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(with a geological map of Somalia 1:1,500,000)

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Cover photograph: a water well near Garbaharrey (Central Somalia)

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PETROLEUM EXPLORATION IN SOMALIA

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ABSTRACT

Petroleum exploration activities in Somalia have spanned the past 40 years. The first well was drilled in 1956, and a total of 57 petroleum tests have been completed as of the end of 1987.

Exploration is currently brisk; several concessions are undergoing geophysical surveys and additional wells will be drilled in 1988.

Somalia can be divided into six major basinal areas, each with a somewhat distinct geologic history. Sedimentary columns are thick, up to 5 or 6 km in several areas, and range in age from Jurassic or Triassic to Tertiary. Tectonics for the past 200 my have been extensional, leading to these thick and varied columns. Facies changes, faults, arches, and folds associated with the extensional tectonics provide many possible combinations of trap, reservoir, seal, and source rock.

Many of the previous tests were drilled on old or inadequate seismic data. Better geophysical techniques and modern exploration concepts will provide improved opportunities in the future. We remain optimistic about Somalia hydrocarbon potential.

INTRODUCTION

This paper reviews petroleum exploration in Somalia. In this review, we will cover some aspects of the past history of explorations discuss current activity, and touch upon the future. That future has considerable promise in our estimation.

Petroleum exploration has extended over 40 years. The first exploratory well, the Sagaleh-l, was completed in 1956. As of 1987, a total of 57 exploratory holes have been drilled. None of these wells has been commercially successful, although some have had shows of hydrocarbons, a point which we will discuss in greater detail later.

STRUCTURE AND STRATIGRAPHY

Fig. 1 indicates the well locations in Somalia and other wells in adjacent countries. The wells are fairly broadly distributed throughout Somalia, but they are very widely spaced in most areas. In most cases, adjacent wells are at leas 50 to 100 km apart and in some places spacing is 250 to 400 km.

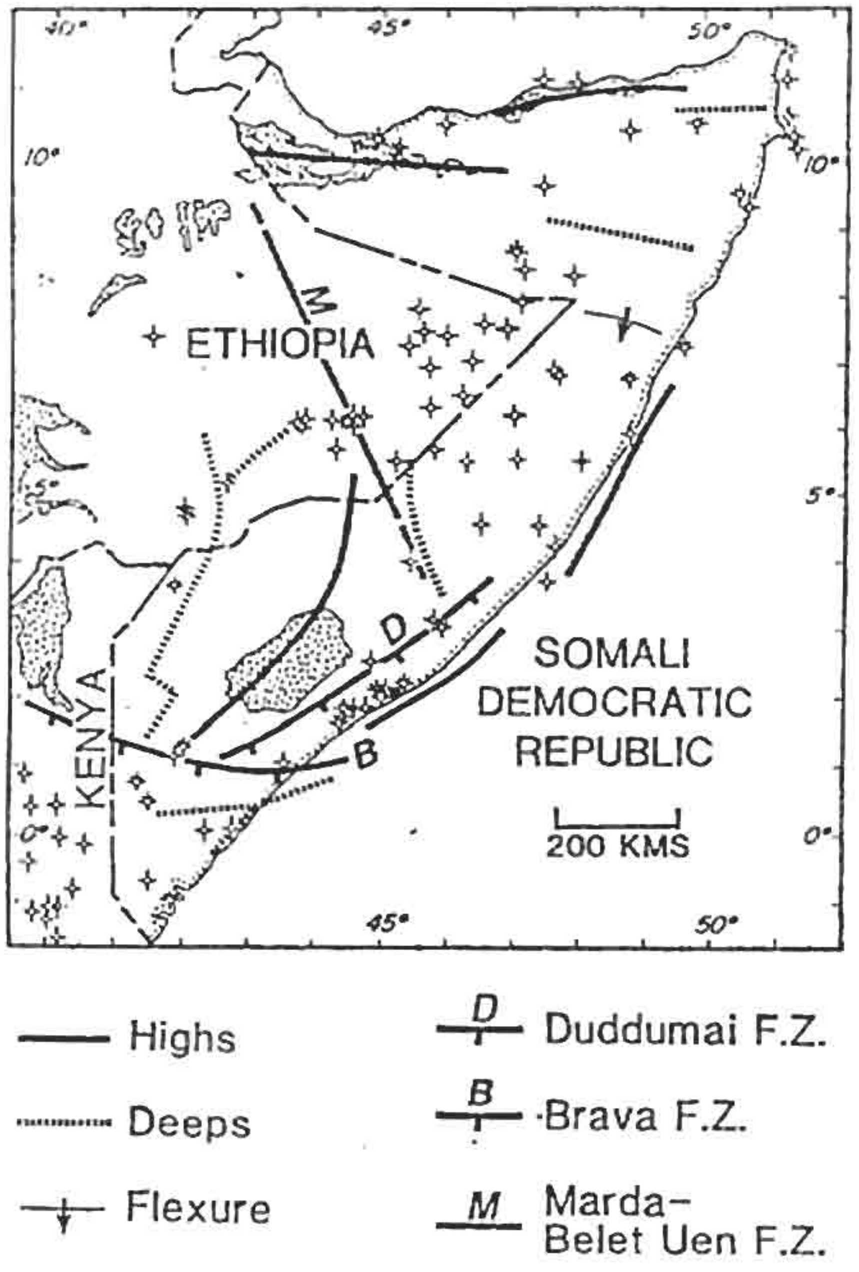

Fig. 1 - Map of Somalia showing principal tectonic elements.

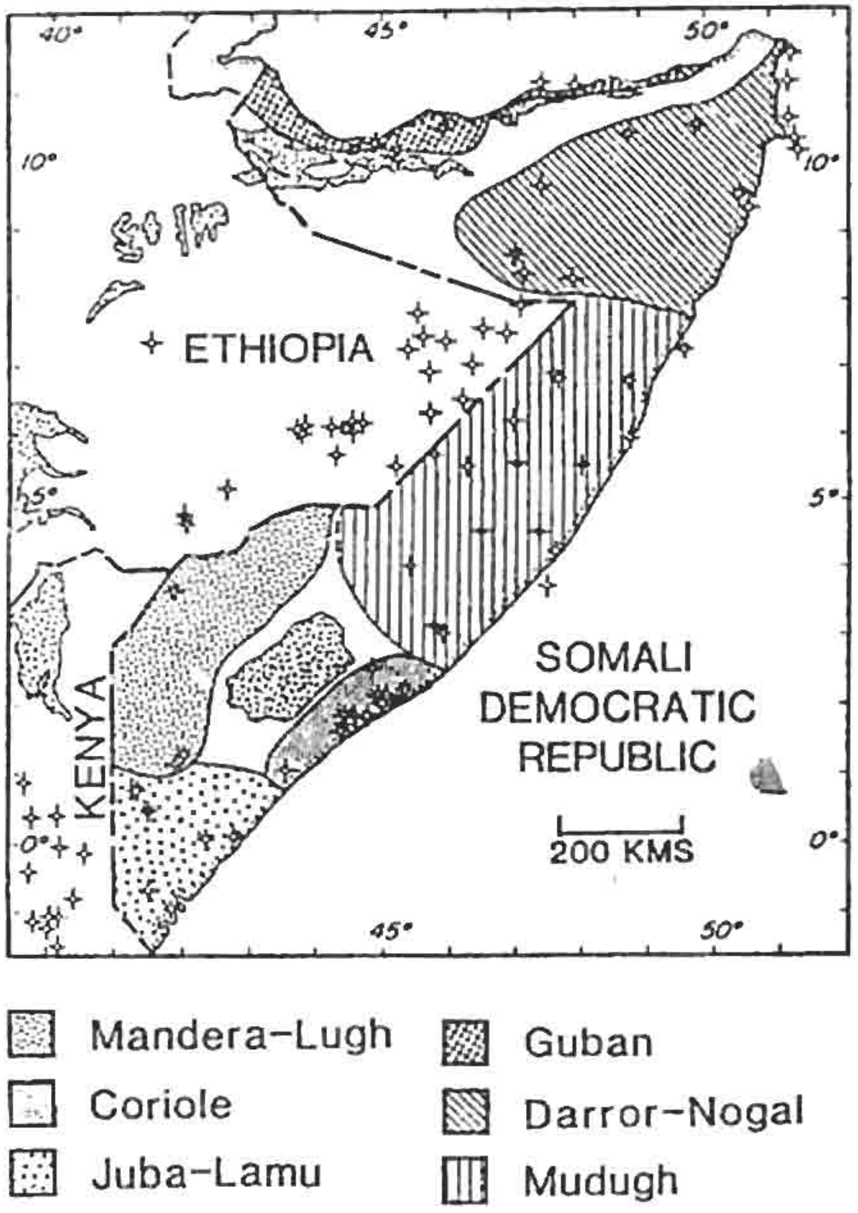

Fig. 2 - Sedimentary basins.

Major tectonic elements are also shown on Fig. 1. Areas with exposed crystalline basement occur at Bur Acaba in South-central Somalia and along the northern coast. Regional arches exist on the north plunge of Bur Acaba and along the central and southern coastal areas. Major fault zones exist at Brava, Duddumai, and along the Marda-Belet Uen trends, and a zone of flexure near El Hamurre separates the deeper basins to the south from the higher areas of the northern Somali plateau. The northern coastline is much faulted on a scale too small to be represented on this map, but basement blocks with exposed crystalline cores are bounded to the north by fault zones down thrown toward the Gulf of Aden.

Somalia is largely covered with sedimentary rocks ranging in age from Tertiary to Triassic or older. Fig. 2 shows six major basinal areas, some of which contain sedimentary sections more than 5 or 6 km thick. The basins are varied in the age and character of fill. The Mandera-Lugh basin is mainly Jurassic, possibly underlain by a thick Karroo sequence. The Juba-Lamu and Coriole basins have thick Tertiary sections, so that petroleum prospects are mainly Tertiary or Upper Cretaceous. The Mudugh basin is mainly Jurassic and Cretaceous, but with an increasingly thick Tertiary section toward the south and along the coastline. The Darror and Nogal valleys in the north-eastern plateau are downfaulted basins filled with mainly Cretaceous and/or Jurassic covered near the surface by Eocene. The Guban area contains Jurassic, Cretaceous, and locally thick Tertiary sections in small basins related to Gulf of Aden and earlier rifting.

Table 1 - Exploration in Somali basins.

EXPLORATION IN SOMALI BASINS

	AREA (Sq Kms)	WELLS	DRILLING DENSITY AREA/WELLS (Sq Kms)
MANDERA-LUGH	70,000	3	23,000
JUBA-LAMU	45,000	6	7500
CORIOLE	25,000	11	2300
MUDUGH	150,000	16	9400
DARROR-NOGAL	160,000	14	11,400
GUBAN	35,000	7	5000

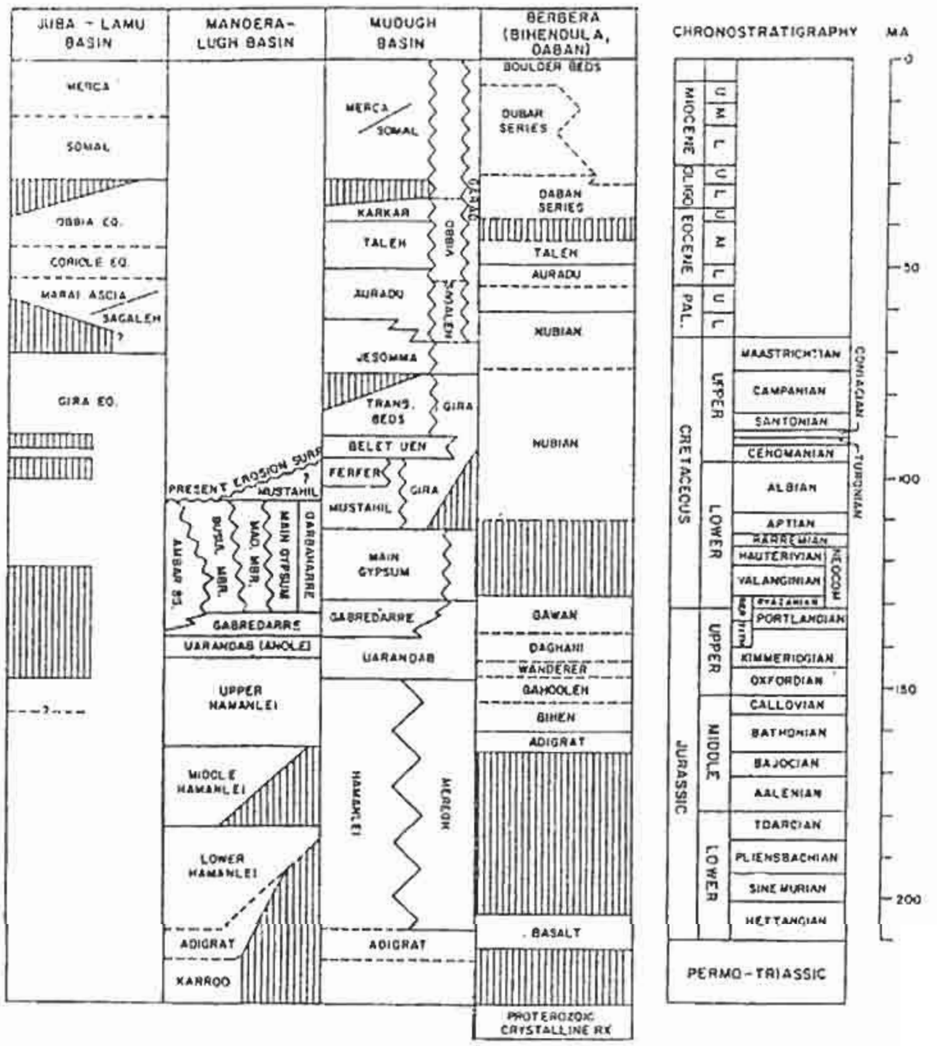

Fig. 3 - Stratigraphic columns of Southern, Central, and Northern Somalia.

These uplifts, arches, and basins are the result of broad plate motions that have occurred over the past 200 or more my. The general tectonic setting has been one of extension, first the Permo-Triassic Karroo rifting, then the Jurassic separation of Madagascar and India from Africa along the Indian Ocean coast and finally the formation of the Gulf of Aden by the relative northward movement of Arabia beginning in the Oligocene. These movements have formed many structures of scales and types that could contain hydrocarbons.

Drilling density in Somali basins is very low by comparison to other areas in the world. Table 1 shows the area of each of the six basins and the number of wells. Drilling density ranges from one well for every 2,300 km^2 to one well for every 23,000 km^2.

In many places, distances between wells range from 100 to 250 km or more, leaving many opportunities for additional exploration.

Despite the low well density, the contribution of petroleum exploration to the knowledge of geology of Somalia has been very significant. The seismic, gravity, and magnetic surveys and drilling have all added significantly to the understanding of structure and stratigraphy.

For petroleum exploration purposes, the stratigraphic column can be divided into five major sequences, illustrated for Central, Southern, and Northern Somalia on Fig. 3. The oldest is a detrital phase of the Karroo-Adigrat, related to the earliest Mesozoic rifting phase. Sandstones within this sequence represent potential reservoirs and finer grained parts provide some source rock potential. The Jurassic is dominated by carbonate rocks, reflecting broad marine inundation of Eastern Africa.

This transgression occurred at different times in various parts of Somalia, so that the transition from Adigrat to carbonate rocks ranges in age from Early to Middle Jurassic. Shallow water carbonates of the Hamanlei in Central Somalia interfinger eastward with more basinal Meregh facies. The wide-spread Uarandab shaly unit indicates the broadest flooding onto shelf areas, followed by depositional regression. The Jurassic-Lower Cretaceous sequence is thick and complex, and represents many possible intervals of reservoir, seal, and source rocks. Beds of Neocomian age are largely absent in Northern Somalia.

In Central and Northern Somalia, Aptian and younger Cretaceous rocks represent renewed flooding and largely normal marine deposition, where basinal facies to the east are separated from more restricted facies by broad shallow banks. This system of lagoon to bank and basin offers additional reservoir, seal, and source rock combinations in some areas. The Upper Cretaceous of North-western Somalia is locally thick and very sandy and represents fluvial facies (Nubian) which become marine to the east and south-east.

The Cretaceous, in about Maastrichtian, appears to be marked by broad uplift over the central and northern area of Somalia. This uplift caused erosional truncation followed by fluvial deposition over a vast alluvial plain, the Jesomma Sandstone, which interfingers to the east and south-east with marginal marine and basinal facies. Marine inundation followed in Paleocene, Eocene, and Early Oligocene time with the

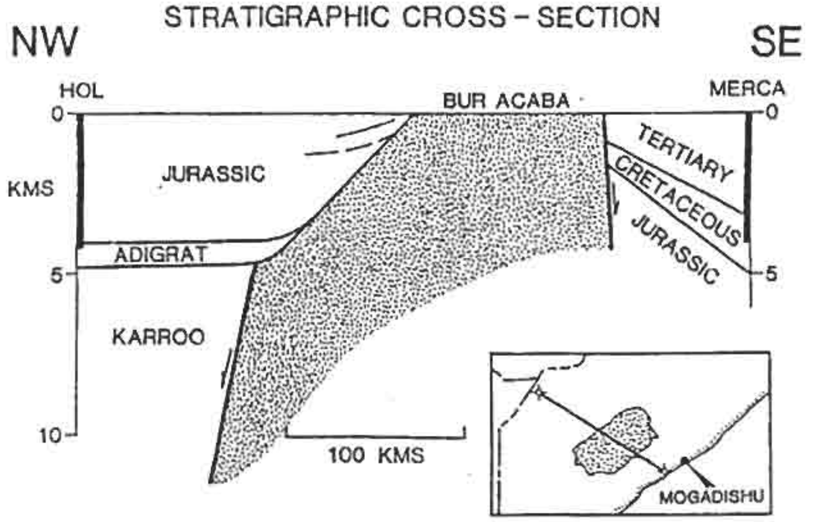

Fig. 4 - Stratigraphic cross-section Hol-Bur Acaba-Merca.

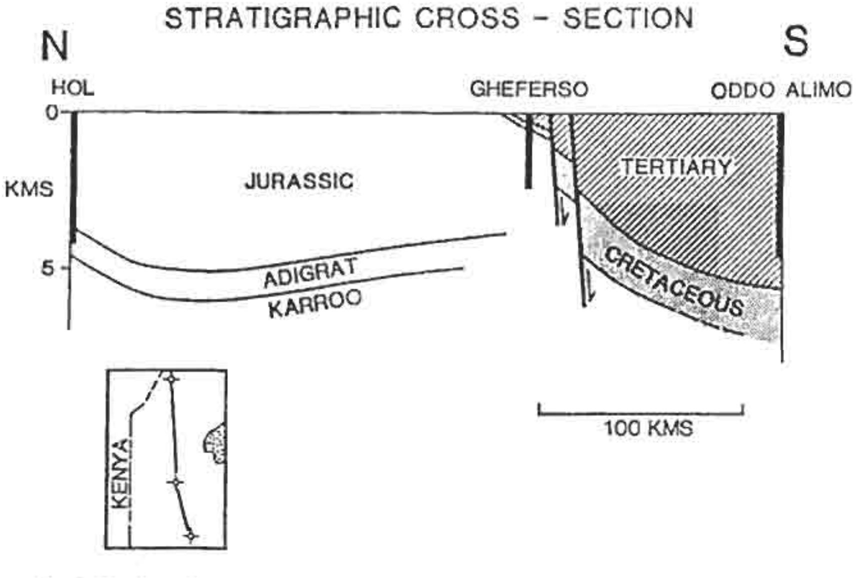

Fig. 5 - Stratigraphic cross-section Hol-Gheferso-Oddo Alimo.

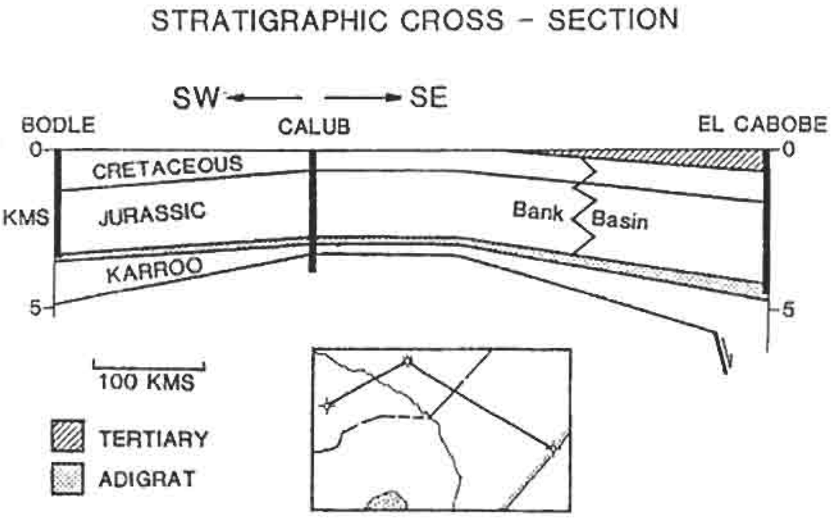

Fig. 6 - Stratigraphic cross-section Bodle-Calub-El Cabobe.

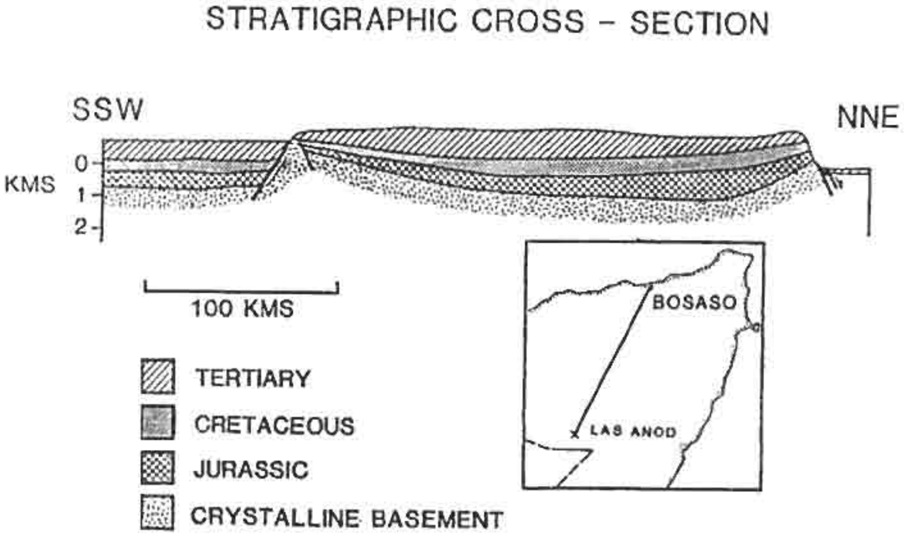

Fig. 7 - Stratigraphic cross-section Las Anod-Bosaso.

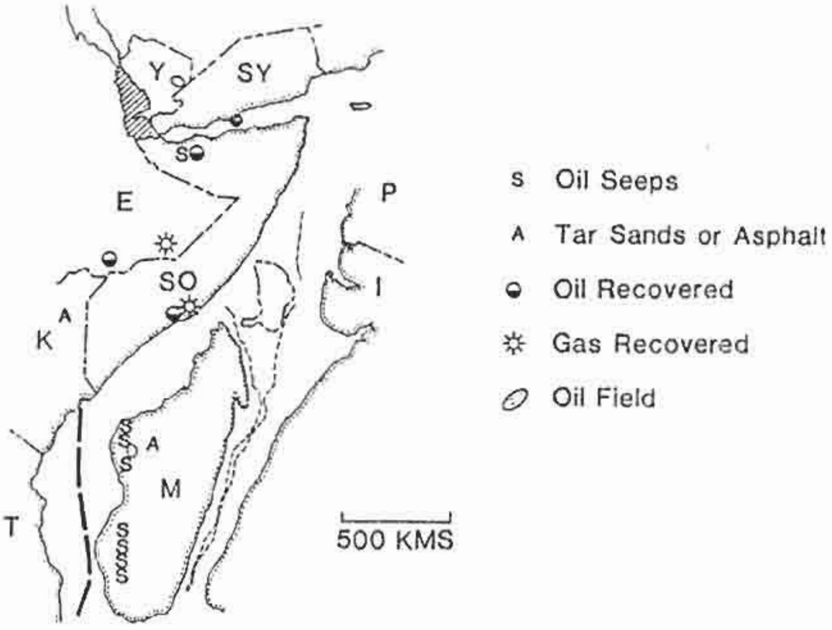

Fig. 8 - Oil and gas occurrences in Somalia and surrounding areas.

well known northern platform sequence of carbonates and evaporites changing to basinal equivalents the east and south. Paleo-Scebeli and Juba River systems supplied detrital material to the central and southern coastal basins. These deltaic-prodeltaic areas have some promise as reservoirs and sources.

The Middle Oligocene provides another major sequence break, related to the general low sea level stand, erosion, and subsequent transgression which covered most of the southern coastal basins, but otherwise flooded only a rather narrow fringe of the continental margin. This sequence is for the most part too shallowly buried over much of Somalia to be prospective of hydrocarbons. However, in parts of the Guban basin, deep basins developed during Oligocene rifting and the development of the Gulf of Aden. Some rotated fault blocks accumulated large thicknesses of Oligocene and Miocene sediments. These local basins may have also had high heat flows and favourable thermal histories.

The stratigraphy and structure of the various basins can be illustrated using simple cross-sections based on well control. Fig. 4 shows a section from the Hol well in the Mandera-Lugh basin to the Merca well near the coast. Over 4 km of Jurassic sediments were penetrated at Hol, which in that area appears to be underlain by additional Karroo, based on geophysical data. In contrast, the east side of Bur Acaba is faulted, and

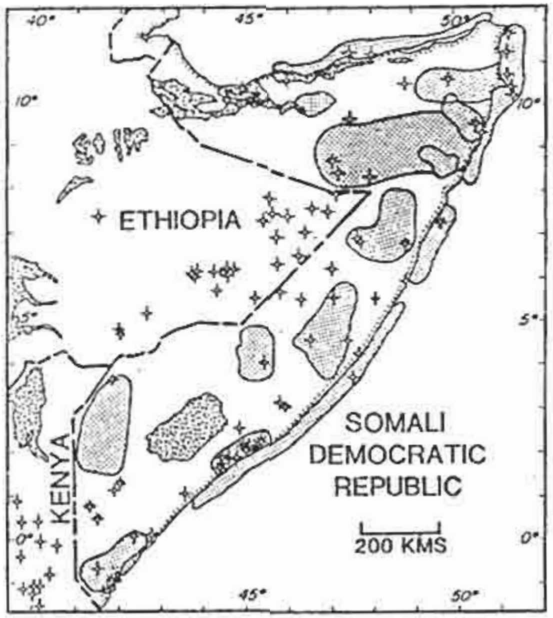

Fig. 9 - Areas with grid of post-1972 seismic coverage (slipped). Basement rocks, dashed.

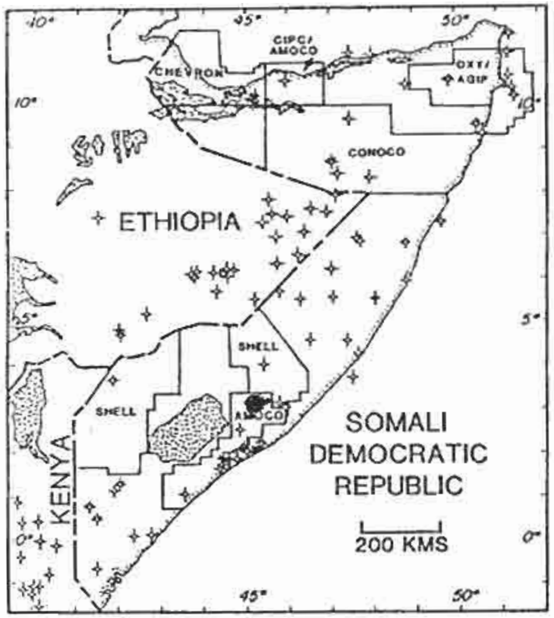

Fig. 10 - Areas under license October, 1987.

Cretaceous and Tertiary beds form a wedge which thickens toward the coast. Older strata have not been penetrated by wells, so that the character of the deeper section is unknown.

Southward from the Hol well (Fig. 5), the Lugh basin remains predominantly Jurassic until the Gheferso well, where downfaulting to the south accommodates a thick Tertiary and Cretaceous section in the Juba-Lamu embayment. Here the paleo-Juba drainage provided a large supply of detrital material and built a delta complex of significant thickness.

The north plunge of Bur Acaba forms a regional arch which separates the Mandera-Lugh basin to the west from the Mudugh basin to the east. Jurassic units thin somewhat over the arch, indicating that it subsided less rapidly during the Jurassic (Fig. 6). Jurassic and Cretaceous beds show facies changes from bank to basin within the Mudugh basin. The Calub well encountered significant quantities of gas in sands of the Adigrat and Karroo, and has been successfully offset.

A very simplified section of the northern plateau area is shown in Fig. 7. In general, the plateau lies at a higher elevation, has a thinner total section, and is separated from more basinal areas to the south by a zone of flexure or faulting. The section does not do justice to the complexity of the Gulf of Aden coast, where the section is dramatically downfaulted and local basins hold thick Oligocene and Miocene deposits.

Not all of the plateau south of the coastal area is structurally featureless. Eocene and older rocks are downfaulted in east-west trending basins along the Darror and Nogal valleys, where displacement of the Eocene Auradu exceeds 1,000 m in some areas.

This brief review of structure and stratigraphy suggests that there are thick and varied sedimentary sections ranging in age from Triassic or Jurassic to Tertiary and areas of faulting, folding, or doming. All of these elements suggest that there is a good possibility of hydrocarbons. What has actually been found in Somalia and adjacent areas?

HYDROCARBON OCCURRENCES AND POTENTIAL

Table 2 shows some of the oil and gas occurrences in Somalia and surrounding areas. Shallow asphalt has been found in NE Kenya within the Karroo. Several wells in Ogaden have recovered oil or gas, some in significant quantities. Gas or oil have been recovered from wells in three areas in Somalia. Wells drilled around the Dagah Shabel oil seep in Northern Somalia recovered some oil from Cretaceous sandstone and Jurassic carbonate in a structurally complex area. Two wells in the Coriole basin recovered gas and condensate or oil in Tertiary to Upper Cretaceous zones.

Although these wells in Somalia were not commercial discoveries, they must be regarded as significant in that hydrocarbons were generated and trapped. Viewing these and adjacent areas on a larger scale (Fig. 8), other significant hydrocarbon accumulations do occur around Somalia on a restoration of plate positions to the

Jurassic. In addition to the areas mentioned, there are large tar sand accumulations in Madagascar, and many wells with hydrocarbon shows.

Finally, and perhaps most significant, commercial oil production has been found in North Yemen. Before the Oligocene and Miocene separation in the Gulf of Aden, this area lay close to and has similarities to basins in Northern Somalia.

Many of the wells drilled in Somalia were located without the benefit of modern seismic surveys. To illustrate this point, Fig. 9 shows areas of post-1972 seismic coverage. Many wells fall outside of this coverage, and some of these surveys were recorded after wells within the areas had been drilled, notably in the Coriole basin. Older seismic techniques did not give adequate representation of structural configuration at depth, so in many instances the wells were in reality drilled "blind". Certainly modern methods provide much more accurate interpretations of structure and stratigraphy, and future wells will be much better located.

Present activity in exploration is brisk. Six permits were in force as of October, 1987, as illustrated in Fig. 10. Seismic and other geophysical crews were operating at that time in the Chevron, IPC/Amoco, and Conoco blocks.

One well was completed in early 1987 offshore by Oxy/AGIP. We anticipate that three new wells will be drilled in 1988 one in the Lugh basin and two in the western Guban basin. We are optimistic about the prospects of these wells.

Table 2 - Significant oil and gas occurrences.

	AGE/FORMATION	DEPTH (FT)	COMMENTS
NE KENYA-TARBAJ	Karroo ss	Shallow	Asphalt
ETHIOPIA			
KURAN-1	Hamanlei ls	9500	Oil Recovered on Test
HILALA-1	Hamanlei ls	5300	Oil Recovered on Test
SHILLABO-1	Hamanlei ls	6900	1 MMCF/D
CALUB-1	Adigrat ss	9000	17 MMCF/D + Condensate
	Calub ss	12,000	24 MMCF/D + Condensate
SOMALIA			
CORIOLE-1	Eocene ls	6500	2 Bbls Oil Recovered on Test
	U.K. (?) Volcanics	11,500	2 MMCF/D + Condensate
AFGOI-1	Paleocene-U.K. ss	12,700	4 MMCF/D + Condensate
DAGAH SHABEL	U.K. ss & J frac ls	Shallow	Seep; Oil Recovered on Test

CONCLUSIONS

To recapitulate, Somalia has six major basin areas with thick sedimentary sequences ranging in age from at least the Early Jurassic to the Tertiary. These basins were formed over a 200 my span by plate motions mainly of extensional style. There are many structural features created by these movements that are capable of trapping oil and gas. Future success will depend on identifying good potential hydrocarbon source rocks, tracing their thermal maturation history, and identifying associated structures with reservoir and sealing beds that existed before hydrocarbon migration. We are confident that there are areas with combinations of source rocks, reservoirs, seals, and structures which have not been adequately tested by previous exploration. We are optimistic about Somalia future as a hydrocarbon producer.

Final editing, January 1990

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MINERAL DEPOSITS AND OCCURRENCES IN THE PRECAMBRIAN OF NORTHEAST AFRICA AND ARABIA: A REVIEW

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ABSTRACT

A review of the mineral deposits and occurrences in the Precambrian of Northeast Africa and Arabia is presented in the form of four descriptive tables (Appendix A) each accounting for the distribution, types, economic importance and geological controls of the mineralizations within a large scale geotectonic unit: the Nubian Shield (Table A - 1), the Arabian Shield (Table A - 2), the Northwestern Branch of the Mozambique Belt and the adjacent African (East Sahara) Craton margin (Table A - 3) and the Northeastern Branch of the Mozambique Belt (Table A - 4). A discussion of the collected data is based on a general geostructural scheme synthesized from the most recent studies and interpretations. A brief synopsis summarizes the well-differentiated metallogenic pattern of the domain.

INTRODUCTION

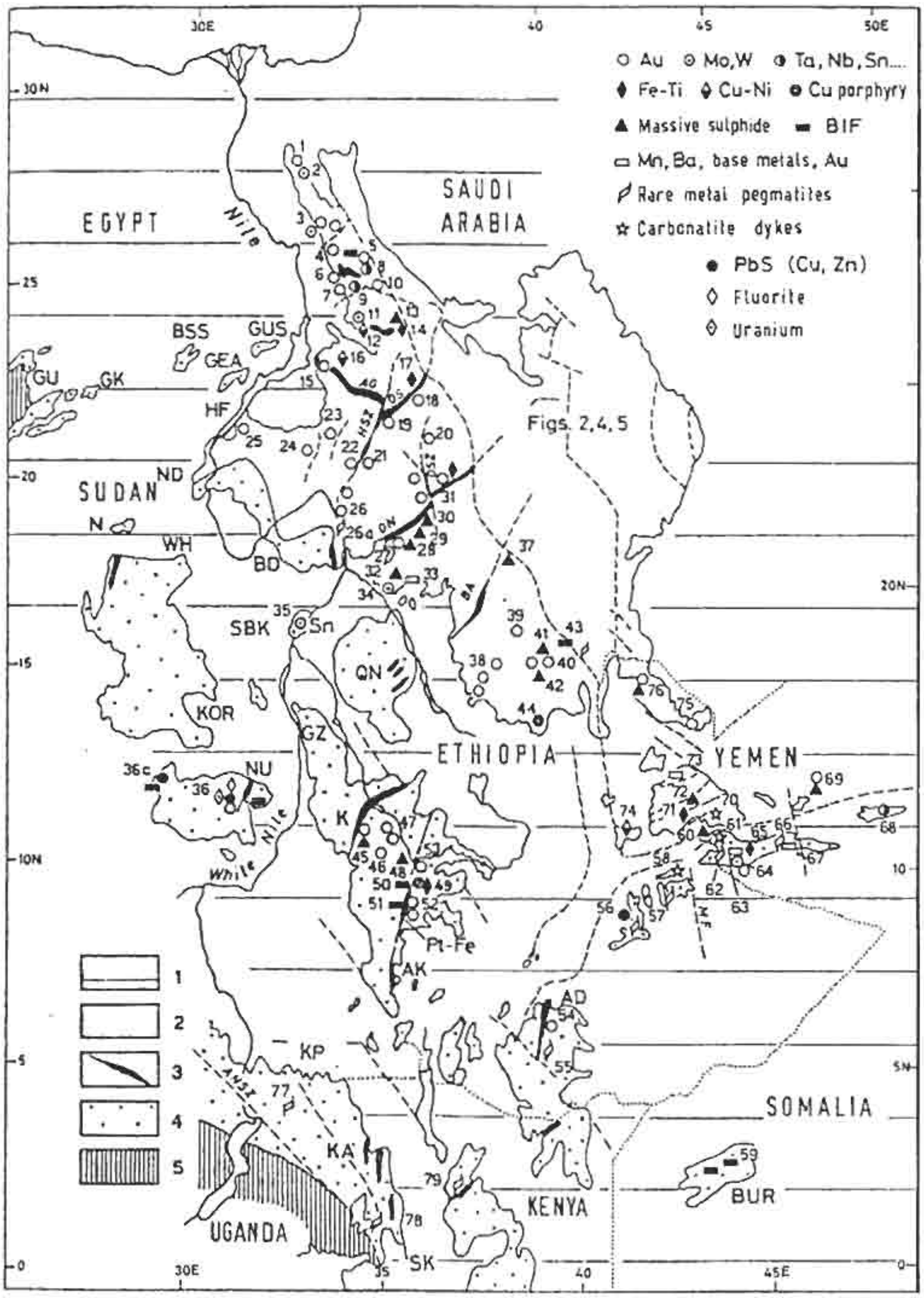
In the last few decades, exploration for mineral resources other than hydrocarbons has led to significant discoveries in the Precambrian terrains of Northeast Africa and Arabia. A better understanding of the origin and tectono-stratigraphic setting of the mineral deposits and occurrences has been made possible by a wealth of general and ore geology studies. The purpose of this review, compiled on invitation of GEOSOM 87 organizers, is to summarize the results of these investigations. Available data about distribution, types, economic importance and geological controls of the Precambrian mineralizations in Somalia, Ethiopia, Sudan, Egypt, Saudi Arabia and Yemen have been distilled and assembled into four tables (Appendix A) each concerning a large-scale geotectonic and metallogenic unit: the Nubian Shield (Table A - 1), the Arabian Shield (Table A - 2), the Northwestern Branch of the Mozambique belt and the adjacent African (East Sahara) Craton margin (Table A - 3) and the Northeastern Branch of the Mozambique Belt (Table A - 4). According to a more general and correlative scheme (JACKSON, 1987) the Precambrian of Northeast Africa and Arabia can be subdivided into the following domains: (1) a central (Afro-Arabian) domain comprising the Late

Proterozoic juvenile Arabian-Nubian Shield and the southern extension of the Nubian Shield into the Kurmuk-Wollega-Akobo region at the Sudan/Ethiopia border. This domain is considered by several workers as composed of independently evolved terranes of island arc or mixed continental-island arc affinity, bounded by suture zones containing fragments of oceanic crust; (2) an eastern domain of seismically different, Proterozoic to possibly Archaean lithosphere underlying Eastern Arabia, the Persian Gulf and the Zagros mobile belt, the junction with domain (1) lying within the Al Amar suture zone; (3) a southern domain comprising the Northern Somalia-Yemen block, the Harar inliers, the Adola rift zone and the Bur region of older Proterozoic continental crust extensively reworked in Late Proterozoic (NE branch of the Mozambique Belt). A differentiated Late Proterozoic crustal evolution characterizes the southern outcrops (Adola, Bur) with features correlative with the main trunk of the Mozambique Belt of Kenya-Tanzania, with respect to the North Somalia-Yemen block, whose complex pattern reflects the transition to the geotectonic framework of the southern Arabian Shield; (4) a western domain of older (Archaean to Middle-Proterozoic) continental crust. In Southern Egypt and Northern Sudan, the largely concealed boundary of this domain with domain (1) represents the northern extension of the main Mozambique Belt orogenic front against the African (East Sahara) Craton, involving in the collision the younger, greenschist facies ophiolite-island arc assemblages of the Nubian Shield (Fig. 1).

Fig. 1 - Simplified sketch map of the mineral deposits and occurrences in the Precambrian terranes of the Nubian Shield (cf. Table A - 1), the East Sahara Craton margin and NW Branch of the Mozambique Belt (Table A - 3) and the NE Branch of the Mozambique Belt (Table A - 4).
1) Phanerozoic cover. 2) Arabian-Nubian Shield. 3) Sutures (ophiolite-bearing p.p.). 4) East Sahara Craton + Mozambique Belt gneisses. 5) Tanzanian Craton.

Localities: G. Uweinat GU, G. Kamil GK, Bir Safsaf BSS, G. Umm Shagir GUS, G. El Asr GEA, W. Halfa HF, Nubian Desert ND, Nukheila N, W. Howar WH, Bayuda Desert BD, Sabaloka SBK, Qala en Nahl QN, Gezira GZ, Nuba Mts. NU, Kurmuk-Ingessana-Wollega K, Akobo AK, Adola AD, Kapoeta KP, Karamoja KA, Sekerr SK.

Lineaments: Allaqi-Gerf-Onib-Sol Hamed suture AGOS, Hamisana Shear Zone HSZ, Oshib-Nakasib suture ON, Oko Shear Zone OSZ, Baraka lineament BA, Aswa-Nimule Shear Zone ANSZ, Marda Fault MF.


○ Au
⊙ Mo,W
◑ Ta, Nb, Sn....
♦ Fe-Ti
♦ Cu-Ni
● Cu porphyry
▲ Massive sulphide
▬ BIF
▭ Mn, Ba, base metals, Au
Rare metal pegmatites
☆ Carbonatite dykes
● PbS (Cu, Zn)
◇ Fluorite
◇ Uranium
1
2
3
4
5
30E
40
45
50E
30N
25
20
20N
15
10N
10
5
5N
0
35
45E
EGYPT
SAUDI ARABIA
SUDAN
ETHIOPIA
YEMEN
SOMALIA
KENYA
UGANDA
Nile
White Nile
Figs. 2,4,5
BSS
GUS
GEA
GU
GK
HF
ND
N
WH
BD
SBK
Sn
KOR
NU
QN
GZ
K
Pt-Fe
AK
AD
KP
KA
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HSZ
ASZ
ON
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MF

AFRO-ARABIAN DOMAIN (Tables A - 1, A - 2, A - 3 p.p.)

The evolution of the Afro-Arabian domain began prior to 950 Ma as a consequence of large-scale rifting of the northeastern margin of the African craton, followed by the formation of an ocean basin characterized by active subduction regimes from 950 to 630 Ma (STOESER and CAMP, 1985). Geological and isotopic evidence suggests that the oceanic environment grades east-and westwards to transitional-continental margin settings. Evolved continental fragments are recognized east of the Nabitah suture in the Arabian Shield (Figs. 2, 3) and in the western margins of the domain where, according to the proposed evolutionary models the incorporation of such fragments appears as most probable. The style of arc magmatism shows significant variations in space and time. Primitive mafic to bimodal, possibly rift-related volcano-plutonic assemblages are mostly preserved in the southern Arabian Shield (Asir terrane). A main period of more evolved arc/oceanic back-arc basin growth occurred between about 800 and 700 Ma in the central part of the domain. Associated plutonic rocks are predominantly diorite, tonalite, granodiorite and trondhjemite; sediments are mostly "cannibalistic" volcaniclastics (AL-SHANTI and GASS, 1983; CAMP et al., 1984). Apparently, there is a migration of the volcanic centres from the ensimatic central arc region towards the continental margins (eastern and northwestern Andean type arcs: AGAR 1985; STACEY and AGAR 1985; KRÖNER, 1985). Although the formation of intraoceanic island arc systems is considered a dominant crustal process from about 900 to 700 Ma (CAMP et al., 1984; STERN et al., 1989) we observe that a parallel, more protracted evolution also characterizes the continental margin settings, early developed as passive environments draped by abundant continent-derived clastics, then converted into active continental margins as suggested by KRÖNER (1985) for eastern Nubia. The continent-derived, distal fine grained detritus interbedded with the oldest arc-derived sediments of the southern Arabian Shield (JACKSON and RAMSAY, 1980) is one of the earlier manifestations of a process of greater amplitude, involving both western and eastern (WHITE, 1985) erosional sources. Active continental margin complexes such as the 720-690 Ma old Siham group described by AGAR (1985) at the western edge of the Afif microcontinent contain lithological components (mio- to eugeosynclinal type sediments, associated with extension-related basalts and intrusive ultramafic-gabbroic rocks besides subduction-related, mature andesite-dominated volcanics and plutonic bodies) whose equivalents can be recognized throughout the western Nubian Shield and in the Kurmuk-Wollega wedge-shaped indentation of the Nubian Shield into the ensialic Mozambique Belt (Fig. 1).

In the ensimatic core of the Arabian-Nubian Shield the absence of accretionary prisms, ophiolitic mélanges and high-P metamorphic assemblages suggests a possible formation of complex arc terranes (microplates) by lateral transport of arc material along ophiolite decorated, steep dipping shear zones in an intra-arc setting (JACKSON, 1987). A similar mechanism is envisaged by CHURCH (1988) for microplate assembly involving strike-slip lateral migration and transport of ophiolite slivers far from the site

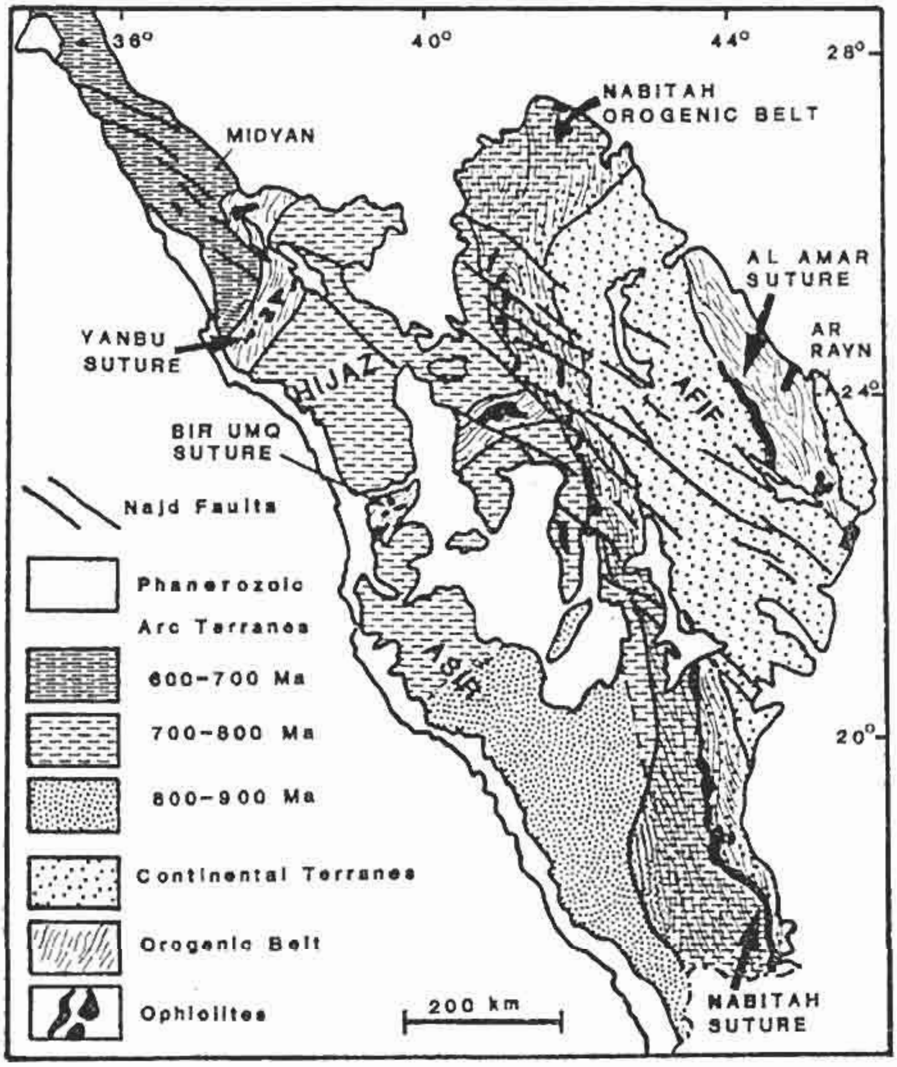


Fig. 2 - Tectonic sketch map of the Arabian Shield (after STOESER and CAMP, 1985).

of their formation. Arc-arc suturing in Arabia did not include either intense orogenesis or synorogenic plutonism (STOESER and CAMP, 1985) and well-preserved arc/basin fragments with significant volcanogenic ores are found along the main Yanbu and Bir Umq suture zones (Fig. 2). However, apparently higher shear/strain overprint characterizes the corresponding Onib-Allaqi and Nakasib suture segments in Nubia (MANKEL et al., 1987; HUSSEIN et al., 1987). In contrast, intense collisional orogenesis associated with high-grade granulite to amphibolite facies metamorphism, crustal remobilization and synorogenic plutonism occurred in the middle of the 700-600 Ma interval during arc-continent suturing in the east (continental collision between the Arabian Shield and a major continental plate to the east) and in the west (Nubian Shield collisional nappes against the African craton).

Following the progression of suturing in the central and in the lateral parts of the domain, subduction-related volcanism and sedimentation gave way to intracratonic deformation and magmatism, formation of pull-apart basins and molasse deposition, intermediate to silicic volcanism and intrusion of peralkaline to peraluminous granites. In the Arabian Shield, the patterns of sedimentation and magmatism are influenced by a major NW-trending sinistral wrench-fault system, the Najd, active between 630 and 550 (530) Ma displacing the northern part of the Arabian Shield by as much as 400 km to the NW. The Najd shear system demonstrably extends from the northwestern Arabian Shield (Midyan terrane) into the central Eastern Desert of Egypt (SULTAN et al., 1988). In contrast, in the northern Eastern Desert a 600-540 Ma period of extensional tectonics has E-NE trend (STERN and HEDGE, 1985) reflected by regional dyke swarms and, according to STERN et al., (1988) also controls the Dokhan volcanism/plutonism and the Hammamat molasse sedimentation. In Southern Egypt, an easterly dextral wrench-fault system is observable in the easternmost inliers of the East Sahara Craton (Bir Safsaf-Aswan uplift, Fig. 1) where it is considered as a conjugate of the Najd system (SCHANDELMEIER et al., 1988). Whilst in Saudi Arabia and central Eastern Desert the Najd shear system modifies the earlier collision-related tectonic fabrics mostly oriented N-S or NE-SW (MOORE, 1979), in the Red Sea Hills of Sudan and southwards the latter directions are maintained up to the late deformation events (Hamisana Shear Zone: 610-560 Ma old; STERN et al., 1989).

MINERALIZATION

VOLCANOGENIC MASSIVE SULPHIDE ORES

1. Southwestern Arabian Shield (Figs. 2, 4): in the Asir terrane the numerous mineralizations of the W. Bidah and W. Shwas districts (Table A - 2) occur in north-trending belts of predominantly mafic to bimodal volcanics belonging to the oldest (>900-800 Ma) and intermediate age (800-700 Ma) cycle respectively. Sheared lenses of massive pyrite-Cu (Zn) ore characterized by low tonnages and base metal grades

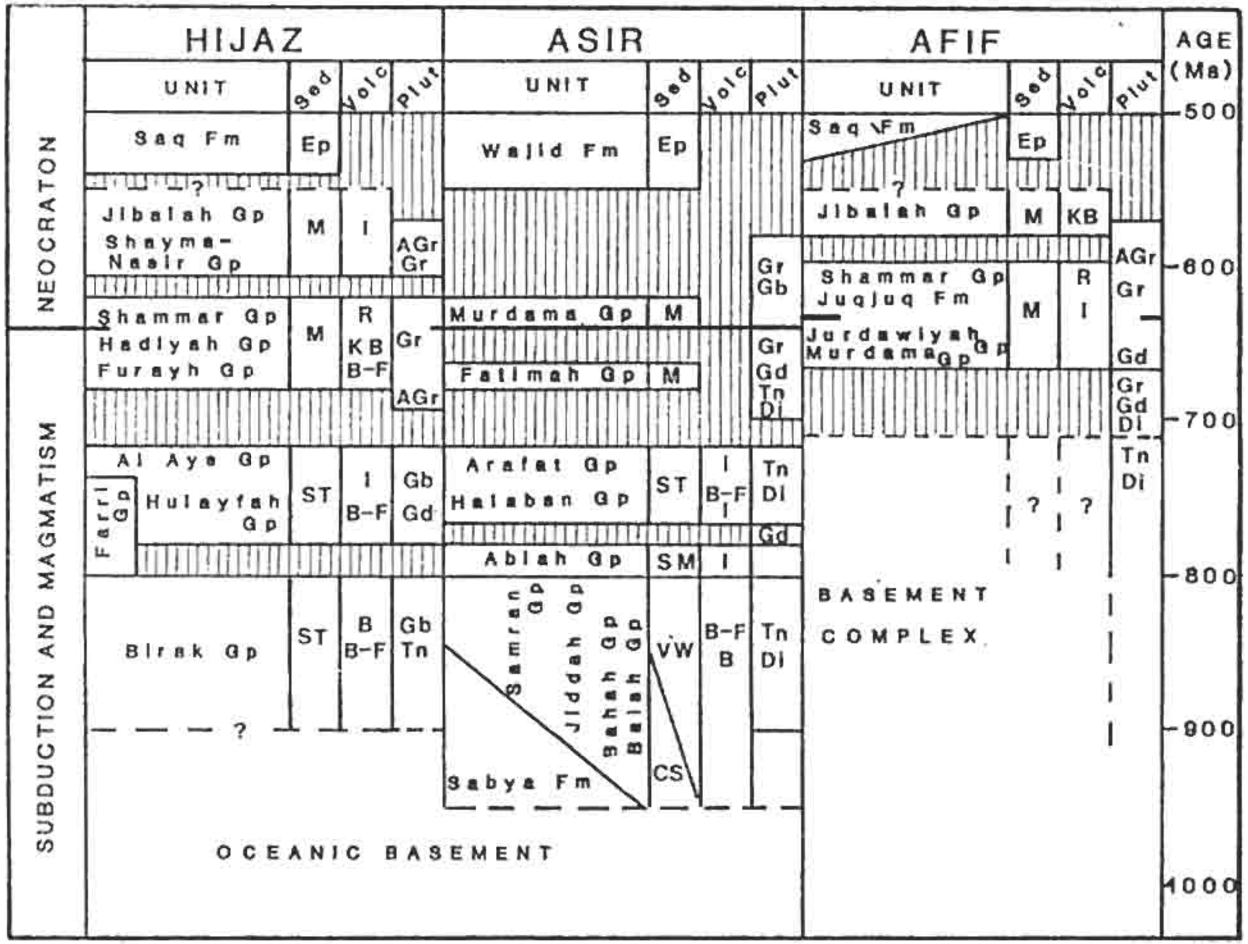
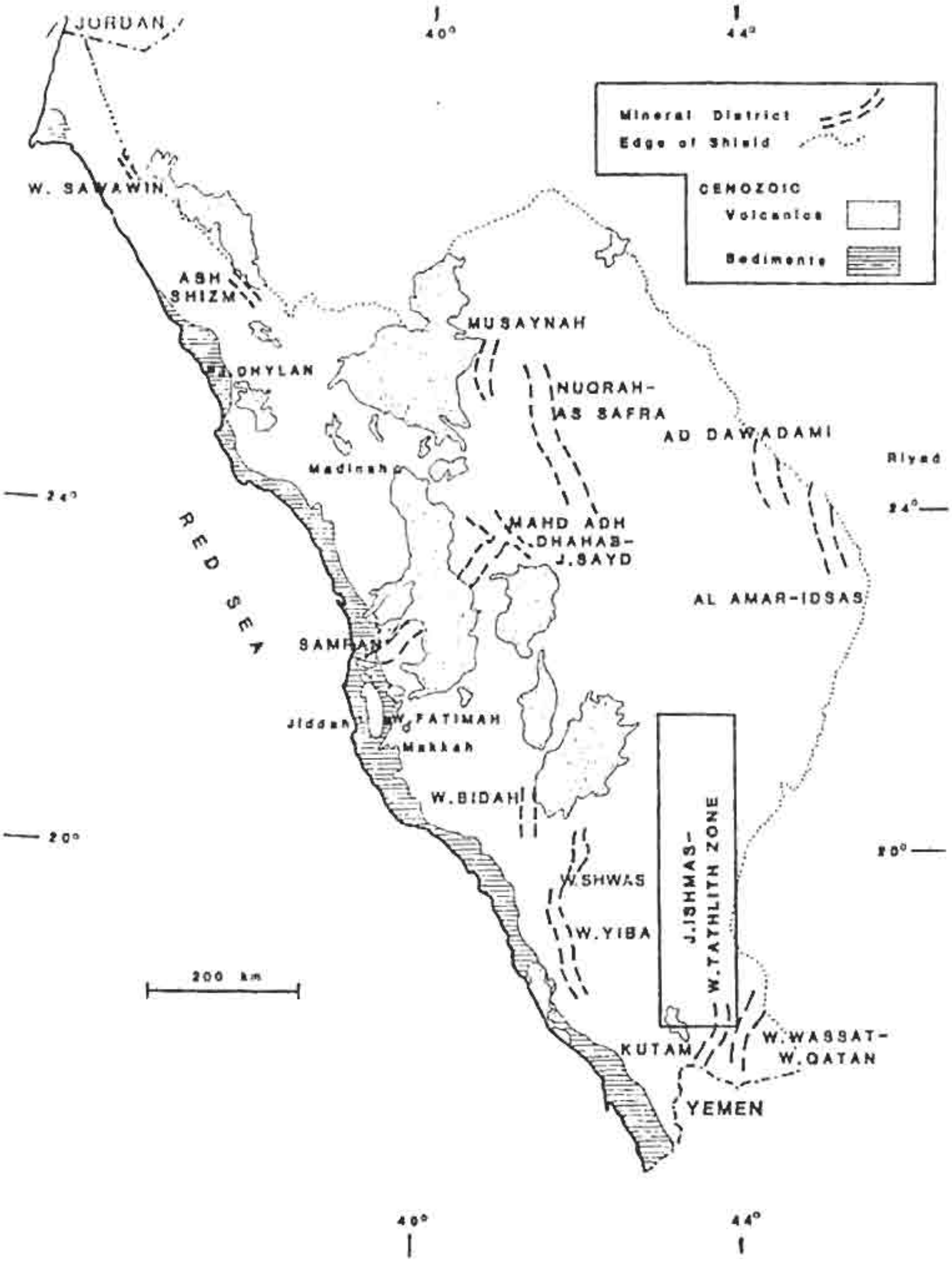


Fig. 3 - Lithostratigraphy of the Hijaz, Asir, and Afif terranes of the Arabian Shield (modified after STOESER and CAMP, 1985). Sedimentary: Ep = epicontinental, M = molasse, SM = shallow marine, ST = subaqueous (partly turbidites), VW = continental shelf. Volcanic: B = basalt, B-high-K basalt, B-F = bimodal (basalt/felsic), I = intermediate, R = rhyolitic. Plutonic: Gb = gabbro, Di = diorite, Tn = tonalite, trondhjemite, Gd = granodiorite, Gr = granite, AGr = alkali granite.

with only traces of Au, Ag are related to minor felsic pyroclastics and local rhyolite domes in the upper section of thick piles of low-K tholeiitic basalts. More calc-alkaline components are reported in the W. Shaws area, where some primary stockwork occurrences contain promising gold grades in the gossan. Gold enrichment also occurs in late remobilized veins of the W. Bidah belt, namely (Mamilah) within sheared packages containing abundant hematite jaspilite lenses. In the intervening, elongated Ablah graben epiclastic sediments are host to low-sulphur copper ores of little economic importance (W. Yiba, J. Sarbon).

2. Central Arabian-Nubian Shield (Figs. 1, 2, 4 and Tables A - 1, A - 2): this area is characterized by several mineralized clusters including economically significant, partly gold-rich massive sulphide ores. The deposits are genetically related to the main cycle (800-700 Ma) of arc/oceanic back-arc basin growth, and typically lie along the main suture zones (J.Sayid, Samran, Ariab, Ash Shizm districts). The stratabound ores are associated with large stratovolcanoes floored by immature island arc tholeiites evolving upwards to thick, more calc-alkaline, facies differentiated felsic successions reflecting a mature stage of ensimatic arc development. The mineralized horizons lie in the upper section of the felsic piles, often near rhyolite domes, and are unconformably overlain by the products of younger (< 700 Ma) intracratonic extensional volcanism and sedimentation (Shammar, Murdama, Awat sequences). The orebodies comprise large tonnage, low grade Cu-Zn (Au, Ag)-bearing lenses of pyrite preserving relict collomorphic fabrics (J. Sayid, Ariab) in a dominantly silica-carbonate (chlorite) gangue. The lenses are underlain by copper-rich discordant pipe-stockworks and veins (J. Sayid) associated with "mafic" hydrothermal alteration products such as Fe-Mg black chlorite, talc, tremolite-actinolite, locally chromite (Ariab), and showing increasing contents of silver and gold (tellurides, selenides). At Ariab, the introduction of gold as tellurides and of Ag-rich gold during a peculiar phase of silica-barite metasomatism is reported to supercede deformation, shearing and recrystallization of early sulphides. In the J. Sayid district, to late introduced tellurides is also assigned (AFIFI et al., 1988) part of the important gold enrichment in the fissure-bound deposit of Mahd and Dhahab, whose lead model age (685 Ma) is younger than J. Sayid stratabound ores (750-720 Ma). The Mahd adh Dhahab vein-type deposit is hosted by a hydrothermally altered (talc, carbonate) sequence of distal felsic pyroclastics and ash fall sheets grading in the footwall to andesites, and unconformably overlain by younger volcanic agglomerate, tuff, breccia. The ore emplacement is apparently controlled by a north-trending ancient extension zone and exhibits close analogies with the younger Al Amar-Umm ash Shalahib deposit in the easternmost Arabian Shield (J. P. MILESI and G. POUIT, in POUIT et al., 1989).
3. Eastern Arabian Shield (Figs. 2, 4 and Table A - 2): several small to medium size deposits (Nuqrah, As Safra, Sha'ib Lamisah, Al Masane-Halahila, Kutam) are

Fig. 4 - Mineral districts of Saudi Arabia (modified after RIOFINEX, 1977).


JORDAN
40°
44°
Mineral District
Edge of Shield
CENOZOIC
Volcanics
Sediments
W. SAWAWIN
ASH SHIZM
MUSAYNAH
W. DHYLAN
NUQRAH-AS SAFRA
AD DAWADAMI
Riyad
Madinah
24°
24°
MAHD ADH DHAHAB-J.SAYD
AL AMAR-IDSAS
RED SEA
SAMRAN
Jiddah
W. FATIMAH
Makkah
W. BIDAH
20°
20°
W. SHWAS
W. YIBA
J. ISHMAS-W. TATHLITH ZONE
200 km
KUTAM
W. WASSAT-W. QATAN
YEMEN
40°
44°

located along the western margin of the Afif continental microplate. These deposits differ significantly from those of the Arabian-Nubian Shield central ensimatic core. Host sequences are andesite-dominated, with an upward increase of felsic pyroclastics and domes, abundant carbonaceous-pyritic shales, dolomitic marbles and are covered by a thick blanket of black shales and explosive volcanism products. The deposits are mostly stratiform, zinc-dominated (Cu, Pb, Ag) and characterized by the presence of Cu-Sb-Pb(Ag) sulphosalts besides Bi-Ag tellurides and sulphides. Copper-rich stockworks and veins (As Safra, Kutam) are probably generated by late remobilization in tectonized zones. Ba-Mn-Zn-Ag stratiform deposits hosted by high-grade metamorphosed sediments (Ash Shaib, Hanash) show analogies with the Abu Samar ores in Sudan (Table A - 1) of sedex type according to EL SAMANI et al. (1986). A further variation in deposit style is observable in the southeastern part of the Arabian Shield and in the adjacent Sa'dah area (Yemen) where Ni(Co, Mo)-bearing massive pyrite ores represent a typical feature of the Arabian-Nubian Shield domain (POUIT et al., 1989). In the Ar Rayn terrane, the Al Amar deposit group (Al Amar, Umm ash Shalahib, Khnaiguiyah) is hosted by a sequence of polyphase felsic explosive volcanism products, comprising carbonate beds and extensive subconcordant sheets of hydrothermal alteration (pyrite, silica, carbonate, talc, chlorite, epidote). In the footwall, intermediate-mafic tuffs contain Zn, Cu, Pb anomalies in pyritic, stratiform alteration zones. Significant concentrations are mostly localized in the upper felsic horizons, in the form of stockworks and veins surrounded by extensive K, Ba, Si, Mn alteration envelopes. The Al Amar zinc-gold (Cu) deposit, controlled by a fault zone with Najd trend, is comparable with Mahd adh Dhahab (POUIT et al., 1989).

4. Eastern Desert of Egypt, Eritrea-Tigre, Wollega (Fig. 1 and Tables A - 1, A - 3): in the Eastern Desert, the Shadli andesitic metavolcanics host a group (Umm Samiuki) of small polymetallic deposits characterized by a Zn(Cu, Pb, Ag) metal assemblage comparable with some massive sulphide ores of the eastern Arabian Shield. Associated are several Algoma-type BIF deposits, also known in the adjacent Midyan (Saudi Arabia) terrane. In Eritrea-Tigre, stratabound Zn-Cu ores are related to andesite-dominated volcanics, varying from lenses lying in wide zones of epidote-carbonate alteration (Embaderho) to more felsic, barite-lead enriched deposits at the transition with the overlying metasediments (Debarwa, Adi Nefas). Copper-rich stockworks (Adi Rassi) and banded magnetite quartzites (Agametta) are also present. In Wollega, minor copper (Zn) anomalies are related to abundant magnetite quartzites with barite beds, pyritic-carbonaceous shales and blue quartz porphyries (Kata). Significant polymetallic suphide ores seem to be absent.

GOLD ORES

1. Nubian Shield, Wollega (Fig. 1, Tables A - 1, A - 3): the majority (70%) of the known mineral deposits and occurrences in the Nubian Shield are of dominant gold. True gold potential is unknown, but modern reserves of primary gold could confidently

be estimated at several tens of metal tons (20 t Au only in the Red Sea Hills province of Sudan). From north to south, the following types of deposits (excepting Ariab) can be recognized.

- Dyke type gold, i.e. auriferous quartz-pyrite-Zn(Cu) stockworks in late extensional felsic and mafic dykes of the northern Eastern Desert of Egypt (Umm Mongul, Abu Marawat).
- Shear zone gold: disseminated and vein quartz (carbonate) gold ores in the central Eastern Desert are related to shear zones and thrust faults mostly controlled by Najd deformation (SULTAN et al., 1988). The mineralizations (El Sid, Umm Rus, Barramiya, Hamash, Angaliya) are hosted by sheared and hydrothermally altered lithologies such as propylitized metavolcanics, graphitic mylonitic schists, listwaenitized serpentinites, silicified and sericitized granitoids. Besides pyrite and arsenopyrite, the mineral assemblage contains chalcopyrite, tetrahedrite, minor sphalerite, galena and cinnabar. In the Red Sea Hills of Sudan, a solid group including gold deposits partly re-evaluated for mining (Gebeit, Abirkatib, Nigeim, Kamoeb) is distributed along the mostly north-trending "braided" shear zones (Hamisana, Oko, Abirkatib) containing greenschist to amphibolite facies tectonites lithologically similar to those of the Eastern Desert, and showing comparable hydrothermal alteration patterns. The auriferous mineral assemblage comprises pyrrhotite, pyrite, arsenopyrite, minor chalcopyrite and scheelite, and traces of galena, sphalerite, tellurides, wolframite, cassiterite. In Eritrea-Tigre, the western gold ores (Ugaro, Barka-Anseba) are shear zone-related in the proximity of Baraka lineament. The eastern ores (Hamasien-Asmara group) are likely controlled by late veining and hydrothermal activity near the batholitic intrusions, and probably predate the emplacement of undeformed younger granites.
- In Wollega, small gold deposits are hosted in volcano-sedimentary belts characterized by the development of amphibolite grade mylonitic foliation (Birbir). Gold is contained in chalcopyrite-pyrite-tourmaline quartz veins and in arsenopyrite-bearing micropegmatite veins grading to barren tourmaline pegmatites (Ondonok, Laga Bagudu, Tulu Kapi-Ankori, Sudanese border area).

2. Arabian Shield (Figs. 4,6; Table A - 2): in the Arabian Shield gold is abundant in some discordant orebodies of the massive sulphide districts (Mahd adh Dhahab with estimated 70 tons of gold, Al Amar) as well as in some gossans (Al Hajar). Apart from these occurrences, in the case of Mahd adh Dhahab representing a very important individual concentration, the number of promising gold prospects in the Arabian Shield is reduced with respect to the Nubian Shield. Gold occurrence is restricted to the Nabitah and Al Amar suture zones and orogenic belts. The types of deposit correspond to gold-bearing quartz vein stockworks in granitoid intrusions (Sukhaybarat), auriferous listwaenites at the border of tectonitic serpentinite massifs along the Nabitah and Al Amar suture zones, and gold veins within the J. Ishmas-W. Tathlith northerly shear-fault zone (WORL, 1980; Fig. 6). In the latter zone, the emplacement of gold-enriched quartz veins predates Najd faulting, whereas in the

mineralized clusters at the intersection of the main fault with the Najd faults Ag, Cu, Zn, Pb sulphides become predominant.

ORES IN OPHIOLITES AND MAFIC-ULTRAMAFIC COMPLEXES (Figs. 1, 2 ; Tables A - 1, A - 2, A - 3)

Back-arc ophiolites as part of preserved island arc/back-arc basin systems are recognized in the two principal arc-arc suture zones of the Arabian-Nubian Shield (Allaqi-Onib-Yanbu, Nakasib-Bir Umq). The ophiolites have harzburgite-type mantle-gabbro section, and contain exploitable high-Cr, PGE (Ru, Os, Ir)-bearing podiform chromite. The observed presence of depleted mantle sequences, low-Ti gabbroic complexes, wehrlite rather than troctolite, and podiform chromite with PGE-enrichment influenced by primary magmatic fluids suggests generation of back-arc/arc crust above the same subduction zone (NASSIEF et al., 1984; PEARCE et al., 1984b; PRICHARD and LORD, 1988). Podiform chromite is also exploited at Ingessana (Sudan) where a sliver of marginal basin ophiolites marks the western boundary of the Wollega greenschist belts with the African craton. In the dismembered Egyptian ophiolites several chromitite varieties are associated with magnesite, steatite, antophyllite asbestos and vermiculite along highly tectonized shear zones. Likely similar chromitite blocks are embedded in a sheared serpentinite matrix at Al Amar. Cyprus-style pyrite (Cu, Zn) showings in ophiolite extrusives (pillow lavas) are rare (Bir Umq, Tuluha).

The mafic-ultramafic rocks aligned along the Nabitah, Baraka and Tulu Dimtu (Dimitri) suture zones are not true ophiolites. The Nabitah suture, considered as a terrane boundary with sharp isotopic and structural discontinuity (HARRIS et al., 1990) contains chromite-free tectonitic serpentinite masses which are not normal ophiolites according to STOESER and STACEY (1988). Likely similar are the serpentinite slices carrying uneconomic chrisotile asbestos, garnierite, magnesite (chromite) of the Baraka lineament, separating the Haya and Eritrea-Tigre terranes. The Tulu Dimtu (Dimitri) suture is defined by an alignment of oval-shaped ultramafic-mafic bodies of serpentinized dunite, wehrlite, clinopyroxenite, olivine gabbro, hornblende gabbro and hornblendite locally preserving a zoned structure. These complexes, showing LREE-enriched geochemical patterns unlike normal ophiolites, host Pt-Fe mineralizations (Yubdo) with high (Pt+Pd)/(Ru+Os+Ir) ratio accompanied by high Pt/Pd ratio, characteristic of the Alaskan-type PGE ores. Also indicative of this setting are the associated, recently discovered Gimbi-Dalati Fe-Ti-apatite occurrences in hornblendites at the periphery of an oval intrusion of gabbro-anorthosite, and the presence of Fe-Ti enriched pegmatoids. In the northwestern Arabian-Nubian Shield several coexisting older (metamorphosed) and younger mafic-ultramafic complexes contain Cu-Ni and Fe-Ti (V, apatite) mineralizations (Abu Swayel, El Gencina, Gabbro Akarem, Abu Dahr, Umm Effein, Hamra Dome in the Southern Eastern Desert of Egypt; W.Kamal-W.Murattiyah and W.Hayyan-W.Qabqab in Saudi Arabia). Some of these complexes are considered to be emplaced along deep-seated fracture zones, possibly continental extensions of transform faults (MITCHELL and GARSON, 1981).

