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SAMIA A. IBRAHIM

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by

SAMIA A. IBRAHIM

***(University of Khartoum, Sudan; and
Visiting Research Student - Sandwich Program - EGRI-HAL, School of Geosciences,
University of the Witwatersrand, Private Bag 3, P.O. Wits 2050,
Johannesburg, South Africa)***

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ABSTRACT

Volcanogenic massive sulphide deposits have been found associated with two ophiolite complexes in the Red Sea Hills region of northeast Sudan. These include the Oshib ophiolite in the Ariab belt and the Abu Samar ophiolite occurrence in the Abu Samar area of Haya. The most important massive sulphide prospects in the Sudanese sector of the Pan-African Nubian Shield are situated in the Ariab-Nakasib-Arbaat belt, which consists of metavolcano-sedimentary rocks and dismembered ophiolitic mélanges. This belt continues across the Red Sea into Saudia Arabia where it is known as Samran and Jabel Sayid belt, and where many volcanogenic massive sulphide deposits have been discovered.

The Ariab Mineral District in the Red Sea Hills region of Sudan possesses mineral deposits that differ from vein-type deposits and occur mostly as supergene-enriched ores derived from volcanogenic massive sulphide occurrences of Late Proterozoic age. The host formations, referred to as silica-barite rock, correspond to silicified and hydrothermally altered pyroclastic rocks or rhyolitic lavas hosting and directly in contact with the massive sulphides. The silica-barite facies rocks vary in colour, mineral constituents (gypsum, jarosite, and alunite), element leaching, and gold and silver grade.

The hydrothermal origin of the gold-barite-silica association best accounts for most genetic aspects of the gold enrichment and gossan formation in the Ariab area - as opposed to subsurface weathering processes. This view is reinforced by the recent discovery of hydrothermally formed gossans and supergene gold enrichment in submarine environments at active plate margins.

The Proterozoic volcanogenic massive sulphides deposits of the Ariab region share metallogenic characteristics with sulphide occurrences from Archaean greenstone terranes, similar to those found in Canada, and to Kuroko-type deposits found in Phanerozoic geological settings. The intermediate character of the Ariab volcanogenic massive sulphide occurrences appears to support suggestions invoking evolutionary changes in volcanism and tectonism through time.

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AURIFEROUS VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS OF THE ARIAB MINERAL DISTRICT, RED SEA HILLS, NORTHEAST SUDAN

INTRODUCTION

The Neoproterozoic (Pan African) Red Sea Hills region of northeast Sudan forms part of the Arabian-Nubian Shield. It lies in the central part of the Nubian Shield segment and extends northwards across the Eastern Desert of Egypt and southwards across the Sudan-Eriterian border to the Ethiopian Plateau (Fig. 1A). It is bound in the east by the Red Sea Coastal Plain and in the west by the Nubian Desert. The Ariab Mineral District (situated between latitudes 18° 20´- 19° 00´N and longitudes 35° 10´- 36° 00´E), is located in the central part of the Red Sea Province, midway between Atbara and Port Sudan (Fig. 1B).

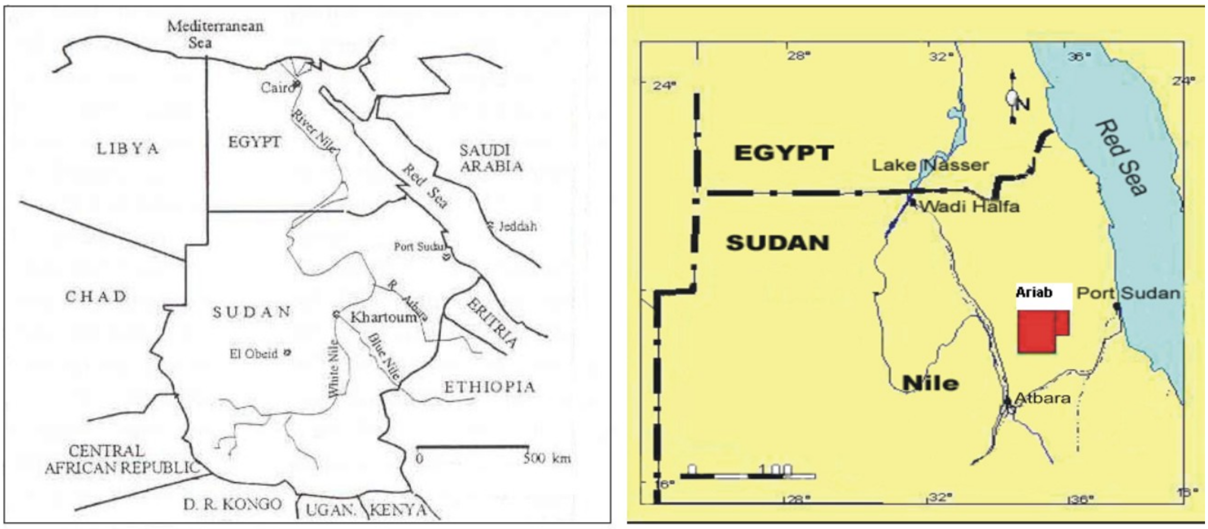

Figure 1: *Maps showing: (A) the position of Sudan relative to neighbouring countries in northeast Africa; and (B) the location of the Ariab Mineral District, Red Sea Hills area, Northeast Sudan.*

REGIONAL GEOLOGICAL SETTING OF THE RED SEA HILLS

Much of the North African segment of continental Africa has been relatively stable tectonically for the past 500 Ma. Neoproterozoic (Pan African) orogenic episodes divide the region into two major tectonic domains including: (1) cratons, which have not suffered major orogenic deformation after about 1000 Ma; and (2) mobile belts, comprised of rocks which have been stable since *c*. 550 Ma (Vail, 1983). The Pan-African belts, in turn, occur: (1) as arc assemblages and associated ophiolites and granitoids (e.g., forming part of the Arabian Nubian Shield; (2) as older crustal terranes rejuvenated during the Pan-African event (e.g., the Mozambique Belt); and (3) as sedimentary and/or volcanic rocks that accumulated in tectonic basins or aulacogens and were subsequently metamorphosed and deformed during the Pan-African event producing major geotectonic features (e.g., the Damara-Katanga belts) - (Vail, 1983).

Two important Neoproterozoic orogenic domains are exposed in east and northeast Africa. These include (1) the low-metamorphic grade, juvenile-arc complexes of the Arabian Nubian Shield in the Red Sea Hills region of Sudan, as well as in Ethiopia, Eritrea, north Somalia, Sinai, western Saudi-Arabia, the Eastern Desert of Egypt, and Yemen; and (2) the medium- to high-grade gneiss terrane of the Mozambique Belt extending from Sudan, Ethiopia, Somalia and Kenya, southwards to Mozambique. In Sudan four areas are related to Pan-African development. These include: (1) the Red Sea Hills Region northeast of Khartoum; (2) the Bayuda-Gabgaba area north of Khartoum;

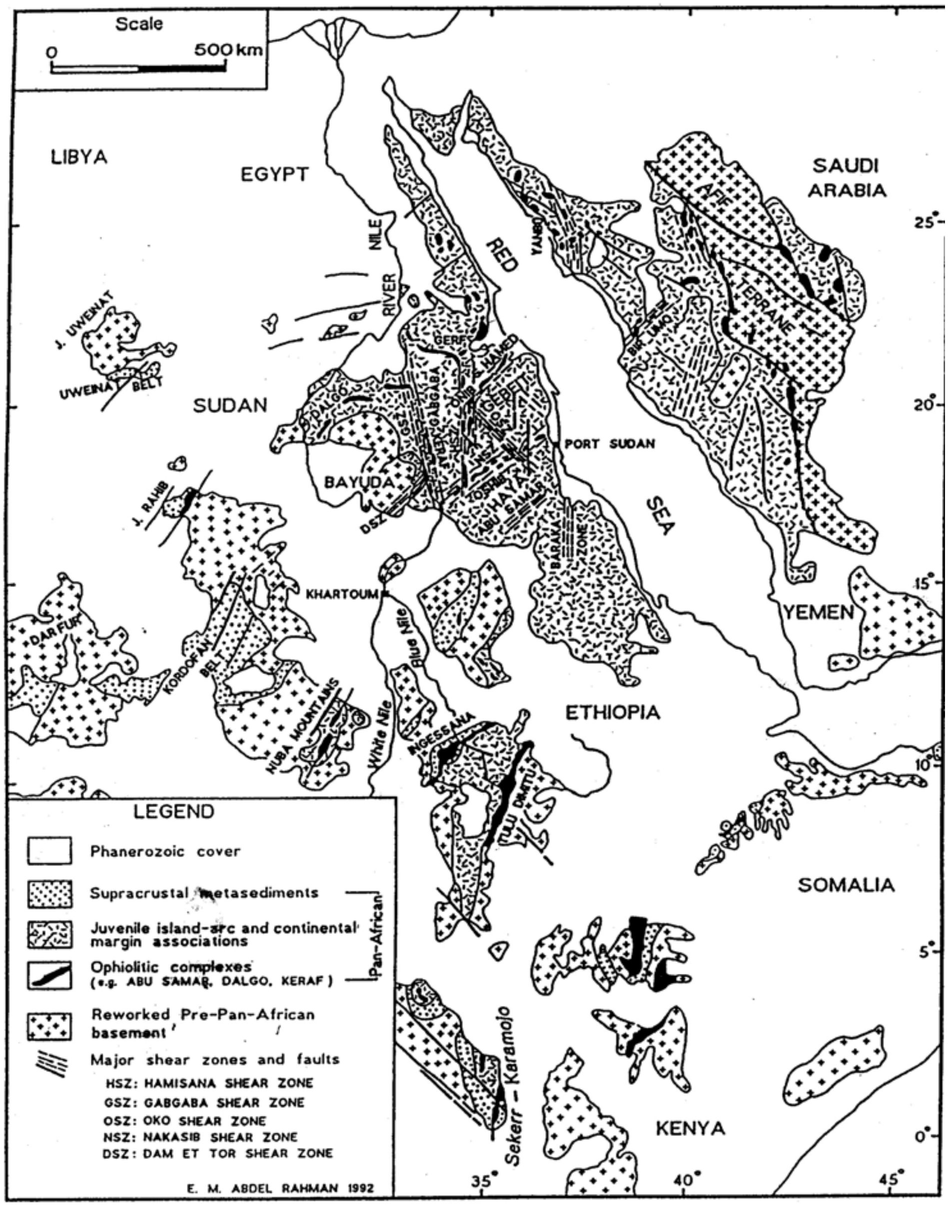

Figure 2: *Simplified geological map showing the distribution of the pre-Pan-African basement in Sudan and adjacent areas, and the Pan-African island arcs and ophiolite complexes in northeast Africa and Saudi Arabia.*

(3) the Ingessana-Kurmuk area south-southeast of Khartoum; and (4) the Jebel Rahib Belt west-northwest of Khartoum (Fig. 2).

