GEOCHEMISTRY OF ANKUR IRON ORE DEPOSITS, NE SUDAN

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ABSTRACT

The iron ore deposits of Ankur area, northeast Sudan, occupy a constant geological position slightly transverse and discordant to the general foliation of the host rocks (biotite schists and andesitic tuffs). The normative composition of the studied ore is calculated to cover the following mineral assemblage; quartz, orthoclase, albite, anorthite, corundum, acmite, wollastonite, enstatite, ferrosilite, magnetite, hematite, ilmenite, apatite and pyrite. Magnetite and hematite showed opposit distribution patterns, which may suggests that hematite is a product of marti- tization of magnetite.

The iron ore of the area under investigation are remarkably enriched in the trace elements; Y, Cu, Co and Cr, and depleted in the content of Ni, Zn, Rb and Sr, compared to the average of the earth's crust. The V module of magnetites reflects a metamorphic origin of the deposits. V^{3+} is believed to be accommodated in the magnetite lattice, substituting for Fe^{3+}, while Cr, Co, Ni and Zn are most probably accumulated by the alumino-silicates. Rb occurs in the potash alumino-silicates, replacing for K. The absence of the correlation between Sr and Ca may favour the believing that the studied deposits are of metamorphic origin.

INTRODUCTION

The iron ore rank of Ankur area is estimated to be about four million tons (of 50—60% Fe). The area belongs to the most important iron ore occurrence in Sudan, namely; Sofaya (Salala), northwest Port Sudan, Red Sea coast.

The rock mass of Ankur area (Precambrian) may be regarded as minor intrusives associated with abundant effusive rocks. The iron ore occupies a constant geological position slightly transverse and discordant to the general foliation of the host rocks, which are composed of biotite schists and weakly schistosed andesitic tuffs.

The petrographical and mineralogical investigations on the same ore (Shaalan, *et. al.,* in preparation) indicated that the ore occurs mainly as magnetite lenticular masses, tabular bodies, veins, disseminated stringers and beds. Five types of country rocks were recognized, namely; metarhyolites, andesitic tuffs, biotite schists, granites and andesites.

EXPERIMENTAL

Complete chemical analyses for forty representative bulk samples of the ore were performed. The samples were collected from three bore holes (BH2 BH3 and BH4). The major oxides; SiO_2. Al_2O_3, total Fe, MgO, CaO and MnO were determind by means of the atomic absorption spectrometry. Na_2O and K_2O were analysed by flame- photometer, while TiO_2 and P_2O_5 by the photocolorimetric techniques. The ferrous iron was determined by the oxidation reduction titration against potassium dichromate. The total sulphur and the ignition loss were determined gravimetrically. The analysis

was done in duplicate, for some samples, using a standardized X-ray fluorescence technique, to ensure the accuracy of the obtained data.

The trace elements; V, Cr, Co, Ni, Cu, Zn, Rb, Sr, Y, Zr, Nb, La, Co and Nd were analysed quantitatively by the X-ray fluorescence spectrometry, using Co and Mo Kα radiation. The methods used for the analysis are given in detail by NORRISH and CHAPPELL [1966] and EASTON [1972].

DISCUSSION

The averages of the obtained results are given in Table 1. The iron ores were classified into three main categories, according to their total Fe content, namely; high grade (>50% Fe), medium (50—30% Fe) and low grade (30—20% Fe). The country rock contains less than 20% Fe.