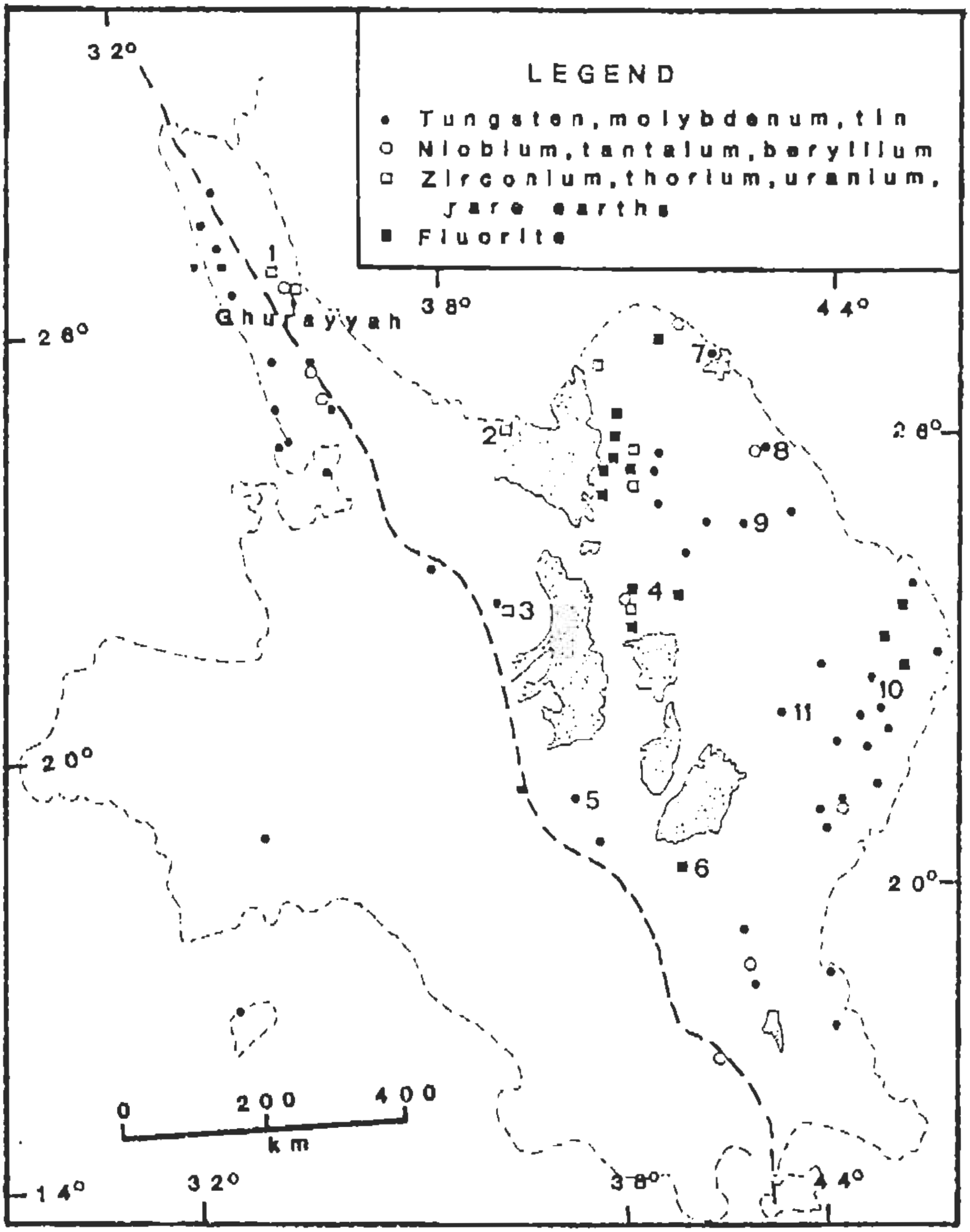


Fig. 5 - Mineral occurrences and geochemical anomalies associated with late felsic plutonism in the Arabian-Nubian Shield (modified after STOESER and ELLIOTT, 1980). Main occurrences in Saudi Arabia: 1) J. Tawlah, 2) J. Hamra, 3) Umm al Birak, 4) J. Sayid, 5) Jabalat, 6) Ablah, 7) J. Akash, 8) J. as Silsilah, 9) Baid al Jimalah, 10) J. Thaaban, 11) Bir Tawilah.

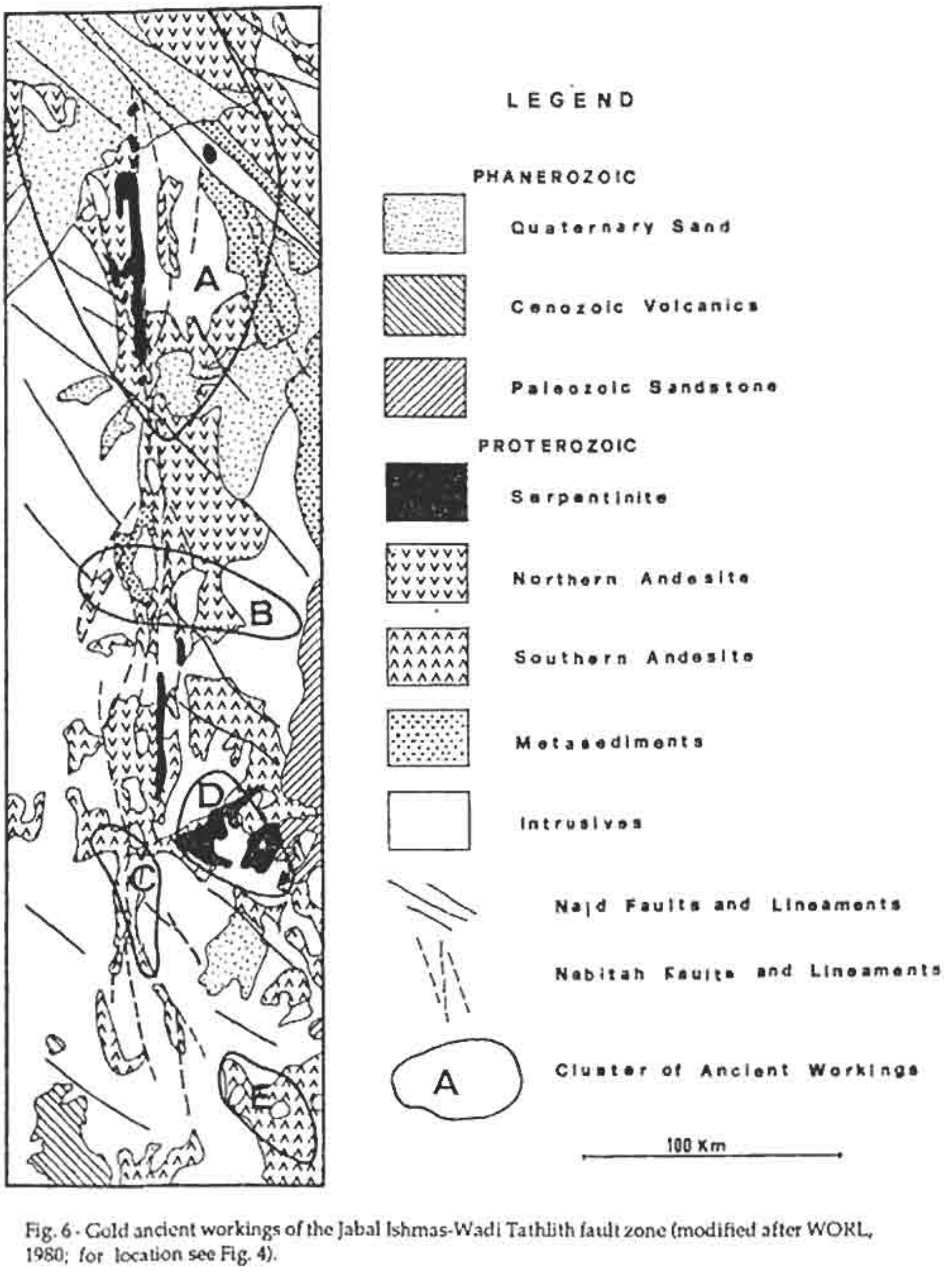


Fig. 6 - Gold ancient workings of the Jabal Ishmas-Wadi Tathlith fault zone (modified after WORL, 1980; for location see Fig. 4).

ORES RELATED TO LATE FELSIC PLUTONISM (Figs. 1, 5; Tables A - 1, A - 2, A - 3).

This group of mineralizations is well-studied, in particular in Saudi Arabia, and some excellent reviews are available (JACKSON and RAMSAY, 1986; DRYSDALL et al., eds., 1986). Known rare metal ores related to the late felsic plutonism are abundant in the Arabian Shield and Eastern Desert of Egypt, becoming rare in the remainder of the Nubian Shield and in Wollega. The high-level intrusions of specialized and mineralized granitoids cluster within zones of extension and deep crustal lineament reactivation generated after terrane accretion but before Najd faulting. However, several ore enrichments are observable at the intersection with the Najd faults. JACKSON and RAMSAY (1986) define in the Arabian Shield four groups of specialized granites and ores, and namely the alkali granite, alkali-feldspar syenite, alkali-feldspar granite and monzogranite-granodiorite associations. Considering the type and distribution of the mineral occurrences in the whole Afro-Arabian domain, we can recognize two separate metallogenic zones.

(1) Western Arabian Shield, Eastern Desert of Egypt: the western Arabian Shield contains all the deposits of the alkali granite and alkali-feldspar syenite associations, characterized by geochemically comparable mineralizations (Zr, Nb, REE, U, Th, fluorite). In the central and northeastern areas the rare metal orebodies (J.Sayid aplite-pegmatite, Umm al Birak microgranite, J.Hamra silexite and pegmatites) display high absolute contents of REE, LREE-enrichment and negative Eu anomaly. Abundant are fluorite pipes (Ablah) and veins (Mahd adh Dhahab-J. Sayid, Zarghat-Hanakiyah-Nuqrah, J. Hamra). In the northwestern area (Midyan terrane) the Ghurayyah and J.Tawla mineralized leucomicrogranites show increased contents of Sn and Ta compared with J. Hamra, and a different REE pattern with low absolute contents of LREE, very high HREE and Y, markedly negative Eu anomaly (DRYSDALL et al., 1984). The genesis of these mineralized granitoids is assigned by DRYSDALL et al., (op.cit.) to high-T dry melting of island arc crust. More generally, JACKSON and RAMSAY (1986) maintain that the presence of Nb-Zr-REE-U-Th ores in the Arabian Shield is restricted to areas underlain by island arc crust. Another interpretation envisages for the Midyan alkali granites the generation of magma by partial melting in the lower crust in the presence of mantle-derived (fluorine) volatile phases (HARRIS and MARRINER, 1980). A sharp change of mineralization style is observable, according to DRYSDALL et al., in the Eastern Desert of Egypt where Nb-Ta-Sn(Be) mineralized apogranites such as Abu Dabbab, Nuweibi, Igla are found in a domain characterized to the north and southwest (Aswan) by significant continental crustal components (STACEY and STOESER, 1983; DIXON and GOLOMBEK, 1988). We observe however that, besides comparable tantalum grades (Abu Dabbab-Nuweibi vs. Ghurayyah-J.Tawla) some earlier, thrust-related Egyptian metasomatic ores (Abu Rusheid) share more than one feature with the Midyan ores, i.e. high Nb/Ta ratio, conspicuous contents of Zr, REE, U, Th, and HREE-enrichment with strongly negative Eu anomaly. A true change in style of the

Eastern Desert rare metal mineralization is observable in the northern extensional terrane underlain by continental-transitional crust (molybdenite-wolframite-fluorite veins), and in the south where along the Red Sea line some Egyptian (Homr Akarem, Zargat Naam, Gash Amer) and Saudi Arabian (Al Wajh, Sidarah, Jabalat, Wadi as Salile) deposits contain variable but significant amounts of Mo, Sn, W, Bi, Cu, Ag suggesting, as indicated by JACKSON and RAMSAY (1986, Fig. 6) for the southwestern part of the Asir terrane, the presence of continent-derived detritus in the island arc assemblage.

(2) Eastern Arabian Shield: this zone is very rich in rare metal mineralizations of a type consistent with the presence of evolved older continental crust and continent-derived detritus in the protolith. Well-represented are the alkali-feldspar granite and monzogranite-granodiorite associations, to which are related some economically significant vein and greisen deposits of cassiterite and wolframite (J. as Silsilah, Baid al Jimalah, Bir Tawilah, J. Akash) as well as some Mo-pyrite stockworks (J. Kirsh, J. Thaaban, Bir Tawilah p.p.). Base and precious metals (Pb, Zn, Cu, Ag, Bi, As, Au) are locally abundant. In the easternmost Ad Dawadami province the presence of Zn-Pb-Ag-Cu(Sn) metasomatic (Ar Ridayniyah) and Najd fault-controlled veins (Samrah) reflects a protolith of mixed island arc and continent-derived sediments from which the felsic magma is derived (JACKSON and RAMSAY, 1986). The same authors also observe that the eastern Arabian Shield represents the area with the greatest ore potential owing to the emplacement of the post-orogenic metalliferous intrusions into abundant, water-saturated low-metamorphic clastics filling pull-apart basins along faults of the strike-slip Najd system.

In the remainder of the Nubian Shield, examples of rare metal mineralized younger granites are known to the authors only NW of the Baraka-Qala en Nahl ultramafic-mafic alignment, in the transitional domain between the Nubian Shield and the western Mozambique Belt gneisses (Fig. 1). The wolframite (cassiterite, scheelite, molybdenite, fluorite) ores carried by younger specialized granites in the high-grade gneisses of the Abu Samar-Derudeb region (J. Eyob) and in the Middle Pan-African granulites of Sabaloka strongly differ in age and composition from the Bayuda Desert mica pegmatites (630 Ma old) belonging to the group of the northwestern Mozambique Belt pegmatites outcropping farther south (see next section). In Wollega, alkali granites and pegmatites anomalous in Mo, Sn, Be are rare and apparently devoid of economic significance.

WESTERN DOMAIN (Fig. 1; Table A - 3)

The complex progression of suturing events in the microplate collage of the Afro-Arabian domain provides the rationale to explain the difficulties in reconstructing both the polyphase collisional pattern of the western Nubian Shield terranes against the African craton, and the interconnections between the Nubian Shield and the northwestern branch of the Mozambique Belt, as well as the lack of general consensus in the existing geological interpretations. From the Bayuda-Nubian Desert southwards, two main lithotectonic units are involved in the west-vergent Mozambique Belt collisional chain: (a) a segment of continental gneisses and migmatites, with N-NE foliation trends, that are part of the eastern foreland of the African (East Sahara) Craton, preserving Late Archaean to Middle Proterozoic relict ages but strongly affected by Late Proterozoic structural overprinting and isotopic resetting; (b) a Late Proterozoic (Early Pan-African?) sedimentary unit of continent-derived shallow-shelf deposits resting upon the foreland gneisses and apparently continuous southward with the quartzites and marbles coating the eastern edge of the Tanzanian craton in western Kenya. We remark that facies-equivalent quartzo-feldspathic detritus is largely recognized at the base of the volcano-sedimentary succession in the Arabian-Nubian Shield.

Unit (a) is devoid of metallic mineralizations, in that differing significantly from the northeastern limb of the Tanzanian craton in western Kenya, which replaces to the south the East Sahara Craton as foreland to the Late Proterozoic Mozambique thrust belt. The Tanzanian craton is relatively young, the east-trending granite-greenstone terranes lacking ages older than 2800 Ma (BELL and DODSON, 1981). Dominant features are 2500 Ma old granite-granodiorite, an abundance of andesite-rhyolite compared with other greenstone belts (DAVIS and CONDIE, 1977), the low metamorphic grade, and a metallogenic pattern characterized by economic gold and copper (zinc) reef and massive sulphide deposits, the latter being associated with banded iron formation and felsic tuffs (SANDERS, 1964; VAN STRAATEN, 1984). In contrast, in the East Sahara Craton basement only the development in Late Proterozoic of north-trending intracratonic rift basin systems parallel to the main Wollega trough (Nuba Mountains, South Kordofan, J. Rahib) and the subsequent magmatic and low-grade metamorphic events related to basin opening, compression and basin closure (750-500 Ma) allowed the emplacement of some mineral occurrences such as BIF, fluorite, uranium, galena, gold (Fig. 1). In Table A - 3 we also describe some belts of unknown age located in Southwestern Sudan and having promising ore potential (Cu-tourmaline ores of the Hofrat en Nahas belt).

Unit (b) hosts some syn- late kinematic pegmatitic bodies, mostly carrying REE, Y, Nb, U, Th in NE-Uganda and NW-Kenya, and exploited mica in the eastern Bayuda Desert (Sudan). The pegmatites are genetically related to a major event of anatexis and granulite-amphibolite facies metamorphism developed in the western Mozambique Belt collisional chain between about 700 and 650 Ma. As already mentioned, the 700 Ma old Sabaloka granulitic gneisses host a much younger, specialized granite complex bearing W, Sn(Mo) disseminated ores.

SOUTHERN DOMAIN (Fig. 1; Table A - 4)

The southern domain is composed of a mosaic of crustal blocks, likely evolved independently in Late Proterozoic, separated and displaced by a system of regional NW-trending strike-slip faults active since the Precambrian.

The southern outcrops (Adola, Bur) have features which may be correlated with those exhibited by the differentiated eastern main trunk of the Mozambique Belt. The 150 km-long, east-vergent Adola belt, situated east of the Kenya - Southern Ethiopia central granulite root zone, witnesses for a complex lithostratigraphic and magmatic evolution (WARDEN and HORKEL, 1984) comparable under several aspects with that characterizing the east (SE-) vergent Namama belt in Eastern Mozambique, flanked to the west by the granulitic Lurio chain (CADOPPI et al., 1987). Available radiometric data for SE-Ethiopia and N-Kenya (WOLDE, 1987; KRÖNER et al., 1989; KEY et al., 1989) seem to suggest that Adola is somewhat younger than the "Kibaran" (~1000 Ma old) Namama belt. However SACCHI and CADOPPI (1987) in agreement with previous statements (WARDEN and HORKEL, op. cit.) consider both the Adola and Namama belts as Upper Proterozoic examples of widespread aborted rifting in a regime of limited lithospheric mobility, where the opening of basins floored by "near-ophiolitic" greenstones was soon followed by basin closure and obduction, without formation of subduction-related calc-alkaline volcano-plutonic suites. The metallogenic signature is basically similar. However, economic grade tantalum pegmatites are far more frequent in the Namama belt and, conversely, the gold potential is much higher in Adola. Disseminated Fe(Cu,Zn) sulphide ores are known in the Adola greenstone complex, but no typical BIF. Moreover, the mineral assemblage of the primary gold mineralizations, including tellurides (Lega Dembi) is observable in a number of deposits of the ArabianNubian Shield.

The Bur region contains high-tonnage BIF deposits belonging to a geological setting probably older than Late Proterozoic. The polymetamorphic Bur basement is affected by a long-lasting metamorphic and magmatic overprinting, coming to an end in very Late Pan-African times. Since the granulitic mineral assemblages as yet recognized in the Bur rocks were generated at about 700 Ma, a comparison is suggested (LENOIR, pers.comm.) with the similarly evolved Eastern Granulite complex of Kenya-Tanzania (ANDRIESSEN et al., 1985; MAKOBO et al., 1985). In the Bur high-grade gneisses, also noteworthy are the effects of late Pan-African metasomatic processes carrying uranium and other metals, and considered by some workers the result of fertilization of the lower crust by fluids released from the upper mantle (ANDREOLI and HART, 1986).

The Northern Somalia-Yemen block records the lineament-controlled transition of the ensimatic Arabian Shield to a zone underlain by a continuous, older continental crust. The boundary is neither sharp nor homogeneously defined. A regional N-NW oriented discontinuity separates two domains. In the east, the ensialic Sa'dah-Lawdh-Al Mukalla-Erigavo belt contains gold (Cu) ores in intraplate rift-related greenstones, and tin-bearing veins and pegmatites related to younger granites. The western volcano-sedimentary belts of Yemen-NW Somalia are part of the less mineralized southern periphery of the Arabian-Nubian Shield, showing barite beds as well as disseminated, vein and skarn-type Cu (magnetite) bodies as in Wollega, but lacking iron formation and gold. The transition to the continental gneisses of the Mozambique Belt, marked in Wollega by a northerly alignment of Alaskan-type mafic-ultramafic bodies, occurs in Yemen and Northern Somalia through a characteristic sublatitudinal belt of ensialic gabbro-syenite-carbonatite carrying Fe-Ti (V, apatite, PGE), Ni-Cu(Co), Mo(Bi), Nb, REE, Zr, Ba, Sr mineralizations. We observe that in the north a Fe-Ti gabbro and shonkinite belt parallel to the Red Sea line (STOESER and ELLIOTT, 1980) intervenes between the Asir and Eritrea-Tigre terranes. Moreover, the NE-trending Tsehafi Emba Ridge at the southern edge of Tigre is also composed of sheared gabbros and syenites (MORTON in CHEWAKA and De WIT, 1981) suggesting the presence in the southern Red Sea-Gulf of Aden region of a system of Late Proterozoic mafic-alkaline belts emplaced along lines of crustal weakness later exploited by the Tertiary rifting. The gneissic basement of Northern Somalia and Harar is characterized by the presence of abundant pegmatite fields, carrying beryl and columbo-tantalite in Somalia. In the Harar inliers, mica and garnet were exploited from pegmatites bearing REE, Y, Th, U, Zr(Be, Mo), locally associated with phlogopitic carbonatite dykes. NW of Hargeisa the Somalian basement hosts a group of apparently impersistent gold-bearing showings of uncertain (thrust/shear bound?) genetic type.

SYNOPSIS

A review of the Precambrian mineralizations and related mining/exploration activity in Northeast Africa and Arabia is presented in the form of four descriptive tables (Appendix A). A discussion of the table contents is exposed in the preceding sections based on current geotectonic schemes. The resulting picture of mineral deposit distribution, types, economic importance and geological controls can be summarized as follows.

1. AFRO-ARABIAN DOMAIN

ARC VOLCANISM-RELATED ORES

- Low tonnage stratiform pyrite-Cu(Zn) lenses in dominantly mafic, primitive arc volcanics.
- High-tonnage stratabound pyrite-Cu, Zn(Au, Ag) bodies and discordant Cu-rich stockworks, related to thick felsic piles in more evolved ensimatic arcs, preserved along ophiolite-bearing suture zones. Likely younger but space-time connected gold enrichment, either associated with the introduction of tellurides, silica, barite after early sulphide deformation or as important, fracture-controlled individual concentrations.
- Small to medium size, Zn-dominated pyritic (Ag, Pb, Cu, Au) stratiform ores in calc-alkaline volcanics of active continental margin setting. Rare sedex-type stratiform Ba-Mn-Zn-Ag mineralizations in eugeosynclinal sediments with minor volcanism.

Gold-enriched epithermal vein deposits in thick felsic explosive/subaerial volcaniclastics with extensive hydrothermal alteration.

- In the southernmost Arabian Shield/N-Yemen: Ni(Mo, Co)-bearing massive pyrite bodies. Stratiform barite beds, magnetite quartzites and Cu (magnetite) disseminated, vein and skarn-type bodies, of minor economic significance, in the volcano-sedimentary sequences of the ensialic southern periphery of the Afro-Arabian domain.

GOLD ORES

- In the Nubian Shield, mostly shear zone gold. Disseminated and vein-type in dilational structures, with levels of ore emplacement shallowing from south to north (mineral indicators pegmatitic tourmaline, scheelite-wolframite-cassiterite, tetrahedrite-cinnabar).
- In the Arabian Shield, important individual concentrations related in space and time to massive sulphide deposit clusters.

Mostly in the eastern Arabian Shield: "porphyry" gold in granitoid intrusions, listwaenitic gold in tectonitic serpentinite massifs, veins in shear/fault zones.

ORES IN OPHIOLITES AND INTRUSIVE MAFIC-ULTRAMAFIC COMPLEXES

- Podiform chromite (PGE) in harzburgite-type back-arc ophiolites. Sheared chromitites in tectonitic mélanges, associated with asbestos, magnesite, steatite, vermiculite (garnierite), the latter occurrences also found in sheared serpentinites devoid of significant chromite.
- Alaskan-type Pt-Fe, Fe-Ti(V, apatite) and Cu-Ni(Pt, Au) mineralized intrusive mafic-ultramafic complexes, emplaced in rifted/extensional continental margin settings.

ORES RELATED TO LATE FELSIC PLUTONISM

- In western Arabian Shield: alkali granite and alkali-feldspar syenite associations, Zr-Nb-REE-U-Th-fluorite disseminated ores, in areas underlain by island arc crust. Grading to Nb(Zr, REE, U, Th) and Nb-Ta-Sn(Be) mineralized apogranites, as well as to Mo, W, Sn, Bi, CU, Ag veins in areas (Egypt, Arabian Red Sea coastal region) underlain by transitional-continental crust or containing abundant continent-derived detritus in the protolith.
- In eastern Arabian Shield: alkali-feldspar granite and monzogranite-granodiorite associations, economically significant vein and greisen deposits of cassiterite-wolframite, Mo-pyrite stockworks, locally abundant base and precious metals. Presence of evolved older continental crust and continent-derived detritus in the protolith, availability of meteoric fluids from water-saturated clastics filling basins along Najd faults.

- In the central-southern Nubian Shield and Wollega, isolated occurrences of W, Mo, Sn, F granite-related ores, mostly (Wollega) devoid of economic significance.

2. WESTERN DOMAIN

- High-grade gneisses and migmatites of the East Sahara Craton foreland: barren. Greenschist facies volcano-sedimentary belts infolded with the gneisses, correlated to the Late Proterozoic development of an intracratonic rift basin system parallel to the north-trending main Wollega trough. Occurrences of BIF (magnetite quartzites), fluorite, uranium, galena, gold.
- Metasedimentary unit highly deformed and thrust onto the foreland gneisses (northwestern branch of the Mozambique Belt): syn-late kinematic pegmatites of mid Pan-African age, carrying REE ,Y, Nb, U,Th in NE-Uganda and NW-Kenya, and mica (exploited) in the Bayuda Desert of Sudan.

3. SOUTHERN DOMAIN

- Adola ensialic rift zone: major zone of aborted rifting related to a major north-trending discontinuity dividing the main trunk of the Mozambique Belt of Kenya into two tectonic zones with opposite vergence. High gold potential (alluvial and primary), presence of ore-grade tantalum pegmatites, some tungsten and disseminated Fe(Cu, Zn) sulphides in greenstones. Lateritic nickel in altered ultramafics.
- Bur region: high-tonnage BIF in an older continental gneissic sequence metamorphosed to granulite-amphibolite facies in mid Pan-African. Relict granulite and related metamorphic-metasomatic mineral assemblages comparable with some parageneses of the coeval Eastern Granulite complex of Kenya-Tanzania. Late Pan-African metasomatic alteration (episyenitization) associated with modest concentrations of U-Th(Fe, Ti, Zr, REE, Pb, Zn, Cu).
- Northern Somalia-Yemen block: gold and tin occurrences in the eastern, N-NW oriented Sa'dah-Lawdh-Al Mukalla-Erigavo belt. E-NE trending belt of ensialic gabbro-syenite-carbonatite bearing Fe-Ti (V, apatite, PGE), Ni-Cu(Co), Mo(Bi), Nb, REE, Zr, Ba, Sr mineralizations, localized at the boundary between the Arabian-Nubian Shield and the Mozambique Belt gneisses and belonging to a system of Late Proterozoic mafic-alkaline belts emplaced along ancient crustal weaknesses of the southern Red Sea-Gulf of Aden Region, later exploited by Tertiary rifting. In the Somalian and Harar basement, presence of subeconomic rare metal pegmatites. NW of Hargeisa, possibly thrust/shear bound gold-bearing showings.

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APPENDIX A - MINERAL DEPOSITS AND OCCURRENCES IN THE PRECAMBRIAN OF NORTHEAST AFRICA AND ARABIA.

Table A - 1. NUBIAN SHIELD

Eastern Desert of Egypt (Northern, Central, Southern: NED, CED, SED)

NED (north of the Qena-Safaga ENE-trending shear zone): contains rocks of continental to intermediate isotopic affinity (STACEY and STOESER, 1983; DIXON and GOLOMBEK, 1988). The role of Late Proterozoic rift tectonics is manifested by ENE fracturing and dyking (BENNETT and MOSLEY, 1987). Some authors (STERN and HEDGE, 1985; STERN et al., 1988) connect to the rifting episode (600 - 540 Ma) the Dokhan volcanics, Hammamat clastics and pink (Late Gattarian) granites besides felsic/mafic dykes. According to a different interpretation (EL-GABY et al., 1988) the Dokhan+Hammamat ensemble, together with calc-alkaline granites and younger mafic-ultramafic intrusions, pertain to a Cordilleran stage association.

CED: dominated by an ophiolite-island arc assemblage (>700-600 Ma) of mafic to intermediate metavolcanics (Shadli), related immature metasediments, gabbro, serpentinite, quartz diorite and granodiorite (RIES et al., 1983; STERN and HEDGE, 1985). Clastic sediments (high-grade gneisses) below the arc-ophiolite assemblage belong to a passive continental margin sequence that fringed in early Pan-African the previously rifted and thinned Middle Proterozoic crust of the East Sahara Craton (KRÖNER et al., 1988; SCHANDELMEIER et al., 1988). Collision events are responsible for the high strain pattern of CED, with thrusting and retrothrusting, N-NW directed nappe transport and formation of gneissic domes (Meatiq, G. Sibai, Hafafit; GREILING, 1987; GREILING et al., 1988). Significant is the discovery of a Pan-African (660 Ma) typical granulite facies for the gneisses exhumed in the exceptional frame of the Zabargad island (LANCELOT and BOSCH, 1991). Persistent deformation in CED is concentrated within a mostly NW-trending system of curvilinear, mylonitized belts decorated by serpentine, talc and graphite schists, separating relatively unstrained passive blocks or slices (BENNETT and MOSLEY, 1987).

SED: between the Hafafit dome and the newly defined W. Allaqi-Gerf-Onib-Sol Hamed ophiolitic suture, dissected by the Hamisana shear zone. Older ophiolite-island arc assemblage (800-700 Ma) underlain by amphibolite grade metasediments (STERN and HEDGE, 1985; KRÖNER et al., 1988; ZIMMER et al., 1987; MANKEL et al., 1987; STERN et al., 1989).

(a) ORES RELATED TO OPHIOLITE-ISLAND ARC ASSEMBLAGE

Very frequent occurrences of chromite in serpentinite belts of CED *and* SED. *Locally mined, output 1955-1979 less than 5000 t.* (EL RAMLY et al., 1970; IVANOV et al., 1973; AFIA and IMAM, 1979; CLARKE, 1983).
Podiform chromite (58% Cr_2O_3) in serpentinized dunite at Sudan border (W. Allaqi-G. Gerf suture). Cut by shear zones with magnesite, asbestos and steatite. Fine grained chromite (W. Ghadir) ore (35% Cr_2O_3) in sheared phyllonitic talc-rich variety (GARSON and SHALABY, 1976). Antophyllite asbestos and vermiculite in sheared serpentinite/pegmatite contact zone (Hafafit). In sheared serpentinites, lower Cr grades owing to increasing amounts of magnetite replacing chromite (TAKLA et al., 1975).

Umm Samiuki, Darhib, Hamata/Atshan Zn-Cu-Pb-Ag ores Fig. 1, n. 13 *(possibly G. Atawi, W. Allaqi). Umm Samiuki: 250.000 t grading 9.9-21.8% Zn, 1.04-4.35% Cu, 0.5-2.3% Pb, 260-1500 ppm Ag, 0.3-3.5 ppm Au.* (SHALABY and ROSSMAN, 1983; SHALABY, 1985). Strata- and shear-bound volcanogenic polymetallic deposits, hosted by thick, weakly metamorphosed Shadli metavolcanics (715 Ma Rb-Sr wr age; KRÖNER, 1985). Stratabound disseminated sulphides (up to 0.96% Zn, 0.41% Cu, 0.25% Pb) in lower sequences of andesitic-dacitic crystal tuffs (SHUKRI and SABER MANSOUR, 1980). Massive lenses of sphalerite, chalcopyrite, galena, magnetite, tetrahedrite, Ag-minerals along talc-(carbonate, tremolite-actinolite, pyrophyllite) decorated shear zones (IVANOV et al., 1973). Kuroko-type ores according to GARSON and SHALABY (1976), MITCHELL and GARSON (1981). EL-AREF et al. (1985, EL-GABY et al., 1988) describe the massive lenses in shear zones as mobilized products from primary disseminated ore.

G. El-Hadid, Umm Nar (Fig. 1, n. 5), *W. Kareim, Semna, and other occurrences in* CED. *Banded iron formation (total ore stock about 60 Mt, grading 37 to 69% Fe).* (AFIA and IMAM, 1979). *Contain traces (0.3 to 0.6 ppm) of gold* (SABET et al., 1976h).
Several dismembered lenses of Algoma-type BIF (magnetite-hematite-silicates) deformed and metamorphosed into greenschist facies. Layered alternances with chert/jaspilite. Locally sulphide-facies (G. El-Hadid, Umm Nar). More (Semna) or less strictly connected with island arc calc-alkaline andesite-dacite sequences of tuffs with intercalated basalt-andesite porphyritic flows, concomitant diorite intrusions (age range 715-615 Ma). Compared to W. Sawawin BIF in Midyan terrane, NW Saudi Arabia. (IVANOV et al., 1973; GARSON and SHALABY, 1976; SIMS and JAMES, 1984; EL-GABY et al., 1988)

(b) ORES IN MAFIC-ULTRAMAFIC INTRUSIONS

Abu Swayel (Fig. 1, n. 16). *85,000 t of Cu-Ni ore grading 2.85% Cu, 1.53% Ni, Co 450-1800 ppm (Au 16.17 ppm, Pt 9.33 ppm in one sample).*
Magmatic segregation pyrrhotite-pentlandite-chalcopyrite ore (bravoite, violarite, cubanite) in a lenticular mass of amphibolite (metagabbro). Probable sill (mantle-derived, 800 Ma old) intruding garnet-staurolite bearing metasediments with negative ε_{Nd} suggesting supply from older (Archaean to Early Proterozoic) continental source and evolution at an active continental margin (GARSON and SHALABY, 1976; WUST et al., 1987; KRÖNER et al., 1988).

El Geneina (SED, *180 km east of Aswan*). *Cu-Ni showings.*
Thrust slices of peridotite, pyroxenite, olivine-gabbro, metagabbro, diorite. Probably layered mafic/ultramafic intrusion within an ophiolite belt. Cu-Ni showings (malachite, garnierite gossans) in weathered ultramafics. (GARSON and SHALABY, 1976; MITCHELL and GARSON, 1981).

Gabbro Akarem (Fig. 1, n. 12). *Cu-Ni ore (Cu 0.7%, Ni 0.74%, Co up to 0.18%; very low traces of Au, Pt, Pd).*
Norite intruded by an ore-bearing (pyrrhotite, mackinawite, pentlandite, chalcopyrite, cubanite) assemblage of peridotite, plagioclase-peridotite, melanorite, pyroxenite. (SHALABY, in GEOL. SURV. EGYPT, 1974; BUGROV and SHALABY, 1973; GARSON and SHALABY, 1976). According to MITCHELL and GARSON (1981) layered complex intruded along deep-seated fracture zones, ENE-trending, possibly continental extensions of transform faults.

Abu Ghalaga (Fig. 1, n. 14), *Fe-Ti ore (proved reserves 2.5 Mt, probable up to 10 Mt, 36-41%* TiO_2*). Other occurrences: Abu Dahr, Umm Effein, Hamra Dome* (Fig. 1, n. 7).
Ilmenite-hematite (magnetite, chalcopyrite, pyrite) layers alternating with gabbroic matrix, at the top of a titaniferous gabbro stock likely intrusive in metavolcanics. (GEOLOGICAL SURV. EGYPT, 1974; GARSON and SHALABY, 1976). As for Gabbro Akarem, linked to transform faulting (MITCHELL and GARSON, 1981).

(c) VEIN - AND SHEAR ZONE GOLD (EL-RAMLY et al., 1970; SABET et al., 1976h)

Umm Mongul (Fig. 1, n. 1). *Group Umm Mongul-Umm Balad-Wadi Dib in* NED.
Dyke type gold. Quartz-pyrite stockworks within shattered dykes of quartz porphyry, felsite porphyry, mafic dykes (gold grades up to 15 g/t).

Fatiri, Abu Marawat, Semna (Fig. 1, n. 3). *In the Abu Marawat prospect, reported reserves* (MINING ANN. REV., 1990) *are 308,000 t grading 5.5 g/t Au, 63.2 g/t* Ag, *0.61% Cu, 2.28% Zn.*

Dyke-type gold at Semna and Fatiri (flatlying felsite porphyry dyke, 300 m long, 1-2 m thick). The Abu Marawat auriferous quartz veins average 5.8 m width, 6.2 g/t Au, 84 g/t Ag (Fin Vein) and 6.5 m, 4.4 g/t Au, 51.8 g/t Ag (C Vein, to a depth of 60 m). Maximum intersected width in the C Vein is 16 m grading 2.8 g/t Au and 70.9 g/t Ag (MINING ANN. REV. 1989, 1990).

El Sid (Fig. 1, n. 4). *Group Erediya-Atalla-El Sid. El Sid output (to 1958) 6.7 t of gold.* Shear zone gold, 900-1200 m along strike, 100 m wide, 500 m along dip. Quartz veins 3-6 m thick and swarms of parallel veinlets. Western contact of the Fawakhir granite with listwaenitized serpentinite through a band of blastomylonitic graphite schists. Metasomatic silicification, possible large tonnage sulphide impregnation veinlets. Pyrite, arsenopyrite, minor sphalerite with chalcopyrite inclusions, galena (model age 500 Ma), rare chalcopyrite, free gold (average grade 23 g/t Au), traces of Te, Bi, Sb, Ag. (EL BOUSEILY et al., 1985).

Umm Rus (Fig. 1, n. 5)
Ring-like gabbro to granodiorite intrusion through ferrogabbro, diorite, quartz diorite (615-573 Ma). Scapolite (actinolite, epidote, albite) alteration. In ferrogabbro, apatite-ilmenite-titanomagnetite assemblage and disseminated arsenopyrite, chalcopyrite, tetrahedrite, gold. Quartz-gold veins in silicified and pyritized granodiorite, stockpiled as ore. REE patterns suggest upper mantle derivation for gabbro and an island arc / continental margin setting for granodiorite. (KAMEL et al., 1987).

Barramiya zone (Fig. 1, n. 6) *including Talat Gadalla-Umm Samra group in thrust/shear zone, Dungash, Samut, Umm Ukab Rashid.*
Gold-quartz veins in graphitic schists. Possible large tonnage ore (12 to 24 g/t Au) in sheared gabbro, diorite (mined as ore at Samut), granite, metavolcanics.

Hamash (Fig. 1, n. 7)
Intense hydrothermal alteration controlled by sheared lithologies (silicified-sericitized granitoids, propylitized volcanics with disseminated copper ore, listwaenitized serpentinites, pyritization at depth). Veins of Cu-bearing pyrite, gold, chalcopyrite, tetrahedrite-tennantite, Pb-Zn-Ag. (HILMY and OSMAN, 1989).

Angaliya-Sukari-Umm Ud (Fig. 1, n. 10).
Shear zone gold. According to DARDIR and GREILING (1987) ore remobilized and concentrated by shearing (and metamorphism?) at Angaliya where the gold-bearing veins are parallel to and synchronous with low angle thrust zones. In the Wadi Garf area abundant listwaenites with impregnation of pyrite, chalcopyrite, talc, tremolite, axinite, serpentine, fuchsite, chromite and vein stockworks of quartz, carbonate, cinnabar and gold (SABET et al., 1976k).

W. Allaqi (Haimur)-Umm Garayat (Fig. 1, n. 15).
SE-trending veins with gold (up to 12-14 g/t), pyrite, arsenopyrite, chalcopyrite, probable tellurides. Also geochemical anomaly of Cu-Mo, reflecting a possible porphyry-tipe body at depth (geophysical anomaly). Within a sheared belt of graphitic schists, tectonized volcanics, inferred stratabound polymetallic sulphide ores. (GARSON and SHALABY, 1976; SHALABY, 1985).

(d) TIN, TUNGSTEN, MOLYBDENUM AND RARE METAL ORES RELATED TO LATE FELSIC PLUTONISM

Abu Hammad-G. Gattar/W. Dib, Abu Marwa (Mo,W) - Fig. 1, n. 2. *G. El Dob (Mo), W. Fatiri El Beida-Abu Kharif (W)* - Fig. 1, n. 3. (EL RAMLY et al., 1970).
Low grade, thin molybdenite-quartz veins in pink granites. Wolframite (p.p. hubnerite), quartz+mica, K-feldspar, fluorite veins (at Abu Hammad trending E-W to E-NE) in pink granites near mafic dykes and in Hammamat greywackes (Umm Bissila, Magrabiya).

Homr Akarem, SED (Fig. 1, n. 11). *Mo (0.14-0.61%, max. 2-4%)*. (BUGROV et al., 1973; SHALABY, in GEOL. SURV. EGYPT, 1974).
Pink granite intrusion in metasediments. Granite cut by fluorite and quartz veins, beryl pegmatites, traces of chalcopyrite, galena, molybdenite. In the metasediments, stockwork of veins with molybdenite (powellite), chalcopyrite, cassiterite, fluorite (beryl, topaz, Bi). South of Homr Akarem, only wolframite occurrences at Zargat Naam (mined) and Gash Amer on the Red Sea coast near Sudan border.

G. El Ineigi (fluorite), G. El Hudi (barite). (EL RAMLY et al., 1970; EL SOKKARY and ABDEL MONEM, 1977).
Fluorite is an abundant component of the rare metal mineralizations of CED, locally forming separate veins (Igla). At G. El Ineigi, quartz-fluorite (galena) vein in pink granite. The G. El Hudi barite (galena, sphalerite, chalcopyrite, pyrite) veins lie east of Aswan granite (with crustal signature).

Abu Dabbab (Sn 0.11%, Ta_2O_5 0.03%), Nuweibi (Ta_2O_5 0.015-0.018%), Igla (Sn-Be), El Mueilha (Sn,W) - Fig. 1, n. 8; 9. (DE KUN, 1965; BUGROV et al., 1973; GARSON and SHALABY, 1976; SABET et al., 1976 c, d, e; SABET et al., 1980).
Mineralized apogranites. Precursors are late-phase Gattarian granites, forming shallow intrusions not accompanied by pegmatites, characterized by widespread fluorine metasomatism and anomalous in W, Sn, Ta, Nb, Be, Mo, Li. Apogranites with disseminated rare metal ores derive from multistage metasomatic alteration of Gattarian granites, and form apical domes (Nuweibi, Mueilha) or stock-like bodies (Abu Dabbab, Igla) at the intersection of N/NW with E/NE faults (Abu Dabbab, Nuweibi) and in NW-trending shear zones (Igla). (SABET et al., 1976a, b).

Sn-Ta mineralization is associated with albite-lepidolite (fluorite, topaz, beryl) varieties, carrying cassiterite, tantalite, bismuthinite, columbotantalite, wolframite-scheelite (garnet, monazite, radioactive zircon, Mn-oxides, Pb-Zn sulphides and gold). (SABET et al., 1976c, d; KAMEL and EL TABBAL, 1980). Sn-Be (W) ores are concentrated in stockworks, greisen and quartz veins, with cassiterite, wolframite, scheelite, beryl (molybdenite, chalcopyrite, pyrite, galena). (SABET et al., 1976e; BUGROV et al., 1973; DE KUN, 1965).

Abu Rusheid (Nb_2O_5 *up to 0.14%,* Ta_2O_5 *0.016%, Nb/Ta ratio 8.75; Zr 0.3%, Sn).* (SABET et al., 1976f). *Umm Naggat (Nb » Ta).* (SABET et al., 1976g).
Sill-like Abu Rusheid "apogranitic" body of cataclastic-sheared and mineralized psammitic gneisses (continent-derived, carrying 1800-1600 Ma zircons; KRÖNER et al. (1988) of the Hafafit dome. The gneisses are dissected by folding/thrusting into major horses forming antiformal stacks (GREILING et al., 1988) and are in thrust contact with overlying phyllonitic mica-hornblende (garnet) schists with abundant slices of serpentinite and talc-carbonate rocks (HASSAN, 1973). Amazonite, albite, fluorite, Li-biotite+columbite (Sn-bearing), cassiterite, fergusonite, cyrtolite (radioactive zircon), beryl, xenotime, monazite, orthite, thorite. Late silicification, Fe-As-Cu sulphides, possibly gold. At Umm Naggat: cassiterite, columbite, thorite, zircon.

Beryl (emerald) mineralization (G. Zabara, Sikait, Umm Kabu).
Shear-bound mineralization according to DARDIR and GREILING (1987). At a regional contact psammitic gneisses-biotite schists within irregular pockets of glimmerites (whitish grey or black mica), coarse actinolite and talc-carbonate rocks. Emerald occurs either disseminated in glimmerites or in associated quartz veins (HASSAN, 1973).

Red Sea Hills, Sudan (Fig. 1)

Geotectonic domain developed earlier in the SE (STERN et al., 1989; Fig. 1) with a progression (870-700 Ma) of primitive arc suites, accretion of arc terranes (Haya, Gebeit-Gabgaba) along ophiolite-decorated massive shear zones (Oshib-Nakasib, Onib-Sol Hamed-W.Allaqi sutures), post-amalgamation calc-alkaline diorite-granodiorite plutonism. In the 700-550 Ma interval, later deformation concentrated along north-to NW-trending diffuse braided shear zones (Oko, Hamisana, Abirkatib), post-orogenic alkaline magmatism. (STERN et al., 1987; ALMOND and AHMED, 1987; KLEMENIC and POOLE, 1988).

(a) ORES RELATED TO OPHIOLITE-ISLAND ARC ASSEMBLAGE

Chromite (asbestos, etc.) occurrences in ophiolite ultramafics of Oshib-Nakasib, Onib-Sol Hamed (800 Ma), W. Allaqi-Gerf (740-730 Ma) sutures. (FITCHES et al., 1983; MANKEL

et al., 1987; ZIMMER et al., 1987).
Chromite pods in serpentinites of Oshib ultramafics (COTTARD et al., 1986). Chromite and asbestos occurrences at Sol Hamed (WHITEMAN, 1971). Chromite as cumulate layers in dunite interlayered with clinopyroxenite and gabbro, Onib ophiolite (KRÖNER, 1985; HUSSEIN et al., 1987). Chromite showings (WHITEMAN, 1971) at the Sudan-Egypt border (W. Allaqi-G. Gerf belt of serpentinites with podiform chromite and shear-bound magnesite, asbestos and steatite of southernmost Egypt).

Ariab district, Fig. 1 *(Oderuk-Ganaet n. 28, Hassai n. 29, Hadal Auatib n. 30). Massive sulphides+stock.works, several tens of Mt at 2% Cu, 1-3.8% Zn, 10 g/t Ag, 1-2 g/t Au* (COTTARD et al., 1986). *Gold-rich silica-barite ore (reserves 13 t Au) now mined in the gossan, planned production 250 kg/yr of gold* (MINING ANN. REV., 1990).
Massive sulphide deposits associated with gold deposits in silica-barite rocks within the Ariab-Arbaat greenschist facies volcano-sedimentary sequence of the steep-dipping, strongly folded and sheared Oshib-Nakasib suture, continuous with the Bir Umq suture of the Arabian Shield before Red Sea rifting (AYE et al., 1985; COTTARD et al., 1986). Main ore lenses intercalated in island arc acidic flows and tuffs at the top of a mafic volcanic pile adjacent to Oshib ultramafic package. Strong Cr-Ni enrichment in the basal mafic lavas, as well as high vanadium and Ti/V ratio in basalts interleaved with upper acidic volcanics (COTTARD et al., 1986; HOTTIN and ALOUB, 1990) suggest interference of arc and back-arc/intra-arc basin settings close to subduction zone (HAWKINS, 1980; SHERVAIS, 1982). Though associated with acidic volcanics, ores have "mafic" signature, and the presence of new-generated chromite in Cu-rich stockworks and hydrothermal alteration envelopes suggest (HOTTIN and ALOUB, 1990) gold leaching from Oshib listwaenites and Ariab-Arbaat mafic basal units. Metallogenic cycle developed prior to and during polyphase deformation and shearing throughout the Oshib-Nakasib suture: (1) deposition of massive pyrite with collomorphic cores (GROS et al., 1987) cemented by chalcopyrite, sphalerite, quartz, rarer tennantite, carbonate, barite; (2) deformation and recrystallization of sulphides and introduction of gold as tellurides; (3) further precipitation of silver-rich gold during silica-barite metasomatism and early sulphide remobilization. Residual alteration products (now mined) are microbreccias of altered quartz-sulphides, barite, sheared metavolcanics cemented by silica, iron oxides, jarosite and barite with micron-sized pure gold (RECOCHE and KOSAKEVITCH, 1989).

Abu Samar-Allaikaleib-Bashikwan (Derudeib region), Mn-Ba-Zn-Cu occurrences (Fig. 1, n. 33). *Abu Samar sulphide layers: 3.6 Mt averaging 4.9% Zn, 0.6% Cu, 72 g/t Ag* (EL SAMANI et al., 1986). *Imasa massive sulphide occurrence,-* Fig. 1, n. 32 - (POUIT et al., 1989).
Stratiform mineralized horizon in the cordierite-rich zone of a medium- to high-grade gneissic belt enclosed in batholitic granodiorite and granite. Outcrops of magnetite quartzites, manganese-barite layers, barite-bearing Fe-Mn gossans grade at depth to sulphide-enriched lenses (altered pyrrhotite, magnetite, sphalerite, chalcopyrite, galena,

Ag-minerals in chloritite gangue). Closed-system contact metamorphism induced crystallization of Zn-Mn spinels, alabandite with exsolutions of pyrrhotite, myrmekitic intergrowths of pyrite-sphalerite and mobilized veinlets of sulphides with Mo, Au, Bi. Primary ore: Mn-Ba-Zn-dominated hydrothermal metalliferous sediments (exhalites) not directly connected to the acidic and mafic volcanics present in the sedimentary pile. Ages of plutonic rocks in the Haya terrane, slightly younger than 900 Ma (STERN et al., 1989) suggest older (Early Pan-African?) age for the intruded depositional sequence of the Derudeib region.

The Imasa showing is hosted by the greenschist facies Imasa volcano-sedimentary sequence, probably overthrust from the south by the higher grade Abu Samar gneisses (EL SAMANI et al., 1986).

b) Ores in mafic-ultramafic intrusions

Dirbat Well (19°- 54' N, 36°- 35' E,- Fig. 1, n. 31-) *titanium ores.*

Skarn deposit associated with gabbros intruded into marbles of the Nafirdeib Formation. Contains good quality wollastonite, grossularite, schorlomite, diopside and idocrase. Idocrase and schorlomite are titaniferous (up to 16% TiO_2). In some lenses, up to 38% TiO_2. Fe-Ti ores are also reported at Onib Gorge, and some dyke-type magnetite concentrations (Oyo Formation) are probably of basic affiliation (WHITEMAN, 1971).

c) Vein - and shear zone gold

Oyo (Fig. 1, n. 18), *Onib* (n. 19), *Eikwan* (n. 21), *Nabi-Nabi Tana* (n. 23), *Umm Nabari* (n. 24), *Doishat* (n. 25), *Serakoit (Shigriyay)-Tibiri Habilad group* (n. 31).

Gebeit (n. 20): *Production prior to 1981: 4.33 t of gold* (GASKELL, 1985). *Re-opening 1987, small reserves according to recentmost estimates (41,700 t grading 10 g/t Au;* MINING ANN. REV., 1990).

Abirkatib (Aberketeib, n. 22): *re-opening 1989, mined tailings grading 7.4 g/t Au. Explored quartz veins averaging 12-14 g/t Au.*

Nigeim (n. 26) *quartz veins and stockworks assaying 70 g/t (up to 260 g/t) gold* (MINING ANN. REV., 1984).

Kamoeb (n. 27): *quartz veins grading 7.5 g/t Au, contained more than 4 t of gold* (COTTARD et al., 1986).

As for Egypt, in the Red Sea Hills area gold occurrences are very numerous. Overall, estimated reserves for explored deposits since 1986 amount to 20 tons of gold, including Ariab (MINING ANN. REV., 1989).

Gold deposits mostly associated with braided-type shear zones (Oko, Hamisana, Abirkatib, 10-50 km wide) sometimes at the intersection with the massive shear zones. In the braided shear zones rocks are commonly mylonites formed under greenschist facies conditions, although early shearing along the Oko shear zone took place at higher temperatures, resulting in amphibolite facies gneissose tectonites (ALMOND and AHMED, 1987). The Hamisana shear zone (STERN et al., 1989) evolved after 660 Ma up to 570 Ma across gneisses, foliated granodiorites, meta-volcanics, metasediments and serpentinized ultramafics. On local scale, shear zones often develop at tectonic or stratigraphic unconformable contacts. Gold-hosting sheared lithologies are mostly mafic metavolcanics, tuffs and ferruginous horizons, carbonaceous schists, plutonic rocks and altered ultramafics. Gold ores occur in the dilational parts of the brittle-ductile shear systems, thus economic grade ore shoots are irregular, with some secondary enrichment at the water table. Coarse (up to 200 mm size) free gold is associated to milky white to bluish-grey and reddish quartz in massive veins and anastomosing quartz stringers separated by sheared country rocks. Gold paragenesis comprises pyrrhotite, pyrite and arsenopyrite, minor chalcopyrite and scheelite, as well as traces of galena, sphalerite, tellurides (Ag), wolframite, cassiterite. Gold-bearing quartz is anomalous in As, Mn, Ti, V, Cr, Zn, Cu,(W,Bi) at Gebeit. The mineralized veins are of variable length and thickness, and predate latest shearing, folding and faulting. Hydrothermal alteration envelopes resulted in wallrock silicification, sericitization, intense pyritization and auriferous sulphide disseminations with little or no quartz, and carbonate metasomatism over wide areas. In ultramafic zones, auriferous listwaenites are common (M. LEBLANC, pers. comm.). In the Onib ophiolite, hydrothermal gold-PGE (Pt, Pd, Rh) ores associated with Ni-Cu-Co sulphides are found at the intersection with the Hamisana Shear Zone (G. MATHEIS, pers. comm.). (WHITEMAN, 1971; ALMOND et al., 1984; FLETCHER, 1985; GASKELL, 1985; CORTIAL et al., 1985; GRIFFITHS, 1986).

d) ORES RELATED TO LATE FELSIC PLUTONISM

J. Eyob (Fig. 1, n. 34). *W(F)*
Eyob muscovite leucogranite, locally greisenized. Hosting quartz veins with wolframite (fluorite). The late granite is intruded into the biotite zone of the Tolik-Abu Samar gneissic belt. (EL SAMANI et al., 1986).

Eritrea-Tigre

The Eritrea-Tigre domain is separated from the Haya terrane (Southern Red Sea Hills, older ages 870-850 Ma) by the NNE-trending Baraka lineament (VAIL, 1985a) characterized by serpentinite slices comprised between sheared pyritiferous shales and marbles, and carrying uneconomic occurrences of chrisotile asbestos, garnierite, chromite and magnesite in the Shameghe and Barka valleys (JELENC, 1966). NNE- to NNW-trending alignments of asbestos showings are also known at the southeastern boundary of the Eritrea-Tigre domain in the Adigrat region, often consisting of the lavender blue Fe-Na amphibole variety (crocidolite) besides serpentinite asbestos in low-grade marbles, talc schists, quartzites with sill-like boudinaged and hydrothermally altered "basic dykes" (JELENC, 1966). The Late Proterozoic Eritrea-Tigre fold belt is chiefly composed of calc-alkaline metavolcanics ranging from basalts to rhyolites with dominant andesites (Tsaliet group) grading west and south to prevailing metapelites bearing evidence of shallow water environment (Tambien group). Regional metamorphic grade is low, but local thermal aureoles characterized by cordierite (andalusite), garnet, epidote schists are reported in the Tsaliet metavolcanics, induced by the syn-to late tectonic intrusion of a large composite calc-alkaline batholith of Andean type (KAZMIN, 1975; KAZMIN et al., 1978; DE WIT, in CHEWAKA and DE WIT, 1981). The volcano-plutonic complex is underlain by (or thrust onto?) high-grade gneisses and migmatites of unknown age. Dating of the volcano-plutonic complex is also uncertain, although some radiometric data (in HAMRLA, 1978) suggest an Early Pan-African age pattern comparable to that of the adjacent Southern Asir oceanic domain of Saudi Arabia. We observe that probably late stage bimodal volcanics of the Eritrea-Tigre composite terrane (Tokar, Sudan) are 854 Ma old (U-Pb zircon age) though massively reset at 720 to 650 Ma (STERN et al., 1989; see also LINNEBACHER et al., 1987).

The known metallogenic potential of the Eritrea-Tigre region is provided by some volcanogenic massive sulphide deposits and by a great number of auriferous quartz veins, exploited only near the surface and mostly concentrated around the town of Asmara. The stratabound volcanogenic Zn-Cu ores are found at different horizons in the Tsaliet volcanic pile, varying from lenses lying in wide zones of epidote-carbonate alteration (Embaderho) to more felsic, barite (lead)-enriched deposits in the transition zone between Tsaliet metavolcanics and overlying Tambien metasediments (Debarwa, Adi Nefas). Typical copper-rich stockworks are also represented (Adi Rassi). The western gold ores (Ugaro, Barka-Anseba groups) are mainly localized within the dilational segments of shear zones in the proximity of the Baraka lineament. The eastern ores (Hamasien-Asmara group) seem to be more clearly controlled by late veining and hydrothermal activity connected to the batholitic granodiorite intrusions. They probably predate the emplacement of undeformed younger granites.

(a) STRATABOUND VOLCANOGENIC SULPHIDE ORES

Embaderho (Fig 1, n. 41). *High tonnage ore grading 1.83% Zn, 0.52% Cu. Recognized by drilling up to 200 m depth.* (HAMRLA, 1978).
Hosted by pyrite-magnetite-bearing quartzites and chlorite schists interbedded with abundant "quartz-keratophyre" layers. Na-rich volcanics affected by intense Ca-Mg alteration (epidote, carbonates, chlorite) adjacent to a quartz diorite intrusion. Zn>Cu, traces of Pb, As, Ag, high Co/Ni ratio. Pyrrhotite, pyrite, magnetite, sphalerite (also Fe-

poor, remobilized), chalcopyrite. In the greenschists adjacent to ore layers, swarms of quartz veins with pyrite, chalcopyrite, chlorite, calcite, epidote and some brown-pink garnet. The ore zone is cut by abundant aplite dykes and by the mined Medrizien quartz-gold veins.

Adi Nefas (Fig. 1, n. 41). *1-3 Mt grading 1.2-2% Cu, 3-1.5% Zn, 0.8% Pb, Au 2.3-4 g/t, Ag 110 g/t, Cd 0.1%.* (DE WIT, in CHEWAKA and DE WIT, 1981; WARDEN, 1981).
Host rocks are quartz-sericite schists with deformed felsic clasts, interbedded in a sericite-chlorite schist horizon with quarzitic ironstones and metapelites, intruded by gabbroic granodiorite and quartz porphyry. Zn>Cu, Pb locally enriched with As, low Co/Ni ratio. Pyrite, iron-poor sphalerite and less abundant chalcopyrite, traces of galena, tennantite,enargite (HAMRLA, 1978; DE WIT in CHEWAKA and DE WIT, 1981; WARDEN, 1981). Massive chalcopyrite-sphalerite ore has barite besibes quartz gangue.

Debarwa (Fig. 1, n. 42). *Developing and mining in 1970s by* NIPPON MINING CO. *Exploited Cu-rich zone (less than 1 Mt ore grading 7.6% Cu, 1.8% Zn, Ag 809* g/t *traces of Au).* (EVANS, in CHEWAKA and DE WIT, 1981).
Limonite-barite gossan. Bedded and massive ore (paragenesis as Adi Nefas) hosted by dacitic-rhyolitic metavolcanics, locally greywackes, black shales and phyllites. Several ore types (barite, pyrite-quartz, chlorite, chalcopyrite). Abundant silicification, kaolinization, pyritization. Defined as Kuroko or Besshi-type deposit. (HAMRLA, 1978; DE WIT, in CHEWAKA and DE WIT, 1981; WARDEN, 1981; GETANEH ASSEFA et al., 1987).

Adi Rassi (Fig. 1, n. 42). *4.5 Mt grading 1% Cu, 0.7 g/t Au.* (DE WIT in CHEWAKA and DE WIT, 1981).
In a sequence of dominant chlorite schists, associated with a kaolinized metaporphyry. Copper (chalcopyrite) rich stockwork ore. (HAMRLA, 1978).

(b) Vein and shear zone gold

Ugaro group (Fig. 1, n. 38). *Production 1932-37: 0.3 t Au.*
Conformable, thin quartz lenses (up to 350 m long) in locally kaolinized chlorite-sericite schists and nodular mylonitic quartzites. Pyrite, chalcopyrite, gold (5-30 g/t Au). Possible polyphase shearing episodes with gold upgrading (60 g/t) near the kaolinized wallrock contacts.

Barka-Anseba group (Fig. 1, n. 39).
NNE-trending shear zone with foliated sericite schists, greenschists, diorites. In dilational segments (N-S to NW) fillings of milky white quartz, calcite, pyrite (Cu, Pb).

8-20g/t Au. Strong wallrock brecciation and crushing, cavities with quartz crystals and free gold.

Asmara-Hamasien group (Fig. 1, n. 40). *Around Asmara, about 130 explored occurrences, partly mined to a maximum depth of 90 m.* (USONI, 1952; ATKINS and Partners, 1963 in JELENC, 1966; EVANS in CHEWAKA and DE WIT, 1981).
N-S elongated area, about 70x30 km wide, bounded by granitoid intrusions and underlain by low-metamorphic volcanics grading to garnet and cordierite schists. In the eastern sector the mineralized veins (foliation-parallel, 100-200 m long) are hosted by sericite-chlorite schists showing pyritic-argillic alteration and interlayered with talc schists, albite felsites, jasper and coarse psammitic quartzites. The auriferous quartz ore contains pyrite, chalcopyrite, chlorite, siderite pseudomorphically replacing pyrite, and garnet. In the western sector (cordierite schists, several diorite plugs) the veins contain zinc besides copper. The gold-bearing quartz is white and saccharoidal, bluish stained and fracturing yellowish (Medrizien). Acicular tourmaline, bronze mica, chlorite and garnet are minor gangue components.

(c) OTHER OCCURRENCES

Agametta-Gumhod, Fe (Fig. 1, n. 43). *560,000 t averaging 50% Fe.* (WALSH in CHEWAKA and DE WIT, 1981).
Banded magnetite (martite) quartzites (chlorite schists, marbles) associated with a diorite intrusion. Part of the ore is contact-metamorphosed (epidote-garnet-amphibole-magnetite skarn). In the Firfira (W Tigre) intrusive complex, magnetite-Cu showings are associated with skarn assemblage at marble/granodiorite contacts. (HAMRLA, 1978; MORTON, in CHEWAKA and DE WIT, 1981; GETANEH ASSEFA et al., 1987).

Tsehafi Emba, Cu (Fig. 1, n. 44).
Reported as "porphyry-type" ore. Veinlet and disseminated chalcopyrite in metagabbros from the Tsehafi Emba Ridge (Firfira complex, W Tigre). NE-trending, marginally sheared belt of deformed gabbro, syenite (K-rich), fine grained basic rocks and minor granites. (MORTON, in CHEWAKA and DE WIT, 1981).

Pegmatites
SW of Massawa (Ghedem) gneisses, amphibolites, chlorite schists and phyllites are intersected by pegmatitic veins containing mica (exploited), quartz, feldspar, garnet and rare beryl (Shilicki Fig. 1, n. 43). In the Mareb granite bounding the Firfira complex, aplites and simple pegmatites are associated with swarms of quartz veinlets (in granite, rimmed by greisen) including calcite, muscovite, tourmaline, pyrite, and locally beryl. (JELENC, 1966; MORTON, in CHEWAKA and DE WIT, 1981).

Qala en Nahl region (E Sudan)

Domain adjacent to and probably continuous with the Baraka lineament and the Eritrea-Tigre terrane (Fig. 1). Ultramafic belt of serpentinites, chromite- and magnetite-bearing with conspicuous concentrations of chrisotile asbestos (exploited). Connected talc-carbonate bodies, estimated 200 Mt of magnesite (WHITEMAN, 1971). Within a sequence of pyritiferous sericite phyllites, graphite-chlorite schists, iron quartzites, marbles, spilites. Locally developed cordierite, andalusite, epidote, carbonate hornfels (WILCOCKSON and TYLER, 1933 and RUXTON, 1956 in WHITEMAN, 1971). In this region, mineral occurrences other than asbestos, magnesite... are not reported.

TABLE A - 2. ARABIAN SHIELD

Midyan terrane-Yanbu suture (Fig. 2)

(a) Ores related to ophiolite-island arc assemblage

Yanbu suture: low-metamorphic belt including the J. Al Wask-J. Ess back-arc ophiolite fragments and adjacent arc volcanics. Development of the arc/basin system in the range 780-740 Ma, ophiolite thrusting onto the arc volcanics at 750-720 Ma (BAKOR et al., 1976; SHANTI and ROOBOL, 1979; CLAESSON et al., 1984). Low intensity of suturing, deformation by folding/thrusting not accompanied by intense crustal remobilization and synorogenic plutonism (CAMP, 1984; STOESER and CAMP, 1985). Later, fragmented and displaced by Najd strike-slip faulting.

Podiform chromite in harzburgite-type ophiolite mantle-gabbro section.
In mantle tectonites (depleted harzburgites and minor dunites) abundant Cr-rich podiform chromite occurrences (over 350 lenses at J. Al Wask). Chromites have high Cr/Fe vs. Ti/Fe ratios (NEARY and BROWN, 1979; AUGÉ, 1982) and plot in the field of Troodos and Shetland chrome spinels (PRICHARD and LORD, 1988; Fig. 4). PGM (Ru, Ir, Os-bearing) are present as separate phases in chromite (PRICHARD et al., 1988, Plate 15, g-h). Chromite ores (less Cr-rich, no data about PGE contents) are also present in ultramafic cumulates (clinopyroxenites, wehrlites).

Ash Shizm district, (Fig. 4). J. *Ash Shizm Cu-Zn, Mt (2.9% Cu, 0.74% Zn, 11 g/t Ag).*
Tectonic association of J. Ess ophiolite poorly amygdaloid basaltic pillow lavas (SHANTI and ROOBOL, 1979) with Farri arc sequence of basal pillow lavas, highly amygdaloid, forming horst structures, and andesitic to rhyolitic lavas and pyroclastics filling adjacent troughs. Close to horst flanks develop the hydrothermal alteration columns affecting the top of the pillow lavas (Mg-chlorite, talc, tremolite-actinolite) and the acidic volcanics (sericite), as well as the Cu-Zn stockwork ores of Ash Shizm. The mineralization is Cu-rich, grading at the top to massive sphalerite ore in carbonate gangue, and chert. Dominant pyrite, chalcopyrite, sphalerite (minor galena, pyrrhotite, bornite, magnetite, mushketovite). Presence of Ag_2S, Ag, Ag-Au-Pb-Bi tellurides, Pb(Bi) selenides. (DONZEAU et al., 1980/81; SABIR and POUIT, 1984; POUIT et al., 1989).

Midyan terrane: 700-600 Ma old, contains volcano-plutonic sequences mostly younger than 680 Ma (STOESER and CAMP, 1985) likely correlative with coeval sequences of CED, NED, and South Sinai.

Wadi Sawawin (Fig. 4) *BIF, 391 Mt (42% Fe, 30% SiO_2, 0.4% P_2O_5).*
Compared with the jasper-hematite ore of Wadi Kareim in the Eastern Desert of Egypt. Algoma-or Lahn Dill-type oxide facies BIF, closely associated with the volcanics (massive "diabase"), sandstones and shales of the Silasia Formation. Tightly folded, locally affected by thermal metamorphism. (JAPANESE GEOLOGICAL MISSION, 1969).

(b) Ores in mafic-ultramafic intrusions

Wadi Kamal Wadi Murattiyah Fe-Ti, Cu-Ni ores.
Layered ultramafic-mafic complex in the Yanbu suture, carrying anorthosites, Cu-Ni ores (up to 0.51% Ni, 0.21% Cu) associated with the earliest pyroxene-rich cumulates, and Fe-Ti ores (up to 1% V_2O_3) connected with late melanogabbro intrusion. The complex is intruded by late quartz diorite (610 Ma), monzonite, pegmatites and aplites. (CHEVREMONT and JOHAN, 1980/81).

Wadi Hayyan Wadi Qabqab Fe-Ti ores (400,000 t averaging 18% TiO_2).
In Midyan terrane (27°N, 35-36°E). Gabbrodiorite ring complex, intruding a sequence of granite gneisses overlain by greenschists, volcanics, slates and sandstones. Cut by late granite. Contains ilmenite-magnetite (hematite), apatite-ilmenite-magnetite, and olivine (clinopyroxene)-ilmenite-magnetite ore varieties. (JAPANESE GEOLOGICAL MISSION, 1970).

(c) Rare metal ores related to late felsic plutonism (Fig. 5).

Ghurayyah, up to 250 m depth 440 Mt (Zr 8578, Nb 2256, Y 1326, Th 399, Sn 290, Ta 212, U 117 ppm). Jabal Tawlah (Fig. 5, n. 1), *up to 85 m depth 6.4 Mt (Zr 3.73%, Nb 3405, Y 5216, Th 693, Sn 381, Ta 175 ppm).* (DRYSDALL et al., 1984).
Post-tectonic alkali granite association (Midyan suite, 600-550 Ma) emplaced in shallow crustal levels during Najd cycle of transcurrent faulting. Anomalous in iron, REE, F, Nb, Y, Zn, Zr (HARRIS and MARRINER, 1980; DUYVERMAN et al., 1982; RAMSAY et al., in DRYSDALL et al. eds., 1986). Magma generation by partial melting in the lower crust in the presence of mantle-derived volatile (F) phases (HARRIS and MARRINER, 1980) or by high T° dry melting of Late Proterozoic island arc crust (DRYSDALL et al., 1984). Specialized to mineralized disseminated ore facies (Ghurayyah stock and J. Tawla sill of leucocratic microgranite) enriched in Zr, Nb, HREE, Y, Th, Sn, Ta, U. Main mineral phases are zircon, columbite-tantalite and pyrochlore, Y-aeschynite, samarskite, xenotime, monazite, thorite, uraninite, cassiterite (JACKSON and RAMSAY, 1986).

Al Wajh.
W-Sn-Au occurrences (JACKSON and RAMSAY, 1986).

Jabal Sawda Nb, Zr.
Nepheline syenite complex, (553±4 Ma), Nb-Zr sub-economic grades. (LIDDICOAT et al., in DRYSDALL et al. eds., 1986).

Hijaz terrane-Bir Umq suture (Fig. 2)

(a) ORES RELATED TO OPHIOLITE-ISLAND ARC ASSEMBLAGE

BIR UMQ SUTURE: low-metamorphic belt with structural evolution comparable with Yanbu suture (STOESER and CAMP, 1985). The belt comprises the J. Thurwah and Bir Umq back-arc, SSZ ophiolite fragments (NASSIEF et al., 1984; AL-REHAILI and WARDEN, 1980). A possible northern extension of the belt to the ~ 800 Ma old Tuluha ophiolite zone in the western Hulayfah region is suggested by DELFOUR (1980/81). Adjacent (to the south) mineralized arc volcanics are in thrust contact with the ophiolites (Samran-Shayban and J. Sayid sequences).

Podiform chromite in harzburgite-type ophiolite mantle-gabbro section
Cr-rich podiform chromite (J. Thurwah, Tuluha), Cr/Al ratio similar to harzburgite chromites of Tethyan ophiolites (NASSIEF et al., 1984). Less Cr-rich chromite in ultramafic cumulates at J. Thurwah.

Cyprus-type pyritic (Cu, Zn) ores.
At Bir Umq and Tuluha, abundant pillow lavas host pyrite (Cu-Zn) occurrences and beds of chert and jaspilite (AL-REHAILI and WARDEN, 1980; DELFOUR, 1980/81).

Volcanogenic stratabound Cu-Zn massive sulphide ores in island arc volcanics (J. Sayid, Umm ad Damar, Samran-Shayban). Partly fissure-bound gold ores (Mahd-ad-Dhahab) (Fig. 4).

J. Sayid, estimated up to 40 Mt of Zn,Cu(Pb) ore averaging 1.7% Cu, 1% Zn (RIOFINEX, 1977). *Recoverable reserves 9.8 Mt, 1.88% Cu* (MINING ANN. REV., 1988). *Umm ad Damar Cu-Zn ore, more than 1 Mt, 2% Cu* (MINING ANN. REV., 1984).
J. Sayid rhyolitic volcanics, 770-750 Ma old (CALVEZ and KEMP, 1982 in STOESER and STACEY, 1988). Weakly metamorphosed acidic pyroclastics, rhyolite domes, breccia pipes, tuffaceous graphitic sediments. Lower stockwork and fissure-filling Cu-rich ore (J. Sayid, Umm ad Damar), well-crystallized aggregates of pyrite-chalcopyrite, chlorite gangue, widespread Ag-Bi-Pb-Hg tellurides, Bi, Au. Upper zone of massive

(disseminated, fragmental) fine-grained pyrite-sphalerite ore, bordered by banded chert. Collomorphic textures, framboidal pyrite, rare sulphide banding. Quartz-carbonate gangue with disseminated arsenopyrite. Pb model ages 750-720 Ma. (SABIR, 1979, 1980/81; DELFOUR, 1980/81; STACEY et al., 1980; SABIR and POUIT, 1984; POUIT et al., 1989).

Mahd-ad-Dhahab Au-Ag(Zn,Cu,Pb), estimated (South Zone) 1.1 Mt averaging 27 g/t Au, 73 g/t Ag; 70 t of gold (RIOFINEX, 1977). *Brought into production by processing 400 t/d of ore averaging 26 g/t* (MINING ANN. REV., 1987-89).

Pyroclastic rhyolitic flow and breccia complex, underlain by andesite flows and intruded by rhyolite dome and breccia pipe. Two ore zones in a north-trending, extensional fissure system related to left- lateral strike-slip faulting. Cockade quartz veins and veinlet stockworks.

Si- and K-metasomatism, Ba anomaly. Pyrite, chalcopyrite, sphalerite, galena (Pb model age 685 Ma) mineralization, with silver-rich sulphides and sulphosalts. Gold linked to sphalerite and late introduced Ag-Au (Bi, Pb) tellurides. The sulphide ore is characterized by δ^{34} S + 0.8 to + 3.2 and T 210-290° C. Prominent cataclastic post-ore deformation. Lateral zoning, with transition from Au-Ag-Zn-Cu-Pb veins to gold-quartz veins. (WORL, 1979; SABIR, 1979; RYE et al., 1979; SABIR and POUIT, 1984; HAKIM and EL-MAHDI, 1986; AFIFI et al., 1988; POUIT et al., 1989).

Samran-Shayban Cu-Au-Zn district (south of J.Thurwah ophiolite). (SABIR and POUIT, 1984).

The explored district (TAWFIK et al., 1985) is correlated with J. Sayid by POUIT et al. (1989). Differs in having a distinctly more "basic" host sequence, characterized by old (>800 Ma) immature low-K arc tholeiites (ROOBOL et al., 1983). The Samran basic rocks also share some geochemical features with the adjacent J.Thurwah ophiolite, and are considered to have formed above the same subduction zone (NASSIEF et al., 1984). The type of deposits (mineralized stockworks overlain by massive sulphide layers) and the main paragenesis are similar to J. Sayid. A possible connection with rhyolite domes is also suggested.

