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The massive sulphides and magnetite deposits of northern Ethiopia

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Abstract

The massive sulphides of northern Ethiopia occur within the Upper Precambrian eugeosynclinal sequence locally known as the Tsaliet and Tambien Groups belonging to the Red Sea Proterozoic basin. The geotectonic history of the basin is interpreted as a cratonised island arc. The age of the sequence is in the order of 1.000 Myr. The early sodic extrusive-intrusive rocks were followed by peralkaline granitoides. The primary mineralisations originated in submarine conditions by volcanic exhalative-sedimentary processes. Sulphide and oxide iron facies coexist, both on a regional as well as on a microscopic scale. Later hydrothermal episodes affected the deposits and rearranged and enriched the ore minerals. The altered enclosing rocks display greenschist facies metamorfphism, whereas the ore minerals and ore texture seem to be little affected. The massive sulphide deposits fit well with the Pb-Zn-Cu-Ag proterozoic type, with zinc and copper strongly prevailing over lead, the metal tenors variable and generally very low.

Kratka vsebina

Masivni sulfidi so v severni Etiopiji vezani na eugeosinklinalne kamenine zgornjega predkambrija, in sicer na spodnji del zaporedja, ki ga v debelini več kilometrov predstavljata lokalno poimenovani grupi Tsaliet in Tambien. Skupaj s še mlajšimi predkambrijskimi kameninami gradita rdečemorski proterozojski bazen, ki obsega današnjo severovzhodno Afriko in Arabijo. Po izvoru vulkanogene in sedimentogene metamorfne kamenine ne presegajo zelenega faciesa. Po izotopskih podatkih je starost zaporedja okrog 1000 milijonov let. Geotektonsko zgodovino severne Etiopije in bližnjega Sudana je mogoče tolmačiti kot kratoniziran predkambrijski otočni lok.

Severna Etiopija pripada metalogenetski provinci s stratiformnimi rudišči pirita, barvnih kovin, magnetita in zlata. Primarna orudenja so nastala v povezavi z geosinklinalnim magmatizmom v obliki izlivov lav na morskem dnu in intruzij v nastalo skladovnico. Zgodnje magmatske kamenine so natrijske in kažejo značilnosti spilitsko-keratofirske skupine. Poznejše granitne intruzije pa so po sestavi peralkalne.

Od znatnega števila doslej znanih rudnih nahajališč jih je bilo le malo nadrobno raziskanih v globino. Orudenja so nastala na morskem dnu pri čemer so rudni minerali precipitirali iz rudonosnih raztopin, ki so uhajale iz razpok, ter se plastovito nakopičili izmenoma med sedimenti in različnimi lavami. Obseg posameznih nahajališč je v splošnem relativno majhen. Za rudne parageneze je značilno, da skupaj nastopajo oksidni in sulfidni železovi minerali. Za nastanek obeh faciesov je bila merodajnejša sestava raztopin kot sedimentacijsko okolje. Zveza s poznejšim plutonizmom pa je bila hidrotermalna rejuvenacija prvotnih rudnih mineralov. Pri tem je prišlo do nadomeščanja, premeščanja in obogatitve mineralnih komponent tako v prvotno sedimentiranih rudnih telesih kot v bližnjih strukturnih prepustnih conah. Na ta način so nastale tudi zlatonosne kremenove žile, ki so jih v Eritreji do nedavnega rudarsko odkopavali.

Izvor rudnih komponent je po vsej verjetnosti magmatski. Za žveplo pa so izotopske preiskave pokazale poleg magmatskega še organogeni morski izvor. Iz tega sklepamo, da so bile v rudonosnih raztopinah udeležene tudi konatne vode.

Vpliv regionalne metamorfoze na masivne sulfide je bil majhen. Po Hutchinsonovi klasifikaciji ustrezajo rudišča proterozojskemu tipu sestave Pb-Zn-Cu-Ag, pri čemer količini cinka in bakra daleč prevladujeta nad svincem. Vsebnosti kovin so zelo nizke in nestalne, posebnost pa je lokalno znatna količina magnetita. Zlato in srebro sta prisotna. Ekonomsko pomembne vsebnosti kovin je mogoče pričakovati le tam, kjer je primarna ruda obogatena zaradi cementacije.

INTRODUCTION

The northern part of Ethiopia is a distinct metallogenetic province characterised by the occurrences of pyritic base metal sulphides, iron oxides and auriferous quartz reefs. Pyritic base metal concentrations have been revealed in the Asmara area and on the plateau, in the Eritrean lowlands and in Tigre Province. The mineralisations appear in the Precambrian eugeosynclinal metamorphic sequence as gossans or massive magnetite bodies, ferruginous cherts and sulphidic disseminations, displaying mainly elongated lens-like shapes cut by numerous veins of white quartz. Their basically syngenetic stratiform features are well evident.

World-wide studies of ores of volcanic-sedimentary affiliation have made much progress during the last two decades, and a large number of papers have appeared. The present article may contribute to this subject. The author was involved in investigations of Ethiopia's ore deposits intermittently since 1962 when employed with the Ethiopian Government; the presented data refer mainly to the pre-1973 period. As regards detailed exploration, little systematic research has been done in northern Ethiopia, access to the field being limited. Regional information is scarce and especially lacking in petrological, geochemical and structural data of the vast region. Regarding the mineralisations, the present conclusions center on five or six more or less explored deposits, the rest of the localities being known mainly from author's reconnaissance work or other cited sources. This paper summarises the gathered information and points to the variety of problems awaiting solution.

Field mapping, core logging, sampling and microscopic examination of rocks and ores have been done by the author who completed also the drafting work. Chemical analyses were performed in the Chemical Laboratory of the Ministry of Mines in Addis Ababa, mainly by S. Kandare. The permission of the Ministry of Mines, to publish this paper and the linguistic help by Dr. John Walsh are gratefully acknowledged.

REGIONAL GEOLOGICAL SETTING

The area referred to in this paper, shown in Figure 1, comprises the extreme southern part of Eritrea Province and the extreme north of Tigre Province.

Knowledge of the regional geology of this part of Ethiopia is still sketchy. Some systematic work has been initiated in Tigre by different authors, but no comprehensive regional mapping has yet been done in Eritrea. The older information such as G. Dainelli (1943), G. Merla and E. Minucci (1938) and others was compiled by P. Mohr (1962) and adapted in the recent Geological Map of Ethiopia (V. Kazmin and A. J. Warden, 1975). Hunting Geology and Geophysics in 1971—1972 carried out an airborne geophysical survey of parts of northern Ethiopia and produced a photogeological interpretation map at 1 : 50,000 scale. Most information, however, resulted from geological investigations of ore deposits and occurrences. A geological sketch-map of the area has been compiled from the available data and is shown in Figure 2.

The Tigre-Eritrean plateau is composed basically of steeply dipping Precambrian metamorphic rocks, intruded by a variety of granitoids. This basement is unconformably overlain by erosional remnants of Paleozoic and Mesozoic sediments, in places covered by the erosional remnants of flood basalts of the Trap Series and intruded by swarms of doleritic dykes. The flows have been dated at 25—19 Myr (P. W. Jones, 1976) and even 36 Myr (G. F. Brown, 1970). The youngest magmatics are late Tertiary alkaline trachytic and phonolitic plugs, most typically developed in the Adua and Senafe areas. The volcanic activity has been continuous to recent times.

The oxidic and sulphidic massive mineral occurrences are intercalated within the Precambrian sequence at numerous localities, and there are probably many more localities still to be found. The mineralisations are closely associated with the Precambrian environment, which is represented by a heterogeneous succession of volcanic and sedimentary rocks, exhibiting a uniform greenschist facies metamorphism. The low metamorphic grade is, in general, the quartz-albite-chlorite-sericite subfacies of the greenschist facies.

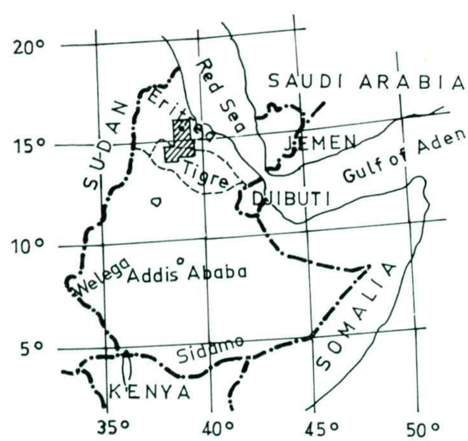
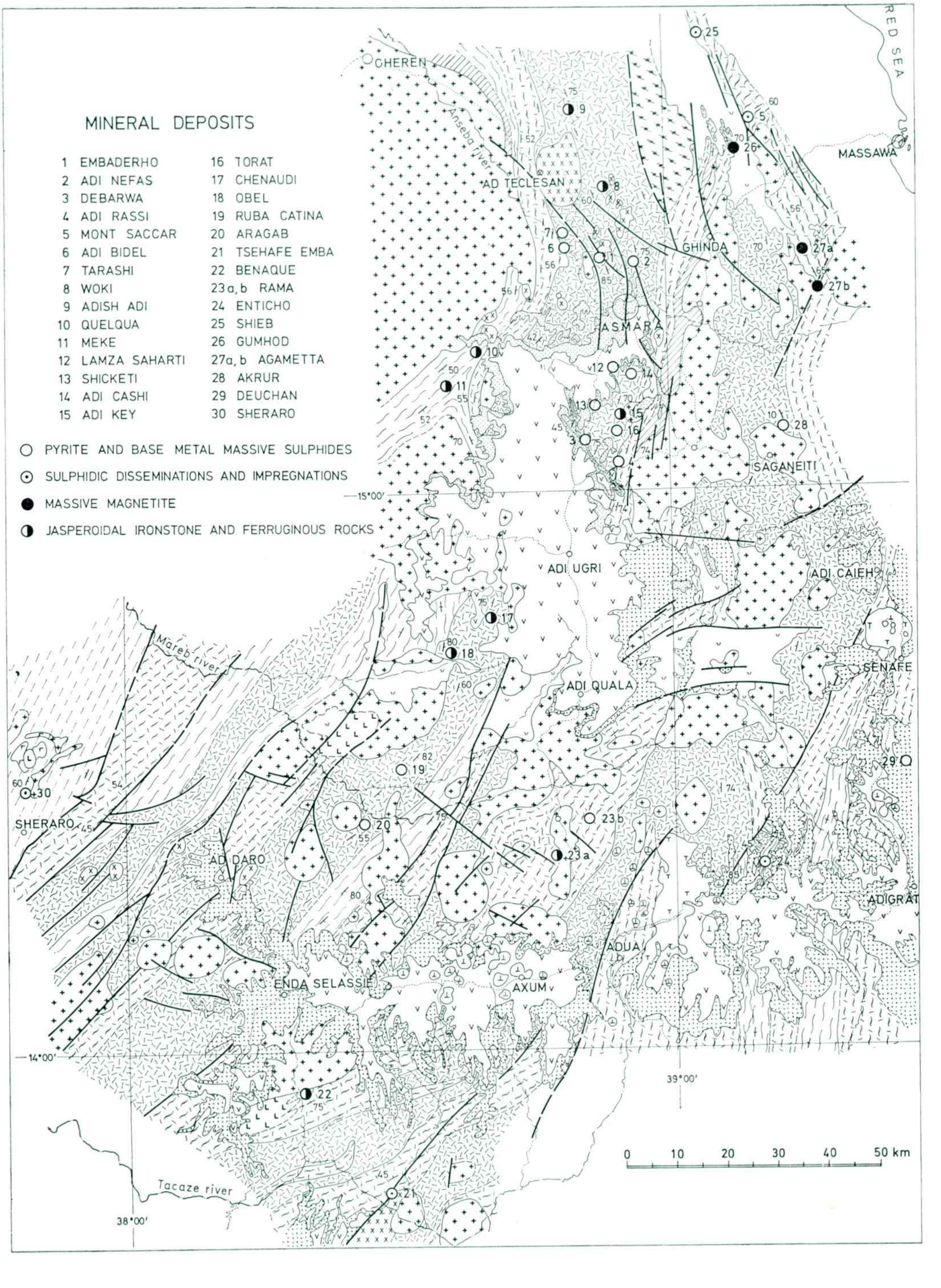


Fig. 1. Location map of the area examined

REFERENCE

LOWER PRECAMBRIAN ?		GRANITIC-GNEISSIC MIGMATITE, AMPHIBOLITE
UPPER PRECAMBRIAN TSALIET GROUP		MASSIVE METAVOLCANICS: INTERMEDIATE AND FELSIC LAVAS; TUFFS, PYROCLASTICS AND AGGLOMERATES; SCHIST, SLATE, FERRUGINOUS CHERT, GRAYWACKE
		SCHISTOSE METAVOLCANICS: VOLCANOGENIC GREENSCHIST, SLATE, PHYLLITE, QUARTZITE, GRAYWACKE; INTERBEDDED LAVAS AND AGGLOMERATES, LOCALLY MINOR LIMESTONE
TAMBIEN GROUP		METASEDIMENTS: SHALE, SLATE, ARGILLITE, GRAPHITIC PHYLLITE, QUARTZITE, GRAYWACKE, LIMESTONE, MINOR CONGLOMERATE
SHERARO FORMATION		SCHIST, PHYLLITE, SANDSTONE, CONGLOMERATE
		HORNFELS (SILICIFIED CONTACT ROCKS)
PERMIAN, TRIASSIC-JURASSIC		QUARTZ SANDSTONE, VARIEGATED SANDSTONE, SILTSTONE, SHALE, GLACIAL TILLITES (EAST OF ADUA)
TERTIARY TRAP SERIES	V V V V	VOLCANICS: BASALT WITH MINOR TUFFS AND CLAYS
	T T	TRACHYTIC VOLCANICS; PHONOLITIC PLUGS
		LATERITE: MOTTLED KAOLINISED AND FERRUGINOUS ROCKS
INTRUSIVES	+ + + +	GRANITE, GRANODIORITE, PORPHYRITIC GRANITE
	X X X X X X X X X	QUARTZ DIORITE, DIORITE
	L L ᒥ ᒥ	GABBROIC ROCKS. ALKALINE SYENITES
RECENT		VALLEY ALLUVIUM
	76	STRIKE AND DIP OF FOLIATION
		FAULT, DOTTED WHERE INFERRED
		MAIN ROAD AND SETTLEMENT
		MAJOR RIVER
		MINERAL DEPOSIT

Fig. 2. Geological sketch-map of the Asmara-Axum area, showing the occurrences of massive sulphides. Compiled from various sources


MINERAL DEPOSITS
1 EMBADERHO
2 ADI NEFAS
3 DEBARWA
4 ADI RASSI
5 MONT SACCAR
6 ADI BIDEL
7 TARASHI
8 WOKI
9 ADISH ADI
10 QUELQUA
11 MEKE
12 LAMZA SAHARTI
13 SHICKETI
14 ADI CASHI
15 ADI KEY
16 TORAT
17 CHENAUDI
18 OBEL
19 RUBA CATINA
20 ARAGAB
21 TSEHAFE EMBA
22 BENAQUE
23a, b RAMA
24 ENTICHO
25 SHIEB
26 GUMHOD
27a, b AGAMETTA
28 AKRUR
29 DEUCHAN
30 SHERARO
PYRITE AND BASE METAL MASSIVE SULPHIDES
SULPHIDIC DISSEMINATIONS AND IMPREGNATIONS
MASSIVE MAGNETITE
JASPEROIDAL IRONSTONE AND FERRUGINOUS ROCKS
RED SEA
MASSAWA
CHEREN
Anseba river
AD TECLESAN
GHINDA
ASMARA
SAGANEITI
ADI UGRI
ADI CAIEH
SENAFE
ADI QUALA
Mareb river
SHERARO
AD DARO
ADIGRAT
ADUA
ENDA SELASSIE
AXUM
Tacaze river
15°00'
14°00'
38°00'
39°00'
0 10 20 30 40 50 km

The rocks were affected by regional metamorphism and only locally by thermal metamorphism. Porphyroblastic textures and recrystallisations are evident.

The Upper Precambrian volcanic-sedimentary sequence originated as a eugeosynclinal accumulation, with felsic magmatics intruded and extruded in more stages during its evolution. The complex was folded and faulted under east-west directed stress, the regional trend of foliation submeridional, the dips variable but near-vertical. The intensely folded sequence may be manifest in the repetition of certain lithologies occurring in alternating parallel belts and zones.

After extensive Paleozoic peneplanation, the Permian continental sedimentation produced sandstones and tillites associated with clays, corresponding to the Dwyka Series of South and East Africa (R. M. Shackleton and K. Lomax, 1974). Mesozoic marine sedimentation followed, the beds largely removed by pre-Trapean (late Cretaceous-early Tertiary) peneplanation, which levelled both Precambrian and younger rocks. It caused extensive surface alteration, the peneplain being evident as a conspicuous horizontal plane of ferruginous-lateritic crust, usually marked by the presence of resistant Paleozoic-Mesozoic sandstones. Tertiary Trap basalts spread on the peneplain, the preserved thickness of the basaltic cappings being not more than several hundred metres.

Lithology

In terms of the division of the Ethiopian Precambrian, the majority of the rocks in northern Ethiopia belong to the Upper Complex, which forms a thick inhomogeneous succession of different lithologies of volcanic and sedimentary origin, and is subdivided into the lower Tsaliet Group and the upper Tambien Group.

Certain rocks are suspected to belong to the Lower Complex: the foliated granodiorites below the metavolcanics in the Enticho area, the amphibolites and biotite granite on the Buri Peninsula southeast of Massawa, and the granitic-gneissic migmatised rocks in the coastal region northeast of Asmara (G. Merla et al., 1973). Similar older rocks also form small outcrops in the Danakil area (J. Brinkmann and M. Kürsten, 1970).

Upper Precambrian volcanic-sedimentary rocks. The Tsaliet Group comprises mostly volcanic rocks of varied character: basic, intermediate and felsic extrusives are interbedded with pyroclastics ranging from coarse agglomerates to fine tuffaceous mudstones and siltstones, with minor interbeds of argillaceous and arenaceous sedimentary rocks such as shales, quartzites, greywackes, in places biohermal limestone and subordinated conglomerate. The strongly chloritised massive and schistose volcaniclastics appear as chlorite-sericite schist, micaceous and augen schist, quartzitic and sericitic greenschist, exhibiting frequently a greywacke affinity. The massive varieties are strongly epidotised, the original texture and mineralogy obliterated; such rocks may have been originally mafic or lithic pyroclastics. The rocks are intimately interbedded with considerable vertical and lateral variations.

