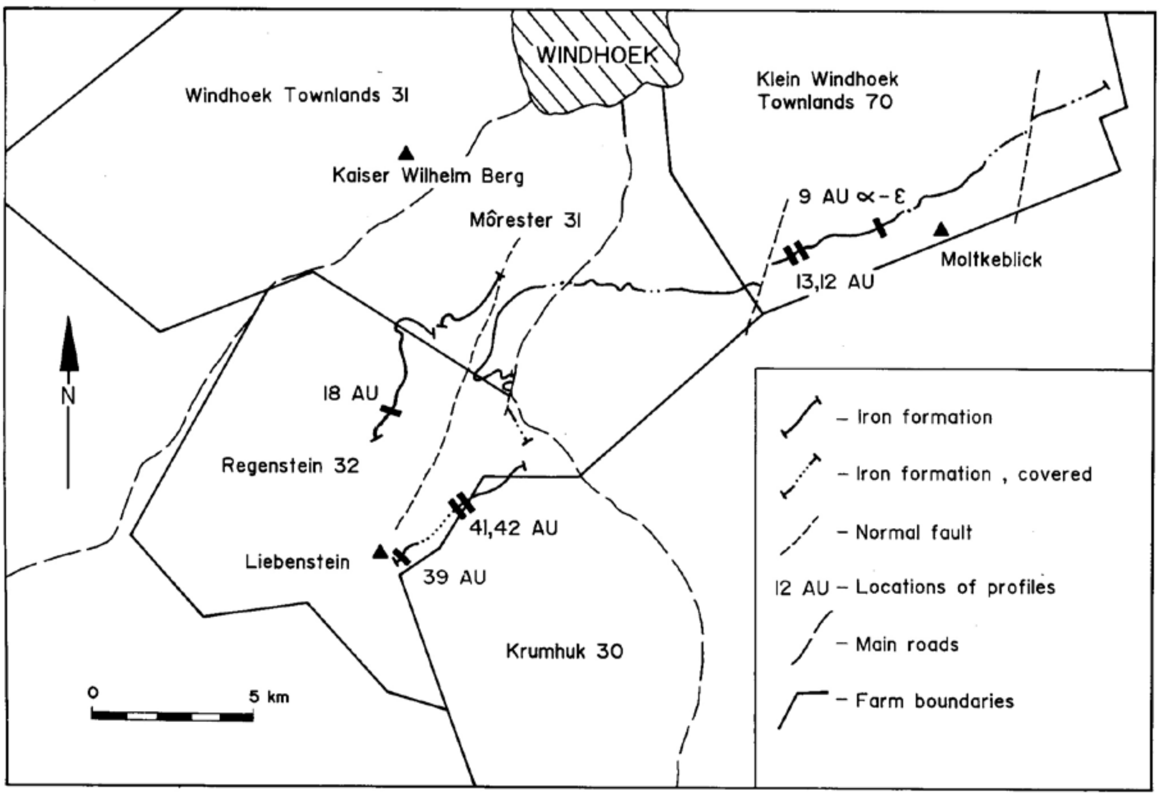


Fig. 2: Distribution of iron formation in the Auas Mountains south of Windhoek.