Musayna'ah Cu-Zn (close to Tuluha ophiolite).

Stringer/vein-type deposit, characterized by pyrite, pyrrhotite, sphalerite, chalcopyrite, electrum, molybdenite, Fe-Ti oxides, chalcophanite (SABIR and POUIT, 1984; POUIT et al., 1989).

(b) Rare metal ores connected to late felsic plutonism (Fig. 5)

J. Hamra (Fig. 5, n. 2)

Alkali-feldspar syenite association, hosting besides the J. Hamra mineralized plug, Nb, Zr, REE-enriched pegmatites, fluorite veins and large pyritized zones. The J. Hamra deposit is a plug of cataclastic silexite with disseminated ore (18 Mt) of Zr (1.33%), La

+ Ce (6025 ppm), Y (1592 ppm), Nb (1713 ppm), Sn (194 ppm), Ta (146 ppm), traces of Th and U. (JACKSON and RAMSAY, 1986).

Umm al Birak (Fig. 5, n. 3)
Stock of porphyritic aegirine-arfvedsonite microgranite, with disseminated ore (6.6 Mt) of Zr (5129), Nb (1663), La+Ce (1171), Y (311), Ta (121 ppm) and traces of Th and U. (DRYSDALL et al., 1984).

J. Sayid (Fig. 5, n. 4)
Aplite-pegmatite complex, alkali granite association. Estimated 23 Mt at 1290 ppm Nb, 1888 ppm La+Ce, 4151 ppm Y, 834 ppm Th, 134 ppm U and more than 1.7% Zr. Principal REE minerals are bastnaesite, Y-synchysite (monazite, synchysite, pyrochlore, thorite). (JACKSON and RAMSAY, 1986). Near Mahdad-Dhahab, fluorite vein (100.000 t CaF_2).

Asir terrane (Fig. 2)

Composed of a central (Bidah) north-trending belt of older (950-800 Ma) low-K tholeiites and greywackes associated with diorite-tonalite plutons. In the southwest, this assemblage is intercalated with pelitic and quartzo-feldspathic clastics (Sabya Formation, Fig. 3) derived from the East Sahara Craton to the west. The central belt is flanked by two younger arc systems (Taif and Tarib) developed in the 800-700 Ma interval (STOESER and CAMP, 1985).

(a) Ores related to ophiolite-island arc assemblage (Fig. 4)

Wadi Bidah district: N-trending (Baish-Bahah Group). a) Lower, greenschist facies metabasites, barren (2000 m); b) metasediments, chiefly pyroclastics (1600 m); c) upper pillow lavas (basalts, andesites) with intercalated rhyolitic pyroclastics and local domes (4000 m). > 900 Ma, immature low-K arc tholeiites with high Na/K ratio, scarce ultra-low K, LILE-depleted rhyolites. (EARHART, 1971; JACKSON and RAMSAY, 1980; GASS, 1982; ROOBOL et al., 1983).

Rabathan Cu (Zn,Ag,Au) 1.5 Mt (2.1% Cu, 0.02% Zn, 2.45 g/t Ag, 0.14 g/t Au; slightly higher values in JOHNSON and VRANAS, 1984).
Base of the b) metasediments, in pyrite-quartz-graphite schists, chlorite schists, cherty tuffs, silicified carbonate lenses, iron formation. Distal basic, strongly sheared lenses of massive/disseminated sulphides, sharp hanging- and footwall contacts. Mutual iron formation/massive sulphide exclusion. Pyrite with interstitial chalcopyrite and local sphalerite, native Au, Ag, $\delta^{34}S + 0.8 \pm 4.0$. (EARHART, 1971; RIOFINEX, 1977; RYE et al., 1979; JOHNSON and VRANAS, 1984; POUIT et al., 1989).

Sha'ab at Tare Zn,Cu,Ag 4 Mt (0.36% Cu, 1.09% Zn, 3.4 g/t Ag, 0.5 g/t Au up to 200 m) and Gehab, Mulgatah, Wadi Leif.
Distal acid, massive/disseminated sulphides. Sheared segments in fold hinges, with fine sulphide banding. Within the upper c) horizon, chiefly in acid lavas and pyroclastics with strong pre-shearing setricitizzation and pyritizzation. Pyrite, chalcopyrite, iron-rich sphalerite, native Au, Ag, barite. Epigenetic (remobilized) carbonate, quartz, chlorite, barite, rhodochrosite; $\delta^{34}S + 0.8 \pm 4.0$. (Ref. as above, and ROBERTS et al., 1977).

Mulhal Au
Wadi Bidah (Baish) mafic pyroclastics of c) horizon at the intersection of folding- and faulting axes/lineaments. Au quartz vein, with lead (galena) isochron model age of 650 Ma. (EARHART, 1971; STACEY et al., 1980).

Mahawiyah Zn,Cu,Au, Ag,Ba (Rabathan group, southern end).
Host sequence b) as for Rabathan, intruded by a rhyolite-dacite dome with peripheral argillic/phyllic-chloritic alteration halo. Dome acting as "heat source". Vein and stratabound orebodies. Post-ore shearing and local remobilization in quartz veins, with minor sulphides, traces of Au, Ag. Disseminated pyrite, chalcopyrite and sphalerite, traces of Au, Ag in several tuff and agglomerate horizons. Quartz veins, with minor sulphides, Au, Ag. (MOORE, 1978).

WADI SHWAS DISTRICT, N-TRENDING (HALABAN/JIDDAH GROUP): associated Surgah formation (tholeiitic basalts and rhyolites, depleted in LREE, both positive and negative Eu anomalies, persistent high Na/K ratio) and Shwas dacitic-andesitic volcaniclastic formation (calc-alkaline). Rb-Sr errorchron age for Surgah Fm.: 721±55 Ma. Metamorphosed to greenschist facies. (JOHNSON and VRANAS, 1984; BOKHARI and KRAMERS, 1981).

J. Jadmah Cu (Zn,Ag) 0.7 Mt (2.8% Cu) or 1.6 Mt (1.83% Cu, 1.37% Zn, 18.3 g/t Ag).
Chloritized metarhyolitic ash flows and tuffs of Surgah Formation. Three lenses of disseminated sulphides over a strike-length of 300 m. Massive ore is well-banded. Lead isotope model age 720-659 Ma, 695 Ma (whole-ore). Pyrite, chalcopyrite, sphalerite, traces of pyrrhotite and galena, $\delta^{34}S + 3.2 \pm 9.4$. (RYE et al., 1979; STACEY et al., 1980; BOKHARI and KRAMERS, 1982).

Hajal (up to 3.1% Cu, 0.45% Zn, 12.1 g/t Ag). Au-Ag-bearing gossan. Recent exploration (Al Hajar prospect, MINING ANN. REV., 1989) *has demonstrated reserves of the order of 3 Mt grading 3-4 g/t Au.*
Dacitic and rhyolitic volcaniclastics, near rhyolite plugs. Disseminated and stringer ore. Pyrite, chalcopyrite. (JOHNSON and VRANAS, 1984; POUIT et al., 1989).

Al Wakaban (Cu 1.65%, Zn 1.3%, Pb 0.36%, Ag 47.2 g/t, Au 1.25 g/t).
Sheared and faulted andesites+marbles. Stockworks, silicification, carbonatization (?). Pyrite, chalcopyrite, sphalerite. (JOHNSON and VRANAS, 1984).

Wadi Yiba district, Ablah graben: dominantly epiclastic Ablah Group (800-770 Ma) resting unconformably upon a dioritic-tonalitic batholitic mass which intrudes the oldest layered Baish-Bahah rocks. The Ablah copper-bearing sequence includes coarse- to fine grained clastics and mafic/intermediate volcanics overlain by stromatolitic and calcarenitic dolomites. Some of the minor showings of disseminated chalcocite (Al Munayzir, W.Raysh, W.Hali, Um ar Rumf) are sediment-hosted. At least partly volcanic-hosted are the major occurrences (W. Yiba, J. Sarbon).

Wadi Yiba Cu (up to 6.8% Cu over 3.4 m).
Cu mineralization as chalcocite and bornite disseminations and fracture-fillings in sheared siliceous dolomite with tuffaceous intercalations. Stratigraphically controlled and areally extensive, the mineralization is at least in part connected to metamorphosed volcanics.

Jabal Sarbon Cu (up to 1.4% Cu).
Disseminated copper (Zn) sulphides in conglomerates, marbles and amphibolites (metamorphosed andesite flows and sills).
(RIOFINEX, 1978; JOHNSON and VRANAS, 1984; BINDA, pers. observations).

(b) Ores in mafic-ultramafic intrusions

Chromite, Ni,Fe-Ti occurrences.
Several chromite, nickel and Fe-Ti occurrences are reported by DELFOUR (1980/81, Plate 1) and JOHNSON and VRANAS (1984, Fig. 1) along the mineralized belts (Bid [illegible], Shwas) of the southern Asir terrane. According to CAMP (1984) in this area ultramafic/mafic rocks represent fragments of a thin oceanic floor incorporated in NE-trending segments of braided fault zones, originally related to extension and rifting in the Bidah interarc basin, then reactivated during later compressive stages.

(c) Gold ores

Mamilah (Wadi Qust) 21° 03' N - 41° 18' E. Au, Ag, Cu.
Several quartz veins along a NE-trending shear zone up to 30 m wide in Bahah metamorphics (quartz-biotite-sericite schists, hematite jaspilite lenses).
Disseminated sulphides (pyrite, chalcopyrite) and free gold intermittent. Common Pb age 575 Ma (STACEY et al., 1980).

(d) Rare metal ores related to late felsic plutonism (Fig. 5)

Jabalat, Sn (Fig. 5, n. 5).
Sn-rich greisen associated with low-Ca alkali feldspar granite. (JACKSON and RAMSAY, 1986).

Ablah, fluorite (Fig. 5, n. 6). *20,000 t of acid grade fluorite* ± *Cu, Pb, Zn (Ag, Au) sulphide ores (to 50 m depth).*
Elliptical vertical pipe, emplaced at about 215 °C and at maximum depth of 1.1 km in a pegmatitic-aplitic breccia body with matrix of quartz weakly mineralized (Pb, Zn, Mo, Sn, Au, Ag). The breccia body is related to a quartz-alkali feldspar syenite ring complex. (JACKSON and RAMSAY, 1986; AL-ZUBAIDI and EL-MAHDI, 1986).

Wadi as Salile (east of Yiba district), scheelite.
Disseminated and vein-quartz-scheelite (Mo-free) mineralization spatially associated with a post-tectonic garnetiferous muscovite-biotite granite. Scheelite also occurs as disseminations in hornblendites, Ca-silicate layers, mafic amphibolites and pegmatite sills of a typical "variegated" sequence (according to the present authors, possible mineralization of perianatectic type). Scheelite in alluvium is also abundant west of the W. Bidah belt. (JOHNSON and VRANAS, 1984; JACKSON and RAMSAY, 1986).

Nabitah suture and orogenic belt-Afif terrane (Fig. 2)

According to STOESER and STACEY (1988) the Nabitah orogenic belt is the result of the collision between an ensimatic accreted arc terrane (950-720 Ma) in the west and the Afif composite terrane, partly underlain by the Early Proterozoic Khida basement, in the east to form the 1200 km long north-trending Nabitah suture. The orogenic belt, 100-200 km wide, was built up during a 680 to 640 Ma cycle of deformation and crustal remobilization which affected, along the Nabitah suture, an assemblage of pre-orogenic, active continental margin arc volcanic and plutonic rocks (<800 Ma), mio-eugeosynclinal type sediments and mostly intrusive ultramafic/mafic complexes emplaced across the Afif microplate western edge (AGAR, 1985; STACEY and AGAR, 1985). The Nabitah belt is characterized by early (680-650 Ma) catazonal gneiss domes and granitoid intrusions with amphibolite to granulite facies metamorphic aureoles where are locally involved pre-metamorphic ores such as Ash Shaib and Hanash, and by late (650-640 Ma) suites of diorite, tonalite, monzogranite. Significant orogenic uplift and erosion resulted in the formation of major basins of clastics (Murdama group). At 630-600 Ma compressional stress continues from the east only, with the formation of the major left- lateral transcurrent Najd fault system. Related to crustal thickening, widespread post-orogenic peraluminous to peralkaline silicic magmatism occurred in the 600-570 Ma interval.

(a) Ores related to ophiolite-island arc assemblage (Fig. 2)

Asbestos, steatite, magnesite mineral showings. Gold in listwaenites. No chromite.
The Nabitah ultramafic belt (Nabitah suture, Fig. 2) is characterized by several highly deformed serpentinite masses which are not normal ophiolites (STOESER and STACEY, 1988). Abundant are listwaenites (DELFOUR, 1980/81). In the Bir Arja and Ad Dafinah

sections, chromite-free serpentinites are associated with pyroxenites, gabbros and tonalites (FRISCH and AL-SHANTI, 1977). At Zalm (Zalim) dunite, pyroxenite, gabbro and diorite form layered sill complexes and sheet-like bodies intrusive in the lower sedimentary members of the Siham group (AGAR, 1985), in part tectonically emplaced, widely carbonatized (listwaenites) and gold-bearing (BUISSON and LEBLANC, 1985; 1987). According to AL-REHAILI and WARDEN (1980) the Hamdah serpentinized dunite-peridotite-pyroxenite complex represents a deep-seated tectonic intrusion with deformation, shearing and late formation of cross-fibre serpentine asbestos replaced by magnesite and steatite.

Volcanogenic massive sulphide deposits

NUQRAH-AS SAFRA DISTRICT (Fig. 4). Sequence: a) clastics, andesitic pyroclastics, andesite flows (Afna Fm.); b) mixed rhyo-andesitic pyroclastics, soda-rhyolite domes (basal Nuqrah Fm.); c) water-lain mixed pyroclastics with intercalated dacite-rhyolite flows and dolomitic marbles; d) upper, dominant rhyolitic pyroclastics. Probable presence of Siham age volcanics, 720-690 Ma. Volcanism of andesitic to calc-alkaline affinity, soda trend, spatial relationship mineralization/ rhyolite domes. (DELFOUR, 1980/81; STOESER and STACEY, 1988).

Nuqrah Zn,Pb,Cu,Ag,Au N. Nuqrah 0.39 Mt (6% Zn, 1.22% Pb, 0.75%Cu, 332 g/t Ag, 2.5 g/t Au) S.Nuqrah 1.0 Mt (5.6% Zn, 1.83% Pb, 0.82% Cu, 220 g/t Ag, 4.33 g/t Au). (RIOFINEX, 1977).
Graphitic and chloritic tuffs, rhyolitic crystal- and lapilli tuffs, dolomitic marbles at the transition of b) and c) sequences. Two deposits 5 km apart, both consisting of stratiform massive and disseminated sulphides, with dolomite-graphite gangue. Fine ore banding. Lead isochron model age for galena ore: 680 Ma. Sphalerite, pyrite, galena, chalcopyrite. Abundant Cu-Pb-Sb(Ag) sulphosalts, Au-Ag (Bi, Hg) tellurides, association gold (electrum)-hessite (±FeAsS) δ^{34}S - 1.2 to + 3.9. (RYE et al., 1979; SABIR, 1979; STACEY et al., 1980; SABIR and POUIT, 1984; POUIT et al., 1989)

An Nimahr Zn,Pb,Cu,Ag. (SABIR and POUIT, 1984) .
Sphalerite, galena, pyrite (marcasite), pyrrhotite, chalcopyrite (cubanite, mackinawite). Presence of MoS_2 and alabandite MnS, rutile, ilmenite. (POUIT et al., 1989).

As Safra Cu(Zn), 2.75 Mt (2.1% Cu) or 4.5 Mt (1.29% Cu) and the similar deposit Ash Shaiba, 50 km to the south. (RIOFINEX, 1977).
In sequence c) dacitic and rhyolitic tuffs (altered to siliceous chlorite-sericite-muscovite schists) with andesites and dolomitic marbles. Cu(Zn) sulphide disseminations, veinlets, stockworks in a large shear zone. Low-grade disseminated Pb, Zn, Cu, Au (1 g/t) ore in dolomitic marbles. Bi-paragenesis in the lower horizons. Pyrite, chalcopyrite (sphalerite, galena, magnetite, pyrrhotite). Widespread tetrahedrite, Bi_2S_3, Bi, Ag-Bi(Cu) tellurides and sulphides. (EL-MAHDI, 1980).

SHA'IB LAMISAH DISTRICT, SHAM GROUP: eugeosynclinal deep water sediments and volcanics in association with ultramafic rocks. Andesites, subordinate dacites and rhyolites with crystal and lithic tuffs. Carbonaceous shales (Lamisah Shale), exhalative chert and marbles. Grading eastwards to shallow marine marbles and quartzites lying unconformably upon the basement high-grade gneisses (western continental margin of the Afif terrane). Volcanics plot in the field of active continental margin environment, volcanism and caic-alkaline plutonism 720-690 Ma (U-Pb zircon age). (AGAR, 1985; STACEY and AGAR, 1985).

Sha'ib Lamisah Zn,Cu. (SABIR and POUIT, 1984).
Massive sulphide ores in tuffs at the base of Lamisah shale, exhalative chert and carbonates, marbles. Pyrite, chalcopyrite (bornite, cubanite, mackinawite), sphalerite. Minor galena, pyrrhotite, arsenopyrite, MoS_2, Bi_2S_3 + Bi, Ag-Bi tellurides. (POUIT et al., 1989).

ASH SHAIB DISTRICT: 19° - 15' N - 43°- 40' E (in the J. Ishmas-W. Tathlith zone, Figs. 4, 6). Tathlith-Najran terrane, E of the Nabitah suture. Belt of strongly deformed layered rocks, metamorphosed to pyroxene-hornfels facies and locally migmatized in an area of granite gneiss domes and plutons of diorite, gabbro and granite (675-640 Ma Nabitah orogenic belt; STOESER and STACEY, 1988).
Layered rocks represent a shelf-facies succession of arkose, sandy siltstone, carbonaceous shale and dolomitic limestone with minor felsic and mafic-volcanics, grading eastward to continent-derived quartzo-feldspathic rocks (Mahanid Formation) suggesting a continental margin to the east (WHITE, 1985). Zinc-dominated stratabound disseminated ores, rich in barite and manganese (share many features with the Abu Samar-Allaikaleib sedex mineralization in Sudan, see Table A - 1.).

Ash Shaib, Zn(Cu,Ag). 1.72 Mt averaging 5.5% Zn, 0.24% Cu, 136 g/t Ag.
Pyrite, pyrrhotite, sphalerite, chalcopyrite, galena (tetrahedrite) disseminations and veins in massive to schistose magnetite-rich hornfels and dolomitic marbles within a sequence of graphite schists, magnetite- and Ca-silicate schists, amphibolites, minor felsic metavolcanics. Barite (4% in the ore, 14% in the gossan) and manganese (Mn-garnet, and wad in the iron cap) rich gangue. The sulphide mineralization (characterized by the significant presence of gahnite and magnetite, cubanite, molybdenite) has metamorphic recrystallization-mobilization fabric, interstitial to granoblastic and gneissic aggregates of gangue silicates.

Hanash (drill intersections up to 1.5 m-thick ore grading 0.7-12% Zn, 0.1-0.4% Cu).
Pyrite and massive sphalerite (pyrrhotite, galena, tetrahedrite, chalcopyrite, cubanite, molybdenite, magnetite) in medium- to coarse grained amphibole-feldspar-quartz granofels. More intensely metamorphosed, deformed and intruded by granite gneiss. (JOHNSON and VRANAS, 1984; POUIT et al., 1989).

KUTAM-AL MASANE DISTRICT (Fig. 4): southern andesite-greywacke assemblage, older than 730 Ma. a) Lower pillow basalts; b) andesitic-dacitic lava flows, sills, pyroclastics; c) alternating fine-grained pyroclastics and black shales; d) dominant black shales, acidic explosive volcanism. (WORL, 1980; JOHNSON and VRANAS, 1984; POUIT et al., 1989).

Al Masane Zn,Cu. 7.6 Mt (1.4% Cu, 6.1% Zn, 1.4 g/t Au, 48 g/t Ag).
In unit c) of dacitic tuffs and pyritic argillites, minor marbles and quartz porphyry dykes. Three stratabound massive sulphide lenses, the upper one with Zn(Pb) Cu, Au, Ag (sulphosalts and tellurides). Partim stringer ore by mobilization within shears (N-S trending shear zone). Hydrothermal alteration: chlorite, sericite, talc, dolomite, chert. Pyrite, chalcopyrite, sphalerite, galena, FeS. Presence of tetrahedrite, Ag, Pb, Bi tellurides, native Au-Ag, Ag; Hg anomaly, $\delta^{34}S$ + 5.3 to + 6 5. (RIOFINEX, 1977; ROBERTS et al., 1977; RYE et al., 1979; JOHNSON and VRANAS, 1984; POUIT et al., 1989).

Al Halahila Zn,Cu. 1.04 Mt (0.44% Cu, 2.99% Zn, 25 g/t Ag, 0.45 g/t Au).
In unit c). Narrow zone of quartz-feldspar-chlorite-sericite schists, graphitic schists, minor dolomitic marbles. Disseminated and massive banded ore. Pyritization of enclosing tuffs. Pyrite, chalcopyrite, sphalerite, galena, pyrrhotite, bornite. Presence of tetrahedrite, Ag, Pb tellurides, magnetite, hematite.

Dabhah (up to 23.68% Zn, 1.45% Cu, 20.6 g/t Ag, 0.36 g/t Au).
Shear zones in unit c), marked by chlorite and sericite schists. Lenses of disseminated and massive ore. Pyrite, sphalerite, chalcopyrite.

Kutam Zn,Cu (4 Mt, 2% Cu, 1% Zn).
In felsic pyroclastics (chlorite-sericite schists), minor amphibole- and graphite schists, jasperoidal marbles. Intruded by quartz porphyry, mafic dykes, and monzonite plutons. Disseminated and vein sulphides in NW-trending fracture zone. Syngenetic pyrite, Cu and Zn introduced during hydrothermal phase, with quartz, chlorite, biotite and tourmaline gangue. Lead model age of massive ore 600 Ma, of vein galena 580 Ma. Pyrite, chalcopyrite, sphalerite (galena, FeS). Presence of Bi_2S_3 and of Ag, Pb, Bi tellurides, $\delta^{34}S$ + 3.1 to + 5.6. (ROBERTS et al., 1977; STACEY et al., 1980; JOHNSON and VRANAS, 1984; POUIT et al., 1989).

QATAN-WASSAT DISTRICT (Fig. 4): island arc lavas (Wadi Qatan andesites and Wadi Wassat rhyodacites) with high Na_2O and K_2O contents. (JACKAMAN, 1972 in GASS, 1982).

Wadi Wassat Fe (pyrite), 125 Mt (80% FeS_2)
In andesitic lavas, pyroclastics and sedimentary rocks, isoclinally folded and faulted. Massive sulphide lenses, locally stratiform (syngenetic). Pyrite, pyrrhotite, minor chalcopyrite and sphalerite, $\delta^{34}S$ - 22.9 to - 30.5.

Wadi Qatan-Hadbah Cu, Pb,Zn,Ni (<1000 ppm base metals, up to 4% Ni in FeS).
As above, N-NW shearing parallel to bedding. Stratabound Fe sulphides, replaced by Ni-sulphides during later event. Pyrite, pyrrhotite ($CuFeS_2$, ZnS). Ni-sulphides: pentlandite, bravoite-violarite, gersdorffite. Presence of MnS and Mo (MoS_2 anomaly. δ^{34} S - 40.2 to - 46.4. (RIOFINEX, 1977; ROBERTS et al., 1977; RYE et al., 1979; POUIT et al., 1989).

(b) Gold ores

Zalim (Shakhtaliyah, Bir Tawilah, etc.) gold project, estimated reserves 738,500 t averaging 5.5 g/t Au. (MINING ANN. REV., 1982, 1984, 1986, 1987).
Gold is connected to listwaenite lenses (up to 200 m wide) flanked by magnesite-talc zones at the border of tectonitic serpentinite massifs along the Nabitah suture. Listwaenites are composed of Fe-Mn-dolomite with accessory talc, Mg-Cr-chlorite, fuchsite, pyrite (gersdorffite NiAsS), and are transected by veins of quartz with calcite, fuchsite, K-feldspar, pyrite and hematite. Gold zones (1-10 g/t Au) correspond to pyrite-rich listwaenites on the wallrocks of quartz veins. Native gold is associated with oxidized pyrite crystals. (BUISSON and LEBLANC, 1985, 1987).

Sukhaybarat (Nuqrah area), 5-6 Mt grading 2.9 g/t Au. Recoverable 1.5 t of gold. (MINING ANN. REV., 1985, 1986, 1989).
Stockwork of shallowly dipping quartz veins associated with the altered roof zone of a diorite-granodiorite intrusion. The veins contain native gold (with some Ag and Hg), pyrrhotite, arsenopyrite, chalcopyrite. (JACKSON and RAMSAY, 1986).

J. Ishmas-W.Tathlith gold zone (Figs. 4, 6). *38 recorded ancient workings. At one site drilling has suggested potentially 350,000 t averaging 7 g/t Au.* (MINING ANN. REV., 1982).
North-trending belt with five clusters of ancient workings. Exploited occurrences are located in second and third order fractures related to the major J. Ishmas-W. Tathlith fault/shear zone (segment of the Nabitah suture).
Cluster A: foliated package, parallel to the Ishmas-Nabitah fault system, of calc-alkaline volcanics, marbles, serpentinites, talc-actinolite schists, listwaenites, strongly sheared gabbros, transected by NW-trending Najd faults. Gold is abundant in quartz veins predating Najd faulting, while Ag, Cu, Zn, Pb sulphides predominate in the enrichments at the intersection of N-S with Najd lineaments. (ROOBOL et al., 1983; WORL, 1980; EL MEDANI and HUSSEIN, 1988). **Cluster B**: contains promising gold ores in a sheared quartz porphyry and in quartz veins cutting gabbro and greenstone. **Cluster C**: includes only scarce auriferous veins in gabbro. **Cluster D**: has gold deposits mostly associated with felsic dykes beneath flat-lying serpentinite lenses. Felsic dykes are related to a 660±12 Ma old quartz monzonite. Gold ores of **Cluster E**: are commonly associated with massive and stringer deposits of Fe-Cu-Zn sulphides within a shear zone. (WORL, 1980)

(c) RARE METAL ORES RELATED TO LATE FELSIC PLUTONISM

J. Akash, Sn (Fig. 5, n. 7).
Tin-rich greisen (JACKSON and RAMSAY, 1986). West and south-west: Nb,Th,REE in granites of Ha'il area, and several fluorite occurrences in the Zarghat-Hanakiya-Nuqrah region (STOESER and ELLIOTT, 1980).

J. as Silsilah, Sn (Fig. 5, n. 8). *1 Mt grading 0.18% Sn* (MINING ANN. REV., 1986).
Alkali feldspar granite association. High grade cassiterite in quartz-topaz greisen. In the same area, stibnite-gold association. (JACKSON and RAMSAY, 1986).

Baid al Jimalah, W-Sn (Fig. 5, n. 9). *821,000 t averaging 0.117% WO$_3$, 0.01% Sn.*
Alkali feldspar granite association. In metasediments and greisenized sheet-like granite overlying a buried granite cupola. Vein swarms over 1400 m, early generation of quartz-feldspar-wolframite (fluorite), late quartz-muscovite-fluorite-cassiterite assemblage containing polymetallic (Fe-Cu-Sn-As-Pb-Ag-Bi-Sb-Mo) sulphides. (JACKSON and RAMSAY, 1986).

J. Kirsh, NNE of Bir Tawilah, Mo.
Disseminated molybdenite + pyrite in highly silicified breccia pipe within fine grained pink calc-alkaline granite. Enclosed in kyanite-rich schists and quartzites (750,000 t grading 40% kyanite; MINING ANN. REV., 1986).

Bir Tawilah, Sn-W (Fig. 5, n. 11). *Estimated 265,000 t grading 0.69% WO$_3$, 0.13% Sn, 26 g/t Ag.* (SALPETEUR, 1985).
Monzonite-granodiorite association. Western prospect: WNW-trending thin veins, up to 600 m long, of quartz, wolframite, minor cassiterite, Fe-Cu-As-Pb-ZnAg sulphides, tetrahedrite, gold, electrum. Central prospect: Mo(Sn,Cu) stockwork extending at depth. (JACKSON and RAMSAY, 1986).

J. Thaaban, Kushaymiyah batholith, Mo-W (Fig. 5, n. 10).
In biotite monzogranite, affected by sericitization and greisenization. Two vein systems, mineralized with disseminated pyrite, molybdenite, scheelite (galena, chalcopyrite, bismuthinite). (JACKSON and RAMSAY, 1986).

J. Umm al Suqian, 80 km NE of Bishah, Sn.
Albitized apogranite, Sn(F, Li, Rb, Zn) anomaly. Not economically significant mineralization of fluorite, ixiolite, monazite, bastanaesite, betafite. (BOKHARI et al., in DRYSDALL et al. eds., 1986).

J. Tarban, Be.
Beryl pegmatite forming a carapace on a small stock of alkali feldspar microgranite. (JACKSON, in DRYSDALL et al. eds., 1986).

Al Amar suture zone-Ar Rayn terrane (Fig. 2)

The Al Amar suture zone separates the Afif block from the Ar Rayn easternmost terrane in the Arabian Shield. The Ar Rayn terrane contains subduction-related intermediate volcanics with abundant calc-alkaline to high-K calc-alkaline components (ROOBOL et al., 1983) suggesting active continental margin setting (COULOMB et al., 1980/81). The volcanics are older than 670 Ma (CALVEZ et al., 1984 ; STACEY et al., 1981) and are associated with a mantle-derived tonalite-trondhjemite suite (LE BEL and LAVAL, in DRYSDALL et al. eds., 1986). The presence of significantly older continental crust beneath the Ar Rayn terrane is controversial (CALVEZ et al., 1985; STOESER and CAMP, 1985; STOESER and STACEY, 1988). Syn- to late tectonic calc-alkaline intrusions and post-orogenic alkali feldspar granites are considered the product of remelting of the early subduction related plutons (LE BEL and LAVAL, op.cit.). The Al Amar suture zone resulted from the collision of the Ar Rayn terrane with the older Afif block during the Al Amar orogeny (670-630 Ma) followed (up to 580 Ma) by the Najd cycle of transcurrent faulting. During this time interval, the involved rock units, consisting of an assemblage (~700 Ma old) of accretionary prism clastics (Abt schist) and ophiolitic mélange (AL-SHANTI and MITCHELL, 1976; AL-SHANTI and GASS, 1983) were intruded by calc-alkaline plutons and post-orogenic alkali feldspar granites (Ad Dawadami province) partially derived from anatexis of the Afif block (LE BEL and LAVAL, op.cit.). The structurally, magnetically and lithologically different Ar Rayn and Ad Dawadami-Abt schist provinces also have different (Cu-Zn-Au vs. Pb-Zn-Ag) metallogenic signature (CAMP et al., 1984).

(a) ORES RELATED TO OPHIOLITE-ISLAND ARC ASSEMBLAGE

Chromite, asbestos, auriferous listwaenites.
Ultramafic-mafic belts along the Al Amar fault and at the boundary Abt schist-Ad Dawadami granitoid province. Fragments of ophiolitic lithologies in a sheared and carbonated serpentinite matrix. Reported are blocks of chromitites (AL-SHANTI and GASS, 1983), asbestos showings (BRGM prospects 1969), auriferous listwaenites in the Al Amar-Asihailiya district (BUISSON and LEBLANC, 1985, 1987).

Jabal Idsas, Fe. 47.3 Mt grading 20.8% Fe. (RIOFINEX, 1977).
Magnetite pods, blebs, disseminations, stringers in tectonized meta-andesite and gabbro. Larger bodies strongly folded and faulted.

AL AMAR-IDSAS DISTRICT (Fig. 4). VOLCANOGENIC SULPHIDE ORES

Umm ash Shalahib Cu, Zn, Ag, Au. Zn grades up to 18%.
a) Basal pyroclastics (pumice flow/fall sequence), large subconcordant silicified and pyritized zones. b) Carbonates. c) Explosive ash-sand fall sequence. Intrusive bodies in

a), b): rhyolite dykes and domes cut by breccia pipes, in c) rhyolite + carbonate vein networks. Hydrothermal alteration: carbonatization of dome hyaloclastic ring, talc lenses in carbonates, stockworks (silica, pyrite). Mineralization: stratabound in carbonates (Au ,Ag, Ba, Zn ,Mn, Pb), stockwork in breccia pipe (Au, Ag, Zn, Cu). Pyrite, chalcopyrite, sphalerite, galena, minor pyrrhotite, bornite, mackinawite, tetrahedrite, Au (electrum), magnetite, hematite, chalcophanite. (SABIR and POUIT, 1984; POUIT et al., 1989).

Al Amar Au, Ag, Zn, Cu. 5.67 Mt (9.2 g/t Au, 5.0% Zn, 0.75% Cu). (RIOFINEX, 1977; SABIR and POUIT, 1984). *Reduced tonnage and grades in more recent estimates* (MINING ANN. REV., 1986).
Sequence and mineralization: a) Intermediate/basic green tuffs, extensive (up to some 100 m) subconcordant hydrothermal alteration zones with FeS_2 and traces of Cu, Pb, Zn. Disconformity. b) Tectonism, formation of paleo-graben floored with polymict conglomerate. c) Active explosive volcanism, spreading of pyroclastic flows and breccias centered on graben-controlled breccia pipe. Intercalated red chert layers (with pyrite-Cu). d) Deposition of fine-grained ash-sand pumice fall sequence, intercalation of exhalites (talc, carbonate) with Zn, Ba, Au mineralization. e) Formation of main mineralized stockwork, connected to N 140 left-lateral strike-slip faulting. Disconformity. f) Upper ash fall, carbonate, acidic pyroclastic, green tuff sequence. 150 m-wide cockade quartz-vein stockwork. Potassic alteration, barite. Pyrite, sphalerite (with chalcopyrite inclusions), minor chalcopyrite, galena, tetrahedrite. Abundant native gold (not argentiferous) strictly associated with ZnS and Au-Ag tellurides (petzite, sylvanite), minor hessite, altaite. Traces of magnetite, hematite, carbonate-quartz gangue, δ^{34} S + 10.1 to + 19.6. (SABIR, 1979; RYE et al., 1979; POUIT et al., 1989).

Umm ad Dabah, At Taybi, Marjan (Zn, Pb ,Ag, Au).
In upper explosive tuff units (overlain by sedimentary carbonates at Umm ad Dabah), intrusive rhyolite dome and silicic lava networks in carbonate masses. Structural controls: dome fracturing, collapsed dome border breccias. Hydrothermal alteration: carbonatization of dome hyaloclastic ring, carbonate vein stockworks. Rare stratabound magnetite, Cu, Zn ores (Umm ad Dabah); disseminated and stockwork Ba, Zn, Mn, Ag, Au(Pb, Cu) ore. Marjan: pyrite, chalcopyrite, sphalerite, galena, tetrahedrite, chalcophanite. (SABIR and POUIT, 1984; POUIT et al., 1989).

Muhtiag Pb(Zn,Mn)
In lapilli tuffs. "Mega" stockwork of carbonate-manganese gangue with disseminated galena ore (2% Pb). Galena, sphalerite, hematite. (COULOMB et al., 1980/81).

Khnaiguiyah Zn, Cu. 30 Mt (3.3% Zn, 0.4% Cu). Reported sections with Zn grades up to 9.9% and Cu up to 1.7%. (RIOFINEX, 1977)
a) Basal green tuffs and flows (pillow-lavas?) of intermediate composition. b) Intense ignimbrite subaerial volcanism: banded ignimbrites, extensive subconcordant alteration

haloes (pyrite, epidote, silica). c) Ash-sand fall sequence, upon syndepositional fault-controlled paleo-surface. Intercalated lenses of carbonates (siliceous-dolomitic brecciated "marbles" grading to bedded carbonate-chert alternances), chloritites, epidosites. d) Reported "cap" of sedimentary carbonates in Area I, Orebodies 3-4. Discordant bodies: rhyolite plugs (and sills) in tuffs, in carbonate masses silicic lava networks. Four bodies of disseminated, massive and stockwork ore. Metasomatic disseminated and massive Mn-rich Zn, Cu ore in carbonates+silicic lava networks. Stratabound ores in epidotized tuffs (zoning: central hematite-pyrite with later mushketovitisation; Cu-Zn zone with tellurides; Zn, pyrite, hematite peripheral zone). Stockwork ore: chlorite, pyrite, chalcopyrite with strong Si, Ba, Mn alteration. Pyrite, chalcopyrite, sphalerite, galena, FeS, magnetite, hematite, chalcophanite, Ag,Bi(Hg) tellurides. Reported presence of Cu-Bi sulphides and of the rare Cu-Zn-Sn sulphide kesterite, $\delta^{34}S$ + 17.3 to + 40.3. (RYE et al., 1979; TESTARD et al., 1980; SABIR and POUIT, 1984; POUIT et al., 1989)

(b) ORES RELATED TO LATE FELSIC PLUTONISM

Ar Ridayniyah Zn,Ag,Sn Estimated 400,000 t grading 4% Zn (RIOFINEX, 1977, 1981) *to 2.7 Mt at 2.65% Zn, 20 g/t Ag* (JACKSON and RAMSAY, 1986).
In impure dolomitic marbles, replacement-type massive sulphide lenses related to leucogranite sills and stocks. Finely laminated pyrrhotite and sphalerite (pyrite, chalcopyrite, galena, cubanite, Ag-Bi minerals). Younger veins, also cutting granite, contain stannite, cassiterite and arsenopyrite.

Samrah Ag, Pb, Zn 330.000 t grading 425 g/t Ag, 4.5% Zn, 0.9% Pb.
In a shear zone related to the Najd system. Several veins mineralized with pyrite, sphalerite, galena, chalcopyrite, Ag-minerals (JACKSON and RAMSAY, 1986). More generally, the Ad Dawadami district Ag-Pb-Zn mineralized veins (Fig. 4) with lead model ages clustering at about 570-530 Ma, develop in dilational structures of the Najd master faults (AL-SHANTI, 1976; MOORE and AL-SHANTI, 1979; STACEY et al., 1980).

TABLE A-3. EAST SAHARA CRATON-NORTHWESTERN MOZAMBIQUE BELT BRANCH

Eastern margin of the East Sahara Craton: polymetamorphic basement-extending west of the Nile and White Nile from the Sudan-Egypt border to the Equatoria province (Fig. 1). High grade gneisses and migmatite represent the dominant lithologies of a linear zone of Middle Proterozoic and Pan-African structural reworking of an ancient continental crust (KRÖNER, 1979; HARRIS et al., 1984; BLACK, 1985b; SCHANDELMEIER et al., 1988; VAIL, 1988). The polyphase evolution of this zone embraces: (a) a Late Archaean to Early Proterozoic episode of deformation and granulite to amphibolite facies metamorphism (2900-2500 Ma) extensively recognized in the older volcano-sedimentary assemblages of the Western Nile Complex, trending E-W and adjacent to the northern edge of the Congo-Tanzania craton (ALMOND 1969; LEGGO, 1974; CAHEN et al., 1984; BLACK, 1985a; VAIL, 1988). To the north, comparable Archaean crustal evolution is only recognized in the G. Uweinat-G. Kamil inlier (KLERKX and DEUTSCH, 1977; SCHANDELMEIER et al., 1988) and farther west (Tibesti); (b) a Middle Proterozoic regional tectono metamorphic event with NE to NNE fold axis trends and widespread anatexis (1900-1600 Ma) followed by (c) a Late Proterozoic (Pan-African) overprinting of the new-generated Middle Proterozoic crust, of intensity notably increasing towards the tectonic boundaries with the Mozambique Belt and the Arabian-Nubian Shield (CIVETTA et al., 1980; SCHANDELMEIER and HARMS, 1987; HARMS, 1987; SCHANDELMEIER et al., 1988).

Western greenschist belts: the high grade gneisses of the East Sahara Craton margin are apparently devoid of metallic mineralizations. Known occurrences lie only within, or in close proximity to some widely spaced greenschist facies volcano-sedimentary belts infolded with the gneisses, NE-to NNE-trending and recognized at variable distances from the assumed craton margin along the Nile longitude (VAIL, 1985a, 1988; WHITEMAN, 1971). Lithologic assemblages include abundant fine-grained, often tourmaliniferous clastics, metavolcanics with bimodal tendency, and iron formation. Ultramafic-mafic rocks of ophiolitic affinity are recorded in NE Nuba Mountains (HIRDES and BRINKMANN, 1985; STEINER, 1987; SALAM and DAWOUD, 1987; BRINKMANN et al., 1989) and by HARMS and ABDEL-RAHMAN at J. Rahib west of Wadi Howar (G. MATHEIS, pers. comm.). The ophiolite slices are tectonically emplaced during a cycle of strong deformation, low-grade metamorphism, strike-slip faulting, granite intrusion and pegmatitic hydrothermal activity which affected the belts in middle to Late Pan-African (750-500 Ma). The assumed general picture is that of a Late Proterozoic intracratonic rift basin system, with opening and extension only slightly predating the onset of compression and basin closure. Known mineralizations comprise iron, copper, uranium, molybdenum, fluorite, lead, zinc and gold occurrences.

Hofrat En Nahas (Darfur province). Estimated reserves 20 Mt grading 5.9% Cu to a depth of 200 m (MINING ANN. REV., 1990).
Linear array, 125 km long, of copper showings. Mining workings at Hofrat en Nahas (9°-48' N - 24°-05' E) delineate a branching lode of copper-rich tourmaliniferous breccia surrounded by an extensive hydrothermal alteration envelope at the contact between sheared quartzites and mafic-ultramafic schists, intruded by granitic and syenitic dykes. Associated with copper are gold (up to 9 g/t), U, Mo, Co, Ag, Pb, Zn.

Kutum (El Fasher, Western Sudan), Pb-Zn
Granite-related NW-trending veins of galena, sphalerite, pyrite with minor chalcopyrite, arsenopyrite, marcasite, traces of silver. Wallrock alteration (chloritization, kaolinization). At depth, increase of Zn and Cu grades. The veins predate late quartz porphyry and dolerite dykes (WHITEMAN, 1971).

NE Nuba Mountains, Abu Zabed-Southern Kordofan BIF, U, F, Pb, Au, chromite (Fig. 1, n. 36, 36a)
Hydrothermal ores of uranium, fluorite (galena) related to late alkali granites, and gold-bearing smoky quartz veins. At J. Dumbeir, indicated are 100-300.000 t of fluorite, in part of acid grade. Soda granites with traces of fluorite, Zn, Cu, Mo, Ni, Cr, as well as fault-controlled "reef" quartz breccias carrying hematite, Fe-Mn hydroxides, rare Ba-Mn(Co) oxides (Ba-hollandite) and tourmaline are recorded by HIRDES and BRINKMANN (1985) in the Nuba (Kabus-Balula) greenstone sequence overlain by graphite-rich schists, immature tourmaliniferous psammites and quartz-pebble conglomerates. In the Cr-Ni enriched greenstones, magnetite-bearing hydrothermal chloritite layers (HIRDES and BRINKMANN, 1985) are precursors for high-grade magnetite/martite bodies (65-95% Fe_2O_3, 180 ppm Zn, 350 ppm Cu) isoclinally folded with garnetiferous amphibolites enveloping a gneiss dome (STEINER, 1987). In Kabus North, some banded iron formation occurrences (25-55% Fe_2O_3, 0.74-1.28% Cr_2O_3, 0.27-0.90% NiO + Co, As, Cu, W, Zn, Au) are recorded in the ferruginous metachert horizon at the top of greenstones (HIRDES and BRINKMANN, 1985). Characteristic of the BIF are traces of Cr-tourmaline and fuchsite. Banded iron formation is also known at J. Abu Tulu in South Kordofan where magnetite (martite) bodies (36 Mt, 55-65% Fe, n. 36a) are found in quartz-sericite schists associated with metavolcanic layers (WHITEMAN, 1971). Within the Nuba belt scarce, strongly altered ultramafic lenses of talc schists and serpentinites carry disseminated chromite, magnesite (10 Mt) as well as As-Ni-Co anomalies (HIRDES and BRINKMANN, 1985; MINING ANN. REV., 1984).

Northwestern Mozambique Belt gneisses: Pan-African domain of severe deformation, remobilization and plutonism (VAIL, 1985a, 1988) which occurs along the rifted continental margin of the East Sahara Craton from Southern Egypt to the Sudan-Kenya-Uganda international boundary, where is described as the western orogenic front of the

Mozambique Belt (ALMOND, 1969; LEGGO, 1974; CIVETTA et al., 1980; VEARNCOMBE, 1983a, b). Dominated by likely time-equivalent (1150-1000 Ma: CAHEN et al., 1984; HARRIS et al., 1984; RIES et al., 1985) supracrustal sequences of quartzo-feldspathic gneisses, graphitic metapelites, Ca-silicates, amphibolites and minor marbles (WHITEMAN, 1971; VAIL, 1975 1988; MEINHOLD, 1979; VAIL and HUGHES, 1987; DÜRR and DAWOUD, 1987) which mostly represent shallow shelf deposits resting upon the Middle Proterozoic migmatitic gneisses of the East Sahara Craton foreland. Detrital components indicate precursor materials derived from 2650 to 1700 Ma old erosional source regions (HARRIS et al., 1984; KRÖNER et al. in SCHANDELMEIER and HARMS, 1987). Mature quartzites become abundant only in the Karasuk/Cherangani metasediments coating the edge of the Archean Congo-Tanzania craton (VEARNCOMBE, 1983b). Metasediments (and foreland gneisses) apparently underwent an extended period of Pan-African deformation and metamorphism, starting at about 850 Ma (MEINHOLD, 1979; HARRIS et al., 1984; CAHEN et al., 1984; VAIL and HUGHES, 1987) but reaching its climax in the 700-650 Ma interval. Large-scale crustal shortening, tectonic thickening and the establishment of a high P/T gradient are evidenced by granulite to amphibolite grade metamorphism, generation of charnockitic magma and widespread formation of anatectic migmatites. Kyanite is ubiquitously recorded, locally in mineable concentrations (Bayuda Desert), besides sillimanite, garnet and staurolite (SANDERS, 1964; WHITEMAN, 1971; VAIL, 1975; LEGGO, 1974; CIVETTA et al., 1980; VEARNCOMBE, 1983a, b; KRÖNER, 1985; KRÖNER et al. in SCHANDELMEIER and HARMS, 1987; DÜRR and DAWOUD, 1987; VAIL and HUGHES, 1987).

Pegmatites (Fig. 1, n. 26a, 77, 78, 79)

650-600 Ma old pegmatitic bodies (VAIL, 1975; CAHEN et al., 1984; VAIL, 1985b) of radioactive (in the migmatitic gneisses) and mica/rare metal (in the high-grade metasediments) types. In the North Karamoja migmatitic gneisses of NE Uganda (635±30 Ma LEGGO, 1974) biotite-rich pegmatitic schlieren and pegmatoid bodies carrying abundant radioactive allanite, greenish-black sulphur-bearing and yellow monazite, zircon, ilmenite, rutile are reported (VON KNORRING, 1970; Fig. 1, n. 77). Mica, samarskite, columbite (Y, REE, Nb, U, Th) bearing pegmatites are known at West Suk in Western Kenya (Fig. 1, n. 78) where the Turbo migmatites and granites, with Nd model age of 1950 Ma (VEARNCOMBE, 1983b; HARRIS et al., 1984) grade to the Cherangani metasediments rimmed by granitized hornblende schists and gabbros. In this zone, north of Kitale at Sebit, a sodolithic pegmatite body contains gem quality beryl, microlite and columbo-tantalite. Some beryl with ruby mica is also recorded at Baragoi, Fig. 1, n. 79 (VON KNORRING, 1970). The Rubatab-Shereik (Fig. 1, n. 26a) mica pegmatite belt of Eastern Bayuda Desert (Sudan) is hosted by high-grade metasediments interlayered with amphibolite and gabbro bodies (DE KUN, 1965; WHITEMAN, 1971; VAIL, 1975). Scrap mica low in Rb, Li, Cs (MATHEIS and KÜSTER, 1987) is exploited from elongated veins, foliation-parallel and boudinaged, carrying tourmaline, garnet, apatite and disseminated beryl. In the wallrocks, tourmalinization is common together with an unusual enrichment in kyanite and biotite. The pegmatites are dated at about 630 Ma (VAIL, 1975, 1985b) largely prior to the intrusion of late ($\leq$550 Ma) undeformed, K-rich granites.

Sabaloka (North of Khartoum, Sudan) W,Sn (Abu Dom, reserves unknown; Fig. 1, n. 35) Group of Bayuda Desert and Sabaloka alkali granites, assigned by PEARCE et al. (1984a) to the within-plate group of intracontinental ring complexes and dykes. The Sabaloka Complex, apparently coeval with a bimodal sequence of K-rich basalts and subaerial ignimbritic rhyolites (ALMOND, 1967) is considered to be about 385 Ma old (HARRIS et al., 1983) but older ages are recorded too. The complex is of "specialized" type, including granite, microgranite and greisen varieties carrying traces of fluorite, cassiterite, Li-mica, zircon and topaz. The main mineralization consists of a stockwork of quartz-wolframite veins with minor cassiterite, jarosite (galena, malachite) and disseminated fluorite, powellite, scheelite and flaky molybdenite.

Eastern greenschist belts: east of the Nile and White Nile, a composite lithotectonic and metallogenic zone with sublongitudinal structural trend straddles the Sudan-Ethiopia border (Eastern Bayuda Desert, Sabaloka Gezira, Ingessana-Kurmuk-Wollega) extending southwards to the NE Uganda and NW Kenya (Fig. 1). The zone is characterized by the predominance of volcano-plutonic ophiolite-bearing assemblages, forming imbricate thrust stacks over the sediment-draped East Sahara Craton continental shelf (VAIL 1988). The northern Qala en Nahal-Butana and East Bayuda Desert exposures lie close to the Nubian Shield conventional boundaries and are included in the related Table A-1. The southern exposures comprise the blocks of Kurmuk-Wollega-Akobo (Sudan-Ethiopia) and Sekerr (Kenya) considered to form a major wedge-shaped indentation of the Nubian Shield into the ensialic Mozambique Belt (KAZMIN et al., 1978; KRÖNER, 1979; POHL, 1984, 1988; EL-GABY and GREILING, 1988). East of the wedge, the basement terranes showing E-W structural relics (MOORE et al., 1987) pertain to the northeastern branch of the Mozambique Belt (WARDEN and HORKEL, 1984) continuous up to North Somalia as confirmed by recent radiometric data (KRÖNER et al., 1989). The wedge is dissected by a system of NW-trending faults transversal to the main N-NE foliation trend (Fig. 1) and active since Late Precambrian as sinistral shear/mylonite zones (ALMOND, 1969g; KAZMIN, 1980; CIVETTA et al., 1980; SHIFERAW in CHEWAKA and DE WIT, 1981; VAIL, 1983; MOHR, 1986; BERHE 1986) of the type recognized elsewhere in East Africa (SUTTON and WATSON, 1959; MC CONNELL, 1980). The wedge is underlain to the south by older sialic crust, as suggested by the Nd model age (1950 Ma) of the Marich granite (593±49 Ma: HARRIS et al., 1984) east of the Sekerr ophiolite. High grade gneissic-migmatitic fragments, lacking E-W structural relics (MOORE et al., 1987) are also embedded within the lower grade volcano-sedimentary belts of the Kurmuk-Wollega block, representing possible continental microplates detached from the craton margin (MOORE et al., 1987; VAIL, 1988). According to SCHANDELMEIER et al. (1988) radiometric dating on craton margin west of the Nubian Shield boundary, (Wadi Howar, Nubian Desert, Bif Safsaf inlier, Fig. 1) has provide evidence of rift-related granitic magmatism at about 1200-1000 Ma. Interestingly, coeval granite intrusions are also reported in Southern Sudan, west of the Aswa-Nimule shear zone (CIVETTA et al., 1980). Interposed between the high-grade gneissic domains (Kadalo-Qeissan, Baro Geba) of the Kurmuk-Wollega region is a branching network of N-NE to NW trending sheared, low- to medium-grade metamorphic belts hosting platinum iron, titanium, chromite and base metal occurrences (Fig. 1, n. 45-53).

BIRBIR (WOLLEGA, WESTERN ETHIOPIA) BELT

The north-trending Birbir tectonitic belt (Birbir Shear Zone of TEKLEWOLD et al., 1987) records intense plutonic and volcanic activity, starting at about 800 Ma, accompanied and followed by multiphase transcurrent shear and development of mylonitic foliation up to considerable crustal depth (MOORE et al., 1987; TEKLAY, 1987). Different types of volcano-sedimentary assemblages are recognized throughout the belt, (a) high-Ti (locally high Mg) metabasaltic flows and tuffs widespread in the Tulu Dimtu and Yubdo Koree areas (WARDEN et al., 1982; JELENC, 1966) associated with deep-water sediments including the Sai River copper-bearing carbonaceous-pyritic shales (SIGHINOLFI et al., 1987); GETANEH ASSEFA et al., 1987); (b) turbidites with minor andesite to rhyolite flows and shallow intrusions in the plutonite-dominated Baro River area (MOORE et al., 1987; TEKLAY 1987); (c) andesite to rhyolite volcanics and volcanoclastics, associate shallow-water sediments, some subaerial tuffs at Kata (DE WIT, in CHEWAKA and DE WIT, 1981); (d) continent-derived, late quartzites and psammite (WARDEN et al., 1982; SIGHINOLFI et al., 1987). An alkalic trend characterizes the plutonic intrusions associated with conspicuous dyke systems, ranging from early (about 800 Ma) high-K calc-alkaline diorite granodiorite to late (>500 Ma) post-tectonic, LREE-enriched potassic granites (TEKLEWOLD et al., 1987). Depositional facies changes and magmatism geochemistry suggest emplacement of the Birbir group across rifted continental margin between a sialic marginal high (Baro) and a major continental plate (Geba) to the east. Several oval-shaped ultramafic-mafic bodies of serpentinized dunite, wehrlite, clinopyroxenite, olivine gabbro, hornblende gabbro, hornblendite, locally preserving a zoned structure are mapped throughout the belt, and the Yubdo-Dalati-Tulu Dimtu alignment is currently considered as an ophiolitic suture (KAZMIN et al., 1978; WARDEN 1981; DE WIT, in CHEWAKA and DE WIT, 1981; VAIL, 1985a; SIGHINOLFI et al. 1987; SHACKLETON, 1986, 1988). However, WARDEN et al. (1982) remark the atypical, LREE-enriched geochemical pattern of the Tulu Dimtu (Dimitri) ultramafics. CABRI (1981) includes the Yubdo Pt-Fe deposit into the Alaskan type class, implicitly rejecting an ophiolitic nature for the related ultramafic complex.

Pt,Fe-Ti,BIF,Au,Cu (Fig. 1, n. 48-53)

a) Alaskan type ores

The Yubdo platinum-gold placer (output to 1965 = 1856 kg Pt, estimated reserves 2000-3000 kg Pt, 300 kg Au) associated with a serpentinized dunite-wehrlite-clinopyroxenite complex (USONI, 1952; JELENC, 1966; DE WIT and BERG in CHEWAKA and DE WIT, 1981) is comparable to the Tulameen (British Columbia) deposit in the North American Cordillera as concerns type of placer mineralization (NIXON et al., 1990) and geological setting (FINDLAY, 1969; PRETO, 1977; MORTIMER, 1986). Old chemical assays reported by AUGUSTHITIS (1965) and modern mineralogical analysis (CABRI et al., 1981) of Yubdo Pt-Fe alloy nuggets reveal a characteristic Alaskan type composition of the primary ore with high (Pt+Pd)/(Ru+Os+Ir) ratio accompanied by high Pt/Pd ratio. Among the silicate inclusions, traces of olivine (Fo_{93}-Fo_{94}) are compositionally similar to the forsterite of Tulameen chromitites, considered by NIXON el al., to be the source of placer mineralization. At Yubdo, this source is unknown. However, the "secondary" generation of sperrylite ($PtAs_2$) found in the ferrichromite-magnetite alteration zones of Tulameen chromitites, can be compared with the reported widespread formation of sperrylite (optical and X-ray identification) and magnetite at the expenses of chromite in an advanced alteration stage of the Yubdo dunite (AUGUSTHITIS, 1965). The highly resistant platinum arsenide also survives in the end-product of the process, consisting namely of collomorphic silica+limonite (birbirite). Traces of eluvial-alluvial platinum are reported both south and north of Yubdo. At Tulu Dimtu, platinum occurs in chromite-magnetite heavy streaks on hill slopes (DE WIT and BERG in CHEWAKA and DE WIT, 1981) and magnetite, chromite and PGM are reported by GETANEH ASSEFA et al. (1981) in the serpentinized ultramafics. Traces of PGE in the Tulu Dimtu ultramafic and gabbroic rocks (SIGHINOLFI et al., 1987) have abundances and distribution pattern analogous to those found at Tulameen by ST. LOUIS et al. (1986). Consistent with the extension of the "Alaskan" type to other metallic ores (LAZNICKA, 1985) is the very recent discovery (MINING ANN. REV. 1990) near Gimbi/Dalati of hornblendite-hosted apatite-magnetite-ilmenite occurrences (23.8% Fe_2O_3, 7.32% TiO_2, 4.6% P_2O_5, 0.03% V_2O_5) at the periphery of an oval intrusion of gabbro-anorthosite. Pegmatoids bearing titaniferous iron oxides (hematite-ilmenite and magnetite-ilmenite) are reported in the Gambela-Dembidollo area, at the confluence of Baro and Sacco rivers (JELENC, 1966).

b) Iron ores (Fig. 1, n. 48 ,50, 51)

Oxide facies iron formation (Fig. 1, n. 50-51) is widespread west of the Yubdo-Tulu Dimtu aligment. Ferruginous quartzite/metachert horizons reaching a maximum thickness of 15 m, mostly associated with ferruginous and quartzose metapelites are described north of Yubdo and in the Kata area (JELENC, 1966; WALSH, in CHEWAKA and DE WIT, 1981). Iron content is low (18-40%) with some Mn (<1%). Traces of Pb, Zn, Cu, Ag, Ba, W are reported, and boron contents are regarded by JELENC (1966) as a possible source for the tourmaliniferous breccias observed in nearby intrusives. The

BIF horizons include low silica, high grade (63-70% Fe_2O_3) martitized magnetite lenses, the size of which is dependent on the thickness of the host iron quartzite horizon (JELENC, 1966). The high grade lenses account for less than 1 Mt of iron ore and are probably generated by tectono-metamorphic concentration. Higher tonnages are reported for lower grade ores (18 Mt; MINING ANN. REV., 1989). South of Yubdo, magnetite lenses are interlayered in basic amphibolites and chlorite schists. This type of ore is often Cu- and Zn-bearing (Wabera Chiltu, Fig. 1, n. 48; MMA Japan, 1974 in OMENETTO, 1984).

c) Copper and gold-tourmaline ores (Fig. 1, n. 49, 52,53)
Stratiform copper anomalies are recorded by GETANEH ASSEFA et al. (1987) in the Sai River pyritic-carbonaceous shales with interbedded limestone lenses. At Kata by Nejo (DE WIT, in CHEWAKA and DE WIT, 1981) pyrite-rich andesite-dacite-rhyolite volcanics and volcanoclastics comprise marbles lenses, bedded ironstones and quartzites locally grading to martite-rich breccias with quartzitic and metavolcanite fragments, as well as layers up to 40 cm-thick of barite. Drilling has indicated that high-Cu geochemical anomalies at surface give way to magnetite-chalcopyrite concentrations (average Cu 0.5%) at depths of 150-200 m. Zn (to 1%) and Cu anomalies in quartzites are also recognized. Evidence of syngenetic ore appears as largely destroyed by metamorphic recrystallization and remobilization connected to transcurrent shear and related magmatic/hydrothermal activity as pointed out by MOORE et al. (1987). Normally barren marbles host at depth contact-metasomatic bodies of gold-bearing pyrite-magnetite-chalcopyrite. Magnetite (Cu) enrichments are observable at the sheared periphery of metadiorite-granodiorite domes which at Kata, in DE WIT's opinion, unconformably underlie the volcano-sedimentary sequence. A low grade chalcopyrite-bornite mineralization of porphyry-type is also described in the Kata blue-quartz porphyry, intrusive in granodiorite and metasediments (Fig. 1, n. 49).
Gold (Ag, As, S) traces in the Tulu Dimtu ultramafics have been introduced, according to SIGHINOLFI et al. (1987) from the enveloping metasediments during serpentinization and silica metasomatism. However, gold-copper minerals (cuprian gold, bornite, chalcopyrite, cubanite) are reported as primary inclusions in Pt-Fe alloy matrix at Yubdo (CABRI et al., 1981). Chalcopyrite, pyrite and tourmaline are the distinctive companions of gold in the explored occurrences of Birbir belt as well as of the entire *Kurmuk-Wollega district. Gold-bearing pyrite-chalcopyrite disseminations and veinlets* are reported within conformable quartz lenses in amphibolites at Tulu Kami (Fig. 1, n. 53), in quartzites at Tulu Kapi-Ankori (n. 52) and in metadiorites at Laga Bagudu (n. 52). Average grade is commonly less than 5 g/t Au (USONI, 1952; JELENC, 1966; EVANS, in CHEWAKA and DE WIT, 1981; GILARDI, 1910 in OMENETTO, 1984). Enhanced gold grades occur at the intersection with late quartz-tourmaline (Laga Bagudu) or arsenopyrite-bearing micropegmatitic veins cutting sheared diorites and syenites (Tulu Kapi-Ankori) as demonstrated by UNDP drilling (1972, in OMENETTO, 1984).

South of the Baro River, the Akobo alluvial gold is connected to the southern extension of the Birbir belt, comprising quartz-tourmaline veins and ultramafic-mafic bodies with copper disseminations in the vicinity of the Akobo NW-trending shear zone (ALEMU SHIFERAW in CHEWAKA and DE WIT, 1981).

KURMUK-ASOSA (WOLLEGA, WESTERN ETHIOPIA) BELT

The Kurmuk-Asosa volcano-sedimentary belt is composed of a principal branch running NNE along the Sudan-Ethiopia border between the Kadalo-Qeissan and Baro gneissic blocks. North of Asosa, a southeast-directed subsidiary branch merging eastward into the Birbir belt develops parallel to the Diddessa River fault system. The belt lithologies comprise greenschist facies metamorphosed and sheared basic-acidic volcanics, quartzitic and graphitic sediments, dioritic intrusions and Yubdo-type ultramafic-mafic bodies (Nazile-Shungu alignment).

Au, Cu ores (Fig. 1, n. 45-47)
Prospecting (GULIEV, 1982 in OMENETTO, 1984) has revealed a variety of metallic anomalies, hydrothermal alteration patterns and mineralized showings (pyrite-Cu(Zn), Ni-As-Pb-Ag-Cu gold-bearing sulphides) mostly aligned along NNE shear zones at the intersection between the principal and subsidiary branches of the belt (Fig. 1, n. 45). Tourmaline, recognized as a component of the heavy mineral fraction in gold placers (Sirekole; JELENC, 1966) is abundant in the auriferous quartz veins of the Asosa region. In the nearby Sudan similar primary sources are suggested by TOUM and ABDEL RAHMAN (1987) for Fazughli alluvial gold (MINING ANN. REV., 1985). NE of Asosa, significant gold-tourmaline ores are known at Ondonok and Bomu Menghi-Oda Godare (Fig. 1, n. 46-47). Ondonok (DESIO, 1940; USONI, 1952) is an example of a complex vein field controlled by the north and NW-trending lineaments dominant in the subsidiary branch connecting the Kurmuk-Asosa and Birbir belts. Despite locally high gold grades, the exploration results are referred as discouraging (EVANS, in CHEWAKA and DE WIT, 1981) and reliable reserve estimates are not available.

At Ondonok the mineralized veins grade to barren white pegmatites with tourmaline. In the Kurmuk-Wollega region, rare metal pegmatites carrying beryl (Nejo) and molybdenite (Chiltu) are scarce and, together with local Mo-Sn anomalies connected with late, silicified and greisenized alkali granites, devoid of economic significance.

INGESSANA (SUDAN) AND SEKERR (NW KENYA) OPHIOLITE ZONES, CHROMITE OCCURRENCES

In the Ingessana Hills of Sudan west of the Kadalo-Qeissan exotic block, a thrust/faulted complex of island arc volcanics and derivative sediments, older than 680 Ma and accreted to the foreland plate (Kurmuk-Marafa Formations; VAIL and HUGHES, 1987; VAIL 1988) includes a slice of chromite-bearing serpentinites, ultramafic cumulates and gabbros representing the lower section of harzburgite-type ophiolite (SHACKLETON, 1986 1988; ABDEL RAHMAN, 1987). At Ingessana, a small production of high-grade chromite ore (48-52% Cr_2O_3) is known and greater reserves of lower-grade ore (35-40% Cr_2O_3) are reported together with some uneconomic asbestos and magnesite (WHITEMAN, 1971 MINING ANN. REV., 1976/1984).

Podiform chromite (massive and leopard ore) is also recognized in the Sekerr (NW Kenya) ophiolite (VEARNCOMBE, 1983b). We observe that both Ingessana and Sekerr ophiolite have poorly developed upper components such as sheeted dykes, plagiogranites and pillow lavas.

TABLE A - 4. NORTHEASTERN MOZAMBIQUE BELT BRANCH

Yemen-Northern Somalia Transitional Domain

In Northern Yemen the Precambrian is represented by the southernmost extensions of the An Nimas-Al Qarah and Najran terranes of Saudi Arabia, separated by a northwest- to north-trending shear fault system (Mulha, Ashara faults) replacing southwards the Nabitah suture (STOESER and STACEY, 1988). In Yemen, this fault system could be identified in a major lineament with Najd (NW) trend, actually bounding the Wadi Jawf Jurassic graben but demonstrably active since the Precambrian (CHRISTMANN et al., 1983). To the west BERHE (1986) suggests the presence of a system of ancient crustal weaknesses, oriented ENE, later controlling the Gulf of Aden opening. Related to this tectonic pattern, three zones with different geological and metallogenic characteristics can be recognized in the Yemen-Northern Somalia block: (1) the Sa'dah-Lawdh-Al Mukalla belt east of the Wadi Jawf lineament, continuous with the Mait-Erigavo eastern basement segment of Northern Somalia; (2) the NE- to E-NE-trending western volcano-sedimentary belts of Yemen, including the Abdul Qadr volcanics of NW Somalia, bounded to the south by (3) a composite, fragmented gabbro-syenite (carbonatite) belt, recognized in both Northern Somalia and Yemen, intrusive into the high-grade gneisses of the western basement segment (with Middle Proterozoic relict ages recognized in Somalia: KRÖNER et al., 1989).

SA'DAH-LAWDH-AL MUKALLA-ERIGAVO BELT

Sa'dah area, Fe(Ni), Au, Sn (Fig. 1, n. 76).
Southern extension of the Malahah-Najran terrane of Saudi Arabia. Isotopic constraints (Najran feldspar and Hailan-Jabali Jurassic galena) suggest rapid transition to a domain underlain by older continental crust (STOESER et al., 1980; STACEY and STOESER, 1983).
Basal clastics and volcano-sedimentary sequences (>1000-700 Ma) evolving in a passive then active continental margin setting. Inferred presence of a continental landmass to the east (WORL, 1980; ROOBOL et al., 1983; DARBYSHIRE et al., 1983; WHITE, 1985). During both Nabitah (675-640 Ma) and Najd (640-570 Ma) tectonic cycles, style of tectonism characterized by dominant vertical movements in a regime of still hot crust, and shear zone activity along major faults (STOESER and STACEY, 1988). Persistent structural control on mineralizations, typical of the southernmost Saudi Arabia ores (Kutam, Dabhah, Al Hajira, see Table A - 2).
Occurrences in the Sa'dah area:
Several hematite-goethite gossans corresponding to iron sulphide layers, with traces of Ni, in graphitic schists (comparable to Qatan-Wassat ores) and siderite veining in late faults (EL-SHATOURI and AL-ERYANI, 1979; LESCUYER, 1990). A fine grained massive pyrite-chalcopyrite sphalerite ore sample, said from Marib area, and reported

to contain 2% Pb besides Cu and Zn, as well as conspicuous traces of Ba, Sb, Ag, Bi in a Ca-Mg(Sr) rich matrix (EL SHATOURI and AL-ERYANI, 1979) has geochemical analogy with the structurally controlled Kutam ores close to Yemen border, yielding lead model age of 600-580 Ma.
In sheared and hydrothermally altered (pyritized, sericitized) metavolcanics and metasediments, auriferous quartz veins with disseminated Fe-Cu-Pb sulphides (LESCUYER, 1990). Comparable to the **Cluster** E ores of the W. Tathlith gold belt (Fig. 6).
Cassiterite-quartz veins at J. Abla. Persistence of Sn(W) mineralization recognized near the Yemen border in Saudi Arabia (STOESER and ELLIOTT, 1980) where the tin granite of Jabal al Gaharra, lying close to the Ashara fault zone, has a very young (308 Ma) lead isochron model age (STACEY and STOESER, 1983).

Lawdh, Au (Fig. 1, n. 75).
Gold-quartz veins with disseminated Fe-Cu-P sulphides in post-tectonic gabbro intrusion fractured and widely carbonatized (LESCUYER, 1990). Comparable to **Cluster C** ores of the W Tathlith gold belt (Fig. 6).

Baihan, Sn.
Cassiterite-bearing quartz veins (EL-SHATOURI and AL-ERYANI, 1979).

Mukalla, Au,Cu (Fig. 1, n. 69).
Gold, Wadi Maddan prospect. Auriferous quartz veins with disseminated Fe-Cu-Pb sulphides related to mafic metavolcanics affected by hydrothermal chloritization in a shear zone. Late, up to one km-long mafic dykes flanking gold mineralization. Shear zone-controlled copper occurrences in Wadi Ghabar metasediments unconformably overlying the Al Mukalla volcanics (LESCUYER, 1990). Wadi Ghabar group of Late Proterozoic arenaceous clastics, quartzite, shale, dolomite and limestone with gypsum, tuffaceous layers and basal conglomerates with volcanic clasts correlated with the Inda Ad and Hadibu (Socotra) complexes (WARDEN and HORKEL, 1984).

Dalan-Majia Yian (NE Somalia), Sn (Fig. 1, n. 68). *At Dalan, 80 t of cassiterite concentrates from placers containing 55% Sn recovered in 1976.*
Dykes and pegmatites hosted by the Inda Ad Complex eastern inlier. Thin dykes of milky to pale grey quartz, mainly running E-W and grouped in swarms of north-trending long axis. Cassiterite associated with thin white/pale green mica selvage containing accessory feldspar, apatite, rutile.

At Majia Yian, grades up to 1.5% of cassiterite, worked 1939-41 by COMINA (USONI, 1952). Wallrocks commonly silicified and tourmalinized. At Majia Yian only a part of the dykes carries cassiterite in potentially economic quantities. Pegmatites (max. 1 m thick, 700 m long) have the best potential for tin. Quartz, K-feldspar, albite, muscovite with columnar enrichments of cassiterite, muscovite, lepidolite, tourmaline, minor apatite and Fe-Zn-Cu sulphides, occasional molybdenite, columbo tantalite and beryl (references in FRIZZO 1987 and this volume). Outcropping close to Dalan is the Las Bar postorogenic calc-alkaline complex of gabbrodiorite, quartz diorite, granodiorite and monzogranite intrusive into the Inda Ad and containing (U/Pb mineral dating) >1000 Ma inherited zircons, 620 Ma magmatic zircons, and 550 Ma sphene generated during hydrothermal alteration and greenschist facies retrogression (KÜSTER et al., 1990; LENOIR pers.comm.). Significantly younger Rb-Sr age for the Las Bar, Infero, Arar intrusion (510-490 Ma) are reported by ABBATE et al. (1987) and DAL PIAZ et al. (1987b).

Seinat (Cu), Kudut (Mn) in the Inda Ad Complex (NE Somalia).
Small copper and manganese sediment-hosted mineralizations occur in the western inlier of the Inda Ad Complex, consisting of locally pyritiferous mudstones interbedded with sandstones, graphitic limestones and dolomites with some evidence of very shallow water depositional facies. Similar occurrences are not recorded in the eastern inlier, where arenites become the dominant lithology (WARDEN, 1981; WARDEN and DANIELS 1984; ABBATE et al., 1987). The Inda Complex is weakly metamorphosed and affected by large-scale open to isoclinal folding associated with spaced to penetrative axial plane cleavage. According to different radiometric data, deformation must have occurred prior to about 620 and 500 respectively. The older age corresponds to the deformation age of Murdama sediments in the southern Arabian Shield (STOESER and STACEY, 1988). However, the Inda Ad depositional facies is better comparable to that of the Jubaylah (Jibalah) group of the Arabian Shield (HADLEY and SCHMIDT, 1980) with age estimated at 600-570 Ma (BINDA, 1981) and even younger (550 Ma) well into the Cambrian (STOESER and CAMP, 1985; see Fig. 3 of this paper).

Mait (Erigavo) greenstones, possible ore potential (FRIZZO, 1987 and this volume).
North-trending greenstone belt flanking the Inda Ad western inlier and "hosted" by a basement of psammitic paragneisses with amphibolite intercalations (ABBATE et al., 1987). Greenschist facies pillowed to massive, sheared metabasalts with MORB affinity, interlayered with phyllites,, and lacking the remaining components of a typical ophiolitic suite (DAL PIAZ et al., 1987b) Correlation with Al Mukalla (Yemen) basic metavolcanics has suggested to Frizzo (op.cit.) the possible presence of massive sulphide and gold ores.