The Tsaliet Group is about 1,500 metres thick in Central Tigre (M. Beyth, 1972), its thickness increasing northwards to an estimated order of several thousands of metres in Eritrea. The volcanogenesis is evident; practically the

Table 1 Chemical composition of some extrusive rocks (per cent)

Locality	Sample No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	H_2O^-	H_2O^+	Total
Embaderho	1	66.00	0.30	17.70	1.73	0.84	0.03	1.44	5.67	3.82	0.51	0.17	0.19	0.23	2.09	100.72
	2	71.10	0.18	15.10	0.97	2.08	0.04	0.98	2.15	5.12	0.53	0.15	0.02	0.15	1.21	99.78
	3	66.90	0.30	17.20	1.67	0.71	0.03	1.38	5.70	3.85	0.63	0.17	0.19	0.18	2.05	100.96
Adi Nefas	4	73.60	0.05	15.46	0.56		0.06	0.21	1.50	5.43	1.37				2.14	100.38
	5	64.08		18.58	1.64		0.06	1.24	3.99	2,50	2.00			0.09	5.78	99.96
Adi Rassi	6	59.27		18.05	5.43		0.15	4.07	5.39	4.70	0.70			0.12	2.23	100.11
	7	49.38		15.84	18.85		0.24	3.43	2.98	2.95	0.80			0.50	4.98	99.95
Marahano	8	78.83		10.79	2.35	1.16		0.33	0.19	5.61	0.88	tr			0.67	100.81
Hamasien	9	54.21	0.52	15.11	3.94	5.25		6.42	8.19	3.96	1.91	0.14			1.28	100.93

Provenance of samples:

No. 1 Embaderho. Porphyrite; drillhole EMB 1/70, depth 85.50 m
No. 2 Embaderho. Quartz keratophyre; EMB 1/70, depth 224.15 m
No. 3 Embaderho. Quartz porphyrite; EMB 1/70, depth 310.50 m
No. 4 Adi Nefas. Quartz keratophyre; drillhole AN 5 A/68, depth 76.40 m
No. 5 Adi Nefas. Altered dacite (andesite?); drillhole AN 5 A/68, depth 120.50 m
No. 6 Adi Rassi. Porphyrite outcropping east of the North Hill
No. 7 Adi Nefas. Spilitic magnetite andesite; drillhole AR B/1, depth 105 m
Data from G. Dainelli (1943):
No. 8 Marahano (about 10 km south of Asmara). Keratophyric quartz porphyry
No. 9 Hamasien. Diorite porphyry

whole Group can be accounted for in terms of volcanic provenance. The succession is submarine though some coarse pyroclastics could also have originated subaerially.

The extrusives are recognisable as quartz porphyrites, keratophyres, andesites and more spilitic varieties, texturally massive and schistose, their sodic nature obvious microscopically and chemically. Porphyritic albite is ubiquitous with chlorite, epidote and calcite the alteration products of original mafic silicates. Silica is abundant, forming layers of chert and jasperoidal rocks. Intraformational breccia occurs in places, the clasts lithics and chert fragments, grading to greywacke, the matrix tuffaceous and siliceous. Interbedded mudstone proves subaqueous accumulation.

The extrusives spread as flows on the sea floor probably from fissure openings, together with ejected water-lain pyroclasts and tuffaceous products, some of which may have originated also through nuée ardente type of activity. A metamorphic change of the original lavas of various mineralogic nature to a spilitic-keratophyric assemblage must be assumed as a consequence of the deuteric-fumarolic alteration which will be discussed below. Whether or not there is any cyclicity in the composition of the extrusive layers is not known. P. F. Pagnacco (1969) noted in the area south of Asmara a change from felsic rock types in the west, to mafic types prevailing in the east. More magmatic cycles, starting with basic and terminating with more felsic magmas, could nevertheless be expected.

The chemical composition of the extrusive rocks examined is shown in Table 1. The extensive alteration, as reflected in the present whole-rock chemistry, makes classification difficult. Two analyses (Nos. 8, 9), obviously referring to the same rock types, have been added from G. Dainelli (1943).

The Tsaliet Group is overlain by the more sedimentogeneous Tambien Group, its thickness apparently of the order of several thousand metres. It consists of shale, slate and quartzite with interbeds of volcanogeneous rocks and dark limestone which merge into the former, making differentiation practically impossible. The younger Didikama, Sheraro and Mateos Formations overlie the former two Groups on the margins of the discussed area, either conformably or unconformably, and consist of limestone, dolomite, calcareous sandstone and finer marine sediments (V. Kazmin and A. J. Warden, 1975).

Ultrabasic rocks and their metamorphic derivatives have not been encountered and do not, to the writer's knowledge, exist in the area discussed. Serpentinites exist in the Lower Barca valley in extreme northwest Eritrea (L. Usoni, 1952), and reportedly also in southwestern Eritrea (V. Kazmin and A. J. Warden, 1975).

For practical purposes, and as shown in Figure 2, the Upper Precambrian sequence can be roughly subdivided, on the regional scale, into three lithostratigraphic units: massive metavolcanics are prevailingly massive and schistose extrusives and pyroclastics with subordinated sedimentary rocks, schistose metavolcanics are prevailingly schistose bedded volcanogeneous sediments, and metasediments, on the top of the succession, have been derived mainly from argillaceous-arenaceous-calcareous sediments with very minor reworked volcanic material.

Sulphidic and oxidic ore deposits and occurrences, usually accompanied by quartz veins and skarn-type epidotised rocks, are intercalated within the Tsaliet and Tambien succession. Ferruginous chert and purple siliceous zones also occur in the upper sedimentary unit.

Intrusive rocks. A variety of felsic rock of apparently granitic-dioritic composition intrudes the Upper Precambrian sequence. No systematic petrological examinations and no differentiations on the regional scale have ever been done. The granitoid rocks show variations from foliated gneissose granite merging into surrounding schist, porphyritic granite and granodiorite to fine-grained micrograrite, syenite and diorite, with subordinated gabbro in places. The form of the masses varies between huge irregular or elongated complexes with schistose rocks preserved as roof pendants only, and rounded circular masses of quite restricted dimensions.

The intrusive rocks cover more than half of the area referred to, as in other parts of the northeastern Africa and Arabia, where foliated gneissose granite has been considered "syntectonic", the others, especially minor, rounded or circular, clearly intrusive bosses "posttectonic". Such a simplified division seems inadequate since the intrusives obviously differ in composition, origin and age.

The greater part of the granitic rocks in northern Ethiopia have been identified with the Mareb Granite of the Central Tigre, which intrudes the Tsaliet and the Tambien Groups. The prevailing rock type is a leucocratic, pink, alkali potassic porphyritic granite, euhedral orthoclase and microcline perthite being the prevailing phenocrysts, and sodic plagioclase quite subordinate. The mafic minerals are biotite and hornblende. There are variations in texture and mineral composition within the intrusive bodies. Medium-grained granodiorite is widespread, with quartz and sodic plagioclase present in larger amounts. Quartz may be absent and the rocks grade to monzonite and syenite, the latter occurring as small isolated bosses. M. Beyth (1972) gives the following composition for the Mareb Granite:

SiO_2	Al_2O_3	Na_2O	K_2O (per cent)
68.2-63.6	18.4-14.0	7.12-5.85	2.94-2.67

Some older data for various granites by G. Dainelli (1943) show the following composition (Table 2).

The rocks are peralkaline. C. R. Neary et al. (1976) stressed this feature as being typical of the "Younger granites" in Sudan.

Field evidence suggests that certain rather smaller masses, by their mineralogy, colour index and composition, are closer to diorite. Typical examples are the intrusive rocks northwest of Asmara in the Embaderho-Ad Teclesan area; these sodic granitoids correspond compositionally and mineralogically to porphyritic quartz keratophyre interlayered with massive ore in the Embaderho sulphide deposit.

The chemical composition of the Embaderho quartz diorite, together with two examples of dioritic rocks quoted by G. Dainelli (1943) is shown in Table 3 (Nos. 2, 3).

Table 2 Chemical composition of various granites (After G. Dainelli)

Sample No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5	H_2O^+
1	73.19	-	13.55	0.46	-	0.28	0.94	5.68	4.82	tr	0.40
2	73.96	tr	13.75	0.52	0.99	0.48	1.90	5.62	2.55	0.17	0.25
3	58.67	tr	17.68	2.21	3.85	3.28	4.82	5.86	3.27	0.57	0.49
4	74.36	-	13.56	0.67	1.19	0.29	0.89	4.51	4.93	tr	1.01

Provenance of samples:
No. 1 Adi Enfi (Decamerhe). Granite
No. 2 Fort Cheren. Granite
No. 3 Elabaret east of Cheren. Granite
No. 4 Coatit (Senafe-Saganeiti area). Quatrz diorite

Table 3 Chemical composition of dioritic rocks

Sample No.	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	H_2O^+
1	69.00	0.18	15.30	1.68	0.59	0.03	0.91	5.23	3.83	0.53	0.15	0.04	2.55
2	58.67	0.19	16.21	4.17	3.54		3.19	6.25	5.09	1.89	0.25		1.29
3	51.04	0.72	17.81	3.75	6.17		5.30	8.98	3.81	1.01	0.72		1.48

Provenance of samples:
No. 1 Embaderho. Quartz diorite; drillhole EMB 4/70, depth 198.4 m
No. 2 Adi Berim (Coatit). Quartz diorite
No. 3 Brigantia (Cheren). Amphibole diorite

Although little can be said from one analysis, the composition of the Embaderho quartz diorite (No. 1) seems close to the composition of batholitic granites in Sudan, quoted by C. R. Neary et al. (1976). The rock is, however, extensively altered and difficult to classify.

Some smaller dioritic bosses occur adjoining the granite west and east of Asmara. P. F. Pagnacco (1969) mapped diorite in the Adi Daro area, C. R. Garland (1972) in the Adigrat area and R. M. Parsons (1965) on the eastern escarpment. M. Beyth (1972) observed dioritic stocks associated with the Mareb Granite in Tigre and named them Forstaga Diorite, the typical being a quartz-amphibole diorite with biotite and pyroxene, foliated in places and containing secondary minerals, its composition ranging as follows:

SiO_2	Al_2O_3	CaO	K_2O (per cent)
58.6-53.5	16.2-12.5	6.3-6.0	2.7-1.24

He stated, that diorite was intruded before the Mareb Granite. However, textural and compositional variations between granitic, granodioritic and dioritic rocks are common. Rocks of dioritic appearance, grading into granite, were noted on the margins of the Decamere granitic stock near Adi Rassi, near Dongolo Basso, in the Agametta area, south of Adi Quala, near Adi Daro, at Tsehafe Emba, north of Axum and elsewhere. Dioritic rocks apparently originated by differentiation. However, not all the recognised diorites seem to be comagmatic.

Apart from peralkaline granite characterised by potash feldspar, there is, at least, an intrusive generation of dioritic rocks with abundant secondary minerals replacing virtually all primary mafic minerals. It is subalkaline, sodic, very low in potassium and ferrous iron, with rather high lime content. The petrochemical similarities with the porphyritic-keratophyric types of Tsaliet metavolcanics suggest a common origin, the rocks of the same magmatic episode probably formed by some sort of differentiation of original melts, emplaced partly as domes and partly extruded as flows on the sea floor.

Other rock types present in forms of smaller bosses, apparently differentiation products as well, are gabbros and syenites. The Gemahlo ring complex in the extreme west of the area has a gabbroic-syenitic core surrounded by porphyritic microgranite. Many similar rings, about 83 recognised so far, occur in the northeastern Sudan and appear to be of the "Younger granite" type, their actual age uncertain (J. R. Vail, 1971; 1973; J. C. Briden, 1973).

The thermometamorphic effects are hardly to be found on the contacts with intrusives; they emplaced apparently at shallow depths and were relatively poor in volatiles, producing only modest metamorphic aureoles.

Numerous aplitic and porphyritic dykes intersect all rock types in various directions, their age uncertain, apparently belonging to further stages of magmatism. The prevailingly fine-grained leucocratic rocks are rich in feldspar and mostly strongly weathered (kaolinised) on the surface. Melanocratic metadoleritic dykes occur in places.

Auriferous quartz veins. Following the planes of weakness along foliation, there are numerous auriferous quartz veins and reefs in Eritrea, the gold grades variable between 2 and 30 grammes per ton. Epidote, chlorite, carbonate and sericite are associated with scarce sulphides, copper stainings frequent. The veins are varied in lenght, width and depth, the largest up to several hundred metres long and several metres wide. They were extensively mined in Eritrea in the past (L. Usoni, 1952; D. Jelenc, 1966). The age of emplacement of auriferous reefs is uncertain.

Time relations and correlation

Regarding the ages of Precambrian rocks in Ethiopia, no systematic dating has been done. A correlation was attempted by V. Kazmin (1975), who originally ranged the Tsaliet Group within the 1,000—750 Myr interval, but considered later lowering it within the middle part of the Upper Proterozoic (1976).

The number of random radiometric age determinations of the Precambrian in Ethiopia is more than 50. The majority of ages in different rock types fall within to range of 550 $\pm$ 100 Myr, defining the Pan African thermo-tectonic episode or event (W. Q. Kennedy, 1964; H. M. E. Shürmann, 1964), and reflecting the Mozambiquan rejuvenation which is evident over the whole of East Africa.

Seven K/Ar determinations from northern Ethiopia and nine from southern Ethiopia gave isotopic ages older than 650 Myr, of which three Rb/Sr ages of gneissose-granites fall within the range of 680 Myr, and one, for a metamorphic rock, gave an age of 1,030 ± 40 Myr (A. M. Chater, 1971). In western Ethiopia two K/Ar ages near 1,400 Myr were obtained on granitic rocks, and one age 794 ± 40 Myr for a "younger" dioritic rock intruding the former, its lithology variable and comprising also syenitic and gabbroic rocks (Metal Min. Ag. of Japan, 1974, unpublished report).

A summary of age determinations higher than 650 Myr is given in Table 4.

The scattered isotopic data of varied provenance and mainly by K/Ar method, with little reliable field geological information and even less complementary petrological, geochemical and structural studies, must be treated with caution. They nevertheless suggest that the basement might have originated much earlier than the discrepant Pan African 550 ± 100 Myr apparent ages indicate.

There has been much uncertainty about the ages of the granitoids in Sudan. The earlier Batholitic granite shows gradational assimilation boundaries, whereas the Younger granite appears in discrete bodies of variable lithologies intruding the earlier, and associated with comagmatic extrusives (I. R. Gass and C. R. Neary, 1970). The granite of the northeastern Sudan shows apparent Mozambiquan K/Ar age in the 630—420 Myr range (J. R. Vail and D. C. Rex, 1970; J. R. Vail, 1971). A. J. Whiteman (1971) reported a minimum 740 ± 80 Myr age for the Younger granite. B. J. Cavanagh (1974) gave, on Rb/Sr analyses, a 465 Myr age for the Younger granite, and for the Batholitic granite the order of 590 Myr, but for the extrusives 670 Myr. C. R. Neary et al. (1976) established that the Batholitic granite, together with the oldest phase of the Younger granite and volcanics as well, all carry an isotopic age of about 700 Myr and belong to the same magmatic cycle.

The age of emplacement of younger granite ring complexes was believed by J. R. Vail (1973) to be mainly Paleozoic. J. C. Briden (1973), however,

Table 4 Isotopic age determinations higher than 650 Myr

Province	Number of determinations	(Minimum) age range Myr	Method	Rock types
Eritrea	5	690–650	K/Ar	granitoids; porphyrite
	1	754	"	pegmatite
	1	976	"	mica schist
Sidamo	5	around 650	K/Ar	gneiss, pegmatite, granites, amphibolite
	3	680	Rb/Sr	gneisses
	1	740 ± 15	K/Ar	gneiss
	1	1,030 ± 40	Rb/Sr	phyllite
Welega	2	1,400	K/Ar	foliated granitoids
	1	794 ± 40	K/Ar	"younger" granite (diorite)

gave the corresponding minimum age estimate of 750 ± 50 Myr by paleomagnetic reversal chronological study. There are at least three phases of younger granites in Sudan, the last two having ages of 500 Myr and 100 Myr (C. R. Neary et al., 1976).

For southern Egypt, M. Y. Meneisy (1972) reported a number of Rb/Sr ages in the range of 1,365—1,150 Myr, which might be "the age of the main Precambrian metamorphism". However, the ages of synorogenic plutonites in Egypt range between 1,000—800 Myr. Another widespread magmatic activity took place around 600 Myr, and a younger episode took place between 100—70 Myr.

In Saudi Arabia, according to G. F. Brown (1970), the major plutonic events seem, from mostly Rb/Sr determinations, to have occurred at about 1,000, 735—720, 670—660 Myr, the latest 570 Myr data reflecting the Pan African event. An extremely thick volcanic-sedimentary sequence is cut by intrusives of the 1,000 Myr epoch. Syntectonic gneissic rocks and intermediate massive, discordant calc-alkaline granites, comparable to synorogenic plutonites in Egypt, range in age from 1,000—710 Myr (G. F. Brown and R. O. Jackson, 1960). The discordant post-tectonic younger granites generally occur as circular batholiths. Intrusive felsic rocks of Mesozoic age were found as well (M. Gillmann, 1968).

In light of these data, a tentative dating of the basement in northern Ethiopia can be attempted. The Tsaliet and the Tambien Groups are intruded by granitoids, and the field data suggest more stages of felsic intrusions. The petrochemical data, insufficient as they are, point to a similarity between some of the intrusives and the extrusives of the Tsaliet Group. It might be therefore possible that the oldest foliated granitoids such as quartz diorites, the early stages of later granitoids and the extrusives of the Tsaliet Group are comagmatic, representing the intrusive and extrusive phases of the same magmatic event, limited to a relatively short time interval. C. R. Neary et al. (1976) came to similar conclusion for the early magmatism in north-eastern Sudan.

If the isotopic ages around 1,000 Myr are "real" relict dates reflecting the earlier metamorphic events, then the Tsaliet succession would be at least 1,000 Myr old. How "real" two 1,400 Myr K/Ar ages for Welega granitoids are is not clear for the time being; they are better treated with caution. If the early intrusive magmatism was coeval with the eugeosynclinal volcanism, then the oldest granitoids might correspond to the synorogenic plutonism of 1,000—800 Myr age in Egypt and Saudi Arabia. This was a period of major tectonic activity in the Earth's geological history, accompanied by magmatism of regional proportions (H. P. Bott, 1971). The early magmatics probably originated from differentiated (ultramafic) mantle and possibly also, at least partially, by anatectic crustal melting. Later upsurges of the magma followed, the "younger" intrusive events indicated to have occurred at about 800—740 Myr and 690—650 Myr, possibly followed by the early Paleozoic and later Mesozoic-Tertiary plutonism, corresponding to the established phases in Sudan, Egypt and Saudi Arabia, the ages of the later plutonism bearing the regional Mozambiquan inprint.

The stratiform sulphide deposits apparently originated from the oldest magmatic cycle of 1,000 Myr range. Later episodes were involved in subsequent hydrothermal rearrangements. Massive base metal deposits of volcanogenic origin exist in Saudi Arabia in similar environment (Dr. Garnet, pers. comm.), as well as in southern Egypt (T. Ivanov et al., 1973).

M. Beyth (1972) and V. Kazmin (1975) attempted correlations of the Upper Precambrian formations with those of the adjacent countries. The absence of reliable chronological data and facial variations at widely separated localities make such attempts difficult. Nevertheless the Tsaliet Group was correlated with the Halaban Formation of Saudi Arabia and the Dokhan Formation of Egypt, and the Tambien Group with the Murdama Formation of Saudi Arabia. However the thickness of the geosynclinal volcanic-sedimentary sequence in Saudi Arabia is of the order of tens of kilometres (G. F. Brown, 1970), and something less in Egypt. The lower limit of the Halaban, set at about 1,000 Myr (A. H. Sabeth, 1972) might be, together with the Dokhan Formation, even older. The Tsaliet Group may therefore correspond to the lowest part of the Halaban Formation or even to the Baish greenstones underlying it, the corresponding element in Sudan the Nafirdeib Series (A. J. Whiteman, 1971; A. H. Sabeth, 1972).