The Arabian-Nubian Shield is a major geotectonic feature formed during the Neoproterozoic assembly of greater Gondwanaland and is believed to have resulted from plate tectonic processes similar to those operating today (i.e., oceanic-island arc/back-arc accretion and/or microplate (terrane) collision - Stern, 1994). Low-Sr initial ratios (Fleck *et al*., 1979; Stern and Hedge, 1986) led to the hypothesis that the Arabian Nubian Shield formed by accretion of intra-oceanic island arcs, which were subsequently welded together and accreted onto the older African craton (Greenwood *et al*., 1976; Neary *et al*., 1976). El Nadi (1984) proposed that the Red Sea Hills region evolved in a mature island arc environment adjacent to what was termed the Nile Craton. The arc-craton gap, with its older sediments, is thought to have been destroyed by successive island arc collision advancing from the east.

The Arabian-Nubian Shield began to form some time prior to 800 Ma with the initiation of an island arc complex on the northeast margin of an ancient African continent (Vail, 1978). The main events pertaining to the evolution of the Arabian-Nubian Shield are shown in Table 1.

Table 1: The geological evolution of the Red Sea Hills area of northeastern Sudan over an approximately 2500 Ma time span

6. circa 500 Ma: consolidation ended and sediment cover commenced. Anorogenic igneous activity occurred only briefly in Arabia, but continued in the NE Africa throughout Phanerozoic time (e.g. anorogenic intrusives in Bayuda area)
5. circa 625 Ma: consolidation and intra-cratonic activity
4. circa 720 Ma: suturing and accretion of arcs continued for about 100 Ma. Some major batholiths post-date arc accretion (e.g. syntectonic batholith in Red Sea Hills)
3. circa 800 - 700 Ma: arc volcanism
2. circa 800 Ma: formation of earliest island arcs of NE Africa (e.g. Haya terrane)
1. circa 3000 Ma: the oldest dated rocks of the continental nuclei (e.g. Nile Craton)

RED SEA HILLS GEOLOGY - A BRIEF REVIEW

Introduction

The geology of the Red Sea Hills region has been discussed by a number of authors (e.g., Whiteman, 1971; Vail, 1976, Ahmed, 1979). However, although significant new information has become available, the lithographic classifications established during the 1950s have remained the same (Table 2).

The Red Sea Hills region (Fig.3) constitutes an integral part of the Pan-African Arabian-Nubian Shield and is dominated by stratified orogenic accumulations of oceanic island-arc and plate-margin Andean-type volcanic, volcanogenic and shallow-water sedimentary rocks (Vail, 1988). Discrete belts of medium-to high-grade paragneisses (Kashebib Series) occur in structurally lower parts of the stratified sequences, followed upwards by well-developed, stratified, low-grade volcano-sedimentary units (Nafirdeib Series). These rocks are overlain, in turn, by more differentiated, less metamorphosed volcano-sedimentary formations (Awat Series). The successions mentioned thus far constitute distinct crustal entities (Embleton *et al*., 1983) or terranes (Kröner *et al*., 1987), which are separated by geosutures with dismembered ophiolite belts that have also been subjected to intense plutonic activity. The geology of the region is outlined below using the geochronological order adopted by previous authors (Table 2).

Red Sea Hills Ophiolite Belts

The ophiolite belts of the Red Sea Hills area of Sudan are considered to represent suture zones and were probably continuous with their equivalents on the Arabian side of the Pan-African Nubian-Arabian-Nubian Shield (Bakor *et al*., 1976; Camp, 1984; Vail, 1985b). Kröner *et al*. (1987), on the basis of ophiolite-decorated sutures and associated major shear zones, subdivided the Red Sea Hills area into five terranes. From south to north, over a distance of approximately 250 km, these include the Tokar, Haya, Gebeit, Gabgaba, and Gerf Terranes (Figs. 3, 4).

Table 2: Lithostratigraphic subdivisions of the geology of northeast Sudan, according to previous workers. Source: Vail *et al*. (1984)

GASS (1955)	RUXTON (1956)	GABERT et al. (1960)	KABESH (1962)	VAIL (1979)
ASOTERIBA VOLCANICS (felsic lavas, tuffs)				
(dykes) YOUNGER GRANITES	(mafic and felsic dykes and sills) INJECTION GRANITES	(dykes) YOUNGER GRANITES	(dykes) YOUNGER GRANITES GREY GRANITES	(dykes) Younger igneous activity (gabbro, granite, syenite) CENTRAL VOLCANIC GROUP (HOMOGAR) (felsic volcanics)
	AWAT SERIES (felsic volcanics, sediments)	AWAT SERIES (felsic volcanics, sediments)	AWAT SERIES (felsic volcanics, sediments)	GREENSCHIST ASSEMBLAGE
MAFIC INTRUSIVES (gabbro, tonalite, pyroxenite)	MAFIC INTRUSIVES	MAFIC INTRUSIVES	GABBROS	(serpentinites)
BATHOLITHIC GRANITE (assimilation granite)		BATHOLITHIC GRANITE		BATHOLITHIC GRANITOIDS
OYO SERIES (metasediments, intermediate-felsic volcanics)	NAFIRDEIB SERIES (mafic and intermediate volcanics, sediments)	NAFIRDEIB SERIES SALALA SERIES (intermediate volcanics, sediments)	NAFIRDEIB SERIES (intermediate volcanics, sediments)	GREENSCHIST ASSEMBLAGE (metavolcanics, sediments and ultramafic rocks)
GRANITE GNEISS (schists, volcanics) (schists, volcanics)	PRIMITIVE SERIES MAFIC DYKE SWARMS (felsic gneisses, schists)	KASHEBIB SERIES (paragneisses)	GNEISSES (para-and orthogneisses)	METASEDIMENTARY GROUP GREY GNEISS GROUP

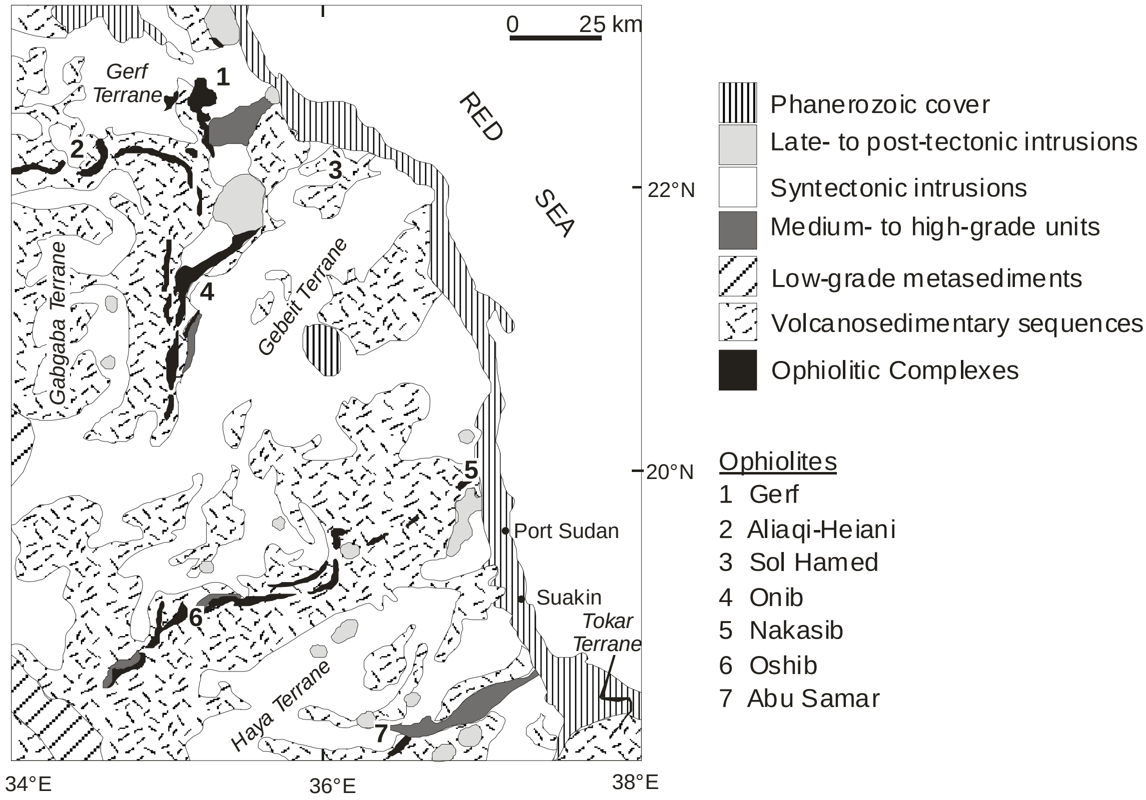

Figure 3: *Generalized geological map of the Red Sea Hills region, northeast Sudan (modified after Abdel Rahman, 1991).*

The Sol Hamid and Onib ophiolites (Fig. 4) constitute the most prominent ophiolite complexes in the Red Sea Hills region (Fitches *et al*., 1983; Hussein *et al*., 1984). Although the two complexes are tectonically detached, they retain most of the diagnostic components related to oceanic crust (Kröner *et al*., 1987). The Onib Complex, characterized by very thick interlayered gabbros and cumulate ultramafic rocks with podiform chromite lenses, has chemical characteristics typical of a marginal basin or inter-arc basin setting (Kröner *et al*., 1987). The ophiolite belt is considered to be a continuation of the Yanbu suture in Saudi Arabia (Camp, 1984).