WESTERN VOLCANO-SEDIMENTARY BELTS

In Yemen, SE of Sana'a: NE-trending discrete (northern, central, southern) volcano-sedimentary belts, truncated eastward by the Wadi Jawf lineament. Low-grade metamorphosed intermediate to acidic volcanics, associated with pelitic schists more abundant in the NW. Underlain (unconformably?) by higher grade metasediments (abundant marbles, quartzites, meta-arkoses pelites) with interlayered metabasites (Aden Metamorphic Group; WARDEN and HORKEL, 1984) resting upon high-grade granite gneisses and migmatites of unknown age (CHRISTMANN et al., 1983; BABTTAT et al., 1987). The structural trends are almost perpendicular to those dominating NW Sana'a, in the Asir terrane southern extension where the old Baish-Bahah primitive arc volcanics and derivative sediments interdigitate with the continent-derived clastics of the Sabaya (Sabya) Formation (FAIRER, 1983 in WHITE, 1985; STOESER and CAMP, 1985; see Fig. 3 of the present paper). The western volcano-sedimentary belts and intercalated gneisses are affected by multiple deformation developing at successively shallower crustal levels accompanied by the intrusion of syn- to post-tectonic diorites and granites. Worth mentioning is the presence of NE-striking major ductile shear zones and of SE-verging thrusts indicating nappe structures (BABTTAT et al., 1987). According to LESCUYER (1990) the western volcano sedimentary belts are practically devoid of significant syngenetic polymetallic ores.

Au, Sn, scheelite.
Rare traces in syntectonic intrusions (Au, Sn) and in migmatized zones (scheelite) (CHRISTMANN et al., 1983).

Mo-Cu anomalies.
In the graphitic-pyritic schists of the northern belt. (CHRISTMANN et al., 1983).

Wadi Siryan, Ba (Fig. 1, n. 73).
Barite layers of sedex-type, related to subaerial acidic volcanics and lacking significant base and precious metal contents (LESCUYER, 1990). In the central belt characterized by subordinate silicic volcanism and Pb-Ba-Cu showings (CHRISTMANN et al., 1983).

Al Bayda, Al Fadahah, Cu (Fig. 1, n. 72).
In the southern belt, small copper ore concentrations along shear zones in gneisses or mafic metavolcanics, locally (Al Bayda) invaded by dominant basic dykes showing thermal metamorphism (LESCUYER, 1990; BABTTAT et al., 1987). Al-Taffa (Al Bayda) prospect with mineralized quartz veins (Cu 1-10%) in rhyolite porphyries (EL-SHATOURI and AL-ERYANI, 1979). Al Ma'adan and Saba' chalcopyrite-magnetite veins and magnetite-pyrrhotite skarns (CHRISTMANN et al., 1983). In the Al Fadahah district, veins and "shear zones" with chalcocite and bornite (CHRISTMANN et al., 1983).

In northwestern corner of Somali basement (some further outcrops reported to the east): Abdul Qadr (Abdulkadir) basic to acidic volcanics, with bimodal tendency (DAL PIAZ and SASSI, 1986) preserving relict perlitic, pumiceous and ignimbritic textures (WARDEN, 1981; WARDEN and HORKEL, 1984). Abundant intercalated phyllites, minor thin beds of marbles and quartzite. Low-grade metamorphosed, possibly during a late Pan-African tectonometamorphic event (DAL PIAZ and SASSI, 1986; FERRARA et al., 1987). Unconformably underlain by higher grade metasediments (polymetamorphic with granulite facies relics; SASSI and VISONÀ, 1987) characterized by abundant marbles, quartzites with kyanite layers, amphibolites, talc-tremolite-biotite-graphite schists (Harirad-Mora Series; WARDEN and HORKEL, 1984).

Abdul Qadr and North Darkainle, Fe, Cu, Zn, Pb (Fig. 1, n. 60).
Sedex Fe-Cu-Zn-Pb sulphide occurrences in the Abdul Qadr metarhyolites and geochemical anomalies (Cu, Zn, Pb) in stream sediments (ref. in FRIZZO, 1987 and this volume).

GABBRO-SYENITE (CARBONATITE) BELT IN THE HIGH-GRADE WESTERN BASEMENT

The high-grade western basement of northern Somalia consists of two polymetamorphic complexes preserving relict granulite mineral assemblages and strongly affected by anatexis (DAL PIAZ and SASSI, 1986): the Qabri Bahar Complex (psammite gneisses interlayered with amphibolites and Ca-silicate rocks) and the overlying Mora Complex (marbles and quartzites in migmatites and psammitic gneisses). This lithostratigraphic scheme substitutes the former subdivision of the basement into the Gebile psammites, Borama-Ubali pelites and Harirad-Mora carbonates (WARDEN and DANIELS, 1984; WARDEN and HORKEL, 1984). These strongly deformed metasediments contain frequent lenses of manganese silicate ore, locally associated with iron quartzites with traces of copper (Hudiso, Fig. 1, n. 67 Bur Mado and Marodile, Fig. 1, n. 63; FRIZZO, 1987 and this volume). The age of the metasedimentary assemblage is unknown. Older granitoids with zircon ages in the range 840-810 Ma include 1730-1820 Ma old corroded zircon xenocrysts suggesting the presence of Middle Proterozoic crustal component (KRÖNER et al., 1989). The Qabri Bahar and Mora complexes host several bodies of ensialic metagabbro and foliated syenite, and are later intruded by foliated to undeformed younger granites, aplites and pegmatites. Mineralized granitic pegmatites, containing beryl, tourmaline columbo-tantalite, apatite, monazite, samarskite, garnet and locally cleavelandite, lepidolite and crystals of piezoelectric quartz are known in the districts of Daarburuk-Lafarug (Fig. 1, n. 66) and Bur Mado (Il Haggar Humbeli range, Fig. 1, n. 62).

A peculiar feature of the western basement segment of northern Somalia is the presence of the Mora-Sheikh gabbro-syenite intrusive belt (DAL PIAZ and SASSI, 1986; GATTO et al., 1987) representing a protracted episode of crustal thinning and extension, accompanied by the uprising of mantle-derived material. This episode brackets in the 700-600 Ma according to Rb-Sr data (FERRARA et al., 1987; VISONÀ, 1987) though a syenite with 778±8 Ma old uniform zircons is reported by KRÖNER et al. (1989). According to one of us (A.J.W.) the dominant gabbro bodies form an eastern and a western group of different compositional and textural characteristics. The eastern group is devoid of significant mineralizations, and appears as the most involved in processes of regional re-foliation and local high-grade blastomylonitization coeval with the emplacement of these mobile and still hot bodies (SASSI and IBRAHIM, 1981; SACCHI et al., 1985; DAL PIAZ et al., 1987a; VISONÀ, 1987; SAID AHMED ABDURAMAN, 1987). The western group of broadly E-W aligned gabbro (syenite, carbonatite) bodies is metallogenically fertile and is also recognized in southwestern Yemen, where the mineralized complexes lie at the southern boundary of the western volcano-sedimentary belts (LESCUYER, 1990). A comparable situation occurs in the northwestern corner of the Somalian basement, the Darkainle nepheline syenite complex flanking to the south the Abdul Qadr volcanics (VISONÀ et al., 1983). In both Yemen and Somalia, the western group preferably intrudes the marbles-rich upper basement unit.

Gabbro-related ores: Fe-Ti (V, apatite), PGE, pegmatites.
Mukayras and Mura, Yemen (Fig. I, n. 71), layered gabbros. Enrichment of Fe, Ti, V (titanomagnetite, ilmenite) and apatite in discontinuous lenses (LESCUYER, 1990). Hamar gabbro, Somalia (Fig. 1, n. 65). Fe-Ti-V(0.44%) ores in pyroxene-olivine gabbro and anorthosite. PGE anomalies derived from Hamar gabbro and the sheared Barkasan-Mandera mafic-ultramafic complex (FRIZZO, 1987 and this volume). Pegmatites related to the Hamar gabbro contain besides K-feldspar, albite tourmaline, rare beryl and garnet, also phlogopite, apatite, Nb-Ta rich betaphite and REE rich orthite.

Al Hamurah (Yemen) Cu-Ni(Co), Fig. 1, n. 74.
Disseminated pyrite, chalcopyrite and pyrrhotite-pentlandite in late lamprophyre dykes (LESCUYER, 1990). EL-SHATOURI and AL-ERYANI (1979) report NW-trending veins with high copper (10%) and Co+Ni (2-5%) grades, possibly corresponding to the mineralization described by NAKHLA (1974) as fissure fillings in a quartz monzonite, carrying chalcocite, bornite, covellite and minor chalcopyrite, pyrrhotite, pyrite, sphalerite and Ni-Co arsenides.

Lawdar (Yemen) carbonatite, Fig. I, n. 70.
Carbonatite dykes in association with marbles and intruding low-grade gneisses (BABTTAT e al., 1987). Near syenite bodies. Barite, magnetite, apatite, celestite, strontianite, monazite, pyrochlore, molybdenite (LESCUYER, 1990) .

Darkainle (Somalia) nepheline syenite and carbonatite, Mo (Fig. 1, n. 61).
Deformed sheet of nepheline syenite intruding gneisses, metapelites and amphibolites. Molybdenum anomalies in late stage pegmatitic schlieren and veins in nepheline-bearing gneisses. Pegmatitic schlieren have a core of massive nepheline with scattered flakes of molybdenite up to 1 cm across, and a rim of feldspar+pyrrhotite. Veins contain sheared molybdenite besides pyrite, chalcopyrite and sphalerite. Mo-halo in enclosing

gneisses (up to 650 ppm). Molybdenite altered into molybdite, ferro-molybdite and powellite. Carbonatite (sovite beforsite) differentiates in syenite carry molybdenite altered to powellite, traces of Cu, Zn, radioactive pyrochlore, apatite, orthite, riebeckite and cm-sized zircon crystals. Limonitic carbonatites average 250 ppm Mo (max. 3000 ppm), non-limonitic carbonatites 5-7 ppm Mo. Average Mo grade for Darkainle carbonatite 87 ppm, higher than in other carbonatites (GELLATLY and HORNUNG, 1968; GELLATLY et al., 1971).

Barka Aggar (Bohl, Somalia) nepheline syenite, Mo-Bi (Fig. 1, n. 64).
Numerous quartz-feldspar dykes (max. 200 x 3 m) containing disseminated molybdenite and bismuthinite (0.1-2% Mo, 0.5-0.6% Bi) with traces of galena, chalcopyrite, scheelite (Frizzo, 1987 and this volume).

NW of Hargeisa, gold (polymetallic sulphides, scheelite) ores (Fig. 1, n. 64).
Gebile-Ged Deble-Ubali-Hamar area of metasediments intruded by mineralized gabbro and syenite bodies. Clustering in this area are mineralizations of uncertain genetic type, mostly carrying gold: (1) Biyo Ase (Arapsiyo) lens-shaped auriferous quartz dykes (up to 17 g/t Au) with pyrite, gold, iron-rich sphalerite, pyrrhotite, chalcopyrite. (2) Bohl gold-bearing copper disseminations associated with epidote, quartz and sulphides in a shear zone. (3) Gal Ado-Ged Deble gold-bearing (up to 13.5 g/t Au) magnetite layers with Fe-Cu-Zn-Pb sulphides, barite and tourmaline, hosted by deformed and boudinaged ferruginous quartzites and Ca-silicate felses. Auriferous chalcopyrite with pyrite is also reported from the kyanite-quartz lenses, running E-W for more than 7 km at Ged Deble. Scheelite alluvial showings at Gebile and near Ubali (Frizzo, 1987 and this volume).

Harar Inliers (Eastern Ethiopia)

Separated from the Northern Somalia block by the Marda-Gara Mulata fault zone, active with sinistral transcurrent movement since Late Precambrian and Palaeozoic (BERHE, 1986; MOHR, 1986). High-grade granite gneisses and migmatites surrounded by the epicontinental to miogeosynclinal metasediments of the Boye Group (quartzites, meta-arkoses, stromatolitic dolomitic marbles, amphibolites) metamorphosed into the lower amphibolite facies, and the weakly metamorphosed Adola-type Soka Group of graphite-talc-chlorite schists, phyllites and greenstones containing small magnetite lenses (WARDEN and HORKEL, 1984). A serpentinite body near Harar (Gara Jabbe) is characterized by veinlets of columnar to fibrous amphibole asbestos and some vermiculite. Pegmatites are abundant (Fig. 1, n. 57) carrying mica and almandine garnet (both exploited in the past), large amounts of pink K-feldspar, rare beryl and molybdenite (JELENC, 1966). REE-Y-Th-U-Zr minerals in graphic pegmatites are recorded, among which disseminated crystals of Ce-Y rich sphene (grothite) in a clinopyroxene-bearing pegmatitic granite (MORGANTE, 1943). Interesting is the presence of carbonatite dykes (Fig. 1, n. 58) rich in phlogopite (A. BIANCHI, 1961, pers. comm. to P.O.). Several showings of vein-type galena (Cu) both in the basement schists and in the Mesozoic cover (JELENC, 1966) are included in the sketch-map of Fig. 1 (n. 56) in that they are very similar to those, not reported in Fig. 1, abundant in Northern Somalia and according to Frizzo (1987, and this volume) linked to the post-Jurassic geothermal activity along the Aden rift zone. Comparable late fissures filled with fluorite and traces of sphalerite, galena and chalcopyrite at Irqah (South Yemen) are related (LESCUYER, 1990) to the development of the Late Jurassic Wadi Jawf graben.

Adola Belt (Sidamo, Southern Ethiopia)

The Adola Belt is well-known for alluvial gold mining and for the recent discovery of some exploitable primary deposits (Lega Dembi gold, Kenticha tantalum pegmatite). Truncated in the south and apparently offset along the NW-trending Diddessa-Mutito sinistral shear fault system, the belt is exposed for about 150 km in a N-S direction and consists of a complex Pan-African package of east-verging, polyphasically folded and sheared thrust slices, intruded by syn- late to post-tectonic granites and pegmatites. Metamorphic grade is variable, reaching the greenschist/amphibolite facies boundary in the supracrustal section (KAZMIN et al., 1978; KAZMIN in CHEWAKA and DE WIT, 1981; WARDEN and HORKEL, 1984; BOGLIOTTI, 1989). The polyphase deformation and the easterly vergence of the Adola thrust belt are consistent with the differentiated structural pattern of the main trunk of the Mozambique orogenic belt of Kenya, where east-facing nappes develop east of a granulite root zone centred beneath the East African Rift (KEY e al., 1989) and continuing west of Adola, in the Turkana-Chew Bahir and Chamo lakes area (ALEMU SHIFERAW in CHEWAKA and De Wit, 1981; WARDEN and HORKEL, 1984). In Central-northern Kenya the assumed picture (KEY et al. op. cit.) is one of thinning and extension of a widely homogenized (1200 Ma) crust, overlain by abundant clastics locally associated wit mafic-ultramafic intrusive complexes, possibly of a sub-continental mantle affinity (compare PROCHASKA and POHL, 1983). The whole sequence was subsequently involved in an extended cycle (820 to 480 Ma) of collision controlled, superimposed orogenic events.

Within the Adola belt, WARDEN and HORKEL (1984) recognize the following lithostratigraphic units: (a) a strongly sheared, in places heavily migmatized basement (Lower Complex) of "grey gneisses" associated with early supracrustals including leucocratic magnetite- and biotite-magnetite gneisses; (b) an overlying succession (Middle Complex) of continent-derived arenites, containing Early Proterozoic (2350 Ma) components besides Pan-African zircons (KRÖNER et al., 1989); (c) the Adola greenstones and ultramafics (Upper Complex) probably evolved in an aborted rift which never attained oceanic dimensions. The massive to pillowed greenstones (amphibolites) reportedly include high-to low-Ti intrusive types and low-K tholeiitic flows (Y. FUCHS, pers.comm.). Altered ultramafics form long, sheared lenses of talc, talc-serpentine, talc-tremolite and antophyllite schists, associated with chlorite-magnetite schists and minor massive serpentinites (dunites). Interlayered with the greenstones are abundant graphitic phyllites and banded iron quartzites, grading upwards to a marble-rich sequence closing the Adola volcano-sedimentary cycle.

The Adola belt contains the largest gold placers in Ethiopia (about 10 t of recoverable gold estimated in 1970). Gold occurs in active alluvial (gravels) and in older terraces. The correlation of gold with the Adola greenstones is emphasized by JELENC (1966) with the richest deposit occurring in areas draining chlorite-talc-tremolite schists and amphibolites. Serpentinites are also indicated as a theoretically possible gold source by CLARK (1979) but this assumption is not supported by analytical evidence. An obvious additional source is represented by the recently discovered, economic grade primary gold ores such as Lega Dembi. However, we observe that a considerable variety of primary mineralized showings (pegmatites, skarns, veins and disseminated stratabound sulphides) contain traces of gold (JELENC, 1966; HAMRLA, 1977). Therefore, a multisource and differentiated origin could be envisioned for the various gold placers known in the region. The Adola belt also has potential for lateritic nickel in weathered rocks capping serpentinite bodies (JELENC 1966; KAZMIN in CHEWAKA and DE WIT, 1981) although the occurrences examined so far proved to be sub-economic (two zones with 10.6 Mt averaging 1.37% Ni and 6.5 Mt at 0.5% Ni; MINING ANN. REV., 1985). Traces of PGM ($Os_{70}Ir_{30}$ siserskite) in Demi Denissa alluvium containing pyroxenite float are quoted by KAZMIN (op.cit.) together with some eluvial chromite and in situ low-quality asbestos (Agere Mariam).

Lega Dembi (SW of Shakisso), gold (Fig. 1, n. 54). 8.8 Mt averaging 3.6 g/t Au, 32 t of gold recoverable (MINING ANN. REV., 1988-90).

North-trending ore zone, 500 m long, at the blastomylonitic west-dipping contact between greenstone-ultramafics and metasediments. Two orebodies in sheared quartz-feldspar micaschists and graphitic schists underlying a blanket horizon of talc-tremolite schist granite intrusion acting as heat source (Y.FUCHS, pers.comm.). According to FIORI et al. (1987 and this volume) gold preconcentrated in mafic volcanics remobilized during regional metamorphism ar shear zone activity. Quartz veins, lenses, stringers containing iron sulphides (pyrite, pyrrhotite) associated with auriferous chalcopyrite, iron-rich sphalerite and abundant galena (anomalous in Ag, Bi, Sb). In galena, inclusions of gold, electrum, tellurides (hessite, petzite, altaite) and Cu-Pb-Sb sulphosalts. Erratic distribution of gold grades. Fluid-ultramafic rock interaction suggested by the frequence of Ni-minerals (ullmannite, breithauptite, nisbite $NiSb_2$).

Kenticha, tantalum pegmatite (Fig. 1, n. 55). *Ore grading 0.02-0.03% Ta_2O_5, treated in 1989 in semi-industrial plant* (METALS AND MINERALS ANN. REV.,1990).

Pegmatitic field, structural and lithologic control (western branch of the Kenticha fault, mafic-ultramafic Kenticha belt). Small post-tectonic granites. Ta-Nb-Be(Bi,Sn) zoned sodolithic pegmatite, 40-45 m thick, some 100 m long. Ta-columbite, beryl, spodumene, lepidolite. Genetically related to a group of post-tectonic granites (510-480 Ma) including albitized granites carrying beryl and greisenized granites (Y. FUCHS, pers. comm.).

Wollena-Saccaro, gold.

Low-grade gold in silicified zone and gold bearing (4.8 g/t Au) saccharoidal quartz veinlets at the contact graphitic schists/amphibolites. Pyrite, galena arsenopyrite (0.5-1.5%) with minor sphalerite, boulangerite, chalcopyrite, tetrahedrite, traces of cassiterite, wolframite, native silver. Free gold associated with limonitized sulphides (HAMRLA, 1977; EVANS, in CHEWAKA and De WIT 1981; Y. FUCHS, pers.comm.).

Gayo, gold.

Veins in schists and at contact granite/gneisses. Pyrite, chalcopyrite, gold (up to 26 g/t). (HAMRLA, 1977).

Dermi Dama (Kenticha), gold.

North-trending tremolite-chlorite schists, foliated talc schists, serpentinites, dipping 55° west, in contact with quartzo-feldspathic rocks cut by swarms of yellowish quartz veinlets (limonite, gold). (HAMRLA, 1977; EVANS, in CHEWAKA and DE WIT, 1981).

Kumudu, gold.

Low-grade gold in quartz veins, sheet dykes and stockworks, with abundant tourmaline within a talc mass deriving from shearing of a talc-tremolite schist (Y. FUCH pers. comm.).

Chambi, Gari Boro, tungsten

In the Adola alluvials, wolframite and scheelite are frequent (USONI, 1952). At Chambi, north of Kibre Mengist, tungsten contents up to 1% are reported from a group of tourmaline-rich pegmatite, skarn, breccia and vein ores also carrying Mo, Bi, Sn, Be, Cu(Zn) with traces of Ag and Au (up to 0.4 ppm). Wolframite-bearing pegmatites are associated with the Gari Boro granite gneisses (HAMRLA, 1977). Molybdenite and Fe-Ti oxides are typical of old pegmatites, and comparable MoS_2 occurrences are described by ALEMU SHIFERAW (in CHEWAKA and DE WIT, 1981) in the basement migmatites of the Omo River area west of Adola.

Stratabound disseminated Fe(Cu, Zn) sulphides in greenstones and schists.

In the Tulla-Demi Denissa-Kajimiti area, soil geochemistry and some drilling have revealed the presence of disseminated, stratabound Fe(Cu,Zn) sulphide horizons in amphibolites, graphitic quartzites and sericite-chlorite schists bearing garnet, tourmaline and amphibole. Slight traces of gold (0.2 ppm) correlated with Cu(Co). Abundant swarms of mobilized quartz (tourmaline, rutile, sulphides) veinlets (HAMRLA, 1977).

In the Dawa Valley, copper showings are related to garnet- and epidote-rich layers in greenstones (JELENC, 1966). In the Awata River area, low anomalies of Cu and Zn are present in heavily pyritized graphitic argillites and quartzites (HAMRLA, 1977).

Bur Region (Southern Somalia)

The Precambrian gneissic-migmatitic basement of the Bur region comprises the Olontole Complex (migmatites, paragneisses, minor amphibolites, and quartzites) and the Dinsor Complex (pelitic to psammitic gneisses and migmatites, quartzites, marbles and BIF) affected by NW-trending thight to isoclinal folds re-folded about NE axes, and cut by syn- to late-post kinematic granitoids (WARDEN and HORKEL, 1984; DAL PIAZ and SASSI, 1986; BAKOS et al., 1987). The basement was involved in the Pan-African orogenesis (LENOIR, pers.comm.) with regional climax at 690 Ma recorded by widespread granulitic mineral assemblages (clinopyroxene-scapolite-garnet, hypersthene in the BIF) followed by amphibolitic retrogression at 540 Ma. According to KÜSTER et al. (1990) the ≤500 Ma old post kinematic granites of the Bur area differ from those of Northern Somalia in having high Sr_i and enrichment in LIL- and HFS-element contents, suggesting contribution of older, Late Archaean to Early Proterozoic continental crust. Extensive are deuteric/metasomatic alteration processes ("episyenitization": CARMIGNANI et al., 1987) extended to the high-grade gneisses and locally associate with modest concentrations of uranium ores (Alio Ghelle deposit of uranothorite, minor pitchblende and galena, 1500-2000 t of contained U_3O_8: BAKOS and SASSI, pers. comm.). The Alio Ghelle area is also described by CAMERON (1970) as bearing evidence of albitization by S, B-bearing fluids enriched in Th, U, Fe, Ti, Zr, REE, Pb, Cu, Zn. According to ANDREOLI and HART (1986) Alio Ghelle and comparable occurrences of the central Gondwana granulitic terranes (Madagascar, Tanzania, Mozambique-Malawi) are the result of fertilization of the lower crust by deep-seated fluids released from the upper mantle under shear/fault assisted protorifting and crustal thinning. In the Bur area, reminiscent of this framework also are some local concentrations of apatite, diopside, phlogopite, sphene and forsterite in marbles, already assigned by ILIYN (1967, in FRIZZO this volume) to metamorphic-metasomatic processes.

Bur Galan, Dinsor and neighbouring areas, BIF (Fig. 1, n. 59). *170 Mt grading 35-40% Fe* (MINING ANN. REV., 1971).
Synsedimentary stratiform BIF deposits within metasedimentary relics in granite gneiss terrain. Possibly older than the layered metasediments of Northern Somalia. Martite after magnetite, Fe-pyroxenes and amphiboles quartz. Ores are free from objectionable impurities such as Ti, Mn and S, and the content P-content is below the Bessemer limit. The ores fall within the same field as Lower Proterozoic BIF on a SiO_2-FeO-Al_2O_3 diagram (WARDEN, 1981).

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ORE GEOLOGY OF THE CRYSTALLINE BASEMENT OF SOMALIA

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ABSTRACT

The Somali crystalline basement includes metasedimentary rocks (Middle (?)-Upper Proterozoic/Lower Cambrian in age) and various intrusive and effusive magmatic products. Stratiform syngenetic orebodies are associated with: 1) high-grade polymetamorphic formations of pre-Mozambiquean (or partly Mozambiquean) age: ferruginous quartzites (BIF) and marble and apatite layers (Dinsor Formation, Bur Basement); Mn "gondite" type, Fe-Mn and/or cupriferous + Au quartzites and sometimes quartz-silicate-carbonate polymetallic auriferous stratiform orebodies (Gebile Psammitic Series and *pro-parte* Uhali-Mora Pelitic Series, Northern Somalia Basement); 2) exhalative-sedimentary massive polymetallic sulfide occurrences (Abdul Qadr) and probably Cu- and Au-bearing deposits (Mait) linked to volcano-sedimentary sequences of the Arabian-Nubian Mobile Belts (Late Proterozoic); 3) stratiform low-Cu mineralization, and some manganesiferous layers in epimetamorphic molasse (India Ad Series, Lower Cambrian).

Important *plutonic events* from the metallogenic viewpoint are: 1) gabbro-syenitic plutonism (700 Ma), with attributed segregation mineralization of Fe, Ti and possibly PGE (in gabbros); occurrences of molybdenite + bismuthinite and carbonatites with REE, zircon and apatite (in nephelinic syenites); 2) Younger Granites plutonism (510-490 Ma), with numerous pegmatitic bodies (Nb, Ta, Be, Li, piezoelectric quartz) and with quartz or quartz + K-feldspar dykes with cassiterite.

INTRODUCTION

An attempt at describing the essential metallogenesis of Somalia presents several difficulties. The mineral deposits briefly described in a number of unpublished reports are often poorly known, due to the lack of recent studies; at the same time, geological knowledge of the area has undergone rapid evolution. In spite of these facts, a useful exercise appears to be the tentative grouping of the deposits on paragenetic, lithostratigraphic and structural grounds. The resulting framework, when considered in the larger picture of Arabian-Nubian metallogenesis, may help in defining possible new metallotects and therefore in orienting future exploration.

Most of the mineral deposits known in the territory of Somalia are found in the crystalline basement: the others lie in the Meso-Cenozoic cover and Quaternary sediments.

This report considers essentially the mineralization genetically linked to the rocks of the crystalline basement. A later report will examine more recent occurrences connected with the Meso-Cenozoic and Quaternary paleogeographic and paleodynamic evolution.

GEOLOGICAL FRAMEWORK

The Precambrian (and p.p. Cambrian) crystalline basement outcrops in two separate areas:

1 - on the northern escarpment of the Somali Plate ("Northern Somali Basement") along a discontinuous belt about 600 km long parallel to the Gulf of Aden and covering an area of about 30,000 sq. km.

2 - In Southern Somalia ("Bur Basement") as a dome-like area of about 20,000 sq. km. Decidedly larger are the outcrops of the sedimentary and partly volcanic rocks of the Mesozoic-Tertiary cover: the transgressive basal sequences show different ages in the various areas, the oldest being Lower Jurassic.

The basement of Somalia lies in the transitional area between the "Proterozoic Mozambique Mobile Belt" and the "Arabian-Nubian Shield" (POHL, 1983).

NORTHERN SOMALIA BASEMENT

The crystalline basement of Northern Somalia (Fig. 2), from bottom to top, contains:

- Adadleh-Qabri Bahar Series, made up of gneiss, migmatites and granitic gneiss with paragneiss, showing relics of granulitic facies;
- Gebile Metapsammitic Series: quartz-feldspar metasediments, micaschists and marbles;
- Borama-Ubali Pelitic Series: pelitic and psammitic rocks with intercalated amphibolites;
- Harirad-Mora Calcareous Series: predominant marbles and quartzites with metapelitic intercalations.

These sequences represent the oldest portion of the crystalline basement of Northern Somalia, and are probably part of a basement microplate of Middle Upper Proterozoic age.

This plate lies between mobile areas of Late Proterozoic age related to the evolution of the Arabian-Nubian Shield, well represented in Northern Somalia by the volcano-sedimentary series of Abdul Qadr and Mait. This is in agreement with the results of SASSI and VISONÀ (1985) who, on the basis of the migmatitic characters and occurrence of granulitic facies relict paragenesis, assign the various units, from the Qabri Bahar to the Mora Complexes, to an old basement similar to the African Craton.

Otherwise, according to WARDEN and DANIELS (1983); WARDEN and HORKEL (1984), only the rocks of the Adadleh-Qabri Bahar Series are part of an old pre-Mozambiquean shield (probably more than 1.400 Ma old), while the overlying sequences of Gebile, Borama-Ubali and Harirad-Mora are part of the "Variegated Mozambiquean Series" attributed to the sedimentary and p.p. volcanic cycle of the Mozambique Mobile Belt. According to the above authors, these sequences were deposited in ensialic intracratonic and epicontinental rift basins, discordantly on the rocks of the "Pre-Mozambique Basement". They are more than 1.000-1.100 Ma old and earlier than the NNW-trending folding event which developed on a regional scale and which is linked to the high-grade metamorphism (in amphibolite and p.p. granulite facies), dated at about 827 Ma in some sequences of Southern Kenya (SHIBATA, 1975) and Tanzania (SPOONER et al., 1970). This metamorphic event involved all the rocks of the Mozambique Mobile Belt in an extremely uniform way, including the sequences of Northern Somalia (POHL and HORKEL, 1980), where preliminary age determination indicate an amphibolite facies metamorphic event around 800 Ma (DAL PIAZ et al., 1985) involving the local paragneiss sequence with amphibolitic intercalations of amphibolities, granitic gneisses and migmatites.

The Abdul Qadr Volcanic Series and the Mait Greenstones are considered as transgressive on the Harirad Mora Calcareous Series (WARDEN and DANIELS, 1983). They represent the continuation into Somali territory of the volcanitic sequences of island-arc or active continental margin type (*sensu* DELFOUR, 1980-81) of the Arabian Nubian Shield. In Northern Somalia rocks of this type may be recognized in the areas of Abdul Qadr, Las Dureh and Mait. They are characteristic of various belts of the Arabian Nubian Shield, where a series of events such as the opening of oceanic basins, formation of young lithosphere, active continental margin volcanism and, later, ensimatic island-arc volcanism occurred, during rifting and drifting over a period of almost 300 Ma (POUIT et al., 1987). Various volcanitic sequences, sometimes lithologically similar but not comparable from the chronological viewpoint, were thus formed. The Abdul Qadr area contains a calc-alkaline sequence with basalts, dacites and ignimbrites (Abdul Qadr Volcanic Series) with intercalated pelitic schists, especially towards the bottom, sometimes indicating an almost gradual passage to the underlying Harirad-Mora Calcareous Series. The metamorphic grade varies from greenschist to lower-grade amphibolite facies. In the Las Dureh area, a succession with predominant rhyolites and ignimbrites are found in the isolated Jirba basement and, slightly further east, in the Mitka basement stretch, tuffaceous schists with associated calc-schists and epidosites. Further east again, the Mait Greenstones Series outcrops like a narrow belt with greenschists to metabasalts, faulted metatuffites with intercalations of phyllites or metasiltites, and subordinate calc-schists.

Sequences which may be correlated with those of the Abdul Qadr Series probably outcrop in the Gebile-Gogeisi and Hamar-Mora areas, where metapelites, metapsammites and subordinate acidic and basic epimetamorphic metavolcanites occur.

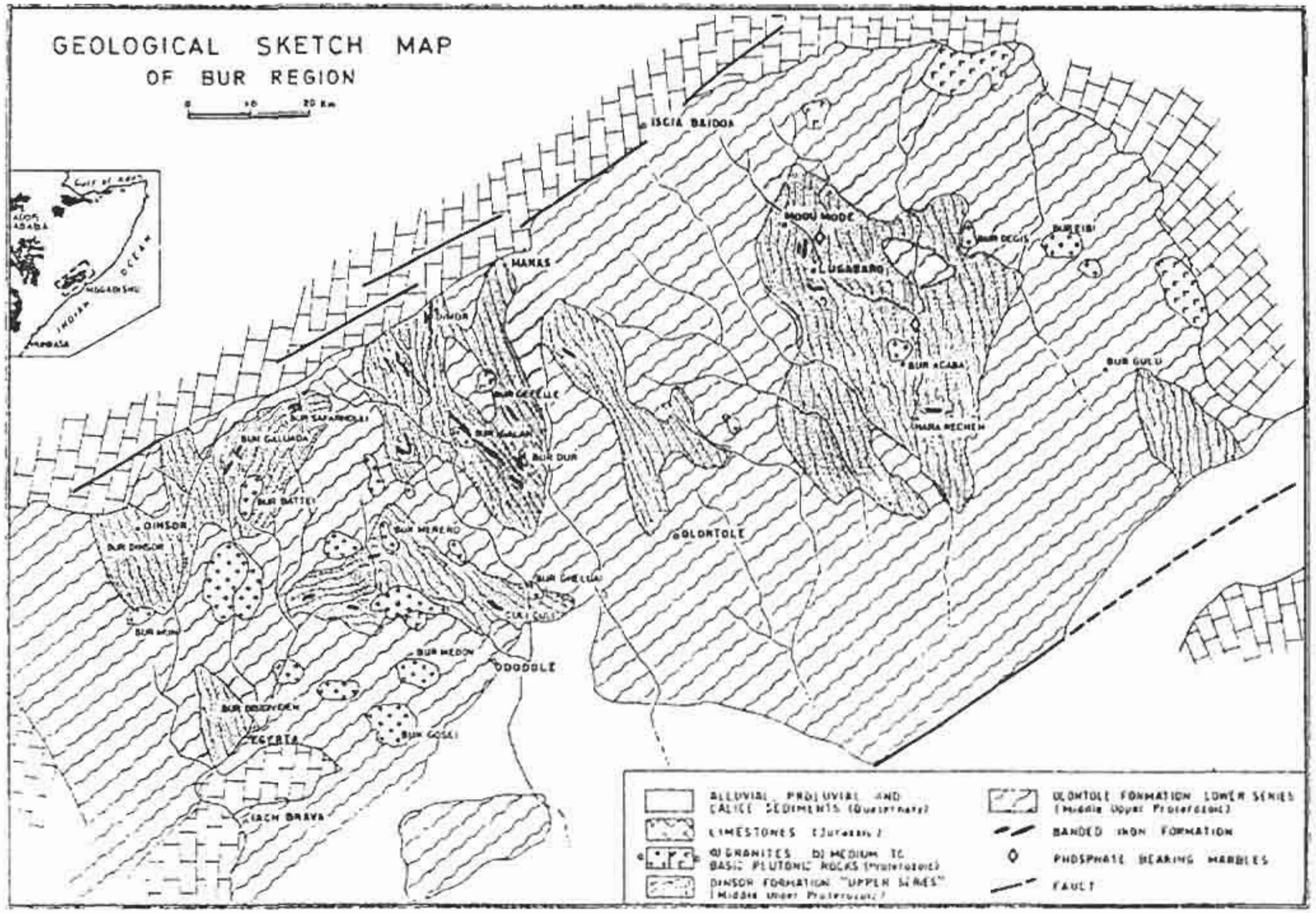


Fig. 1 - Geological sketch map and ore deposits of Bur region.

The rocks of the Inda Ad Series (conglomerates, sandstone, siltstones, marls and limestones), only weakly metamorphosed, close the metasedimentary sequence of the Northern Somalia Basement. These Lower Cambrian molasse sediments were deposited during the erosional phase following the Najd orogenetic cycle, considered responsible in the Arabian-Nubian Shield for the effects of a metamorphism of variable grade (from greenschist to low-grade amphibolite facies) which occurred in various areas 670-625 Ma ago (STOESER and ELLIOTT, 1979) and for the progressive cratonization of the crust, which continued in later phases until 570 Ma ago (Najd Fault). In Northern Somalia the imprint of this metamorphic event is well recorded in the Late Proterozoic volcano-sedimentary series of Abdul Qadr and Mait.

The oldest sequences of the basement are crossed by numerous bodies of cumulitic gabbros and nephelinic syenites, slightly older than and comagmatic with the gabbros. This plutonism, dated at about 700 Ma (FERRARA et al., 1987), is linked to crystal spreading and thinning. Smaller masses of olivinic gabbros, leucosyenites and porphyric granites, occurring mainly as polyphase intrusions in some gabbroid masses, are linked, according to VISONÀ (1987), to further crustal thinning which took place about 600 Ma ago. The whole basement, including the most recent sequences, is also crossed by a series of granitic intrusions related to the Pan-African Cycle s.s. (550-500 Ma), including prefolded granites (e.g., Daimoleh Granite), younger granites, and alkaline-subalkaline granites, sometimes followed by complex pegmatitic and quartz dykes containing metallic minerals.

BUR BASEMENT

According to D'AMICO et al. (1981), the crystalline basement of the Bur region may be divided into a Lower Series (Olontole Formation), made up of biotitic-migmatitic gneiss, granulitic amphibolites and quartzites, and an Upper Series (Dinsor Formation), made up of pelitic and psammitic gneiss, ortho- and para-amphibolites, marbles, quartzites and banded ferriferous quartzites (BIF). The latter mainly occur at the base of the Upper Series, within ortho-amphibolites and some marbles. The basement rocks underwent regional polyphase metamorphism in amphibolite and granulite facies.

The regional metamorphism in the Bur area reaches the amphibolite to almandine and locally the granulite facies.

Paragneisses with pyroxene are common in both the paragneisses and the BIF. Some granitoids show charnockitic affinity. The high-grade overprint may be attributed to the "Mozambiquean" dynamo-metamorphic peak (825-800 Ma).

Small gabbro-dioritic masses outcrop some km north of Bur Galan and seem to be related to a shear zone which crosses the granitic gneisses. The Olontole and Dinsor Formations are crossed by the younger granitoids (granites, syeno-granites and monzo-granites), dated at approximately 500 Ma by Rb/Sr and K/Ar isochrons (CARMIGNANI et al., 1987).

ORE DEPOSITS IN THE BUR BASEMENT

MINERALIZATION IN THE OLONTOLE FORMATION

Conformable quartz-feldspar pegmatites

Zoned lens-shaped pegmatitic bodies are found in the amphibolitic gneiss sequences or, with transitional contacts, in granitoid rocks (ILIYN, 1967). The most important pegmatite outcrops about 10 km N-NE of Bur Acaba and is more than 5 m thick. The marginal bands of quartz + feldspar have a graphic texture; the central band is about 1 m thick and is composed of dm/m-sized crystals of pink microcline (UNDP phase II, 1970). ILIYN (op. cit.) also mentions a second generation of pegmatites transversal to the metamorphic structures and bearing rare earth minerals.

MINERALIZATION IN THE DINSOR FORMATION

Mainly stratiform and strata-bound mineralizations are essentially reported in the Dinsor Formation: ferruginous quartzites, marbles with apatite, calc-silicatic rocks with sphene and marbles with rhodonite.

Ferruginous quartzites

These outcrop in the central-southern sector of the Bur Basement (Fig. 1). The most important orebodies are those of Daimir, Bur Galan, Qadia and Culi-Culi; others outcrop near Lugabaro, Bur Galuado, Dimor, and Bur Dibidwiden.

Important magnetic anomalies have also been recorded at Bur Eibi. In accordance with BAKOS and SASSI (1979) and ABDULLAHI HAYDER et al., (1983), the ferruginous quartzites form part of the base of the Dinsor Formation. This unit, about 100 m thick, has a decametric layer of paragneisses at its base, with lateral passages to calc-schists or pure and impure marbles, overlain by ferruginous quartzites (50-60 m) which are in turn covered by barren white quartzites. The ferruginous layer is mainly composed of banded quartzites with low Fe contents (20-25%), characterized by alternating cm-thick quartz layers with mm-thick layers of Fe oxides. Over stretches sometimes extending for several km with thicknesses between 15 and 20 m, the middle portion of the ferruginous layer shows poorly defined banding and Fe_2O_3 contents between 35% and 44%. The metallic paragenesis includes magnetite, deeply transformed into martite, in mm- to cm-sized aggregates of isometric grains, sometimes bordered with limonite; rare flakes of pyrrhotite, pyrite and sometimes chalcopyrite occur locally. The quartz is mainly concentrated in the quartzitic bands. Amphibole (cummingtonite-grunerite), clinopyroxene (diopside-hedenbergite series), biotite and chlorite, the latter mainly on amphibole and pyroxene, are accessory minerals.

From chemical data (ABDULLAHI HAYDER et al., 1983) on the Dahimir-Bur Galan and Qadia orebodies, the following average compositional values may be extrapolated: Fe_2O_3 38.7% (range: 34.4-44.3%), SiO_2 60.1% (52.8-63.7%), Al_2O_3 0.54%; CaO 0.09-1.27%; MgO 0.16-2.95%; MnO 0.03%; TiO_2 0.03%; Na_2O 0.1%; K_2O 0.03%; P_2O_5 0.08%; Cr 35 ppm; V 5 ppm; Ni 1 ppm; Co 6 ppm; Zn 28 ppm; Rb 10 ppm; Sr 10 ppm; Ba 140 ppm; Zr 7 ppm. CaO and MgO show contents under 0.5%, except at Bur Galan where the ferriferous layer directly overlies some layers of marbles.

The ferruginous quartzites are involved in a system of subparallel folds generally running NW-SE. Dykes and granitic and migmatitic bodies intersect at various places, dismembering the mineralized layer and often revealing evident recrystallization of the magnetite.

The Dahimir orebody includes numerous linear outcrops which, taken together, define two SE-convergent subparallel branches, limbs of an antiform structure which may be followed for about 30 km. The real thickness of the orebody is about 50 m, of which 30-35 m of banded quartzites with low Fe contents. Reserves of 48 Mt, of which about 31 Mt are economically workable, having Fe contents between 35% and 40% (UNDP Phase II, 1972), have been found in the most interesting mineralized part, about 3 km long and 50 m on average. The Dahimir orebody also shows traces of gold (45-90 ppb; ABDULLAHI HAYDER et al., op. cit.).

The Bur Galan (Bur Qalin) deposit outcrops for about 12 km and, like that of Bur Dahimir, includes two subparallel bands corresponding to the limbs of the same layer, folded as an anticline. Reserves have been indicated at 119 Mt of crude ore, of which 41 Mt are economically workable (UNDP, Phase II, op. cit.). A tonnage of 394 Mt has been indicated (CHINA REPORT, 1972) to a depth of 200 m, with average Fe contents of 38.2%.

HOLMES (1954) indicates reserves of 64 Mt (37.7% Fe contents); in the Culi-Culi orebody.

Phosphate-Bearing Marbles; Calc-Silicatic Rocks With Sphene; Marbles With Rhodonite.

Interesting concentrations of apatite have been reported in some points near Bur Acaba, in the layers of pure or silicate-bearing and calc-schists, up to 10 m thick, within the gneisses of the Dinsor Formation. In the Modu-Mode deposit 24% of P_2O_5 has been found, probably originally phosphatic carbonatic sediments in coastal basins. Elsewhere, particularly along the bed of the Tug Bur Acaba and its tributaries (e.g. near Modu-Mode and Lugabaro), levels of calc-silicatic rocks with diopside, tremolite, phlogopite and forsterite, show discontinuous, m-thick lens-shaped seams, containing up to 10% sphene in tabular millimetric crystals. Sphene enrichments (ILIYN, op. cit.) are related to metamorphic and metasomatic processes. The Bur Acaba area also contains Mn-silicate marbles, with incrustations and superficial pisolitic growths, with Mn and Fe oxides and hydroxides.

ORE DEPOSITS IN THE CRYSTALLINE BASEMENT OF NORTHERN SOMALIA

The ore deposits in this basement (Figs. 2, 3) may be divided into:

1 - stratiform syngenetic, and
2 - magmatic, pegmatitic and vein types.

STRATIFORM SYNGENETIC OCCURRENCES IN THE GEBILE PSAMMITIC SERIES

Stratiform Gondite Mn Deposits

The most important Mn deposits outcrop near Hudiso, south of Berbera, in the metamorphite belt called the "Gebile Psammitic Series" (*sensu* DANIELS and WARDEN, 1983), lying between the intrusive masses of the Sheik Gabbro and the Daimoleh Granite. Other small deposits are known further west between Qabri Bahar, Bawn and Gebile, and further east (Ras Hantara and Afka Dehemid). Their common features are: stratiform geometry; time-space link with metasedimentary layers of paragneisses with intercalated hornblende-bearing biotite schists; the basic paragenesis of spessartine, rhodonite, quartz, amphibole (grunerite), magnetite and sometimes apatite. Manganesiferous mineralization develops in lens-shaped bodies from a few dm to some m thick, sometimes with evident banded texture. Average Mn content is 10-15%: higher concentrations (HUNT, 1954) have been recorded in some mineralized bodies near Hudiso (Mn 23.8%; Fe 7.4%; SiO_2 39.7%) with an overall tonnage of 4 Mt of ore. The absence of significant supergenic enrichments means that these deposits are not economically workable.

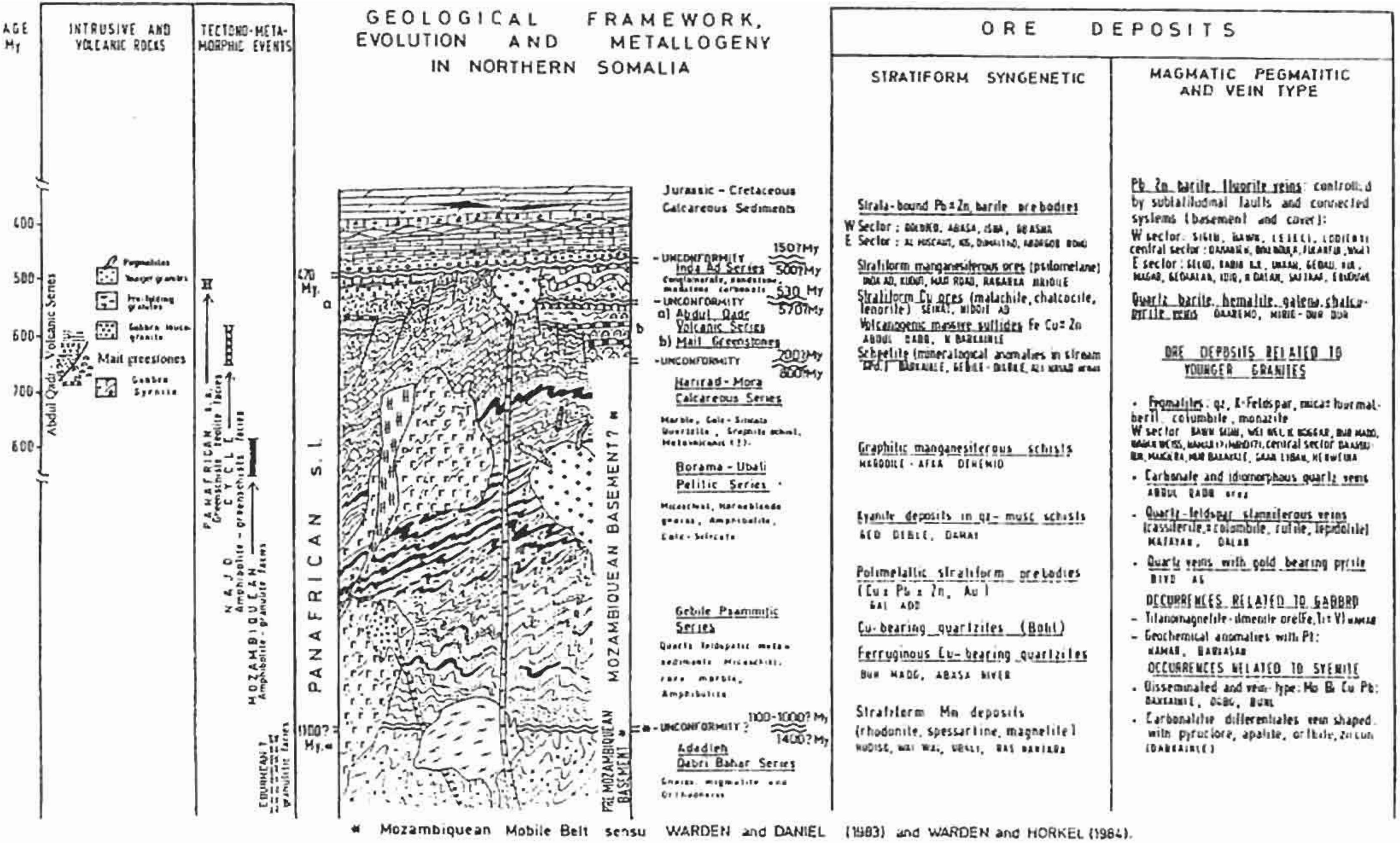
Belonging to the above group, the western sector includes the deposits of the Abasa River SW of Bawn, where DANIELS (1961) reported the occurrence of "Banded Ironstones", and manganesiferous rocks, Wai-Wai near Bur Mado, Ubali, about 3 km west of the Mora hill, and Humbeli SE of Laferug.

In the Hudiso area, minor deposits (Manja, Asseh, Fulanful and Maqado) outcrop between Bihendula and Daimoleh, and more important ones (Hairamodle, NE Hudiso, Asaha Gotin, Lalis, Hair, Marso) lie on a layer which may be followed, with various interruptions, for about 15 km.

The Marodile orebodies, outcropping near the track for Ged Deble, not far from the Hamar Gabbro, and the Afka Dehemid outcrop seem to differ from the deposits of this group, being associated with hornblende-bearing graphitic schists with local intercalations of marbles. For this reason, they have been tentatively assigned to the "Borama-Ubali Pelitic Series" (Fig. 2).

Ferruginous (Cu-bearing) quartzites

Ferruginous quartzites have been reported near the Abasa River (DANIELS, 1961) south of Bawn, in the same sequence of paragneisses and hornblende-bearing schists which contains the Abasa River banded Mn-bearing deposits. Ferruginous quartzites



* Mozambiquean Mobile Belt sensu WARDEN and DANIEL (1983) and WARDEN and HORKEL (1984).

Fig. 2 - Geological framework, evolution and metallogeny in Northern Somalia.

with disseminated sulfides with 0.4% Cu outcrop in a similar stratigraphic context at Bur Mado in the valley of Wai-Wai Dur Dur Ad (KAMENOV, 1976).

Polymetallic (Fe, Cu + Pb, Zn, Au) stratiform orebodies

Oxides and sulfides outcrop between Gal Ado and Ged Deble, north of Arapsiyo, in the predominantly quartz-carbonatic, weakly mineralized, polymetamorphosed layer. It lies in stratigraphic conformity in the local polymetamorphic sequence with metapsammites and, pro parte, metapelites with intercalations of amphibolites and rarer quartzites and marbles. In the Gal Ado area, the orebody outcrops quite continuously for several hundred m, thicknesses ranging between some dm and some m. It is segmented eastwards into numerous decametric to pluridecametric bodies, due to intense refolding of the frequent boudinages and transpositions; some km further east, at Ged Deble, the same orebody outcrops for about 150 m with a thickness of 2-3 m. Its westward continuation is marked by small occurrences near Tobsi, 10 km NE of Arapsiyo. The deposit is composed of cm/dm-sized alternating layers, including more or less carbonatic ferruginous quartzites, ankeritic-dolomitic marbles with silicates and biotitic-muscovitic schists, sometimes with abundant carbonates, amphiboles of the tremolite-actinolite series, garnet, and sometimes tourmaline. Of the metallic minerals (up to 15-20% of the paragensis); more or less martitized magnetite dominates, in isolated euhedral grains or polycrystalline aggregates, usually oriented in small layers concordant with the schistosity. Hematite, chalcopyrite, galena, blende, pyrrhotite, pyrite, rutile, ilmenite, sphene, and barite also occur. Supergenic products are oxides, Fe and Mn hydroxides (mostly derived from carbonate alternations), tenorite, digenite, chalcocite, covellite, malachite, azurite, cerussite, etc.. Chemical analyses (UNDP, Phase III, 1975) on some series of samples show variable contents of copper (0.1-1%), zinc and gold (Au from traces to 13.5 ppm).

Cu-bearing quartzites (Bohl)

A quartzitic "layer", with disseminated pyrite and chalcopyrite and widespread flakes and supergenic impregnations of malachite, azurite and tenorite, outcrop for almost 3 km in an E-W direction 50-70 m from the syenites of the Bohl-Barka Aggar hill. This layer is substantially concordant with a biotitic-muscovitic-garnetiferous meta-arkose. The orebody, with low contents of Cu (0.29%) and Au up to 5 ppm, has been considered "a clear example of strata-bound metalliferous layer" by ABDULKADIR (1978). Instead, according to the CHINA REPORT (1972), it is epigenetic and related to quartz impregnation and development of epidote and sulfides in a shear zone.

Kyanite deposits in quartz-muscovite schists

Layers of muscovitic quartzites and sometimes finely banded biotitic quartzites, with widespread blue or colourless kyanite, are known in various areas of the western sector of the Northern Somalia Basement. They are probably part of the Gebile Psammitic Series. In these layers, e.g., near Damal and Mirid, Tug Bagai basin, near Bawn (Dabodilla and Dobo), Ged Deble-Dagah-Kureh and Labeh Arowleh (Hudiso), the kyanite is locally enriched, reaching 30-65% in some lens-shaped bodies concordant with quartz and kyanite, between 1 m and 10 m in thickness and extending from some tens to some hundreds of m.

The most significant orebodies have so far been identified near Damal, at Mirid and in the Ged Deble area. At Damal (about 65 km SE of Zeila), a limb of micaceous quartzites with kyanite is tectonically folded between the epimetamorphic volcano-sedimentary sequences of the Abdul Qadr Volcanic Series. The orebody contains an average of 35% kyanite, in mm/cm-sized blasts, accompanied by mosaic quartz and subordinate white mica, rutile and magnetite being accessories. DANIELS (1961) reports 400 Kt to a depth of 20 m. At Mirid the occurrence of a quite continuous layer of "massive kyanite" has been reported (UNDP, Phase II, 1972). In the Ged Deble-Dagan Kureh area (UNDP, Phase III, 1975), many bodies of kyanite-bearing quartzites run latitudinally for more than 7 km. The largest body outcrops for about 350 m in and is very thick (up to 10 m). It is composed of quartzites with blue and white kyanite and a central band 40/50 - cm thick with dominant kyanite. The kyanite is accompanied by pyrite and rarer, probably auriferous, chalcopyrite near Dagah Kureh (TEKNOEXPORT, 1976).

Occurrences Between Harirad Mora Calcareous Series And Abdul Qadr Volcanic Series

Scheelite (mineralogical anomalies) in stream sediments

Significant concentrations of scheelite grains were identified during exploratory alluvial prospecting carried out in some areas of the NW Somalia basement (W of Berbera). The most interesting anomalies were found in the alluvial sands of three separate areas (FRIZZO and ABDULKADIR, 1983; FRIZZO, 1986) and deal with some minor basins located N and NW of Mora, the high basins of the Tug Dikrile and Gogeisi in the Gebile area, and some tributaries of the middle course of the Tug Darkainle. Although preliminary, the available data show that scheelite is absent or very sporadic in the stream sediments derived from the oldest polymetamorphic sequences (Adadleh-Qabri Bahar Series, Gebile Psammitic Series and Borama-Ubali Pelitic Series) and from the intrusive granitoid complexes. Instead, it probably favours rocks at the base of the Abdul Qadr Volcanic Series (Darkainle), the sequences with metapelites, metapsammites and metavolcanites of the high basins of the Tug Dikrile and Gogeisi, and the rocks, probably linked to the preceding ones, outcropping N and NW of Mora, but mapped together (Sheets 33-Gebile and 21-Qabri Bahar, GEOLOGICAL SURVEY, Som. Dem. Rep.) as part of the "Harirad-Mora Calcareous Series".

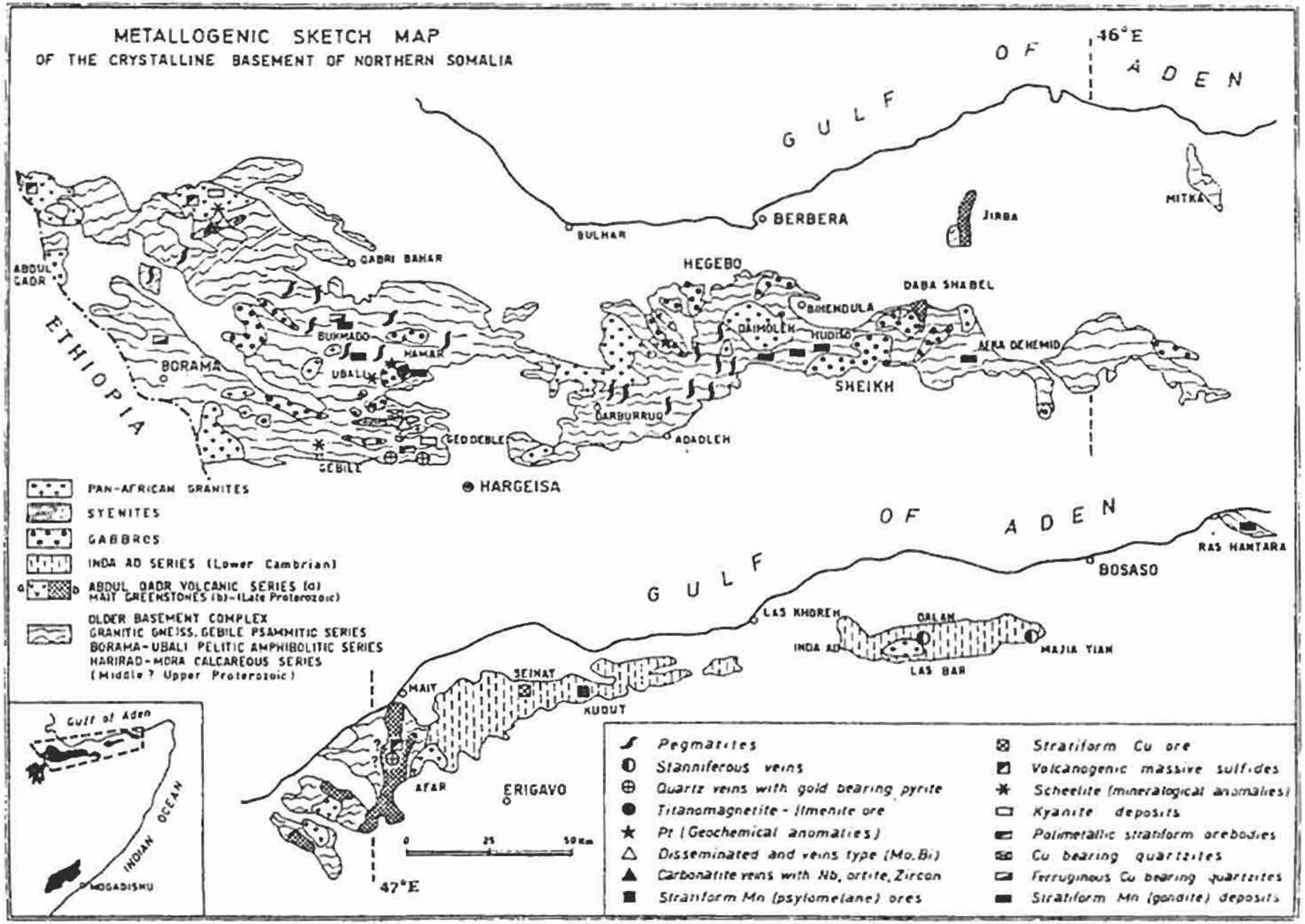


Fig. 3 - Metallogenic sketch map of the crystalline basement of Northern Somalia.

OCCURRENCES LINKED TO ABDUL QADR VOLCANIC SERIES AND HEIS MAIT GREENSTONES

Massive volcanic sulfides (Fe, Cu, Zn, Pb + Au)

Occurrences related to exhalative-sedimentary deposits (Abdul Qadr and North Darkainle) in the Abdul Qadr Metarhyolitic Complex (Upper Proterozoic) are reported by MOHAMED YUSSUF and MOHAMED SAID (1976), UNDP Phase III (1975) and KAMENOV (1976). Geochemical anomalies (Cu, Zn, Pb) in stream sediments have been identified in the same area, e.g., near Jira.

No orebodies have yet been reported in the eastern sector, in Heis Mait Serie, composed of basic and mesosilicic metavolcanites with intercalations of phyllites, quartzites and marbles, more frequent towards the top and crossed by several intrusive bodies, although, on metallogenic grounds, pyrite-copper and gold occurrences could be suspected.

In the Al Mukalla area (Southern Yemen) numerous orebodies are associated with a homologous volcano-sedimentary sequence, the counterpart of the Heis Mait Series, dismembered red and translated by the opening of the Gulf of Aden.

OREBODIES LINKED TO THE INDA AD SERIES (CAMBRIAN)

Stratiform Cu ores (malachite, chalcocite, tenorite + chalcopyrite and pyrite)

Typically stratiform orebodies, all with low contents (Cu 0,3% with local enrichments up to 2.5%; Ag 3-15 ppm; Ga 15-20 ppm; Pb 10-80 ppm), are intercalated in the medium-high belt of the lower member of the Inda Ad Series (GHELLE ABDI and HASSAN DAHIR, 1972; UNDP Phase II, 1972; CHINA REPORT, 1972; MOHAMED SAID ABDI, 1973; KAMENOV, 1976). Most of these outcrop in the Tug Seinat Valley and Hiddit Ad area. Two coeval parallel and longitudinally-trending "cupriferous belts" several hundred m thick also outcrop at Seinat, being respectively the western and eastern limbs of a N-S-trending synclinal structure containing more recent carbonatic-terrigenous metasediments, barren or with local intercalations of manganesiferous mudstones. The cupriferous layers so far identified (12 in the western and 9 in the eastern limbs) vary in thickness between 0.3 m and more than 2 m, and run for as far as 7-10 km. They are composed of sericitic siltstones (50% quartz; 30% sericite, 4% chlorite and variable quantities of plagioclase, garnet, zircon and sphene), intercalated at distances varying between 30 m and more than 100 m.

The metallic paragenesis is essentially composed of supergenic products (malachite, azurite, tenorite, chalcocite and limonite), mainly occurring as impregnations, films and thin veinlets filling microcracks or joints and sometimes in small nodular concentrations: relics of the primary mineralization (pyrite, chalcopyrite) have been found in sample cores taken at depths of some dozen metres (UNDP, Phase III, 1975). The copper concentrations generally show progressive reduction from the stratigraphically lower mineralized layers to the higher ones and, in the coeval layers, from the western to the eastern sectors.

Stratiform manganesiferous (psilomelane) ores

Stratiform manganesiferous orebodies are concordantly found in the lower portion of the upper member of the Inda Ad Series. Chronostratigraphically, they appear to be contemporaneous or later than the Seinat cupriferous orebodies. The most important Mn-bearing deposit lies in the basin of the Tug Gambado, about 50 km west of Las Koreh. It lies in a layer about 100 m thick composed mainly of finely stratified silty-clayey and marly metasediments and of some carbonatic layers with low Mn contents. Near Kudut the orebody outcrops for 400 m and is about 17 m thick. It is mainly concentrated in three main levels with predominant psilomelane (Mn contents: 35.8-48.6%), each about 1 m thick, lying in a rhythmite of mm-thick silty-clayey or Mn oxide alternations (Mn contents 10-30%). Kudut has about 1.3 Mt of ore with average contents as follows: Mn 41.5%; Fe 39%; SiO_2 11.4%; S 0.1%, P 0.2%; CaO 2.3%; MgO 2.2% (CHINA REPORT, 1972).

On the basis of some outcrops and detritus distribution, the orebody may he hypothesized to persist for about 10 km northwards, hidden over long stretches by the alluvial deposits of the Tug Gambado and other smaller rivers. Apart from the Kudut area, only the Mait Road orebody is considered important. Of even less importance are the more easterly orebodies of Ragarka Jiridle (about 7 km west of the Dalan stanniferous orebody), showing features of Carbonaceous siltite with Mn oxides (GELLATLY, 1961) and Manja Yahan and Asileh in the area where the cupriferous layers of the India Ad Series outcrop.

MAGMATITIC, PEGMATITIC AND VEIN-TYPE DEPOSITS

MINERAL DEPOSITS RELATED TO GABBROS AND SYENITES

Dozens of gabbroid masses and numerous syenitic bodies outcrop, often closely associated, in the Northern Somalia basement. They are derived from comagmatic melts which rose from the mantle after a widespread event of crustal thinning, dated about 700, during which the syenitic products followed the gabbroid products, sometimes directly intruding them. The gabbros contain Fe, Ti ± V ores, with some Pt anomalies. Mo ± Bi ores and local carbonatitic differentiates with pyrochlore, apatite, orthite and zircon are associated with the syenites.

Titanomagnetite-ilmenite ores (Fe Ti + V)

Titaniferous magnetite and ilmenite are frequent accessories and locally fundamental mineralogical components of the gabbroid massifs. Quite important concentrations (1.6 Mt of Fe, according to DANIELS, 1960) occur in the western sector of the Hamar gabbro. This orebody, a result of magmatic segregation processes, lies in a gabbro-anorthositic band about 200 m thick, running N-NE for about 2 km. Its granular-textured rock is composed of plagioclase (6-40%), ilmenite + magnetite (20-30%) and variable quantities of pyroxene and olivine intensely transformed into cummingtonite, hornblende, tremolite, serpentine, chlorite and chloritoid. The Fe and Ti oxides are enriched, forming a massive body between 20 cm and 5 m thick inside the gabbro-anorthositic hand, and equally extensive (CHINA REPORT, 1972). The paragenesis is composed of titaniferous magnetite with widespread exsolutions of ilmenite and spinel, ilmenite in cm to mm-sized, grains, subordinate silicates and traces of pyrrhotite, chalcopyrite and bravoite. The average chemical composition (CHINA REPORT, op. cit.) includes: Fe_2O_3 36.4%; TiO_2 17-2%; V_2O_5 0.44%; SiO_2 15.6%; Al_2O_3 6.4%; MgO 6.1%; CaO 2.7%, etc..

Geochemical anomalies with Pt

Anomalous concentrations of Pt (160-910 ppb) have recently been found (FRIZZO, 1986) in some samples of stream sediments coming respectively from the outcrop areas of the Hamar Gabbro (1 anomalous sample) and the Barkasan-Mandera Complex (3 anomalous samples). The basic-ultrabasic complex of Barkasan-Mandera, not thick but very extensive, lies in a shear zone (SACCHI et al., 1986), and contains gabbros and subordinate ultramafites, intensively amphibolitized and crossed by various granitoid bodies. Data refer to exploratory geochemical prospecting in which only some gabbroid bodies were examined.

Disseminated and vein-type Mo + Bi occurrences related to syenites

Occurrences of some interest are associated with the syenite masses of Darkainle and Barka Aggar (Bohl). The Darkainle mass is composed of predominant syenites and biotitic nephelinic syenites (GELLATLY et al., 1971), with lens-shaped differentiates of syenite with hornblende and aegyrine, syenites with magnetite and also later and rare dm- to m-thick dykes and lenses, of pluridecametric extent, of pegmatitic leucocratic syenites (albite, biotite, nepheline, carbonate) and carbonatite dykes. The dykes of leucocratic syenites contain 200-500 ppm of Mo and the carbonatites on average between 80-200 ppm of Mo with peaks of 3.000 ppm. The dykes of pegmatitic leucocratic syenites show marginal areas with dominant feldspars containing widespread pyrrhotite and cores of spathic nepheline with disseminated molybdenite (0.06-0.1%), carbonate, pyrite, and zircon (e.g., Darkainle Tug and Mobeleh Hill). Molybdenite may also be found: disseminated in quartz-feldspar veins, sometimes as stockworks, embedded in the syenites and nearby metamorphites (up to 0.1% Mo): examples are the Dobo Year and Dobo Wein occurrences (UNDP Phase II, 1972; KAMENOV, 1975; MOHAMED SAID, 1973). Further occurrences lie in metasomatic areas, both in syenites and embedding schists; in shear zones characterized by extensive neoformation of biotite; in carbonatite dykes (UNDP Phase II, 1972;

KAMENOV, 1975/6; MOHAMED SAID, 1973).

In the eastern sector, in the biotite-nepheline syenites of Barka Aggar (Bohl area) about a hundred quartz-feldspar dykes with disseminated molybdenite and/or bismuthinite, mainly some dm in thickness and extending for some tens of metres, have been identified. The largest dyke (up to 3 m thick and 200 m long) outcrops between the syenites at Dagah Weraba (BERESFORD, 1957) and contains 0.1-2% Mo and 0.50-0.60% Bi. As well as molybdenite and bismuthinite, the metallic paragenesis includes traces of galena, chalcopyrite and scheelite.

Carbonatite differentiates with molybdenite, pyrochlore, apatite and orthite-zircon

Carbonatite differentiates (sövite and beforsite) occur in the syenites, both as lenses concordant with the foliation and in discordant dykes, and represent about 0.1% of the syenite complex of Darkainle (GELLATLY et al., 1971). The ferriferous carbonatites are deeply limonitized. Molybdenite, altered into powellite, is more frequent in the sövite (calcite and/or dolomite), e.g., on the right bank of the Tug Darkainle, where chalcopyrite, sphalerite, malachite, covellite and chalcocite are also found.

In the carbonatites, as in the nephelinic leucocratic syenites, radioactive pyrochlore also occurs, in clusters of tiny grains (DANIELS, 1960), together with apatite, zircon in cm-sized crystals, orthite and riebeckite.

MINERAL DEPOSITS RELATED TO YOUNGER GRANITES

Quartz veins with gold-bearing pyrite

In the Dagah Kureh area (ENE of Arapsiyo) some coarsely lenticular quartz dykes, discordant with respect to the embedding schists, outcrop on the left bank of the Tug Biyo Ase. They vary in thickness (0.5-1.5 m) and length (5-18 m). The milky, massive quartz contains disseminated crystals, nodules and short irregular veinlets of partly limonitized gold-bearing pyrite. The analysis of many samples (UNDP Phase III 1975) revealed variable contents of Au, from traces to 17 ppm. This dyke may also contain a paragenesis with polymettallic sulfides (iron-rich sphalerite, pyrrhotite, chalcopyrite and native gold in decimillimetric grains; ABDULKADIR, 1978).

Quartz and quartz-feldspar stanniferous veins

Dozens of dykes of milky quartz and some pegmatitic dykes with cassiterite, mostly embedded in the epimetamorphic pelitic schists of the Inda Ad Series, are concentrated in the areas of Dagan Kureh-Dalan and Ahl Medo-Majia Yian, forming two stanniferous dyke fields (USONI, 1952; PALLISTER, 1959; GELLATLY, 1961b). The milky quartz dykes, sometimes pale grey in colour, are generally some dm in thickness and several dozen metres in lenght. They generally run E-W and are grouped in characteristic swarms of 5-10 subparallel dykes, echeloned in narrow belts running N-S. Cassiterite is closely associated with white or pale green mica, apatite ± rutile, forming cm-thick layers with sometimes banded texture, or nodules and irregular veins, near the edges of the quartz dykes; clusters of large cassiterite crystals sometimes form conspicuous aggregates in the massive quartz. SnO_2 contents vary between 0.2%, and 1.5%. The pegmatitic dykes, much less numerous than the milky quartz dykes, are essentially composed of quartz, K-feldspar, albite and muscovite, and vary between 30 cm and 1 m in thickness and between 200 and about 700 m in length.

Some, like the milky quartz veins, run E-W, while others run NNE-SSW; they are all usually sub-vertical. Exploitable ore is concentrated over decametric stretches, forming columnar enrichments with dark cassiterite, muscovite, tourmaline, lepidolite, a little apatite, sometimes sphalerite pyrite and chalcopyrite and, more rarely, molybdenite, columbo-tantalite and beryl (CHINA REPORT, 1972; MOHAMED SAID, 1973).

Much research has been carried out in the Dalan area (GREENWOOD, 1960; PALLISTER, 1959; GELLATLY, op. cit.). The dyke field of Majia Yian was evaluated and some attempts at exploitation were made between 1938 and 1941 by the COMINA company (USONI, 1952).

Pegmatites (quartz, K-feldspar, muscovite + beryl, tourmaline, columbo-tantalite, apatite and monazite)

Many pegmatites, generally related with the younger granites are widespread in the old basement of Northern Somalia. They are mostly concentrated in two separate basement sectors: the western Bur Mado pegmatite district, corresponding to a belt of almost 100 x 30 km of sublatitudinal trend extending from Bawn to Waran-Weiss, NW of Hargeisa, and the central Daarburuq-Lafarug pegmatite district, SW of Berbera. When the pegmatites are not directly embedded in the granitic domes, they are found clearly discordant in the oldest sequences of the basement with the highest metamorphic grade: in the migmatites, gneisses and orthogneisses of the Adadleh Qadr Bahar Series, in the metasediments of the Gebile Psammitic Series and, less frequently, in the Borama-Ubali Pelitic Series and Harirad-Mora Calcareous Series. The pegmatite district appears to correspond to areas of culmination of great antiform structures, strongly eroded after the Pan-African Orogenesis. The pegmatite bodies are generally 1-3 m thick and 100-200 m long, although the largest may be between some 10 m thick and 1 km long. Many pegmatites show a simple paragenesis (quartz, K-feldspar, subordinate muscovite); others are more complex and also contain beryl ± tourmaline and/or columbo-tantalite, apatite, accessory biotite and monazite and, in some cases, cleavenalite, lepidolite and crystals of piezoelectric quartz. The generally weak internal zoning is occasionally well-defined, especially in the complex pegmatites, which generally show marginal bands of graphic texture with internal transition to a coarse-grained association, sometimes with dominant crystals of pure feldspar, interstitial quartz, muscovite (sometimes with decimetric flakes), and cm/dm-sized prismatic crystals of greenish beryl, tourmaline, columbo-tantalite and apatite. The cores are generally of glassy ± massive quartz, occasionally with sporadic crystals of pale blue beryl; open cavities with walls coated with large transparent crystals of quartz with excellent piezoelectric characteristics also sometimes occur (UNDP Phase II, 1972, UNDP Phase III, 1975). The greatest concentrations of piezoelectric quartz are surrounded by areas of cleavelandite ± lepidolite, making up lens-shaped bodies sometimes arranged transversally to the direction of the main pegmatite dyke (e.g., Wai-Wai in the Bur Mado district). This may indicate a variation in the tectonic arrangement and a time gap between the main pegmatitic phase and the last phase of albitization and growth of piezoelectric quartz crystal. In 1970-1971 about 70 tons of piezoelectric quartz crystals were extracted from the Wai pegmatite (UNDP, Phase II, 1972).