Structural features

The available data on pre-Cretaceous (pre-Rift) tectonic in northern Ethiopia suggest that major orogenic deformations affected the region. The absence of systematic studies makes the interpretation of the early regional tecto--geology difficult.

A dominant submeridional geological trend is obvious in the structural pattern of the Precambrian assemblage, swinging from the meridional direction in the Asmara area gradually westwards in central and western Tigre. The foliation and bedding are generally conformable. The rocks have been tightly folded, the axes of isoclinal folds trending in the same direction, the variable dips generally steep. C. R. Garland (1972, unpublished report) observed monoclines, open folds, also recumbent folds and thrusts in central Tigre, the axial planes of overturned folds dipping west and northwest. Tight isoclinal folding is clearly evident in western Tigre, the attitude of the beds steep. Vertical dips prevail also in the Asmara area where the folding is evident in the repetition of units. All the deformations were caused by east-west directed compression.

Major faulting, trending in the same directions, has been recognised, the fault planes either vertical or steeply inclined west. Low-angle thrust-faulting is suspected as well, paralleling the bedding and hence difficult to recognise. Such a structure is indicated in western Tigre, where the Sheraro Formation discordantly overlies the volcanic-sedimentary complex. These dislocations within the Precambrian sequence are considered to be mainly of early origin, forming arcuate lineaments more or less oblique to the trend of the eastern escarpment, which is associated with the post-Cretaceous rifting. The faulting, representing the main tectonic stage in the post-Paleozoic period, is associated with the formation of the Rift system. The uplifting of the plateau is confined mainly to the proximity of the escarpment, the fault planes dipping steeply east, the displacements eastwards (P. M o h r, 1962). Younger faults on the plateau cut across the Precambrian lineaments either parallel to the Rift trend or obliquely to it, with minor lateral and vertical displacements. Rift tectonism was accompanied by basaltic eruptions, from the Trap Series covering the plateau to the recent volcanism, which is still active in the Afar today.

DESCRIPTION OF DEPOSITS AND OCCURRENCES

The known ore deposits and occurrences are shown in Figure 2. They appear as conspicuous elongated outcrops, conformable with the bedding of the enclosing rocks, but exhibit also irregular, breccious or fissure character, their size rather restricted in dimensions. Some of them have been more or less explored and the majority reconnoitred only. The main primary ore minerals in order of abundance are pyrite, sphalerite, chalcopyrite, pyrrhotite, magnetite, galena and some minor sulphides. Silver and gold are present and associated with the sulphides. The primary gradings are rather low; increased tenors have originated mainly in secondary enrichments.

Embaderho

The prospect is situated 10 km northwest of Asmara. It was explored during 1969—1971 by detailed mapping, soil geochemistry, some magnetic and electromagnetic survey and deep drilling (7 holes totalling 1,363 m).

The "S" shaped gossan is about 1 km long and up to 100 m wide, conformable within the foliated rocks and dissected by longitudinal faults, as illustrated in Figure 3. Weathered quartz diorite outcrops to the east, and another smaller boss of granite porphyry merges into the adjacent schists to the west. The enclosing lithologies are massive epidotised volcaniclastic greenstone, tuffaceous greenschist, quartzose hornfels rock, chlorite schist, mica-sericite schist, pyritised quartzitic rock, all varying laterally and vertically, intimately interbedded with porphyritic-keratophyric layers and massive amphibole--chlorite cherty rocks. Numerous aplitic dykes and quartz veins are scattered in the area, the largest the 600 m long Medrizien quartz reef nearby, being mined for gold in the past, the grading 3 to 8 grammes per ton (L. U s o n i, 1952). It is surrounded by hydrothermally affected sericitised and silicified rocks.

Beds of massive sulphides occur within the sequence. Drillhole EMB 1/70 (45^0, 315.15 m) intersected 20 layers of massive ore, some several metres thick, and numerous beds, bands and zones of disseminated sulphides, together with more than 40 layers of porphyritic extrusives. Drillhole EMB 7/71 (45^0, 114 m) intersected more than 30 m (true thickness) of massive pyritic ore, and other drillholes revealed abundant ore and extrusive layers as well. Drill sections are illustrated in Figure 4.

Petrography. The interlayered porphyritic rocks are prevailingly leucocratic fine- to medium-grained with low, slightly variable colour index, the textures felsophyric and felsitic. Quartz and feldspar occur as phenocrysts, the former

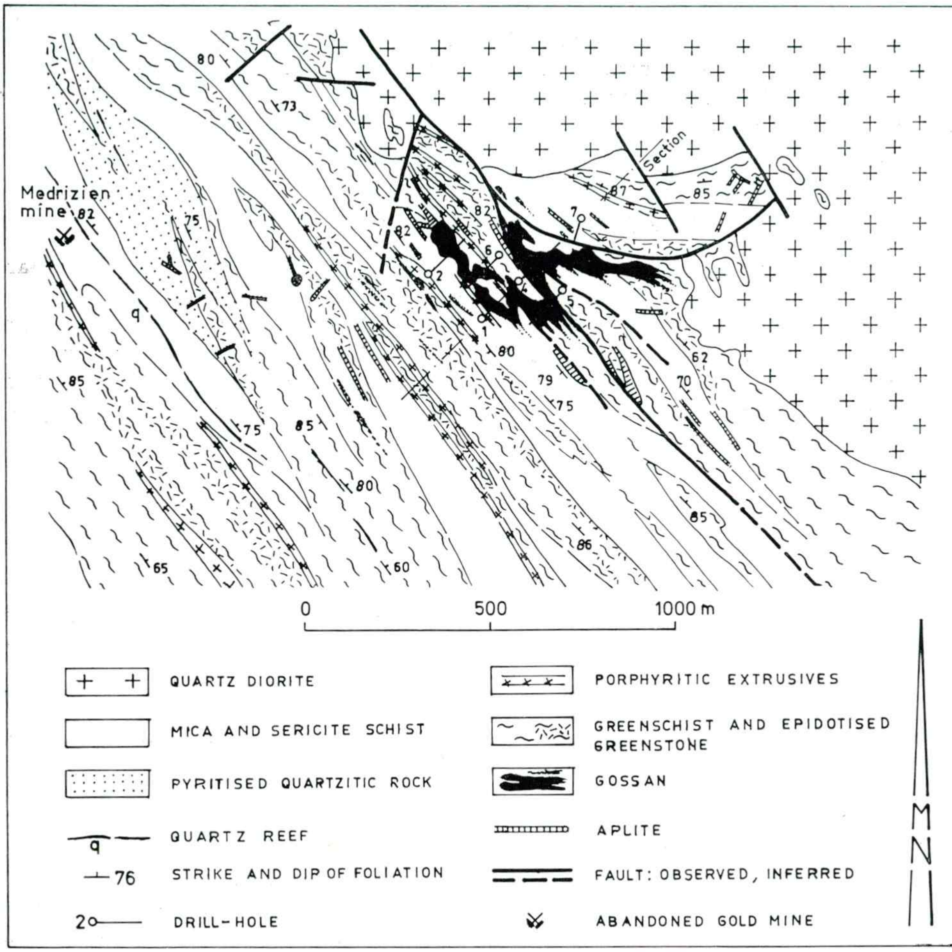


Fig. 3. Geological map of the Embaderho prospect

in bluish, corroded, rounded grains up to 5 mm in size, the latter smaller and strongly replaced by a turbid, opaque aggregate. Twin measurements normal to (010) indicate albite to albite-oligoclase. Remnants of hornblende are rare. There is white mica but no biotite, and chlorite and epidote are ubiquitous. Strong alteration has replaced the primary minerals by a fine-grained mosaic of chlorite, zoisite, sericite, epidote, calcite and quartz, all of them forming the microcrystalline matrix. Minor irregular sulphides are present as well.

The outcropping intrusive rock in the Embaderho area, though weathered, is similar in appearance. Encountered at depth in drillhole EMB 4/70, a gradual textural transition from porphyritic into hypidiomorphic granular massive rock was revealed, the mineralogy essentially the same as in the extrusive porphyritic layers. The strongly altered rocks can best be designated as quartz diorite.

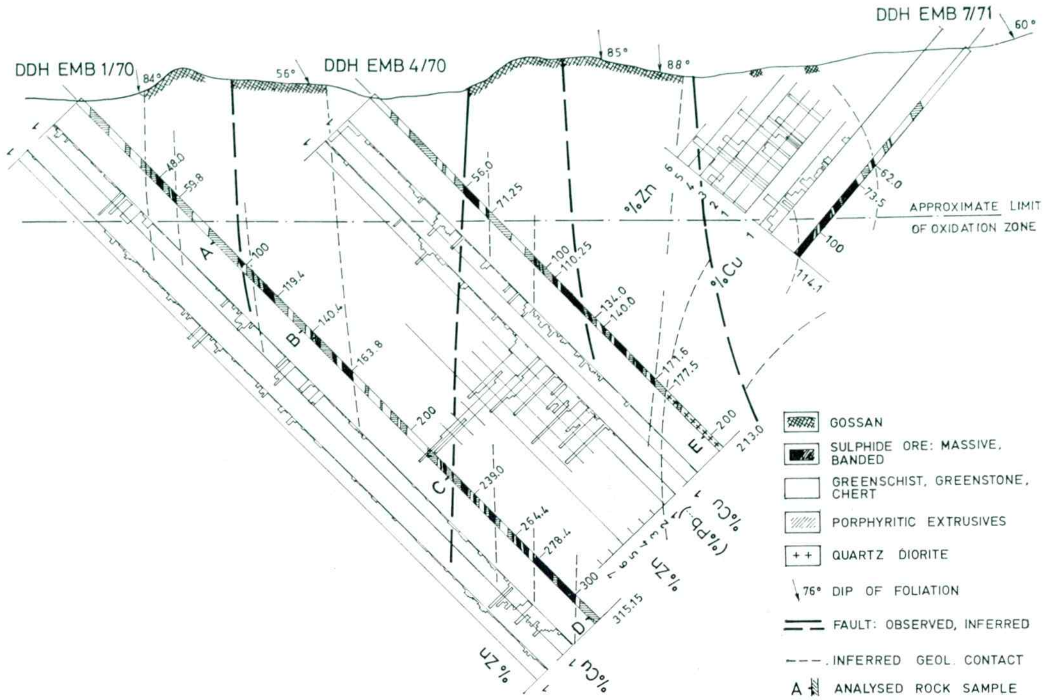


Fig. 4. Sections of drill-holes EMB 1/70, 4/70 and 7/71, and Cu, Zn tenors at Embaderho

The quantitative mineral composition of 4 samples of the Embaderho extrusives and one sample of quartz diorite is given in Table 5.

Compositional and chemical similarities (Tables 1, 3 and 5) suggest that the intrusive and the porphyritic rocks are comagmatic, derived from the same source and apparently coeval. These rocks have been extensively altered. To what extent the present composition — high alumina, magnesia and lime contents, low sum total of alkalies with sodium exceeding potassium nearly 7:1 and low ferrous iron — reflects that of the original magma, or if it is due to a later metasomatic redistribution of components, has not yet been sufficiently examined. The determinations of alkalies and earth alkalies on a number of rock samples, visually selected as altered to different degrees show, as Table 6 illustrates, that magnesium and calcium contents sharply increase with stronger alteration, whereas sodium seems to decrease and potassium remains unaffected.

A tentative conclusion can be made that the original early magma produced shallow domal intrusions under the depositional basin, at the same time erupting subaqueously on the sea floor forming alternating flows with sediments and stratiform sulphides. A close genetic link with the formation of the sulphides is implied via solutions to which, partially at least, the extensive rocks' alteration must be attributed. Whatever the origin of albite — either magmatic or due to soda metasomatism in the early stages of magma consolidation from earlier more calcic plagioclases — lime and magnesia must have been intro-

Table 5 Mineral composition of magmatic rocks at Embaderho

	Porphyritic extrusives				Quartz diorite
Samples:	A	B	C	D	E
Phenocrysts: Quartz	5	2	8	7	15
Feldspar (albite)	35	35	30	30	35
Hornblende	-	-	-	-	2
White mica (sericite)	10	15	8	15	10
Chlorite	10	7	20	5	8
Epidote and zoisite	12	5	8	8	5
Calcite	3	2	2	3	3
Granular opaque matrix	25	34	24	32	32

Samples are:
A Porphyrite; drillhole EMB 1/70, depth 85.5 m
B Quartz keratophyre; drillhole EMB 1/70, depth 136.2 m
C Mesocratic quartz keratophyre; EMB 1/70, depth 224.2 m
D Quartz porphyrite; drillhole EMB 1/70, depth 310.5 m
E Quartz diorite; drillhole EMB 4/70, depth 198.4 m

Table 6 Alkalies and earth alkalies in variously altered extrusives at Embaderho

Drillhole	No. of samples	MgO	CaO	Na_2O	K_2O	Rock type
EMB 4/70	5	1.02	4.15	4.34	0.69	Quartz diorite, slightly altered
	1	0.96	4.00	7.40	0.78	Aphyric porphyrite, slightly altered
	9	1.34	5.68	4.21	0.76	Altered porphyrite
	1	1.55	8.40	6.30	0.72	Aphyric porphyrite, strongly altered
	1	2.01	9.6	1.25	1.27	Porphyrite, strongly altered
	1	8.8	13.4	0.33	0.19	Quartz keratophyre, extremely altered
	2	1.1	3.03	6.25	0.61	Contact of porphyrite with ore

duced from an extraneous source by solutions, which apparently caused epidotisation, zoisitisation and carbonation of the original rock.

The same low-temperature hydrous mineralogy is observed also in the schistose members of the volcanic-sedimentary pile: chlorite, white mica, epidote-zoisite, tremolite-actinolite, talc, quartz and some albite and calcite are the essential constituents. Pyrite metacrysts (?) in these rocks are arranged in bands parallel to foliation, often corroded, fragmented and altered to secondary limonitic products surrounded by patches of chlorite and epidote. Biotite is completely absent in the schists as well, though there is phlogopite in certain parts of the rocks, usually associated with sulphides, and seemingly a secondary mineral.

Contacts of ore with greenschists are mainly gradational, with streaks of disseminated sulphides and magnetite in chlorite- and epidote-enriched schists, the rocks dense and cherty. Contacts of porphyritic flows with massive ore are sharp and marked by a narrow zone of fine-grained granoblastic of nematoblastic intergrowth of lime-bearing silicates, with abundant chlorite, sericite, phlogopite and calctie. In ore, coarse crystalline pyrite marks the contact, with interstitial quartz and locally concentrated chalcopyrite.

Ore mineralogy. The mineral paragenesis of the Embaderho ore is rather simple.Pyrite is the most abundant sulphide mineral. At least three generations are present. The early euhedral pyrite in grains up to 15 mm in size is usually poeciloblastic and corroded. It apparently crystallised first, together with lime silicates and magnetite, and was replaced by other sulphides. Another generation forms irregular granular masses, clustering around larger grains and interbanded with younger sulphides (Fig. 5). The bulk of pyrite occurs as a globular aggregate of densely packed oval grains, with interstitial quartz, calcite and small amounts of other sulphides. There is also a microcrystalline gel-pyrite, occuring in irregular rounded forms of apparently colloform origin.

Magnetite forms individual euhedral crystals up to 10 mm in size; poecilitic inclusions of pyrite, and blebs of pyrrhotite and sphalerite are common (Fig. 6). The bulk of magnetite occurs as finegrained masses, usually associated with granular sulphides in narrow alternating bands. It is intimately associated with sulphides but much less abundant than pyrite.

Pyrrhotite, too, occurs in fine-grained porous form, mixed and interbanded with other sulphides (Fig. 7). Together with magnetite it is found in deeper parts of the sequence only, forming massive ore and in places prevailing over pyrite. Associated with coarse chalcopyrite it forms also distinct vein-like inclusions in massive ore.

Chalcopyrite seems to occur in at least three generations: as inclusions in the early euhedral pyrite and magnetite, as unoriented exsolution blebs in dark sphalerite associated with massive magnetite-pyrrhotite ore (Fig. 8), and as individual subhedral grains and interstitial fillings. It forms replacement rims around the early pyrite, and it is seen to grade into gel-pyrite.

Sphalerite is the most abundant base metal sulphide. It occurs in irregular grains and shows mutual boundaries with chalcopyrite. At least three generations are present. A dark brown xenomorphic variety is closely associated with granular magnetite and contains minute exsolution blebs of chalcopyrite. It is also poecilitic in the early pyrite and forms interstitial fillings in mosaic pyrite, replacing it. Another deep yellow resinous variety appears interstitial on higher levels, and in veins with quartz and other sulphides.

Galena is obviously a later constituent and is present in very minor amounts, mainly in globular pyrite ore, replacing pyrite. It is found also in bands of disseminated sulphides within the greenschist, and occurs associated with lime silicates and vein quartz as well.

Chalcopyrite and bornite occur occasionally at upper levels, both apparently of supergene origin.

Quartz is the main gangue mineral. Silicate gangue minerals epidote, tremolite-actinolite, chlorite, white mica and phlogopite occur in prismatic crystals and felted aggregates, usually idiomorphic against opaque minerals, or forming the matrix in which they are embedded. Crystalline calcite is abundant in places. Gypsum was also identified in banded ore, its hypogene or supergene nature unclear. Deep green chlorite and epidote occur with sulphides in vein quartz, and andradite is exceptionally present as well.