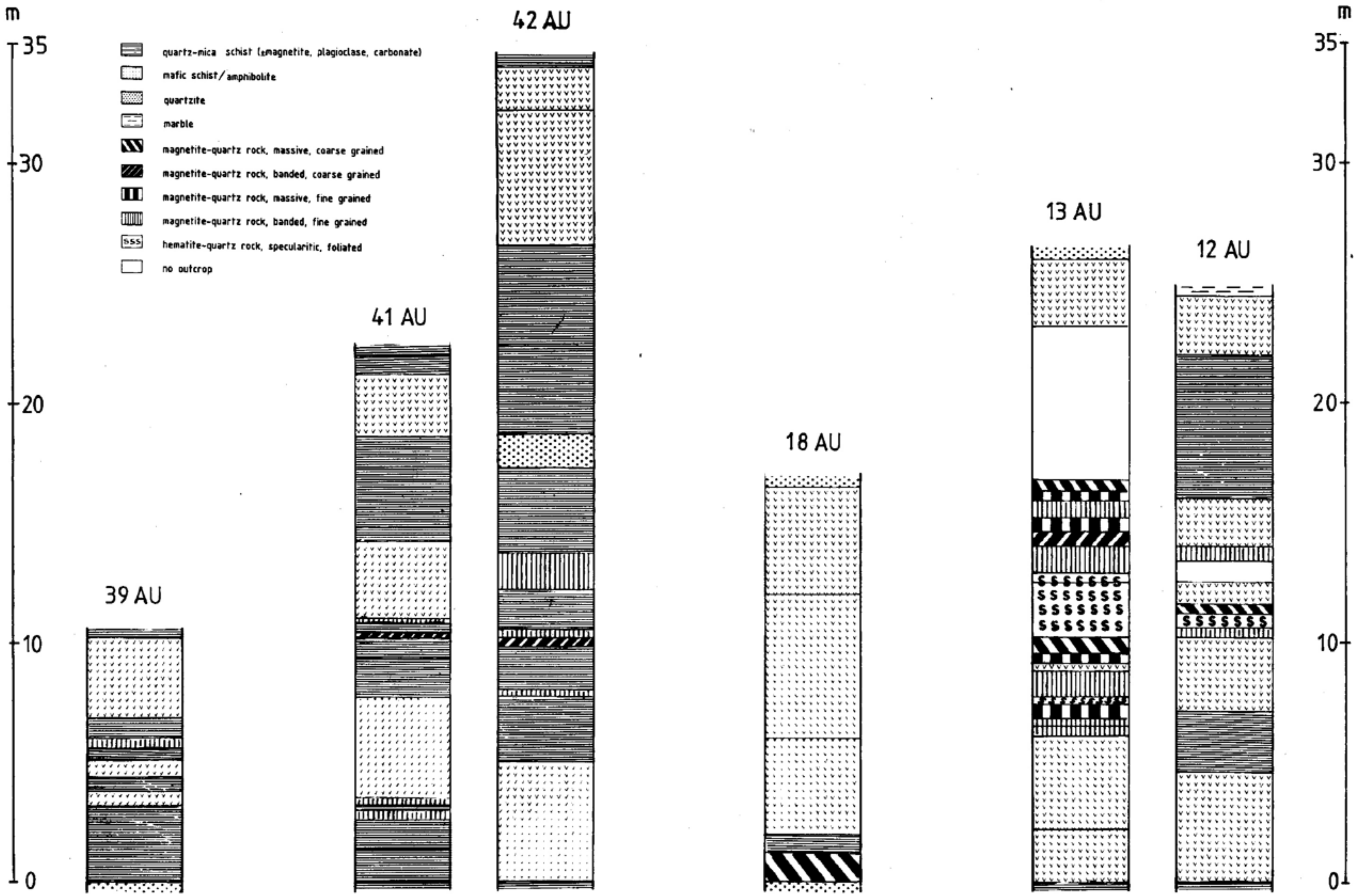


Fig. 3: Profiles of iron formation on Regenstein (39 AU, 41 AU, 42 AU and 18 AU) and on Klein Windhoek Townlands (12 AU and 13 AU). For location of profiles see Fig. 2.

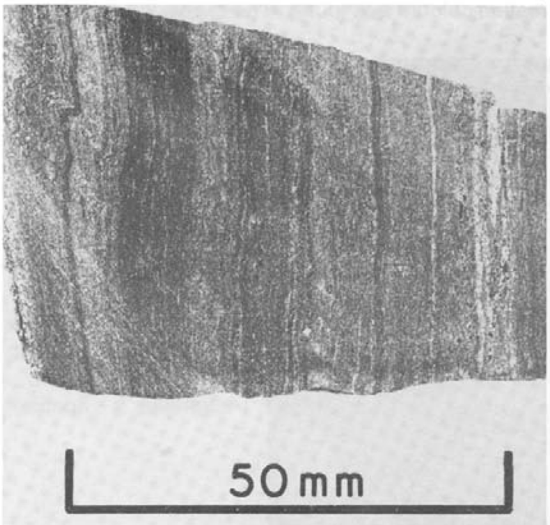


Fig. 4: Fine-grained laminated magnetite-quartz rock.

pronounced foliation. Tectonic thickening by tight intrafolial s- and z-folds is common in these less competent horizons. Quartz bands, up to few millimetres thick, are lenticular in nature. It is not clear whether this is entirely due to boudinage of the bands, or whether it is partly an original feature. Thickening of the bands in the closures of intrafolial folds is a common feature. Leaching of quartz bands and boudings by supergene processes has created elongate pores and cavities which were subsequently filled or stained by limonite. Specularitic hematite flakes weather out of surface exposures, covering the ground around outcrops, and can be traced for many kilometres in river beds.

3.4 Quartz-magnetite-mica-(plagioclase-carbonate) Schist

Quartz-magnetite-mica-(plagioclase-carbonate) schist occurs only in the southern part of Regenstein at locations 39 AU, 41 AU and 42 AU (Figs. 2 and 3). It always occurs immediately adjacent to horizons of magnetite-quartz rock. The magnetite-bearing schist contains less than 15 per cent total Fe and therefore does not classify as iron formation according to the definition given by James (1954; see discussion below). The rock is generally grey to brownish-grey in colour. The common mica is biotite. It occurs equally as a friable rock (with large amounts of biotite) or as a hard rock (with large amounts of quartz and/or feldspar). A fine-grained variety is generally rich in mica, whereas in coarse-grained varieties quartz and/or feldspar grains are macroscopically visible. The rock shows one pronounced foliation (s_1). Limonite patches are commonly found, covering the surface of outcrops. The contact of the quartz-magnetite-mica schist to footwall and hanging-wall pelitic or mafic schists is usually gradational. Contacts with quartzite and magnetite-quartz rock are usually sharp and thus the rock represents a transitional facies between magnetite-free metapelite and iron formation. Due to its relatively low iron content the schist is not considered as part of the iron formation and is therefore excluded from the following discussion.

3.5 Facies Variations

Lithologic changes across strike include the interbedding of various iron-rich bands and variable proportion of clastic metasediment, metavolcanic rock and chemical precipitate within the stratigraphic succession. Bands of iron formation occur interbedded in mafic schist (e.g. 12, 13 AU; Fig. 3), in quartz-mica schist (41, 42 AU; Fig. 3) or in a mixed metavolcanic/metasedimentary succession (41 AU, Fig. 3). Less commonly, quartzite is found in the footwall or hangingwall of iron-rich horizons. The boundaries of the iron formation are generally sharp. In places (e.g. 41 AU) quartz-magnetite-mica-(plagioclase-carbonate) schist shows gradational contacts with adjacent quartz-mica schist.