Some pegmatites embedded in the Hamar Gabbro have rather special paragenesis consisting of K-feldspar, albite, tourmaline, phlogopite, apatite, rare beryl, garnet, Nb- and Ta-rich betaphite and REE-rich orthite (DANIELS, 1960).

The Lafarug district has a large swarm of pegmatites out-cropping in the Hanweina Valley north of Gallan Libeh, between Danaeh Hos, Rol Hanod and Wearear (HUNT, 1958). These are mainly weakly zoned bodies with marginal bands of quartz, microcline and subordinate muscovite with quartz cores and disseminated dm-sized prismatic crystals of greenish beryl and large tabular crystals of columbo-tantalite. Sporadic quarrying of some pegmatites in the Lafarug district by the MINERAL and RESEARCHES DEVELOPMENT CORPORATION were carried out in 1955-1956, producing about 1200 tons of feldspar (mostly detritic), 33 tons of beryl, 1,300 kg of columbo-tantalite and about 100 kg of large-flaked muscovite.

Carbonate veins with idiomorphic quartz

Dykes with calcite and quartz up to 6-7 m thick and more than 50 m long are found in the Abdul Qadr volcano-sedimentary series. They contain quartz crystals 5-20 cm long with transversal sections of 5-10 cm, quite transparent but rich in fluid inclusions, not suitable for piezoelectric purposes. Similar dykes are also found in the Bawn area, embedded in biotite-muscovite paragneisses and amphibolite. These orebodies are referred to shallower occurrences with respect to the pegmatites, to which they are probably connected.

Other ore deposits

Many discordant ore bodies, characterized by the constant occurrence of lead (galena) in a barite ± fluorite and/or quartz gangue (Fig. 2), are found along the belt of deep sublatitudinal fractures and connected system of transversal faults.

These fractures, which involve both the basement and the Mesozoic-Tertiary cover and, partly, also older structures, are linked to the uplifting and rifting processes of the Gulf of Aden. Most of the occurrences, sometimes lying at the tectonic contacts between basement and carbonatic cover, are clearly related to post-Jurassic geothermal activity, although some of them may be linked to the Pan-African granitoid event. A later report (FRIZZO, in prep.) will deal with these mineralizations, together with the uranium deposits in the Bur Basement and those linked to the Mesozoic-Tertiary and Quaternary covers.

METALLOGENIC CONSIDERATIONS

The ore deposits considered belong to metallogenic events whose chronological ceiling is represented by the Pan-African Magmatism of the Younger Granites (approximately 500 Ma).

1- The high-grade polymetamorphic sequences (Middle? and Upper Proterozoic) contain many syngenetic-sedimentary deposits:

a) in the Bur Basement, the extensive layer of ferriferous quartzites (BIF) at the base of the Dinsor Formation must be noted. These Fe and Si chemical-sedimentary deposits come from a shallow-sea environment with minimum detritic contribution, as also shown by low Al, Ti, Na and K values and impoverished low Ni, Ca and V (ABDULLAHI et al., 1981). They may be correlated with the BIF of the Awata Gneiss Formation in southern Ethiopia, part of a "pre-Mozambiquean" basement (WARDEN and HORKEL, 1984). Moreover, some layers of marbles with phosphates and rhodonite around Bur Acaba probably correspond to original sediments from coastal basins, adjacent to areas of structural highs and swept by warm currents;

b) in the Northern Somalia Basement, many conformable deposits are found in high-grade metamorphic sequences attributable on lithostratigraphic grounds to the Gebile Psammitic Series and *pro parte* to the Borama-Ubali pelitic Series. The most widespread are manganesiferous orebodies of the "gondite" type, derived from original sediments of quartz and Mn ± Fe oxides and clayey material, comparable to the much larger Mn-silicate deposits of the "Sausar Group" in central India, with a sedimentation age dated at 1700-2000 Ma and an amphibolite facies metamorphism of 846-986 (ROY, 1973, 1976, in HUTCHINSON, 1983). In the western sector (Gebile-Qadr-Bahar-Bur Mado area) the same lithostratigraphic context contains layers and lenses of graphitic-manganesiferous schists, ferruginous quartzites and quartz-carbonate stratiform bodies with Fe ± Mn, Cu ± Zn and Pb. These probably correspond to mineralized fringes, marginal with respect to the more important Mn-silicate deposits. The same area also contains Cu-bearing quartzites (Bohl) and layers of kyanite, sometimes with sulfides (e.g., Udan Tug). The persistent occurrence of gold is common to many of these deposits. The presence of significant quantities of Au (1-10 ppm) is well-known worldwide scale in quartz-carbonate stratiform deposits (ankerite, dolomite, sideroplesite), ferruginous ores (oxides and sulfides) and frequently in silicates (biotite, tremolite, cummingtonite, tourmaline, etc.), space/time-bound with ferriferous stratiform (BIF) or ferro-manganesiferous domains. Apart from the Fe-Mn and Au-bearing mineralization of the Archaean Greenstone Belts (FRIPP, 1976) (the most important for gold), it should be recalled that the Lower Proterozoic is of particular interest as regards the belt of Barremian ferriferous quartzites extending from Western

Africa to Southern America, immediately to the east of which is the coeval "Mangano-Auriferous Province" (ROUTHIER, 1980).

The Middle Proterozoic contains typical Mn-bearing deposits (silicates, carbonates, ± oxides), sometimes associated with graphitic schists and characteristic of extensive areas of India and Gabon. Lastly, the Middle-Upper Proterozoic contains widespread Mn-bearing deposits of the gondite type (Mali, Ivory Coast, High Volta) and lesser BIF with Au, dated at 1500-1100 Ma, in the Sangbam region of Eastern India (HUTCHINSON, 1983) and perhaps also in Tanzania, Mozambique, Ethiopia and Somalia (Bur): otherwise POHL (1982) attributes the BIF occurrences in East Africa to sequences of Mozambiquean age. There is also a recurrent spatial association between this type of stratiform mineralization with low contents of Au and quartz dykes with sulfides and higher contents of Au, whose formation was due to thermal and hydrothermal mobilization induced by later granitic intrusions ("revealer granites"). In the Somalia basement, the quartz dykes with Au-bearing pyrite of Biyo Ase may belong to this type together with some areas with widespread pyrite (with Au), e.g., at the contact between the ultrabasic massif of Udan and the country metamorphites and presumably an aplitic dyke with Au-bearing pyrite crossing the Udan massif.

The Late Proterozoic volcano-sedimentary sequences (Abdul Qadr Volcanic Series and Mait Greenstones) deposited in the mobile belts of the Arabian-Nubian Shield, contain exhalative-sedimentary sulfide deposits, similar to the much larger Egypt, Ethiopia and the Arabian peninsula (DELFOUR, 1976, 1980-81; POHL, 1982; KRÖNER, 1985; POUIT et al., 1987). The Abdul Qadr Volcanic Series, characterized by abundant pyroclastites, is noted for its deposits of massive polymetallic sulfides. The widespread mineralogical anomalies with scheelite, recorded in the western sector of the crystalline basement of Northern Somalia, may indicate exhalative-sedimentary occurrences linked to a layer of metabasites and metapsammites between the base of the Abdul Qadr Series and the underlying Harirad-Mora series. In the Mait Greenstones with dominant basaltic metavolcanites, Cu- and/or Au-bearing deposits, which represent a constant in similar sequences in the whole Arabian-Nubian Shield, are hypothesized.

In the Lower Cambrian epimetamorphic molasse (Inda Ad Series), both the stratiform cupriferous (Seinat, Iddit Ad) and manganesiferous (Kudut) occurrences are chemical-sedimentary in origin. Copper and manganese may derive from weathering and erosion from the nearby Mait Greenstones, on which the Inda Ad series appears to be transgressive. The many layers with low Cu contents are referred to cyclic chemical precipitations of copper, concomitant with efficient clastic sedimentation under reducing conditions. The Mn deposits have been genetically assimilated (KAMENOV, 1976) to those of Nikopol and Chiaturi (U.S.S.R.) and their deposition related to a sudden passage from a rainy subtropical climate to a cold one.

The most important mineralization linked to the plutonic rocks are connected to two intrusive events, well separated and defined in time:

a) the gabbroid and/or syenitic magmatism which took place about 700 Ma ago, related to general crustal thinning. The gabbros are associated with segregation mineralization composed of magnetite, ilmenite and probably platinum, with PGE occurrences.

The syenites include occurrences of molybdenite disseminated in lenses of leucocratic syenites, dykes and lenses of carbonatites sometimes rich in REE, zircon and apatite, primary alteration area linked to shear zones, dykes and stock-works with quartz ± feldspar, sometimes with bismuthinite and native Bi and other polymetallic sulfides (e.g., Bohl).

b) The acidic magmatism of the Pan-African Orogenesis s.s. and particularly the Younger Granites (510-490 Ma) which intersect all the basement sequences. To the Younger Granites are linked: 1) the numerous bodies of simple and complex pegmatites (Nb, Ta, Be) of the Bur Mado and Lafarug-Daarburuq districts: 2) stanniferous dykes with quartz and K-feldspar (Dalan Majia Yian), related to granite domes; 3) carbonate dykes with idiomorphic quartz crystals rich in fluid inclusions. According to POHL (1982), in East Africa mineral concentrations related to acidic plutonic rocks are specific to two the triple junction with the Zambesi Belt, the Mozambique belt and its southern extension into Antartica; and in Northern Somalia-Yemen, the transition from N and NE of the Mozambique Belt and the Arabian-Nubian Shield.

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BLACK HEAVY-MINERAL BEACH SANDS FROM BATALEH (BERBERA, N. SOMALIA)

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ABSTRACT

The beach sand deposit of Batalaleh is derived from marine reworking of alluvial sediments drained from the nearby Sheik-Hudiso area, in which the crystalline basement outcrops behind the coastal belt composed of sedimentary cover.

Studies were carried out on the shallowest part of this beach sand along a stretch about 1000 m long and 100 m wide. Grain-size ranges between 1 mm and 0.063 mm, representing almost all the sands sampled.

Gravity separation was carried out on 59.24% light and 40.76% heavy minerals, mainly concentrated in the 250-125 m fraction. Light minerals are represented by quartz (the most frequent component), feldspars (plagioclase + lesser K-feldspar), calcite and phyllosilicates. The average weight percentage of the more important heavy minerals are: titanomagnetite 19.75%, ilmenite 8.33%, zircon 0.36%, monazite 0.27%, and rutile 0.18%.

INTRODUCTION

The Somali coast along the Gulf of Aden contains many concentrations of black sands with heavy minerals (DANIELS, 1958), mainly along the stretches of beach which received larger quantities of alluvia from the nearby outcrop and erosion areas of the crystalline basement.

The crystalline basement of northern Somalia outcrops quite clearly for almost 600 km along a narrow belt parallel to the coast (Fig. 1). It contains (WARDEN and DANIELS, 1983; SASSI and VISONÀ, 1985): granitic gneisses and schists with paragenesis showing relicts of granulitic facies, probably part of an ancient "pre-Mozambique basement", and a "Mozambique sequence", sedimentary and partly volcanic, metamorphosed in the amphibolite facies (WARDEN and HORKEL, 1984). The latter is composed (from bottom to top) of metapsammites (Gebile Psammitic Series), pelitic-psammitic rocks with intercalated amphibolites (Borama-Ubali Pelitic Series), and a carbonate-quartzitic series (Harirad-Mora Calcareous Series). Volcanites

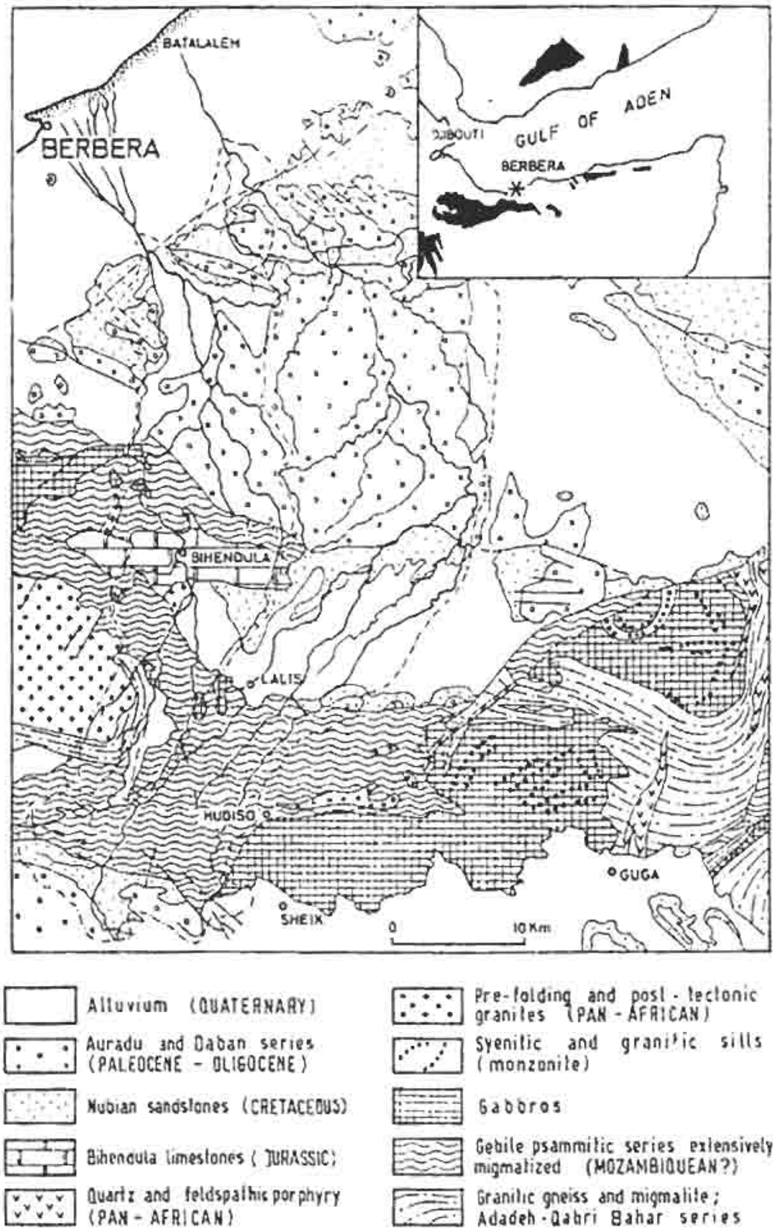


Fig. 1 - Geological sketch of Berbera-Sheik area. The black patches in the inset indicate the basement outcrops.

metamorphosed in the green schist facies discordantly overlie these units and outcrop in the western (andesites, dacites and rhyolites of the Abdul Qadr Volcanic Series) and eastern sectors (basaltic pillow lavas of the Mait Greenstones). Rocks of the Inda Ad Series (Cambrian conglomerates, sandstones, siltites, marls and limestones), only weakly metamorphosed, close the metasedimentary sequence of the Northern Somali Basement in this area.

The basement is crossed by many bodies of cumulitic gabbros and syenites, linked to distension and crustal thinning about 700 Ma. ago (FERRARA et al., 1987), and by a series of granitic intrusions related to the Pan-African cycle s.s. (550-500 Ma.), including pre-folding granites (e.g., Daimoleh Granite), younger granites, and alkaline granites sometimes followed by complex pegmatitic dyke and ore-bearing quartz dykes.

BATALALEH PLACER

some tens of km wide extending to the foot of the steep escarpment of Mesozoic-Tertiary and Precambrian rocks produced by uplifting and rifting processes (Eocene-Quaternary) connected with the opening of the Gulf of Aden. The sands of this beach are rich in heavy minerals (mainly magnetite and ilmenite) derived from the reworking and marine concentration of alluvial sands from the Bihendule and Lalis areas (Fig. 1). This area contains eroding metamorphites which may be attributed to the Adadleh-Qabri Bahar Series and the Gebile Psammitic Series (sensu WARDEN and DANIELS, 1983), the eastern extension of the Daimoleh Granite, some minor gabbroid bodies, and aplitic-pegmatitic or quartzous sulfide dykes.

Further towards the coast the sedimentary cover outcrops, made up of the Bihendule Limestones (Jurassic), Nubian Sandstones (Cretaceous) and carbonate-clastic rocks of Auradu Series (Eocene-Miocene).

This study was carried out on an exploratory population (12 samples) from the shallowest part (about 50 cm) of the black sands along a stretch of beach about 1 km long and 100 m wide.

SAND COMPOSITION

Analyses were carried out on the grain-size fraction between 1.00 and 0.063 mm, representing on average 96,5% of the bulk sands. The remaining 3.5% is principally composed of grains larger than 1 mm (2.8%), mainly lithic and shell fragments, and of grains smaller than 0.063 mm (0.7%), with a composition substantially similar to that of the 0.125-0.063 mm size-range.

Gravity separation settling for each sample was carried out with bromoform (d = 2.88) on four granulometric grain-size classes, furnishing the mean percentages of light (L) and heavy (H) minerals (Table 1 and Fig. 2).

Table 1 - Granulometric analysis of the bulk sands.

Gravimetric fraction	Weigth	% of grain-size	classes		Total weigth %
	1000-500µ	500-250µ	250-125µ	125-63µ	1000-63µ
H	0.26	6.11	31.98	2.41	40.76
L	8.10	43.62	7.14	0.38	59.24
L+H	8.36	49.73	39.12	2.79	

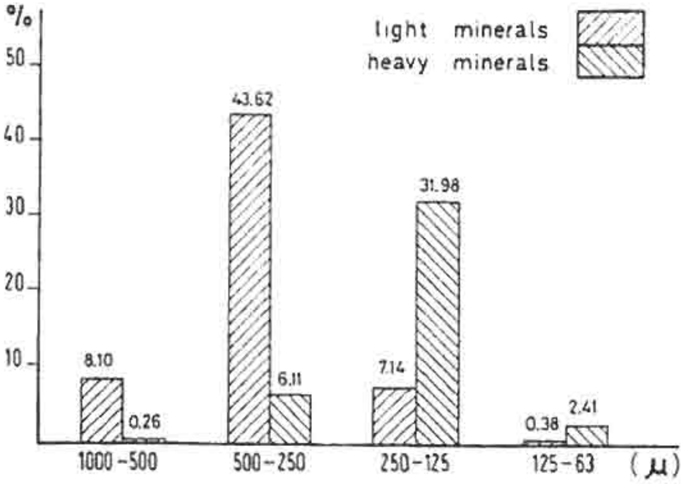


Fig. 2 - Weight % of the various granulometric fractions of light and heavy minerals.

The light fraction is mainly composed of quartz and plagioclase, with minor K-feldspar, calcite (partly organogenic), biotite and chlorite.

A statistical count of grains, both under the binocular microscope and in polished section, was carried out on each grain-size class, in order to estimate the numerical percentages of each component. These values were then transformed into weight percentages, considering the density of each mineral. Mean weight percentages of the bulk sands (L + H) in the range 1.00-0.063 mm are shown in Table 2 and Fig. 3.

The heavy fraction of one composite sample was subdivided into three parts using a

Frantz magnetic separator. The minerographic study carried out on each part gave the mean numerical compositions shown in Table 3.

Table 2 - Weight percentages of the heavy minerals in the 1000-63 m (in various grain-size classes and total 1000-63 m).

	grain - size classes				total %
	1000-500μ	500-250μ	250-125μ	125-63μ	1000-63μ
"Titanomagnetite"	0.06	1.50	16.73	1.46	19.75
"Ilmenite"	0.04	0.61	7.12	0.56	8.33
Amphibole	0.10	2.74	3.55	0.10	6.49
Garnet	0.04	0.62	1.73	0.04	2.43
Titanite	-	0.15	0.31	0.03	0.49
Epidote	0.01	0.11	0.26	0.01	0.39
Zircon	-	0.02	0.28	0.06	0.36
Monazite	-	-	0.24	0.03	0.27
Rutile	-	-	0.17	0.01	0.18
Clinopyroxene	<0.01	0.09	0.06	0.01	0.17
Orthopyroxene	<0.01	0.03	0.06	<0.01	0.09
Apatite	-	0.02	0.06	<0.01	0.08
Tourmaline	-	-	<0.01	<0.01	<0.01
Staurolite	-	-	<0.01	<0.01	<0.01
Biotite	-	<0.01	0.05	<0.01	0.06
Muscovite	<0.01	-	0.01	-	0.02
Other Transparents	<0.01	0.04	0.08	0.01	0.14
Other Opaques	<0.01	0.17	1.27	0.05	1.49
Shell fragments	0.01	-	-	-	0.01

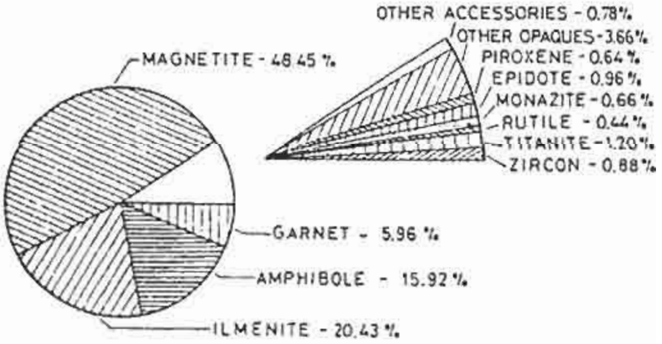


Fig. 3 - Weight % of the minerals in the heavy fraction.

Table 3 - Percentage composition of the magnetic fractions.

Fraction with strong magnetic susceptibility : 51.96 % of heavy minerals

± martitized titanomagnetite	titanomagnetite with exsolutions of ilmenite	transparent minerals with magnetite inclusions
92 %	6 %	2 %

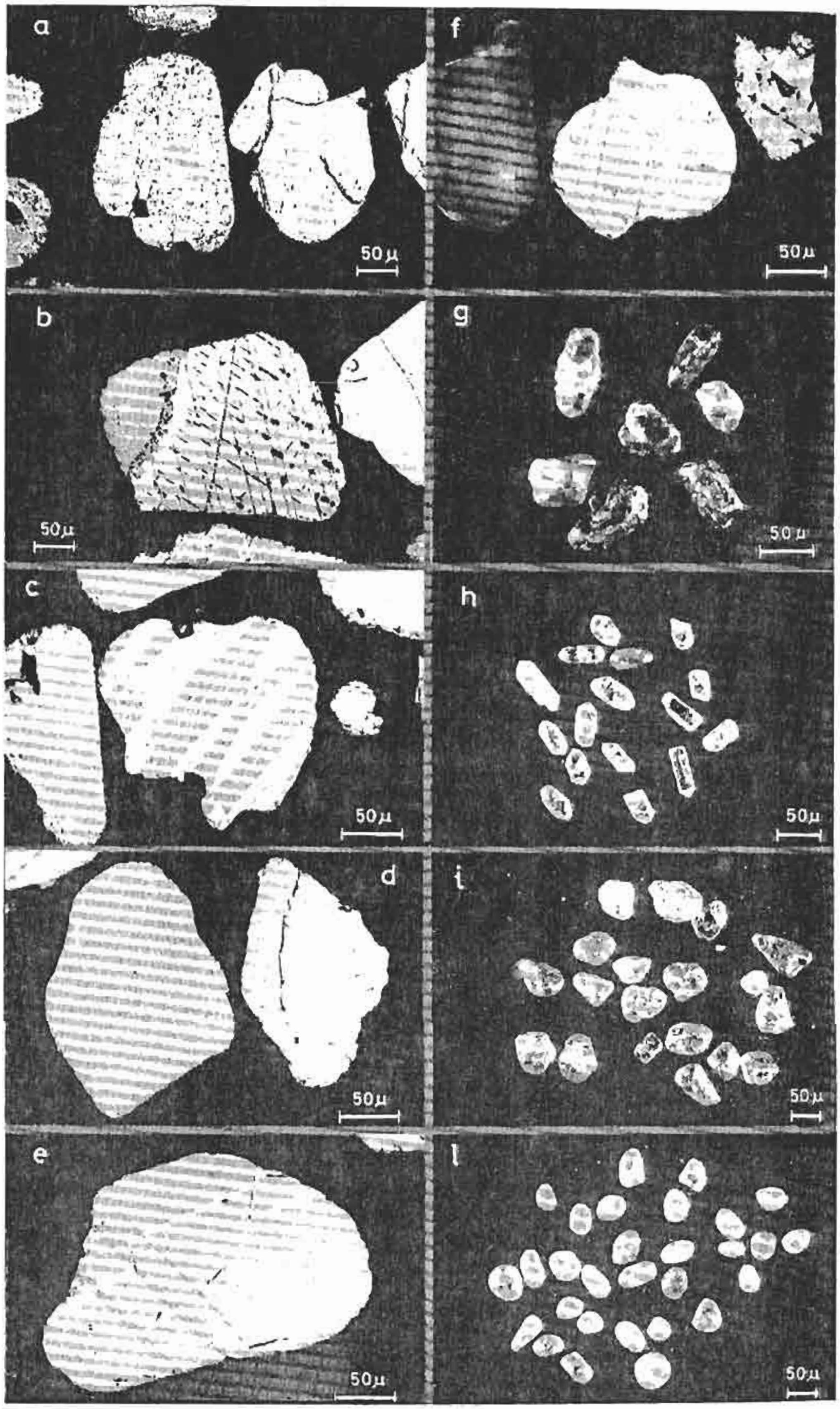
Fraction with intermediate magnetic susceptibility : 23.15 % of heavy minerals

± homogenous ilmenite	aggregates of exsolutions ilmenite-hematite		martite	altered oxides on ilmenite	transparent minerals with inclusions
	ilm>hem	hem>ilm			
38 %	24 %	24 %	0.5 %	4 %	9.5 %

Fraction with weak magnetic susceptibility : 24.89 % of heavy minerals

aggregates of exsolutions hematite ≫ ilm.	leucoxene	limonite	transparent minerals
6 %	4 %	1.5 %	88.5 %

Fig. 4 - a) Magnetite with advanced martitization. N. partl. cross., imm. b) Ilmenite and spinels exsolved along different orientation in titanomagnetite; on left side, intergrowth between ilmenite and magnetite. N. partl. cross., imm. c) Ilmenite with exsolution bodies of first and second generation of hematite; on left, magnetite partially martitized. N. partl. cross., imm. d) Different size and kind of exsolutions of hematite in Ilmenite. Both grains have small trasformation in leucoxene. N.partl.cross., imm. e) Pure ilmenite with lamellar twinning. N.partl. cross., imm. f) Hematite-Ilmenite with exsolution "needles" of rutile in at least four directions. Grains of zircon (left) and magnetite (right). N. partl. cross., imm. g) Rutile grains typically poorly rounded. h) Euhedral zircon grains. i) Titanite grains with some ilmenite inclusions. l) Well rounded monzanite


a
50µ
b
50µ
c
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d
50µ
e
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f
50µ
g
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h
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i
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l
50µ

MINERALOGY

Titanomagnetite represents about half the heavy fraction. This general term includes the following: large quantities of octahedral or rounded grains of more or less titaniferous magnetite lacking exsolutions of ilmenite, subjected to incipient to almost total martitization (Fig. 4a); definitely smaller quantities of magnetite grains with thin exsolutions of ilmenite and or spinel, sometimes oriented in various crystallographic directions (Fig. 4b); polycrystalline grains due to intergrowths of magnetite and ilmenite; rare grains characterized by myrmekitic associations between magnetite and silicates.

Ilmenite occurs in subhedral to euhedral grains, of which slightly less than half are composed of homogeneous ilmenite with a few tiny microgranular or lamellar exsolutions of hematite, more common towards the nucleus (Fig. 4e; d). The remainder is composed of associations of discoidal or lens-shaped exsolutions between ilmenite and hematite, and one or the other mineralogic species may prevail (Fig. 4d, c): evidence of two successive generations of ilmenite-hematite exsolutions is common (RAMDOHR, 1980). The presence of some grains with dominant hematite with exsolution rutile needles is characteristic (Fig. 4f). These are variously oriented and always transversal with respect to (0001) of ilmenite exsolutions. Grains composed of leucoxenic products are quite frequent.

Amphiboles occur in blue or green, slightly rounded prismatic crystals, generally hornblende, sometimes accompanied by other minerals of the tremolite-actinolite series. Garnets occur in euhedral grains, often fractured, only slightly rounded, and colourless or slight to deep pink in colour. *Rutile* occurs in rounded or splintered grains, varying in colour from reddish-yellow to brownish-red (Fig. 4g). In polished section, it shows red or yellow-orange internal reflections and is sometimes twinned. *Zircon* is found both in well-preserved euhedral grains and in variously rounded grains (Fig. 4h), commonly colourless or slightly pink. Zoned crystals or ones containing Fe and Ti oxide inclusions are frequent. *Sphene* is in generally slightly rounded, brownish-yellow, anhedral grains. A transformation ring is sometimes visible on the rims of some ilmenite grains (Fig. 4i). *Monazite* occurs in well-rounded, sometimes flattened grains (Fig. 4l), from yellow-orange to reddish in colour. Electronic microprobe analysis showed important contents of Sm, Nd, Gd, Th and U. Among the *epidotes*, pistacite prevails over clinozoisite: zoisite is rare. *Apatite* is found as colourless or whitish, more or less rounded, prismatic grains. *Pyroxenes* are widespread, both as orthopyroxene (prismatic and more or less rounded crystals with incipient alteration along the mineral cleavage and as clinopyroxene (slightly rounded, generally well-preserved, prismatic crystals). Other less common mineralogic species are represented by: *tourmaline*, with brown pleochroism; **biotite** in sometimes decoloured lamellae sometimes transformed into vermiculite; flakes of *muscovite*, often with tiny inclusions of Fe oxides or amphibole, mainly in the 1000-500 m size-range; *staurolite* in often fractured anhedral grains.

The term *other opaques* is applied to various kinds of grains, mainly occurring in the fraction of weak magnetic susceptibility. In polished section these were identified as: ilmenite, deeply or totally altered to leucoxene; grains of limonite ± hematite from the alteration of magnetite or sulfides (pyrrhotite or calcopyrite relics in the core of some grains); and rare hematite-ilmenite aggregates.

Other transparent minerals are mainly represented by semi-opaque microcrystalline aggregates and metamict alterations of monazite.

CONCLUSIONS

The mineralogical composition of the black sands of the Batalaleh beach agrees with the lithological features of the erosion basins (high-grade metamorphic metasedimentary sequences, basic and acid intrusive bodies, rare aplites and pegmatites, and a few sulfide-bearing quartzose dykes).

The present study, carried out on an exploratory sample population, does not allow economic evaluations to be made. However, the abundance of magnetite mainly in monomineralic, more or less martitized grains, without exsolutions of ilmenite, and moderate quantities of ilmenite grains without or almost without exsolutions of hematite, should be stressed. With respect to DANIELS (1958) report on the placers futher west along the coast between Berbera and Bulhar, the Batalaleh placer contains more rutile, but definitely less monazite and apatite (up to five times less); zircon, although less plentiful, does occur in comparable quantities.

The heavy-mineral sands reported by DANIELS (1958) derive from alluvial rocks coming from erosion basins with very extensive outcrops of granitic rocks and pegmatitic bodies.

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SOME GEOTECHNICAL CHARACTERISTICS OF THE SUPERFICIAL ALLUVIAL SOILS OF SHABELLE RIVER BETWEEN AFGOYE AND JANNALE (SOUTHERN SOMALIA)

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ABSTRACT

A study of the geotechnical characteristics of the alluvial soils of Shabelle River has been made necessary by the accelerating social and economical development of the region. Three types of superficial soils has been recognized on the basis of their similarity in the geotechnical characteristics. The geotechnical characteristics of the soils has also revealed that they are clay with various content of silt. An increase of clay content from Afgoye (up stream) toward Jannale (down stream) and its influence on the determined geotechnical parameters has been observed.

INTRODUCTION

The Shabelle River originates in Ethiopia in the regions of Bale, Arussi, and Hararge; it has a total length of about 2,488 km and catchment basin of about 300,000 km^2. In the Somali territory it does not recieve any perennial tributaries and describes an Arch from north to south-west from Beled Weyne to the swamps of Jilib (POZZI, 1982). Out of the Somali territory the river and its tributaries run across the basaltic rocks of Bale and Arussi the sandstone of Adigrat Formation the rocks of the basement, the carbonatic and marly rocks of Antalo and Mustahil formations, and the main gypsum formation. From south of Beled Weyne, in the Somali territory, down to Mahaddai Weyn, the Shabelle River Valley has a width of about 10 km and is delimited by the carbonatic rocks of Mustahil and Beled Weyne formations, and the sandstone of Jesoma Formation (MERLA et al., 1973). From Mahaddai Weyne the valley has larger width of about 60 km and is delimited at the east by the quarzitic eolian sands (coastal dunes) and at the west by the eluvial and colluvial deposits of the crystalline basement of the Bur area (Fig. 1).

It is in this latter part of the valley that a profittable and intensive agricultural activity with some small industries has been set up. Strictly connected to it, is the rapid

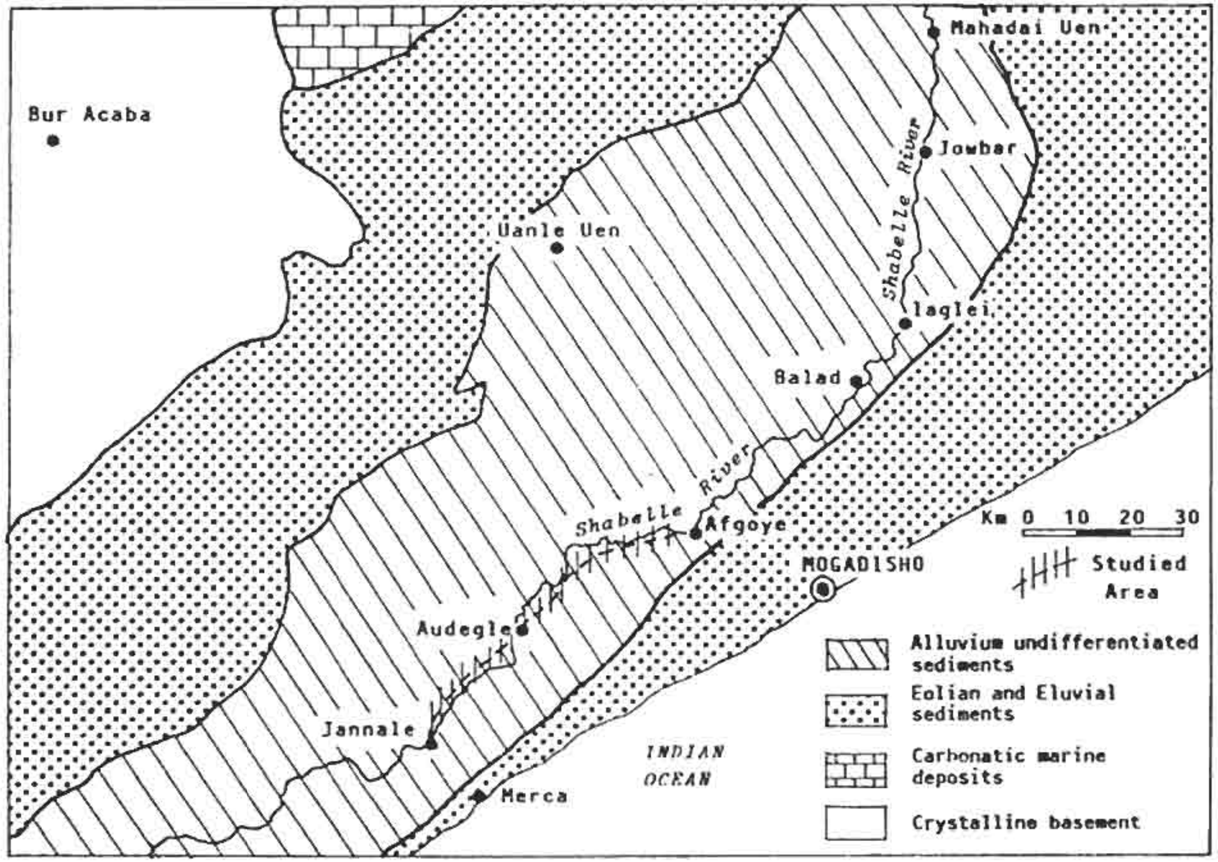

Fig. 1 - Geological map (BIANCONI et al., 1979).

growth of villages and cities specially in the last few decades. In the view of this accelerating social and economical development of the region, the study of the geotechnical characteristics of the alluvial soils of Shabelle valley becomes of considerable importance. This research is a part of more ample research programme carried out by the faculty of science of the Somali National University in order to provide the needed geological and geotechnical data of the Shabelle alluvium soils both for their use as a material for embankments, for cores of dams, as inert for construction materials, as material for manufacturing bricks and as foundation soils for the various civil engineering projects.

This paper deals with the results of the geotechnical determinations carried out on a first group of samples taken from the area between Afgoye and Jannale, as a first approach to the classification and distribution of the superficial soils of this region.

A good criteria of classification must take into account the geotechnical properties and the present and past geological and geomorfological processes, but for the lack of previous geological and geomorfological data in the area, a tentative of classification of the analyzed samples is made on the basis of their similarity in geotechnical properties.

The analyzed samples were taken (disturbed) from depths that vary between 0.30 m and 0.50 m. The laboratory procedures followed in the determinations of the index properties are those of the A.S.T.M standards (1961), while the laboratory procedures for the determination of the mechanical properties will be discussed later in the following paragraphs.

GEOTECHNICAL PROPERTIES OF THE EXAMINED SOILS

INDEX PROPERTIES

The grain size distribution curves of all the samples (see grading envelope of Fig. 2) shows that these superficial soils are fine grained consisting mainly of clays and silty sandy clays. Their content of fines varies between 99.1% and 69.3% while the clay fraction C (<0.002 mm) varies between 72.4% and 27.0% (Table 1).

As regards to the Atterberg limits, the liquid limit varies between 90.2% and 34.0%. The plastic limit varies between 36.9% and 18.1% (Table 1). In the plasticity chart the points plot slightly above the "A" line ranging in the field of medium to high plasticity inorganic clays (Fig. 3).The relationship between plasticity index (Ip) and liquid limit (Wl) of these soils is expressed in the equation:

$Ip = 0.74\ (Wl - 14.0)$

The coefficient of linear correlation (r) is equal to 0.99. The correlation of the clay fraction variation with the geographical distribution of the samples, is observable from the diagram of Fig. 4, which relates the clay fraction variation with the variation of elevation and distance from Afgoye (up stream) The diagram shows a tendency of increasing clay fraction content in the superficial soils from Afgoye to Jannale (down stream). Since one of the principal factors that determine the behaviour of soils is their clay fraction content, a tentative of statistical correlation between index parameters and clay fraction (C) has been carried out. Concerning the relationship between liquid limit and clay fraction the curve of Fig. 5a has been obtained. The liquid limit satisfies a linear expression:

$$Wl = 1.35\ (C - 4.96)$$

where C denotes the clay fraction. The coefficient of linear correlation (r) is equal to 0.96. The relationship between plastic limit (wp) and clay fraction (C) gives the curve of Fig. 5b characterized by a linear correlation between the two variables - expressed in the equation:

$$Wp = 0.35\ (C + 25.6)$$

The coefficient of linear correlation (r) is equal to 0.86. For the case of the relationship between shrinkage limit (Ws) and C, we adopt a linear expression connecting Ws and C (Fig. 5c):

$$Ws = -0.004C + 15.78$$

The coefficient of linear correlation (r) is equal to 0.4, this low value being probably due to the fact that there actually exists a real curvature of the function Ws = f (C) (NOVAIS-FERREIRA, 1967). In Fig. 6 the three functions Wl = f (C), Wp = f (C) and Ws = f (C) are riported in the diagram W = f (C), where it is observable that in average the relationship Wl>WP>Ws is respected, and that the straight line of the function Wp = f (C) intersects that of Ws = f (C) immediately before that of the function Wl = f (c) at a value of C equal to 19.27%. The plasticity index (Ip) obviously shows a linear variation with C (Fig. 7) and this relationship is expressed by the equation:

$$Ip = C - 15.6$$

The coefficient of linear correlation is equal to 0.95. In the Fig. 8 is showed the curve Is = f (C), with a coefficient of linear correlation equal to 0.97. This function has the equation:

$$Is = 1.39\ C - 22.47$$

The colloidal activity (A) of the soils defined as the ratio between plasticity index and clay fraction varies between 0.47 and 0.85. According to the classification of soils in base of their activity (SKEMPTON, 1953) these values classify the soils as inactive and normal activity clays. This slight variation can also be observed from the Skempton activity diagramm of Fig. 9, where the points plot in the field of the kaolinitic illitic clays. Also distinguishable from the diagram are three groups of points: those near to illitic curve, those near to the koalinitic curve, and those approximately in the middle.

Table 1 - Legend = Wl: liquid limit; Wp: plastic limit; Ip: plasticity index; Ws: strinkage limit; Is: strinkage index; C: clay fraction; Fine: fraction fine than 0.074 mm; A: colloidal activity; G: specific gravity; Wn: natural moisture content.

Sampl. No.	Wl	Wp	IP	Ws	Is	C	Fine	A	G	Wn
1	47.5	24.8	22.7	13.3	34.2	44.0	94.0	0.52	2.7	10.8
2	51.8	27.4	24.4	15.0	36.8	45.0	98.7	0.54	2.77	26.5
3	37.0	22.2	14.8	15.5	21.5	27.0	95.0	0.55	2.73	10.7
8	34.0	19.3	14.7	14.9	19.1	31.2	87.4	0.47	2.74	19.5
14	36.0	18.1	17.9	14.5	21.5	33.0	69.3	0.54	2.7	9.3
4	63.8	26.4	37.4	13.4	50.4	54.4	96.1	0.69	2.71	20.9
6	82.5	35.3	47.2	14.9	67.6	72.4	98.8	0.65	2.78	6.3
10	62.2	25.5	36.7	10.9	51.3	54.0	85.1	0.68	2.7	16.7
12	63.5	21.2	42.3	10.7	52.8	53.0	~5.0	0.80	2.72	10.6
16	90.2	36.9	53.3	14.2	76.0	64.0	97.8	0.83	2.71	10.2
18	85.5	31.1	54.2	13.6	71.9	63.5	99.1	0.85	2.72	8.99
20	89.8	32.5	57.3	11.5	78.3	69.5	99.1	0.83	2.73	14.8

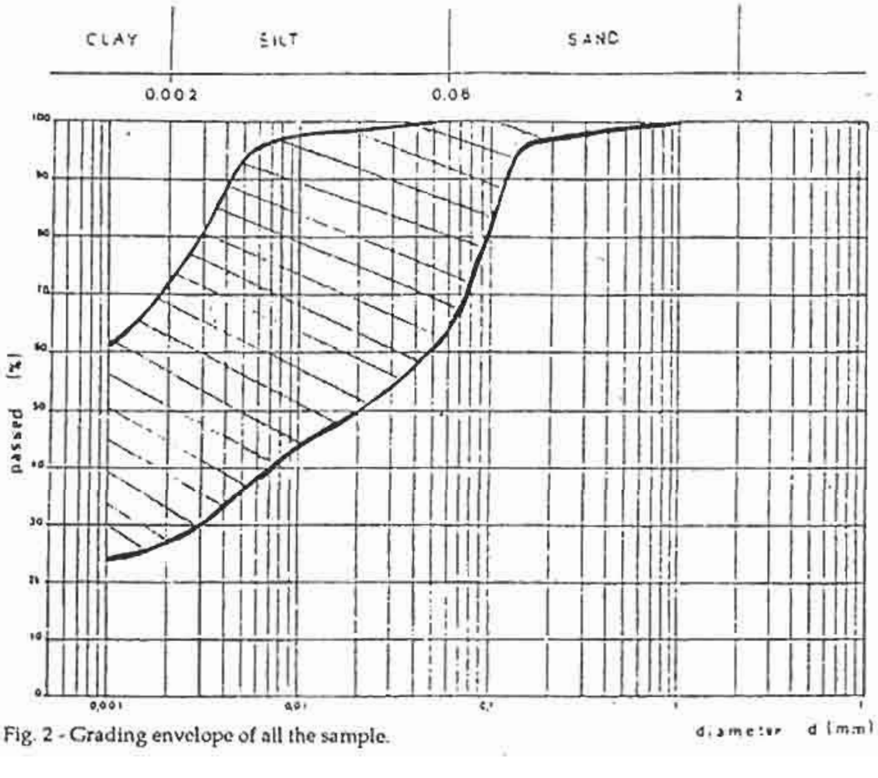

Fig. 2 - Grading envelope of all the sample.

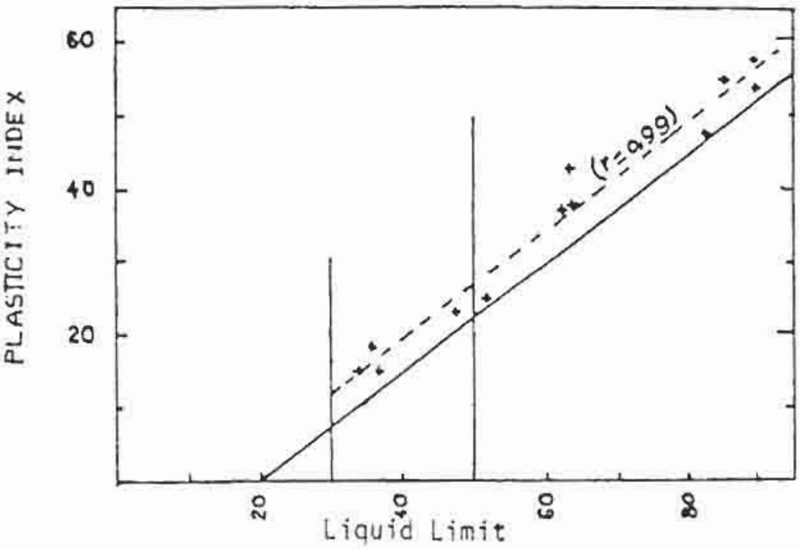

Fig. 3 - In the Plasticity chart the experimental values fall in the fields of medium to high Plasticity inorganic clays.

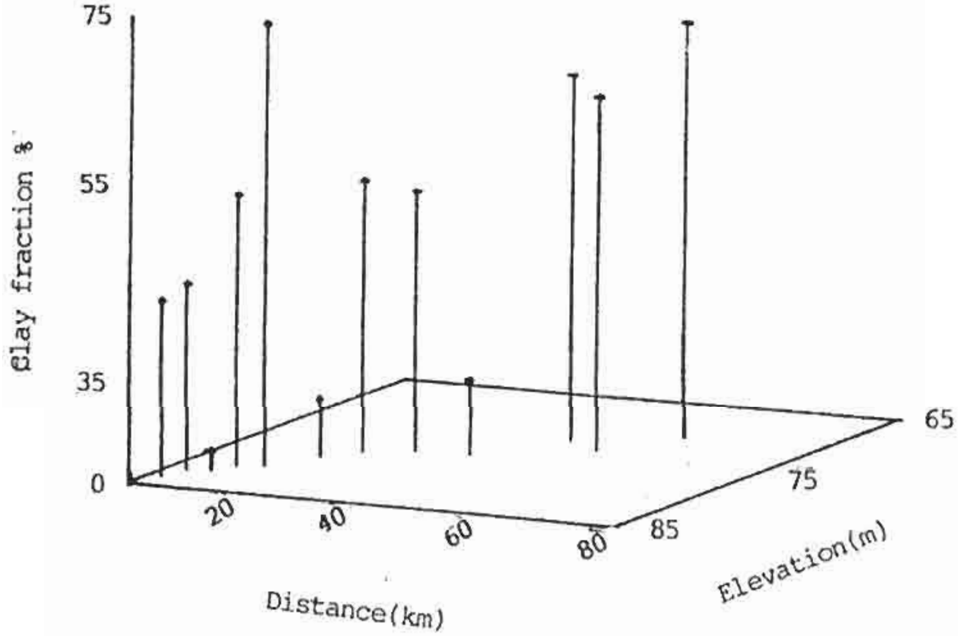

Fig. 4 - The variation of the clay content in the analyzed sample in relation to their distance from Afgoe and the elevation of the sampled points.

All the samples, remoulded at a water content equal to their liquid limits, were subjected to the routine oedometric tests. The results of which are shown on Table 2.

In order to define the influence of clay fraction content on the compressibility of these soils, a statistical correlation between compression index of the remoulded clays (C'c) and C is made. The result is plotted in the diagram of Fig. 10 and shows that the compression index satisfies a linear expression. The coefficient of linear correlation is equal to 0.84. This relationship is:

C'c = 0.012 (C - 0.62)

Correlating the compression index with the liquid limit the curve of Fig. 11 has been obtained whose equation is:

C'c = 0.002 (Wl - 4)

The coefficient of linear correlation is equal to 0.94.

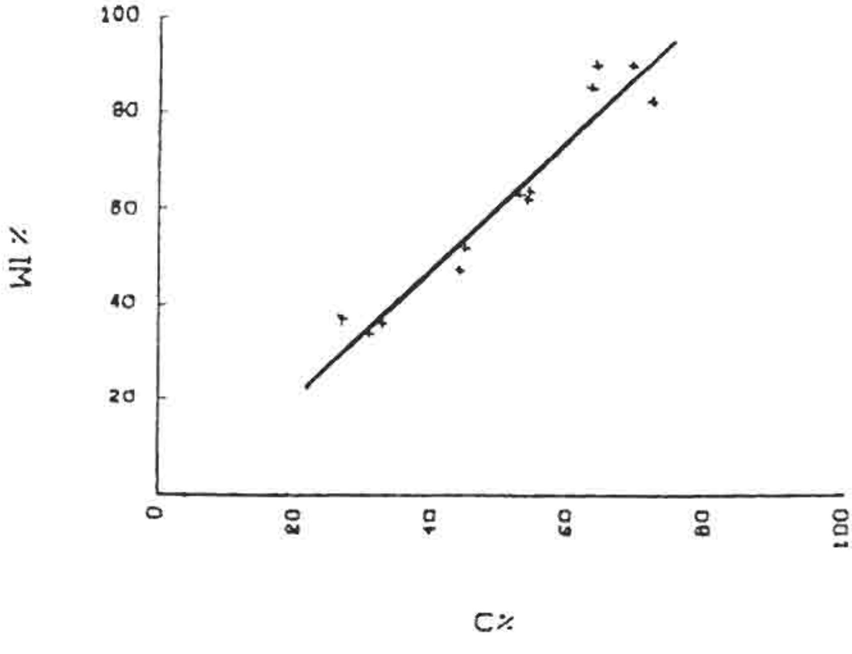

Fig. 5a - Influence of the Clay fraction (C %) on the Liquid Limit (Wl %).

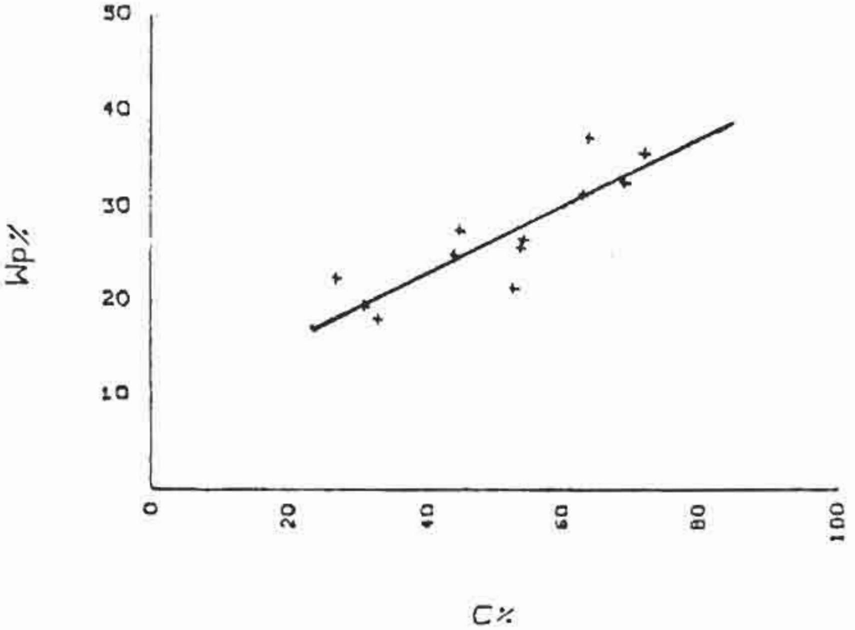

Fig. 5b - Influence of the Clay fraction (C %) on the Plastic Limit (Wp %).

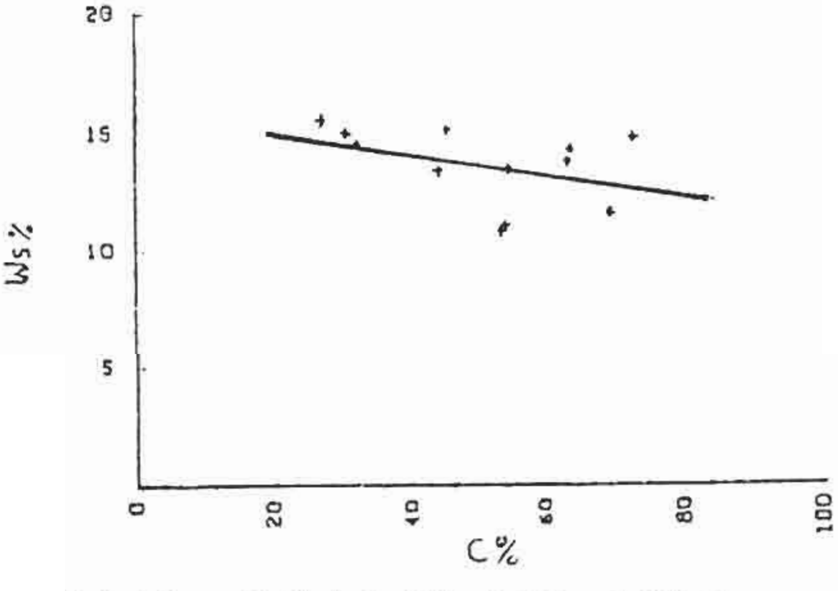

Fig. 5c - Influence of the Clay fraction (C %) on the Strinkage Limit (Ws %).

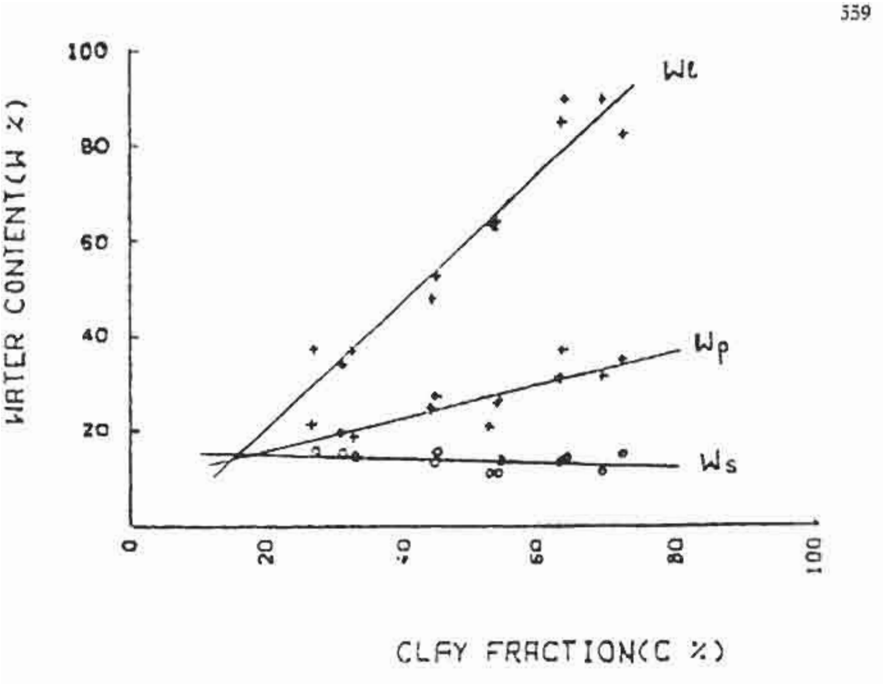

Fig. 6 - Influence of the Clay fraction (C %) on the Consistency Limit (W %).

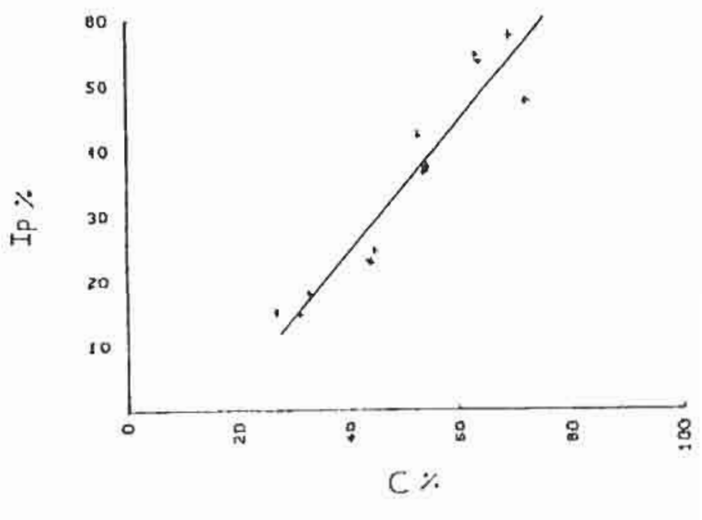

Fig. 7 - Influence of the Clay fraction (C %) on the Plasticy Index (Ip %).

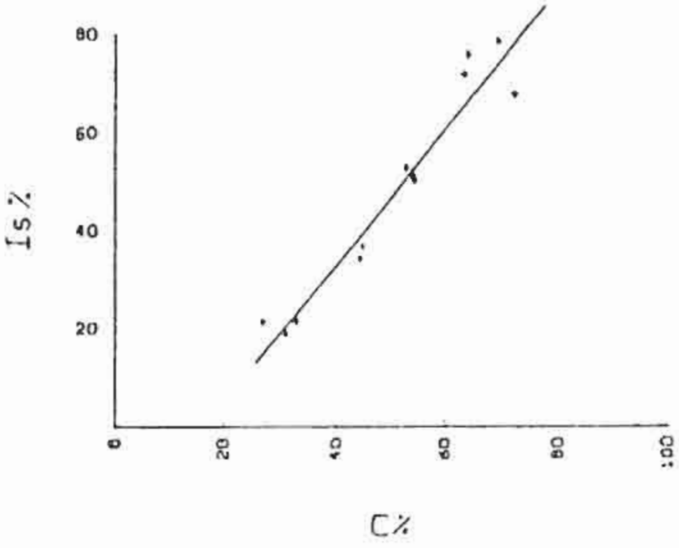

Fig. 8 - Influence of the Clay fraction (C %) on the Strinkage Index (Is %).

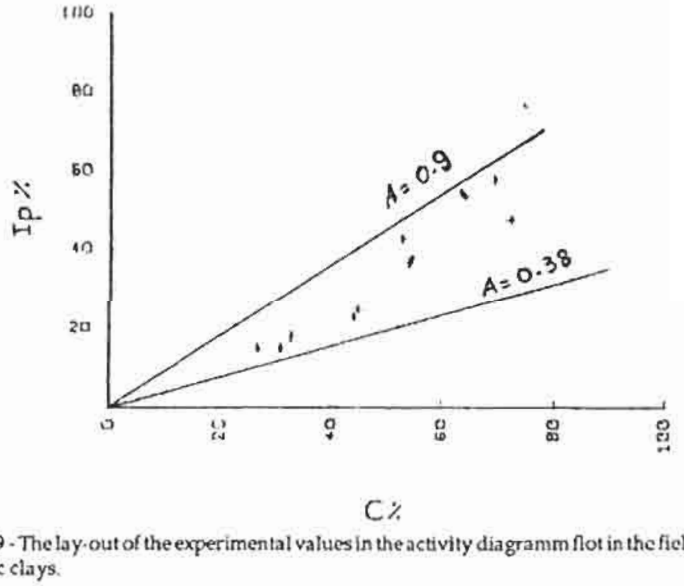

Fig. 9 - The lay-out of the experimental values in the activity diagramm flot in the field of the Kaolinit Illitic clays.

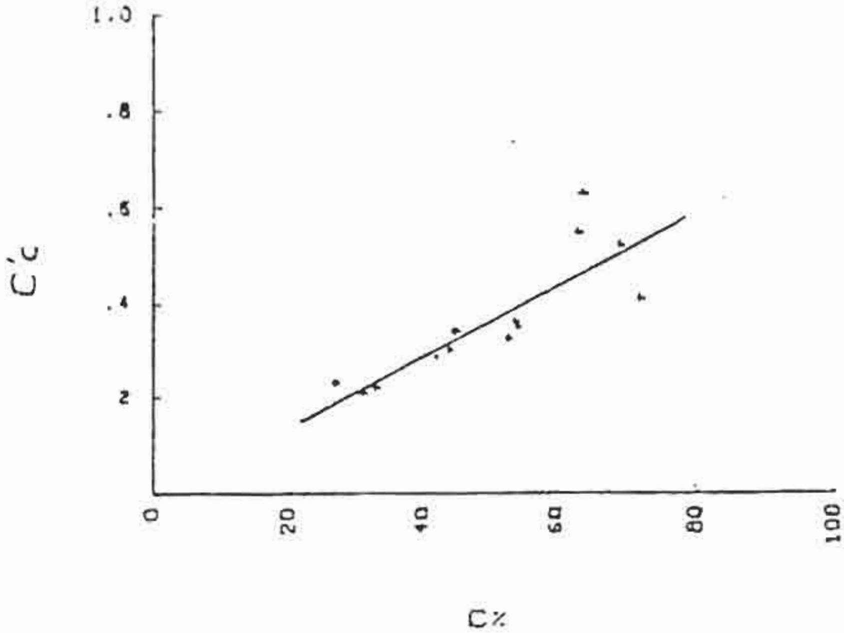

Fig. 10 - Influence of the Clay fraction (C%) on the Compression Index (C'c %) of the remoulded clay.

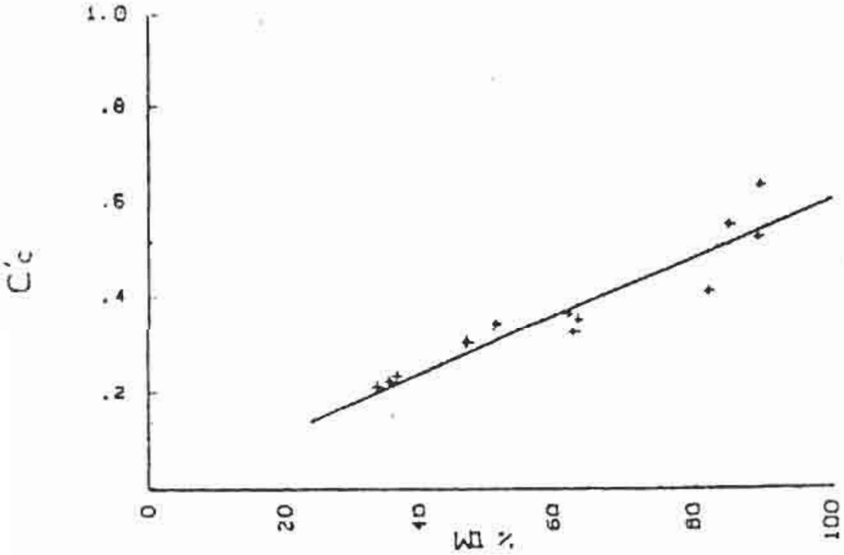

Fig. 11 - Relationship between the Compression Index (C'c %) and the Liquid Limit (Wl %).

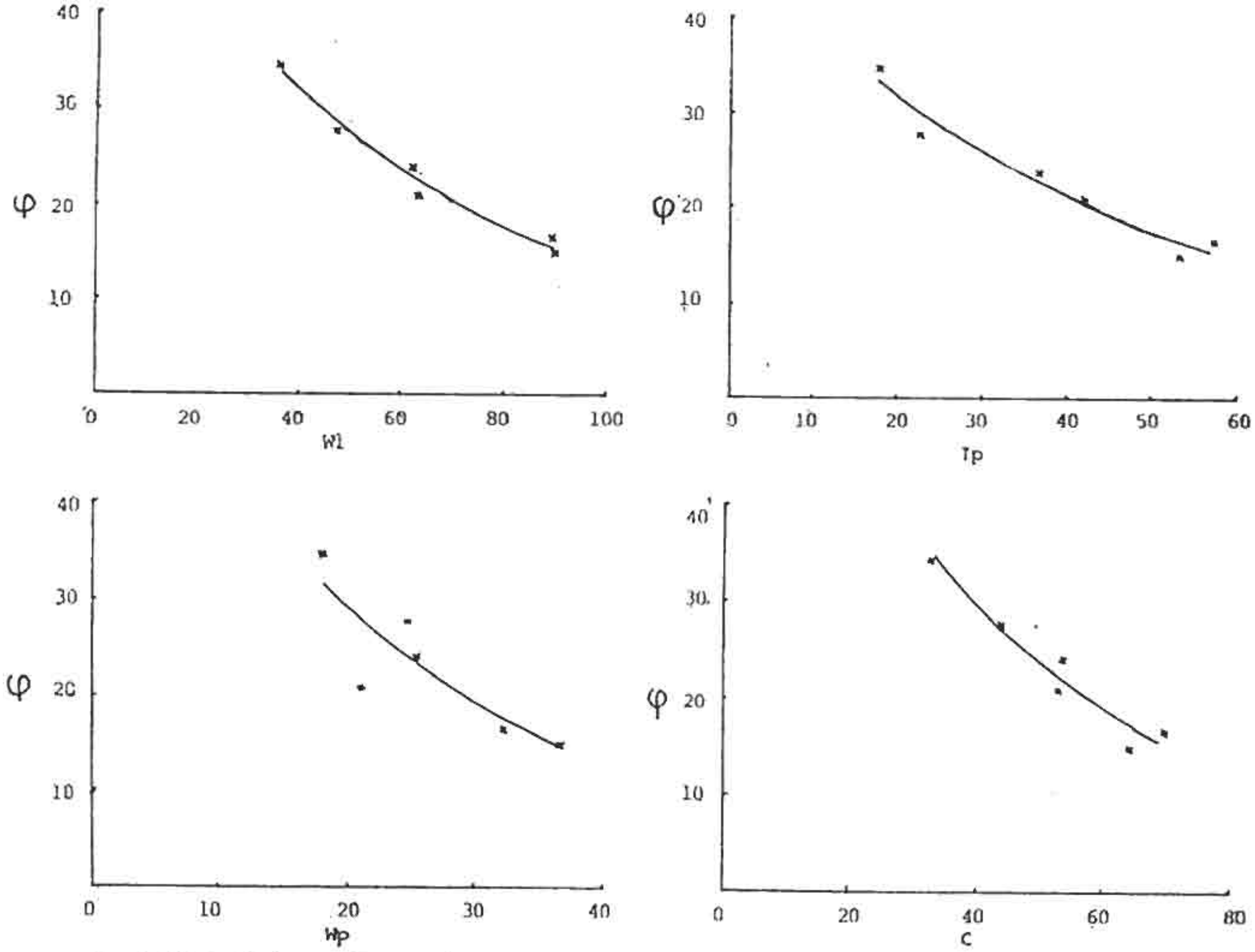

Fig. 12 - Relationship between friction angle (φ) and index parametres: a) φ = f(Wl); b) φ = f(Wp); c) φ = f(Ip); d) φ = f(C).

As regards to the drained direct shear tests, they were carried out on some of the samples which were remoulded at a moisture content equal to their liquid limit. Using a 60 mm^2 by 20 mm deep shear box the specimens were consolidated and were cut at different normal pressures of 1 kg/cm^2 for each sample. The results are shown on Table 2.

In order to define the relationship between the friction angle (φ) and some physical characteristics of the soil such as Wl, Wp, Ip and C, a tentative of statistical correlation between the above mentioned variables was made. The best fitting is obtained using the exponential regression of the type:

$y = ae^{-bx}$

previously adapted by BJERRUM (1960). As regards to the relationships φ = f (Wl), φ = f (Wp), φ = f (Ip), and φ = f (C) the curves of Figs. 12a, 12h, 12c, 12d were obtained. The equations of these curves are as follows:

$\varphi = 51.80\ e^{-0{,}012\ Wl}$

$\varphi = 51.43\ e^{-0.03\ Wp}$

$\varphi = 45.64\ e^{-0{,}018\ Ip}$

$\varphi = 54.73\ e^{-0{,}016\ C}$

Although underlining the scarcity of the data used in the calculations, high values of the coefficient of correlation (r) were obtained which are respectively as follows: 0.92, 0.76, 0.94 and 0.79.

Table 2 - Legend = Wl: liquid limit; A: colloidal activity; C'c: compression index of the remouled soils; Φ: friction angle.

Sample No.	Wl	A	C'c	Φ
1	47.5	0.52	0.30	27.9
2	51.8	0.54	0.34	——
3	37.0	0.55	0.23	——
4	63.98	0.69	0.35	——
6	82.5	0.65	0.41	23.0
8	34.0	0.47	0.21	——
10	62.2	0.68	0.36	24.0
12	63.5	0.80	0.32	21.0
14	36.0	0.54	0.22	34.6
16	90.2	0.83	0.63	15.1
18	85.5	0.85	0.55	——
20	89.9	0.83	0.52	16.7

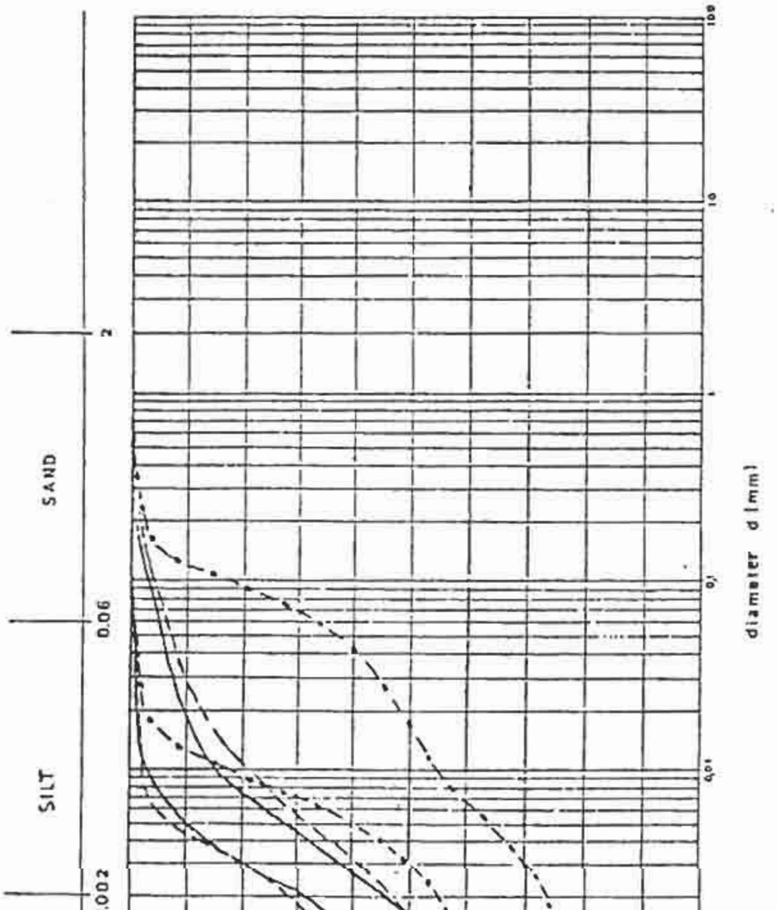

Fig. 13 - Grading envelopes of the major soil group: Group A, Group B, Group C

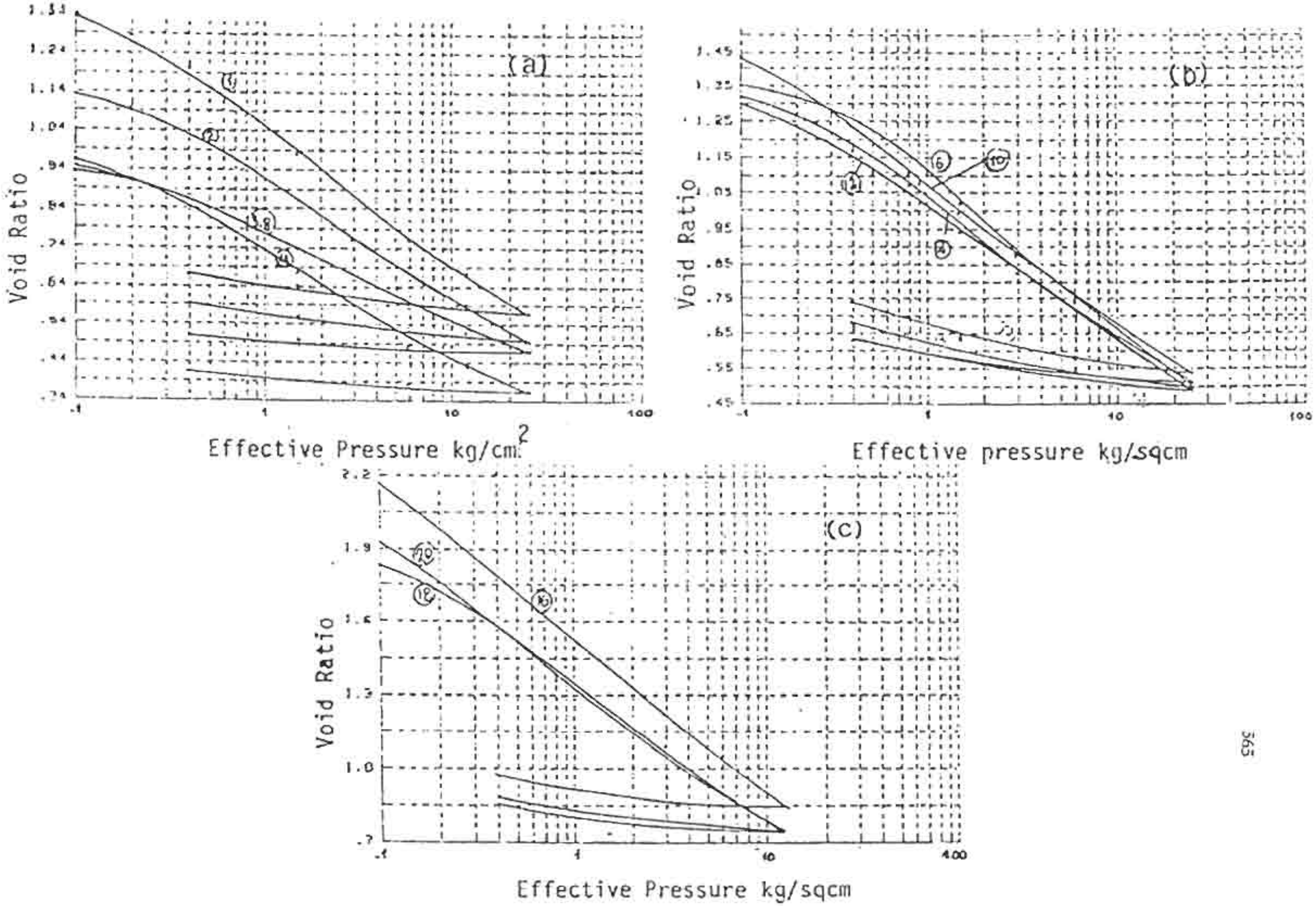

Fig. 14 - Oedometric curves of the major soil. Groups: a) Group A, b) Group B, c) Group C.