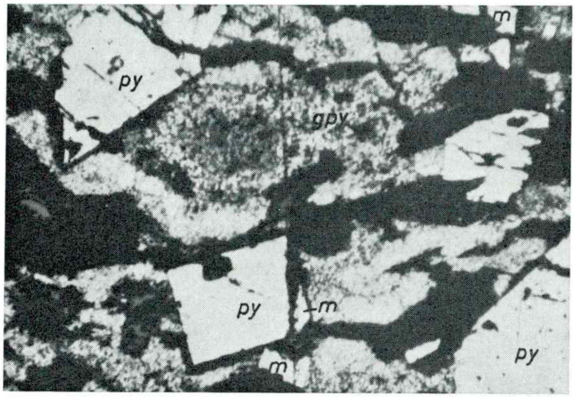


Fig. 5. Early euhedral pyrite surrounded by gel-pyrite. Spec. EMB 1/70; No. 15. × 150

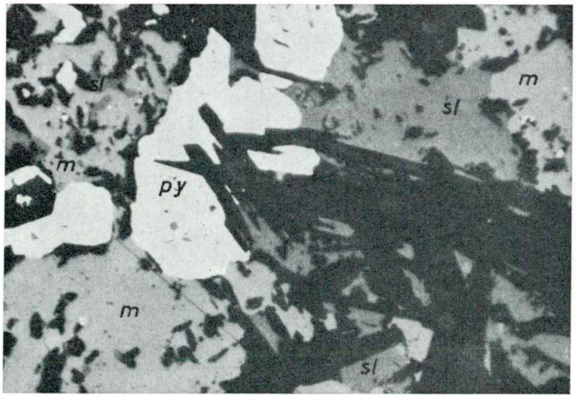


Fig. 6. Granular pyrite-magnetite-sphalerite ore, intergrown with lime-iron silicates. Spec. EMB 4/70; No. 59. × 150

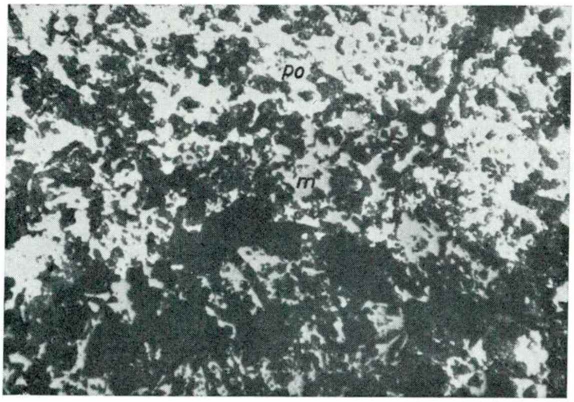


Fig. 7. Irregularly shaped texture of pyrrhotite-magnetite ore. Spec. EMB 1/70; No. 15. × 150

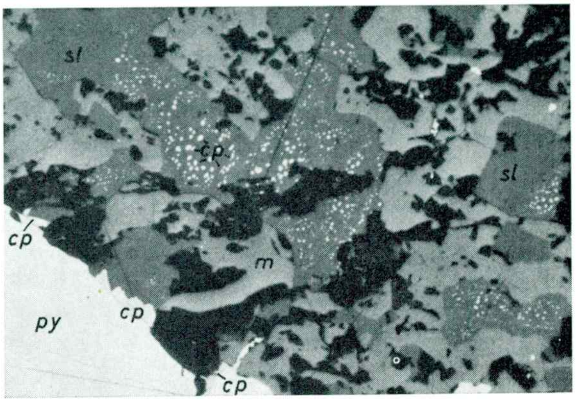


Fig. 8. Magnetite-sphalerite ore with exsolved chalcopyrite in dark sphalerite. Spec. EMB 4/70; No. 66. × 150

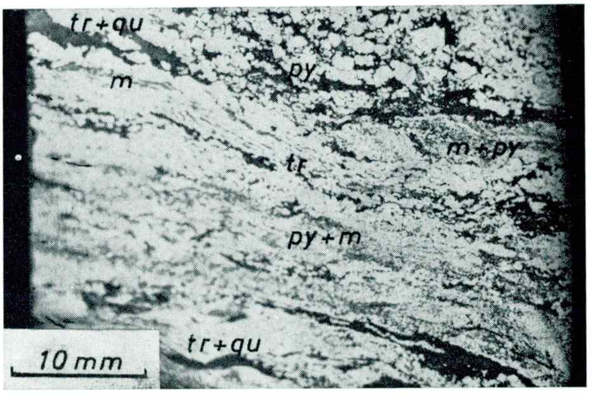


Fig. 9. Banded massive sulphide ore: pyrite, magnetite and tremolite-actinolite interbanding. Granular pyrite embedded in quartz at top. Spec. EMB 1/70; No. 87

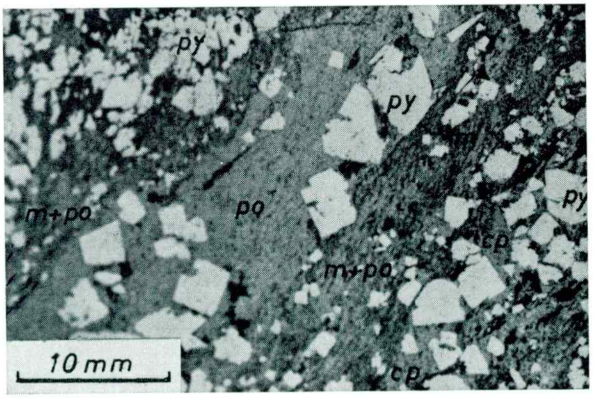


Fig. 10. "Porphyroblastic" ore: early subhedral pyrite surrounded locally by chalcopyrite, in a fine-grained, banded matrix of pyrrhotite and magnetite. Spec. EMB 1/70; No. 18

Texture, paragenesis and zoning. The ore is fine- to medium-grained, prevailingly banded (Fig. 9) but also dense, even-grained massive, occasionally with larger grains ranging to 15 mm in diameter scattered in places. Very fine-grained masses with colloform-like texture are rare. »Porphyroblastic« texture (Fig. 10) is confined rather to lower levels, and mosaic-textured pyrite ore to upper ones.

The apparent mineral paragenetic sequence, as deduced from examinations of polished sections, indicates that the euhedral pyrite, magnetite and lime-iron silicates formed first. The flowage-textured magnetite and pyrrhotite followed, embedding the early minerals and interbanding with other components. Sphalerite, chalcopyrite, second generation pyrite and galena seem to be associated with the later surges of the mineralising fluids. The following succession is normally observed in banded ore:

Quartz, chlorite and lime-iron silicates
pyrite prevailingly
magnetite and pyrrhotite
magnetite and pyrite.

The syngenetic zoning is expressed morphologically and mineralogically. In deeper parts of the deposit, closer to the dioritic dome, magnetite and pyrrhotite prevail, together with the early coarse-grained pyrite and lime-iron silicates, with pyrrhotite-chalcopyrite channels cutting across the ore mass. This portion obviously corresponds to "stringer ore" of D. F. Sangster (1972). Pyrrhotite decreases upwards whereas magnetite persists and pyrite prevails, the texture both banded and massive granular. The highest levels, thought to be most distant from the magmatic source, are composed of mosaic-textured ore of even-grained pyrite, the grain size about 1 mm, with interstitial quartz, calcite, chalcopyrite, yellow sphalerite and galena, with traces of magnetite and lime silicates but no pyrrhotite. Microcrystalline colloform gel-pyrite occurs only in the lowest levels, chalcopyrite and sphalerite on all levels and galena is associated mainly with the yellow sphalerite.

The zoning pattern may be simply explained by decreasing temperature of the ore-bearing solutions with the distance from the magmatic source. There were however more surges of fluids at variable temperatures, as evidenced morphologically and paragenetically. Swarms of quartz veins with pyrite, chlorite, chalcopyrite, calcite, epidote and even brown-pink garnet can be seen in the greenschist adjacent to ore, the features apparently channelways in which the solutions moved.

The composition of the ore can be seen from the assays of drill cores. The bulk composition encountered in some drillholes is shown as average values in Table 7, and in Figure 4, the expected average tenors in Table 12. There is no trend in metal contents and no correlation between pairs of metals. Gold has not been determined; it is low if there is a linear relationship with base metal values (J. Kaliokoski, 1965). Gold values up to 1.2 ppm have been detected in soil, the corresponding silver values up to 4 ppm, and molybdenum values up to 7 ppm.

The tonnage of the deposit is indicated in the order of several millions of tons of the ore mass.

Table 7 Metal contents of drill cores at Embaderho

Ore layers Number	True thickness (m)	Cu (per cent)	Zn	Pb	Cd	As (ppm)	Co	Ni	Ag (g/t)	Metal ratio Cu:Pb:Zn
Drillhole EMB 1/70										
11										
max.	9.50	1.40	0.43	56	490	59	519	28	8	
min.	1.53	0.10	0.05	17	5	17	49	12	2	
average	5.07	0.77	0.23	31	66	39	230	22	4.7	250:1:74
Drillhole EMB 4/70										
10										
max.	11.40	1.14	3.8	790	?	58	515	90	14	
min.	0.96	0.01	0.11	6		20	30	13	4	
average	3.84	0.39	1.81	135		36	121	35	8	30:1:134
Drillhole EMB 6/71										
7										
max.	5.16	0.64	6.55	121	196	73	?	?	32	
min.	1.42	0.04	2.11	76	9	14			4	
average	2.72	0.31	3.49	90	87	43			12	34:1:390
Drillhole EMB 7/71										
4										
max.	12.85	0.76	3.84	158	124	65	?	?	17	
min.	1.32	0.25	1.77	28	36	23			11	
average	5.66	0.49	2.49	104	87	49			14	50:1:250
Weighted mean composition of the ore mass		0.52	1.83	87	80				10	

Adi Nefas

Situated 5 km north of Asmara, the prospect was explored between 1967 and 1971 by soil sampling, detailed mapping, electromagnetic and magnetic survey and deep drilling (9 holes totalling 953.9 m).

The deposit shows up as a 2 km long and up to 20 m wide dark siliceous gossan dipping 78^0 east, surrounded by, and petering out into schists. The country rock is an alternation of green chlorite schist, quartz-chlorite-sericite schist, massive greenstone, violet spotted schist, phyllite, mica schist and subordinated dark brown quartzite. Dyke-like porphyritic layers 3 to 15 m wide are aligned in the steeply dipping sequence. There are numerous quartz reefs in schist, some of them auriferous (L. Usoni, 1952). Figure 11 illustrates the deposit.

The magmatic rocks are white-green banded porphyritic types, with quartz and feldspar phenocrysts up to 7 mm in size. Feldspars are polysynthetic lamellar twins of slightly altered albite-oligoclase, and turbid anorthoclase, showing fine gridiron twinning, peripherally intergrown with quartz and calcite. Quartz phenocrysts are corroded. There is some white mica, little chlorite, the groundmass a microcrystalline aggregate of quartz, calcite, sericite and kaoli-

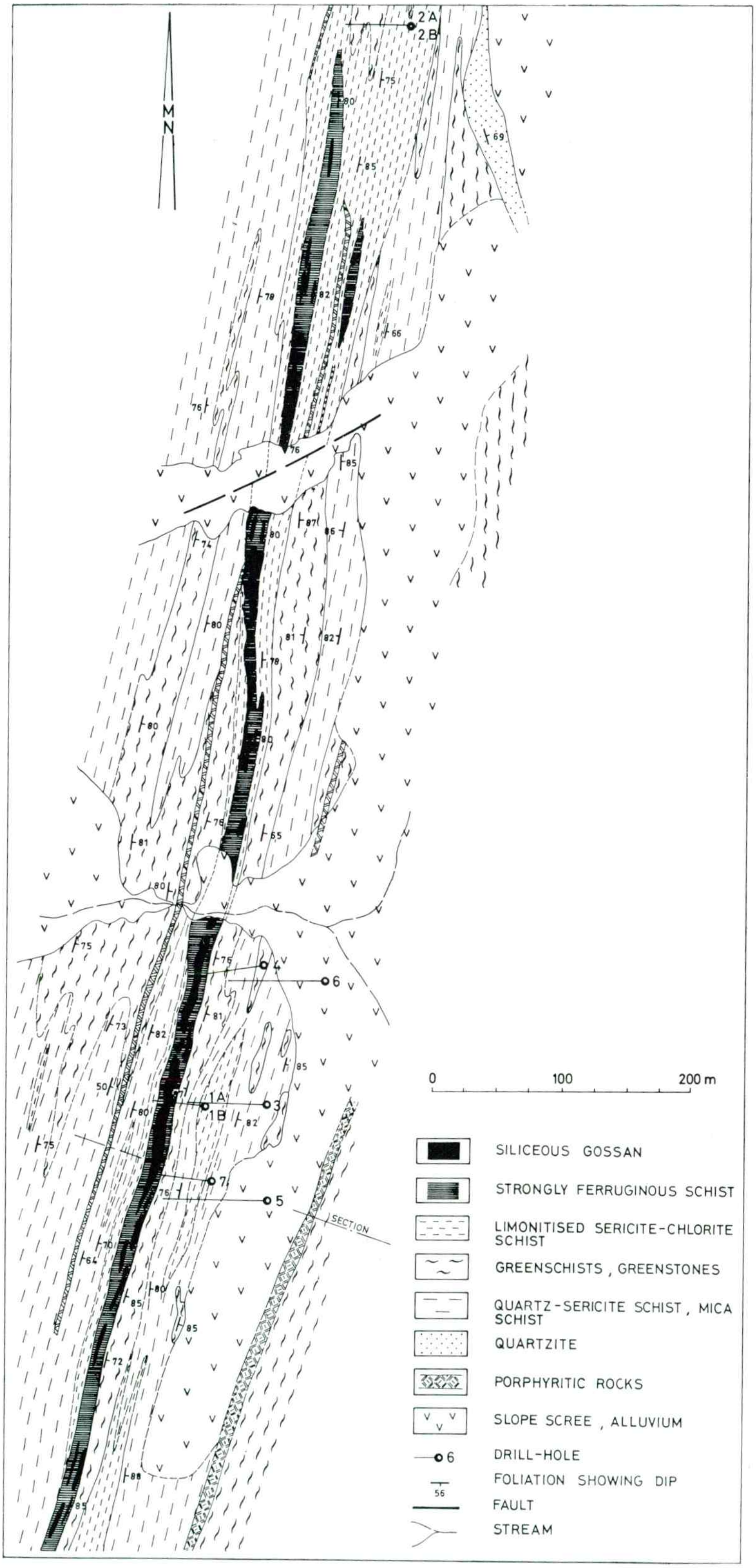


Fig. 11. Geological map of the Adi Nefas prospect

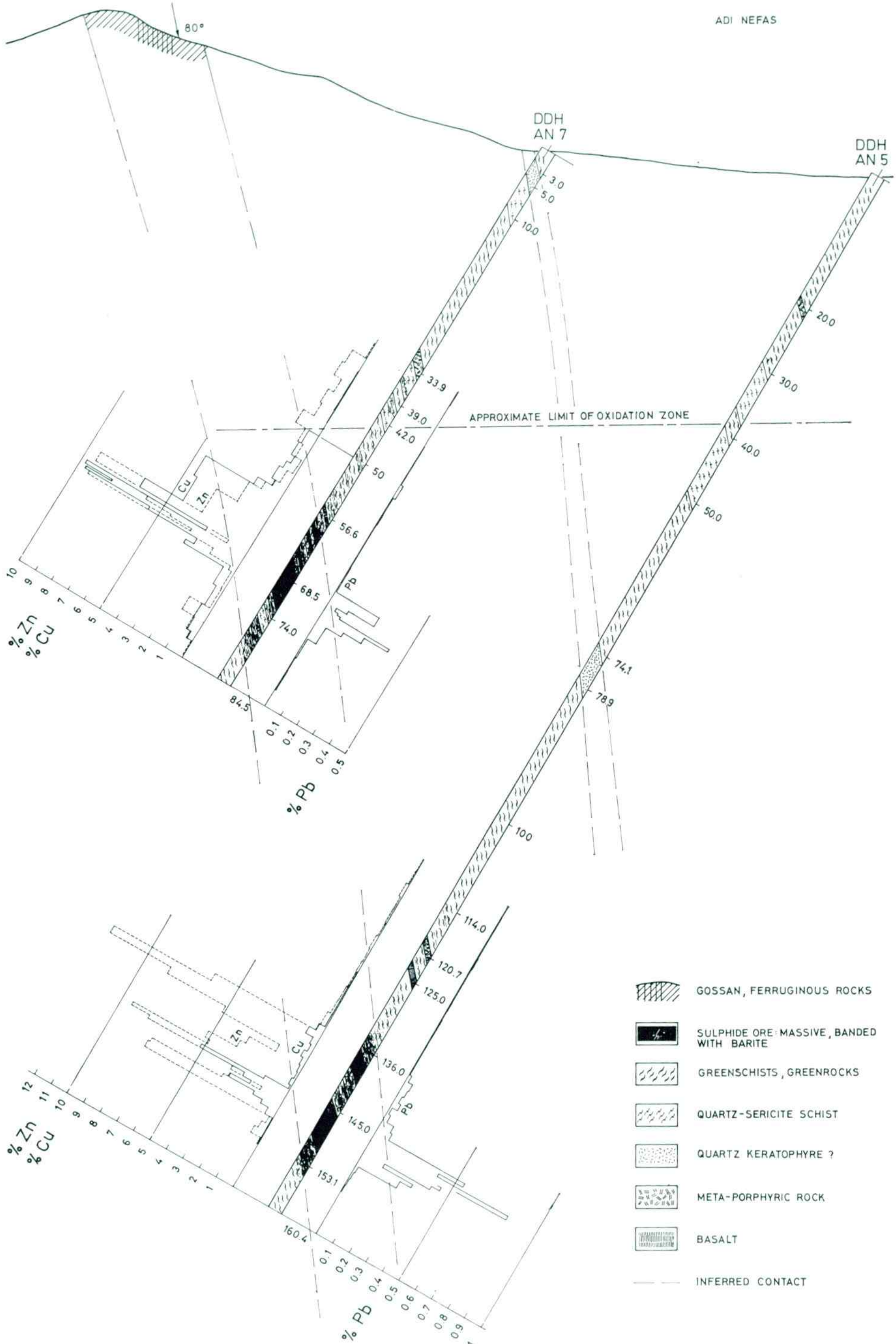


Fig. 12. Sections of drill-holes AN 5 and 7, and Cu, Zn, Pb tenors at Adi Nefas

Table 8 Mineral composition of magmatic rocks at Adi Nefas

	Sample No. (see Table 1) 4	5
Phenocrysts: Quartz	15	20
Albite	20	15
Anorthoclase	10	15
Calcite	3	6
Matrix: sericite, quartz, calcite, kaolinite, chlorite	52	44

nite. Calcite surrounding feldspars suggest alteration of initially more calcic plagioclase, and hence albite would be secondary. The sodic rock is comparable to quartz keratophyre. However field evidence on its syngenetic nature is not conclusive.

Another example of felsic, greenish gray medium-grained porphyritic rock is strongly altered and shows unclear feldspar phenocrysts, few quartz grains in a mass of epidote, chlorite and calcite. The original identity of the highly aluminous rock is obscured by alteration. It may have been originally dacite or andesite or even a tuff-lava. The chemical composition of both rock types is given in Table 1, and the average quantitative mineral composition in Table 8.

Drill intersections revealed massive, fine-grained, usually banded ore, composed alternately of pyrite, sphalerite and chalcopyrite, with quartz and barite gangue. In places, sulphides are intimately interbanded with schists. A typical section is shown in Figure 12. Vein-like sulphide concentrations appear also as open space fillings, apparently originated through later hydrothermal rearrangements.

The mineralogy of the polymetal ore, as visible to the unaided eye on drill cores, is simple. The hypogene ore paragenesis and textural features, as developed from examinations of polished sections, can be summarised as follows. The prevailing pyrite is the oldest mineral, forming coarse-granular banded aggregates, the corroded grains rounded, with poecilitic chalcopyrite and sphalerite (Fig. 13). The early pyrite is embedded in and strongly replaced by a younger sequence of sulphides; the atoll replacement texture is conspicuous. A fine-crystalline second generation pyrite replaces sphalerite and galena (Fig. 14).