The Nakasib shear zone, in the central Red Sea Hills (Fig. 4), probably represents the southwestern extension of the Bir Umq ophiolite belt in Saudi Arabia (Camp, 1984) and is formed of discontinuous serpentinized and carbonated lenses of ultramafic rocks. It represents one of the oceanic sutures along which the island-arc / back-arc terranes and continental microplates of the Arabian-Nubian Shield were welded together (Vail, 1985b). The Baraka suture of the southern Red Sea Hills region that extends across the Sudanese border into northwest Eriteria (Fig. 4), has not been studied in any detail, but it may represent an extension of the Afaf belt of Saudi Arabia (Kröner *et al*., 1987).

Gold Occurrences in the Red Sea Hills

Precambrian gold deposits, most of which occur mainly as gold quartz veins and silicified zones hosted in volcanic rocks and their associated sediments, occur in many parts of Africa (Boyle, 1979).

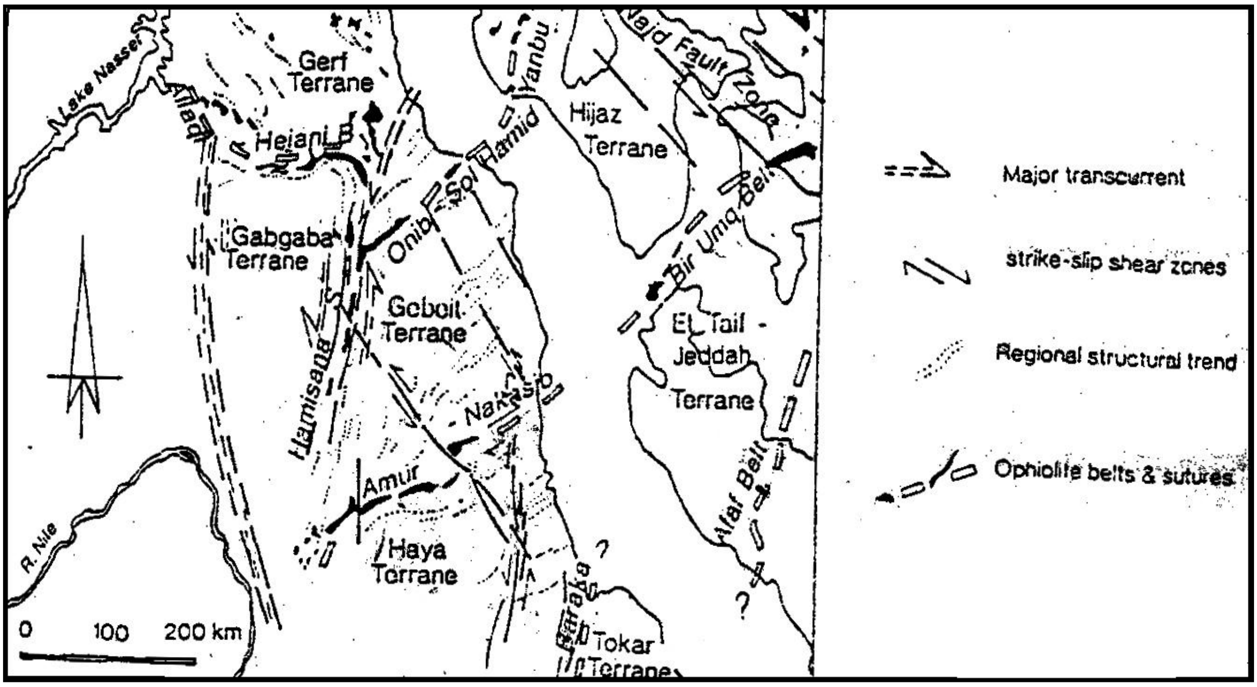

Figure 4: *Schematic tectonic map of the Red Sea Hills area showing ophiolite belts, major shear zones, lineaments, and tectonic terranes before the opening of the Red Sea (compiled from Kröner et al., 1987; Abdel Rahman, 1991).*

Geologically, Sudan consists of Precambrian granite-gneiss terrane together with occasional, long, narrow greenstone belts, the latter characterized by discontinuous zones of highly sheared mafic and ultramafic rocks. The known gold occurrences in Sudan are located in six greenstone belts as shown in Figure 5. These include occurrences in: (1) the Blue Nile area south-southeast of Khartoum; (2) the Nubian Desert east of the Nile River and south of the border with Egypt; (3) the Hofrat En Nahas area (i.e., the Darfur region of western Sudan near the border with the Central African Republic); (4) the Nuba Mountains area west of the Nile River and approximately 400km south of Khartoum; (5) the Equatoria region of southern Sudan (near Juba and close to the border with Uganda, and near Kapoeta, close to the border with Kenya); and (6) the Red Sea Hills area of northeast Sudan, described in this paper.

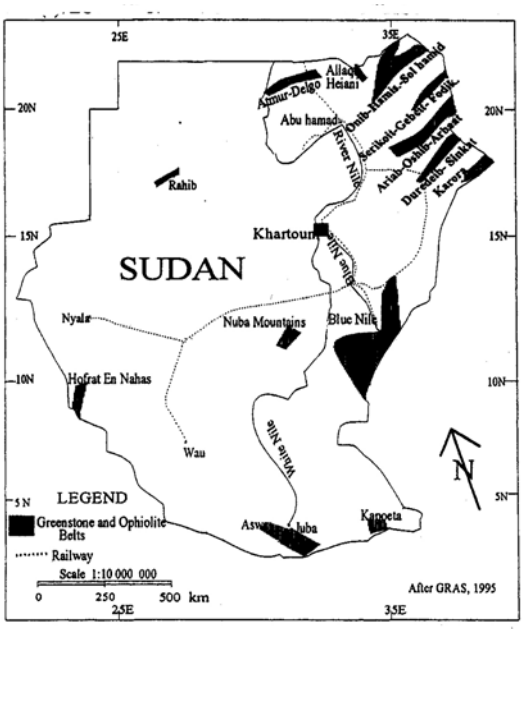

Figure 5: *Map showing the location of greenstone belts in Sudan.*

Most of the economic gold deposits of Sudan are located in the Red Sea Hills area and occur mainly in five northeast-trending subparallel greenstone-ophiolite belts (Fig. 5). The history of gold mining in these belts dates back to Pharaonic times. Numerous gold mining sites in this region have since provided valuable indicators for modern day prospecting and exploration.

The lithological association of gold in the Red Sea Hills has demonstrated that the major sources of the metal are the mafic-ultramafic sequences and associated volcano-sedimentary rocks (GRAS, 1995). Gold mineralization in the region occurs in different geological environments and at least three types are present (Aloub and Elsamani, 1991):

(1) pre-metamorphic mineralization associated with stratiform massive sulphide deposits: this type of gold occurrence is syngenetic and predates the regional metamorphism that affected the gneissic and volcanosedimentary formations throughout the Red Sea Hills;

(2) gold mineralization related to the regional tectono-metamorphic episodes. The known occurrences of this type are lithologically controlled and assigned to particular gold- bearing horizons in the oceanic sequences. Two varieties have been categorized: (a) gold collapse breccias, which occur in the form of auriferous units that are essentially composed of silica, barite and iron oxides. This type was first recognized in the Ariab area and is referred to as Silica Barite Rocks (Cottard *et al*., 1986b); and (b) gold in recrystallized host rocks close to sulphide minerals. Anomalous gold values occur in places in the vicinity of massive sulphide bodies; and

(3) gold mineralization related to shear zones. This type of gold mineralization is very common throughout the region and is exclusively in the form of auriferous quartz veins which are always located along fracture zones and their emplacement appears to be structurally controlled.

The Ariab mineralization attracted renewed attention of prospectors in early 1960s. Remnants of exploration workings are claimed to belong to the Geological Survey team whose geologist most probably overlooked the oxidized cap-rock over the sulphides and directed the exploration activities to the copper-stained chloritite in the footwall to the sulphides. However, no written account of this activity is available and no exploration results exist. Malachite staining is reported at several localities along the eastern and central extensions of the Ariab-Araat belt (Ahmed, 1979). Since 1977 extensive regional mineral prospecting in the Ariab region has been conducted jointly by BRGM-GRAS staff, and has resulted in the discovery of a new, large and economically important metallogenic district of polymetallic sulphide bodies and associated gold (Cottard *et al*., 1986a). To date drilling has only been carried out on the major gossans of Hadal Awateb, Hassai, Oderuk, Adaiamet and Shulai. In addition, new drilling at Medadip 1 and 3 indicated the presence of massive and/or disseminated sulphide mineralization. The Hadal Awateb occurrence has been the most intensively drilled and is recognized as a large massive sulphide deposit with a complex structure particularly in the western Cu-Zn rich zone.

Geology, Structure and Metallogenic Setting of the Ariab Area

Ariab gold-bearing sulphide occurrences are located within the Late Proterozoic Ariab-Arbaat volcanic arc sequences (Fig. 6) forming the western extension of a narrow, 250 km belt, parallel to the northeast-striking geological features of the Red Sea Hills area. The volcanic arc comprises a complex upper sequence of rhyolitic and andesitic rocks overlying basaltic lavas. These, together with pyroclastic and epiclastic rocks, are intruded by early granodiorite and tonalite and are capped by thick epiclastic deposits into which the Oshib ultrabasic complex has been tectonically emplaced. The belt trends generally in an ENE direction parallel to the northern edges of the intra-oceanic island arc of the Haya terrane (Kröner *et al*., 1987).