CONCLUSION

Although the information and the data at present available are not sufficiently high, some preliminary conclusions can be drawn: The index parameters wl, wp, Ip and Is show a linear variation with C, while Ws does not satisfy a linear expression with C. The compression index (C'c) of the remoulded samples varies linearly with the liquid limit (Wl) and with the clay fraction (C),while the relationship between the friction angle (φ) and C shows a tendency of diminishing of the friction angle (φ) with increasing clay fraction content (C). The same tendency is also observable from the relationship between (φ) and the index parameters Wl, Wp and Ip. This interdependency is expressed with an exponential equation of the type:

$y = ae^{-bx}$

The geotechnical properties, field observations and the geographical distribution of the samples have shown:

a) A general tendency of increasing clay fraction between Afgoye and Jannale that is from up stream toward down stream; and

b) the possibility of classifying these soils as a first approach into three groups of similar geotechnical properties which are summarized respectively on the Tables 3; 4; 5. These groups are:

- yellowish silty sandy clay (group A);
- brownish grey clay (group B);
- dark brown clay (group C).

On this basis the grading envelope of Fig. 2 is divided into three grading envelopes corresponding to the above mentioned three groups (Fig. 13). The oedometric curves relative to the three groups are riported in Figs. 14a, 14b, 14c. The geographical distribution of these soils in the area is as follows:

- between Afgoye and Mordinle the superficial soil coverlet consists mainly of the soil group A;
- from Mordinle to Barirre outcrops mainly the group B;
- between Barirre and Jannale the group C is the main outcropping soil.

This approximate distribution of these soil groups-especially as regards to their limits refers to the area along the rough track Afgoye-Mordinle-Barirre-Audegle on the left bank of the river and along the rough track between Audegle and Jannale on the right bank of the river. In order to reduce the uncertainties relative to the boundaries of these soil types further research must be carried out aided with photogeological base maps.

Table 3 - Group A.

	Wl	Ip	Ws	Is	C	A	G	C'c
Max. value	51.8	24.4	15.5	36.8	45.0	0.55	2.77	0.34
Min. value	34.0	14.7	13.3	19.1	27.0	0.47	2.7	0.21
Mean value	41.3	18.9	14.6	26.6	36.0	0.52	2.73	0.26
Stand. deviation	7.9	4.5	0.8	8.2	8.0	0.03	0.03	0.06
Coeff. variation	19.1	23.7	5.7	30.9	22.3	6.12	1.08	21.9

Table 4 - Group B.

	Wl	Ip	Ws	Is	C	A	G	C'c
Max. value	82.5	47.2	14.9	67.6	72.4	0.8	2.78	0.41
Min. value	62.2	36.7	10.7	50.4	53.0	0.65	2.7	0.32
Mean value	68.0	40.0	12.47	55.52	58.45	0.70	2.73	0.36
Stand. deviation	9.69	4.88	2.03	8.11	9.32	0.07	0.04	0.04
Coeff. variation	14.25	11.94	16.28	14.61	15.94	9.3	1.32	10.39

Table 5 - Group C.

	Wl	Ip	Ws	Is	C	A	G	C'c
Max. value	90.2	57.3	14.2	78.3	69.5	0.85	2.73	0.63
Min. value	85.5	53.3	11.5	71.9	63.5	0.83	2.71	0.52
Mean value	88.5	54.9	13.1	75.4	65.67	0.84	2.72	0.57
Stand. deviation	2.61	2.1	1.42	3.24	3.33	0.01	0.01	0.06
Coeff. variation	2.94	3.82	10.8	4.3	5.07	1.38	0.37	10.03

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AN OUTLINE OF THE METALLOGENIC HISTORY OF ETHIOPIA

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ABSTRACT

A tentative metallogenic history of Ethiopia is reconstructed on the basis of available data and filed and laboratory observations by the authors. It begins not later than the Middle Precambrian, when an old craton was affected by a complete cycle of oceanic opening and closure, producing a wide set of related phenomena, from oceanic crust formation up to final continental phase. An epicontinental sea then covered most of the new craton, from the Upper Paleozoic-Lower Mesozoic up to the Middle Tertiary; however, in the meantime the present drifting cycle, responsible for the opening of the Gulf of Aden, the Red Sea and the East African Rift Valleys, started. All these cycles are characterized by a metallogenic framework. Every ore deposit and occurrence so far discovered in Ethiopia can be fitted into one of these frameworks.

INTRODUCTION

The interpretation of the available data about the geology of Ethiopia on the basis of plate tectonics concepts can help to outline a tentative history of the Ethiopian metallogeny. A number of interesting papers (ref. in SENBETO CHEWAKA and DE WIT, 1981) already deal with local problems from this point of view, reaching interesting results. In this paper we wish to present a tentative synthesis of these results, together with other data and our own field and laboratory observations.

THE GEOLOGICAL OUTLINE

The main rock types, recording the geological history of Ethiopia, are (Fig. 1): the Precambrian rocks with associated intrusives, referred to as "Basement Complex" and cropping out in 23% of the total surface area of the country; the Paleozoic and Mesozoic sequences, covering 25%; the Early Tertiary volcanics, 32%; the Late Tertiary volcanics, 12%; the Tertiary and younger sediments, 8%.

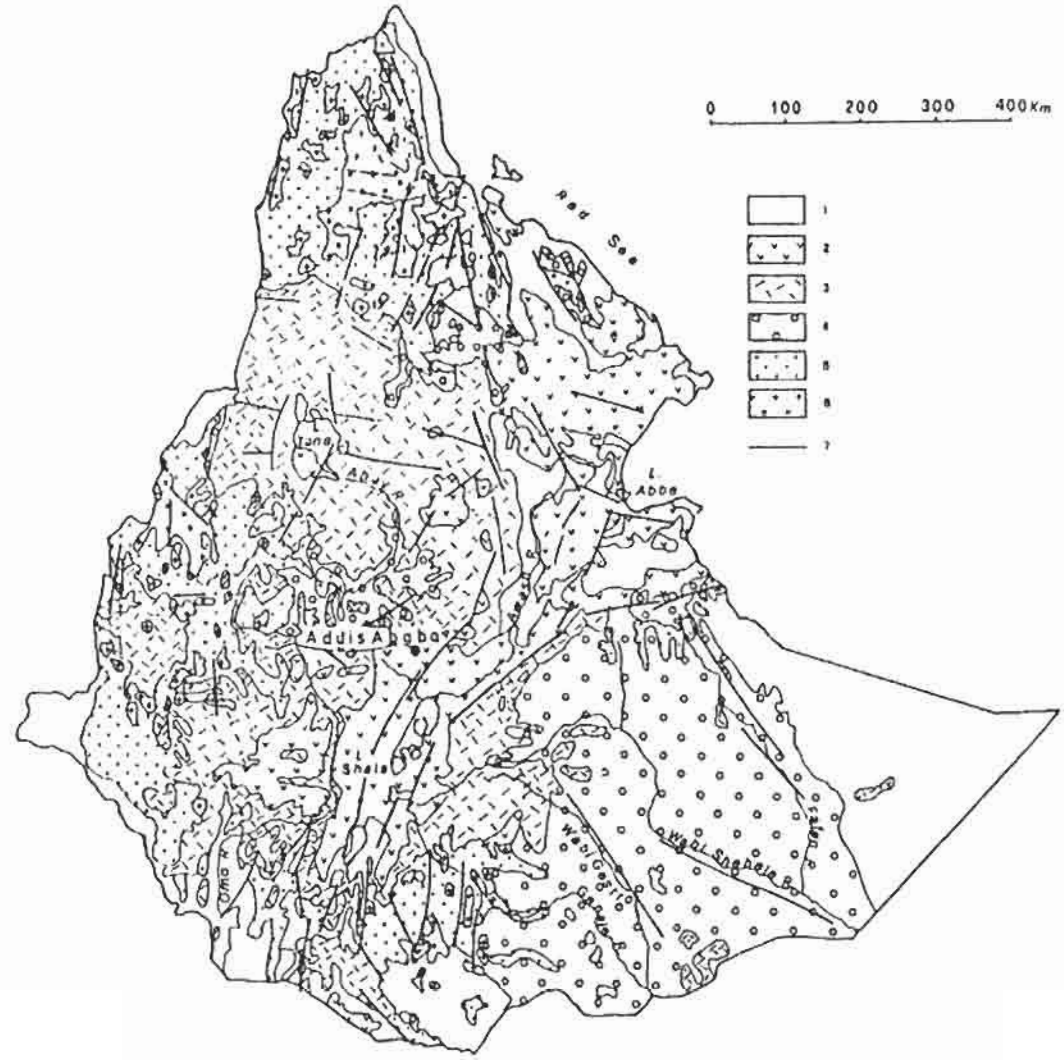

Fig. 1 - Generalized geological map of Ethiopia (modified after GEOLOGICAL SURVEY of Ethiopia, 1975). 1: Tertiary and younger sediments. 2: Late Tertiary volcanics. 3: Early Tertiary volcanics. 4: Paleozoic and Mesozoic sequences. 5: Precambrian complexes. 6: Intrusives, mainly acidic. 7: Major faults.

Exploited and economically interesting minerals occur in most of the above mentioned units, but rocks with proved or theoretical mineral potential can be grouped as follows (GETANEH, 1985):

a) Precambrian rocks and associated intrusives. Principal mineral occurrences: gold, platinum, iron, chromium, niobium-tantalum, tungsten, molybdenum, nickel, copper, tin, lead, vanadium, cobalt, manganese minerals, radioactive minerals, beryl, mica, asbestos, talc.
b) Paleozoic and Mesozoic sediments. The principal associated industrial minerals and bulk materials are limestones, sand, sandstones, gypsum and clays. Favourable conditions for oil and gas are also present.
c) Early Tertiary volcanics. Important deposits of metallic minerals are unknown. Thin beds of lignite and lateritic iron occur locally. Bentonite and other industrial clays may be present. Perlite and pumice are common. Carbonatite occurrences might also be expected (GETANEH et al., 1981).
d) Tertiary and younger sediments. The occurrences of economically relevant materials are similar to those of the Paleozoic and Mesozoic sediments. Sulphur, lignite, diatomite, postash and common salt are also present.
e) Late Tertiary volcanics. The principal associated industrial minerals and bulk materials are: perlite and pumice, road aggregates and building stones. Bentonite and other industrial clays may be expected.

THE METALLOGENIC HISTORY

The long metallogenic history of Ethiopia is obviously related to its geological-structural history. It can be tentatively summarized as follows.

OLD CRATON OF ARCHEAN (LOWER PROTEROZOIC?) AGE

It is composed of high grade metamorphic rocks: amphibolites, gneisses up to granulites, migmatites, granites (KAZMIN, 1971). Economic deposits are not known in these rocks. Few indications of ore minerals have been found: Cu- and Fe-sulphides in south-western provinces and near Gimbi (Wollega); heavy minerals (mostly rutile) between Harrar and Jijga. Pegmatite bodies may prove to be important for both industrial and metallic minerals (quartz, feldspar, micas, garnets; Li, Be, U, Th, Mo, W, Ti minerals) (JELENC, 1966). Extensive pegmatite bodies occur mostly in Sidamo, while particular minerals are known in several places: beryl in Eritrea (Ghedem), Sidamo (Kibre Mengist), Harerge (Jijga) and Wollega (Nejo); molybdenite in Harerge, Sidamo and Wollega; Ti-Th-U-W minerals (traces) in Harege; columbo-tantalite in Sidamo (Kenticha: TWELDEMEDHIN, 1986).

DEVELOPMENT OF HOT SPOTS AND SUBSEQUENT DRIFTING PHENOMENA IN (LOWER?) - MIDDLE PROTEROZOIC - UPPER PROTEROZOIC (-LOWER PALEOZOIC?) TIMES

The site of this old cycle seems to have been roughly the same as to-day's active crustal separation in the Red Sea-Ethiopian Rift domain (KAZMIN et al., 1979). It is still uncertain whether it was connected with the southernmost Mozambique Belt (DE KUN, 1973; KAZMIN, 1971, 1972), since a gap occurs between the latter and the Ethiopian Precambrian rocks. The following events appear to have taken place:

1) Doming, rifting, first shallow basins on attenuating continental crust (Lower?-Middle Proterozoic), erosion and deposition of mostly coarse terrigenous sediments intercalated with the products of some basic volcanic activity (amphibolitic levels). These events let to:

a) concentration and reconcentration of heavy minerals eroded from the basement. The best known so far is gold, which occurs, always related to "quartz veins", almost everywhere in Ethiopian Precambrian rocks. These "veins", whilst sometimes they are pure hydrothermal veins (e.g. when they cut plutonic rocks), often occur conformably within the Precambrian metasediments. Some of the famous gold-bearing "veins" of the triangle Barentu-Asmara-Keren (Eritrea) (JELENC, 1966) have already been recognized to be interbedded "quartzite" lenses. The quartzitic beds forming a well developed, continuous horizon in the Adola-Kenticha belts were believed to be the gold source of the well known Adola placers. The discoveries of Dermi Dama, Sakaro and, specially, very recently Lega Dembi primary deposits near Shakisso confirm this opinion. Their paragenesis (Au, Fe, Cu, Pb, Zn sulphides; Ag, Au, Pb tellurides; tetrahedrite; ullmannite; breithauptite; boulangerite, meneghinite, etc.), along with their position in a sequence rich in amphibolites, suggests an origin of the protore probably bound to a submarine volcanic activity (see also FIORI et al., this volume).

b) Deposition of metals from solutions and/or colloids. The most important is iron: banded iron formation are widely present, even if important reserves have not yet been discovered.

2) Further attenuation of the crust, volcanic products evolving towards magmas of mantle origin, widening and deepening of the basins. Three possible basins are present: a north-western basin, between Sudan and Northern Ethiopia; a central basin, crossing the country from Eritrea to Illubabor, with a NE-SW to N-S trend; an eastern basin, with a similar trend, running from Tigrai to Sidamo (KAZMIN et al., 1979). Volcanic and sedimentary sequences of this phase occur in the three basins. Such rocks, not yet clearly separated from those belonging to later phases, include various volcanic types and sediments, mainly terrigenous and often carbonaceous, all commonly affected by low grade metamorphism. Possibly both volcanic and sedimentary processes supplied metals. Sulphides (mainly pyrite) occur both in greenstones (commonly with magnetite) and in black metapelites. Among the

minor sulphides, chalcopyrite is the commonest. Since these sulphide-bearing complexes have still to be well differentiated from the later ones, they will be dealt with in section D.

3) Formation of oceanic crust. Cr, Pt, Ni (possibly Co, Cu) are associated. Mafic-ultramafic complexes. The known occurrences, however, are always of low-grade.

4) Beginning of basin closure, formation of Benioff zones, development of volcanic arcs. Typical rocks of this phase include greenstones, metapelites and interbedded carbonate lenses (possibly miogeosynclinal basins). The calc-alkaline affinity of some metavolcanics has been suggested. In this phase both Besshi-and/or Kuroko-type and synsedimentary (related to black pelites in closed basins) mineralization may occur. Some possible examples, which here are not separated from those of phase (2), have been reported. Among them, the Debarwa (Eritrea) orebody, cropping out discontinuously for 2 km, interbedded with sericite-quartz-schists (metamorphosed rhyolite-dacite volcanics?). It averages 8% Cu, 2% Zn, 1 gr/t Au, 100 gr/t Ag and contains economically recoverable barite. It has been considered a Kuroko-type orebody. Other examples occur in Wollega: the Katta-Tullu Dimtu (Cu and Au, stratabound) and Yubdo (Cu) indications are related to greenstones, while near the Sai River (Tullu Dimtu) mostly Cu-sulphides occur in a black shale complex, with interbedded limestone lenses.

5) Advanced closure of the basins, intrusion of calc-alkaline bodies (mainly in Wollega, Eritrea, Sidamo), metamorphism, related to intrusions and to subduction, up to amphibolite facies (rarely migmatites), possibly formation of pegmatites. During this phase, metamorphism and hydrothermal activity were the main metallogenic agents. The minerals of the pegmatites are the same as for the oldest cycle. Metamorphic industrial minerals (e.g. asbestos, talc, graphite) are widespread, but still of unknown importance. Hydrothermal veins containing Au, Cu, (Pb, Zn, Ba) form a promising field for prospecting. However, the best known orebodies are related to metamorphosed synsedimentary deposits and of porphyry-copper type. Among the former, the Agametta (Eritrea) Fe(Cu)-bearing skarn belt: here the skarns and the marbles, metamorphosed by thermal (diorite intrusions) and regional agents, contain NW-SE trending magnetite-hematite lenses. Partial explorations in the past showed reserves just over 1 Mt, down to a depth of some 100 m. Porphyry copper-type orebodies are mentioned in Tigrai and Wollega.

In the Tschafi-Emba area (Tigrai) the Firfira Complex (gabbros, syenites, granites, minor ultramafics) is intruded into metavolcanics and metasediments. Copper-bearing veins occur in gabbros. The Katta area (Wollega) includes also "blue-quartz porphyries" intruding granodiorites and metasediments. In these porphyries Cu minerals (chalcopyrite, bornite and malachite) are reported.

6) Collision of continental blocks, Himalaya-type mountain belts, obduction of oceanic crust, intrusion of late granitoids and last metamorphism. To these phenomena, dated 650 to 450 m.y. b.p.t., hydrothermal and metamorphic deposits may be related, even though they have been not yet well distinguished from those of (5) phase. Some remobilization phenomena may have occurred in the ophiolite complexes, but economic bodies are not known so far.

LONG CONTINENTAL PERIOD

Few outcrops of continental, mostly glacial, sediments of this period are known. Possible remobilization phenomena have not been distinguished from later ones.

MARINE TRANSGRESSION INTO THE DEEPLY ERODED CRATON (LATE PALEOZOIC? TRIASSIC?)

An epicontinental sea gradually covered most part of the Horn of Africa up to Gondar-Eritrea, the older and deeper part of the basin being in the Ogaden region. It is possible that this differential deepening of the sea was related to the start of the new cycle of continental drift, whose first doming site was centred on the Red Sea-Gulf of Aden junction. The complete sedimentary pile in this basin includes, as drilling for oil showed, a basal series of Upper Paleozoic continental sandstones (Calub Sandstones), the Triassic-Liassic partly marine Adigrat Sandstones, then a thick Jurassic-Cretaceous carbonate series, with interbedded shales, marls and evaporites near the base and important evaporitic complexes in the upper part (Neocomian Main Gypsum and Upper Cretaceous Ferfer Gypsum). Eastward, while the Mesozoic sequence changes from limestones to shales, a Paleocene-Eocene marine series follows, which changes upwards from partly continental sandstones to mainly carbonatic units with interbedded evaporites. The whole series is several kilometres thick in the deeper parts of the basin (BARNES, 1976). Owing to the lithological variations, both permeable (sandstones, oolitic limestones, dolomitized limestones) and impermeable (evaporites, shales) units are present, as well as possible source rocks (shales, limestones; even the Paleozoic sandstones contain organic matter). Since differential movements of the crystalline basement occurred both before (causing arching of the lower sediments) and during the sedimentation (providing fault contacts between different units) specially along the Marda Fault Zone, structural traps are present, while stratigraphic ones, because of lateral variations, are likely to occur; so, in spite of the disappointing results so far obtained during oil researches, oil and gas accumulation may be expected.

The above mentioned evaporites might be of economic interest for gypsum (already produced on a small scale) and perhaps for other salts.

The Mesozoic sandstones, both Lower and Upper, include iron-rich beds, whose origin has to be seen in the near-shore deposition of eroded residual soils, after uplift episodes. These "ironstones" are particularly frequent near Kulubi, in Harerge.

Other ore minerals are known in the Lower Mesozoic sandstones of Harerge. In the

Galetti and Kunni Valleys, just at the base of the Lower (or Adigrat) Sandstone, the following sequence occurs (JELENC, 1966): brown sandstone (nearly .5 m) cut by veins of Co-bearing Mn oxides (few millimetres thick); green sandstone (.2 - .4 m), with interbedded lenses (few tens of centimetres thick) of quartz clasts cemented by Cu carbonates (traces of Cu sulphides and some gold grains have also been found) surrounded by a leached, whitish halo, sometimes pinkish (presence of Co) or greenish (presence of Ni); reddish-brown sandstone (3-4 m), whose matrix is locally a Mn bearing limonite. The average Cu grade of the mineralised bed (green sandstone) is about .5%. This interesting mineralization has clearly originated from the alteration of Cu-Co-Ni-bearing bodies, possibly ultramafic rocks. The near-shore environment was favourable for the precipitation of oxidized minerals but also some sulphide grains survived and were deposited within the clastic fraction.

In the Mekele-Quiha area some levels of the Antalo Limestones (Callovian-Oxfordian) show a lithofacies rich in Fe sulphides, mainly pyrrhotite, accompanied by minor pyrite, chalcopyrite, sphalerite and galena. The association is typical of a reducing environment and might be an indication of the existence of a low grade Cu, Zn, Pb sulphide-bearing, Mississipi Valley-type deposit of unknown size.

After this transgression, a gradual regression, related to doming, took place, interrupted only by a short marine invasion during the Aptian-Albian period. Minor, marginal basins lasted up to the Lower-Middle Tertiary in the Ogaden region and up to the Lower Quaternary along the Red Sea coast. So, since the end of the Mesozoic, most of the country was a dry land. At the same time, the opening of the Main Ethiopian Rift, from the triple junction in Afar, started and an important, still active volcanic cycle poured its products on wide areas of the Ethiopian Plateau, the Rift and the Afar and Danakil lowlands. In this general framework we can distinguish the following four metallogenic environments.

Continental Processes Of Leaching, Erosion And Reconcentration

All ore-bearing terrains affected by the uplift have been either directly submitted to leaching and erosion, where younger formations did not cover them, or first exumed and eroded later.

These processes have been also active in areas now covered by volcanics, since important residual concentrations of iron oxides and other minerals within soils are known, e.g. in a broad area between Eritrea and Tigrai; from Hamasien (west and south of Asmara) up to Adwa-Axum-Entichio, the Tertiary volcanics cover an alteration crust, rich in hematite-limonite nodules, locally up to several metres thick, which is a potential silica-rich, low-grade iron ore, averaging about 30%.

The most interesting products of these phenomena are the residual-remobilized bodies overlying ultramafic rocks and the gold (platinum-heavy minerals) placers. A well known example of residual mineralization is the Yubdo platinum deposit, where a thick lateritic crust, on a dunite-pyroxenite body, locally averages some tenths of gram per cubic metre of a mainly Pt-Fe alloy (nearly 80% Pt).

A good example of enrichment by remobilization is the Ni-silicate and magnesite occurrence in a quarry opened in 1981 in the Daletti (Wollega) serpentinite. Under a thick cover of laterite, whose Ni content is worthy of investigation, nodules, veinlets and coatings of garnierite and other serpentine minerals occur in the deeply weathered rock, along with a locally well developed stockwork of white magnesite.

Since numerous ultramafic bodies occur along the continental suture zones, in Wollega, Sidamo and elsewhere, their exploration both for platinoids and for Ni-Mg (Co-Cu-Cr) is recommended.

The most important and better known placers are the gold ones. They are widely distributed almost everywhere in the Precambrian areas; their systematic prospecting has to take into account the morphological history of each region, as related to different uplift phases. In addition to the alluvial deposits, also the source rocks and their eluvial cover should be investigated. Among the known areas, the most known so far is Adola, where gold is at present being exploited.

Some placers displaying indications of platinum, in the vicinity ultramafic bodies, have not yet been explored. There is but little informations on other heavy minerals in placers. Chromite, mostly eluvial occurs in Sidamo. Titanium minerals might be found in several places, e.g. in the valley near Harrar-Jijiga, where rutile is abundant in the Precambrian rocks, while a few other localities, specially in Sidamo and Wollega, are mentioned in literature (JELENC, 1966). In the same localities also zircon is normally present.

Low grade (about 4% Fe) magnetite-bearing beach sands occur in an area of several square kilometres at Mersa Gulub in Eritrea.

SEDIMENTATION IN MARINE AND LACUSTRINE BASINS

The most important Tertiary-Quaternary marine basin is the Danakil-Afar area, where a thick (locally over 7,000 m) sequence, formed of volcanics, marine and subaerial sediments and of a very important evaporitic formation, has been disclosed by drilling for oil. Although oil shows have been found, important accumulations are unlikely to exist, because of the very high temperatures (approaching 200°C) measured in several wells.

The potential for salts, specially the potassic ones, appears to be much more promising, chiefly in the Salt Pan (Danakil Depression), where the evaporites crop out.

Drill holes discovered important beds of K- and Mg- salts, together with halite and gypsum; the most severe obstacle to exploitation is the climate. In the Afar Depression also Fe-Mn-Ba deposits have been found; possibly related to both favourable sedimentary environments and hydrothermal activity.

In the Rift Valley some of the present lakes are remnants of the Pleistocene Lake Galla. In these lakes the intense volcanism yielded large amounts of silica, utilized by diatoms, whose accumulations crop out today particularly near the lakes Abyata and Shala.

Several thermal springs discharged into these lakes a great amount of salts, specially Na carbonates: soda ash recovery is planned in Lake Shala, whose water are true brines.

Lignite beds, apparently of no great importance, are known in lacustrine sediments at many places.

VOLCANISM AND RELATED HYDROTHERMAL ACTIVITY

Several sulphur occurrences in the Northern Rift-Danakil Depression (Awash Valley, Dallol) are related to fumarolic activity.

About the hydrothermal deposits little information is available. Epithermal veins, related to volcanism and possibility enriched by remobilization of metals from the basement are likely to occur. As yet, only uneconomic barite (-galena) veins are known in Eritrea in several places.

Another field of investigation is indicated by the presence of fluorine in water and lacustrine sediments. Anomalously high contents are known and accumulations of fluorspar, similar to those known in Latium (Italy), might occur. The extensive sediments of the Rift lakes are worth exploring.

Carbonatite complexes, which are often associated with the East African Rift System (MITCHELL and GARSON, 1976) might be present in Western Ethiopia, related to undersaturated recent volcanics of phonolitic composition.

D) Metallogenic phenomena in the Red Sea.

They represent the most advanced stage of metallogenic events in our area. In various deeps, on the Red Sea oceanic crust, polymetallic deposits rich in Zn-Cu-Fe-Mn are being deposited by hot brines (MILLER et al., 1966).

CONCLUSIONS

The geological evolution of Ethiopia, which has been outlined in the present work, accounts very well for the existence of the various types of mineral deposits known in the country. In the meantime, the big number of indications and mineral showings, together with their mode of occurrence, witness that the different metallogenic environments, as here described are worthy of further exploration and evaluation.

According to our results, particular attention should be devoted to the following topics:

- Mineralization related to intrusive-extrusive magmatism of the Precambrian mobile belts (mainly Au, Cu; pegmatites, Nb-Ta, Li).
- Mineralization related to Precambrian ophiolites (mainly Pt, Ni).
- Mineralization related to Precambrian metasediments (mainly Cu, Fe, Au).

- Mineralization related to Mesozoic-Tertiary sediments (mainly oil, salts; Cu-Zn-Pb sulphides in low grade, big size deposits).
- Mineralization related to present Rift volcanism (base and precious metals, barite, fluorspar, rare earths).
- Recent placers (mainly Au, rutile, zircon).

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THE PRIMARY GOLD DEPOSIT OF LEGA DEMBI (SIDAMO): ORE MINERAL ASSOCIATION AND GENETIC SIGNIFICANCE (PRELIMINARY REPORT)

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ABSTRACT

The primary gold deposit of Lega Dembi occurs as generally concordant quartz veins, lenses and stringers hosted in the volcano-sedimentary sequence of the Proterozoic Upper Complex, Adola area. The gold mineralization is closely related to the presence of quartz, nevertheless valuable gold grades are also reported within the host rocks along the mineralized belt. The mineral association is given by Cu-Pb-Zn sulphides, with pyrite and pyrrhotite, bearing gold, tellurides and sulphosalts. A detailed study of the paragenesis, supported by microprobe analysis, gives evidence of a complex evolution which probably developed from a volcanogenic deposit through metamorphism and repeated remobilization processes, until the present stratabound orebodies.

INTRODUCTION

The Proterozoic crystalline basement of Ethiopia is well represented in Sidamo. Corresponding to its outcrops, since long time secondary gold deposits (placers) were known and exploited, particularly in the Adola area, which is also known as "Adola Gold Fields".

The discovery of the gold source feeding the placers is rather recent. It was the result of a general prospecting and detailed exploration campaign carried out in the Adola Gold Fields by the Ethiopian Mineral Resources Development Corporation (EMRDC) since 1979. The researches were developed according to a scheme of trenching, based in the data supplied by the geochemical survey. The mineralization was discovered during reconnaissance sampling, when one of the prospecting lines crossed a highly mineralized auriferous quartz vein. Now, the Lega Dembi deposit undergoes an intense exploration activity on surface and in underground.

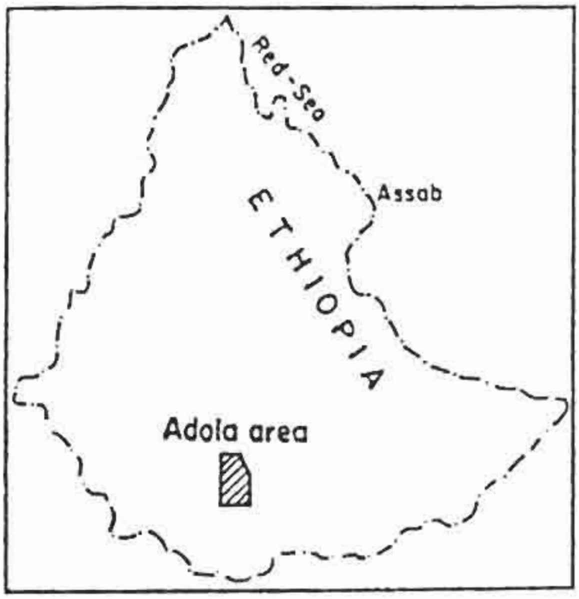

Fig. 1 - Location map.

This study has been carried out on samples collected in underground works, located in different points of the known orebodies, in the northern part of the deposit.

GEOGRAPHY

The Lega Dembi primary gold deposit occurs 500 km South of Addis Ababa, in the Jemjem district of the Sidamo region within the Southern Plateau (Ethiopia) (Fig. 1).

The area of the deposit is characterized by mountainous landscape covered by thick forest. It is situated at an altitude of 2000 m. The climate is sub-tropical to tropical. Rainfall measured in the area (Shakisso) amounts 1200 mm per annum, with annual temperature 18-20°C. The area is bounded by two major rivers: Awata River in the East and the Mormora River in the West.

GEOLOGICAL SETTING

CHATER and GILBOY (1970) divided the Precambrian metasedimentary and metavolcanic rocks of Southern Ethiopia into a thereefold structural and stratigraphic sequence, according to the following scheme:

- Upper Complex (now Adola Group), represented by amphibolites and associated ultramafic intrusive bodies, talc schists, talcites, serpentinites etc., interbedded with layers of graphitic phyllites, arkoses and conglomerates.

- Middle Complex (now Mormora Group) comprising a wide variety of microcline-muscovite-biotite-hornblende bearing gneisses.
- Lower Complex, which consists of uniform biotite gneisses (according to EMRDC, 1985, this complex is not present in the Adola area).

In this frame, the Lega Dembi primary gold mineralization is located in the central part of the Adola Gold Fields, comprising the low grade metamorphic sequences (Greenschists facies: amphibolites, quartz-feldspathic-biotite schists, carbonaceous quartz-chlorite-actinolite schists, graphite quartzites, phyllites and siltstones) of the Upper Complex, underlain by the volcano-sedimentary formations of the Middle Complex, represented by a high grade metamorphic (Amphibolite facies) group, composed of biotite-hornblende gneisses, amphibolites and migmatized micaceous schists.

The Middle Complex is the main geosyncline unit of the Baikalian orogenic cycle. The Upper Complex was formed in a narrow trough initiated upon the Middle Complex during the late Baikalian orogeny (GILBOY, 1970; CHATER, 1971; KAZMIN, 1972; EMRDC, 1985).

The Lega Dembi deposit is confined to the eastern part of the Megado graben syncline (see below), bordered at East by deep faults. A major, near N-S trending structural element developed at the boundary between the Middle and Upper sequences (EMRDC, 1985)

The Megado graben is a narrow N-S trending feature, 120 km long and 5-12 km wide, resulted from the late Baikalian tectono-magmatic reactivation and it is a major structure of the area. the central part of the graben consists of Upper Complex rocks, while the eastern and western blocks are composed of rocks belonging to the Middle Complex (EMRDC, 1985).

A major role in geologic and tectonic evolution of the area of the deposit was played by faults. At West and East the graben is bordered by deep N-S trending faults, initiated in the late Proterozoic phase of tectonogenesis (KAZMIN, 1972). On the surface, these faults are marked by linear bodies of talcites and talc-tremolite rocks in the area of Lega Dembi. These major faults are modified by younger NW and NE trending diagonal faults. The Lega Dembi deposit is confined within the eastern deep fault zone and consists of an extensive swarm of auriferous quartz veins, lenses and stringers.

In the mineralized area of Lega Dembi, Upper Proterozoic volcano-sedimentary and intrusive rock units occur, interested by folding, faulting and metamorphism. Metamorphism is of regional dynamo-thermal type characterized by a rise in pressure and decrease in temperature (CHATER, 1970).

According to petrographic studies, the common metamorphic minerals developed within the area are: hornblende, chlorite, sericite, quartz, microcline, oligoclase, talc, tremolite, actinolite, garnet. The rocks cropping out in the deposit area are biotite gneisses, biotite-quartz-feldspatic schists, carbonaceous mica-quartz schists and

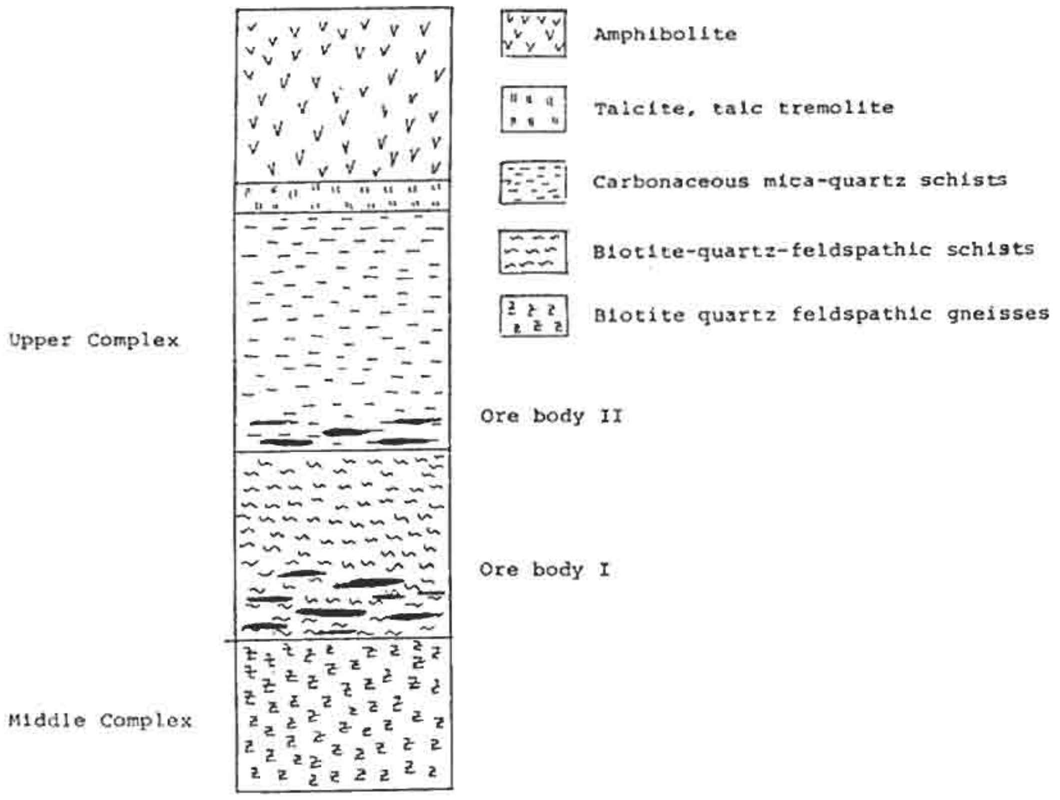

Fig. 2 - Local schematic lithologic sequence, with position of the ore zone.

amphibolite schists (in decreasing order). The thickness of these complexes varies from 500 to 1,000 m. The intrusive rocks of the ore field and its vicinity consist of metamorphosed ultrabasic rocks (now represented by talc-tremolite schists and talcite) and amphibolized gabbro.

A clay rich weathering mantle 10-60 m thick is developed over the entire mineralized area.

At present, the ore zone has been followed for over 2 km. It is explored by geochemical and geophysical surveys, geologic mapping, surface and underground works.

GOLD MINERALIZATION

Our study has been particularly carried out in the northern section of the Lega Dembi deposit, explored by underground mining works. It occurs as a complex paragenesis of Cu-Zn-Pb sulphides, with pyrite and pyrrhotite, bearing gold, tellurides and sulphosalts, in quartz. It is intimately associated with its host rocks, which belong to the greenschists metamorphic facies. The local sequence, crossed by underground works, is reported in Fig. 2.

The ore zone is confined to the rocks composing the member of biotite-quartz feldspathic schists and to the lower part of the member of carbonaceous mica-quartz schists intercalated with hornblende and actinolite schists.

The ore zone is characterized by a number of concordant and few discordant quartz veins, lenses and stringers. Generally, almost all of them trend according to a N-S direction and dip westward at 65-75 degrees. The ore zone has a variable width and has been traced for several hundred metres.

Although the gold mineralization is closely related to the presence of quartz concentrations, valuable gold occurrences are noted within the host rock as well. However, the gold distribution is highly erratic even within the ore zone. Statistical analysis of the data showed that there is no homogeneity among the samples, indicating that the gold is not distributed evenly throughout the deposit and even within the ore zone. Such uneven distribution and erratic gold values may be accounted for due to the presence of different populations and distribution laws among the gold grades, probably related to the various processes accompanying the gold formation (see below).

The quartz of the ore zone, in surface, is sugary, white, fine to medium grained, evolving to a more compact, milky type in depth. Country rock alterations accompanying gold mineralization include: silicification, carbonatization, sulphidization, sericitization, biotitizations, chlorotization.

Table 1 - Differences between Orebody I and Orebody II according to the mineral associations.

LEGA DEMBI I	LEGA DEMBI II
GOLD - ELECTRUM - (Samples: ETH4E - ETH1C - ETH1A - ETH1B - ETH4B - ETH4)	GOLD - ELECTRUM - (Samples: ETH16 - ETH15 - ETH13 - ETH8 - ETH1 - ETH9 - ETH7 - ETH2)
PYRITE - PYRRHOTITE - CHALCOPYRITE - CUBANITE - GALENA - SPHALERITE - (Samples: ETH4 - ETH4A - ETH4B - ETH2)	PYRITE - PYRRHOTITE - CHALCOPYRITE - CUBANITE - GALENA - SPHALERITE - (Samples: ETH4 - ETH8 - ETH13 - ETH3 - ETH15 - ETH10 - ETH16 - ETH1 - ETH9 - ETH14)
ALTAITE - HESSITE - PETZITE - (Samples: ETH4 - ETH4B)	(HESSITE) - (ALTAITE) - (Samples: ETH3 - ETH4 - ETH10 - ETH13 - ETH16 - ETH2)
ULLMANNITE - BREITHAUPTITE - NISBITE - (Samples: ETH4B - ETH2)	AG TETRAHEDRITE - BOULANGERITE - BOURNONITE-MENEGHINITE - (Samples: ETH3 - ETH1 - ETH4 - ETH10 - ETH15 - ETH14)

THE ORE BODIES

At present, it is possible to schematize the geometry of the Lega Dembi deposit dividing the ore zone into two major parallel mineralized belts, called "Orebody n. 1" and "Orebody n. 2". They can be distinguished and characterized by the different lithology of their host rocks: the former occurs in quartz-feldspar micaschists, the latter in a member of carbonaceous mica-quartz schists.

In both orebodies, the mineralization is contained in quartz lenses, veins and stringers, mainly concordant with the setting of the host rocks, locally concentrated so that quartz is the prevailing rock type, sometimes dispersed until disappearance of the mineralization.

The eastern limit of the ore zone, coinciding with the eastern limit of the orebody 1, corresponds to the boundary between the lowest part of the Upper Complex and the uppermost terms of the Middle Complex.

According to the results of researches carried out by ore microscopy and microprobe analysis, it seems possible to put into evidence the existence of differences between the two orebodies also from the mineral association point of view (Table 1).

Orebody 1 is characterized by a paragenesis, where native gold, with a variable Ag content (until true electrum) is accompanied by Fe-Cu-Pb-Zn sulphides, with tellurides and a peculiar group formed by ullmannite, breithauptite and nisbite.

In the orebody 2 pure native gold and Ag-bearing gold (electrum) occur with the same Fe-Cu-Pb-Zn sulfides association, together with very rare free tellurides and a group of minerals formed by Ag-tetrahedrite, boulangerite, bournonite, meneghinite.

From the Te content point of view a typical difference is given by the behaviour of this element in the Pb sulphide. In orebody 1 galena has normally a low Te content (Figs. 3; 4) and Te is present as free tellurides (hessite, altaite, petzite). In orebody 2 galena shows a high Te content, decreasing when tellurides (very rare) appear.

THE ORE MINERALS

The ore minerals association of Lega Dembi deposit, as above mentioned, in the samples analyzed during our researches can be listed as follows: Gold, Electrum, Pyrite, Pyrrhotite, Chalcopyrite, Cubanite, Galena, Sphalerite, Altaite, Hessite, Petzite, Ullmannite, Breithauptite, Nisbite, Ag-Tetrahedrite, Boulangerite, Bournonite, Meneghinite. They will be briefly described.

NATIVE GOLD AND ELECTRUM

Native gold occurs either as free isolated particles of various size (from finely dispersed up to visible nuggets) and dendritic bodies, or as grains and droplets associated with different sulfides, mainly galena. Native gold may contain silver in variable amounts, up to 20%. When the silver content increases, the resulting alloy is called "electrum" (RAMDOHOR, 1980): in our samples some values have been measured up to 50% Ag. In polished section the silver content has a strong influence on reflection colour: from the "luminous golden yellow" to a pure white along with the increase of Ag (Figs. 5; 5a; 6). The microprobe analyses of orebody 1 samples have shown a common high Ag content in gold, whereas in orebody 2 pure native gold has

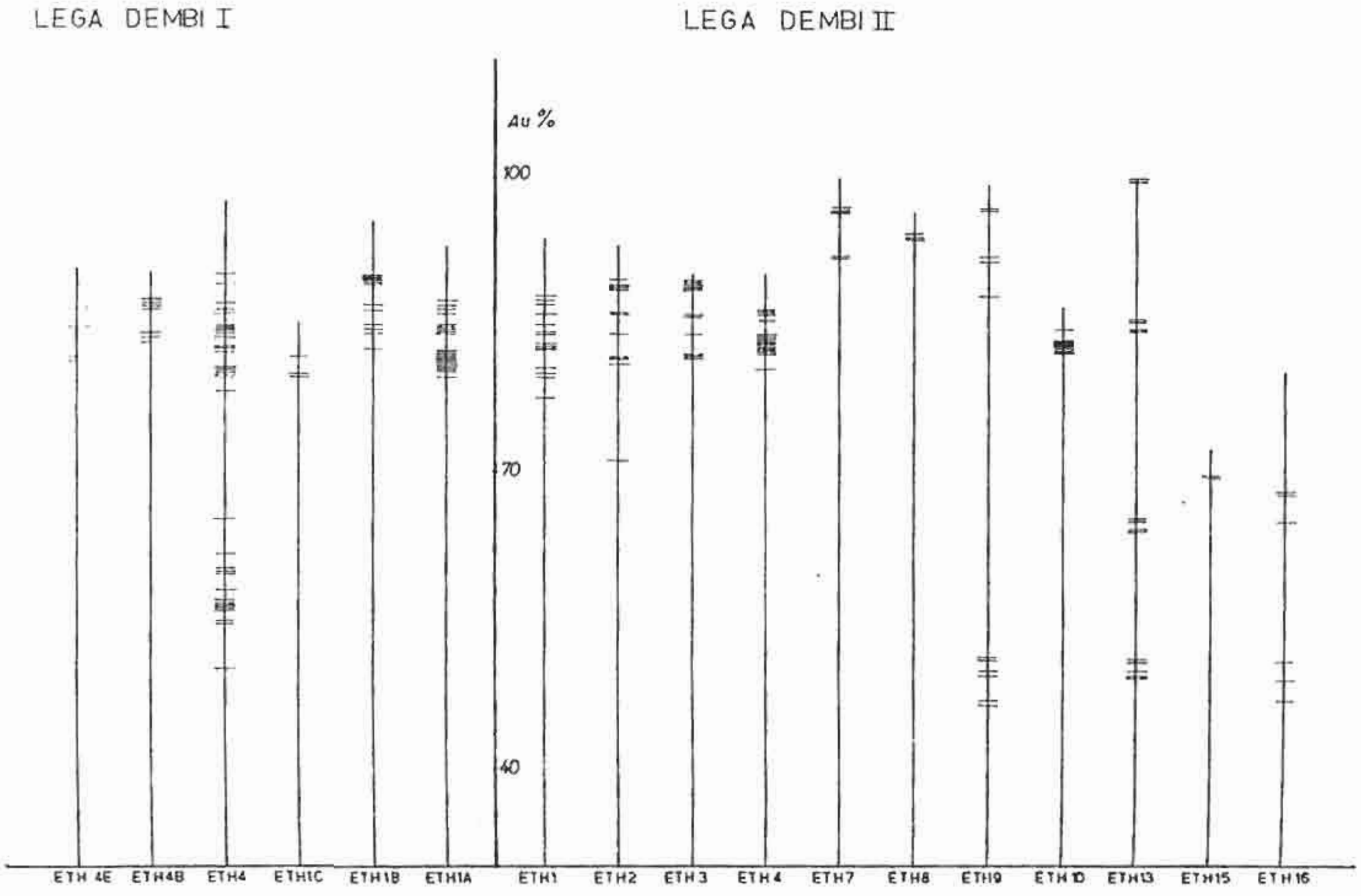

Fig. 3 - Au percent content in native gold and electrum: orebody 1 and orebody 2. Data from microprobe analyses.

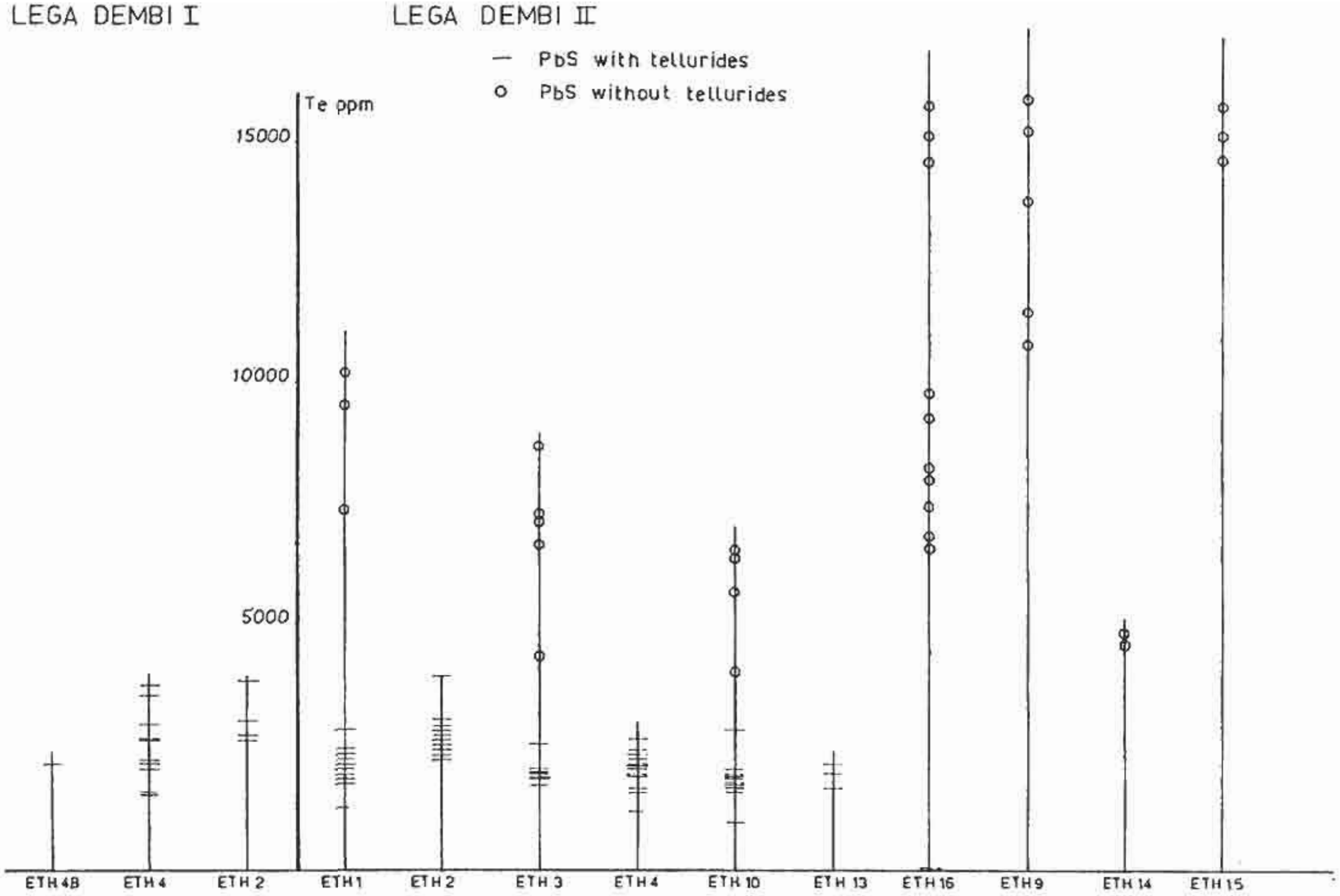

Fig. 4 - The distribution in PbS of orebody 1 and orebody 2. Data from microprobe analyses.

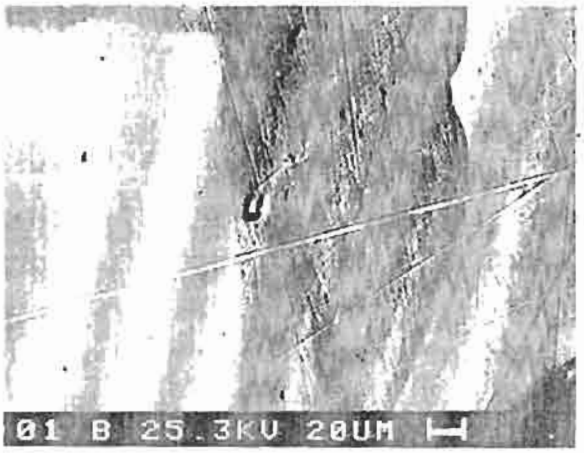

Fig. 5 - Electrum in different colour shades, due to variation of the composition. B.E.I (Backscattered Electron Image).

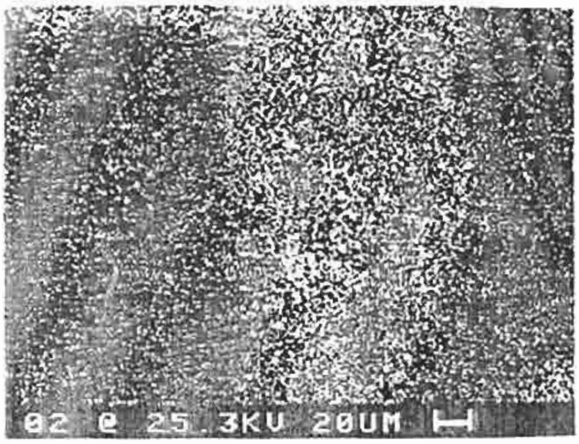

Fig. 5a - Ag (La) distribution map of the same field. A notable increase of the Ag concentration according to the darker area of Fig. 5.

Fig. 6 - Dendritic Au (white) with chalcopyrite (light grey) in silicate gangue (dark grey). B.E.I.

Fig. 7 - Star shaped sphalerite exsolutions in chalcopyrite (clear white), with gangue. Reflected light, 660x.

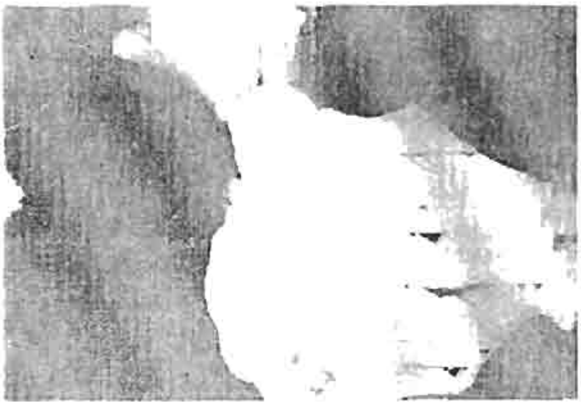

Fig. 8 - Mutual boundaries between gold (white) and galena (medium grey) in silicate gangue. Reflected light, 660x.

Fig. 9 - Small telluride blebs (white) in galena (grey), in contact with gold (light grey). Reflected light, 660x.

shown a common high Ag content in gold, whereas in orebody 2 pure native gold has been observed as well. It is to be noted that other elements have never been found in gold of our samples by microprobe analysis, besides silver.

PYRITE

Very common, probably the most abundant sulphide in both orebodies. Either alone or accompanied with other sulfides. Gold is rarely observed in pyrite.

PYRRHOTITE

It is the second common Fe sulphide. Often associated with pyrite and chalcopyrite, pyrrhotite occurs in large grains or groups of tabular idioblasts, or in isolated crystals. The microprobe analyses gave always stoichiometric composition without any detectable trace of foreign elements. Gold is frequently present as small irregular bodies within the pyrrhotite, or at the contact between pyrrhotite and host gangue minerals.

CHALCOPYRITE

It is very common in individuals of variable size, associated with all other ore minerals. Gold occurs very often either within chalcopyrite, in droplets and small grains, or at the contact between chalcopyrite and the host gangue minerals. A common feature of chalcopyrite is the presence of star-shaped sphalerite exsolutions (Fig. 7). Cubanite exsolutions are also frequently present as well developed lamellae. Both these types of exsolutions give an important information about a stage of temperature undergone by the mineralization process, which can be identified in the interval of 250-300 °C. Microprobe analyses found only stoichiometric composition also in chalcopyrite.

GALENA

Pb sulphide is rather common, in grains of variable size either isolated in the gangue minerals or accompanied by other sulfides, mainly chalcopyrite. Gold occurs very often as blebs within galena, or as grains in close association with the Pb sulphide: the contacts are always of the type "mutual boundaries" (Fig. 8). An outstanding feature of Galena is its content in tellurides: hessite, altaite and petzite in order of abundance appear normally in droplets, blebs and lamellae-shaped exsolutions (Fig. 9). A typical

Fig. 10 - Ag-tetrahedrite (black) in galena (light grey). B.E.I.

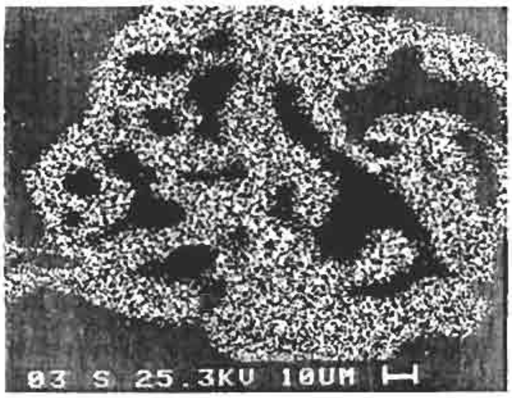

Fig. 10a - Sb (La) distribution map.

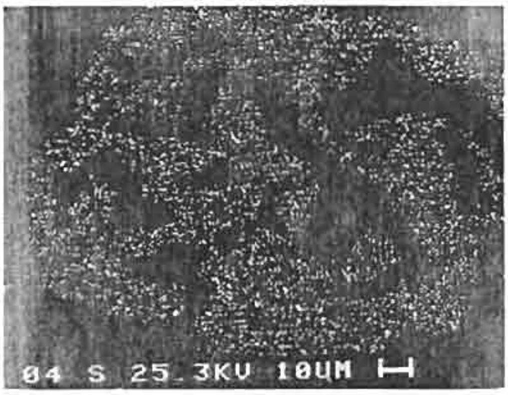

Fig. 10b - Sb (La) distribution map.

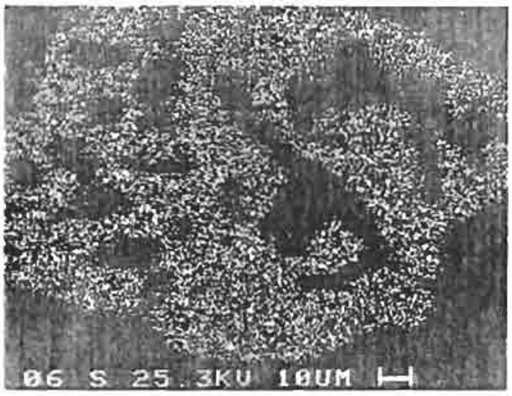

Fig. 10c - Sb (Ka) distribution map.

character is given by the presence of hessite-altaite in the same droplets. As previously mentioned, tellurides are peculiar of the galenas of orebody 1, whereas galenas of orebody 2 have rare free tellurides and high Te content (up to 1,52%). Microprobe analyses show that galenas of both orebodies have a constant low Ag content (850-2000 ppm). Among other elements only Bi and Sb have detectable values, even if low (up to 3800 ppm Bi and 2500 ppm Sb).

Sphalerite

It is the less common sulphide. Rarely isolated, more often associated with other sulfides: chalcopyrite is the most frequent and their relationships may be of the exsolution type, either as sphalerite starlets in chalcopyrite or as chalcopyrite droplets in sphalerite. Less frequently sphalerite is associated with galena: in this case it seems that Zn sulphide is the first formed. Gold can occur associated with sphalerite, but rarely. Microprobe analyses show that there is a high Fe content (up to 9%), giving another prove of the high temperature of formation of the ore minerals association, which is supported also by the chalcopyrite exsolutions in sphalerite. Among other elements, detectable values have been found for Cd (up to 2,8%) and Cu (3800 ppm).

Ullmannite, Breithauptite, Nisbite

This group of minerals has been observed only in orebody 1. They occur in isolated associations, or accompanied by chalcopyrite. Gold is also present as small grains, randomly distributed at the contacts between each other.

Tetrahedrite

It has been observed only in orebody 2. It is normally associated with galena in a typical graphic texture. Microprobe analyses have given the following composition: S 23.61 ±0.25, Ag 17.61 ±0,48, Sb 27.9 ±0.18, Fe 5.48 ±0.26, Cu 25.19 ±0.43 (Figs. 10; 10a; 10b; 10c).

Boulangerite, Bournonite, Meneghinite

This group of minerals has been observed only in orebody 2. They are normally associated with galena, less frequently with chalcopyrite. Tellurides may also appear near the sulphosalts grains, when they occur in galena.

CONCLUSIONS

Field work and laboratory researches have given a number of informations, which can be used for a first interpretation of the genetic processes of the mineralization and of its evolution:

- The ore zone is concordant with the host rock fabric and it is bound to a specific sequence at the bottom of the Upper Complex.
- In the ore zone two different parallel orebodies (or sub-orezones) can be distinguished, according to their stratigraphic position and to some paragenetic differences.

- Typical geologic thermometers (cubanite exsolutions in chalcopyrite); sphalerite starlets exsolutions in chalcopyrite; chalcopyrite exsolutions in sphalerite; high Fe content in sphalerite) witness that a range of 250-300°C has been reached in the temperature of the mineralization process.
- The ore minerals association (Au-Ag, Cu-Pb-Zn sulfides, tellurides) is mentioned in literature as belonging to hydrothermal sub-volcanic environment.
- The occurrence of Ni-bearing minerals, sometimes associated with gold;
- The mutual boundaries between gold and galena.

Taking into account the above mentioned observations, it is reasonable to draw some conclusions about the mineralization processes:

1) The presence of Ni-bearing minerals, together with amphibolite members in the host metamorphic sequence, suggest an origin of the deposit related to mafic volcanism events. Also the ore minerals association points to a volcanic origin.
2) The mineralizing process is repeated in fearly different environmental conditions (orebodies 1 and 2) stratigraphically belonging to different times.
3) The attitude of the orebodies in the host rocks, together with the setting of other known occurrences in the region is an indication of a stratabound character of the Lega Dembi deposit.
4) The structural fabric of the country rocks and their metamorphic grade show that the eventual protore had to undergo severe dynamic and thermal conditions after its first generation. On the other hand, the present undisturbed attitude of the ore minerals is an indication of their repeated remobilization and submission to the developing new conditions, although primary textures and structures have been often preserved (geologic thermometers).

It is therefore possible to propose a first schematic hypothesis on the genetic process of the Lega Dembi primary gold deposit:

1) Volcano-sedimentary sequence, with mafic Au-bearing members at two main levels in the lowermost part of the Upper Complex.
2) Regional metamorphism up to amphibolite facies, with remobilization and reconcentration processes of the ore minerals, with displacements in very narrow surroundings. Gold and galena seem to belong to the same phase, at the low temperature end of the metallogenic processes.

ACKNOWLEDGMENTS

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DISTRIBUTION OF PRECIOUS METALS IN THE TULU DIMTU ULTRAMAFIC BODY (WELEGA, ETHIOPIA)

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ABSTRACT

Precious metals (PGE, Au and Ag) and some chalcophile and siderophile elements (Cu, Zn, Mn, Co, Ni) have been determined in a series of different rock types present in the Tulu Dimtu area, within a linear mafic-ultramafic ophiolitic belt of Central-southwestern Ethiopia (Welega Province). The rocks investigated belonging to the Tulu Dimtu ultramafic body include undeformed serpentinized dunite, dark-green serpentinite, strongly deformed cream-white serpentine, schists, pyroxenite, gabbroic dykes and totally silicified dunite (birbirite). Some metasediments (both carbonatic and pelitic) bordering the dunitic body were also analyzed. Data on the less serpentinized rocks suggest the presence of "normal" PGE concentrations. With increasing serpentinization PGE undergo a redistribution process, concentrating locally in the dark-green serpentinite facies up to 0.1 ppm abundance levels. Silica metasomatism, acting contemporaneously with or immediately after serpentinization, seems not to contribute concentrating PGE in the produced silica-rich rocks. On the other hand, serpentinization and silica metasomatism introduced Au, Ag and, probably, other elements (S, As) into the ultramafics from external sources (metasediments). The distribution of Pt-group elements in the whole ultramafic body seem to exclude the presence in the Tulu Dimtu complex of specific horizons cumulating the PGE.

INTRODUCTION

The occurrence of platinum and gold concentrations in eluvial and alluvial sediments bordering the ultramafic body of Yubdo, Welega Province, Ethiopia, is known from historical times. These findings, together with the presence of Pt anomalies in soils and rocks from neighbouring areas suggested in recent times to carry out reconnaissance studies on a series of ultramafic bodies forming a long mafic-ultramafic belt in central-southwestern Ethiopia. In addition to Yubdo, the largest body of this belt is the Tulu Dimtu massif, which is localized 90 kilometres to the north of Yubdo (Fig. 1).

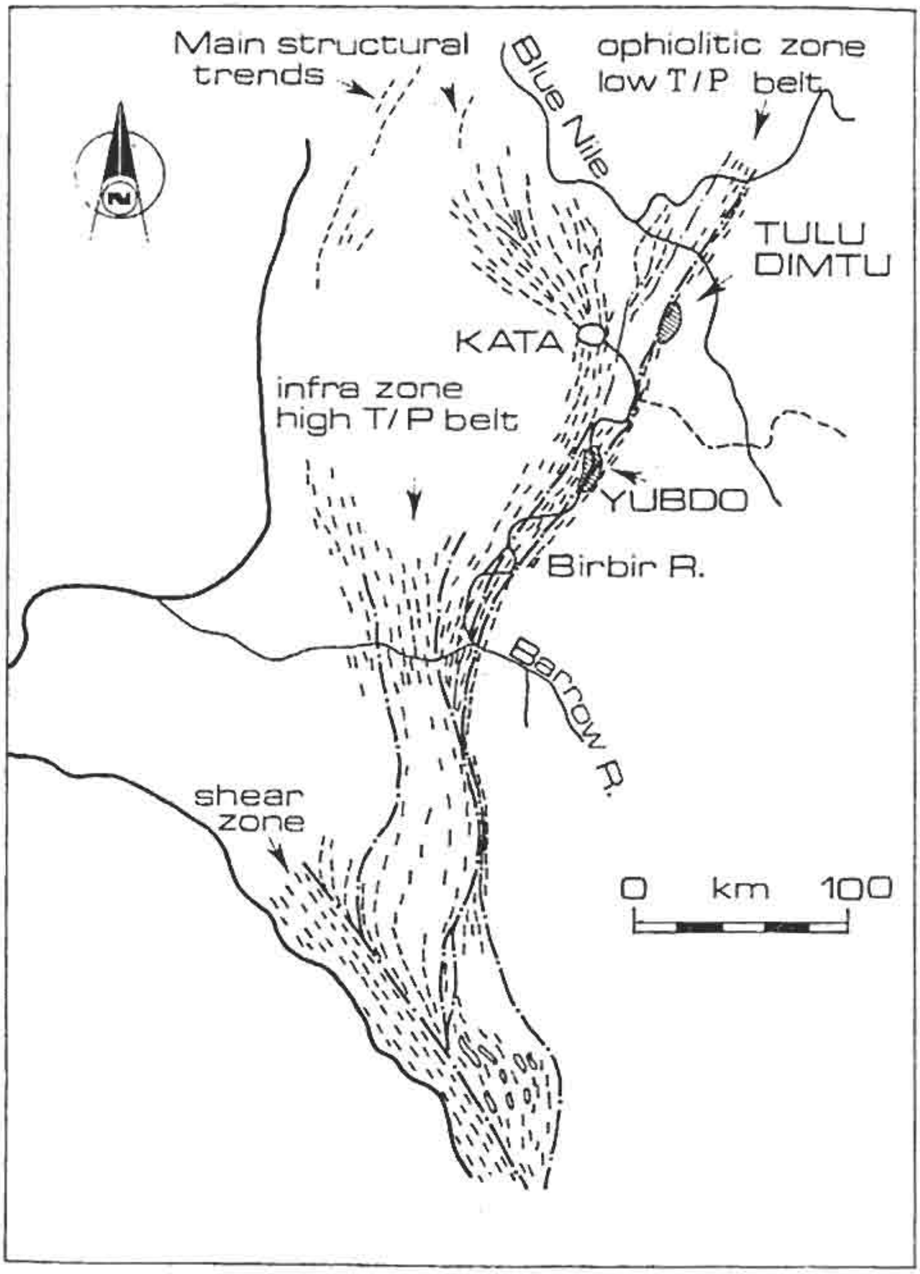

Fig. 1 - Sketch map of the major structural and tectonic trends in the Precambrian of Western Ethiopia (from KAZMIN, 1972 and DE WIT and BERG, 1977a).

This body has drawn the attention of economic geologists not only because of its size, but especially for the presence of peculiar processes (serpentinization-deformation and silica metasomatism), the same which were considered responsible for the Pt mineralizations at Yubdo.

A geochemical survey carried out by the UNITED NATIONS (1972) on soil covering the Tulu Dimtu body indicated the presence of arsenic and nickel anomalies. Some Pt analyses on magnetite and chromite concentrates seemed also to indicate the presence of platinum anomalies. Several researchers (KAZMIN 1972; UNPD 1972; DE WIT and BERG 1977b, etc.) suggested to perform a geochemical study of the hard rocks constituting the ultramafic bodies themselves, in particular as regards the Tulu Dimtu massif. According to these suggestions, it was decided to carry out a preliminary investigation on the distribution of precious metals in the main rock types of this area.

The main aim of this work was to estimate the primary abundance levels of these elements in ultramafics constituting the belt, and to study their behaviour during the sequence of post-magmatic processes (serpentinization-deformation and silica metasomatism) affecting the body.

OUTLINES ON THE GENERAL GEOLOGY OF THE AREA

According to KAZMIN (1972) a linear mafic-ultramafic tectonic belt of Precambrian age runs through central-southwestern Ethiopia for some 500 kilometres, from the Kenya border to the Blue Nile (Fig. 1). In this belt, known to display an ophiolitic character, a number of ultramafic bodies of varying size are present, among which those of Yubdo and Tulu Dimtu are the best known.

The geology of the Tulu Dimtu area has been described in detail in a series of reports (U.N. MINERAL SURVEY, 1972; KAZMIN, 1972; DE WIT and ABERRA AGUMA, 1977). According to these studies, a great part of this area is covered by metasediments of Precambrian age. Among these, at least two, possibly three, units may be stratigraphically recognized. The lower unit (the Tulu Dimtu sequence) consists of predominantly pelitic-psammitic rocks forming a thick succession of sediments grading from fine graphitic schists to coarse conglomerates outcropping along the Sai River. In this unit, one of the most common rock type is a dark-gray to black fine-grained metamudstone presenting a vague bedding or foliation. This intercalates with semipelitic rocks rich in pyrite, graphitic schists, crystalline limestones and quartzites and cherts. The Tulu Dimtu sequence contains also thick bands of basic-intermediate metavolcanics, talc-serpentine and talc-carbonate rocks of uncertain origin. In addition, not well stratigraphically defined acidic metavolcanics (quartz porphyry) are present in the area, which are assumed to be important for gold mineralizations (DE WIT and ABERRA AGUMA, 1977).

The upper unit recognized in the metasedimentary sequence is composed by quartz-muscovite schists and coarse micaceous psammitic rocks which outcrop some kilometres NW with respect to the Tulu Dimtu hill. The relationship between these clastic rocks and the Tulu Dimtu sequence is not well understood, but data from neighbouring areas suggest that this is a younger unit overlapping unconformably the older sediments.

GENERAL FEATURES AND LITHOLOGY OF THE TULU DIMTU MASSIF

Tulu Dimtu is the largest of the ultramafic bodies present in this part of the ophiolitic belt. It measures about six by three kilometres, and is bordered by metasediments of the Tulu Dimtu sequence mostly through a tectonic contact, originating slide zones. Detailed lithologic and structural features are reported by DE WIT and ABERRA AGUMA (1977) and by DE WIT and BERG (1977a, 1977b). Schematically, the rock association may be described in terms of a sequence of increasing serpentinization of a dunitic rock accompanied by strong deformation and contemporaneous or subsequent silica metasomatism.

The end product of such processes is represented by a peculiar rock: a paraquartzite containing oxide minerals which had drawn special attention at Yubdo because of its Pt mineralizations.

Structural studies indicated that conspicuous zones of intense deformation occur in the direct vicinity of Tulu Dimtu, as in the eastern and western slide zones. The eastern slide zone is bounded on its western side by a marble unit, whilst the ultramafics on the eastern slide zone are bordered by talc-carbonates, indicating large-scale CO_2 metasomatism during deformation-serpentinization. According to DE WIT and ABERRA AGUMA (1977), the Tulu Dimtu ultramafics have undergone at least two periods of deformation-serpentinization processes.

Lithologically, the massif is essentially constituted by serpentinized dunites and dark-green to pale-green serpentinites with minor amounts of cream-white silicified serpentine schists, completely silicified ultramafics (birbirites) and clinopyroxenites. The serpentinized dunites consist of more than 80% of serpentine, the rest of the rock being formed by olivine relics and oxides (chromite, magnetite) in variable amounts. The green to pale-green serpentines usually show a schistose structure, especially along the contacts between the altered ultramafics and the surrounding metasediments, due to the strong deformation in these contact zones.

The transition between the schistose serpentine and the homogeneous serpentinized dunite is gradational over several tens of meters. Structural relationships indicate that the serpentinite schist has a tectonic origin, deriving from the massive serpentinized dunite. Cream-white serpentine schists are present along the eastern and western marginal slide zones. They are strongly silicified and normally cut by late quartz veins.

The completely silicified ultramafics (birbirite) outcrop as minor masses in several areas along the marginal zones of Tulu Dimtu. The birbirite is a pale to dark-brown fine-grained quartzite formed by silica metasomatism, which accompanied and outlasted the main deformation. The continuous silicification is expressed by increasing amounts of quartz veins cutting the schists.

The presence of quartz brecciated structures recemented by silica indicates that the deformational processes acting during the final stage of silicification were of brittle nature. AUGUSTHITIS (1965) and DE WIT and BERG (1977 a) hypothize that these paraquartzites are a by-product of the serpentinization process, silica being derived from olivine during its alteration to serpentine and talc.

Clinopyroxenites occur as bands of limited thickness in the southern side of the Tulu Dimtu hill. Their mineralogy (diopsidic pyroxene, talc and chlorite) indicates that they have been involved to a varying extent in the serpentinization process. Several types of dykes (porphyritic, basic) cut the Tulu Dimtu ultramafics, the basic ones consisting of gabbroic rocks formed by plagioclase and clinopyroxene partially replaced by amphibole.