Sphalerite strongly prevails quantitatively. It is a pale brown iron-poor variety, replacing pyrite marginally and centrally (Fig. 15). Chalcopyrite occurs in irregularly shaped grains forming interstitial masses, replacing pyrite and filling cracks in sphalerite. Tennantite occurs in isolated larger grains and is marginally replaced by sphalerite. Minor galena appears in small grains, everywhere associated with tennantite, and is locally replaced by sphalerite; it can be found also in small inclusions in later pyrite (Fig. 16). Enargite is present in very small rare grains, and minor lamellar, apparently hypogene, chalcocite is embedded in sphalerite. Supergene chalcocite shows preferential marginal replacement of chalcopyrite, sphalerite and galena but rarely of pyrite.

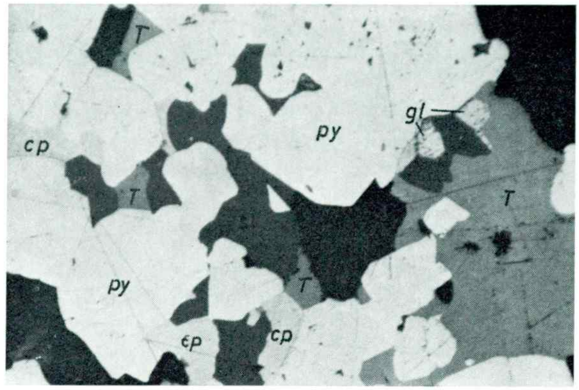


Fig. 13. Granular texture of ore with younger sulphides replacing the early pyrite. Spec. AN 6; No, 17. × 150

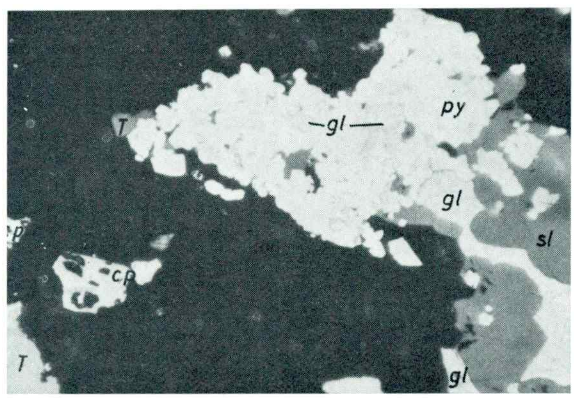


Fig. 14. Late-generation pyrite replacing galena and sphalerite; galena in turn replaced by sphalerite. Matrix is quartz (black). Spec. AN 5/71; No. 1. × 150

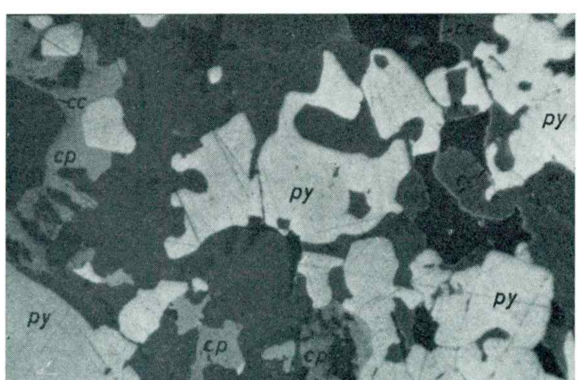


Fig. 15. Atoll-textured early pyrite, replaced by sphalerite and chalcopyrite, with rims of chalcocite. Spec. AN 7; No. 2. × 150

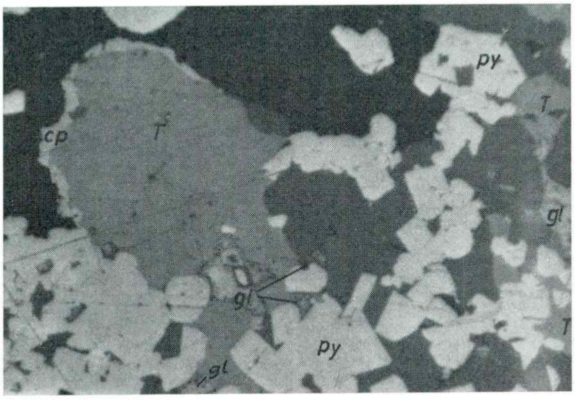


Fig. 16. Granular ore of second generation sulphides in quartz. Spec. AN 6; No. 16. × 150

Table 9 Estimated ore grades of Adi Nefas ore

	Cu (per cent)	Zn (per cent)	Pb (per cent)	Cd (ppm)	Co (ppm)	Ni (ppm)	As (ppm)	Ag (g/t)	Au (g/t)
Range from	0.1	0.1	0.01	180	60	10	380	45	0.8
to	9.3	30	6	1100	120	60	2030	350	7.4
Estimated average	1.5-2	7-10	0.8	300	80	35	500	100	2.3

Quartz is the prevailing gangue. Fine-crystalline barite is abundant especially in massive sphalerite-chalcopyrite ore. Minor calcite is present as well, accompanied by white mica and chlorite.

Galena, bornite, covellite and tenorite have been observed in some quartz reefs in the vicinity of gossan.

Gold and silver in Adi Nefas ore are probably associated with pyrite and tennantite respectively. There is no clear-cut correlation between precious and base metals.

Microscopic evidence indicates that the early sedimentary mineralisation was followed by hydrothermal rearrangements of ore minerals in apparently permeable, tectonically originated features; the superposition is evident in the locally oblique trend of the gossan with respect to the foliation.

The composition of ore is erratic and is shown for some metals in Figure 12. The ranges of metal contents, as determined on assayed split drill cores, and estimated average grades are shown in Tables 9 and 12.

Debarwa

The deposit is situated about 30 km southwest of Asmara. The unsuccessful drilling exploration of 1966—1968 (38 holes totalling 4,586 m) was resumed in 1971; together with detailed geological and geochemical surveys revealed the

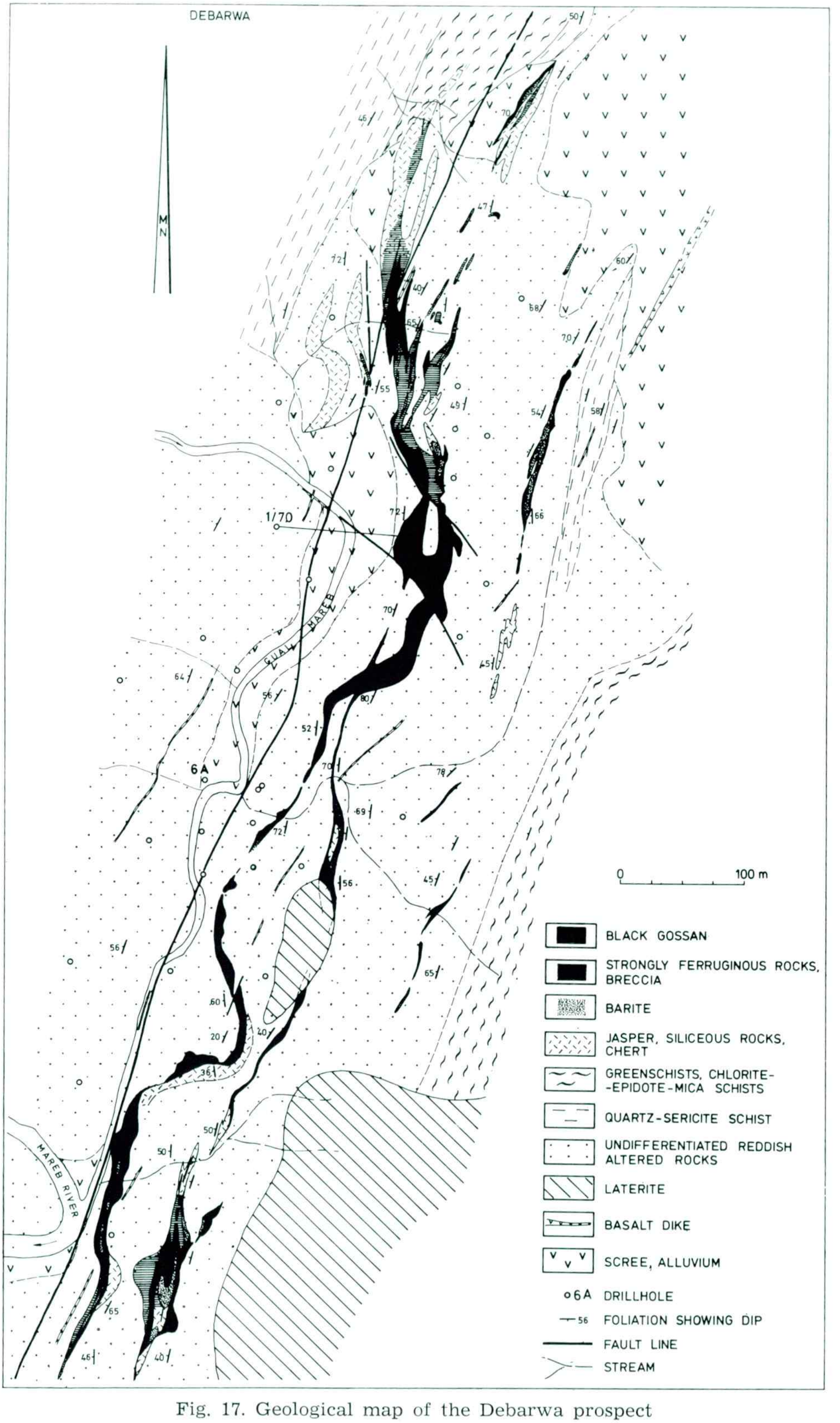


Fig. 17. Geological map of the Debarwa prospect

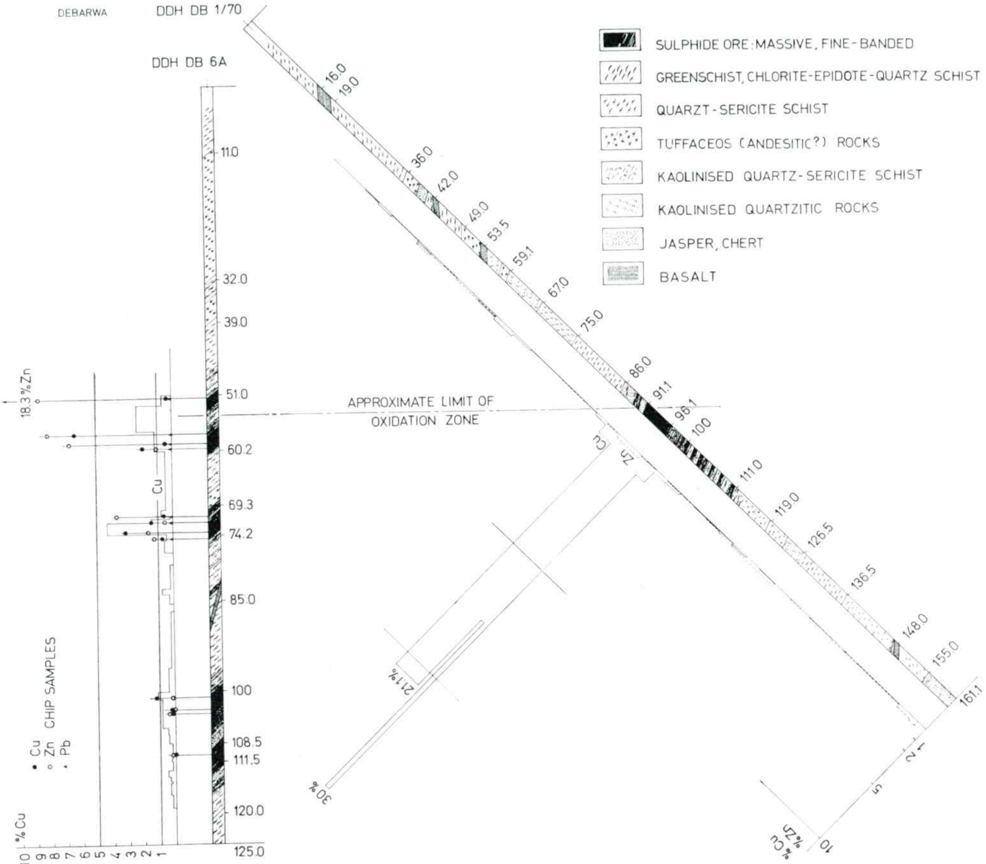


Fig. 18. Sections of drill-holes DB 1/70 and 6 A, and Cu, Zn, Pb tenors at Debarwa

prospect's economic potential. Nippon Mining Co. developed it during 1973—1974 and started mining.

Three mineralised zones are evident on the surface and a fourth has been disclosed by soil geochemistry, trending more or less parallel with the foliation of the extremely weathered schist, dipping west at a medium angle (Figs. 17 and 18). Gossan consists of black botryoidal limonite, ferruginous earthy masse, limonitic breccia and jasper and impure barite, the latter occurring centrally within outcrops or forming »veins« in gossan. The largest barite body is well over 100 m long and several metres thick. No malachite staining can be seen on the surface.

The prevailing rock types are quartz-sericite schist, sericite schist, chloritic greenschist and tuffaceous calc-epidote schist, and locally greywacke. Narrow beds of black shale and grey phyllite are intercalated. Some feldspathic porphyritic rocks were penetrated in drillholes, and interbedded layers of massive

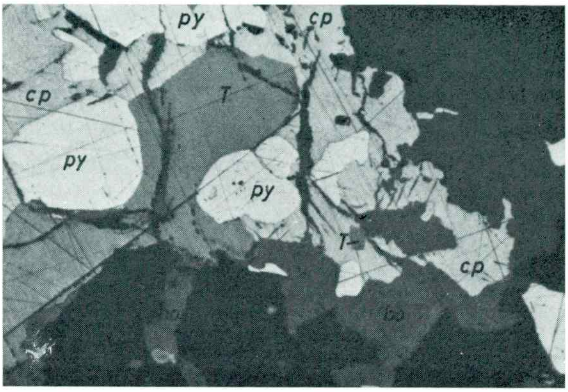


Fig. 19. Replacement texture of ore; black material is quartz. Spec. DB 6 A; No. 58 m. × 150

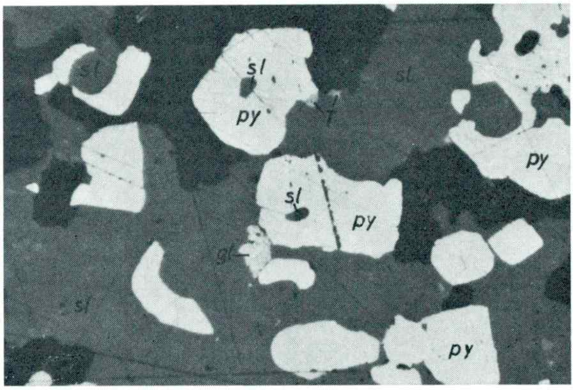


Fig. 20. Strongly corroded pyrite embedded in sphalerite and quartz (black). Spec. DB 3 A; No. 103.5 m. × 150

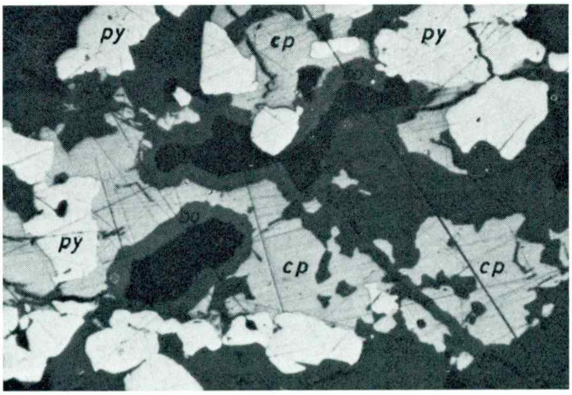


Fig. 21. Selective marginal replacement of younger sulphides by bornite. Spec. DB 6 A; No. 65 m. × 150

greenish rocks probably originated from intermediate volcanic rocks. Siliceous rocks such as silicified schist, chert and jasper are abundant and usually surround the ore. Numerous near-vertical basaltic dykes, belonging to Trap Series volcanism, run slightly obliquely to the foliation, together with numerous barren quartz veins.

Mafic dykes, quartz veins and gossanous zones developed along the tectonic lines of weakness. Post-mineralisation faulting is evidenced by breccias, slickensides and shearing, the most prominent longitudinal fault following the Gual Mareb river valley.

Drilling revealed massive, bedded, fine- to medium-grained polymineral ore, fine disseminations in schists and vein-like sulphide concentrations, the total thickness of several mineralised zones being of the order of tens of metres. The schists near ore are frequently kaolinised. The ore control is stratigraphical and structural, the ore zones dipping apparently under different angles. Soil geochemistry confirmed the multi-stage character of mineralisation, with copper and zinc distribution patterns indicating contemporaneous precipitation of both metals, and the separate deposition of lead, controlled by transversal faults.

Polished sections of a number of random samples revealed hypogene mineral paragenesis similar to that of Adi Nefas. Pyrite is again the prevailing opaque mineral, the oldest in the paragenesis, surrounded by quartz and younger sulphides replacing it (Fig. 19). Its corroded grains are rounded and exhibit caries texture. A younger fine-grained generation of pyrite is also present.

Sphalerite is intimately associated with the younger paragenetic associates chalcopyrite, tennantite and enargite, all of them anhedral and replacing the early pyrite (Fig. 20). Chalcopyrite is replaced by sphalerite and bornite (Fig. 21). Tennantite appears in larger grains and shows mutual boundaries with sphalerite. Rare enargite occurs mainly in pyrite-sphalerite banded ore, marginally replacing the latter. A younger generation of tennantite appears along the rims of enargite, and was clearly derived from it. Galena is the latest sulphide, quantitatively negligible. It occurs also in small veinlets cutting through older sulphides.

Bornite replaces chalcopyrite marginally and along cracks. Together with chalcocite it replaces massive pyrite in the cementation zone, both minerals accounting for the very high copper grade up to 31 per cent (Fig. 22). The observed bornite-chalcocite lattice intergrowth suggests either an exsolution unmixing or a supergene replacement of bornite by chalcocite, the later option being more acceptable since the bulk of anisotropic bluish chalcocite is supergene. There are minor amounts of covellite and ferric hydrous products. An important cementation took place at Debarwa at a depth of about 50 to 60 m below the Gual Mareb valley.

Quartz is ubiquitous, and barite forms the essential part of the outcrops but does not extend to any great depth. Rare calcite is restricted to the oxidation zone.