TABLE 1

Averages of the Chemical Analysis Data of Ankur Iron Ores, NE Sudan

| | High Grade N=15 | Medium Grade N=13 | Low Grade N=2 | Country | | rocks | |
				Meta-rhyolite N=1	Biotite Schist N=4	Andes-ite N=2	Andes-itic tuffs N=3
SiO_2	11.56	26.00	41.05	62.91	48.00	45.00	43.50
Al_2O_3	2.32	5.86	8.90	13.13	12.10	15.90	11.60
TiO_2	0.65	0.40	0.18	0.05	0.16	0.40	0.14
FeO	13.65	14.36	10.39	1.32	5.40	6.80	8.70
Fe_2O_3	64.73	41.14	22.53	7.31	7.32	13.00	16.50
Total Fe	55.85	39.91	23.82	6.29	9.32	14.40	18.30
MgO	2.47	5.87	6.09	2.00	15.50	5.80	7.50
CaO	2.74	4.36	1.98	2.75	0.80	4.90	2.20
Na_2O	0.34	0.22	2.72	5.25	2.60	4.88	4.76
K_2O	0.30	1.22	2.00	0.50	5.60	0.84	1.92
MnO	0.14	0.14	0.09	0.12	0.09	0.15	0.10
P_2P_5	0.61	0.72	0.21	0.28	0.29	0.37	0.67
S	0.16	0.52	0.83	0.07	0.60	0.34	1.01
L. O. I.	1.87	2.37	3.31	4.51	1.77	2.30	1.84
V	279	224	86	13	47	192	62
Cr	38	59	44	15	149	150	92
Co	43	47	38	32	57	111	36
Ni	15	18	19	15	28	56	18
Cu	65	92	154	323	176	194	164
Zn	12	20	19	19	77	37	65
Rb	9	21	32	24	160	26	48
Sr	10	23	40	56	72	319	76
Y	7	29	85	205	127	95	120
Zr	63	154	107	157	24	24	72
Nb	7	10	10	32	21	9	12
La	61	77	59	53	11	16	27
Ce	162	220	166	184	30	50	78
Nd	240	271	195	191	38	52	106

Trace elements in ppm, major components in weight-percent

118

A. Geochemistry of the Major Elements

The geochemical distribution of the major elements was determined by the calculation of the normative composition. The calculation method given by BARTH [1962] and modified by HUTCHISON and JEACOKE [1971] was followed. The averages of the obtained normative composition are given in Table 2.

Averages of the Normative Composition of the Ankur Iron, Ores, NE Sudan

Minerals	High Grade N=15	Medium Grade N=13	Low Grade N=2	Country	rocks		
				Meta-rhyolite N=1	Biotite Schist N=4	Andes-ite N=2	Andes-itic Tuffs N=3
Quartz	3.75	2.38	6.16	22.11	1.10	—	—
Orthoclase	2.32	7.84	13.07	3.10	21.56	5.10	11.82
Albite	3.75	11.62	26.55	49.65	20.67	42.85	41.47
Anorthite	3.37	3.88	4.86	11.35	2.29	18.34	3.13
Corundum	0.64	1.56	0.80	—	0.99	0.50	0.81
Acmite	—	—	—	—	—	—	—
Wollastonite	2.71	4.91	1.57	0.46	0.03	1.74	1.57
Enstatite	8.40	17.60	18.63	5.86	31.11	15.37	18.49
Ferrosilite	—	0.24	—	—	2.47	—	1.11
Magnetite	38.58	33.03	24.39	3.72	11.49	13.70	15.61
Hematite	33.43	14.33	1.30	2.88	0.39	0.13	1.56
Ilmenite	0.90	0.68	0.27	0.08	0.21	0.60	0.21
Apatite	1.67	1.57	0.48	0.61	0.57	0.80	1.47
Pyrite	5.50	1.71	2.43	0.20	1.58	0.92	2.83

The normative calculations showed that iron is distributed among wide variety of minerals. The Fe^{2+} is accommodated within pyrite, ilmenite and ferrosilite as accessory or minor constituents. The main bulk of Fe^{2+} occurs in the magnetite form, with an equivalent quotient of the Fe^{3+} oxidation state. The rest of the Fe^{3+} is mainly present as hematite.

The main alumino-silicates are orthoclase, albite and anorthite. The excess of alumina is calculated as corundum. The extra Ca ofter the calculation of the anorthite was calculated in the form of enstatite.

In general, it can be stated that magnetite and enstatite are main theoretical minerals of the Ankur iron ores and their country rocks. Hematite is a main constituent of the high and medium grades, and it diminishes towards the low grade and the country rocks. The iron ores of the Ankur area are commonly diluted by the alumino-silicates (e.g., feldspars), in addition to enstatite. The three minerals; apatite, pyrite and ilmenite are of minor abundance in all ore deposits.

The contents of magnetite and hematite of the high and medium grades have strong antipathetic distribution patterns. This may support the believing that hematite is a product of martitization of magnetite. Consequently, hematite is formed on the expenses of magnetite.