Lithologic changes along strike reflect possible variations in the depositional environment. Details of lateral variation were recorded on the south-western slope of the Kamelberg on Klein Windhoek Townlands 70 (Fig. 2) where five samples (9 AUα-ε) were taken from west to east along strike of the iron formation. From west to east lithotypes change over 250 m from an evenly banded, strongly magnetic, coarse-grained magnetite-quartz rock (9 AUα, thickness approximately 5 m) to banded, fine-grained varieties decreasing gradually in thickness and magnetite content up the slope towards the east. At the eastern extremity of the section studied, the rock changes to an 80 cm thick horizon of ferruginous schist consisting of magnetite, feldspar and amphibole. Iron formation is developed 350 m further east with a total thickness of 3,7 m and in layers of alternating coarse- to fine-grained magnetite-quartz rock.

4. MINERALOGY

During mineralogical and petrographic studies, two groups of iron formation were distinguished. Group A (described in 4.1.) consists of almost pure magnetite/hematite-quartz rock, whereas Group B (described in 4.2.) contains abundant silicates and variable amounts of carbonate minerals.

4.1 Magnetite/hematite-quartz Rock

Magnetite/hematite-quartz rock is generally coarse-grained, massive (e.g. 18 AU, Fig. 3) or banded (e.g. 9AUα, Fig. 2) and consists of magnetite and/or hematite and quartz as major components (>90 per cent, apatite (up to 8 percent) and the accessory minerals ilmenite, carbonate, minnesotatite, stilp-nomelane, amphibole and chlorite (in places up to 3 per cent). Magnetite and quartz grains form granoblastic polygonal aggregates

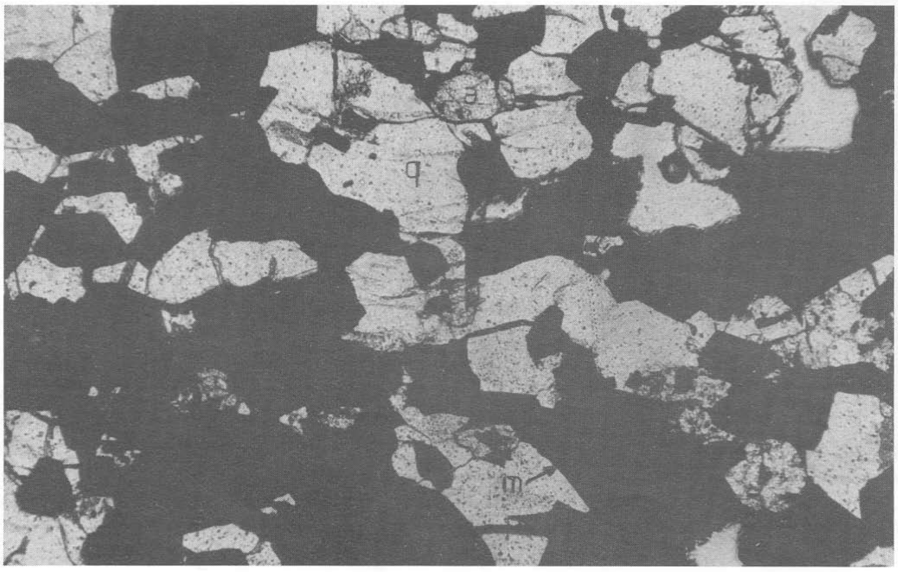


Fig. 5: Photomicrograph of massive coarse-grained magnetite-quartz rock (plane polarised light; x27; q - quartz, m - magnetite, a - apatite).

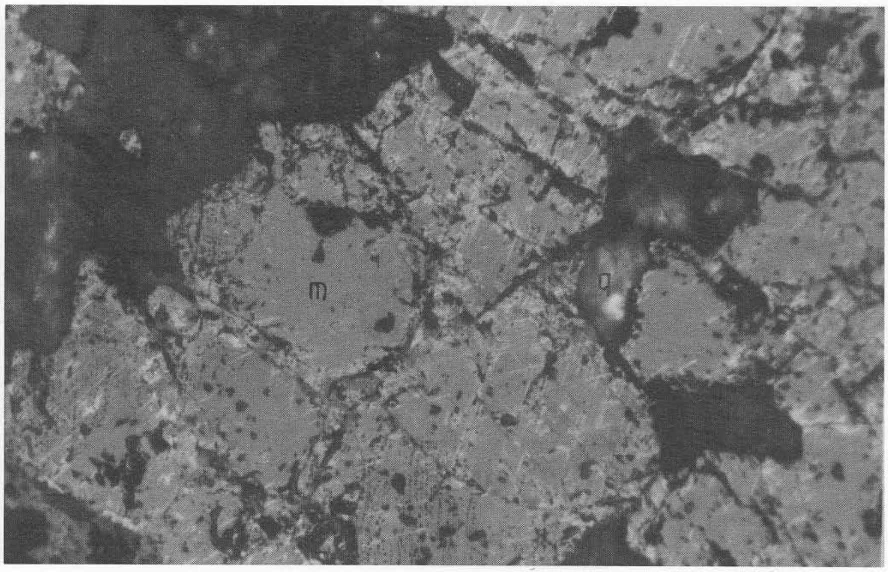
and represent an annealing recrystallisation texture (Fig. 5). The development of triple junctions approaches 120° at the intersections of quartz/quartz, magnetite/magnetite and quartz/magnetite grains, indicating simultaneous growth of these grains and approach to chemical equilibrium after impingement near the peak of metamorphism (Vernon, 1977). Due to exposure to weathering in a semi-arid to arid climate, the magnetite generally shows signs of martitisation/martitisation is defined by Picot and John (1982) as the process of replacement of magnetite by hematite). Martitisation commences at grain boundaries and proceeds into the grains along cleavage planes, consequently hematite retains the shape of the original magnetite grains. The resulting pseudomorphs are known as martite (Fig. 6). The magnetites in the study area have undergone varying degrees of martitisation.