Mutual replacement is evident in the multi-stage hypogene ore paragenesis, the younger minerals replacing the earlier ones, galena seemingly the latest. The following mineral groupings, possibly indicating the successive mineralisation stages, have been observed:

1	2	3	4	Supergene minerals
quartz	pyrite II	enargite	quartz	chalcocite
pyrite I	tennantite I	tennantite II	barite	covellite
	chalcopyrite	galena	calcite	limonite
	bornite		pyrite III	quartz?
	enargite			
	chalcocite			

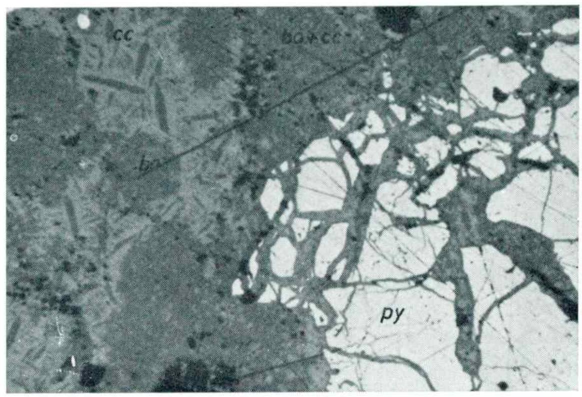


Fig. 22. Lamellar bornite-chalcocite intergrowth, both replacing shattered pyrite. Spec. DB 1/70; No. 4. × 150

Table 10 Estimated ore grades of Debarwa ore

	Cu	Zn (per cent)	Pb	Ag (g/t)	Au
Range from	0.1	1	0.025	tr	0.2
to	31	25	1	3280	2.5
Estimated average	2.15	5	0.5	100	2

Several recognised ore types may be typical for certain parts of the deposit, the ore grades apparently broadly variable from place to place. They can be tentatively listed as follows:

— massive granular pyrite embedded in quartz matrix, with small amounts of base metals

— strongly disseminated pyrite in schists

— banded polymineral ore rich in copper and zinc

— cementation zone ore of any of the above types, enriched in supergene copper minerals but low in zinc.

The ore grades on assayed cores are extremely variable. The observed ranges in primary ore and an assumed average are given in Tables 10 and 12.

Nippon Mining Co. in 1973—1974 exploited ore grading 13.8 per cent copper (M. Hamrla, 1974). The tonnage potential of the deposit might be expected in the order of several millions tons of commercial ore.

Adi Rassi

The Adi Rassi deposit, which has been known since the 16th century, is situated 35 km south of Asmara. Italians explored it during 1938—1939. Renewed exploration in 1965—1966 involved detailed mapping and deep drilling (10 holes totalling 1,771 m). Geochemical soil survey was done later.

Confined to two small hills of altered ferruginous rocks modestly stained with malachite, the deposit occupies a zone about 450 m long and several tens of metres wide. Chlorite-quartz greenschist is the prevailing rock, grading to hornfels-like rock, interbedded with arenaceous schist, sericite schist and minor tuffaceous greywacke, the sequence striking submeridionally and dipping steeply west. Syngenetic porphyritic layers up to 40 m thick are intercalated. Massive epidotised spilitic rock west of the deposit may have been originally andesite or basalt. Geology of the deposit is shown in Figures 23 and 24.

Several magmatic rocks have been distinguished within the sequence.

a) A grey-green, intimately intercalated, mesocratic porphyrite has a normal porphyritic texture with phenocrysts of corroded quartz up to 15 mm in diameter, and albite-oligoclase double that size. The plagioclase is strongly replaced and pseudomorphed by an aggregate of clinozoisite, quartz and calcite. There are minor grains of pale-green amphibole. The matrix consists of lath-shaped feldspar, felty amphibole, minor quartz, calcite and opaque minerals. The mode of the rock is shown in Table 11.

The chemical composition, given in Table 1, shows a peraluminous, strongly sodic, potash-deficient rock derived from an intermediate (dioritic) magma.

b) A dyke-like leucocratic quartz porphyry is deeply weathered and usually malachite stained. Drillholes revealed a siliceous quartz keratophyre; a fine-grained leucocratic matrix containing phenocrysts of quartz and remnants of feldspars is totally replaced by a plumose aggregate of kaolinite.

c) Adjacent to porphyrite is a hornfels-like rock, its texture porphyritic, with rare albite phenocrysts less than 0.5 mm in size, occasional smaller quartz grains, and euhedral rhomboid calcite up to 1 mm in diameter disseminated with magnetite. The matrix is an aggregate of quartz, feldspar, chlorite, epidote, stilpnomelane and calcite. Disseminated pyrite, chalcopyrite, pyrrhotite and magnetite occur in the rock, the grain size under 0.05 mm (Fig. 25). The rock can be designated as spilite. The chemical composition of an iron-rich sample is shown in Table 1 (sample No. 7).

d) Another fine-grained, totally altered, lamprophyric rock appears in a dyke obliquely cutting the top of the South Hill.

The deposit is of stockwork type, consisting of intermingled veins and veinlets of chalcopyrite, pyrite, quartz and calcite, the rocks brecciated and cemented with these minerals, the thickness of the elongated ore body being up to 50 m and averaging about 25 m. The dual nature of the deposit is obvious. Conformable bands of sulphides in schist and disseminations of pyrrhotite, magnetite and pyrite in spilitic layers are the early syngenetic constituents (Fig. 26). The bulk of sulphides occurs in veinlets and breccia, chalcopyrite being the prevailing base metal mineral. No sphalerite is visible, the values of zinc revealed by geochemical soil survey below 2,000 ppm and hence quantitatively unimportant. There is no galena either, the soil lead values being at background level.

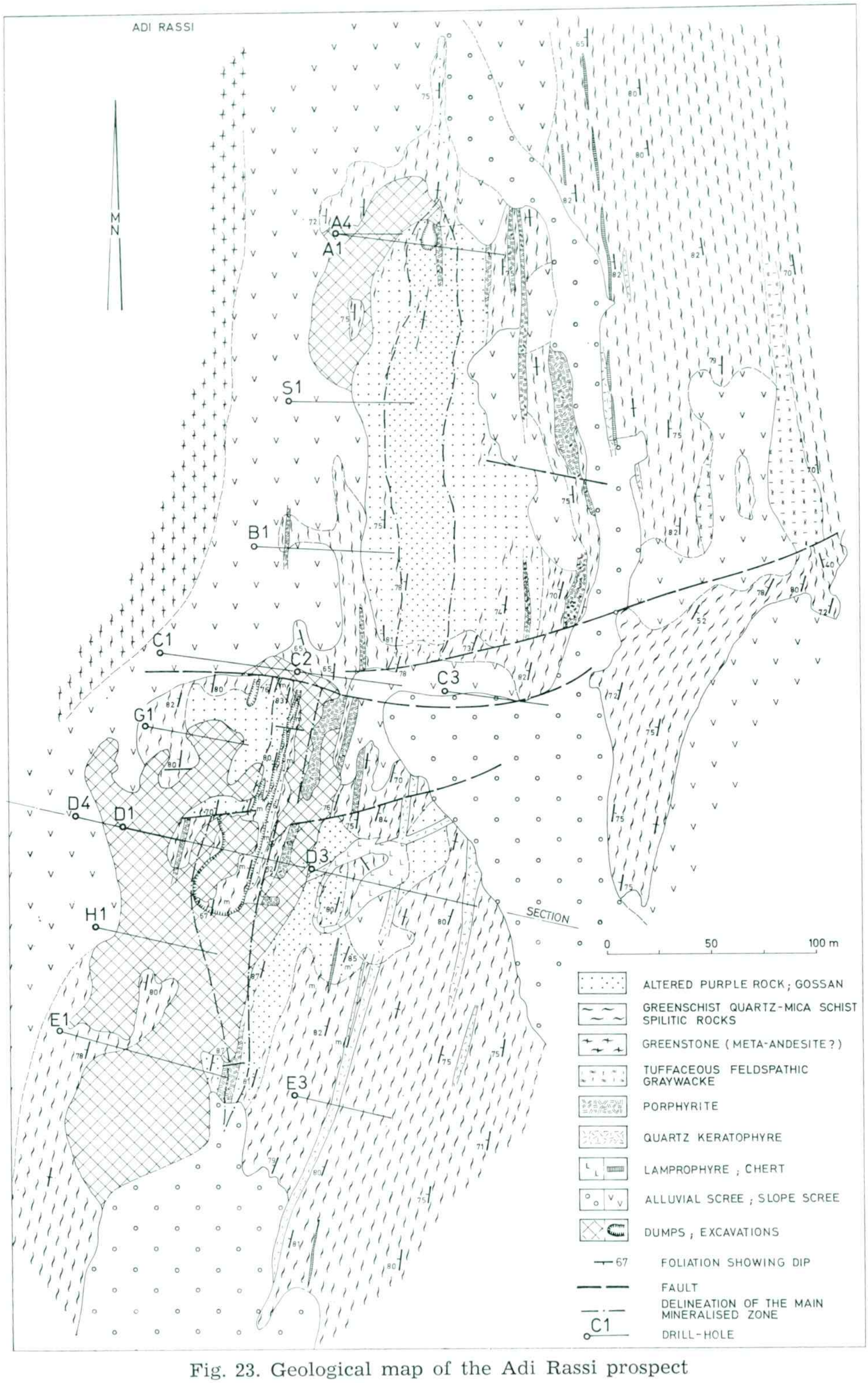


Fig. 23. Geological map of the Adi Rassi prospect

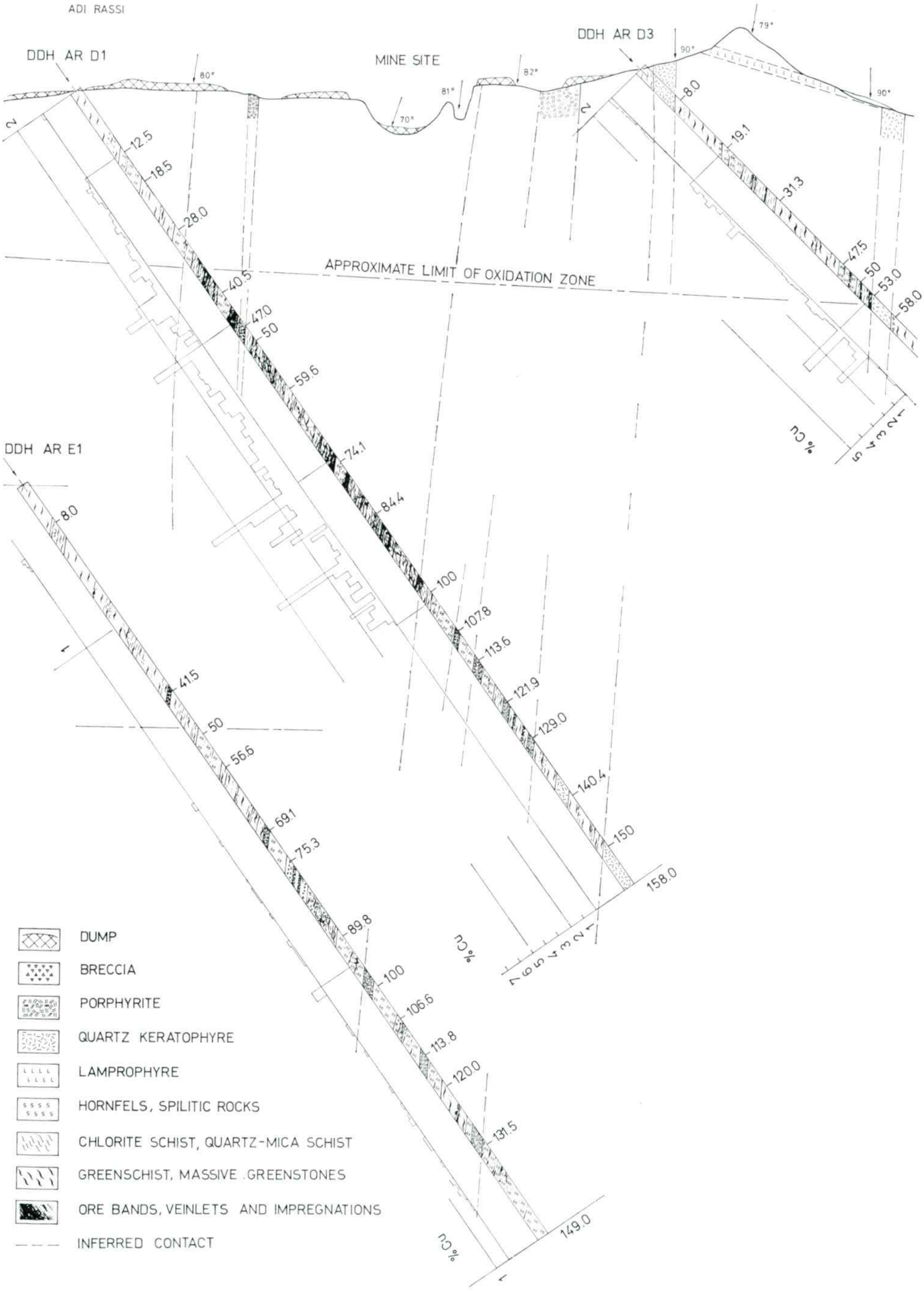


Fig. 24. Sections of drill-holes AR D 1, D 3 and E 1, and Cu tenor at Adi Rassi

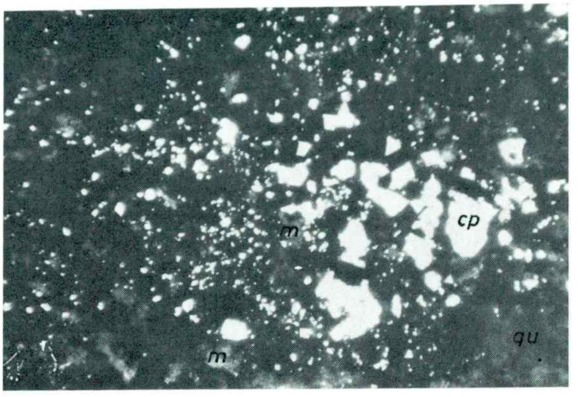


Fig. 25. "Submicroscopic" dispersion of chalcopyrite and magnetite in siliceous "hornfels". Spec. AR E 1; No. 136. × 150

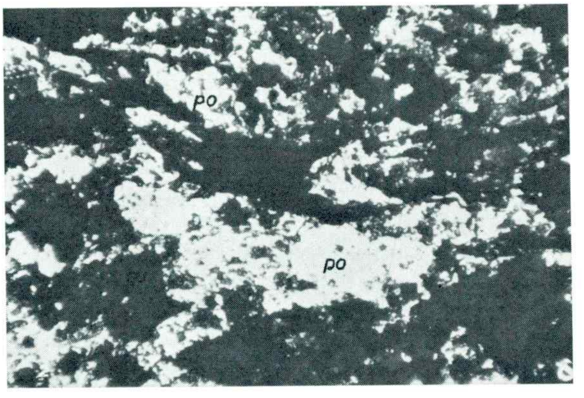


Fig. 26. Irregularly shaped pyrrhotite in siliceous rock. Spec. AR F; No. 134. × 150

Note: Abbreviations used in photomicrographs:
py — pyrite, gpy — gel-pyrite, po — pyrrhotite, m — magnetite, cp — chalcopyrite, sl — sphalerite, gl — galena, T — tennantite, cc — chalcocite, bo — bornite, tr — lime-iron silicates, qu — quartz.

Table 11 Mineral composition of Adi Rassi porphyrite

		Sample No. (see Table 1) 6
Phenocrysts:	Quartz	8
	Albite-oligoclase	15
	Amphibole	7
	Clinozoisite	20
Matrix:	all above minerals plus calcite and chlorite	50

Two generations of quartz are discernible, and carbonate may be ankerite or even siderite locally. Spilitic rock types are always low in copper or devoid of it.

The stockwork mineralisation apparently developed in a permeable zone of tectonic fissuring. That it is a stringer type ore is improbable since it extends along the trend of the sequence and not perpendicular to it, and there are no layers of massive ore in which footwall such structures are found (D. F. Sangster, 1972).

Adi Rassi is a copper deposit. Its relative metal contents may be roughly reflected in the composition of a sample of tailings dump of ore, which was milled for gold:

Cu	Zn	Pb	Co	Ni	(ppm)
4900	103	10	87	77	

The gold tenor of ore ranges between 0.06 and 2.14 g/t, averaging less than 1 g/t (L. Usoni, 1952). Surface sampling showed less than 0.2 g/t and no correlation with copper. Silver was assayed in several core samples, ranging about 60 g/t. Two samples of chalcopyrite concentrate assayed less than 20 ppm molybdenum.

Mont Saccar

The deposit is situated about 20 km north of the Asmara—Massawa highway, at a point 45 km from Massawa. Detailed mapping and deep drilling (9 holes totalling 733 m) were carried out during 1964—1965.

The gently north dipping schistose sequence consists of low-grade calcite-sericite-chlorite schists and grey micaceous quartzites. Some schists appear talcose. Dark green lamprophyric dykes run in various directions. Rich malachite staining occurs in three zones from 50 to 100 m wide, the strongest concentration in narrow schistose layers less than 0.5 m thick assaying up to 8 per cent copper locally. There is no gossan. Quartz veins and inclusions are abundant and stained with copper and limonite. The plain to the west is covered by piedmont sand and gravel, and separated from the mineralised schist by a fault of Red Sea direction. The region belongs to the Red Sea portion of the Rift Valley graben and is a mobile one, marked by very young tectonic uplifting and sinking.

Drilling revealed continuous copper mineralisation in a more than 60 m thick and probably more than 1 km long schistose sequence, featuring impregnation with pyrite and chalcopyrite. Magnetite has been observed as well. Epidote, deep green chlorite and calcite are abundant. The shallow oxidation zone does not surpass 15 m, and there is no secondary enrichment.

The cores were assayed for copper only, the grade being variable between 0.2 and 0.8 per cent for sections about five metres thick, averaging about 0.4 per cent. The tenor is unreliable because of very low core recovery and might be substantially higher. Silver grades between 2 and 6 g/t, and gold about 0.1 g/t, both assayed on some individual samples. There is no direct correlation between copper and precious metals. Zinc and lead were not tested, both metals being apparently low. Molybdenum was found ranging 0.006 to 0.016 per cent, and vanadium 0.03 to 0.13 per cent in some random samples.

The dispersion of sulphides in schists is apparently syngenetic. Hydrothermal remobilisation and concentration of syngenetic copper is indicated in sulphide-enriched quartz veins and lenses. Quartz veins occurring in schists are mineralised, whereas those in the adjacent quartzites are barren of sulphides.

The absence of gossan and secondary enrichment can be explained by the recent tectonic mobility of the area, the radial movements continuously changing the groundwater level and the drainage system.

Adi Bidel

The Adi Bidel deposit is about 8 km northwest of Embaderho, in the same geological environment. It consists of a number of elongated bodies of manganiferous gossan dipping about 50^0 northeast, on both sides of steep slopes of the Mai Bella river valley. Elongated conformable layers within the schistose sequence are up to several hundred metres long and have a thickness of not more than 10 m or so.

The occurrence extends in the northwestern trend of the Embaderho deposit, and its gossan has been apparently derived from massive sulphidic ore, which can be expected at depth. Except for some mapping and sampling in 1973, no depth follow-up has taken place as yet.

Tarashi

Close to Adi Bidel and in its trend, in an environment dominated by greenschists with abundant porphyritic intercalations, a swarm of parallel lens-like bodies of gossan dipping 55^0 northeast occupies the Tarashi village area. The length of individual layers varies between a few metres and several hundred metres, the width no more than several metres. Gossan is prevailingly dark, relatively soft manganiferous ironstone, in places well banded and siliceous, intermingled with white quartz, and has been apparently derived from sulphides. Ferruginous layers can be followed for several kilometres from the village to the northwest.