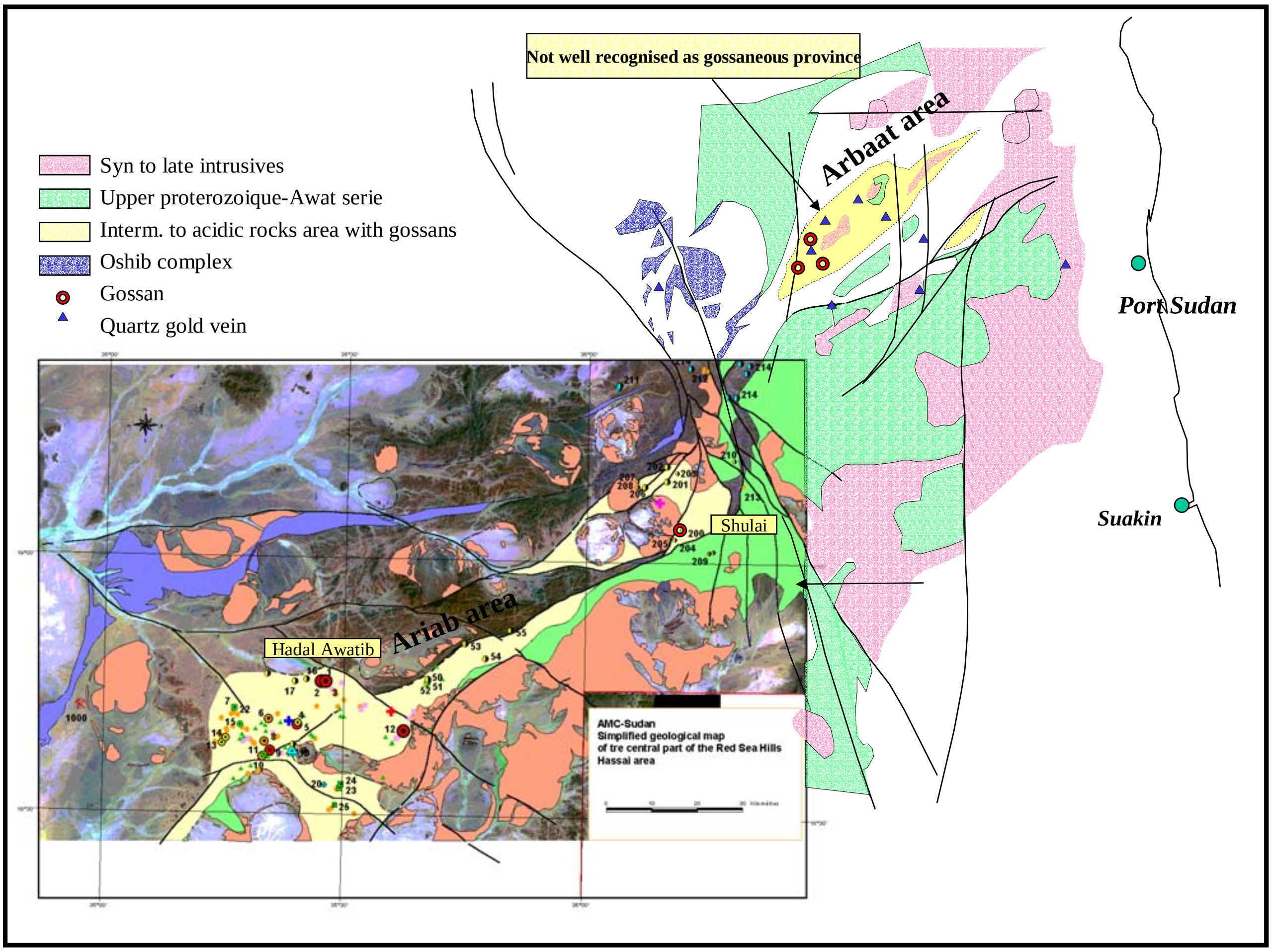

Figure 6: *Geological map of the central part of the Red Sea Hills (Ariab-Arbaat belt).*

The lithologies of the Ariab region (Figs. 6, 9) are generally classified into four major groups, arranged sequentially as follows: (1) Oshib ultramafic complex; (2) Ariab volcano-sedimentary sequences; (3) Awat-Asotriba group; and (4) Granotoid intrusives.

1. Oshib ultramafic complex

The Oshib Complex consists of layered gabbros, peridotite and pyroxinites. Associated with the intrusive rocks are pillowed basalts and various carbonate rocks. The successions exposed to the west and north of the Ariab-Arbaat belt are largely dismembered, but still maintain a linear trail that marks the northern margin of Ariab depositional basin.

2. Ariab volcano-sedimentary rocks

The Ariab volcano-sedimentary rocks occupy the core of the mineralized belt. They have been subdivided by BGRM workers into five lithostratigraphic units (Fig. 7). From the base upwards these units include:

(A) the basal greenstone complex

These rocks are mainly exposed in the core of the Ariab anticlinorium and consist essentially of ultramafic to mafic rocks ranging in composition from hornblendite (probably originally pyroxenite) to gabbros, basalts and basaltic andesites mixed with mesozonal subvolcanic rocks in the form of dykes and sills and small stocks of meta-quartz-diorite and granodiorite. All the rocks are affected by low-grade greenschist facies metamorphism. Chemically they are very similar to

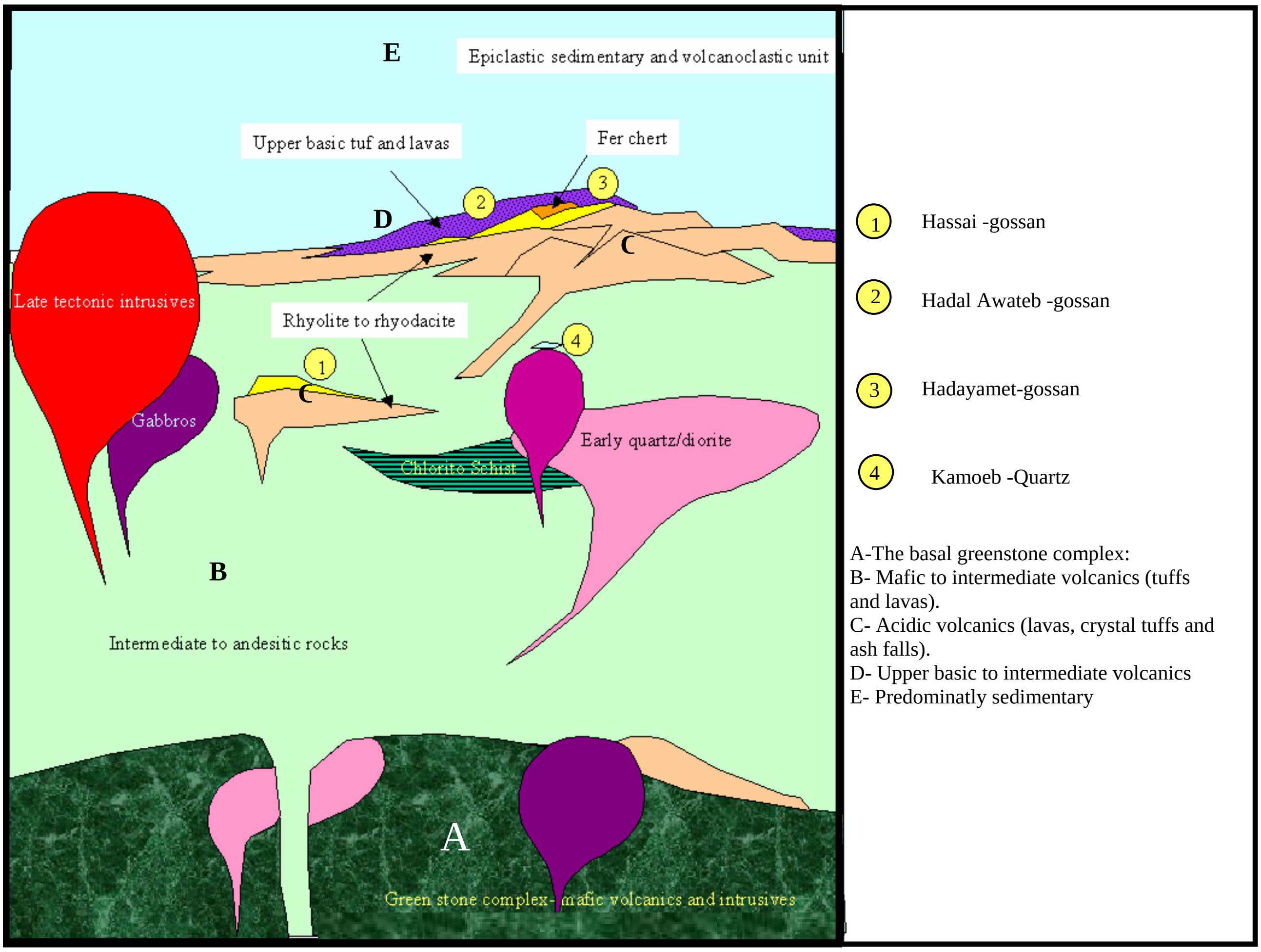

Figure 7: *Lithostratigraphic column of the Ariab volcano-sedimentary sequence.*

low-K island-arc tholeiites and probably represent the earliest stages of oceanic island-arc volcanism. These rocks often appear to form a “basement” upon which the later volcano-

sedimentary rocks developed and they crop out sporadically in places from beneath the volcano-sedimentary formations of the region. The basic greenstones described are best exposed south of Hadal Awateb, the area northeast of Ganaet, and the area south and east of the Kamoeb deposit (Fig. 9). Quartz-diorite bodies intrude both the basal greenstone complex and the overlying metavolcanic sequence. They are best-exposed to the north and northwest of Adaiamet, and south of the Hadal Awateb and Hassai ore bodies and are interpreted to correspond to the intrusions affected by deformation coeval with that of the host volcanic units; hence they have been metamorphosed. The quartz diorites are considered to be genetically related to the rhyolitic volcanic rocks and are therefore believed to be synorogenic in origin;

(B) mafic to intermediate volcanic rocks (tuffs and lavas)

These rocks are the most extensively exposed volcanic rocks in the area, and are composed essentially of metamorphosed basic and intermediate volcanic lavas, tuffs and thin intercalations of carbonaceous marine sediments. They are generally fine-grained and have been deformed and metamorphosed to a variety of schists. The rocks have also been extensively hydrothermally influenced and all primary mafic minerals have been altered to chlorite and epidote and the feldspars are sericitized and replaced by carbonates. Chemical and petrographic analyses indicate that the rocks were mainly derived from basaltic to andesitic volcanic precursors;

(C) felsic volcanic rocks (lavas, crystal tuffs and ash falls)

Rocks of this unit are largely composed of rhyodacitic to rhyolitic lavas and crystal tuffs and volcanic ash and represent the felsic volcanic phase with which the mineralization is temporally and spatially associated. The rocks have been divided into two subunits occurring in distinctively different stratigraphic levels and with different total thicknesses. The two subunits are referred to as C1 and C2 for convenience. Subunit C1 crops out locally within the major mafic to intermediate volcanic member (unit 2 above) as thin lava flows and hosts only a few ore bodies, such as South Hassai and possibly the Kamoeb vein type deposit. Subunit C2, by contrast, is regionally more extensive, is thicker, and occurs above the main mafic and intermediate volcanic pile (unit 2 above). A quiescent volcanic episode followed, during which time (according to earlier work undertaken during the BRGM-GRAS project) major deposition of gold and base metal sulphide mineralization took place. Consequently, C2 is the main host rock for mineralization on a regional scale (Cottard *et al*., 1986b);

(D) upper basic to intermediate volcanic rocks

These rocks appear to consist of thin basaltic lavas that locally overlie the felsic volcanic unit C2 (Cottard *et al*., 1986b); and

(E) predominantly sedimentary rocks

These rocks stratigraphically overlie the island-arc volcanic pile and are exposed all along the margins of the Ariab anticlinorium or fill the synformal refolds in the Ariab megastructure. The sequence is underlain by black siliceous schists followed successively by layered tuffs, greywackes, and schists intercalated with horizons of fine-to coarse-grained pyroclastics of intermediate to acidic lavas (Cottard *et al*., 1986b). These are apparently derived from adjacent and underlying island-arc volcanic rocks.