4.2 Magnetite-quartz-silicate ± carbonate Rock

Magnetite-quartz rock containing large amounts of minerals other than quartz and magnetite was described in the field mainly as fine-grained, banded magnetite-quartz rock. Under the microscope these rocks are seen as banded metamorphosed rocks rich in magnetite (25 - 45 per cent), quartz (20 - 40 per cent) and amphiboles (10 - 20 per cent). Further components are plagioclase (3 - 15 per cent), stilpnomelane (up to 10 per cent) and apatite (up to 6 per cent). In similar rocks developed along strike of the iron formation chlorite was found to be present in amounts up to 10 per cent as a retrograde mineral after amphibole, biotite and stilpnomelane.

Minnesotaite occurs in minor amounts (up to 3 per cent) in two samples from Windhoek Townlands 31. Fine banding on a one to two millimetre scale repre-

Fig. 6: Photomicrograph of magnetite grains showing early to advanced stages of martitisation (reflected light, crossed nicols; x 65; q - quartz, m - magnetite).



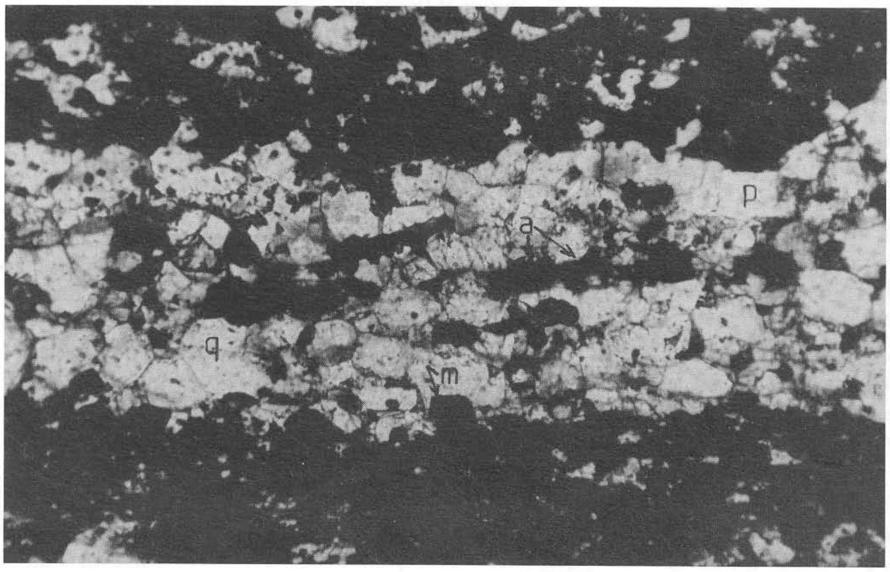
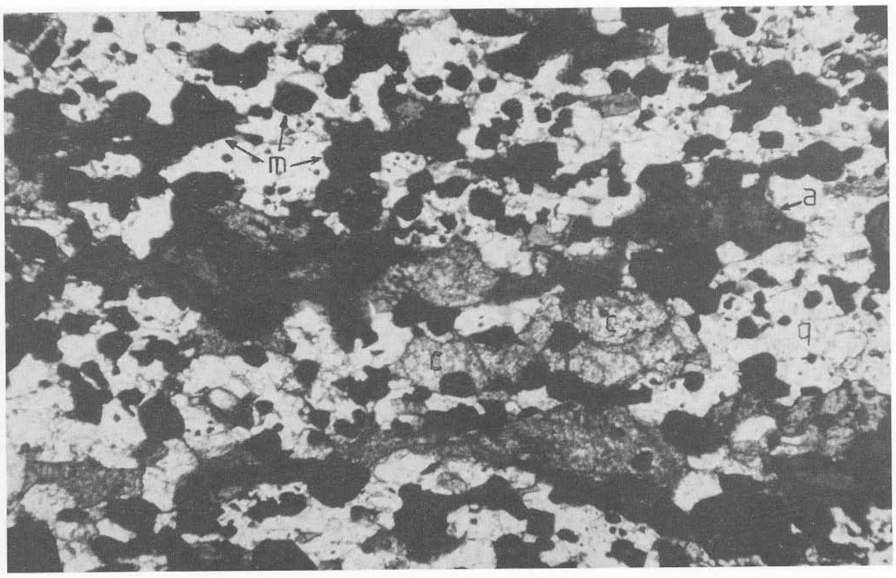


Fig. 7: a. Photomicrograph of magnetite-quartz-silicate rock (plane polarised light; x27; q - quartz, m - magnetite, a - amphibole, p - plagioclase).

sents an alternation of more or less magnetite-rich bands in a silicate-rich microcrystalline metamorphic rock. The impression of fine banding in hand specimen is enhanced by the occurrence of dark-green amphiboles (optically identified as actinolite) and a few colourless amphiboles (possibly grunerite-cummingtonite) in the magnetite-rich layers. Reddish brown blade-shaped minerals (inferred to be stilpnomelane, because of the very low K_2O-content of the bulk composition) are orientated in the same direction. The quartz and minor plagioclase grains are polygonal and commonly elongate in the direction of the fabric. The magnetite grains are generally polygonal in shape. A few grains show evidence of elongation by pressure solution processes. The elongation of grains in the granoblastic texture indicates adjustment to unidirectional stress rather than impingement during crystal growth. Compositional layering reflecting metamorphic, or possibly original sedimentary layering, or both, is emphasized by the occurrence of bands rich in magnetite and actinolite, quartz with minor magnetite, and stilpnomelane and colourless iron-rich clinoamphibole (grunerite-cummingtonite series).