Woki

In the wider area of Woki village some 18 km north-northwest of Asmara, on a surface of about 5×5 km, there are numerous elongated bodies, lenses and narrow zones of gossanous ironstone emplaced conformably within a typical volcanogeneous sequence. The prevailing chlorite-sericite-epidote-quartz greenschist alternate with dense spilitic and porphyritic rocks in narrow interbeds, the whole complex trending meridionally and dipping 50—70^0 east. Minor dioritic bosses occur in the eastern part of the area. Six or seven gossaniferous zones have been recognised, the longest west of Mont Amusat about 3 km long, with individual bodies up to 300 m long and 10 m wide, the outcrops seemingly unrelated to rock type. An ore body several hundred metres long and about 10 m wide runs right through Woki village.

The banded ironstone is a siliceous rock containing magnetite, haematite and hydrated oxides of iron and manganese in varying proportions. In places it is dark, soft and very manganiferous with malachite staining, and in others is of pure red jasper or jaspilite rich in epidote. Laterally, the outcrops grade over into ferruginous greenschist. White vein quartz is abundant, with sporadic magnetite and chalcocite, in places rich in epidote and limonite.

Some time ago the occurrences were considered as iron ore. Though iron content may locally reach 55 per cent or more, the average is far too low, and silica and sulphur too high to be useful as iron ore.

Adish Adi

About 15 km north-northwest from Woki, in the Adish Adi area, there are swarms of elongated lens-like jasperoidal rocks trending within the well foliated greenschist interbedded with layers of quartz porphyrite. The strongly siliceous reddish brown outcrops contain dispersed magnetite but little iron hydroxides. The zone extends reportedly farther northwest towards Maldie, known for its auriferous quartz veins (L. Usoni, 1952).

Quelqua and Meke

These localities are about 30 km west of Asmara. Phyllitic schist with intercalated black quartzite and graphitic schist prevail in the area, the beds dipping 60—70^0 southeast. Some narrow and persistent sills of porphyritic aplite trend in the sequence. At Quelqua lens-like bodies of reddish-black jasperoidal rocks with minor ochreous iron hydroxides are up to 50 m long and several metres wide and follow the foliation, lateral transition to phyllites being very conspicuous. Quartz veins intersect the outcrops.

About 8 km southwest, near the village of Meke, there is a ferruginous body at least 800 m long and more than 10 m wide within the schistose sequence, grading laterally into siliceous phyllite. The banded reddish ironstone contains magnetite and haematite.

Lamza Saharti

12 km south-southwest of Asmara, near Lamza Saharti village, a mineralised zone about 80 m wide crops out just under the volcanic cover. It consists of silicified ferruginous brecciated rock and intermittent smaller lenses of barite. The country rock is highly weathered kaolinised sericite schist and grey tuffaceous schist dipping 35—40^0 northwest. The mineralisation is similar to that of Debarwa; it occurs in its strike extension. No malachite is visible but copper and zinc were determined in samples of ferruginous rock.

Shicketi

Between Lamza Saharti and Debarwa, near the village of Shicketi, a mineralised zone more than 400 m long and about 25 m wide appears in the schistose weathered rock, dipping generally 50—70^0 northwest. It contains lens-like siliceous, ferruginous richly malachite stained rock, in places strongly limonitised and ochreous, with traces of sulphides still recognisable. The outcrops mark the extension of the nearby Debarwa deposit.

Adi Cashi, Adi Key and Torat

Paralleling the Debarwa zone and about 5 km to the east, the Adi Rassi zone is marked by minor sulphide occurrence and auriferous quartz veins. At its northern end near Adi Cashi, within a schistose sequence dipping 50—70^0 northwest, there are several elongated bodies of reddish limonitised jasperoidal rock accompanied by parallel quartz veins, the lenght of both of the order of several tens of metres. The mineralisation is surrounded by altered sericite schist. Sulphide seems not to be abundant, but gold is associated with vein quartz in this area.

At Adi Key, south of Adi Cashi, there are parallel quartz veins several hundred metres long, dipping 70^0 west. Together with similar quartz veins at Ad Doie and Adi Ferhe, they were worked for gold in the past. Near Derbetai large auriferous quartz veins and slight limonitisation occur within the greenschist, the rocks stained occasionally with malachite. Torat gold mine operated here in the past. Quartz veins occur adjacent to continuous layers of dark grey chert of apparent volcanogenic origin.

Chenaudi and Obel

Chenaudi village is about 17 km southwest of Adi Ugri. According to Nippon Mining Co. (pers. comm.) several lens-like outcrops of jasperoidal ferruginous gossan with scarce malachite staining can be followed for quite long distances within the meridionally trending greenschists, dipping steeply west.

In the drainage area of the river Obel 10 km southwest of Chenaudi, there are several elongated jasperoidal bodies with magnetite and occasional barite embedded in ferruginous schist, in places stained with malachite. The dimension of the largest body is reportedly more than 3 km. The volcanogeneous sequence contains abundant layers of porphyritic extrusives.

Ruba Catina

In the drainage area of the Catina river about 30 km southwest of Adi Quala, the volcanogeneous sequence is composed of schistose and massive greenschists, quartz-sericite schists and various extrusive layers, trending meridionally and dipping east. A large body of porphyritic granite extends to the northwest. Near Catina village several bodies of gossan up to 250 m long and several metres wide are aligned in the foliation of the epidotised greenschist. Gossan is prevailingly dark and ferruginous, containing discontinuous patches of barite strongly stained with malachite and iron oxides. There are outcrops of ferruginous jasperoidal rock and abundant quartz veins. In general, the mineralisation resembles that of Debarwa, the adjacent rocks being strongly weathered and kaolinised. There are reportedly many other gossanous outcrops in the surrounding area.

Aragab

This prospect is about 15 km north-northwest of Selaclaca, just south of the Mareb river. Greenschist, sericite schist, quartzite and hornfelse form narrow zones, striking southeast and dipping vertically. A ferruginous belt more than

1 km long runs on both flanks of the Aragab river, containing narrow elongated bodies of limonitic gossan and numerous parallel quartz veins, surrounded by ochreous sericite schist. Malachite staining is abundant. Soil geochemistry shows a mineralisation pattern of base metals analogous to other explored localities.

Tsehafe Emba

This locality is situated close to the Takeze river about 45 km south of Enda Selassie in Tigre. Here, geochemical stream sediment survey indicated anomalous base metal values.

The prevailing rock types are greenschist, quartz-chlorite schist and greywacke with medium-grained grey marble interbedded in places. Coarse porphyritic and finer-grained leucocratic and mesocratic magmatic differentiates are abundant, the rocks intercalated conformably, folded and sheared together with the whole sequence. There are rocks of granodioritic appearance and aplitic offshoots.

Malachite staining occurs in schists but for the most part it is confined to quartz veins and stringers which are abundant but not persistent, proving hydrothermal activity in the area. Quartz is accompanied by epidote, chlorite, calcite, magnetite and remnants of sulphides, evident in limonitised inclusions. Chalcocite can also be seen in vein quartz. Weakly limonitised zones appear at the contacts between marble and schist. M. Ahmed (1974, unpublished report) found more malachite-stained mineralised zones in greenschist, the largest reportedly about 1 km long.

Benaque

In the Benaque area, about 20 km south of Enda Selassie, the country rocks are phyllite, quartzitic schist, graphitic schist and green quartzite, the sequence dipping 70—80° northwest. Ocherous ferruginous beds up to several hundred metres long and tens of metres wide are aligned within the sequence, the primary iron mineral being magnetite, probably detrital. There are no copper stains, no epidote and few quartz veins.

Rama

In the Rama area about 20 km south of Adi Quala, a number of elongated ferruginous outcrops occur within the greenschist sequence, the geological environment being reportedly similar to Ruba Catina area (Nippon Mining Co., pers. comm.).

Enticho

Ferruginous outcrops have been known for years about 7 km north of Enticho village, which is about 35 km northeast of Adua. The area is built up of greenschist, micaceous and phyllitic schists interbedded with green porphyritic derivatives, shale and mudstone intercalated with sandstone, bedded chert, dolomitic slate, grey marble and greywacke, the sequence showing gradations and interbedding over short distances and dipping generally 60—80° northwest.

The ferruginous zone is nearly 2 km long and up to 150 m wide. Several discontinuous lenses of limonitic gossan, the largest up to several hundred metres long and up to 20 m wide, occur in shale and phyllitic schist. The bodies are brecciated and arenaceous, cut by longitudinal dislocations. Malachite stainings are absent and base metal contents in soils are low. Gossan apparently originated from sulphides disseminated in schist and concentrated in dilatant zones.

Shieb

In the Shieb area, in the lowland about 60 km north-northeast of Asmara, strong malachite staining marks a 2 km long zone within the meridionally striking schist, the occurrence being similar to that of Mont Saccar as to the appearance and associated rocks (I. Solomon, pers. comm.).

Gumhod and Agametta

Massive iron ore occurrences appear in a submeridionally trending belt about 40 km east of Asmara in the lowlands. The geologic environment consists of chlorite-sericite-quartz greenschist and quartzite with calcareous interbeds, banded ferruginous quartzite and rare layers of epidotised extrusives. Lens-like bodies of schistose and massive magnetite ore, associated with jasperoidal rocks, alternate with and grade into greenschist, the zone extending intermittently over 40 km from Gumhod in the north to Agametta in the south (M. Hamrla, 1966). Magnetite ore lenses exist on different levels, their dimensions not more than a hundred metres in length and several metres in width, in places associated with epidote-garnet-amphibole-magnetite skarns. Massive magnetite ore crops out, assaying up to 69 per cent iron in bulk samples. Malachite staining is frequently associated with ferruginous rocks.

The ore consists of granoblastic martitised magnetite embedded in a quartz matrix, with admixtures of lamellar haematite, chlorite, mica, epidote and calcite. Minor sulphides are present, small chalcopyrite inclusions occurring within magnetite grains, their size very minute (M. Hamrla, 1966). Later generation quartz and sulphides are associated with skarns.

The intimate textural relationship of copper and iron proves that both metals are of the same origin, the quantitative ratio of sulphidic and oxidic species being strongly in favour of the latter in this area.

Akrur

This locality is about 9 km northeast of Saganeity and, according to an unpublished report of W. S. Atkins and Partners, consists of a stockwork of oxidised veinlets and stringers of limonite and malachite within a sequence of agglomerate, spilite and tuff, dipping gently east.

Deuchan

Two zones of barite with malachite staining, the larger about 400 m long, occur within schist along a small granitic boss about 20 km southeast of Senafe (Y. Urdea and W. R. Alemayehou, unpublished report).

Sheraro

The tuffaceous greenschist within the Sheraro ring complex dips about 60° east and belong to the discordant Sheraro Formation. Modest malachite staining occurs intermittently in a zone about 1 km long adjacent to the ring, and originated probably from sulphide impregnations in sheared zones. Limonite incrusted breccia, vein quartz with chalcocite and specularite occur in scattered float.

The ring itself is composed of a central gabbro core surrounded by alkaline rocks and a microgranite porphyry outer ring, the rocks apparently comagmatic differentiation products. Hydrothermal silicification affected the complex, the copper mineralisation being seemingly epigenetic.

Escarpment area

West of Alid volcano, in the bed of the Maeba torrent at the locality called Buia, large quantities of malachite-stained greenschist gravel can be seen, derived from cupriferous outcrops east of the Adi Caieh area. Similar copper-stained river gravel occurs in the Dandero torrent south of Buia. Copper shows have been reported also at Badda, and Sabba 30 km south of Enkafela; at the latter locality malachite stains chloritic schist interbedded with porphyrite (Y. Urdea and W. R. Alemayehou, unpublished report).

Summary

The ore deposits and occurrences described, though varied, are nevertheless mineralogically and morphologically identical, depending on the differences of syngenetic and epigenetic factors involved. The following field-types have been recognised:

a) Stratiform massive pyrite layers with low to modest primary base metal contents;

b) stratiform massive cherty sulphide concentrations with barite gangue, epigenetically enriched with base and precious metals;

c) stockwork-type sulphide concentrations;

d) stratabound disseminations, and possibly impregnations, in different rocks;

e) cherty jasperoidal ironstones with sulphides and iron oxides, usually manganiferous and epidotised;

f) lens-like concentrations of massive and schistose magnetite grading into jaspilites, with subordinated sulphides;

g) skarn-type epidote-garnet-calcite concentrations of sulphides and iron oxides;

h) vein quartz with dispersed auriferous sulphides.

The individual occurrences are rather small and spatially limited. They all show a tendency to occur in clusters and lineaments, the metal contents varying widely from place to place, and sulphide and oxide facies taking part in variable degrees.

The spatial (stratigraphic) correlation between various types, if any, is unknown.

DISCUSSION

Depositional environment

The structurally aligned Precambrian schistose and granitic rocks of northern Ethiopia belong to the Red Sea Proterozoic geosyncline, itself part of the Mozambiquan Belt, which extends to northeastern Africa and Arabia (R. M. Shackleton, 1964; J. R. Vail, 1964). The type of succession and its thickness prove the eugeosynclinal origin, the elongated structural pattern being indicative of an orogenic belt. It is debatable whether the Red Sea fold belt originated as one subsiding depositional basin or several discrete small basins, the opening and closing of which operated along the lines of the present plate tectonics mechanism (J. Sutton and J. V. Watson, 1974).

Since the plate tectonics concept is becoming more and more accepted in interpretation of the Precambrian tectonic regimes, a plate tectonics model can be envisaged for the evolutionary explanation of remote events in this area. The Upper Precambrian lithology of northern Ethiopia is also similar to the Precambrian greenschist suites containing massive sulphides worldwide; their petrochemical similarity with modern island arc environments, formed at the destructive margins of oceanic plates, is well known (A. H. Mitchell and H. G. Reading, 1971; F. J. Sawkins, 1972). The best example is the Japanese island arc with its numerous Kuroko-type stratiform sulphide deposits and vein type gold deposits. Although of Miocene age, the features of the Kuroko deposits and their geological environment are strikingly similar to the older environments in various parts of the world (P. Gilmour, 1971; D. F. Sangster, 1972; R. W. Hutchinson, 1973; N. A. Duke et al., 1974; S. Ishihara, 1974; D. Williams et al., 1975).

Conformable to the suggestion that the greenstone belts are remnants of Precambrian arc systems, the Upper Precambrian geology of northern Ethiopia can be interpreted through episodes of deposition in an eugeosynclinal basin marginal to an island arc system, and lithospheric subduction and deformation at the plate margins. The development of Benioff zones must be postulated, probably aligned with the present-day submeridionally trending ophiolitic zones in northern, western and southern Ethiopia (M. Hamrla, 1977), as well as in the neighbouring countries (C. R. Neary et al., 1976). They are shown in Figure 27. The stable „continental mass", required for the compressive tectonic, might be evidenced in the Lower Complex rocks along the eastern escarpment, whereas the western equivalent is unknown.

A typical feature of an island arc system is contemporaneous extrusive and intrusive activity, and the trend of compositional change of erupted magmas from tholeiitic through calc-alkaline to alkaline varieties, with K_2O content increasing towards the concave side of arcs (A. H. Mitchell and H. G. Reading, 1971). Although the petrological and geochemical features of the early erupted magmas in northern Ethiopia are little known and the rocks are obliterated by hydrothermal metamorphism, the presence of early mafic, intermediate and felsic magmas of specific subalkaline, sodic nature seems indicative of an island arc magmatic evolution, with later intrusives becoming more felsic, potassic and calc-alkaline with a normal Na/K ratio.

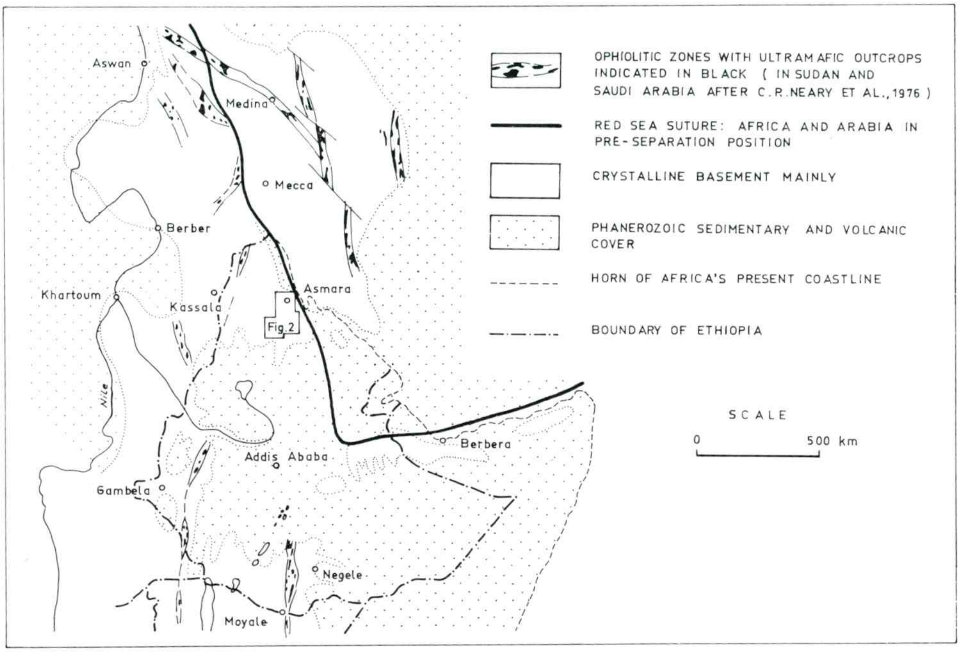


Fig. 27. Ophiolitic zones in Ethiopia and in adjacent countries

The evolution of Proterozoic geosynclines in Egypt, Saudi Arabia and Sudan has been similarly attributed to island arc environments, the subduction-generated volcanism and plutonism being coeval and comagmatic (C. R. Neary et. al., 1976).

On the observation that modern island arcs persist in roughly the same places for long periods (A. H. Mitchell and H. C. Reading, 1971), a cratonisation of the Upper Precambrian island arc can be postulated, implying the migration of the subduction zone and formation of new crust through the gradual accumulation of volcanic, sedimentary and plutonic rocks. C. R. Neary et al. (1976) even presumed, on evidence from Saudi Arabia and Egypt, that more cratonised island arcs could have been brought together to form a new „continent", which provided the source of sedimentary rocks prevailing in the later stages of infilling the subsiding basin.

Metallogenesis

Origin of ore. The mineralogical, structural, textural and paragenetic features of ores suggest their formation basically through two stages of hypogene processes: an original submarine syn-volcanic exhalative-sedimentary deposition of sulphidic and oxidic minerals, and subsequent hydrothermal remobilisation, rearrangement and enrichment of original accumulations, the latter processes probably associated with more episodes of orogeny and magmatism.

A syngenetic volcanic-sedimentary theory has been accepted as the formation concept of massive pyritic ore deposits in northern Ethiopia. The deposits formed apparently at the sea floor from magmatically generated metal-bearing emanations around fumarolic vents, to be covered in a short time by volcanogenic-sedimentary material, consolidated and subjected to metamorphism, and in turn affected by rejuvenating hydrothermal episodes. This second stage involves the ascending solutions generated or activated through the same magmatic activities and crustal tectonic, mobilising the new constituents from depth or remobilising the original „sedimentary" constituents, concentrating them either within the primary deposits by replacement or in newly opened dilatant sites of increased permeability as vein-type concentrations. Shears, faults and fractures served as communication conduits and new loci of deposition, usually not very distant from the original accumulations. It was in fact one prolonged multi-stage hydrothermal event, its sequences overlapping, as evidenced for example at Debarwa. The time interval of these episodes probably extended from the later stages of the Precambrian submarine fumarolic activity to the Tertiary magmatism and tectonism.