3. Awat-Asotriba group

This succession mainly consists of intermediate and felsic volcanic lavas and flows, tuffs and agglomerates of dacitic, rhyodacitic and rhyolitic composition. They overlie the volcano-sedimentary sequence in the Ariab region and are exposed mainly on the northeast part of the Ariab belt. Locally, outcrops have been found north of the Adaiamet deposit and southwest of the Oderuk ore body.

4. Granitoid intrusives

Granitic rocks are exposed in the Ariab area predominantly as late-to post-orogenic igneous bodies that intruded as small plutonic stocks, plugs and ring complexes in and around the volcanic pile. They are formed largely of granodiorites, quartz-diorites, diorites, gabbros and alkali-granites. At present there is no detailed geochemical or geochronological information available on these intrusives, but they are believed to be similar in composition and age to intrusives elsewhere in the Red Sea Hills region described by Vail (1976) and (Neary *et al*., 1976). The late-orogenic intrusions in the Ariab area have caused intensive thermal metamorphism, which is particularly well developed in the Adaiamet area and its southern extensions that include the Hamim and Rawai prospects. The metamorphic alteration is characterized by hornfelsic rocks containing the minerals biotite, amphibole, cordierite and garnet (Cottard *et al*., 1986b).

Structures in the Ariab Belt

The complicated structural history of the Ariab area has not yet been fully resolved, but structural indicators in the Ariab volcano-sedimentary belt suggest that at least four deformational phases (Fig. 8) are present on both a regional and local scale. The main deformation is related to regional dextral strike-slip shearing with a variably developed shortening component. The major strike-slip D_1 deformation stage, which is associated with greenschist facies metamorphism, is also accompanied by en echelon folds, C/S relationships and asymmetrical recrystallization tails. Variable ENE or WSW plunges of the mineral stretching lineation and 'a' fold axes could reflect structural heterogeneity during D_1 shearing and/or a locally well-developed shortening component. Late E-W compressive D_2 deformation probably amplified the dispersion of linear D_1 structures associated with sinistral displacement. D_3 is represented by brittle fracturing and the development of variably trending faults.

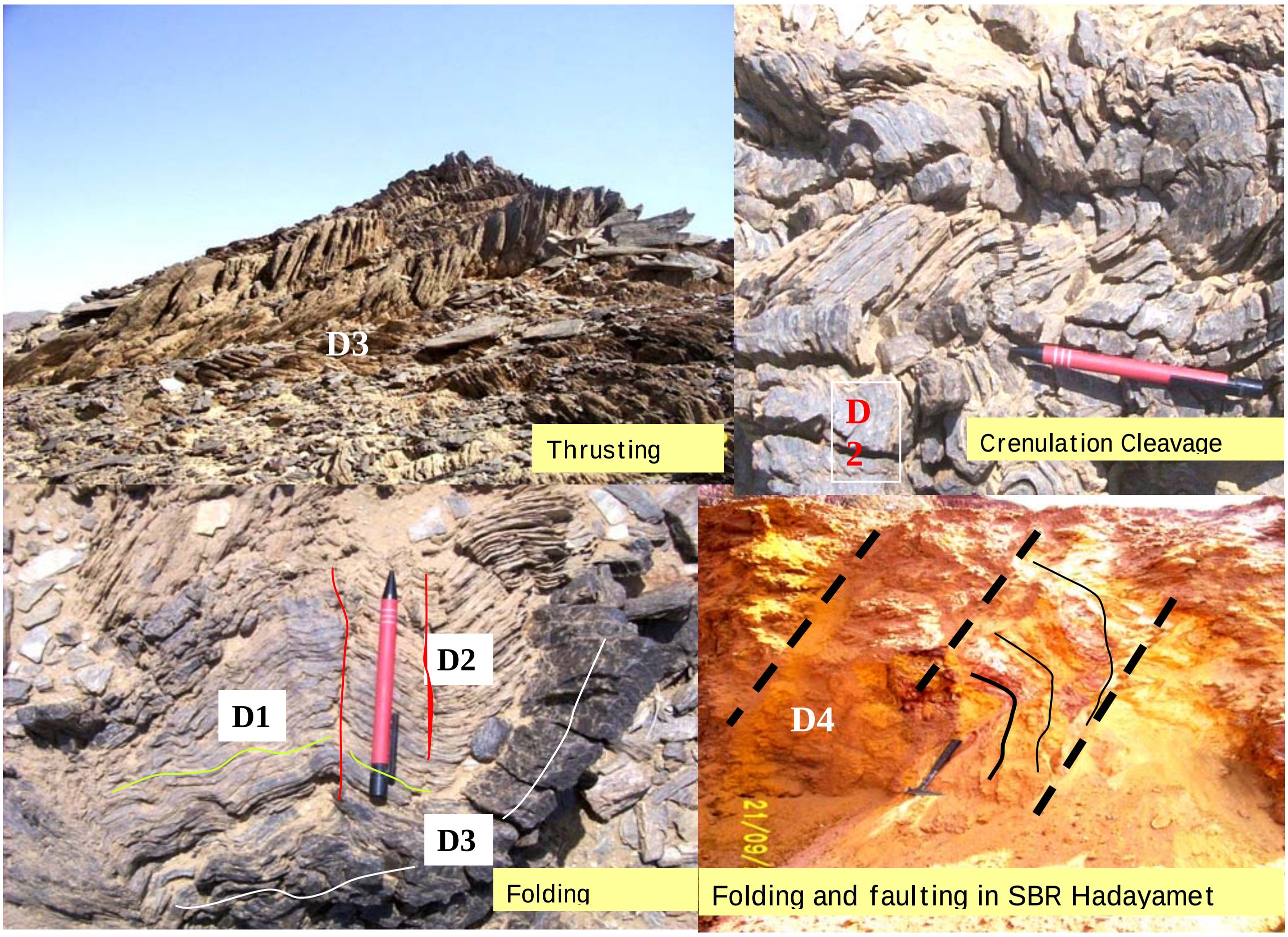

Figure 8: *Ariab deformational phases.*

Geotectonic Environment of the Ariab Area

Geotectonically, the Ariab region is interpreted as an early orogenic environment consisting of a near-trench magmatic arc that was possibly associated with a steeply dipping subduction zone in a dominantly oceanic environment. This interpretation is suggested by the tholeiitic nature of the volcanic suites (Molnar and Atwater, 1978). The tholeiitic character of the Ariab volcanics may suggest an immature arc upon which a calc-alkaline trend has been superimposed by laterally extensive hydrothermal alteration, the latter being a common associate of VMS deposits (MacGeehen and MacLean, 1980).

MAIN MINERAL DEPOSITS OF THE ARIAB AREA

There are five mineralization types involving the economic concentration of gold in the Ariab area. These include:

(1) *volcanogenic massive sulphides (VMS deposits).* This mineralization type consists mainly of primary pyrite, in disseminated to massive form, which occurs in stockworks hosted in hydrothermally altered felsic volcanic rocks. The sulphide mineralization in these deposits has largely been oxidized and now occurs as gossans, many of which are quite large (e.g., Hadal Auateb, Adaiamet, Oderuk, Talaiderut, Hassai and Shulai). This mineralization, also intersected by deep drill holes at Hassai, Hadal Awateb, Oderuk, Adasidakh and Adaiamet consist mostly of massive pyrite. The massive sulphides in the Ariab district are noted for their variable Cu (chalcopyrite) and Zn (sphalerite) grades and their fairly high gold grade (0.6-1.2g/t on average);

(2) *secondary mineralization related to gossans derived from the oxidation of massive sulphides*. This type of mineralization mainly involves supergene enrichment with economic gold and silver grades occurring in a weathering profile composed predominantly of siliceous barite facies rocks that have been partly preserved down to a depth of about 120m. The gold in these rocks is generally very fine-grained (4-20µ) and is invisible and difficult to detect. It is mainly contained in deeply weathered rocks and occurs either between grains or, in places, enveloped by iron oxides. Because of these characteristics this type of gold was undetected during ancient exploration. It is mostly found within silica barite rocks (or SBRs), which are microbreccias of supergene origin, where sulphide minerals have been leached from rocks rich in gangue material. The rocks containing the mineralization occurs as lenses intercalated with, or adjoining the gossan rock. Orebodies belonging to this type are found at Hadal Awateb, Oderuk and Adaiamet (Fig. 9).

(3) *mineralization associated with baritic lenses and with gossans absent*. Gold in these deposits may be coarse- or fine-grained and the silver content can be high. The mineralized bodies, an example being the Ganaet deposit (Fig. 9), are usually quite small;

(4) *mineralization associated with quartz veins* This type, consisting of visible or very fine-grained gold, occurs at Kamoeb (Fig. 9); and

(5) *epigenetic auriferous deposits.* These deposits are related to shearing and secretion dilation metamorphism.

Volcanogenic Massive Sulphide Deposits

Massive sulphide deposits have been found associated with active hot springs in a variety of geotectonic settings in the modern oceans, including mid-oceanic ridges, axis and off-axis seamounts, back-arc spreading centres, and intra-cratonic rifts (Hannington *et al*., 1991). Active vents are found along rift zones at divergent plate margins where heat is provided by the intrusion of magma to within a few kilometres of the sea floor. Seawater-rock interactions at temperatures up to 400˚C leach base and precious metals from the permeable volcanic rocks in quantities large enough to produce ore-forming fluids (Seyfried *et al*., 1988). High concentrations of dissolved H_2S are derived from a combination of reduced seawater-sulphate and basaltic sulphur. These components are leached from the volcanic rocks along with the metals. Sulphides, sulphates and silica are then precipitated from ascending hydrothermal fluids in response to decreasing pH following conductive cooling and mixing with ambient seawater at or near the seafloor (Hannington *et al*., 1991).