In places the rocks are rich in cabonate (up to 20 per cent). The other major components are quartz (30 - 40 per cent), magnetite (25 - 40 per cent), amphibole (actinolite, up to 15 per cent), plagioclase (up to 12 per cent) and apatite. Biotite is an accessory component but in a few samples comprises 8 per cent of the rock. The main textural characteristic of these rocks is the distinct foliation (s_1) defined by the orientation of the elongate green amphiboles. Lenticular bands of quartz and carbonate are up to 1,5 mm thick and generally extend laterally for only a few centimetres parallel to foliation. Generally the carbonate-rich variety of iron formation is not as distinctly banded as other varieties, with amphibole being equally distributed throughout. Microcrystalline, polygonal magnetite grains of varying sizes (max. 1 mm) are disseminated throughout the

Fig. 7: b. Photomicrograph of magnetite-quartz-silicate-carbonate rock (plane polarised light; x27; q - quartz, m - magnetite, c - carbonate, a - amphibole).



rock. The quartz and carbonate grains are polygonal in shape and commonly elongate parallel to the planes of cleavage. Carbonate grains have length/width rations up to 7:1 (Figs. 7 a and b).

4.3 Summary

From examination of 54 polished thin sections two main groups of mineralogical assemblages can be distinguished:

Group A - almost pure. magnetite(martite)- and/or hematite-quartz rock with no or minor (< 3 percent) ilmenite and/or carbonate or silicate minerals; 24 samples

Group B - magnetite-quartz rock with up to 20 per cent carbonate and/or silicate minerals (plagioclase, biotite, amphibole, chlorite, minnesotaite and stilpnomelane); 30 samples.

Apatite was found to be present in 46 samples in amounts ranging from approximately 3 - 8 per cent. Limonite commonly occurs in minor amounts.

5. GEOCHEMISTRY

Whole-rock chemical analyses of 14 samples from both compositional groups described in the previous section were obtained by X-ray fluorescence spectroscopy. Samples from Group A and Group B exhibit a number of chemical differences (Table 2, compositions 1 and 2).

Besides the high SiO_2 and Fe_2O_3 (total Fe) contents which are characteristic for iron formations, the rocks from Group A and Group B differ considerably in their content of major, minor and trace elements. Some distinguishing characteristics are

- Group A rocks contain higher concentrations of Fe, K_2O and Ba;
- Group B rocks are relatively enriched in TiO_2 (10x the Group A average), Al_2O_3 (5x), MgO (10x), Na_2O (8x), Sr (2x), Zr (13x), Nb (>6x) and Y (1,5x).

The iron-rich rocks from both compositional groups show almost equally high concentrations of P_2O_5 (Group A - 0.94 weight per cent, Group B - 0.8 weight per cent).

Table 2 lists a number of iron formations of Precambrian age. Iron formations precipitated in large intracontinental basins of the mid-Precambrian are widely considered to be of sedimentary origin (James, 1966; James and Trendall, 1982) (Table 2, compositions 3, 8 and 9). This type of iron formation (Lake Superior Type; see discussion below) occurs on a worldwide scale and shows only a small range in the concentration of major constituents.

Iron formations of volcanic association (Table 2, compositions 4 and 5) and iron-rich shales (Table 2, composition 6) show a much wider ranger in their chemical composition due to their more variable mineralogical assemblages. Gole (1981) described metamorphic iron-rich shales (Table 2, column 6) from the Yilgarn Block in Western Australia as occurring interbedded in banded iron formation (Table 2, column 7). Fe-shales and BIF are developed in a mixed metavolcanic/metasedimentary sequence of Archean age. The most common metamorphic assemblage of the Fe-shales (hornblende-almandine-biotite with pyrite, Cr-magnetite and ilmenite) is considered to account for the high concentrations in TiO_2, Al_2O_3, MgO, CaO, Na_2O, K_2O and Cr. Evidence of intermittent volcanic activity during the deposition of iron formations has been given by Goodwin (1956), La Berge (1966 a and b), Trendall and de Laeter (1972), Ewers (1980) and others. The most striking evidence is the presence of devitrified glass shards in Fe-shale bands in iron formations in Western Australia, which may have been derived from volcanic ash that has been highly modified after falling into the iron formation depositional basin (Trendall and de Laeter, 1972).

Lohberg and Horndahl (1983) reported that V/Fe and Ti/Fe ratios of iron-rich rocks may be useful for the determination of the origin of iron formations. They distinguished iron formations of 1) sedimentary origin, and 2) orthomagmatic and volcano-sedimentary origin. The data points of the analysed samples from the Southern Margin Zone were plotted on their diagram of V/Fe versus Ti/Fe (Fig. 8).

Plaksenko *et al.* (1972) studied magnetite quartzites from the area of the Kursk Magnetic Anomaly in the USSR. They state the iron formations of volcanic association have a Ti/V ratio> 25 and a Sr/Ba ratio >1, whereas iron formations of terrigenous association have Ti/V < 25 and Sr/Ba < 1.