Regarding the ore mineralogy, the coexistence of oxidic and sulphidic facies is a characteristic feature, both occurring in the same lineaments, in the same deposits and interbanded on a microscopic scale; pyrite, pyrrhotite and magnetite are so intimately interconnected that their primary origin is beyond doubt. The facies are temporal and spatial (stratigraphic) equivalents, their formation implying the existence of oxidising and reducing conditions at the depositional localities. In the regional context, such conditions could be plausibly expressed in terms of water depth and the proximity of shorelines, implying that iron oxide facies is confined to oxidising nearshore environments, and the sulphide facies to deep local troughs. This concept of depositional zones might explain the Gumhod-Agametta magnetite belt in the lowlands. However, in other localities, as for example the Ruba Catina area, massive sulphide lenses and „iron formation" occur close together, and the depositional environment concept cannot give a satisfactory explanation. The fluctuation of oxidising and reducing conditions is still less applicable to explain the presence of both facies in ore on a microscopic scale.

In this context, the recent Red Sea ore forming system, where a base metal deposit is in the making, will be recalled (E. T. Degens and D. A. Ross, 1969). A black fine-banded ooze of gel-like appearance is being precipitated from the submarine brines, consisting of base metal sulphides, oxidic iron and manganese minerals, barite and amorphous silica. The observed precipitation of the amorphous ferric hydroxide (limonite) in close association with iron sulphides is of the utmost importance. J. P. Hackett and J. G. Bischoff (1973) described magnetite coexisting with haematite, both minerals well crystallised diagenetically. The origin of the oxidic facies is interpreted by dehydration of the originally precipitated colloidal limonite to form goethite, and its subsequent dehydration to haematite which, in turn, by continuous supply of ferrous iron from the brine outlet, is transformed into magnetite.

The stability relations of pyrite, pyrrhotite and magnetite are thought to be largely controlled by the pH and Eh conditions of the local environment, the concentration of sulphur and other constituents. In general, low values of pH and Eh favour the deposition of sulphides whereas high values promote oxide minerals. The three minerals are generally stable in very reducing conditions in an alkaline to neutral environment (R. M. Garells and C. L. Christ, 1965; K. B. Krauskopf, 1967). Since magnetite is stable only in an alkaline strongly reducing environment — the precipitation range of sulphides being somewhat broader, with pyrite forming even at slightly positive Eh ranges in either acid or weakly alkaline environments — such conditions must have prevailed during the formation of ore.

Variations in syngenetic as well as epigenetic mineralogy must then be seen in the variable nature of solutions, solubility of the components and in the changing physico-chemical conditions of the local environment. In syngenetic precipitation, certain components may have precipitated within or close to the outlets of the fumarolic vents, the others at a certain distance, laterally or vertically (temporally) from the outlets. This would explain the mineralogical zoning. Variable contents of sulphides, silica, manganese and barite may be explained in this way, the latter two, for example, forming rather marginal parts of the deposits (G. Anger, 1966; W. Gwozdz and W. Krebs, 1977).

Extremely high grade copper concentrations, as at Debarwa for instance, resulted from supergene processes of cementation brought about by descending surface waters. According to present evidence, the supergene enrichment is developed very variedly, depending on the ground stability and movement of the groundwater levels.

The formation of auriferous quartz veins with minor amounts of sulphides seems to be best attributable to rejuvenating hydrothermal activity postdating the syn-volcanic sedimentary mineralisation. The hydrothermal fluids, probably released or activated by anatectic generation of magmas, may have leached gold and other metals plus silica from elsewhere, and transported them into permeable structural sites at different levels of the crust. Gold could have migrated, together with silica, as sol in colloidal solutions. The controlling factors of gold mineralisation are virtually unknown, the reefs seemingly concentrated in the sequence of massive metavolcanics, and hence probably early epigenetic in the main.

Solutions and possible mineralisation mechanism. The syngenetic mineralisations are interpreted to have occurred by means of a liquid phase, its fumarolic source a plausible explanation, and its nature and origin — juvenile, meteoric or connate — little known.

One could speculate that the material in volcanic emanations was in a colloidal dispersed state. Fine banding in the ores featuring sulphidic and oxidic minerals, apparent contraction or shrinkage cracks across the pyrite bands, the colloform textures of gel-pyrite and irregular masses of pyrrhotite and magnetite suggest gel deposition. Silica is abundant in all ore types; the colloidal phenomena in silica deposition are well known, and in submarine deposits it is a direct precipitate from silica gel. The Kuroko ores formed from colloidal siliceous fluids (C. F. Park and R. A. Mac Diarmid, 1970), and magnetite facies and other precipitates in the Red Sea brines formed from sols (E. T. Degens and D. A. Ross, 1969; J. P. Hackett and J. G. Bischoff, 1973).

In colloidal origin of the primary constituents, the metals were probably suspended in solutions as sulphide sols and ferric hydroxide sol. The colloidal metal sulphides are negatively charged and so is the colloidal silica, whereas iron as ferric hydroxide sol is normally positively charged. Discharged through volcanic outlets at the sea bottom, the colloids precipitated possibly on contact with electrolytes of the seawater, or any other way, and as the flocculation of different components proceeded, a banded ore was produced as a chemical precipitate. However, the mechanism of colloidal transportation and deposition is complex and, according to K. B. Krauskopf (1967) little understood.

The hydrothermal solutions responsible for the following migration of ore components might have been diluted aqueous solutions, possibly alkaline brines derived from seawater as connate waters activated by dynamism and magmatism. The presence of seawater sulphate in the early, as well as in the later vein-type sulphides, has been indicated by a preliminary sulphur isotope study. The sea origin of solutions may explain also the possible source of calcium and magnesium involved in metasomatic alteration of the wall rocks, possibly sodium and barium as well. The alkaline nature of solutions might be supported by the ubiquitous presence of chlorite and sericite, whereas kaolinite, which would suggest acid solutions, is absent (K. B. Krauskopf, 1967).

Supposing that precipitation was caused by decreasing pressure and temperature and mixing with sulphide-rich solutions, chloride complexes might be considered as transporting mechanisms according to H. L. Barnes (1972), who nevertheless considers the origin of stratiform volcanic deposits "a solution-mixing process of problematic nature".

Temperature at formation. The intergrowth textures of the lime-iron silicates and the early opaque constituents suggest a simultaneous origin. A plausible interpretation would be the formation of the silicates from exhalatively supplied solutions carrying lime, magnesia and silica and readily entering into reaction. Since lime silicates form at temperatures of about 600 °C (C. F. Park and R. A. MacDiarmid, 1970), such temperatures are hardly likely to persist for long in a submarine environment. The silicates may therefore have formed at lower temperatures, as might be possible in the presence of mineralisers (A. Betektin, 1964).

Further temperature evidence is provided by the exsolution blebs of chalcopyrite in dark sphalerite, which originated by unmixing of solid solutions at temperatures below 350 °C (A. B. Edwards, 1954; C. F. Park and R. A. MacDiarmid, 1970). Consequently, the temperature of deposition from the sulphide bearing agency of that stage should have been higher than 350 °C.

On the other hand, the apparently colloform gel-pyrite, supposed to belong to a relatively later mineralisation stage, indicates a low-temperature low-pressure environment. The same holds for the yellow low-iron sphalerite. found in higher, i.e. later, layers of massive pyrite ore as well as in veins. It has formed at relatively lower temperatures well below 300 °C (A. B. Edwards, 1954; C. F. Park and R. A. MacDiarmid, 1970). On the other hand, andradite in veins and skarn-type concentrations proves, at least locally, high temperature solutions.

The conclusion is likely that the initial temperature of ore formation would have been higher than 300 °C, decreasing gradually but fluctuating during subsequent surges of solutions.

Source of ore components. Regarding the generation of ore components, genetic association with the magmatic source can reasonably be assumed. An igneous source for the metals is a plausible explanation. The early magmatics show a marked deficiency of iron, which was apparently removed in some way from the magma, appearing in solutions from which ferroan minerals precipitated.

As to base metals, the average Cu:Pb:Zn ratios in ores show a strong prevalence of zinc and copper over lead (Table 12). The few available data on trace metals in rocks show the same though less sharp ratios:

Cu	Pb	Zn	
15	1	26	Embaderho porphyritic rocks (average of 4 samples)
4	1	12	Embaderho quartz diorite

The primary source of gold is probably to be looked for in mafic magmas of mantle origin (R. J. Tilling et al., 1973); it might have been originally concentrated in the sulphide phase derived from the melts and precipitated syngenetically, to be subsequently partly remobilised and reprecipitated.

The Co/Ni ratios for different ores are greater than unity and locally very high, suggestive of a volcanic origin. The highest ratio, about 30, was found in the Embaderho massive granular ore, and the relatively lowest values slightly above unity pertain to sulphidic disseminations in schists.

Consequently, a mantle origin may be reasonably assumed for the critical constituents of the deposits.

As for the provenance of sulphur, the isotopic evidence suggests that it originated partly magmatically and partly from the seawater sulphate.

Metamorphism

After deposition the sequence underwent metamorphism in the form of diagenesis, metasomatism and regional metamorphism.

Diagenesis involved the compaction of the loose sedimented ore material during which sulphides and de-watered iron hydroxides crystallised and silicates developed, the mineral components externally introduced by lime- and magnesia-rich solutions. Authigenic chlorite and sericite may have developed at this stage in argillaceous-tuffaceous sediments.

Igneous rocks have been strongly altered, their original nature obliterated by hydrothermal metamorphism, which changed felsic, intermediate and even mafic types into spilitic-keratophyric assemblage of chlorite-albite-epidote--actinolite-calcite minerals. The question arises as to whether the mineral changes in the early erupted rocks, both fissure extrusives and intrusives, could be attributed to autometasomatic (deuteric) changes through the agency of magmatic solutions, or by later hydrothermal solutions, or whether the changes were produced by regional metamorphism. The greenschist mineral assemblage, in both igneous and sedimentary rocks, is typical, though the origin of albite is not clear. The sodium content in the early magmatics seems to be a primary juvenile feature, and albitisation was probably due to internal rearrangements described by F. H. Hatch et al. (1972) as deuteric albitisation.

It can reasonably be assumed that the magmatic metasomatism took place when the magma, extruded under submarine conditions, quickly solidified into a cryptocrystalline solid with a glassy crust, the entrapped volatiles being unable to escape, and permeating the rock and producing low-temperature low-pressure mineralogical and textural changes. At more or less the same time the rocks were affected by ore-bearing solutions which originated from the same magma. The alteration is strongest at contacts with ore, the silicate minerals of the ore assemblage involving the constitutional hydroxyl, direct evidence of the presence of water at their formation. The presence of calcite points to the addition of carbon dioxide to the system. If the ore-bearing solutions were colloidal and the particles flocculated by ions of seawater such as Mg^{++}, Ca^{++} or even Na^{+}, they may have entered into the composition of the newly formed silicate minerals as well.

It is conceivable that low-grade regional metamorphism also contributed to the development of the greenschist mineral assemblage, the temperature-pressure field of the greenschist facies ranging from 200 to 450 or even 600° C and 1.5 to 9 kb, corresponding to 5 to 30 km burial depth (K. B. Krauskopf, 1967; F. J. Turner, 1968). Such ranges of thickness of originally accumulated rocks seem reasonable. Additional metamorphic changes could have been produced by solutions during late-stage hydrothermal events.

Metamorphic and extrusive assemblages similar to those of northern Ethiopia were examined by L. J. G. Schermerhorn (1975) within the Iberian pyrite belt, where the spilitic extrusives are high in alumina, and albite of autometasomatic origin crystallised extratellurically.

It might be also noted that altered low-potassium porphyritic rhyo-dacitic rocks of the circum-Pacific orogenic belt are closely associated with Kuroko type mineralisations (S. Ishihara, 1974). Such rock types are believed to be associated with particular geotectonic settings.

The effects of thermal metamorphism in northern Ethiopia are low-grade too, being evident in the development of discontinuous metamorphic aureoles on later intrusives, marked by modest baking, silicification and development of hornfels, hornblende schist and occasionally of amphibolite and fissile slate, and exceptionally also andalusite, cordierite and garnet schist.

The metamorphic effects in the opaque mineral assemblage are hard to recognise. All three main mineral species — pyrite, pyrrhotite and magnetite — are primary, and there is no evidence that one grew at the expense of another. However, the present granoblastic and „porphyroblastic“ textures (Fig. 10) are usually taken as a proof of metamorphic recrystallisation (J. Kaliokoski, 1965; D. F. Sangster, 1972). Since the original banding in ore is well preserved, it would be difficult to assume that some minerals, like euhedral pyrite, would have been affected selectively by recrystallisation, by breakdown or by any other textural rearrangement, while others would have remained unaffected. In the present case, it is believed, the uneven grain size of ore minerals is rather due to overlapping crystallising events producing distinct and morphologically varied generations. Pyrrhotite, for one, never occurs in large individual crystals.

The regional metamorphism apparently affected the ore by slight recrystallisation only. The opaque minerals are all crystalline, their sizes variable from very fine-grained gel-pyrite to irregularly-grained pyrrhotite and magnetite masses. In places the post-ore movements locally shattered and brecciated the ore minerals.

In the simultaneously crystallised intergrowth of lime silicates and opaque ore minerals, pyrite, magnetite and silicates are euhedral vis-a-vis quartz and calcite. The general order of crystallisation in massive ore seems to be: pyrite-magnetite-tremolite/actinolite-epidote-pyrrhotite-quartz-calcite, corresponding well to the normal crystalloblastic series in thermally metamorphosed rocks and is crystallisation from igneous melts (A. Harker, 1950; C. F. Park and R. A. MacDiarmid, 1970). Since in hydrothermal mineralisation quartz is usually the earliest mineral to form, a blastic growth might nevertheless be indicated in the ore paragenesis, unless the ores formed from colloidal solutions. In this case, according to K. B. Krauskopf (1967), the sequence might be completely irregular.

Classification

Several schemes have been prepared to classify the massive sulphide deposits. R. H. Sillitoe (1973) subdivided the Phanerozoic deposits according to geotectonic environment, P. Gilmour (1971) stressed the observable features, and R. W. Hutchinson (1973) applied the differences in metal contents, the associated rock types, tectonic environment and age as the classification basis.

Accordingly, the base metal sulphides of northern Ethiopia fit well into the Pb-Zn-Cu-Ag Proterozoic type of massive sulphides, associated with felsic to intermediate rocks of prevailing subaqueous volcanism related to coeval plutonism, the lens-like ore concentrations in schistose rocks near the volcanic rocks but not in themselves. Whether or not the extrusive rocks were originally calc-alkaline needs further study.

The estimated average ore grades in some relatively better known deposits are summarised in Table 12.

Table 12 Summary of estimated ore grades in examined deposits

Deposit	Cu	Zn (per cent)	Pb	Ag	Au (g/t)	Approx. metal ratios Cu : Pb : Zn
Embaderho	0.52	1.83	0.009	10	+	51 : 1 : 200
Adi Nefas	1.75	8.5	0.8	100	2.3	2.2 : 1 : 11
Debarwa	2.15	5	0.5	100	2	4.5 : 1 : 10
Adi Rassi	1.2	ND	ND	?	0.65	
Mont Saccar	0.5	ND	ND	?	0.1	

ND not determined (but apparently very low)
? present in all probability
\+ present

The metal ratios in stratiform ores show strong prevalence of zinc and copper over lead, the contents variable. Copper seems to prevail strongly in stockwork and dissemination mineralisation types. Magnetite forms massive concentrations in places and is locally present in appreciable amounts within the sulphide suites. Barite is present too, and though a primary mineral, it has evidently been relocated in the later vein-type stages. Its presence contradicts both C. A. Anderson's (1969) and P. Gilmour's (1971) notes that barite, and similarly gypsum, do not occur with the massive Precambrian sulphides.

CONCLUSIONS

The Upper Precambrian volcanic-sedimentary-intrusive environment of northern Ethiopia is analogous to the geological settings in the neighbouring countries, and could be interpreted in the context of a postulated island arc system, where gradual accumulation of volcanic, sedimentary and plutonic rocks produced new crust with continental characteristics. However, present information on the geotectonic history and magmatism is very modest, leaving the field wide open for all kinds of future investigations.

Northern Ethiopia belongs to a metallogenetic province, in which the pyritic — base metal — magnetite and gold mineralisations orginated coevally with their host rocks. The processes were associated with magmatism, which produced extrusive flows infilling the subsiding basin as well as intrusions into the eugeosynclinal sequence. The early magmatic rocks display the characteristics of a spilitic-keratophyric association, the high Na/K ratio apparently a distinctive original feature. Later felsic plutonic rocks are peralkaline, probably due to a larger proportion of crustal material in anatectic melts. The interpretations and conclusions, at this stage, are necessarily speculative.

The study of ore deposits, too, is in the very initial stage, and due to objective reasons could not be pursued systematically. So far, the investigations focussed on some larger accessible deposits where depth evidence has been obtained by drilling. The primary mineralisations took place in a submarine environment by co-operation of exhalative and sedimentary processes. The megatextures of the deposits and the microstructures of ores and rocks suggest that they formed syn-volcanically around volcanic outlets on or near the sea floor. The close coexistence of the oxide and sulphide iron facies, both on a regional as well as on a microscopic scale, is a characteristic feature. The factors controlling the precipitation of minerals, probably from colloidal solutions, were apparently associated more with their composition than with the depositional environment. Subsequent hydrothermal rejuvenation episodes affected the two-dimensional ore bodies and rearranged and enriched the syngenetic constituents, the loci of redeposition also the newly opened dilatant sites featuring vein-like forms.

The source of ore constituents is believed to be mainly magmatic. However isotopic evidence suggests that part of the sulphur originated from seawater sulphate, indicating a marine origin for solutions (M. Hamrla, 1974).

The features exhibited by north Ethiopian deposits are in many respects analogous to world-wide pyritic base metal deposits of volcanogenic origin. The Canadian Precambrian deposits (D. F. Sangster, 1972), the Rio Tinto deposits in Spain (D. Williams et al., 1975; L. J. G. Schermerhorn, 1975), the Scandinavian deposits (G. Gehrish et al., 1975) and others show strong resemblances, and not least the Japanese Kuroko deposits, both volcanic and sedimentary in origin and syngenetic and epigenetic in nature (T. Matsukuma and E. Horikoshi, 1970; S. Ishihara, 1974).

The Ethiopian deposits fit well with the Proterozoic Pb-Zn-Cu-Ag type of R. W. Hutchinson (1973), with zinc and copper values strongly prevailing over lead. The primary grading of base and precious metals is generally low by any mining standard. However, the subsequent rearrangements and concentrations, hypogene and supergene, can render particular deposits economically interesting propositions, despite the generally very small tonnage potentials. Recent successful mining development at Debarwa confirms this.

Further systematic studies will doubtlessly lead to significant scientific as well as practical conclusions not only in northern but also in western Ethiopia, where similar metallogenetic conditions have been indicated.

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