In the more serpentinized and deformed ultramafics (green serpentines and serpentinite schists) primary oxides are accompanied by secondary oxides formed during the serpentinization-deformation. Chromite and chrome spinel are frequently rimmed by magnetite. Magnetite present in quartz veins is rimmed by goethite and limonite.

Microscopic studies and electron microprobe qualitative analyses made by DE WIT and BERG (1977b) and by us (work is in progress) indicate the presence of a number of different sulfide and arsenide phases, especially in the rocks affected by silica metasomatism. These include pyrite, galena and a series of Ni arsenides and sulfides like millerite, pentlandite, niccolite, rammelsbergite and gersdorffite. Until now, no PGM were recognized in the Tulu Dimtu rocks.

STUDIED MATERIAL AND ANALYTICAL METHODS

PGE, Au, Ag and some chalcophile and siderophile trace elements were determined in most of the rock types present in the Tulu Dimtu massif and in some metasediments bordering the ultramafic body. According to the preliminary character of this research, only the most representative samples of the different rock types were selected for the analysis. Most of the considered samples refer to the above defined sequence of increasing serpentinization-deformation and silica metasomatism. In fact, a large part of them are serpentinized dunites and green serpentines collected in different places of the ultramafic body. Some cream-white serpentinized schists and birbirites come from the western and eastern marginal zones. As regards the metasediments, a crystalline limestone was collected in the eastern slide zone, near the contact with the ultramafics, whereas two graphitic schists were talsen about 400 m westward with respect to the contact.

The analytical method used for the determination of precious metals has been reported in detail by SIGHINOLFI et al. (1984). The attack was performed by using an HF-aqua regia mixture which allows the total solubilization of Au and Ag, but not of PGE, from the considered rocks. Previous experiments and literature data indicate that with the used attack the solubilization of PGE is selective, depending on the specific

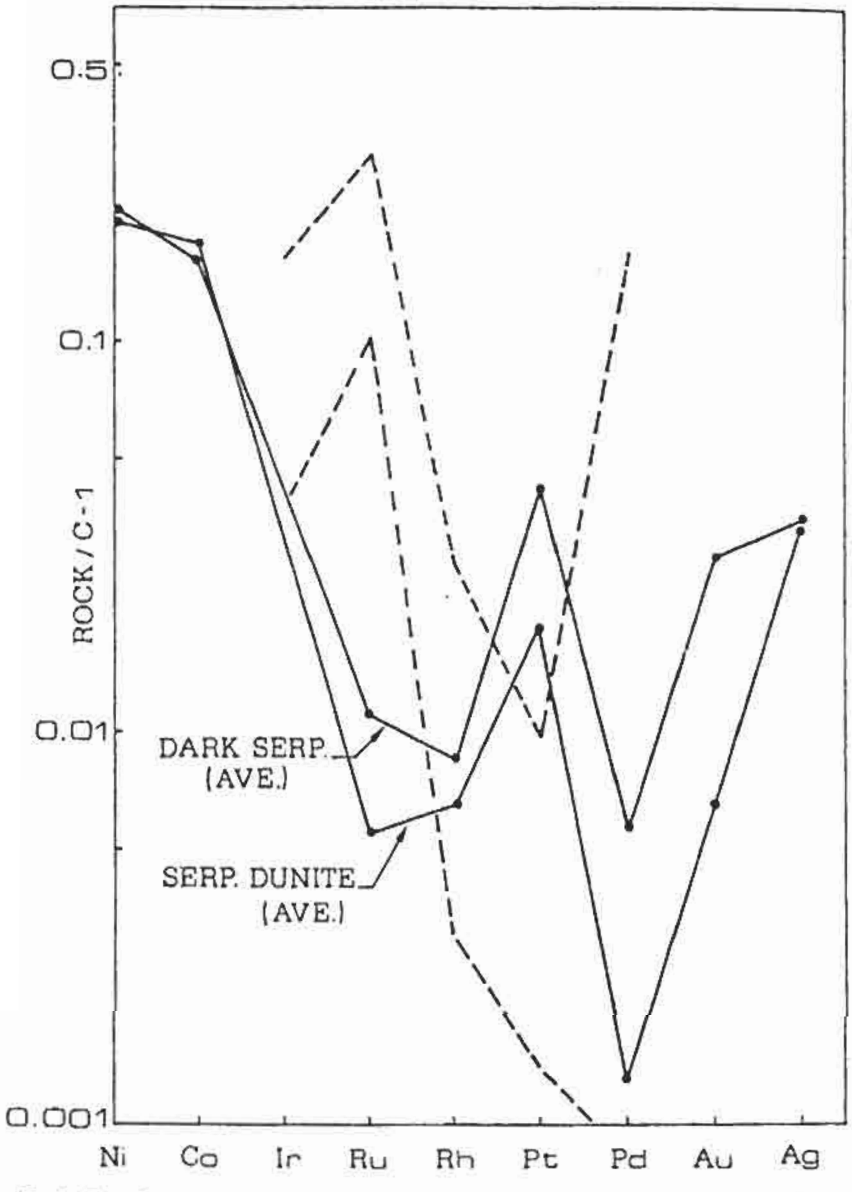

Fig. 2 - Chondrite-normalized element abundances in the Tulu Dimtu rocks and ranges of variation (area between dashed lines) in ultramafic rocks from Newfoundland ophiolites (from PAGE and TALKINGTON, 1984). C-1 values from MASON, 1971; ANDERS and EBIHARA, 1982.

PGE-bearing phases as follows:

a) PGE soluble phases = sulphides, arsenides, tellurides, solid solutions in silicates, Fe-PGE alloys low in Pt (and Ir);
b) PGE insoluble or partially soluble phases = spinels, chromite, Fe-PGM alloys rich in Pt (and Ir).

ANALYTICAL RESULTS

Table 1 reports the analytical results for the Tulu Dimtu massif and surrounding metasediments. For purposes of comparison, the chondrite-normalized average contents are reported in Fig. 2, together with element concentration ranges in ultramafics from other ophiolitic complexes.

Element abundances in Tulu Dimtu rocks fit in general those of other ophiolitic ultramafics, even if they are rather higher in Pt and depleted in Pd when compared with the "average" ophiolitic contents. It is well known (ARUSCAVAGE and HAFFTY, 1983; PAGE and TALKINGTON, 1984) that ultramafics from ophiolitic suites display a PGE abundance pattern characterized by a progressive decrease in the normalized abundances from iridium to palladium. With respect to this pattern, the Tulu Dimtu rocks appear significantly depleted in rhodium and, especially, in ruthenium.

This can be easily explained if we consider that most of PGE contained in chromite and other oxide minerals have not been completely solubilized by the used attack. On the other hand, it is well known that chromite and oxides in general tend to concentrate selectively Rh and Ru with respect to the other PGE (PAGE et al., 1982; PAGE and TALKINGTON, 1984).

If we compare Au and PGE contents in serpentinized dunites and in dark to pale-green serpentinites, an overall increase in the concentration of these elements with increasing rate of serpentinization-deformation is evidenced. On the contrary, the few data on silicified serpentinite schists and birbirites show that, whilst Au (and Ag) concentrate in the more silicified rocks, PGE are absent or present below the detection limits. This last feature distinguishes Tulu Dimtu from Yubdo, where Pt-minerals have been found locally concentrated in the strongly silicified birbirites (CABRI et al., 1981; GIDAY, 1981).

Widespread Au anomalies are present also in other rock types of the Tulu Dimtu area, as in a serpentinized pyroxenite within the massif and in some carbonatic and graphite-bearing metasediments of the Tulu Dimtu Formation.

As regards the other trace elements here considered, Ni shows a rather homogeneous distribution in the less serpentinized dunites. Nickel undergoes a severe redistribution with increasing serpentinization, concentrating locally up to 0.4%. However, the average concentrations for Ni and the other siderophile elements (Co, Zn, Mn) are rather similar in ultramafics affected by different rates of serpentinization-deformation. This would mean that their redistribution has been a small-scale process.

Cu concentrations indicate an extremely low content of chalcophile metals, both in

Table 1 - Cu and siderophile elements and precious metals in rocks of the Tulu Dimtu area.

Sample n.	Cu ppm	Zn ppm	Mn ppm	Co ppm	Ni ppm	Ag ppb	Au ppb	Pd ppb	Pt ppb	Rh ppb	Ru ppb
Cream-white serpentine schist											
Td 24 (silicified)	7	8.8	75	< 10	< 10	< 5	15	< 1	< 10	< 1	< 5
Td 58	<3	12.8	405	60	4000	10	2.8	< 1	< 10	< 1	< 5
Td 59 (silicified)	3	24.	985	120	3940	15	32	< 1	< 10	< 1	< 5
Average	(4.2)	15.2	-	-	-	(10)	17	< 1	< 10	< 1	< 5
Pyroxenite											
Td 44 (serpentinized)	<3	32	905	145	1500	8	25	< 1	< 10	< 1	< 5
Td 45	10	28.	1165	100	1710	5	3.6	8	< 10	< 1	< 5
Gabbro											
Td 181	53	54.4	1090	30	210		3	< 1	< 10	< 1	< 5
Metasediments											
Td 20 (carbonatic)	3	24.8	650	70	1630	9	19	< 1	< 10	< 1	< 5
Td 35 (pelitic)	131	22.4	175	<10	60	12	1	5	< 10	< 1	< 5
Td 23 (pelitic)						52	18	2	< 10	< 1	< 5
Silicified dunite (birbirite)											
Td 25	< 3	33.	1250	115	2810	< 5	11	< 1	< 10	< 1	< 5
Td 27	< 3	20.	1135	100	1750	< 5	6	< 1	< 10	< 1	< 5

( ): approximate average (values below the detection limits arbitrarily taken as one half of the limit).

Table 1 - Continued.

Sample n.	Cu ppm	Zn ppm	Mn ppm	Co ppm	Ni ppm	Ag ppb	Au ppb	Pd ppb	Pt ppb	Rh ppb	Ru ppb
Undeformed or slightly deformed serpentinized dunite											
Td 5	<3	21.6	790	60	2250	5	1.2	1	20	1.5	5
Td 6	<3	23.2	835	115	2880	7	1.6	<1	20	1	<5
Td 13	<3	20.	660	100	2500	<5	<1	<1	10	1	<5
Td 18	<3	15.2	810	70	2130	15	<1	1	30	1.8	5
Average	<3	20.	774	86	2440	(7.4)	(0.9)	(0.7)	20	1.3	(3.8)
Dark green serpentinite											
Td 9	<3	17.6	485	85	2000	<5	4.5	<1	100	2.4	10
Td 40	<3	20.8	930	115	3060	10	4.4	<1	20	1	20
Td 41	<3	21.6	1020	60	1940	<5	3.	6	80	4.2	5
Td 55	<3	26.4	1080	40	1310	10	6.	4	10	<1	<5
Td 57	<3	20.	1010	90	3750	10	2.9	<1	20	<1	<5
Td 60	10	20.	775	100	1500	10	4.9	7	30	1.9	7
Average	(<3)	21.1	883	82	2260	(7.5)	4.3	(3.1)	43	(1.7)	(7.8)

the less serpentinized dunites and in the strongly serpentinized deformed rocks. It is difficult to assess whether this is a primary (igneous) feature or if it correlates to post-magmatic processes. The observed Cu depletion in a serpentinized pyroxenite with respect to a fresh one suggests that serpentinization should play a major role in removing primary sulfides and associated elements. In any case, the Tulu Dimtu ultramafics appear peculiarly poor in chalcophiles when compared to similar serpentinized rocks from other ophiolitic suites. Rather high Cu contents (up to 130 ppm) were found in the analyzed Tulu Dimtu metasediments, confirming the mineralogical data on the presence of abundant sulfide phases in these rocks, particularly in the graphite-bearing metapelites.

SOURCE OF PRECIOUS METALS AND EFFECTS OF POST-MAGMATIC PROCESSES

The knowledge about the source of precious elements and of the mode of their occurrence in primary igneous sources represent a striking point for the economic geology of the area. A wide literature on PGE distribution in mafic-ultramafic complexes indicates that PGE originally contained in the rocks are present under a disseminated form (as solid solution in silicates and oxides, or as alloys or sulfides) or concentrate in specific cumulative horizons. These last are usually very thin and volumetrically negligeable when compared with the complex as a whole. For this reason, they are difficult to identify in spite of their great economic value.

Even if the preliminary data on Tulu Dimtu are largely insufficient to outline any definitive conclusion, we believe that there are indications which tend to exclude the existence of PGE-cumulating levels in the dunite body, suggesting at the same time dispersed PGE-bearing phases as primary igneous sources for PGE.

As a matter of fact, the PGE contents of the less altered ultramafics are essentially of the same order of those in the more serpentinized rocks. The limited PGE anomalies found in these last rocks seem to be plausibly related to an heterogeneous redistribution during serpentinization. If a PGE-accumulating level had been present in the body, much stronger PGE anomalies should have been found somewhere in the serpentinized mass, as serpentinization involved the whole dunite body.

In recent years, there has been an increased recognition of a close link between ultramafics affected by serpentinization and Pt mineralizations. STUMPFL (1974) observed a positive correlation between the degree of serpertinization and the PGE content of serpentine. Hydrothermal activity during serpentinization results in the development of complex PGM associations as transport, redeposition and concentration of Pt may occur over considerable distances. Primary magmatic PGE are remobilized during the hydratation of the ultramafics occurring at temperatures below 500°C.

Basically, serpentinization results in a release of Pt (and Ni) from olivine and spinel lattices. RUCKLIDGE (1971) concluded that in dunitic rocks about one third of the PGE is tied up in silicates. During serpentinization of olivine an homogeneous redistribution of PGE in serpentines is unlikely as their redeposition can occur only in peculiar chemical environments. Depending on pO_2 partial pressure and on sulphur concentration in the fluids, PGE may be redeposited as native metals and alloys or as sulfide minerals, respectively.

The lack of economically significant PGE and PGM concentrations in the investigated Tulu Dimtu rocks indicates that during serpentinization suitable conditions for the redeposition of PGE were not attained. What distinguishes the post-magmatic history of Tulu Dimtu from that of other serpentinized ultramafics is the presence of widespread silica metasomatism processes acting contemporaneously or immediately after serpentinization.

It has been shown that, in contrast with what found at Yubdo, the strongly silicified serpentines are free of PGE. This means that in coincidence with the massive deposition of silica from hydrous fluids PGE tend to be removed rather than deposited in serpentines. On the other hand, the analytical data indicate that the hydrous fluids carry gold and deposit it together with silica.

It is obvious to point out for Au a source different from that of PGE, i.e. an external source as for great part of the hydrous fluids. Specific horizons (graphite-bearing schists ?) of the Tulu Dimtu metasedimentary sequence appear the most likely source for gold, as indicated also by the high Au values found in some of the analyzed samples. The contamination of Tulu Dimtu ultramafics by elements of foreign derivation could have been a much more extensive process than commonly supposed. In this context, As anomalies found in soils covering Tulu Dimtu are likely correlable to the introduction of this element from external sources.

As reported before, several authors (AUGUSTHITIS, 1965; DE WIT and BERG, 1977 b) hypothize for the silica of the silicified ultramafics an in situ derivation by the transformation of olivine in serpentine and talc. On the basis of the element associations in silicified rocks and also of structural relationships between ultramafics and surrounding rocks we are led to suppose that part of the silica may also derive from external sources. If post-magmatic processes at Tulu Dimtu include such long-distance element migrations, it cannot be excluded that also PGE were involved in the same process. In this case, a possible redeposition of PGE outside the primary igneous source cannot also be excluded.

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GEOLOGICAL DEVELOPMENT AND ECONOMIC SIGNIFICANCE OF LACUSTRINE PHOSPHATE DEPOSITS IN NORTHERN TANZANIA

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ABSTRACT

Phosphate-bearing Pliocene or Pleistocene sediments at Minjingu, Northern Tanzania, host one of the few commercially exploitable reserves of this essential fertilizer material in East Africa. However, contrary to the formations of large deposits in Morocco, Algeria, Tunisia, Egypt and the Western Sahara, the geological origin of these resources in Northern Tanzania is completely different and locally restricted. The Phosphorites of Minjingu are mainly formed by bone fragments of birds (*Phalacrocorax* sp.) and fish (*Tilapia* sp.), indicating a former lacustrine environment with an increased paleoalkalinity up to 40 meq/l $HCO_3^- + CO_3^{--}$. The reserves of these phosphorites, commercially exploited since 1983, are limited for approximately 20 years (production target: 100.000 tonnes per year). However, they are one of the overall objectives to advance the agricultural production in Tanzania by building up its own fertilizer industry. Other mainly in the Mbeya region located phosphate deposits (both carbonatites and phosphorites) are presently evaluated in the frame of the Tanzania-Canada agrogeology project, and it is suggested that in future these resources could also contribute as locally available soil additives.

INTRODUCTION

The Minjingu phosphate deposits near Lake in Northern Tanzania (a in Fig. 1) were discovered in the late 1950's in the course of airborne geophysical surveying for minerals (ORRIDGE, 1963; 1965). Subsequently several geological, mining dressing and economic studies in the field and in laboratories by different international organisations have been carried out during the period from 1957 to 1970. From all of these observations to followed that the phosphate are reserves of Minjingu ore sufficient to supply TFC (TANZANIA FERTILIZER CORPORATION) with raw material at less than half of the world market price and much less in foreign exchange.

After another revision of the reserves in 1975 and a borehole drilling campaign carried out by STAMICO (STATE MINING CORPORATION of TANZANIA) in 1976, negotiations of the Tanzianian government with various potential contractors led to the selection of KONE-corporation of Finland to be responsible for the project engineering and the construction of industrial civil work. Plant erection and mine development were completed in August 1982, and the commercial production of phosphates started in January 1983.

GEOLOGICAL SETTING

The Minjingu phosphate deposits consist mainly of a sequence of phosphatic beds alternating with clayey layers. Their stratigraphic age is still uncertain, a younger Pleistocene was assigned (SCHLÜTER, 1986), but also Pliocene or early Pleistocene has been reported (CASANOVA, 1986).

These lacustrine sediments surround unconformably the lower part of the so called Minjingu-Kopje (Fig. 2) of late Proterozoic age (Usagara Formation). The Kopje itself is formed by massive quartzites and in its centre by a banded gneiss. The phosphate formation two ore types which differ both in structure and consistency.

Mineralogically and chemically the lower unit or so called soft phosphates consist of calcium phosphate (70%), carbonates (dolomite and calcite) (10%), quartz and colloidal silica (5-7%), feldspar (3-5%), clay minerals (7%) and minor amounts of biotite, muscovite, amphiboles, pyroxenes, limonite, etc., with a total P_2O_5 content ranging from 24 to 31%. The upper unit or so called hard phosphates consist of calcium phosphate (75-80%), quartz and feldspar (15-25%) and minor amounts (2%) of limonite, clay minerals and apatite, with a total P_2O_5 content of approximately 31% (JONES, 1983). However, for technical reasons presently the hard phosphates cannot be used in the processing of fertilizer raw material.

The commercially mined soft phosphates extend to a maximum thickness up to 20 m, surrounding the flanks of the hill in an oval shape and outcropping especially along its northern slopes. Laterally their thickness decreases and the phosphatic layers are gradually substituted by more clayey lake beds.

The often observable slumping structures in the soft phosphates are due to the regional inclination of the hill's slopes, from which - under the lake level - these not yet consolidated sediments glided into deeper zones. However, these forces were not sufficient to demolish much of the bony material originating from the island. Biostratonomically the abundant isolated bones of birds (*Phalacrocorax* sp.) never indicate a specific flow regime, but their preservation is sometimes exceptionally good, hence leading to the conclusion that these bones were neither destroyed by potential scavengers nor transported far away.

From their microfacial analysis the phosphorites of Minjingu are built up by mostly clastic particles. A distinction of skeletal material (predominant), phosphatic lithoclasts, detrital quartz grains and calcareous biogenic debris seems to be practicable. These components are bound by different cements or matrix types, e.g. calcareous, dolomitic, siliceous, phosphatic and clayey materials.

The abiotic environmental factor of alkalinity in the paleolake can be determined by consideration of the metabolic requirements of fossil fish evidenced in the phosphorites of Minjingu. Already CERLING (1979) used the well known autecology of certain organism groups for the estimation of the paleo-alkalinity in Lake Turkana, Northern Kenya. Most east African lakes are today sodium bicarbonate or sodium carbonate in composition, and their alkalinity is ranging from 2.2 $HCO_3^- + CO_3^{--}$ milliequivalents per litre (meq/l) (Lake Naivasha) to 3.170 meq/l (Lake Magadi) (SCHLÜTER, 1987).

Fig. 1 - Sketch map of Tanzania, showing the locations of principal phosphate deposits. Black squares: carbonatites; black circles: phosphorites. Numbers and letters indicate the following localities: 1: Musensi, Mbeya region; 2: Songwe Scarp, Mbeya region; 3: Sukomaweru, Mbeya region; 4: Sageri Hill, Mbeya region; 5: Mbalizi, Mbeya region; 6: Panda Hills, Mbeya region; 7: Sangu Ikola, Rukwa region; 8: Ngualla, Mbeya region; 9: Zizi near Kisaki, Morogoro region; a: Minjingu, Arusha region; b: Amboni caves, Tanga region; c: Latham island, 60 km east of Dar es Sallam (compiled after different sources).

Fish for example are strongly affected by the composition of water. Lakes with an alkalinity of 40 meq/l or more tend to harbour only cichlid fish (*Tilapia* sp.) with the trend to dwarfism. The very common and comparatively small operculae, vertebrae and fin spines in some of the phosphatic layers belong probably to ancestors of the diminutive species Tilapia amphimelas, which today lives in alkaline springs and small lagoons round Lake Manyara. Another indicator of a high paleosalinity is the occurrence of fossilized fish hyperostoses in some of the phosphatic layers, because the growth of hyperostotic bones in recent fish is almost entirely bound to families living in a salt water environment.

An interesting analogy could possibly indicate that the formation of the phosphorites at Minjingu resulted in a comparatively short period of time. On the island Chincha along coastal Peru approximately 2 million specimens of the recent cormorant *Phalacrocorax bougainvillii* produce 50 to 60,000 tonnes of guano per year. Since the size of this Peruvian island (0.3 km²) is almost equivalent to the area which once has been the resting and breeding place of cormorants on the Minjingu-island in the Paleolake Manyara, it can be assumed that a similar quantity of birds was also responsible for a similar guano production rate. The guano was later washed away and precipitated together with the clastic bony material of the birds and their prey, the fish, shortly behind the shoreline of the island.

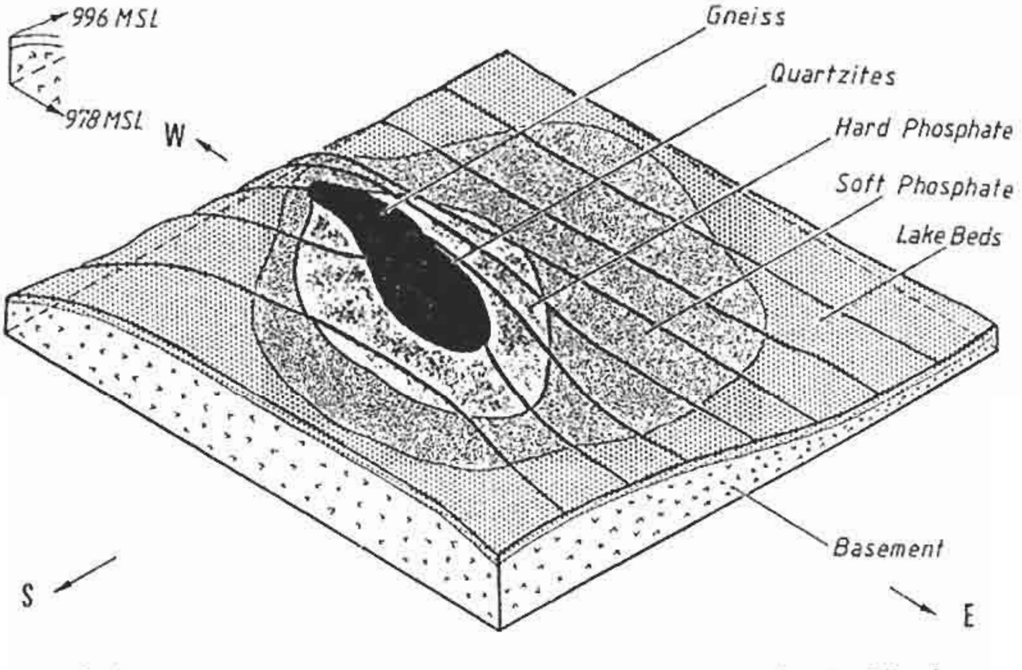

Fig. 2 - Block diagram of the Minjingu Kopje with the main lithological units. Exploitation of the soft phosphates is carried out only along the northern and western slopes of the hill.

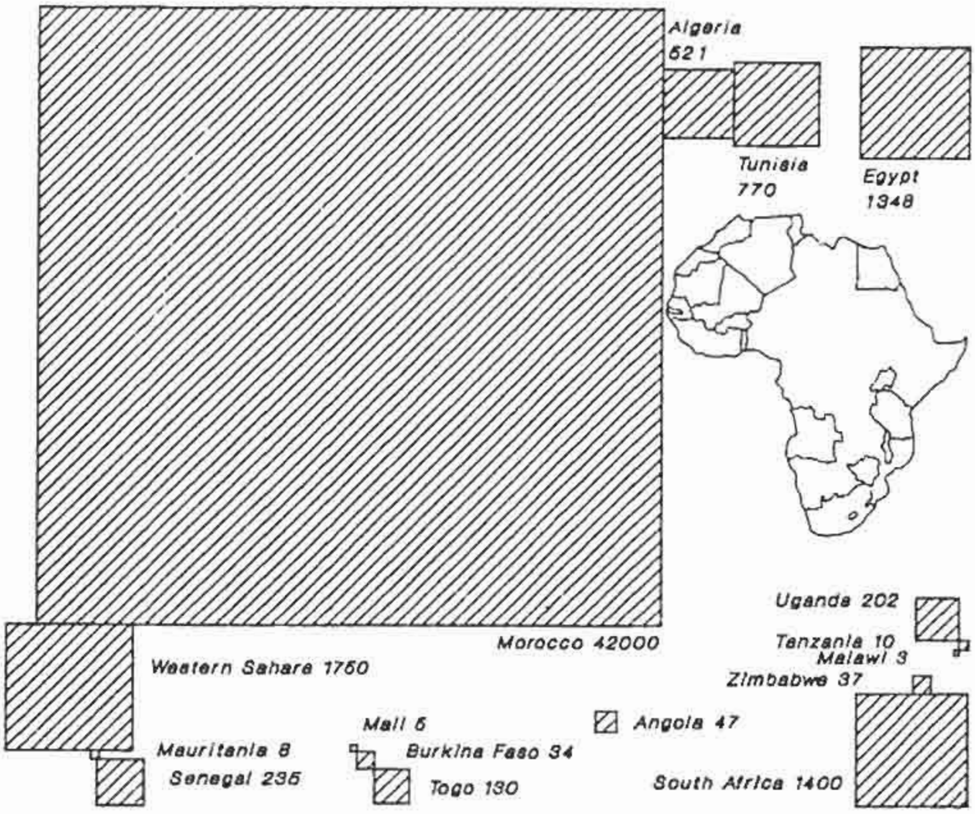

Fig. 3 - Quantitative relations of estimated reserves of phosphatic deposits in Africa (in million tonnes), as indicated by proportional squares for each particular country (compiled after different sources).

The total reserves of phosphorites at Minjingu are estimated of around 9 million tonnes (JONES, 1983), hence leading to the calculation that the whole ore body in the case of a continuous deposition came into existence only within 200 years.

ECONOMIC SIGNIFICANCE

Phosphorus is an essential element in agriculture and in cattle feed. Phosphate concentrates are used for the production of chemical fertilizers (77%), directly applied fertilizers (4%), cattle feed (7%) and in metallurgical, detergent, chemical and other industries (KOGBE and AFILAKA, 1985). Africa ranges with approximately 70% of all identified commercially exploitable reserves of phosphorites on place one, but in the world production of commercial phosphates Africa accounted for example in 1983 only for about 24%.

Also the distribution of phosphatic deposits in Africa is uneven, more than 50% of the world reserves have been discovered in Morocco in marine sediments of Upper Eocene to Cretaceous age. Similar formations occur in the Western Sahara, Algeria, Tunisia, Egypt, Senegal and Togo. In central Africa larger deposits do not exist (KUN 1965), and also East Africa is comparatively poor. The quantitative relations of the estimated reserves are given here in Fig. 3.

However, since in the 1970's internationally the value of phosphate raw material has considerably increased (compared to 1967 - 1969 its selling price more than doubled) the Tanzanian government started a policy to avoid the costs for importation of raw phosphate material (between 1974 - 1978 up to 80.000 tonnes per year) and also for the high freight rates by establishing its own phosphate industry.

The phosphorites of Minjingu were the first choice because their infrastructure was the best:

1) The P_2O_5 contents of the phosphorites are high (about 30%) compared with those of the other phosphatic deposits in Tanzania and do not need up-grading or blending.
2) Minjingu can be reached by a tarmac road from Arusha (presently - 1988 - under reconstruction).
3) A favourable factor for the processing of the phosphorites at TFC (TANZANIA FERTILIZER CORPORATION) is their very low chloride content.
4) The area surrounding the deposit is open and allows waste disposal, loading facilities and laying out of the phosphate dressing without restriction.

However, additionally to the exploitation of the Minjingu phosphorites, in January 1985 the Canada-Tanzania project on agrogeology started with the aim to bring together the traditionally separated disciplines agriculture and geology, and for example to evaluate geological resources as locally available soil additives. Especially in the Mbeya region in Southern Tanzania (Fig. 1) fertilizer raw materials were re-assessed and some new phosphate deposits (both carbonatites and phosphorites) were discovered, which in future could also contribute to the agricultural production of Tanzania.

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RESULTS OF A COUNTRY-WIDE GROUND-WATER QUALITY STUDY IN SOMALIA

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ABSTRACT

A comprehensive study on ground water quality in Somalia, known as the "Water Quality Data Book of Somalia", has just been completed with the financial help of the German Government. The main objectives of this study were to assess the hydrogeological and water quality conditions of rural areas, refugee camps, and major towns; to identify areas potentially suitable for ground water development using various technologies; and to help set up the conditions for the preparation of a country-wide Water Master Plan.

For practical purposes, the large amount of data is distributed in three reports covering Southern, Central, and Northern Somalia. Each of the three areas is reported in two volumes divided into three parts: Part One describes the general hydrogeological and water quality conditions of the area; Part Two describes the hydrogeology and water quality of major towns and refugee camps; and Part Three consists of annexes with the tabulation of data from different water sources.

Altogether 32 major towns and 30 refugee camps have been described; and 32 promising areas have been identified - some for further development of water resources and others for ground water exploration.

The General Report summarizes the main findings detailed in the three technical reports and defines the areas identified for further development of water resources based on water quality and the areas recommended for ground water exploration.

This paper briefly describes the 33 areas identified as promising.

INTRODUCTION

One of the major impediments to the development of water resources in Somalia was the lack of sufficient and readily available information on surface and ground water quality. Several documents and reports describing the ground water conditions of scattered areas have been written during the past 30 years; these reports, however, were not always available and well data needed to be collected and evaluated from various sources. There was a great need to compile all the existing data in a consolidated document aimed at defining the water quality conditions of urban and rural areas and identifying areas promising for future development.

THE REQUEST FOR THE PREPARATION OF THE WATER QUALITY DATA BOOK OF SOMALIA

In 1984 the Somali Government submitted a proposal to the German Government for assistance in the collection and evaluation of the existing hydrogeochemical data, and for carrying out additional water quality surveys wherever necessary. The German Agency for Technical Assistance (GTZ) was appointed as executing agency.

OBJECTIVES OF THE PROJECT

The major objectives of the "Water Quality Data Book of Somalia" project were the following:

- collect all data from existing documents regarding water quality and carry out hydrogeochemical surveys;
- identify areas potentially suitable for ground water development using various technologies;
- examine present water uses and suggest criteria for establishing a water quality standard for the country;
- assess the hydrogeological and water quality conditions of major rural areas, refugee camps, and major towns;
- identify areas for surface and ground water development and help setting up the conditions for the preparation of a country-wide Water Master Plan.

ACTIVITIES

To achieve these objectives the following performed:

Data Collection

The project became operational by the end of May 1985. However, much information had already been collected in a preparatory phase which started in early 1983.

The available information by the end of the preparatory phase, which had a country-wide coverage, was gathered from 55 different sources and consisted in more than 2600 sets of water quality data of wells, springs, rivers, and other surface water sources. During the preparatory phase several field surveys to collect water were also carried out.

During the various phases of the project all the available data on water quality and other pertinent information from reports and other sources were collected, compiled, and tabulated. Hydrogeochemical surveys were carried out to fill gaps. Altogether more than 3600 sets of chemical data were examined.

Computer Programming and data Processing

The evaluation and classification of the information has been performed by using a computer program to: check the ionic balance and validity of the analyses, classify the water types of different areas, compile tables and graphs, and develop program documentation including a Computer User's Manual and a technical description of the program.

Satellite Imagery Interpretation

Satellite imagery interpretation was carried out and represented on 1:500,000 scale maps covering the whole country. The maps include the major hydrogeological provinces, the location of principal water sources and their water quality, the identification of drainage systems, and other relevant information. For the major agricultural areas with a higher density of information the maps have been produced at scales of 1:100,000 and 1:200,000. For major towns 1:10,000-1:25,000 scale maps have been drawn.

Reports

For practical purposes and the easy consultation of the large amount of data, the country was divided into Southern, Central, and Northern Somalia. Each area is reported in two volumes divided in three parts. Part One describes the general hydrogeological and water quality conditions of the area. Part Two describes the hydrogeology and water quality of major towns and refugee camps. Part Three consists of annexes with the tabulation of data from different water sources.

Altogether 32 major towns and 30 refugee camps have been described; and 32 promising areas have been identified some for further development of water resources and others for ground water exploration.

The General Report summarizes the main findings detailed in the three technical reports and defines the areas identified for further development of water resources based on water quality and areas recommended for ground water exploration. This paper briefly describes the selected areas.

SOUTHERN SOMALIA

Southern Somalia is comprised by the following six regions: Gedo, Bay, Bakool, Shabeelle Hoose, Juba Hoose, and Juba Dhexe. The area is predominantly flat with exception of the Coastal Belt, which is mainly hilly, and the Gedo Region and parts of the Bay Region, which have a topography varying from gently rolling to rough, with some flat-topped mesas.

Land and water potential in Southern Somalia is far better than in other parts of the country. Rainfed agriculture is well developed in areas having more than 400 mm/year of rain, such as the Lower Shabeelle, Bay, and Lower Juba regions. Irrigation from the Shabeelle and Juba rivers covers 50,000 ha of controlled irrigated agriculture and about

120,000 ha of uncontrolled flood irrigation.

Population density is high along the fertile alluvial plains of the Juba and Shabeelle rivers. Agriculture and livestock raising absorb a large part of the rural population and provide exports and foreign exchange earnings.

With the exception of the population along the Shabeelle and Juba rivers, which obtains its water supply mainly from surface water, the remaining population relies on ground water for all its water needs. Hand-dug wells and rain-harvesting water reservoirs constitute the traditional water sources. As much of the area is arid or semi-arid and water supplies are often scattered over long distances, people who depend upon livestock are compelled to a nomadic life in continuous search for grazing and water.

Areas Recommended for Ground water Development in Southern Somalia

The results of the ground water quality assessment indicate several areas with favourable hydrogeological conditions which could be developed by drilled wells, dug wells, or other water structures.

Two major ground water programs could be implemented. The first refers to areas already known, to a certain extent, for both qualitative and quantitative aspects which could be further developed once their natural resources, including grazing availability and agricultural potential, have been fully evaluated together with the socio-economic aspects. The second refers to areas with little information on water quality but, from conceptual hydrogeological considerations, are promising and require proper investigations to a certain both the qualitative and quantitative aspects of their ground water conditions.

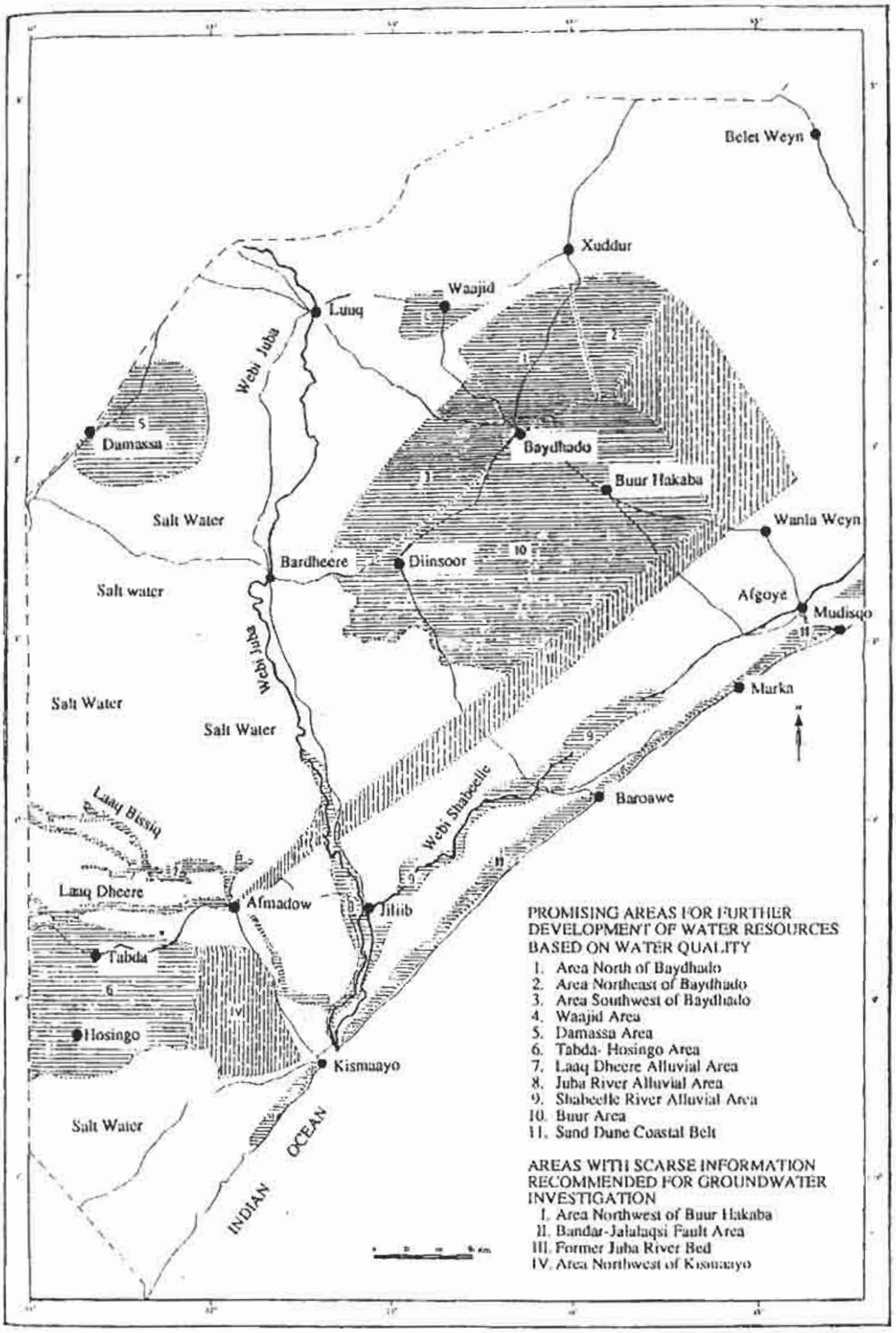
The areas proposed for these two major programs are shown in Fig. 1. The areas not included in these programs are those which either have sufficient information and additional investigation is not needed, or those where ground water is either salty or of marginal quality making the probabilities of success minor. In the latter areas rain harvesting, run-off water, and impounding of local shallow aquifers could be the solution. The selected areas are briefly described below.

Areas with Proven Good Conditions for Ground water Development

Area No. 1: Baydhabo Plateau - Area North of Baydhabo

In this area there are records of 15 drilled wells which have water with a low salt content, with E.C. values ranging from 650 micro mhos/cm in Tagaal to 2250 micro mhos/cm in Goof Guduud.

Fig. 1 - Southern Somalia. Promising areas for further development of water resources based on water quality. Areas with scarce information recommended for ground water investigations.


Belet Weyn
Xuddur
Waajid
Luuq
Webi Juba
5
Damassa
2
1
Baydhado
Buur Hakaba
3
Salt Water
Wanla Weyn
Bardheere
Diinsoor
10
Salt water
Afgoye
Mudisqo
11
Marka
Salt Water
Webi Juba
Salt Water
9
Laaq Bissiq
Baroawe
Webi Shabeelle
7
Laaq Dheere
Afmadow
8
Jiliib
Tabda
6
IV
Hosingo
Kismaayo
Salt Water
INDIAN OCEAN
PROMISING AREAS FOR FURTHER DEVELOPMENT OF WATER RESOURCES BASED ON WATER QUALITY
1. Area North of Baydhado
2. Area Northeast of Baydhado
3. Area Southwest of Baydhado
4. Waajid Area
5. Damassa Area
6. Tabda- Hosingo Area
7. Laaq Dheere Alluvial Area
8. Juba River Alluvial Area
9. Shabeelle River Alluvial Area
10. Buur Area
11. Sand Dune Coastal Belt
AREAS WITH SCARSE INFORMATION RECOMMENDED FOR GROUNDWATER INVESTIGATION
I. Area Northwest of Buur Hakaba
II. Bandar-Jalalaqsi Fault Area
III. Former Juba River Bed
IV. Area Northwest of Kismaayo

Most of the wells have an E.C. lower than 1500 micro mhos/cm. Water is generally of the calcium bicarbonate type indicating that wells were drilled in an active recharge zone where water infiltrates through joints of stratification, karstic depressions, sinkholes, and fractures.

Water in this area is good and could even be used for small-scale supplementary irrigation. A detailed assessment of the ground water potential is required to plan its exploitation. Well depth should be between 100 and 150 m.

Area No. 2: Baydhabo Plateau - Area North-Northeast of Baydhabo

Information about this area comes from the wells located along the perimeter of the area. The general hydrogeological conditions are similar to those of Area No. 1. Wells have E.C. values lower than 1.700 micro mhos/cm. The central part of the area is not known as no wells have been drilled there yet; additional wells are required to assess its ground water potential. Well depth should be between 100 and 150.

Area No. 3: Baydhabo Plateau - Area Southwest of Baydhabo

Ground water quality conditions are less favourable than those of the two areas described above. The numerous recently drilled wells yield water with E.C. values ranging from 900 to 6500 micro mhos/cm. Additional wells could be drilled for rural villages and for livestock; well depth should be between 100 and 150 m.

Area No. 4: Waajid Area

The E.C. ranges from 252 micro mhos/cm in one of the drilled wells in Waajid, to 4200 micro mhos/cm in C. Xaarar.

Wells drilled in Waajid have proven that water quality is good. Several faults, folds, karst holes, and depressions affect this formation and facilitate a fast recharge. Additional wells could be drilled in this area with good prospects of finding water of good to fair quality to be used for rural villages and for watering stocks. Well depth should be between 60 and 80 m.

Area No. 5: Damassa Area

This promising area is covered by the Cambar Formation which is constituted by quartzitic sandstone and sand. The two wells drilled in this formation supply the best quality water of the entire Gedo Region, with an E.C. of 900 micro mhos/cm, and are also highly productive. One of the wells was pump tested for 28 m^3/h with a drawdown of about 54 cm. Three or four exploratory/production wells with depths between 120 and 200 m are required to assess the ground water potential of the area.

Area No. 6: Tabda-Hosingo Area

In this large area the water quality is from good to fair, with E.C. values ranging from 1700 to 5520 micro mhos/cm. Additional wells could be drilled in its central part where hydrogeological conditions appear favourable; well depth should range between 120 and 180 m.

Area No. 7: Laaq Dheere - Laaq Bissic Alluvial Area

From the available information conditions appear favourable for the construction of infiltration galleries, hand-dug wells, and shallow drilled wells along these major laaqs; depth to water is generally within 10 m and water is of good quality. A shallow ground water investigation program is recommended.

Area No. 8: The Juba River - Alluvial Area

The alluvial belt, from Dujuuma as far as Yoontay, has shallow ground water which could be tapped by hand-dug wells or shallow drilled wells. The water quality is in most cases good, with a salt content below 2 gr/l and is suitable for rural village water supplies. However, there are areas where water is much more saline, such as the area of Mana Moofi, near Jamaame, where water contains 7 to 16 gr/l of salts.

Area No. 9 Shabeelle River - Alluvial Area between Buulo Mareerta and Homboy

Water quality is generally good, especially for hand-dug wells and shallow drilled wells located close to river banks, swamps, creeks, or near wherever water stands permanently. Ground water salinity increases towards the coast, as has been proven by the results of several wells drilled along the paved road between Modun and Jiliib.

Area No. 10: Buur Area

The development of shallow aquifers for rural village water supplies and for watering livestock is possible along the major Loggas which are filled by permeable alluvial sediments. The favourable drainage network, coupled with the good recharge conditions of these aquifers, offers good possibilities of finding shallow water along the major togga beds.

Water quality varies considerably from place to place and proper well siting is required in areas where no wells presently exist.

Conditions in the Buur Area also favour the construction of surface and underground dams for storing water in the stream beds to be used for the irrigation of small areas and for the watering of livestock.

No further drilling activity should be carried out as most of the numerous boreholes were either dry or struck very salty water.

Area No. 11: Sand Dune Coastal Belt

Water quality is generally good, depending, however, on the thickness and shape of the freshwater lens which varies greatly proceeding along the coast from Muqdisho to further south. Numerous hand-dug wells are located along the coast and tap the underground water flowing towards the shoreline. Additional investigations are required to assess the potential of the freshwater lens.

AREAS WITH SCARCE INFORMATION RECOMMENDED FOR GROUND WATER INVESTIGATIONS

From general geological and hydrogeological considerations, several areas in Southern Somalia have promising conditions to store ground water in their sediments. However, available information about these areas is scarce and proper ground water investigation programs are required to assess both the qualitative and quantitative ground water conditions.

The areas which could be investigated for this purpose are briefly described below.

Area I: Area Northeast of Buur Hakaba

This large area, estimated at 6,000-7,000 km², has water of good quality between Dolondole and Tayeeglow, along whose line four wells have been drilled. In the remaining area no wells have been drilled with the exception of the well in Yaaq Bari Weyne.

The salt content of water in springs, hand-dug wells, and drilled wells along the perimeter of the area generally does not exceed 2 gr/l. A drilling exploration program is required; well depth should be between 100 and 150 m.

Area II: Area Along the Bandar-Jalalaqsi Fault

The major toggas draining the Buur Area have deposited large amounts of coarse sediments along a large belt covering this important fault. In the Guramai and Ghel Ghel Gudut boreholes these coarse sediments had a thickness of 80 and 105 m, respectively. Water was of very poor quality and they were abandoned. The results of these two boreholes, located in the eastern part of the area, however, are not conclusive for the entire area affected by this major structural fault and a ground water investigation, including drilling and geophysical works, would be required. Well depth should be between 80 and 100 m.

Area III: Former Juba River Bed

Satellite imageries show that the Juba River in the area of Bandar Jidiid deviated south-west in the past, reaching Afmadow. Its former bed is filled by sand and small gravel.

An investigation would be required by drilling a series of shallow wells with depths not exceeding 50 m.

Area IV: Area Northwest of Kismaayo

Several wells have been drilled in this area. Results have shown that there are two aquifers. The upper aquifer is generally salty while the lower aquifer has water of acceptable quality, mainly for livestock. The extension of the second aquifer is not known and a ground water investigation would be required.

To tap the second aquifer, however, appropriate drilling techniques are essential, including the use of borehole logging, appropriate well design, and proper well construction and supervision.

CENTRAL SOMALIA

INTRODUCTION

Central Somalia includes five regions: Banadir, Shabeelle Dhexe, Hiran, Galgadud and Mudug.

The area is characterized by the following main geomorphological features:

- The Shabeelle Alluvial Area, a plain with almost no slope extending down a narrow belt along the Upper Shabeelle River Valley becoming wider south of Jalalaqsi. Its elevation ranges between 200 and 100 m above sea level.
- The Upper Shabeelle Valley, characterized by low undulating hills and steep slopes topped by low escarpments.
- The gentle undulating plain along the inner side of the Coastal Belt, constituted by stabilized dunes and extending as a 50-60 km-wide band in its southern part, narrowing to 15-20 km towards the north-east in the Hobyo area.
- The Coastal Belt, including a variety of morphological features ranging from gentle slopes to very steep slopes with gulleys and drifts. Small cliffs and sand beaches border the Coastal Belt along the ocean.
- The Central Plateau, characterized by gentle micro relief with sand cover and hard caliche patches, sloping gently towards the east. The Central Plateau drops from 400 m along the disputed border to 100 m above sea level towards the coastal zone.

Rainfall varies from 200 mm/year in the northern part to 500 mm/year in the southern part.

People living in the Shabeelle Valley are dedicated to agricultural activities and livestock raising whereas in the Central Plateau people are mainly shepherds.

AREAS RECOMMENDED FOR GROUND WATER DEVELOPMENT IN CENTRAL SOMALIA

The selected areas in the Mudug-Galgadud Plateau and in the Middle and Upper Shabeelle Valley, where it is possible to further develop the shallow and deep aquifers by appropriate well design, are shown in Fig. 2; they are briefly described ahead.

This study has also identified areas with high salinity. Deep wells in two large areas of the Central Rangelands struck very saline water unsuitable for people and livestock. The first is a large area located in the central part of the Mudug-Galgadud Plateau. It extends in a NE-SW direction for about 280 km, from near Xingood to about 20 km north-east of Ceel Buur. Its width ranges approximately from 40 to 100 km. In this area there are several hand-dug wells located along the ancestral drainage system which yield water of fair to marginal quality. Here it is more appropriate to develop the shallow aquifer and to abandon any further attempts of drilling other deep wells.

The second saline area extends along the Coastal Belt from Gal Tardo to Maracaasho, near Xarardheere.

Fig. 2 also shows areas with ground water ranging from marginal to brackish.

MUDUG-GALGADUD PLATEAU - DEEP AQUIFER DEVELOPMENT

Area No. 1: Southwestern Side of the Mudug-Galgadud Plateau

The Yasoomman Formation, constituted by red sand and sandstone, covers a large 30 to 60 km-wide belt along the western side of the Mudug-Galgadud basin. Ground water is one of the best in Somalia due to its low salt content. Water levels vary from 140 m in Teddan, located not far from the Yasoomman escarpment, to 45 m in Guri Ceel. Well depths should therefore range from 100 m to 220 m according to the position of the well site. Well production is expected to be good.

Area No. 2: Border Belt Between Balanbaal and Buur Yaqab

This area is one of the main recharge zones of the Mudug-Galgadud artesian basin and wells yield water of good quality. Water is under unconfined conditions in most cases, with levels varying between 75 m in the area of Caabudwaaq and 150 m in the area of Buur Yaqab. Proper well depth, proceeding south-west to north-east along the border belt, should range between 120 and 250 m.

Area No. 3: Dhuusamarreeb - Gaalkacyo - Balli Busle

There are several aquifers in this large area filled by sandy clay, gypsum, gypsiferous clay, sandy limestone, limestone, and marls. The vertical and horizontal lithological changes create a variety of hydraulic conditions in the water-bearing layers and cause considerable water quality variations both laterally and vertically, ranging from fair to marginal. Water of good to fair quality is generally found in the deeper aquifer; well depth should range from 150 to 200 m. Basalt intercalations should be fully penetrated so as to tap the underlying confined aquifers.

Area No. 4: Dhuusamarreeb - Ceel Buur Artesian Sub-Basin

This is the most interesting and important area Central Somalia due to the high artesian pressure of confined aquifer, its good water quality, and the production of

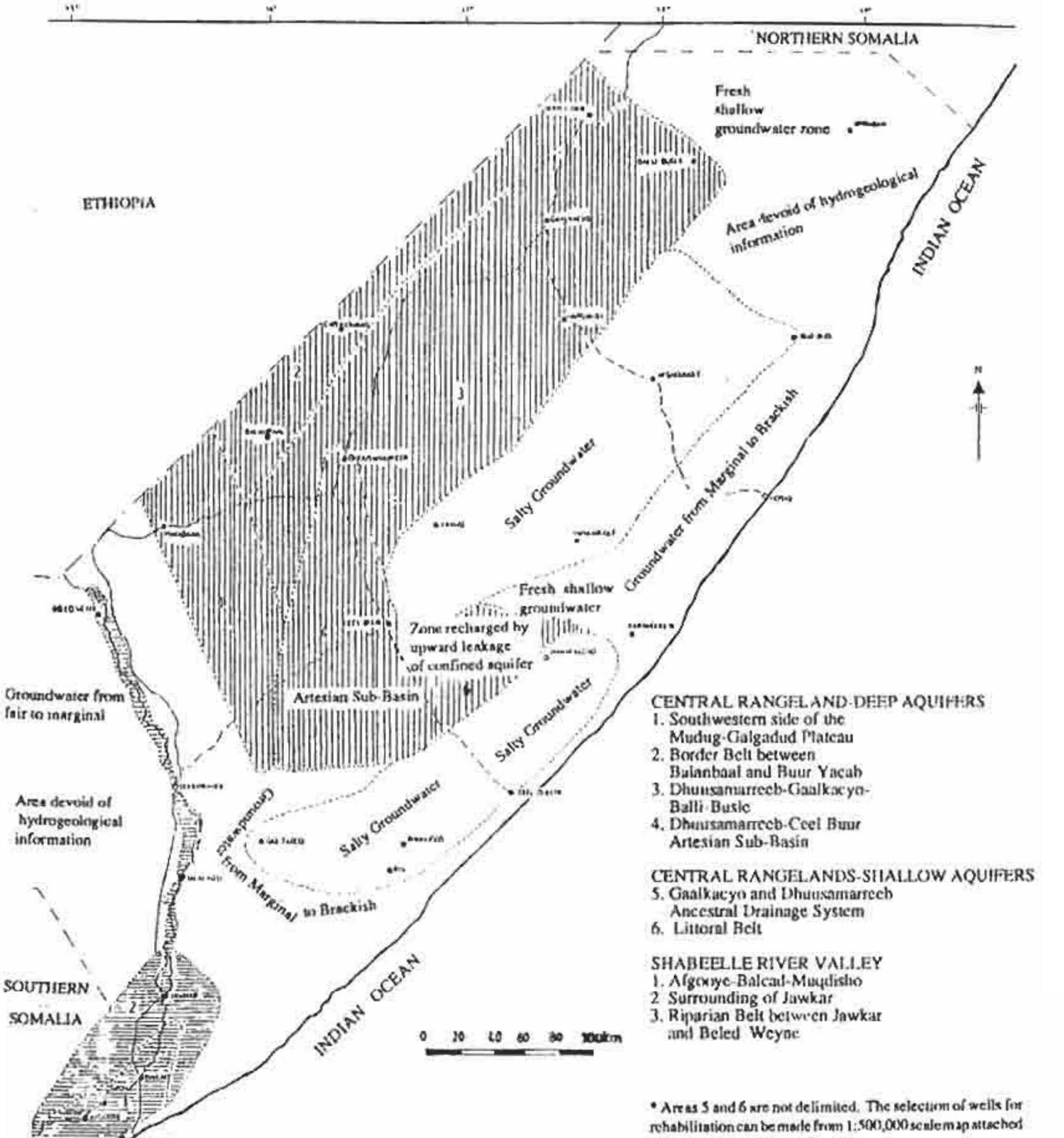


Fig. 2 - Central Somalia. Promising areas for the development of water resources.

some of the existing flowing wells. The intermediate/deep aquifer in this area yields water of quality and should be disregarded. On the other hand the deep confined aquifer overlain by the basalt has a high artesian pressure and both well production and water quality are good. High-production wells like Lhose in Maxaas and Ceel Buur could be also used for small-scale irrigation of vegetable and fruit gardens if other aspects for the development of irrigated agriculture are favourable. Well depth should be between 100 and 200 m, according to well location.

MUDUG-GALGADUD PLATEAU - SHALLOW AQUIFER DEVELOPMENT

Area No. 5: Gaalkacyo and Dhuusamarreeb Ancestral Drainage Systems

The numerous shallow wells dug in karstic limestone depressions and along the Gaalkacyo and Dhuusamarreeb ancestral drainage systems and their terminal floodable areas represent between 70% and 80% of the water Mudug-Galgadud Plateau.

A program aimed at the rehabilitation of existing shallow wells and the construction of new ones in promising areas is highly recommended; well depth should range between 5 and 20 m. Since water will be used mostly by nomads, the proposed shallow aquifer development program has to take into consideration the grazing potential of the area.

COASTAL AREA

Area No. 6: Coastal Belt

Along a narrow coastal belt where the elevation does not exceed 20-25 m above sea level, ground water can be tapped by hand-dug or shallow drilled wells. Water quality varies from good to marginal. The freshwater lens is limited to a few short sections along the coast; it is generally thin, and its exploitation requires the construction of hand-dug wells and infiltration galleries. A careful management is necessary since water quality generally deteriorates with continuous withdrawals. In most cases, however, water is of poor quality but still suitable for livestock.

Shallow aquifer development requires careful planning according to the grazing potential and the delicate ecological systems of the dunal belt.

SHABEELLE RIVER VALLEY

Area No. 1: Afgooye - Balcad - Muqdisho

This area stores ground water of good quality presently used for various purposes, including irrigation and the township water supplies of Balcad and Afgooye. Well depth ranges from 80 to 120 m.

Water of good quality is also stored in the coastal belt surrounding Muqdisho and is intensively exploited for the metropolitan water supply. Well depth ranges from 80 to 200 m.

Area No. 2: Surroundings of Jawhar

In Jawhar and Afgooye the water table is close to the surface and the shallow aquifer can be tapped by hand-dug wells. Between these two localities the water table is 30-40 m deep and drilling is more appropriate.

Water quality in the alluvial area surrounding Jawhar varies from good to marginal. In Jawhar thick layers of gravel at depths between 15 and 45 m contain abundant water of good quality. Well depth ranges from 50 to 120 m.

Area No. 3: Webi Shabeelle Riparian Belt Between Jawhar and Beled Weyne

Between Jawhar and Beled Weyne ground water is found at shallow depths and can be tapped by hand-dug wells or shallow drilled wells. The water level in wells located close to the river banks is generally 5-6 m below ground; water level is deeper and water quality worsens away from the river banks. Water quality changes within short distances. Quality may improve with depth in sandy layers hydraulically connected with the Shabeelle River.

Between Jawhar and Jalalaqsi a well depth of 50-60 m should be sufficient. The alluvial deposits get thinner between Jalalaqsi and Beled Weyne, and well depth should not exceed 20 m in Beled Weyne.

NORTHERN SOMALIA

INTRODUCTION

Somalia covers the following regions: Awdal, N.W. Galbeed, Togdheer, Sanaag, Bari, Sool, and Nugal. It has a variety of morphological aspects: mountainous areas, valleys, plateaus, sloping plains, coastal hills, and dunes.

The eastern area is characterized by mountainous areas, plateaus, and valleys. The T. Nugal has deeply incised the southern part of the eastern area; it has a catchment of 70,000 km^2 and drains the Nugal Region and parts of the Togdheer and Sool regions.

The central area is marked by a high mountain range running parallel to the shore of the Gulf of Aden, incised by numerous toggas flowing towards the Gulf, forming a large plain which gently slopes southwards.

The western area is characterized by a large, gently undulated plateau delimited to the north by a mountain range. The northernmost part of the western area is constituted by the sloping plain and coastal strip which extend along a large belt.

The soil composition and the arid and semi-arid conditions of Northern Somalia are the main factors which in the past have limited agricultural development, leaving the land mainly for livestock grazing.

Soil conditions are good and agricultural activities are widespread along the riparian belts of some of the major toggas. The use of ground water for the irrigation of these alluvial strips of land has increased considerably in recent years.

The climate in the northern region ranges from very arid to semi-arid to temperate. The average yearly rainfall ranges from 50 mm along the coast to 700-800 mm in the mountain range.

AREAS RECOMMENDED FOR GROUND WATER DEVELOPMENT IN NORTHERN SOMALIA

The description of the areas identified as promising for future ground water development is subdivided into: the Coastal Belt and Sloping Plain, the Mountainous Zone, Plateaus and Valleys. The areas identified as promising are shown in Fig. 3, they are briefly described ahead.

COASTAL BELT AND SLOPING PLAIN

Area No. 1: Shallow Aquifer Development along the Coastal Belt

Along the Coastal Belt bordering the Gulf of Aden there is a continuous shallow aquifer which is recharged by the underflow of the numerous toggas draining the Mountainous Zone, by ground water flowing in alluvial deposits and other sediments of the Sloping Plain, and by the run-off water of toggas.

In places close to the shore the water table is within 2-3 m, getting deeper inland.

Shallow wells along the coast supply water of good to marginal quality used by villages, nomads, and for the irrigation of date palms. The most promising areas for ground water development are those close to or covered by inland deltas of toggas with large catchments in the Mountainous Zone.

Date palms could be cultivated nearly everywhere along the coast. Water quality is generally good for this- type of tree and in some cases is excellent.

Area No. 2: Sand-River and Alluvial Cone Aquifers Bordering the Sloping Plain

According to the hydrogeological study carried out by SOGREAH, the run-off water of the four major toggas of the north-western regions reaching the Coastal Plain amounts to 130 million m^3/year. Flowing water in major toggas is of excellent quality.

Ground water in sand rivers and alluvial cones is suitable for most purposes and could be exploited by hand-dug wells and shallow boreholes with a high expected yield.

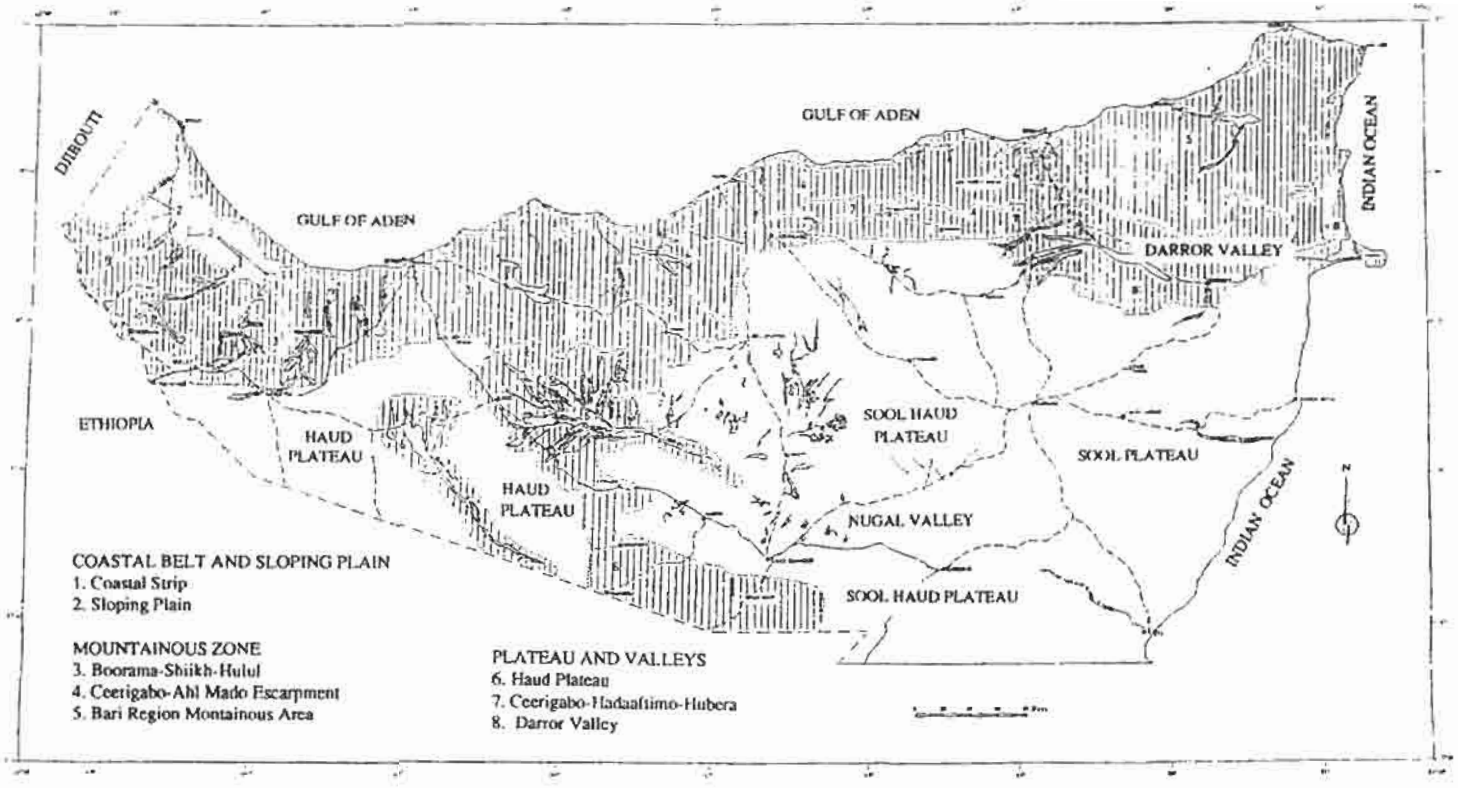


Fig. 3 - Northern Somalia. Promising areas for further development of water resources based on water quality.

MOUNTAINOUS ZONE

Area No. 3: Boorama-Shiikh-Hulul Area

This large area extends for about 500 km. It has a rather rough relief with deep valleys, steep slopes, and mountain ranges reaching about 1,800 m in elevation. Due to the large variety of rocks, the accentuated drainage network, and the rather high rainfall in the mountain range, the surface and ground water conditions of the area are altogether quite good. Several types of programs and projects could be implemented for the development of irrigated agriculture, rural village water supplies, and livestock water supply.

Conditions favor the construction of underground and surface dams in several places across major toggas and their tributaries. Infiltration galleries constructed along major toggas would considerably increase the present exploitation.

There are numerous springs issuing from different geological formations at various elevations; they are little used because water usually disappears after short distances into gravel and sand streams. Spring water is generally of good quality and could be used for most purposes.

Area No. 4: Ceerigabo-Ahl Mado Escarpment

The Mountainous Zone, with elevations higher than 1,000 m, is characterized by a pleasant mild climate. Arable land is limited due to the steep rocky slopes covered by an evergreen vegetation. Some 30-40 springs, generally yielding less than 1 l/sec of water of good quality, are located in this area. Spring water development for small irrigation is recommended for expanding the agricultural activities of the area.

Area No. 5: Bari Region Mountainous Area

Rainfall along the Coastal Belt of the Bari Region is less than 50 mm/year, increasing progressively inland towards the mountainous area of Mt. Bahaja where it may reach 500-600 mm/year.

T. Dugahan, T. Balade, and T. Merera have a permanent underflow which is presently tapped by "laas" dug in their sandy beds. In the terminal sections of toggas water is found in alluvial deposits. A large area covered by coarse alluvium extends south and south-west of Boosaaso. Ground water is presently tapped by numerous wells in the surroundings of this town.

Several springs drain the Mountainous Zone; their water disappears after short distances into coarse sediments of stream beds and recharges the alluvial aquifers filling the main valleys. Many springs are presently used for the irrigation of small gardens and palm groves.

Water quality from alluvial deposits and springs is good; therefore, the first step for the development of these water sources should be to carry out a complete inventory of the springs and to investigate the ground water potential of the alluvial deposits of major toggas. Storage of run-off water in the Mountainous Zone by constructing dams across the numerous streams seems promising and should also be considered.

PLATEAUS AND VALLEYS

Area No. 6: Haud Plateau

This undulated plain has the best grazing potential of Northern Somalia. Water resources, however, are limited and the area is often affected by droughts. The water table gets increasingly deeper from Tug Wajale towards Gumar and Salaleh; in this latter locality water was struck at 282 m.

An investigation program aimed at assessing the ground water conditions of the Bokh Valley and the Horufadhi Buuhoodle area is recommended. Boreholes with depths between 350 and 420 m should be drilled in areas selected on the basis of their hydrogeological conditions and grazing potential.

The shallow aquifers of the T. Togdheer and of the toggas located in the upper catchment of the Bokh Valley require an hydrogeological investigation, including shallow drilling. The study should assess the aquifer potential and define the type of water works most appropriate for each area. The selection and investigation of the most promising sites for impounding run-off water in open reservoirs should also be included in this study.

Area No. 7: Margin of the Sedimentary Basin in Ceerigabo, Hadaaftimo, and Huberra in the Sanaag Region

This area, covering the inland side of the escarpment along a continuous east-west belt extending from Ceerigabo to Hadaaftimo to Huberra and further east, has by far the best agricultural potential of Northeastern Somalia due to good climatic conditions and large areas covered by brown calcareous soils.

The knowledge of the hydrogeological conditions of the area is limited to information obtained from the results of the third well drilled by GTZ in Ceerigabo. This well was 195 m deep and its yield was 180 m^3/hr with only 2.43 m of draw-down, making it the highest production well in Somalia. Water is of excellent quality with a very low salt content.

Prospects for the agricultural development are good. However, soil conditions, surface and ground water resources, human resources, and grazing potential need to be properly evaluated.

Area No. 8: Darror Valley

The Darror Valley is a large elongated structural depression.

Despite its desertic aspect, the Darror Valley has considerable water resources that, if properly developed, could be sufficient to satisfy the water needs of people and livestock living in the area. A proper exploitation of the water resources could lead to small-scale irrigation of vegetable gardens and date palms.

Three potential water sources could be developed:

- The shallow aquifers along the T. Jaceyl and its tributaries containing freshwater found at shallow depths.
- The springs located in canyons of the Mountainous Zone. Water from the Ufeyn spring is only partially exploited and a proper spring intake and a larger diameter pipe are required. The springs of Ufeyn Horse (reported to yield over 30 l/sec), Igieh II, Bug Atoti, and Jassup should be properly investigated and designs for their exploitation should be prepared. The Iskushuban springs are presently used for irrigation; water availability could increase by constructing proper spring intakes, by improving the conditions of the canals, and by introducing better irrigation practices.
- Ground water along the base of the mountains delimiting the northern side of the valley. The ground water conditions of this interesting area should be investigated by drilling boreholes and carrying out geophysical surveys.

The development of the three potential water should form part of an integrated plan for the development of the natural resources of the Darror Valley.

ACKNOWLEDGMENTS

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THE NEED TO USE SIMPLE AND APPROPRIATE TECHNOLOGY TO DEVELOP THE WATER RESOURCES IN SOMALIA

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ABSTRACT

The drilling of deep water wells in Somalia in the past 30 years has solved the water problems in certain areas, while for large areas with saline or brackish groundwater it will be necessary to consider other solutions, more appropriate to local conditions. As for the rural sector, due to the high cost of drilling, operation, and maintenance, and also of fuel and spare parts, deep drilling should be restricted to those areas with favourable hydrogeological conditions where simple and low-cost technologies cannot be implemented.

Taking care of thousands of village water supply systems would require a large organization and a large financial commitment, which Somalia cannot afford. Considering the low income of the rural families and inadequate funding from the Government and donors, low-cost projects using simple technologies or improving indigenous technologies have better chances of success. The most appropriate simple water structures are:

- Hand-dug wells. They are the traditional water sources of Somalia. Their rehabilitation and protection from contamination and improving methods used to withdraw water will result in a major benefit for the health of both humans and livestock. Large areas are supplied by contaminated hand-dug wells which urgently require rehabilitation.
- Infiltration galleries. This simple water structure may be used mainly to tap the underground flow of ephemeral streams in the northern regions, as well as in the Hiran and Gedo regions.
- Underground dams. Their construction across some of the above-mentioned streams would allow storage of large amounts of water for human and livestock consumption and, in some cases, for small irrigation.
- Sand storage dams. To tap sand from flowing downstream and to create artificial aquifers sand storage can be built in areas of Southern and Northern Somalia covered by the crystalline basement. Other types of small dams are equally suitable solutions in several areas.
- Filtering of river water. It is possible to install appropriate simple intake structures along the Juba and Shabeelle rivers water pollution problem.
- Rain harvesting by water reservoirs. The improvement, from both qualitative and quantitative aspects, of the present water harvesting systems by means of reservoirs in large featureless areas where groundwater is brackish or saline is essential and may be obtained by a proper and simple design.

INTRODUCTION

Somalia is mostly an arid country with rainfall ranging from less than 50 mm/year along the northern coast to about 600 mm in the Bay Region. Rainfall is unevenly distributed and scanty in the central and northern areas. Periodic droughts have occurred during the past decades with enormous damages to the agricultural areas and livestock. The rainy seasons occur from April to June and from September to November. There are two perennial rivers: the Shabeelle and Juba; the main part of their catchments is in Ethiopia. Numerous small, medium, and large temporary streams (toggas) flow only in occasion of storms; the most sizeable toggas, however, maintain an underground flow all year.

The population of Somalia has been estimated at about 5.32 million; people living in rural areas amount to 78%; about 50% of the urban population lives in Muqdisho, and the remaining urban population lives in 69 towns each having more than 5000 inhabitants.

Statistically Somalia is considered one of the least developed countries in Africa: income is less than US$ 300 per capita per year, and it has one of the highest rates of infant mortality. Water-related diseases are recurrent and account mainly for the high rate of mortality and morbidity. Therefore, there is an urgent need to improve the water supply situation of the country.

The development of water resources in a country like Somalia, where the population is scattered and where distances are enormous, requires a large financial investment which nowadays can only be afforded by some of the oil-exporting countries. For the Water Decade Planning it has been estimated that the investment cost for 100% coverage of the whole Somali population with water supply and sanitation facilities would amount to US$ 1400 million. The adopted alternative with partial coverage amounts to US$ 500 million; the recurrent costs for the sector total to about US$ 100 million. With this large financial effort it would be possible to have a good distribution of water points to meet the needs of the population and to create indispensable conditions for the implementation of programs and projects which may lead to improved health conditions for people and livestock and towards economic self-sufficiency.