Based on Lohberg and Horndahl's diagram (Fig. 8) the iron-rich rocks of Group A are largely of a sedimentary origin as indicated by their low V/Fe and Ti/Fe ratios; the data points of Group B rocks plot in the field for an orthomagmatic or volcano-sedimentary origin. Based on the scheme of Plaksenko *et al.*, the low Ti/V ratio (4,4) and the low Sr/BA ratio (0,33) for Group A rocks imply a terrigenous association; Group B rocks, however, have to be considered of volcanic association due to their high Ti/V ratio (30,6). The Sr/Ba ratio (0,85) is slightly too low to indicate a volcanic association, but may be accepted bearing in mind the low concentrations and high variability of trace elements in iron formations. Iron-rich rocks from both Groups A and B are strongly enriched in P_2O_5 compared with the other iron formations shown in Table 2. The abundance of apatite in the studied rocks (up to 8 per cent, average 3 - 5 per cent) accounts for the high P_2O_5 values.

6. DISCUSSION

6.1 Types of Iron Formations

The definition of iron formation as a generic lithologic term by James (1954) is widely accepted. He defined iron formation as a "chemical sediment, typically

TABLE 2: Average Compositions of Iron Formations

wt. %	1	2	3	4	5	6	7	8	9	10
SiO_2	42.64	45.76	42.2	50.5	41.83	40.84	49.07	50.62	48.2	63.83
TiO_2	0.06	0.64	0.03	0.14	0.21	0.42	0.04	0.06	0.03	0.03
$A\ell_2O_3$	1.39	7.08	1.39	3.0	0.92	8.88	0.7	1.13	0.47	0.76
$Fe_2O_3^+$	49.49	31.03	44.5	41.1	49,5	40.91	45.26	44.2	47.42	31.86
MnO	0.11	0.18	0.73	0.22	0.07	1.06	0.55	0.72	0.08	0.06
MgO	0.21	2.06	1.24	1.53	1.96	5.06	3.46	3.17	2.39	0.16
CaO	2.21	4.01	1.58	1.51	1.9	3.63	2.68	1.98	1.81	0.21
Na_2O	0.3	2.61	0.12	0.31	.	0.33	0.11	0.06	0.49	0.04
K_2O	0.29	0.15	0.14	0.58	.	1.18	0.1	0.17	0.71	0.06
P_2O_5	0.94	0.8	0.06	0.21	0.17	0.11	0.16	0.09	0.22	0.21
ppm.										
Ti	342	3819	162	839	1259	2520	240	350	180	156
Sr	30	55	42	98	72	.	.	.	.	48
Ba	91	65	180	170	53	.	.	.	.	4491
Ni	13	28	32	83	23	87	11	.	9	9
Cr	30	65	122	78	.	307	13	.	10	37
V	77	125	30	97	31	.	.	.	.	124
Zn	33	56	.	.	.	170	36	.	40	111
Cu	17	57	10	96	34	35	44	.	99	922
Zr	10	131	56	84	.	.	.	.	.	18
Nb	—	6	.	.	.	.	.	.	.	—
Y	37	56	.	.	.	.	.	.	.	5
Fe(wt.%)	34.62	21.71	31.12	28.75	34.62	28.61	31.65	30.91	33.17	22.28
Ti/V	4.4	30.55	5.3	8.9	40.6	—	—	—	—	1.27
Sr/Ba	0.33	0.85	0.23	0.58	1.36	—	—	—	—	0.01

($Fe_2O_3^+$ = total Fe as Fe_2O_3); . = not determined.

1-Group A, this study; 2-Group B, this study; 3-Lake Superior BIF (Gross and McLeod, 1980); 4-Algoma BIF (Gross and McLeod, 1980); 5-Kursk Magnetic Anomaly (Plaksenko *et al.*, 1973); 6-Yilgarn Fe-shale (Gole, 1981); 7-Yilgarn iron formation (Gole, 1981); 8-Biwabik iron formation (Lepp, 1966); 9-Brockman iron formation (Trendall and Blockley, 1970); 10-Magnetite quartzite associated with Matchless copper deposit, S.W.A./Namibia.

thin-bedded or laminated, containing 15 per cent of iron of sedimentary origin, commonly but not necessarily containing layers of chert". Two major types of cherty iron formation most abundant in the Precambrian have been established following the UN Symposium on iron formations in 1970 (Bottke, 1981):

- the Algoma type iron formation, which due to its close association with volcanic rocks is largely considered to be of volcanogenic exhalative origin (Gross, 1956; James, 1966);
- the Lake Superior type iron formation, which is considered to have been chemically precipitated in shallow water in restricted intracontinental basins. Volcanic rocks are normally absent in the close vicinity. The iron-rich rocks are commonly finely laminated or banded. The term banded iron formation (BIF) was introduced during investigations of this type of iron formations (see also Table 2).

6.2 Wallrock Associations of the Iron Formation in the Study Area

Mafic schist (amphibole schist) and amphibolite horizons (from a few centimetres to more than 100 m thick) are interbedded in the Chuos Formation and younger formations of the Vaalgras Subgroup (Table 1). Their mineralogy, geochemistry and tectonic setting were discussed recently by Miller (1983 c). The metavolcanic rocks consist mainly of amphibole (hornblende or actinolite) and plagioclase; other components are chlorite, epidote, biotite, stilpnomelane, carbonate and magnetite. Their chemical composition is that of within-plate tholeiitic basalts. The basalts are considered to have erupted as submarine lavas during continental rifting along the southern margin of the developing Damara geosyncline. The metasediments of the Chuos Formation are thought to be derived mainly from clastic sediments deposited on the continental slope and continental rise. The iron formation in the study area occurs within and is interbedded with the metavolcanics and metasediments of the Chuos Formation.