The hydrothermal precipitates accumulate locally as mineralized chimneys around vents and as hydrothermal mounds. The precipitates, which are formed at high temperature (350°C), consist of pyrrhotite-chalcopyrite-isocupanite assemblages and are known as "black smokers''. Anhydrite is another important constituent of the black smokers. Precipitates formed at lower temperatures (less than about 300°C) are known as "white smokers'' and consist typically of pyrite-marcesite-sphalerite assemblages together with barite.

Massive Sulphide Deposits in Ophiolites

Massive sulphide bodies are commonly situated within pillow lava sequences in many ophiolite complexes (Sillitoe, 1973; Franklin *et al*., 1981) and have a number of common features, including the tendency to be stratabound. The sulphide bodies occupy certain stratigraphic horizons within the volcanic sections and their host rocks have largely been affected by ocean-floor hydrothermal metamorphism (Gass and Smewing, 1973). All these deposits have well-developed 'gossans' consisting of brightly coloured iron oxides, hydroxides and sulphates (Coleman, 1977). A well-known example of this type of ophiolitic volcanogenic massive sulphide deposits is the Cyprus-type (Fe-Cu) sulphide mineralization within the pillow lavas of the Mesozoic Troodos Ophiolite of Cyprus (Gass and Smewing, 1973; Adamide, 1980; Constantino, 1980). The Troodos sulphide deposits all occur within or at the top of the lower pillow lava sequence.

Unlike the Phanerozoic belts, the Precambrian complexes of the Nubian Shield are highly disrupted, being extensively deformed and tectonically dismembered. Recognition of pillow lava sequences and massive sulphide occurrences in such altered ophiolites is therefore difficult. Nevertheless, massive sulphide mineralization and gossans similar to the Cyprus-type deposits have been found associated with two ophiolite assemblages in the Red Sea Hills region of Sudan. These are the Oshib (in Ariab belt) and the Abu Samar ophiolites (Abdel Rahman, 1991; Fig.3). The Oshib ophiolite is overlain by Ariab volcanic rocks and both the mineralization and the host rocks may be assigned to a stage of early subduction (Bakheit, 1991). The Cyprus-type massive sulphides are more Cu-rich and contain less Zn than the Red Sea Hills occurrences and they are hosted by basaltic lavas. In contrast, the Ariab sulphides are dominately hosted by felsic to intermediate volcanic rocks in a manner similar to the sulphide deposits found in the Semail ophiolite of Oman (Coleman *et al*., 1978). The most important sulphide prospects associated with the Semail ophiolite are found within volcanic centres occurring in the uppermost part of the ophiolite complex. The centres appear to represent sea mounts and are not typically ophiolites in that they contain significant amounts of felsic and andesitic volcanic rocks with island-arc affinities (Alabaster *et al*., 1980). This is also the case with the Ariab volcanic suite, which overlies the Oshib ophiolite.

The second most important massive sulphide prospects in the Sudanese sector of the Pan-African Nubian Shield occurs in Abu Samar area of Haya (Fig. 3). The deposits have been described in detail by El Samani (1983) who assigned to them an exhalative environment of deposition. As with the Ariab sulphides the Abu Samar deposits occur as prominent iron-rich gossans. At Abu Samar the gossans are also Mn-rich and in both districts (Ariab and Abu Samar) the deposits are closely associated with auriferous lenses of massive barite, silicified barite and ochres.

Ariab Volcanogenic Massive Sulphide Deposits

In the Ariab area there are at least ten polymetallic exhalative volcanogenic massive sulphide deposits associated with supergene-mineralized gold deposits. These, in turn, are ascribed to complex processes of hydrothermal leaching and occur in a weathering profile that is mainly restricted to the siliceous baritic facies, which has been partially preserved to a depth of 100-120m.

The major massive sulphide deposits of the Ariab Mineral District have been described by Cortial *et al*. (1985) and Bakheit (1991). The deposits are dominantly pyrite-rich occurrences together with associated Cu- and Zn-sulphide mineralization. Only minimal Au and Ag values have been recorded and Pb occurs only as traces of galena enclosed within the major sulphides. Unlike the Cyprus-type massive sulphides, which are more Cu-rich and contain less Zn, and which are hosted by basaltic lavas, the corresponding Ariab volcanic suites hosting sulphides range in composition from basalts and basaltic andesites through dacites to rhyolites. The basalts, which have a tholeiitic affinity, are similar to the sulphide deposits in the Semail ophiolite of Oman (Coleman *et al*., 1978). The mineralization and the host rocks in the Ariab area may be assigned to the early subduction stage (Bakheit, 1991). The mafic, intermediate and felsic volcanic rocks hosting the massive sulphide deposits in the area are considered to be part of the Upper Proterozoic volcano-sedimentary sequence that forms the core of the mineralized belt.

The volcanogenic massive sulphides of the Ariab area are nowhere exposed and were only discovered following the recognition of well-developed gossanous areas rich in iron oxides on the surface. The term gossan is generally defined as ironstone forming the weathered expression of a rock containing substantial sulphide mineralization (Taylor *et al*., 1980). Genetically, gossans are a result of corrosive decomposition of sulphides at or near the water table, and testify to the mobilization of iron in the near-surface weathering regime. Gossans, and the silica-barite rock mentioned earlier, are considered to be the main gold-bearing host rocks in the region as both are intimately related spatially in all the known ore bodies (Fig. 9).

Gold-bearing Volcanogenic Massive Sulphides

Recent studies of volcanogenic massive sulphide occurrences indicate a strong relationship between gold and sulphide mineralization in seafloor hydrothermal systems (Scott, 1985). The discovery of gold-rich sulphides, actively forming at hydrothermal vents on the modern seafloor, has confirmed the existence of gold-bearing fluids in submarine hot springs. This supports a seafloor hydrothermal origin for the gold occurrences found in volcanic arc complexes, such as those in the Red Sea Hills area. In addition, some gold-bearing volcano-sedimentary rocks have been described as possible modern analogues of ancient silicate-oxide iron formations. Many of these deposits resemble the late-stage siliceous (cherty) and Fe-rich chemical sediments that overlie or grade laterally into volcanogenic massive sulphide ores.

The Red Sea area provides a good example of metal-rich brines associated with seafloor spreading (Degen and Ross, 1969). In the Atlantis II Deep (2000-2100 m depth), which lies on the projection of old Nakasib shear zone of the Nubian Shield, the lower brine currently has a stable temperature of about 60°C, but was probably derived from hydrothermal fluids injected into the ocean basin at temperatures up to 420°C (Shanks, 1977).

Gold in Silicified and Massive Barites and Cherty Fe-rich Chemical Sediments

The oxidized ores of exposed sulphide deposits on land are commonly enriched in gold in a zone of secondary Cu-sulphides or Fe-rich gossans. Supergene enrichment of gold in this environment is commonly attributed to exposure of the sulphides to oxidation by near-surface groundwater, following uplift and erosion. However, high concentrations of secondary gold have also been found in oxidized sulphide deposits on the modern seafloor, for example in the TAG (Transactions American Geophysical Union) hydrothermal field of the Mid-Atlantic Ridge (Hannington *et al*., 1988).

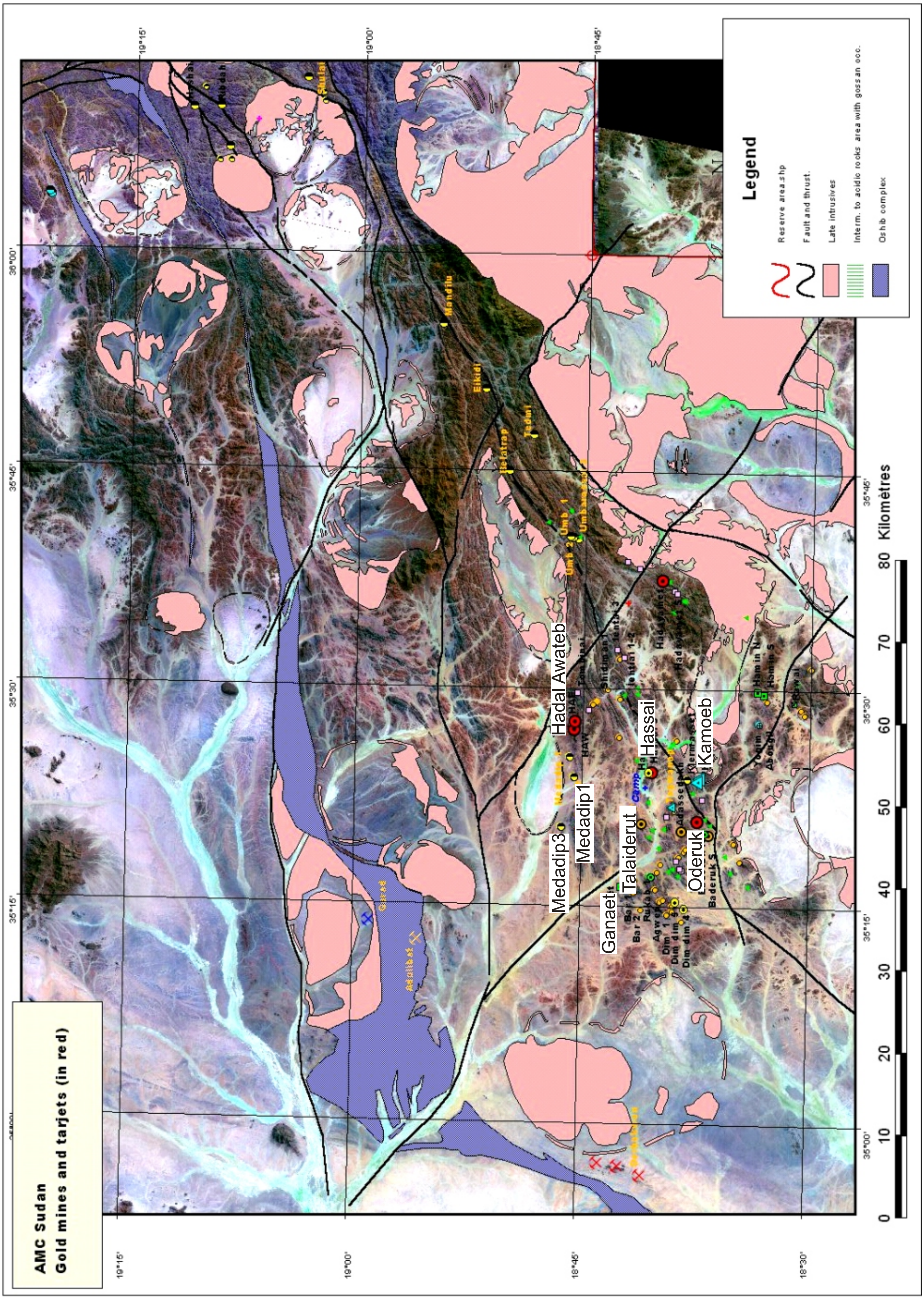

Figure 9: *Main orebodies and gold mines in the Ariab region*

This observation suggests that high concentrations of secondary gold may also occur in ancient deposits that have never been exposed to surface weathering on land.