The distribution patterns of the minerals is very irregular, except that enstatite follows magnetite, wollastonite follows hematite, and orthoclase follows albite, only in the case of the medium grade ore.
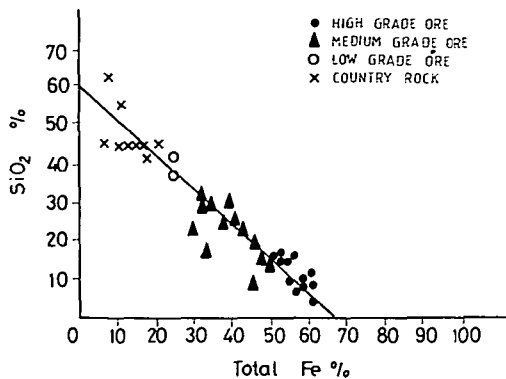
Fig. 1. Relationship between total iron and silica in ores of different grade

The total Fe content of the high grade ore (50 to 64.3% Fe), is almost similar t that of the economic iron ores of Egypt [BASTA *et al.,* 1969], and the Idsas pegmatiti and massive iron ores of Saudi Arabia [ABDELAZIZ, 1977].

The total Fe shows sharp negative relationship with SiO_2 *(Fig. 1)*. Such relatior ship may indicate that the iron ores are mainly diluted by silicate minerals. The corre lation between the two oxidation states of iron is not that simple *(Fig. 2)*. The corre lation is antipathetic for the high grade ore, while it is remarkably proportional fo the medium and high grades, as well as the country rocks. This may indicate tha both Fe^{2+} and Fe^{3+} are mostly accommodated in one mineral form (i.e., magnetite in case of the country rocks and the medium and low grades. In case of the high grad ore, the Fe^{3+} state is predominant, and magnetite is not that preferable mineral form as a result of extensive martitization.

Titanium has a relatively low concentration in all the analysed samples (max 0.78% TiO_2). Ti^{4+} (0.68Å) has a close geochemical affinity to, and may proxy fo
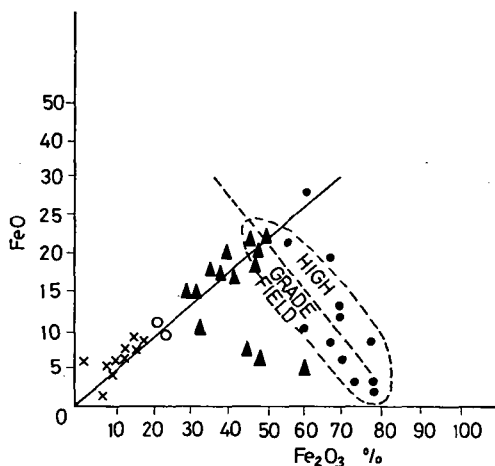

Fig. 2. Relationship between ferrous and ferric iron (denotation of grades is the same as in Fig. 1)

120

Fe^{3+} (0.67 Å). BASTA [1957] pointed out that a considerable amount of Ti can enter to the magnetite structure. Moreover, LISTER [1966] advocated for the opinion that the amount of Ti in magnetite is a rough estimate of the amount of ilmenite in the ilmenite-magnetite intergrowths. Buddington and LINDSLEY [1964] illustrated that the Ti content of magnetite co-existing with ilmenite can be used as a geological thermometer, the Ti content decreases with progressive crystallization, i.e., with decreasing temperature. Regarding the above opinion, the iron ores of Ankur may probably be formed at relatively low temperature.

8. Geochemistry of the Trace Elements:

The mutual abundance distribution of the average trace elements for the different grades of the studied ore *(Fig. 3)* illustrates that the contents of Ti, V, and Mn increase proportionally with iron. Opposite relationships are found for Co, Ni, Cu, Zn, Rb, Sr and Nb, where these elements are relatively enriched in the country rocks.
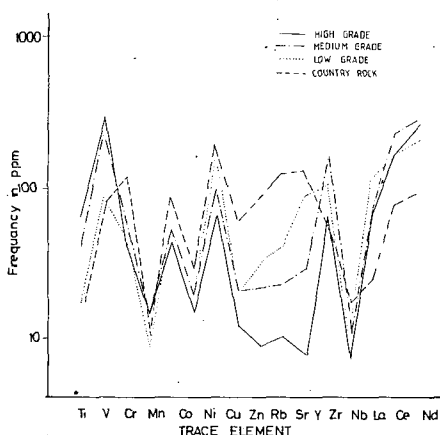
Fig. 3. Distribution of the average of minor elements in the ores of different grades of the Ankur iron ore deposits

The comparison between the obtained average trace elements of Ankur ores and the published averages of other iron ores showed that the heavy metals; V, Cr, Co, Ni, and Cu are much less than their contents in magnetite separated from the pegmatitic ore, magmatic segregation and lavas [ABDELAZIZ, 1977, CHIL-SUP SO, 1978; DUNCAN and TAYLOR, 1968]; But they show some similarities to the metamorphic magnetite deposits of Korea (CHIL-SUP SO, *op. cit*) and the remobilized sediments of Chile (FRUTOS and OYARZUM, 1975).