6.3 Evidence for an Exhalative Origin

The iron-rich rocks of Group A are characteristically composed of iron oxide minerals and quartz with minor amounts of apatite present. In places carbonate represents another minor component. Group A rocks are nearly as abundant as the iron-rich rocks of Group B, occurring over the whole extent of the iron formation. They are banded or massive, generally coarse-grained and rarely contain less than 30 per cent Fe. The compo-

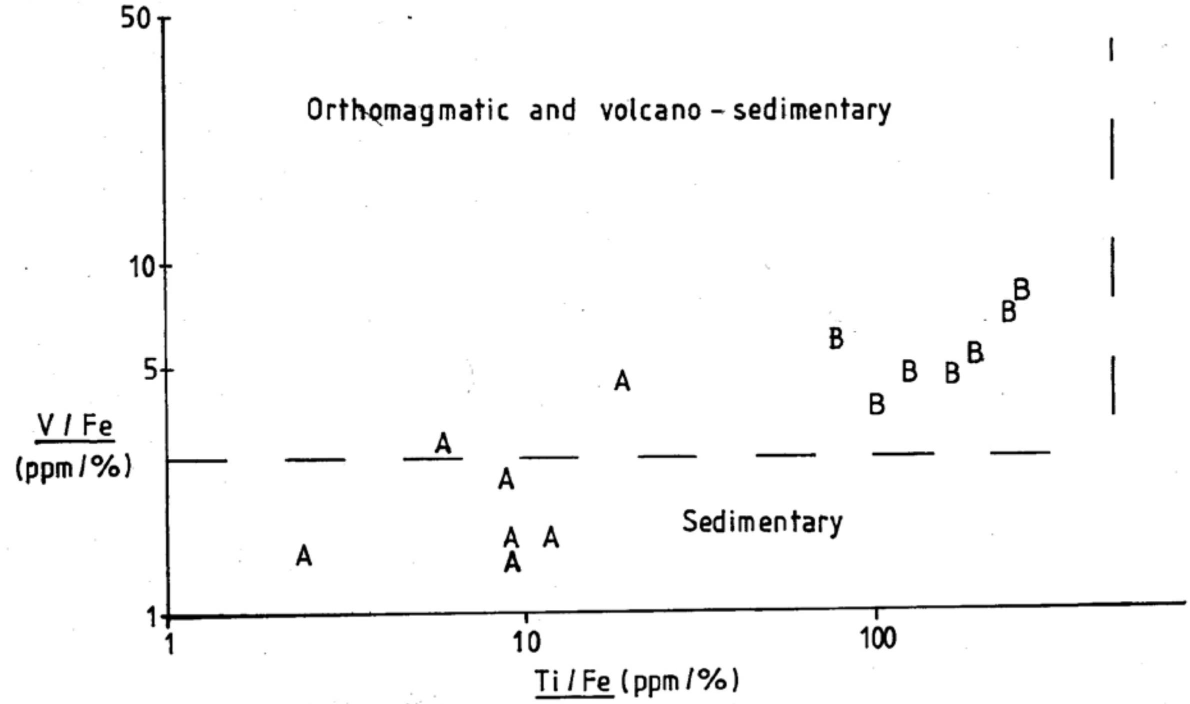


Fig. 8: V/Fe - Ti/Fe ratio distributions (after Lohberg and Horndahl, 1983) of iron formation from the Southern Margin Zone; A - iron formation (Group A), B - iron formation (Group B).

sition of this group of rocks shows low concentrations of Ti, Al, Mg, Na and Zr in contrast to the composition of Group B, which is considered to be due to the low concentrations of silicate minerals. The whole-rock chemistry compares well with the composition of iron formations of the Lake Superior type, the Brockman iron formation in the Hamersley Range and the Biwabik iron formation (Table 2).

In James' (1969) Al-Si-Fe triangular diagram the Group A rock type fits into the field of iron formation proper (Fig. 9). The low content of TiO_2 (0.06 weight per cent) indicates that Ti substitution for Fe in magnetite is restricted, particularly as ilmenite occurs in minor amounts.

Evidence for an exhalative origin is the abundance of P_2O_5 in all analysed samples (maximum value 8 per cent P_2O_5 in a sample from Windhoek Townlands 31). Apatite was recorded as a common constituent in the rocks of both Group A and Group B. High F-rich apatite concentrations (up to 5 per cent P in the iron-rich strata) have been documented by numerous authors from the Kiruna region in Sweden (see Lohberg and Horndahl, 1983). The genetic interpretations of the Kiruna iron ores are still not unanimous but have concentrated after a century of research around two main alternatives, namely an orthomagmatic (ore magma) and a sedimentary exhalative origin.

Iron formation in the vicinity of the Broken Hill orebody in New South Wales, Australia was found to contain a considerable amount of F- and Cl-apatite (P_2O_5 content up to 4 weight per cent). Stanton (1979) suggested that precipitation of the iron formation resulted from a slow leakage of Fe-rich hydrothermal solutions into a sedimentary environment appropriate to the deposition of a chamosite-hematite facies iron formation.