The best example of seafloor-based gossans on land, known as the "ochres'' (Constantinou, 1980), have been found associated with the massive sulphide deposits in the Troodos ophiolite of Cyprus (Herzig *et al*., 1989). The ochres are commonly found at stratigraphic horizons overlying massive ores and are buried by contemporaneous marine sediments or pillow lavas. The gold-rich ochres contain coarse-grained native gold in a matrix of Fe-oxides and jarosite and have been interpreted to be the fossil analogues of gold-rich seafloor gossans at the TAG hydrothermal field of the Mid-Atlantic Ridge (Herzig *et al*., 1989).

The Ariab mineral districts of the Red Sea Hills area might contain equivalent examples of late-Proterozoic fossil analogues of the TAG hydrothermal field. The region is associated with supra-subduction zone ophiolites and contains, in addition, massive volcanogenic sulphides, Fe-rich gossans, and massive and silicified barites (MBR and SBR ores), the latter carrying anomalous gold enrichment (see Fig. 10). Opinions differ over the origin of the gossans, the barites, and the mechanism of anomalous gold enrichment in the Ariab region. It still remains to be determined whether these gossans are the result of residual weathering and leaching (Cottard *et al*., 1986b), or hydrothermal enrichment (Bakheit, 1991).

Silica-barite Rocks (SBR)

The SBRs, to which generally, but not exclusively, economic gold values appear to be restricted, occur as narrow lensoid bodies bound by or intercalated with gossans. They are classified on the basis of their texture, structures, grain size and mineral composition into four facies (BRGM 1989). Geochemical and other data shows that the silica-barite facies varies in colour and mineral constituents (gypsum, jarosite, and alunite), in element leaching, and in grade redistribution of Au and Ag (Fig. 10). Three of these facies (the typical SBR) are characterized by high SiO_2 content (40 to >90% SiO_2) and variable amounts of $BaSO_4$ and Fe_2O_3. The fourth facies, which is predominantly iron-rich, has less SiO_2 and $BaSO_4$ (Table 3). This latter facies is also a typical gossan in every respect, but appears to have been silicified by later gold-bearing hydrothermal solutions. Colour, although an important diagnostic factor, is less reliable in distinguishing between the different facies. This is due to the inhomogeneous distribution of colour tones in each rock facies and is a function of the amount and type of iron oxide and the quantity of silica available.

Table 3: Bulk mineral composition of the SBR facies of the Hadal Awateb deposit, Ariab area (composite samples) (1)

	SiO_2 %	Fe_2O_3 %	$BaSO_4$ %	Au ppm
Facies 1	> 70	30	< 0.2	30.00
Facies 2	> 90	1	1	52.40
Facies 3	36	1 -2	62	41.00
Facies 4	20- 30	> 60	10 -12	13.50

(1) = BRGM (1989)

The gold grade in these rocks is generally well above the mining cut-off grade, with sporadic abnormally high Au values. According to available drilling data the gold-grades persists to depths of 100m (Down or lower oxidation limit, Fig. 10). Unfortunately, following the discovery of gold

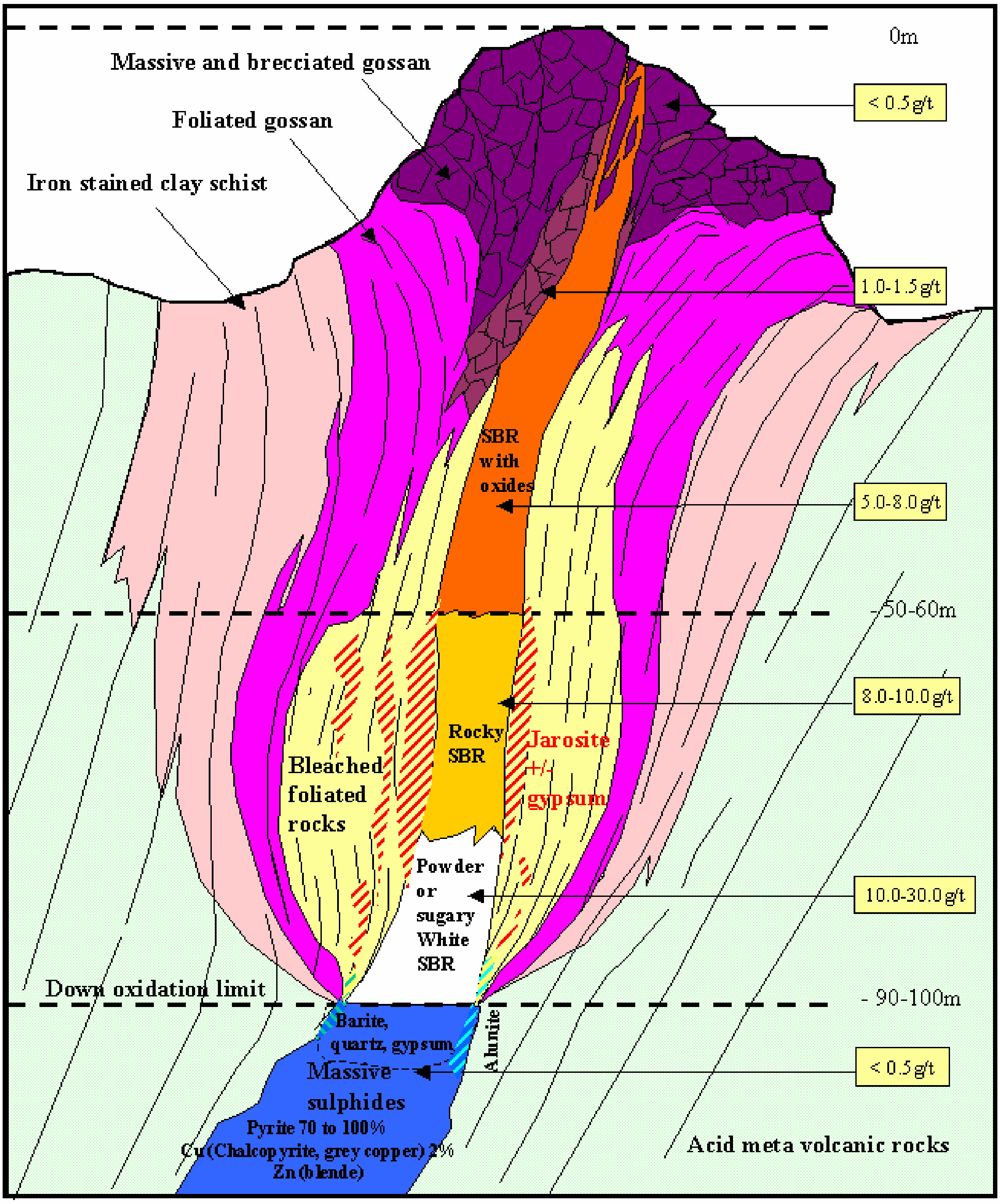

Figure 10: *Schematic cross section of a typical Ariab orebody.*

in the gossans, the exploration priority immediately shifted and was subsequently confined to the upper 100m-depth horizon in search for gold only. Consequently, the massive sulphides beneath the gossans have been totally ignored. Furthermore, the importance of the presence or absence of a transition zone above the sulphides, and the relationship between the sulphides and the iron-rich rocks found on surface remains largely unsolved. It is essential, therefore, that more deep drill holes be sunk in the area so as to assess the nature of the base-metal sulphides present and also the associated gold and silver resources (as strategic reserves). More information is thus needed to establish the geological relationships between the three mineral types (gossans, SBRs and massive sulphides) for future application. Systematic study would enhance the efficiency of any future prospecting-exploration activity in the area and enable the knowledge acquired to be applied effectively in exploration for similar mineralization elsewhere in the country.

Massive Barite

The mineralized massive barite occurrences are distally located relative to the massive sulphide deposits and the gossans. Among the best deposits of this type in the region are the Ganaet and Hamim occurrences, hosted by felsic volcanics and which contain about 20 and 5 ppm Au on, average, respectively. Gold occurs as fine disseminations in barite, pyrite and quartz. Wall-rock alteration is extensively developed and the host rocks are also mineralized. The mineralized massive barite lenses in the Ariab area have been subjected to the same phases of deformation as host rocks. They are also mineralogically and geochemically similar to hydrothermal barite from modern seafloors (Hannington *et al*., 1991). Hence, the hypothesis of their origin as products of subsurface residual weathering of sulphides and the differential weathering of host rocks is unlikely (Cottard *et al*., 1986b).