The following is, however, a brief discussion about some of the analysed trace elements which showed genetic or geochemical significances:

Vanadium: V^{3+} (0.74Å) may substitute for Fe^{3+} (0.67 Å) in magnetite or in the ilmenite-magnetite intergrowth. The titaniferous magnetite is richer in V compared to the pure magnetite [LANDGREEN, 1948]. The relationship between total Fe and V *(Fig. 4)*. favours the above assumption. The segregation of the high grade ore samples in a separate field below the main trend is most probably due to the fact mentioned before that magnetite is not the prevailed mineral form of the high grade ore. GIRGIS [1969]

121

and SHAALAN [1970] are also of the opinion that the content of V increases proportionally with the magnetite content of the rock. MASON [1966] believes that the early segregated magnetite is richer in V.

A quantitative measure of V in magnetite, called the vanadium module ($=100$ V/Fe in magnetite) was introduced by CARSTENS [1939], and followed by many authors, has been calculated for the studied ore. The average V module of the high, medium and low grades are found to be; 0.16, 0.10 and 0.05, respectively, and 0.10 for the country rocks. Such low values reflect, according to VASSJOKI and HEIKKINEN [1952] various effect of metamorphism.

Chromium: Cr^{3+} (0.64 Å) is known to substitute for Al^{3+} (0.56 Å) and Fe^{3+} (0.67 Å) of the iron-alumino-silicates (*e.g.*, spinels), or for Fe^{3+} in magnetite. The Cr content
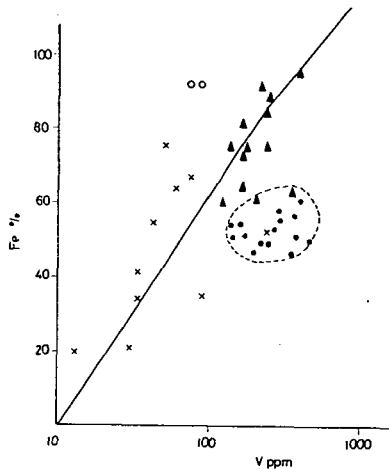

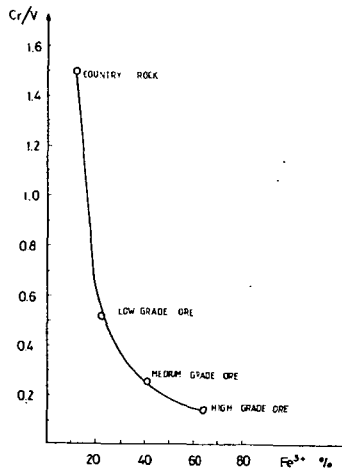*Fig. 4.* Relationship between total iron and vanadium (denotation of grades is the same as in Fig. 1).

Fig. 5. Relationship between ferric iron and Cr/V ratio

122

of magnetite had been correlated to the genetic conditions by WAGER and MITCHEL [1951] and VINCENT and PHILIPS [1954]. They suggested that Cr is separated from the magma mainly during the earliest stage of the fractionation, and accordingly the earlier formed magnetites are richer in Cr. Moreover, TAYLOR [1965] gave the Cr/V ratio similar genetic value, where the ratio decreases as the fractionation temperature decreased.

In the present study the Cr content increases with decreasing of the iron content, and accordingly the highest Cr content is found for the country rocks. V behaves in an opposite manner. Therefore, the Cr/V ratio increases gradually as the Fe^{3+} content decreased *(Fig. 5)*.