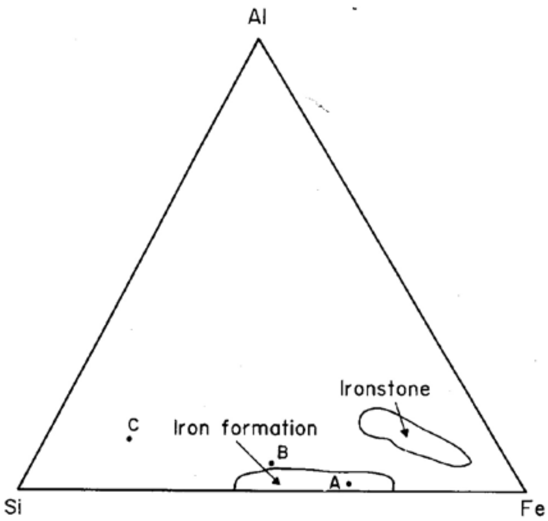


Fig. 9: ASF diagram (after James, 1969) showing compositional fields of typical iron formation and ironstone compared with iron formation and associated metabasalts from the Southern Margin Zone; A - Group A iron formation (7 samples), B - Group B iron formation (7 samples), C - metabasalts (17 samples).

Plimer (1983) considered phosphatic fluorapatite iron formations to be most commonly present as exhalites in sedimentary sequences of the Middle Proterozoic, commonly associated with mafic or bimodal mafic-acid volcanism.

6.4 Evidence for a Volcanic Component within the Iron Formation

Group B horizons in the iron formation contain considerable amounts of actinolite and plagioclase together with Fe-oxides, Fe-silicates (minnesotaite, stilpnomelane, grunerite-cummingtonite), Fe-carbonates and quartz. Minnesotaite, stilpnomelane, grunerite and Fe-carbonates (siderite, ankerite) are common in low- to medium-grade metamorphic phases of iron formation. These minerals are thought to represent the metamorphic equivalents of original assemblages precipitated in environments suitable to the deposition of silicate and carbonate facies of iron formation (James, 1954; French, 1973; Gole, 1981). Fe-Si gels and iron clay minerals (e.g. montmorillonite, illite) are considered original precipitates of the silicate facies; the original precipitates of carbonate facies are mainly iron-carbonate gels (French, 1973). However, compared with the iron formations listed in Table 2, Group B rocks are highly enriched in Ti, AI, Na, P, and Zr. The occurrence of Fe-silicate minerals in the iron-rich rocks of Group B explains the presence of these major elements, but not their anomalously high concentrations. The formation of actinolite and plagioclase implies that silicates other than common Fe-rich varieties existed in the precursor assemblages. It is suggested that these silicates may have been derived from introduced volcanic detritus. The average composition of the interbedded and associated metavolcanics (determined by whole-rock chemical analyses of 17 metabasalts) of TiO_2 = 2.26 weight per cent, Al_2O_3 = 13.26 weight per cent, Na_2O - 2.76 weight per cent and Zr = 128 ppm. suggests they are a possible source for the high concentrations in this group of iron formation. The relatively low concentrations of K_2O (0.15 per cent) and MgO (2.06 per cent) in Group B rocks compared with those of the Fe-shale horizons in the Yilgarn Block iron formation (K_2O 1.18 per cent, MgO 5.06 per cent; Gole, 1981) are attributed to the low amounts of K- and Mg-bearing silicates (e.g. biotite, talc, chlorite) in the assemblages. In James' (1969) diagram (Fig. 9) the Al-Si-Fe composition of the iron-rich rocks of Group B is shown to be intermediate between the composition of iron formation Group A and associated metavolcanic rocks.

7. SUMMARY AND CONCLUSIONS

The iron formation south of Windhoek can be traced in the field as a continuous band along strike. Variations in thickness are related to the number of iron-bearing horizons in vertical succession. Thickening of the unit caused by intrafolial folding was observed mainly in horizons of specularite-quartz rock. The iron formation consists of strongly elongate lenticular iron-rich horizons of varying composition. Lateral variations in composition over a short distance were recorded west of the Kamelberg on Klein Windhoek Townlands 70. In this location the iron formation changes from west to east from a magnetite-hematite-quartz ± apatite rock to a magnetite-quartz-bearing rock dominated by the assemblage amphibole-plagioclase. Based on mineralogical and geochemical features a subdivision into two main groups of iron-rich lithosomes is made. Group A comprises iron-rich quartzites with no or minor silicate and carbonate minerals. Both lithotypes are commonly interlayered in vertical succession. Typical Fe-rich metamorphic minerals in the iron formation are magnetite (martite), specularite, quartz, grunerite (cummingtonite), stilpnomelane, minnesotaite and Fe-carbonates. Martitisation resulting from oxidation of magnetite to hematite was observed at various stages. Microstructures are attributed to an annealing recrystallisation texture. Features of adjustment to unidirectional stress are common in Group B rocks. Significant are the contrast in chemical composition between Group A and Group B and the abundance of phosphorus in both rock types.

We suggest that the iron formation is of volcanic-exhalative origin having been precipitated during a phase of repeated volcanic activity during continental rifting at the margin of a developing geosyncline. The volcanic activity may have provided a sufficient heat source to drive a hydrothermal convection cell leaking Fe-Si-rich fluids into the ocean. Major compositional changes across strike, i.e. inter-bedding of Group A and Group B horizons of iron formation, are attributed to the degree of admixture with volcanogenic material during the sedimentation of the individual iron-rich lithosomes. Chemical precipitation took place in an environment suitable for the deposition of oxide, carbonate and silicate facies iron formation. Iron sulphides were not found in the study area. The iron formation has undergone low- to medium-grade metamorphism.

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