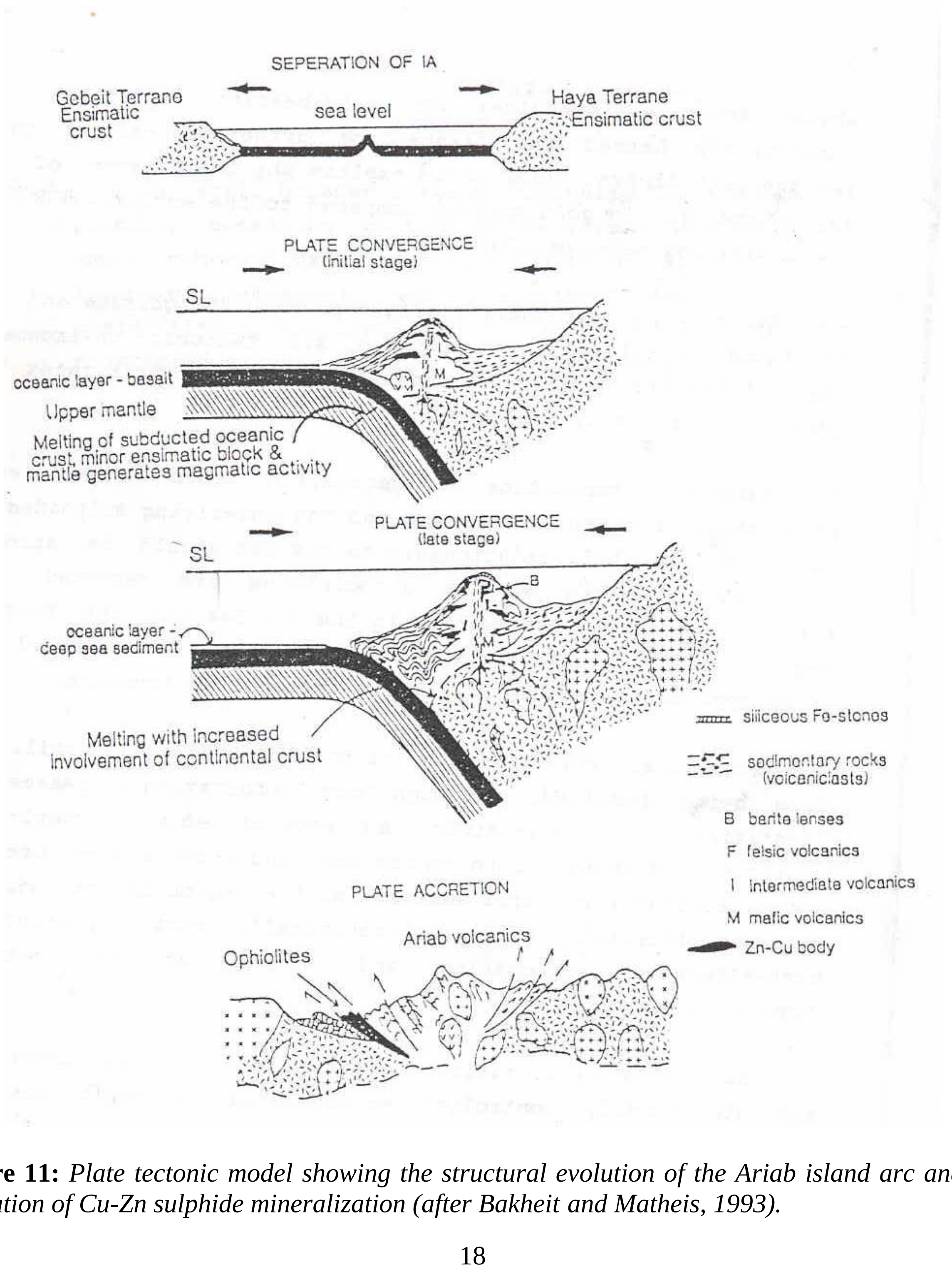

Figure 11: *Plate tectonic model showing the structural evolution of the Ariab island arc and the formation of Cu-Zn sulphide mineralization (after Bakheit and Matheis, 1993).*

Comparison of the Ariab Volcanogenic Sulphides with Others in the World

The sulphides of the Ariab district are broadly similar, in several respects, to the Kuroko, Canadian Shield and west Tasmanian sulphides occurrences, particularly with regard to their regional setting, alignment along tectonic lineaments, hydrothermal alteration, similar types of associated sediments and precious metal contents. In contrast, no zonation in the intensity and type of hydrothermal metasomatism in the host rocks has been reported in the Ariab area. Ariab also differs from other mineral provinces in the intensity of gold mineralization related to hydrothermal processes associated with volcanic activity. These include gold-quartz-barite assemblages that are very rich in gold and in this respect they broadly resemble the Ba and SiO_2 precipitates from the Axial Seamount of the central Juan de Fuca Ridge (Hannington *et al*., 1991) - despite the difference in gold values. Both are characterized by very fine-grained gold in a barite-silica association.

The Ariab sulphides also lack a distinct base metal zonation, which is well developed in other mineral provinces. A further major difference between the Ariab mineralization and that of the Kuroko and Tasmanian types is the lower Pb content in the former, which may partly be attributed to the absence of continental basement below the Ariab district, or the derivation of the Ariab sulphides from primitive magma. Plate tectonic evolutionary models for the Ariab arc, constructed on the basis of field relationships, lithogeochemical characteristics, and structural features observed in the area, are shown in Figure 11 (Bakheit and Matheis 1993).

The Ariab base metal sulphides most closely correspond to the Zn-Cu-type volcanogenic sulphides described by Hutchinson (1973), which are characterized by significant Au and Ag values (Table 4). In this respect, the Ariab sulphide occurrences broadly resemble the Canadian Archaean sulphide deposits even more closely than the deposits of West Shasta, California (Hutchinson, 1973) and they may be assigned to an early subduction stage - a conclusion compatible with the tectonic setting inferred petrochemically.

Origin of Gold

The gold enrichment in SBR of the Ariab area is anomalous, not only with respect to known gold deposits in the Precambrian terranes of Sudan, but also by comparison with most ancient massive sulphide deposits. Bakheit and Matheis (1993) attributed this to volcanic-related, baritic, amorphous silica-precipitating hydrothermal solutions, similar to those found in modern active continental margins (this ignores the age, metamorphism and deformation overprints applicable to the Ariab SBR). Gold enrichment may, however, be due to protracted hydrothermal precipitation along fracture zones which acted as conduits for gold-bearing solutions. This process subsequently barred the gossans from further access to gold-bearing vent fluids and could explain why the gossans of the region are lean in gold content compared to the enclosed SBRs and underlying massive sulphides.

Evidence for the hydrothermal origin of both the gossans and the SBR is found in active plate margins of all tectonic environments where hydrothermal gold-bearing Zn-Fe-Ba-SiO_2 precipitates and gossans have been discovered.

CONCLUSIONS

Field investigations, together with preliminary microscopic and geochemical studies in the Red Sea Hills area have led to the conclusions listed below:

- because of the pervasive hydrothermal alteration and metamorphic overprint, the volcanic rocks of the area are best classified by combining geochemical and petrographic information;

Table 4: Comparative chart showing some geological characteristics of different volcanic sulphide deposits (after Hutchinson, 1973)

Base metal type	Precious metal association	Associated volcanic rock types	Type of volcanism	Type of sedimentation	Tectonism	Age	Examples
(1) Zn-Cu-pyrite	Both Au (with high Cu) and Ag (with high Zn)	-fully differentiated suites of intermediate bulk composition (?); -tholeiitic to calc-alkaline -basalt-andesite-dacite-rhyolite. etc.	-initial deep, subaqueous mafic platform; with differentiation toward felsic volcanism, building domical centres	-chemical; cherts, iron formation -clastic; immature, first cycle, volcanogenic greywackes, volcanoclastics	-early eugeosynclinal-orogenic stage; -major subsidence ditto; early subduction	Archaean Proterozoic (?)	Timmins, Ont. Noranda, Que United Verde, Ariz.
Zn-Cu-pyrite	ditto	ditto	ditto	ditto	ditto	U. Proterozoic mid-Devonion	Ariab,Sudan W.Shasta.Calif
(2) Pb-Zn-Cu-pyrite	Mainly Ag	intermediate to felsic calc-alkaline volcanic suites -andesite-dacite-rhyolite-porphyry-crystal tuff,,etc	-felsic centres of exposure. -cryroclastic and ignimbritic activity. -subaqueous to subaerial	-epiclastic predominates; immature volcanogenic greywackes, manganiferous, shale, graphitic shales and argillites, siltstones -chemical cherts, iron formations -sulphate gangues common	-late eugeosynclinal-orogenic stage: infilling with uplift balances subsidence (?)	Proterozoic Ordovician	Mt.Isa. Queensland Errington. Vermilion (Sudbury Basin) Bathurst, New Brunswick
Pb-Zn-Cu-pyrite	ditto	ditto	ditto	ditto	ditto; later subduction	Triassic Tertiary	E.Shasta.Calif. Kuroko, Japan
(3) Cu-pyrite	Mainly Au	-poorly differentiated mafic-ultramafic (ophiolitic) suites: tholeiitic -basaltic pillow lavas, serpentinite, etc.	-deep subaqueous, quiescent fissure eruptions	-chemical sediments predominate; cherts, ironstones, manganolite, -clastics insignificant	-early stage of continental plate rifting; tension. separation, graben	l-Ordovician u-Cretaceous Jura-Cretaceous Cre-Eocene	W.New foundland Cyprus Island Mountain California Phillipines

- the massive sulphides are associated with differentiated rocks ranging in composition from mafic to felsic volcanics;
- mineral assemblages in the Ariab massive sulphides consist predominantly of chalcopyrite-sphalerite-pyrite, in addition to both Au, Ag and subordinate Pb. In this respect they are very similar to Archaean sulphides found in greenstones generated under conditions of proto-crust development or by the degassing of poorly differentiated proto-mantle (Hutchinson, 1973). On the other hand the presences of abundant barite renders these occurrences more similar to Phanerozoic sulphides, especially the Kuroko type. The Proterozoic age of the Ariab sulphides and the mineral assemblages that show similarities to sulphides from both Archaean and Phanerozoic orogens, may suggest evolutionary processes of crustal development as outlined by Hutchinson (1973);
- field and chemical data on rocks, gossans and gold-bearing barite-quartzite rocks clearly indicate a hydrothermal origin for these units. This implies that the gossans are not products of surface weathering - as it is difficult to account for the presence of barite solely on weathering - but, rather, they may have been oxidized by hydrothermal solutions while still on the seafloor, as inferred from their deformation by the earliest folding phase (F_1), reinforced by the recent discovery of hydrothermally formed gossans in active plate margins; and
- the observation that the gold grades in massive sulphides is (in some ore deposits) often higher than in the overlying gossans, as indicated by the Hassai deposit (as well as others in the Ariab region), where massive sulphides assay up to 2 g/t Au, whereas the overlying gossans ranges from 0.1 to 0.9 g/t Au.

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