The Cr/V ratio of the country rocks (mostly andesitic in composition) is more than 10 times higher than that of the high grade ore. The writers believe, however, that the differences in the Cr/V ratio are related to the mineralogical composition of the ore, and not genetic controls. The ratio increases towards the low grade ore and the country rocks due to the increase of the alumino-silicates, where Al^{3+} can be substituted by Cr, and also because of the decrease of Fe^{3+} which can easily be substituted by V^{3+}.
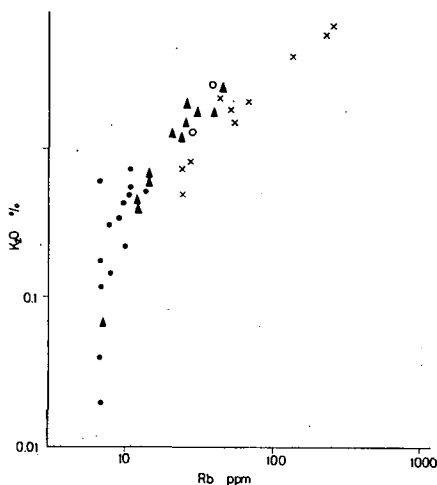

Fig. 6. Relationship between K₂O (in per cent) and Rb (in ppm)

The elements Co, Ni and Zn show tendency to follow Cr in the Ankur ores. Cu shows also some enrichment in the country rocks.

Rubidium: Rb^+ (1.47 Å) is preferentially incorporated in the "12 co-ordination" sites of K^+ (1.33 Å) in the K-bearing minerals. Strong positive correlation is found between Rb and K *(Fig. 6)* in the studied ore. Therefore, the content of Rb increases progressively in the country rocks, where the K-alumino-silicates are predominant.

Strontium: Sr content increases as the total Fe decreases. Y displays similar, but more gradual abundance distribution pattern like Sr *(Fig. 7)*. Sr shows no affinity to follow the Ca content or any Ca-bearing minerals (*e.g.,* anorthite or wollastonite). FAIRBRIDGE [1972] believes that a low level of coherence or the absence of it between Sr and Ca may suggests a degree of metamorphism that is not high enough to allow ass migration and equilibration of the Sr-Ca system. In the studied deposits, Sr (1.12 Å) is most probably entrapped in the alumino-silicate lattice in the K^+ (1.33 Å)
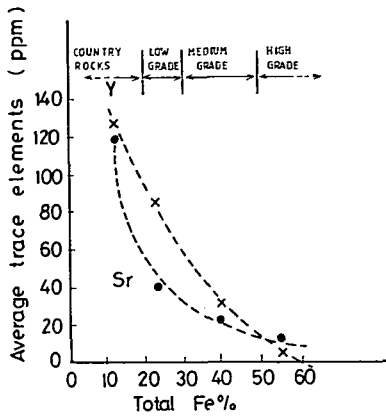
Fig. 7. Distribution of Sr and Y in the ores of different grades, Sr and Y content in ppm plotted
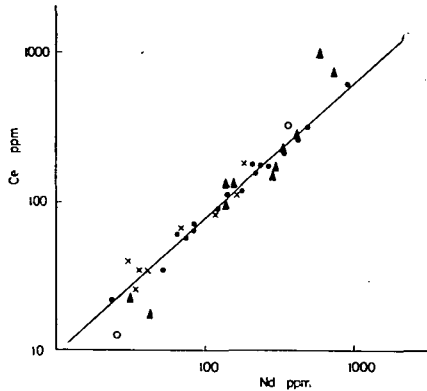*vs* total Fe content (in per cent)

Fig. 8. Relationship between cerium and neodymium (denotation of grades as in Fig. 1.)

position. This indicated from the relative enrichment of Sr in the country rocks which
contain most the alumino-silicates, and also from the sympathetic correlation between
Sr and Al_2O_3.

Rare Earths: In the present work, three members of the rare earths (namely; La,
Ce, and Nd, besides Y) were analysed. It is clear that La, Ce and Nd follow intima·
tely each other *(Fig. 8)*. Y is highly deviated from rare earths, and it shows some simi·
larity to the behaviour of Sr and tends to concentrate in the country rocks as men·
tioned before. In agreement with FAIRBRIDGE [1972]. Zr (0.79 Å) seems to be associat·
ed with the rare earths in the analysed samples.

The rare earths substitute for Ca^{2+} (0.99 Å) in the Ca bearing minerals (WEDE·
POHL, 1972]. In the present study, Ca seems not to be responsible for the accumulation
of the rare earths. They concentrate, however, in the high grade ore and deplate i,
the country rocks.

The highest concentrations of the analysed rare earths are 191 ppm La; 579 ppm
Ce; and 909 ppm Nd. Such concentration magnitude may reflect an acidic compo·
sition of the primary deposits. Metamorphism has not influenced the composition
of the rare earths [HASKIN, *et.al.,* 1966; SCHMIDT, *et al.,* 1963, 1964].

124

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