However, the preparation of such projects requires good knowledge of the hydrogeological conditions of the country. In recent years several studies and investigations have been carried out and a country-wide hydrogeological and water quality study of Somalia has just been completed. This study will be a basic document for future water resource planning as it has identified 32 promising areas, some for further development of groundwater resources, others for groundwater exploration programs. In outline of the methodologies and results obtained by this study is presented by the author in a separate paper to this congress.

APPROPRIATE TECHNOLOGY FOR THE WATER SUPPLY OF THE RURAL POPULATION

With a view to alleviate the pressing water needs of men and livestock great importance has been given in Somalia to groundwater use in the past 30 years by drilling water wells.

Drilling results, however, have been disappointing in large areas for the following reasons;

- the excessive salinity of groundwater, which is often unsuitable for humans and livestock;
- the depth of the water table, which in many places exceeds 250 m;
- the high cost of drilling and pumps;
- the difficulty of maintaining and operating deep wells;
- the high cost of fuel consumption and for covering large distances from the centres of supply; even higher costs are required for wells drilled in areas where grazing lasts only a few months, mainly during and right after the rainy seasons;
- shortage of skilled workers to carry out minor repairs directly at the well sites.

In addition to these problems the following difficulties are quite frequent:

- the use of inappropriate equipment.
- The installation of pumps inappropriate to well characteristics. Available pumps are usually those received from donors and therefore the proper selection is not always possible.
- The lack of spare parts; spare parts are not easily available and local mechanics hardly have the time to get acquainted with the broken pump, so the installation of a new pump may be thought the easiest solution. It is very difficult to solve this problem because donor countries bring in their own equipment and are not interested in standardizing equipment.
- The fuel shortage. The recurrent unavailability of fuel has been another impediment in recent years to the normal operation of drilled wells in Somalia.

In spite of these considerations, however, drilling activities are necessary in some areas for both rural and urban populations and surely will continue to constitute one of the major burdens on the budget funds allocated by the Somali Government in its efforts to develop the water resources of the country. as to the rural water sector, deep drilling should be restricted to those areas with favourable hydrogeological conditions, with large agricultural and grazing potential, and mainly where less expensive technologies cannot be implemented.

THE IMPORTANCE OF CHOOSING SIMPLE, LOW-COST TECHNOLOGIES

There are 5300 registered villages in Somalia with a population of less than 5000 people. Nomadic people are attached to these villages and to towns.

Considering the low income of the rural families and the inadequate funding from the government and donors, low-cost projects using simple technology or improving indigenous technologies have better chances of success. The chosen simple technology has to have a low operation cost and has to be easy to repair.

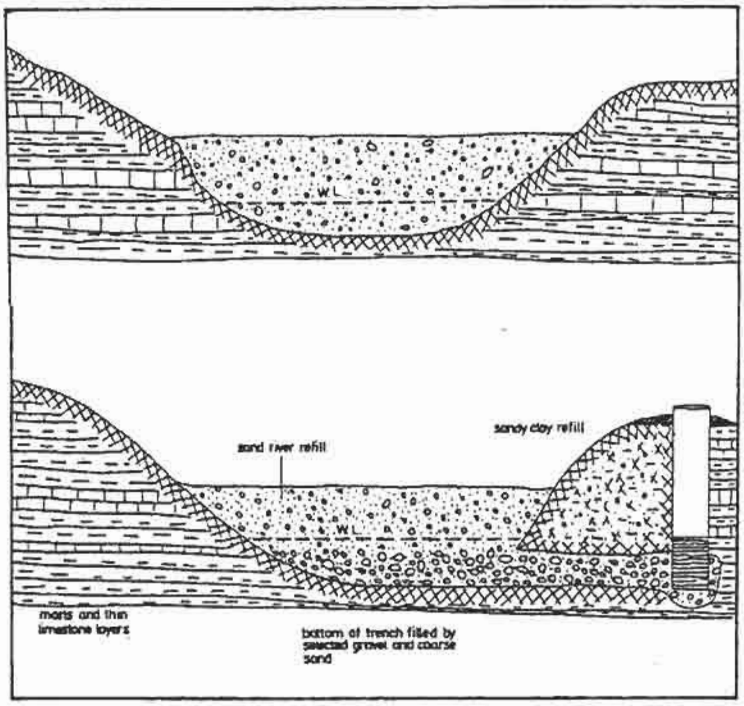

Fig. 1 - Ephemeral river with underflow. Hand-dug well tapping the underflow of an ephemeral river.

THE SELECTION OF THE WATER SOURCE AND AN APPROPRIATE WATER SYSTEM DESIGN

The selection of the water source depends on the quantity and quality of water available, its dependability, population distribution, cost, acceptance by the government and the users, operation and maintenance requirements, power availability, community participation, and other factors.

It is worth mentioning that, if the existing water supply meets the needs of the village, the easiest and most acceptable solution is to rehabilitate and protect the water sources from pollution; the installation of pumps and public taps will be a major improvement.

There is a large amount of information on simple, low-cost technology implemented in developing countries. Some of the simple technologies that could be applied in Somalia are briefly described ahead.

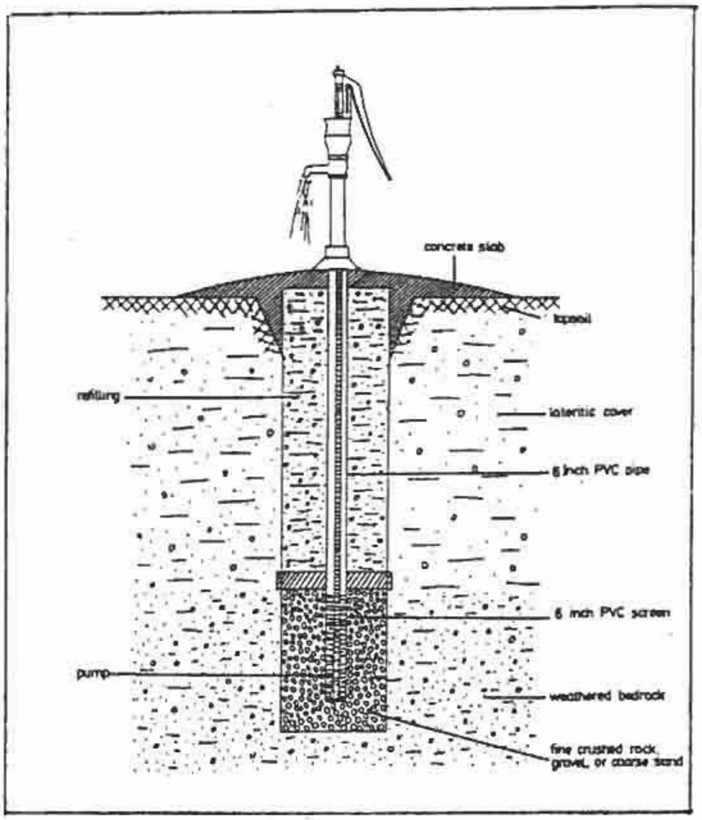

Fig. 2 - Backfilled well.

HAND-DUG WELLS AND INFILTRATION GALLERIES

Hand-dug wells are the traditional water sources of Somalia and much more attention should be given to their rehabilitation by protecting them from contamination and by improving the methods used to withdraw water.

As is well known, there are many types of hand-dug wells, some of which may be quite deep. In Muqdisho it is not unusual to find hand-dug wells 60 to 65 m deep; they are generally lined and equipped with electric pumps.

There are between 3000 to 4000 hand-dug wells in the country, most of which are contaminated and in need of rehabilitation; they are the main cause of water-borne diseases.

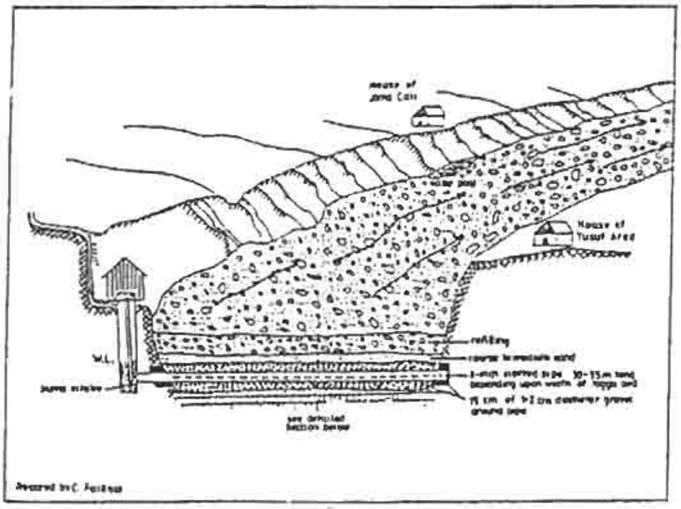

Fig. 3 - Sketch of the proposed infiltration gallery of Togga Laas Caanood.

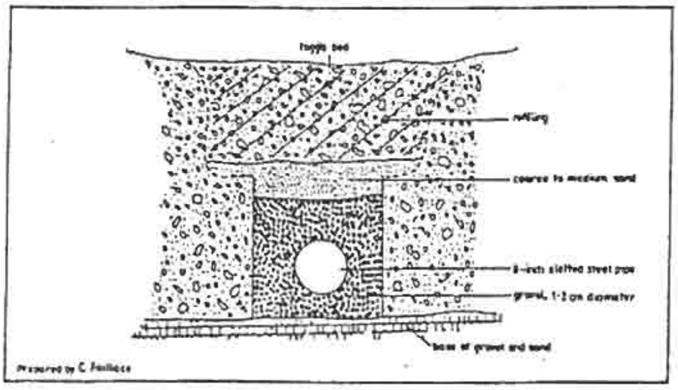

Fig. 3a - Detail cross-section of the infiltration gallery.

Compared with the size of the country, the zone offering favourable conditions for the construction of hand-dug wells are rather limited. The most promising are the following:

- coastal dune belt. The best conditions for manual digging of wells are from 1-20 m above sea level;
- sand river beds and alluvial belts. The numerous large temporary streams inciding the northern regions, Bari, Hiran, Bay and Gedo regions have an underground flow in their sandy beds which is scarcely or inefficiently used by local population;
- riparian belt of Shabeelle and Juba rivers;
- scattered areas in Mudug and Galgadud regions; mainly along depressions forming ancestral drainage systems;
- Ceerigabo Plateau . The numerous karstic depressions store water at shallow depth partly tapped by numerous hand-dug wells;
- Area along the border between Fer-Fer and Dolow. Shallow water exists in many depressions in gypsiferous rocks with relatively low salt content.

Wells located in the beds of ephemeral streams are subject to floods. A simple method to tap the underflow of the ephemeral streams in Somalia is shown in Fig. 1.

Fig. 2 shows a backfilled well which could be adopted in many large villages where a qualified person can take care of the installed pump.

Infiltration galleries in stream beds are simple structures which can be constructed with the participation of the users. They tap the underground flow of ephemeral

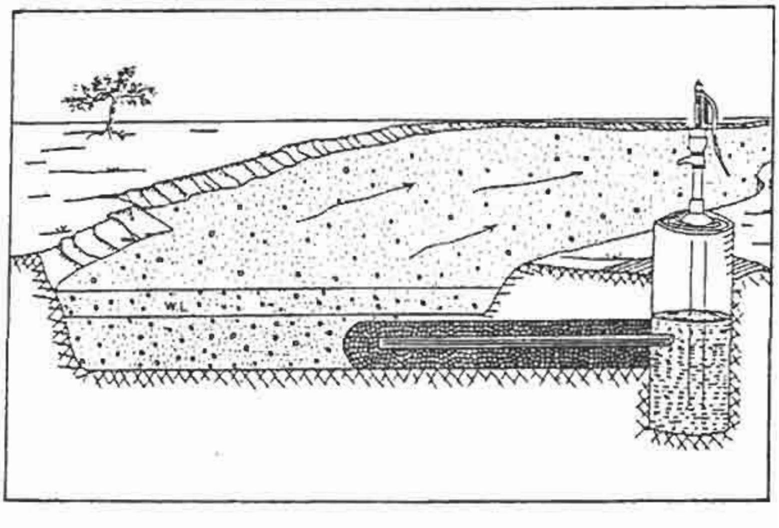

Fig. 4 - Infiltration gallery with collector well in the refugee camp in Northwest Somalia.

streams. Fig. 3 shows the design of an infiltration gallery proposed for the town of Laas Caanood.

Several infiltration galleries have been constructed for some refugee camps in the north-western regions of Somalia since 1980 and during the British Administration; see Fig. 4. This type of infiltration gallery could be replicated in other areas incised by large streams.

SAND STORAGE DAMS

Small sand storage dams may store precious amounts of freshwater to be used by people and livestock. In drought-prone areas they can be built as water reservoirs to be used during critical periods. If the water level is kept at about 1 m below the sand surface the reservoir is practically not affected by evaporation. Sand storage dams are generally constructed across temporary streams to stop the sand from flowing downstream, storing it behind the dam. The dam is built in stages, increasing

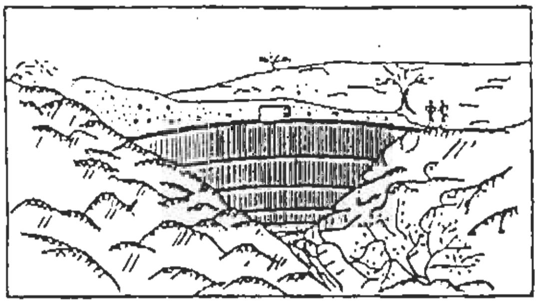

Fig. 5 - Concrete sand storage dam in Southwest Africa. (Source: O. WIPPLINGER).

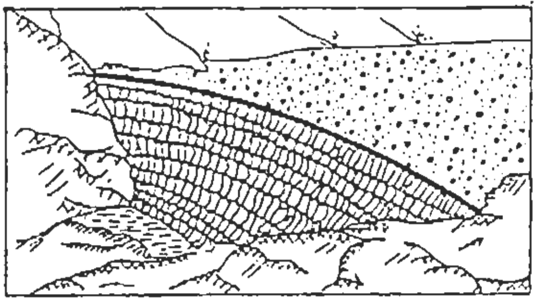

Fig. 6 - Mortar sand storage dam in Southwest Africa. (Source: O. WIPPLINGER).

progressively in height according to the geomorphological conditions of the selected site and the amount of sand transported by the stream during flash floods. The areas of southern and northern Somalia covered by the crystalline basement are the most suitable for the construction of this type of structure.

Figs. 5 and 6 show two types of sand storage dams in Southwest Africa which could be built across temporary streams in the Northern Somalia and in the Buur Area. Fig. 7 shows a favourable situation for the construction of sand storage dams in Yaaq Braawe.

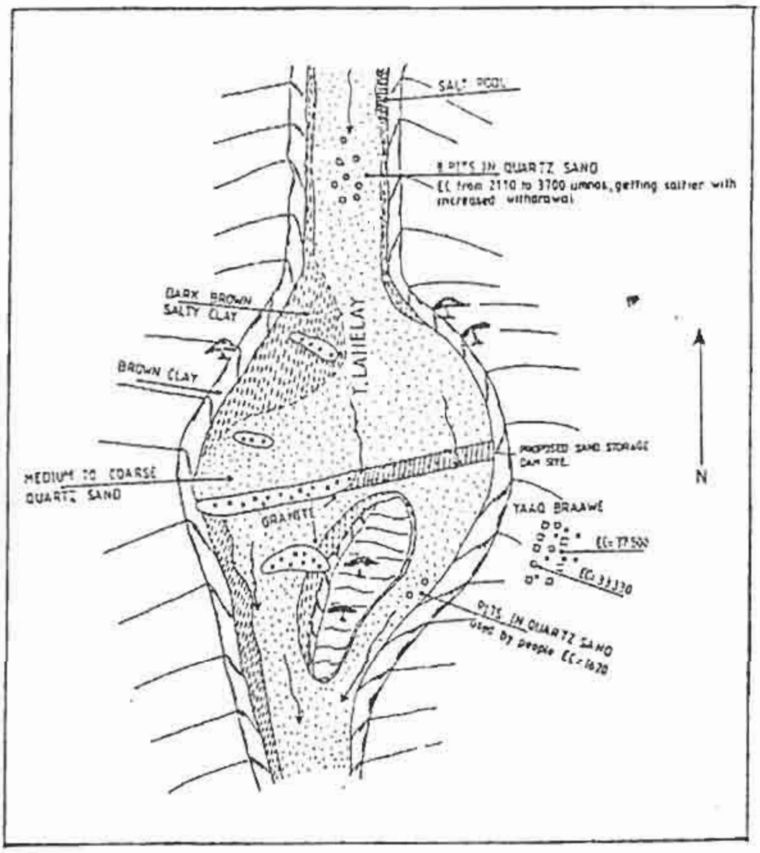

Fig. 7 - Sketch of Yaaq Braawe and T-Lahelay (not to scale).

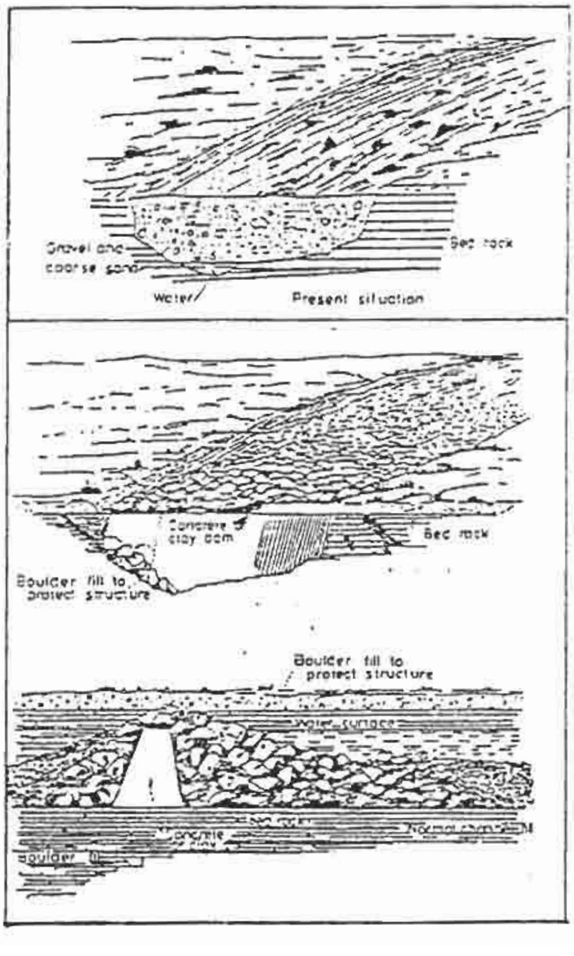

Fig. 8 - Type of underground dam of Toggas in the Northern mountainous area. Hiran, Bay and Gedo regions.

UNDERGROUND DAMS

In numerous temporary streams filled by sand and gravel considerable amounts of water could be stored by constructing underground dams, thus creating artificial aquifers, as for the storage dams.

Some of these streams have seasonal water stored in permeable sediments which are actively recharged during floods. The type of dam suitable for many toggas in Northern Somalia and in the Hiran and Gedo regions is shown in Fig. 8. Other types

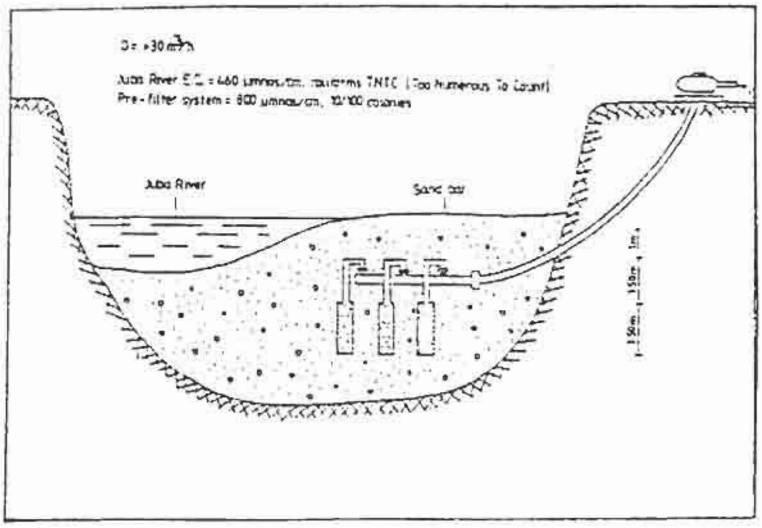

Fig. 9 - Pre-filter installation in Halba Refugee Camp (Source: H. HARTUNG. Elaborated by C. FAILLACE).

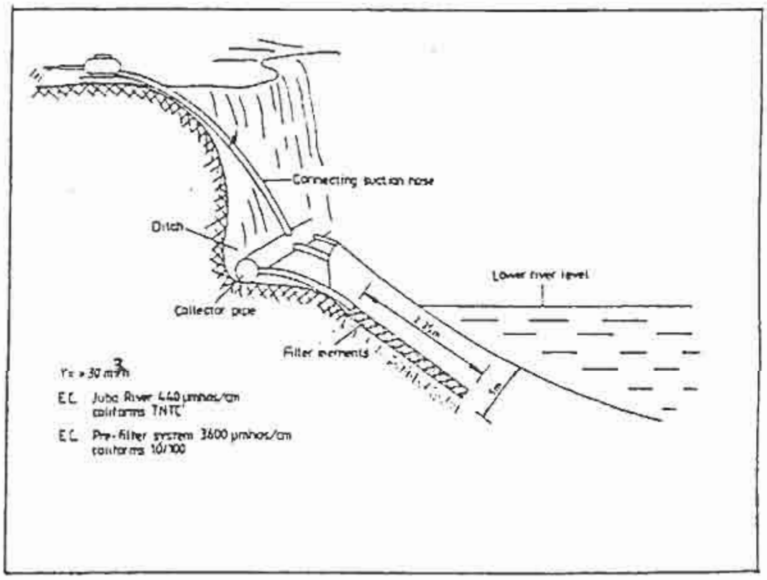

Fig. 10 - Pre-filter system in Ali Matam. (Source: H. HARTUNG. Elaborated by C. FAILLACE).

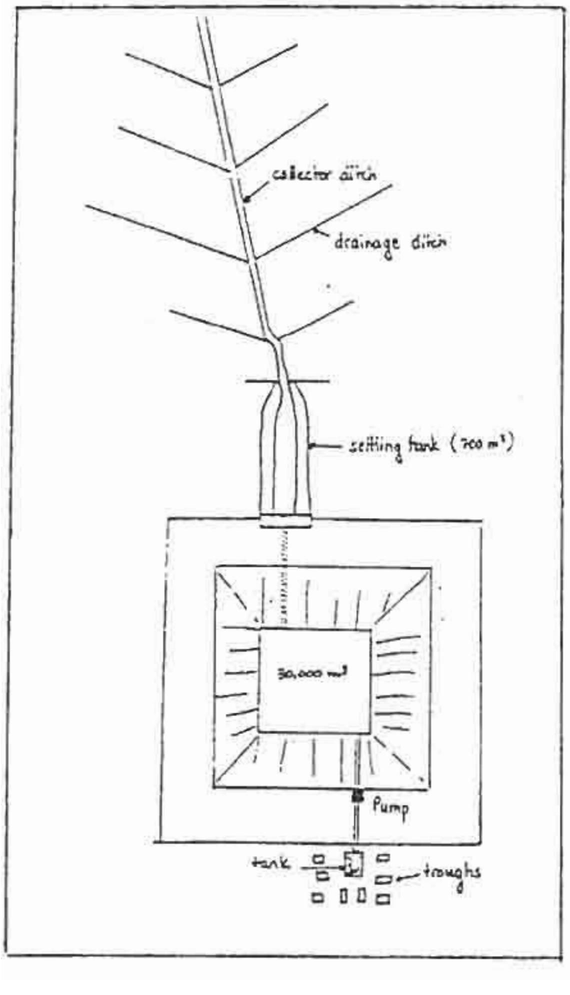

Fig. 11 - Large reservoir constructed in Southern Somalia for rain harvesting.

of underground dams could be equally suitable. Water could be also used for small farm irrigation along riparian belts.

OTHER TYPES OF DAMS

Whenever possible, consideration should be given to the construction of small surface dams for village water supplies, should the above mentioned solutions be unsuitable. This type of dam, (masonry, clay, or concrete), will depend upon the geomorphological conditions of the area, the availability of local material, and the costs involved. Water stored behind the dam, however, requires treatment.

PRE-FILTERING RIVER WATER

For the water supply of refugee camps along the Juba and the Shabeelle rivers a simple method for purifying river water has been adopted. The installation of filters in sand banks or in sand layers hydraulically connected with the rivers has been experimented in several refugee camps; results were good with the elimination of turbidity and a drastic reduction of coliforms. Small-diameter test holes are drilled by jet drilling or auger drilling to check the water quality and the thickness of permeable layers hydraulically connected with the river, then filters connected with a pumping system are installed.

Figs. 9 and 10 show the installation of two pre-filtering systems in refugee camps along the Juba River in Somalia where groundwater from drilled wells was salty.

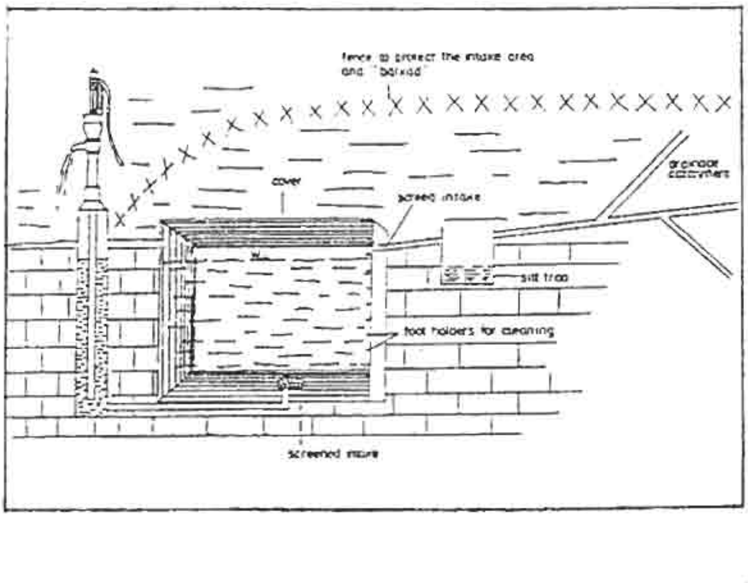

Fig. 12 - Sketch of an improved "Barkad" and of its intake and water distribution (Source: L B I).

RAIN HARVESTING

BALLEYS AND WARS

Two major water harvesting methods are practised in the rural areas using ground catchments for collecting run-off water. The first impounds water in open reservoirs called "balleys" or "wars" and the second stores water in underground reservoirs called "barkads".

Balleys are generally natural depressions which receive run-off water from nearby land drainage; they vary in size according to topographic conditions. Balleys are used in Somalia since ancient times.

Traditional wars are artificial reservoirs created mainly in featureless plains to collect rainwater by means of ditches. Their shape varies from square to round. The old wars are dug using primitive tools and are, in most cases, very small and used for small communities. Maintenance of wars is generally carried out by women and children. Because of the high rate of evaporation most of these wars dry up towards the end of the dry season and the people are compelled to move close to a permanent water point.

A modern large reservoir constructed by E.E.C. is shown in Fig. 11.

BARKADS

Barkads are small underground reservoirs generally lined with water-proof masonry walls. Each barkad impounds only the water required for a family or a few families; their capacity varies from 30 to 1,000 cubic meters. In most cases they are covered with branches and other shading devices which reduce the evaporation. They are used mainly during the dry season.

A small settling basin is generally constructed close to the inlet of the barkad. Sanitary conditions are very poor since the catchment areas of the barkads are not protected and run-off water carries animal dung and other pollutants into these reservoirs. This simple system of storing run-off water was introduced by the Italians during the war and was rapidly adopted especially along the disputed border. These small reservoirs could be easily improved to prevent contamination and reduce evaporation. A proposal for improvement is shown in Fig. 12.

These are some of the simple technologies which could be implemented in Somalia. There is no doubt that other equally simple technologies could be adopted to tap the numerous springs or to recharge the shallow aquifers.

COMMUNITY PARTICIPATION

As stressed earlier, taking care of thousands of village water supply systems would require a very large organization and a large financial input which Somalia cannot afford. State water organizations, however, should make all possible efforts to give technical guidance in designing and constructing water works and should provide regional maintenance workshops offering periodical training courses for water supply system operators and pump repair mechanics to be selected directly from villages. Community participation, to be established through village water committees, is essential during the various phases of the rural water system implementation.

At this point it is important to mention that we are talking of small communities with 100 to 2000 inhabitants. It is mainly within this range that we can consider the use of those technologies which should be implemented by simple methods and with the participation of the villagers. Their participation is essential because if villagers do not agree or are not informed on the proposed scheme and their contribution is not requested they will not take proper care of it as they will not consider the new water system to belong to them and therefore operation and maintenance will be considered the responsibility of the government. Furthermore, women's acceptance of the water site is very important since for them it may mean a new meeting place.

CONCLUSIONS AND PROSPECTS FOR FUTURE WATER DEVELOPMENT

1. In spite of the fact that Somalia is mostly an arid country, conditions are usually favourable for the development of its scarce surface and shallow groundwater resources by means of appropriate and low-cost technology.
2. Deep drilled wells, which are very costly to construct and maintain, should be restricted to large villages and urban towns having favourable hydrogeological conditions. For the rural sector, deep drilling is justified only in areas with large agricultural and grazing potential and where conditions are not favourable for cheaper technologies.
3. The traditional small reservoirs, "wars", are usually unreliable because they may dry up during prolonged droughts. The rehabilitation of traditional wars by proper deepening and lining will assure a permanent water supply and thus prevent people from abandoning villages and grazing areas during the dry months.
4. "Barkads" have proven to be valuable small sources of water for many small settlements, especially in some of the northern regions. Most of them have been constructed by the private sector. This method of storing water could be improved and introduced in other areas of Somalia.
5. Conditions are favourable in large areas for the implementation of a successful hand dug well rehabilitation and construction program. The most important areas are: the coastal dune belt, the main sand river beds and their alluvial plains, the Ceerigabo Plateau, some areas in the Mudug and Galgadud regions, along the disputed border between Fer-Fer and Dolow.
6. Sanitary conditions of wars, balleys, barkads, and hand-dug wells are generally very poor mainly because they are unprotected from pollution. As people are little aware of the dangers of water-related diseases, a strong village health program is required.
7. Conditions are favourable for developing surface and sand storage water reservoirs by means of surface and underground dams with consequent benefits for large areas

which presently suffer from acute water shortages. Numerous small dams could be constructed in the Bari Region, the northern regions, the Hiran Region, the Bay region, and the Gedo Region. Water stored in sand reservoirs would then be tapped by hand-dug wells and infiltration galleries.

8. It is estimated that there are well over 400 natural springs in Somalia; their utilization is, however, negligible as in many cases most of the water disappears in boulders and gravel at short distances from the source. In some cases spring water is presently used for the irrigation of small plots and for watering livestock. A better utilization of this cheap valuable water source could bring considerable benefits to numerous settlements and nomads.
9. The Water Development Agency is presently engaged in drilling deep water wells for rural areas and urban towns. There is a need to strengthen its technical capability and expand its activity towards appropriate and low-cost technologies.

Final editing, January 1990

From *Geology and mineral resources of Somalia and surrounding regions*, Ist. Agron. Oltremare, Firenze, Relaz. e Monogr. 113, 649-664, 1993.

HYDROGEOLOGICAL IMPORTANCE OF THE SUB-SURFACE BASALTS IN THE MUDUG-GALGADUD PLATEAU

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ABSTRACT

Basalt outcrops are not reported in Central Somalia. The scattered basalt outcrops in the Ogaden (located close to the border) and the basalt intercalations struck in water wells in the Mudug and Galgadud regions indicate that the lava flow may have followed three main directions. The sub-surface basalt thickness varies from a few meters to 60-70 m.

The basalt acts as a main confining bed for large areas in Central Somalia. The confined aquifer with low to medium artesian pressure occurs mainly in the middle part of the basin from Dhuusamarreeb to Gaalkacyo. In the lower part of the basin, mainly in the area surrounding Ceel Buur, aquifers confined by the thick basalt sequence have a strong artesian pressure and several wells are flowing.

Prospects of groundwater development of the artesian basin by deep drilling are promising from both qualitative and quantitative aspects. High production wells could be drilled in a large area near Dhuusamarreeb and Ceel Buur for livestock watering and for irrigated agriculture. Knowledge of the recharge, underflow, and discharge zones of the artesian basin and its groundwater potential are limited; therefore, before planning any intensive development of this confined aquifer a proper groundwater investigation is essential.

OCCURRENCE OF BASALT IN CENTRAL SOMALIA

In the upper Shabeelle Valley, basalt outcrops in several areas; the largest, about 70 km long, covers the area of Bugda Caqable and Buur Weyn in the Hiran Region. Two small outcrops are located south of Buur Weyn.

According to BARBIERI and others (BARBIERI et al., 1979), the augitic basalts of Buur Weyn "have to be considered in a special manner since they indicate that volcanic activity in Somalia started during the Cretaceous, and not exclusively during Cenozoic as previously considered." This was indicated by the presence of 10% of volcanic fragments in the upper part of the Mustaxiil limestone from a quarry 30 km south of Buulobarde.

The cited work of BARBIERI and others, and the study of POZZI and others (POZZI et al., 1975), report that basalts were met in the Dhuusamarreeb oil well no. 1. POZZI in particular refers that, "when drilling oil well no. 1 of Dhusa Mareeb the Auradu Formation was encountered at depths ranging from 120 m to about 350 m; the basalt with the Yasoomman sandstone are shown at an approximate depth of 500 m."

Basalt outcrops are found in the Ogaden and are, according to W.O. CLIFT (CLIFT, 1956), intercalated in the Auradu Formation. He states that the lithological sequence in Eastern Ogaden encloses a clastic interval and a basalt flow of the Auradu. The exact localities where this sequence outcrops are not indicated. According to CLIFT, "this lithological unit is equivalent to RUGGERI lower Auradu and WYLLIE Auradu Limestone of the Auradu series."

The age of the olivine basalts of Buur Duldir (Shabeelle Valley) is attributed by BARBIERI to volcanic cycles which occurred during the Cenozoic; in particular, the basalt covering the top of the Buur Makadhuuf should be of Oligocene or younger age since it overlies a sandstone horizon of probable Oligocene age.

A more recent age determination of the basalt encountered in a water well drilled near the village of Xananbur (Bangheelle area) northwest of Dhuusamarreeb is reported by POZZI (1984, 1985). According to the results of the K/Ar age determination carried out at Berne University, the basalt of Bangheelle has an age of 25.3 ± 0.4 m.y., and therefore it was deposited during the Oligocene. Several water wells have encountered basalts at various depths in Central Somalia with thicknesses varying from a few meters to 60-70 m. Basalt was found at depths of 78-82 m in a Gaalkacyo well. Gravel, sand, and fragments of basalt were found in the same well at the depths of 44-66 m, 120-177 m, 185-192 m, and 206-208 m, with a percentage varying from 10 to 50%. The lowermost basalt pebble layer (40% basalt pebbles) was found between 206 and 208 m in what is believed to be the Taleex Formation.

The lithological sequence of the Gaalkacyo well helps to understand the overall conditions prevailing during the Tertiary in Central Somalia; it is reported in another paper presented by Faillace in this congress.

Tertiary-Quaternary basalts were reported in various localities in the Upper Shabeelle Valley by BARBIERI and others. One of the longest lava flows covers a Pliocene-Pleistocene deposit of silicified plants near Bugda Caqable.

From the references indicated above, the age of the basalt found in the Ogaden, in the upper part of the Shabeelle Valley, and in several wells in the Mudug and Galgadud regions is not the same but extends from Cretaceous to Pliocene-Pleistocene. The reconstruction of the sequence of volcanic events in Somalia will require additional K/Ar age determinations and paleontological studies of the sediments overlying and underlying the lava flows. The age determination of the Bangheelle basalt is a good starting point in this direction but, until new data are collected, it cannot be considered to represent the age of all the lava flows which may have occurred in these regions.

WATER WELLS IN MUDUG AND GALGADUD WITH BASALT INTERCALATIONS

Basalt outcrops are not reported in Central Somalia. Several small outcrops can be seen in the Ogaden from the satellite imagery; they are scattered along a NW-SE

Table 1 - Water wells and exploratory wells in the Mudug and Galgadud regions which have penetrated Basalt.

Well Name	Coordinates	Elev. (m)	Depth (m)	Basalt Intercalat. From-To (m)
ARCO 1	4°33'00"/46°33'30"	140?	256	159 - 173
				210 - 217
ARCO 2	4°33'00"/46°33'30"	140?	246	132 - 166
				166 - 170
Bangheelle	5°55'20"/46°22'50"	316	70	50 - 70
Caddo Kibiir	5°40'00"/46°51'00"	250	227	202 - 227
Ceel Buur 1	4°41'30"/46°37'00"	150	220	103 - 166
Ceel Buur 2	4°41'30"/46°37'00"	150	217	100 - 166
Dadle	5°20'40"/46°59'00"	168	105?	65 - 105
Dabad 1	6°24'00"/47°29'00"	232	125	57 - 82
				82 - 100
Doholey 1	6°06'00"/46°59'00"		171	125 - 166
Doholey 1	6°06'00"/46°59'00"		241	140 - 160
Dhuusamarreeb I	5°33'00"/46°24'00"	250	200	87 - 110
En Dibirre (oil)	5°29'45"/47°08'23"			
Gadon	5°41'30"/46°41'40"	256.4	240	110 - 170
Godinlabe	5°52'50"/46°37'50"	274	202	90 - 116
Gaalkacyo	6°46'00"/47°26'00"	286	316	78 - 80
Gaalkacyo I	6°46'00"/47°26'00"	285	195	27 - 36
Gaalkacyo II	6°46'00"/47°26'00"	285	204	27 - 36
Quracley	5°03'20"/47°11'40"		230	170 - 202
				215 - 230
SOARMICO	5°28'00"/46°28'00"	240	>150	90 ->150
Ubadheere	3°37'00"/46°26'00"	165	147	120 - 123
Wargaloh	6°15'40"/47°31'10"	209	252	170 - 200
				200 - 228
Warsho	6°02'00"/46°19'00"		335	20 - ?
Xananbur	5°44'00"/46°15'00"	375?	75	14 - 60

direction, (Fig. 1). The basalt close to the border probably overlies the Auradu limestone.

The basalt outcropping in the Ogaden and that found in water wells in the Mudug and Galgadud regions indicate that the lava flow may have followed three main directions. Along the Warsho-Dhuusamarreeb-Ceel Buur depression, basalt depth increases progressively from 20 m in Warsho, to about 87 m in Dhuusamarreeb, to 103 m in Ceel Buur, and to 159 m in the well. Along the Warsho-Godinlabe-Quracley direction, basalt depth increases progressively from 20 m in Warsho, to 50 m in Bangheelle, to 90 m in Godinlabe, to 130 m in Cadon, and to 172 m in Quracley. Along the Gaalkacyo-Wargaloh direction, basalt was found at depths of 78 m in Gaalkacyo, 57 m in the Dabad well, and 108 m in Wargaloh. The thickness varies from a few meters to 60-70 m. Two basalt layers were found in the ARCO wells; the first was penetrated from 159 to 177 m and the second from 210 to 217 m. The well in Quracley struck basalt from 170 to 200 m, followed by grey calcareous clay from 200 to 218 m; basalt was struck again from 218 to 230 m. This well was abandoned because of the very low yield of the soft sediments and the high salinity of water (16000 micromhos/cm) which was struck at 170 m. The basalt was not fully penetrated; it resulted waterless. In the exploratory well drilled by SOARMICO, located 13 km southeast of Dhuusamarreeb, the basalt was struck at 90 m, and at 150 m had not yet been fully penetrated. Details of the basalt thickness encountered in various water wells are given in Table l; the sub-surface distribution of the basalt in the Mudug-Galgadud Plateau is shown in Fig. 1.

HYDRAULIC MODEL

The hydrogeological importance of the sub-surface basalt and the prospects for the groundwater development in the Mudug-Galgadud Plateau are summarized in the following pages.

A continuous phreatic aquifer extends throughout the western and north-western part of the Mudug-Galgadud basin. It consists of sand and sandstone of the Yasoomman Formation and limestone with intercalations of marls of the lower part of the undifferentiated Oligocene-Miocene sediments. This single aquifer, from west to east and from north to south, is gradually replaced by a series of water-bearing layers which are separated by clay layers and by a thick sequence of impervious basalt sill which is found at increasing depth and increasing thickness towards the centre of the basin; see Fig. 1 and Fig. 2. The basalt acts as the main confining bed for a large area in the central part of the basin. The confined aquifers with low to medium artesian pressure occur mainly in the middle part of the basin from Dhuusamarreeb to Gaalkacyo and further northeast toward Balli Busle, along an approximately 100 Km-wide belt. In this area wells have shown to have multi-piezometric levels. As an example, three wells drilled in Gaalkacyo with depths of 106, 180, and 316 m had water levels at 48, 70, and 50 m, respectively. The shallow perched water table in Gaalkacyo lies between 6 and 10 m deep.

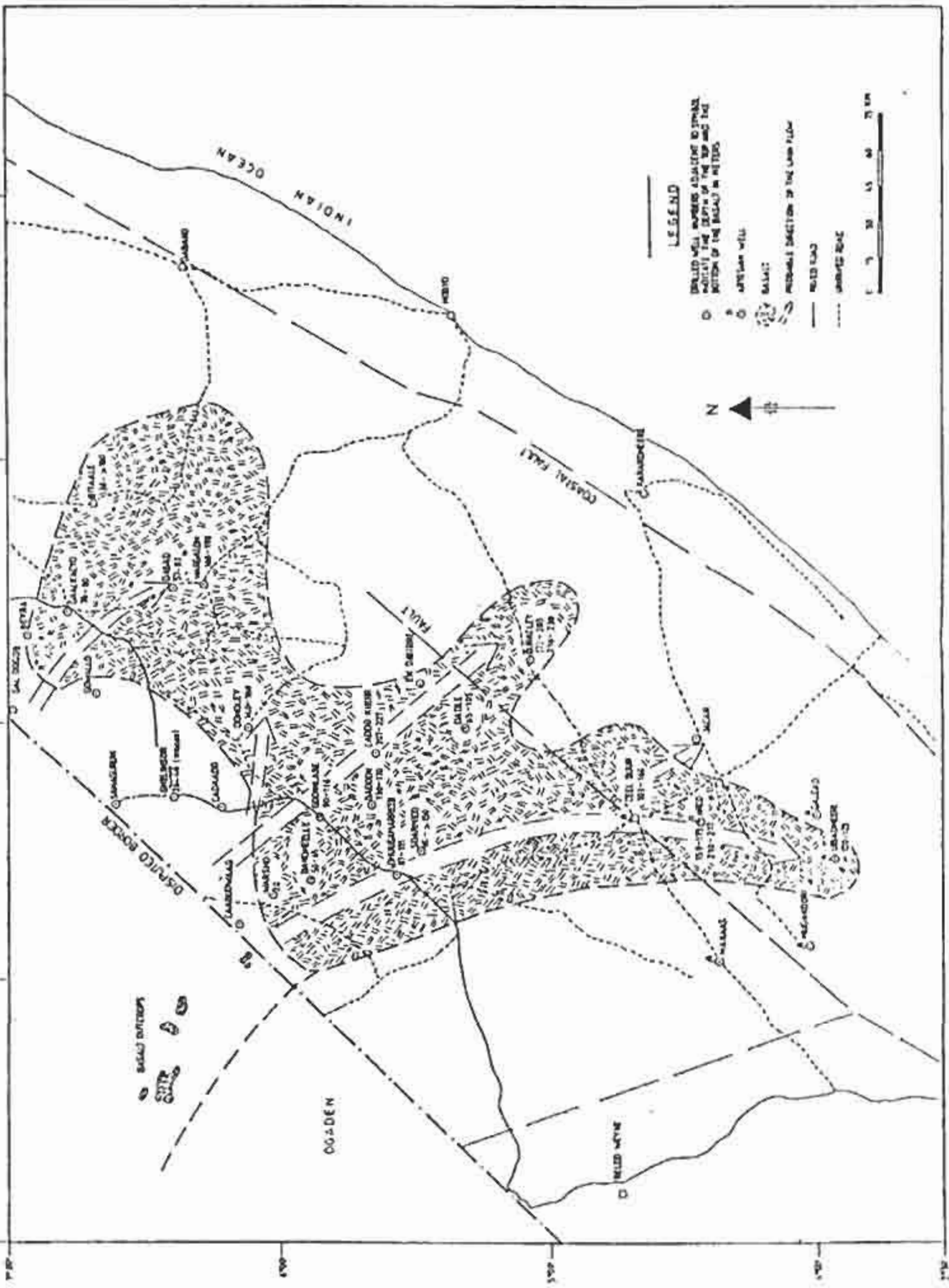


Fig. 1 - Tentative sub-surface Basalt delimitation in the Mudug-Galgadud Plateau. Note: E.C. in micromhos/cm indicated below well name.

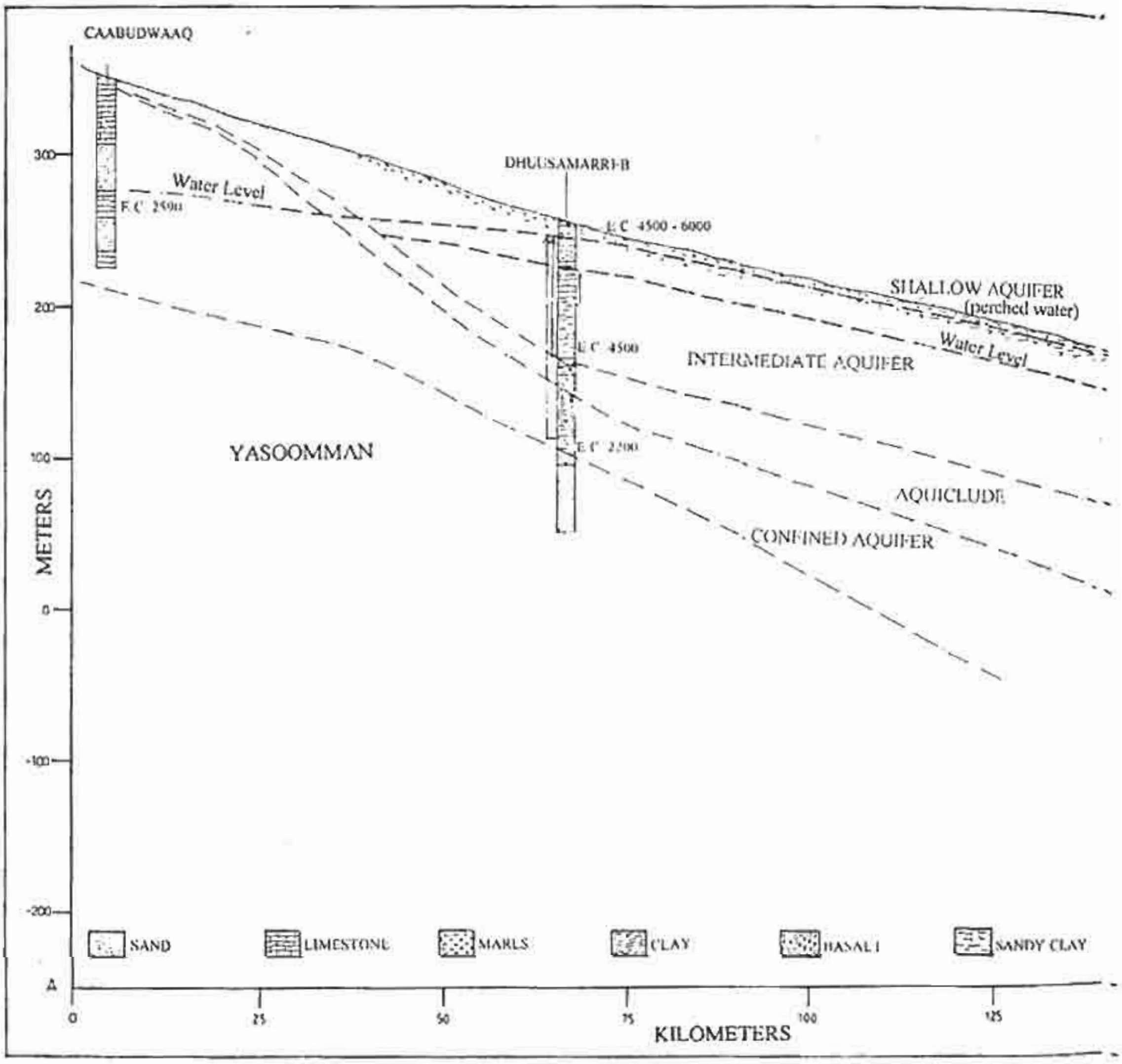
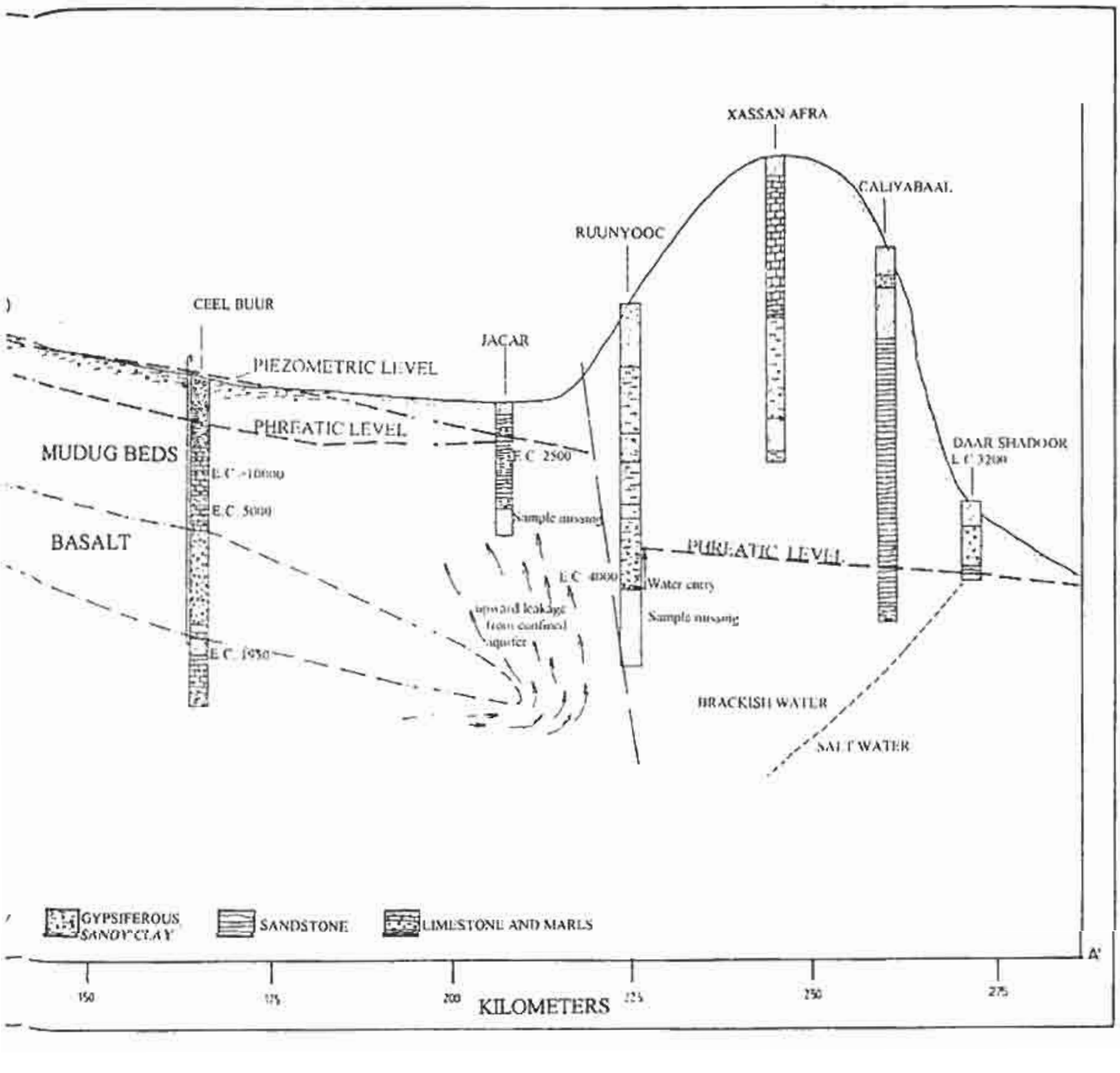


Fig. 2 - Central Somalia. Hydrogeological cross-section Caabudwaaq-Ceel Buur-Daar Shadoor. Note: E.C. in micromhos/cm indicated below well name.


XASSAN AFRA
CALIYABAAL
RUUNYOOC
CEEL BUUR
JACAR
PIEZOMETRIC LEVEL
PHREATIC LEVEL
MUDUG BEDS
BASALT
E.C. >10000
E.C. 5000
E.C. 1950
E.C. 2500
Sample missing
E.C. 4000
Water entry
Sample missing
upward leakage from confined aquifer
DAAR SHADOOR
E.C. 3200
PHREATIC LEVEL
BRACKISH WATER
SALT WATER
GYPSIFEROUS SANDY CLAY
SANDSTONE
LIMESTONE AND MARLS
A'
150
175
200
225
250
275
KILOMETERS

In the lower part of the basin, mainly in the area surrounding Ceel Buur, aquifers confined by the thick basalt sequence have a strong artesian pressure and several wells are flowing; in some cases (GTZ Ceel Buur wells and the Maxaas well) their yield is considered high.

The high artesian pressure found in the area of Ceel Buur is probably due to the coastal fault which may act as a barrier through which groundwater cannot easily flow. Therefore, the groundwater is forced to move along the fault zone and recharge, through upward leakage, the limestone area south and east of Ceel Buur. Some outflow, however, may occur across permeable sections along the fault zone and infiltrate into coastal sediments. The great difference of the water levels in wells on the western and eastern sides of the fault is an indication that the fault acts as a barrier. The hydrogeological conditions described above are shown in Fig. 2.

A description of the hydrogeological conditions of the shallow, the intermediate/ deep aquifers, and the deep confined aquifer with strong artesian pressure follows.

SHALLOW AQUIFER

The shallow aquifer located along ancestral drainage systems of Gaalkacyo and Dhuusamarreeb is under unconfined conditions and is recharged by direct rainfall and run-off water. During prolonged droughts the water table drops, leaving some hand-dug wells dry. During the rainy season groundwater moves along this fossil drainage system and dissolves the gypsiferous and calcrete crusts, with the consequent formation of sinkholes and karstic depressions.

The hydraulic gradient of the upper aquifer along the drainage systems is minimal, and towards the terminal plain water is lost by direct evaporation, evaporation of the capillarity fringe, and evapotranspiration. Soils of the terminal areas are covered by salt crusts. Water salinity in hand-dug wells increases proceeding from west to east, resulting in the formation of shallow brines towards the flood plains.

The nature of the impervious layer at the base of this perched aquifer is unclear. The impermeabilization may be due to clay deposition in fissures or pores by the circulating water. Water in some sections along this old drainage system may leak into the underlying Mudug Beds.

There is no information on yield of hand-dug wells located along the drainage systems. The available information indicates that the deep and shallow aquifers are not in direct hydraulic connection. The wells listed in Table 2 clearly show that the two aquifers have different water levels and water quality.

The Gaalkacyo and Dhuusamarreeb ancestral drainage systems and depressions are shown in Fig. 3.

The calcium sulphate water type of the shallow aquifer and the sodium chloride type in most of the deep aquifers is a further proof that the two aquifers are not hydraulically connected.

Table 2 - Comparison of Water Level and water quality in shallow and deep aquifers.

	HD Well			DR Well		
Well Name	Depth (m)	W.L. (m)	E.C. mmhos/cm	Depth (m)	W.L. (m)	E.C. mmhos/cm
Beyra	16	14	2610	160	88	4400
Gaalkacyo	8	6	5550	106	48	
				180	70	
				316	50	
Wargaloh	6	5	2400	252	100	3200
Mirsaale	5	3	4200	210	51	6900
Dhuusamarreeb	8	6	4985	70	24	2150
				135	4	2470
				156	4	2400
Ghelinsor	17	7	3395	140	100	2400
Cadaado	10	8	2550	128	85	4985
Mareer-Gur	20	19	2100	10	30	3600
Ceel Buur	4	3	4000	122	26	5000
				220	3	1958

INTERMEDIATE/DEEP AQUIFERS

These aquifers are under a variety of hydraulic conditions: unconfined in the recharge zone, semi-confined, and confined along the underflow section. There are considerable lithological changes, both vertically and horizontally, especially in the Upper Mudug Beds sequence; this creates local conditions in which water level variations may occur in the same well during drilling. Fig. 2 shows the lithological variations, the groundwater conditions, and the water quality of the aquifers in the area of Dhuusamarreeb and Ceel Buur. The water quality characteristics of different water-bearing layers may change considerably with depth, as is the case in several boreholes. In Ceel Buur, for example, water in the upper Mudug Beds aquifer comprised between 20 and 70 m has an E.C. of more than 10000 micromhos/cm. Between 70 and 110 m the E.C. drops to 5000 micromhos/cm; this section is under semi-confined conditions. In the same well the shallow aquifer, comprised within the first 10 m of sediments, is subject to seasonal variations of salinity ranging from 2000 to 6000 micromhos/cm. The deep confined aquifer which was struck below the basalt has a low salinity, with an E.C.

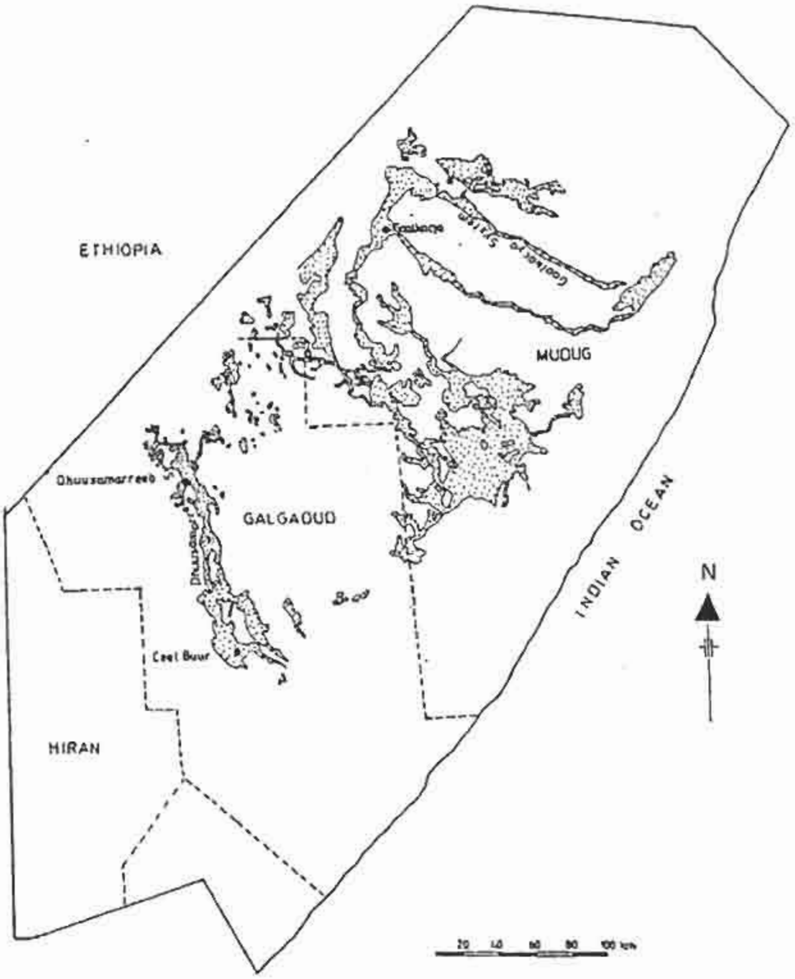


Fig. 3 - Central Somalia. Ancestral drainage system and depressions covered by gypsum and gypsiferous soils. Groundwater at shallow depth tapped by numerous hand-dug wells.

of 2000 micromhos/cm; this aquifer with a strong artesian head is not hydraulically connected to the lower section of the Upper Mudug Beds.

Conditions similar to those of Ceel Buur are found in Dhuusamarreeb, where there is a shallow unconfined aquifer, an intermediate unconfined aquifer, and a deep confined aquifer. The latter includes both the lower section of the Mudug Beds overlying the basalt and the limestone and sand aquifer below the basalt. However, the water quality of the water-bearing layers above and below the basalt differs; water below the basalt is less saline.

DHUUSAMARREEB-CEEL BUUR ARTESIAN SUB-BASIN

Several negative factors do not allow the reconstruction of the aquifer geometries in the artesian basin included approximately in the perimeter of Dhuusamarreeb-Maxaas Mugakoori-Ubadheere-Galcad-Ceel Buur-Gadon Dhuusamarreeb. Among them are the doubts regarding the existence of older sediments bordering the Mudug-Galgadud Plateau and the uncertain and limited knowledge of the Oligocene-Miocene sequence. Also unclear is the hydrogeological significance of the coastal fault (or fault system) and that of other structural motives affecting the sediments of this area.

RECHARGE OF THE ARTESIAN SUB-BASIN

There are no doubts that the main recharge zone of the artesian sub-basin is the area covered by the Yasoomman Formation extending along a large belt in Somalia and in the Ogaden. The great surface permeability of this formation, its large extension, the considerable rainfall (up to 500 mm/year in Northern Ogaden, where this formation outcrops), and its structural conditions (emerging from west to east and from northwest towards the center of the Mudug-Galgadud Plateau) help to understand the groundwater movement within the basin. Two main groundwater flows occur: one from west to east from the Yasoomman escarpment towards Ceel Buur, and another from Caabudwaaq towards Dhuusamarreeb-Ceel Buur. Recharge also occurs in the area covered by the highly karstified basal limestone which is transgressive on the Yasoomman Formation. Water infiltrates in dolines, sinkholes, and fissures. Limestone has a concretionary aspect on the surface, with numerous small fissures due to weathering which allow rainwater to infiltrate rapidly and fill karstic depressions.

STRUCTURAL ASPECTS

Geophysical surveys for oil exploration have identified three main faults. A major fault (or fault system), running approximately parallel to the coast, separates the coastal Pliocene-Pleistocene sediments from the Oligocene-Miocene sediments; a less important fault from Gal Tardo to Matabaan affects the Yasoomman Formation; a fault complementary to the coastal fault passes close to Ceel Buur and mainly affects Oligocene-Miocene sediments. The hydrogeological significance of these faults is not well known. They surely have some effect on the groundwater movement of the deep aquifer and contribute, together with the impervious, large, and thick basalt intercalation, to create semi-confined and confined conditions for the underlying water-bearing layers. These conditions were found to exist in the Dhuusamarreeb GTZ well and in the Maxaas, Mugakoori, Ubadheere, Galcad, ARCO, and Ceel Buur (GTZ) flowing wells.

Clayey intercalations in the Lower Yasoomman sediments and the fault extending from Gal Tardo to Matabaan may also create favourable structural conditions by sealing off the western side of the artesian basin. Some sections of the coastal fault may affect the underground flow towards the coastal line to a certain extent. The sub-surface lava flow, as was found from the correlation of numerous wells drilled in the area, has an extension of over 200 km in a NE-SW direction from Bitaale towards Dhuusamarreeb. It extends over 220 km in a N-S direction from near Caabudwaaq to Ubadheere (Fig. 1). Wells drilled in Dhuusamarreeb, Doholey, Gadon, Ceel Buur, ARCO, and Quracley have proven that the thick basalt sequence is dense, impervious, and acts as an aquiclude for the underlying water-bearing limestone and sands, creating confining conditions with a strong hydrostatic head.

Discharge

There are some indications that the discharge of the artesian basin occurs along the western edge of the sub-surface lava flow. In the past, such discharge may have occurred in much larger amounts than at present. Water in shallow wells and karstic depressions in Maxaas, Gorof, Wabxo, Ceel Dah, Ceel Afweyne, Bud Bud, and Dirri, all surrounding the Ceel Buur area, most likely originates from upward leakage of the aquifer confined below the basalt. Water from these wells has a chemical composition similar to that of water from the Ceel Buur, Galcad, and ARCO artesian wells.

Underground discharge most likely occurs also in the area south and southeast of Ceel Buur. This area, covered by limestone, is probably recharged by upward leakage from the deep confined aquifer. Water wells in Jacar, Bargaan, Gal Dabak, Gal Hareeri, and Qarable have been drilled through this limestone; they tap water under unconfined conditions, but have geochemical characteristics similar to those of the aquifer. The deep karstification of this limestone could be due to the upward groundwater movement. The high temperature of this water, 34-35 degrees, is another indication of its deep circulation.

The absence of discharge evidence along the coastal fault and the difference in water levels between the coastal aquifers and the limestone aquifer of the area described above suggest that the coastal fault in this section impedes or strongly limits the underflow from the confined aquifer towards the coastline. Fig. 2 illustrates the hydraulic scheme of the artesian aquifer from Caabudwaaq to Ceel Buur and further on towards the coast.

Well Hydraulics

Numerous wells have been drilled in the Mudug-Galgadud Plateau; however, few wells have records on yield and hydraulic characteristics. Only exceptionally, as was the case in some of the wells drilled for township water supplies, were pump tests performed to define the hydraulical parameters. At well completion a yield test was usually performed for a few hours to define the well capacity and decide on pump installation. Even the most recent drilling programs carried out in the area followed the same principles. Wells located in the artesian sub-basin with available yield-test records are reported in the following table.

Table 3 - Characteristics of wells drilled in the artesian sub-Basin

Well Name	Depth (m)	W.L. (m)	Interval Tested (m)	Yield m3/hr	D.D. (m)	S.C. m3/hr/m	Temp. °C	E.C. mmhos/cm
ARCO 1	256	13.3	175-248	33.0	15.0	2.20		2150
ARCO 2	246	17.7	190-246	50.0	37.0	1.35		
Bargaan	150	39.9	85-150	20.0	81.0	0.24		2950
Caabudwaaq	126	74.0	80-126	20.0	5.0	4.00	33.0	2590
Calytun	114	82.6	80-113	6.0	17.0	0.35		6100
Ceel Buur1	220	+3.6	185-220	18.4	2.0	9.10		1900
Ceel Buur2	217	+2.0	165-217	61.2	54.2	1.13	35.5	1950
Dhuusam'b	156	4.0	135-155	120.0			34.0	2650
Doholey	219	58.2	114-119	10.0	35.8	0.28	35.0	3000
Gadon	220	58.1	160-218	4.5	76.5	0.06	37.0	3500
G. Hareeri	183	63.0	135-183	20.0	43.0	0.46	34.8	4050
Galcad	70	+1.5	48-64	14.8				2320
Qarable	163	70.0	70-163	20.0	7.3	2.73	34.0	2320
Maxaas	138	+2.7	39-138	120.0	23.7	5.06	34.0	3370
Mugakoori	160	+0.0	132-160	20.0	24.0	0.83	33.0	2130
Nooleeye	200	89.9	120-200	14.0	10.0	1.40	30.0	2400

Of the wells reported in the above table, the Ceel Buur 1 artesian well is the most productive, with a specific capacity of 9.10 m^3/hr/m. In fact, this well yielded 18 m^3/hr of flowing water with 2 m draw-down from its piezometric level of 3.6 m above ground. Ceel Ruur 2 and ARCO 1 and 2, which tap the same limestone and sand aquifer, also had high production rates, but on a lower scale than Ceel Buur l; specific capacity ranged between 1.13 m^3/hr/m in Ceel Buur 2 to 2.2 m^3/hr/m in ARCO 1.

The artesian wells in Maxaas and Mugakoori both tap water from the Yasoomman sandy layers, but also have quite different yields; the Maxaas well was pump tested for a yield of 120 m^3/hr with a 5.06 m draw-down, while the Mugakoori well was pump tested at 20 m^3/hr with a 24 m draw-down. The two wells had a specific capacity of 5.06 and 0.83 m^3/hr/m, respectively.

The Qarable, Galcad, and, to a lesser extent, Nooleeye wells drilled in the limestone formation south and southeast of Ceel Buur also resulted highly productive. The Gal Hareeri and Bargaan wells had a much lower capacity, with 0.24 and 0.46 m^3/hr/m, respectively. The Calytun well also had a low yield, with 6 m^3/hr and a 17 m draw-down. This well, however, seems to receive some additional water from the upper saline aquifer; its quality is rather marginal.

Wells drilled in the confined zone near the terminal edge of the basalt flow struck water under high artesian head (Ceel Buur, ARCO). Similar conditions could exist in Quracley, where basalt, with a clay intercalation between 202 and 216 m, was struck between 172 and 230 m. The further deepening of this well, penetrating the full thickness of the basalt and 40-50 m of the underlying formation, may tap water-bearing layers under a strong hydrostatic head, possibly resulting in a flowing well.

Development Prospects for the Artesian Sub-Basin

Prospects for groundwater development of the artesian sub-basin by deep drilling are promising both from qualitative and quantitative aspects. The area included in the perimeter of Gadon-Dhuusamarreeb-Guri Ceel-Maxaas-Mugakoori-More Ari-Galcad-Nooleeye-Bargaan-Quracle-Ceel Buur-Gadon appears most promising.

The western part of the area is constituted by sand with a few intercalations of clay belonging to the Yasoomman Formation. Wells drilled in Guri Ceel, Qot Qot, Maxaas, Mugakoori, and More Ari struck water of good quality people and livestock, with E.C. values ranging from micromhos/cm in Qot Qot to 3700 micromhos/cm in More Well production is expected to be from good to very high, as indicated by the Maxaas well results. Well depth in the indicated areas should range between 150 and 200 m.

In the remaining area, boreholes should penetrate the basalt sequence and 50-60 m of the underlying aquifer, expected to be either sand of the Yasoomman Formation or basal limestone and sand; well depth should range between 200 and 250 m. All the aquifers above the basalt sill should be sealed off to avoid mixing the good water from the aquifer confined below the basalt with the marginal quality water of the aquifers above the basalt. The confined aquifer and the Yasoomman Formation yield water with E.C. values between 1800 and 3500 micromhos/cm.

High-production wells, like those in Maxaas and Ceel Buur, could also be used for vegetable and orchard irrigation if soil conditions and other aspects are favourable.

Knowledge of the recharge, underflow, and discharge zones of the sub-artesian basin and its groundwater potential are limited. Therefore, before planning any intensive development of the deep confined aquifer, more information on the abovementioned aspects will be necessary. This can be achieved by a proper groundwater exploration which should include photogeology, surface geophysical methods, exploration/production drilling, and the evaluation of groundwater chemical characteristics and evolution. The final goal of the groundwater exploration should be the accurate delimitation of the artesian basin and the assessment of its groundwater potential.

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PRELIMINARY HYDROGEOLOGIC BALANCE OF THE BAIDOA FORMATION (BAY REGION, SOUTH-WEST SOMALIA)

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ABSTRACT

This paper describes some preliminary elements of the hydrologic balance of the Baidoa Formation, calculated on the basis of data in literature. Together with hydrogeologic considerations this evaluation shows that the regulating reserves of the hydrogeologic structure do not appear to be exploited to their full potential: a greater quantity of water could be obtained from this aquifer.

INTRODUCTION

In Somalia, as in many other African countries, water is essential not only for the social development of populations, but also and above all for their survival. Information on the water resources of a region is therefore indispensable for appropriate and optimal exploitation of such resources, bearing in mind needs and availability.

The aim of our research line, of which this paper is a preliminary contribution, considers the water quantity potential in the Baidoa Formation, outcropping extensively in the Bay Region of Southwest Somalia, where agriculture and livestock are important aspects of the national economy.

A more extensive study on the hydrogeologic problems of the Baidoa Formation is under way and will provide further estimates of its subterranean water reserves.

GEOLOGIC AND HYDROGEOLOGIC FRAMEWORK

The Mesozoic sedimentary sequence outcropping in the region, directly transgressive on the Buur crystalline basement (BELLIENI et al., 1982), corresponds to two complete marine sedimentary cycles beginning in the Lower Jurassic and ending in the Lower Cretaceous (ANGELUCCI et al., 1983; PICCOLI et al., 1986). This area forms the southeastern margin of the extensive Luuq-Mandera sedimentary basin, a wide trench running parallel to the actual coast of Southern Somalia.

The Baidoa Formation, forming the lowest part of the series, is about 900 m thick and is made up of four members .

The topmost (Goloda member), about 650 m thick, is composed almost exclusively of limestone .

The stratigraphic sequence follows with the Anole Formation, about 350 m thick and mainly composed of marls, marly limestone and sandstone.

The Jurassic series continues with the Uegit Formation, 300-350 m thick and composed of calcarenites and calcilutites, and then with the Garbaharre Formation, about 650 m thick, composed of calcarenites, dolomies, marly limestone and argillites with layers of chalk and anhydrite. The Mesozoic series ends with the Lower Cretaceous Ambar Sandstones, about 450 m thick.

The dominant regional-scale structural motif is the large syncline between the outcrops of the Buur crystalline basement and those of north-west Kenya, involved in a system of mainly distensive SW-NE running faults.

Of particular interest from the hydrogeologic viewpoint is the tectonic system of direct faults marking the contact between the sedimentary sequence and the crystalline basement near Baidoa.

On the basis of permeability, the following complexes may be distinguished:

- crystalline complex: this has very poor primary permeability increasing to moderate in the fractured zones, while permeability due to weathering generally remains very poor;
- sandstone-conglomerate and marly limestone complex: this includes essentially the Ambar and Uegit Formation, together with the sandstone (Deleb) and marly-limestone (Uanei) members of the Baidoa Formation, its permeability is poor;
- limestone complex: this includes the Goloda member of the Baidoa Formation; its permeability, due both the fracturing and karstism, is high and it is thus by far the most important acquifer of the sedimentary series;
- clayey-sandy complex: this includes the Quaternary deposits covering the limestone outcrops and is mainly composed of brown clays with sandy intercalation; it's permeability is very poor.

Bearing in mind the springs, the hydrostructural conditions of the various complexes, and the geometry of the rocky masses, one of the prevailing flow direction of the subterranean waters seems to be south-east, perpendicular to the contact between the limestone complex (reservoir) and the crystalline complex (impermeable layer) (BERGER L. INT., 1985; FAILLACE C. and FAILLACE E. R., 1987).

HYPOTHETICAL HYDROGEOLOGIC BALANCE

In order to calculate the rainfall and evapotranspiration of the Baidoa Formation, data from the Baidoa station (563 m a.s.l.) were considered for the 54-year period from

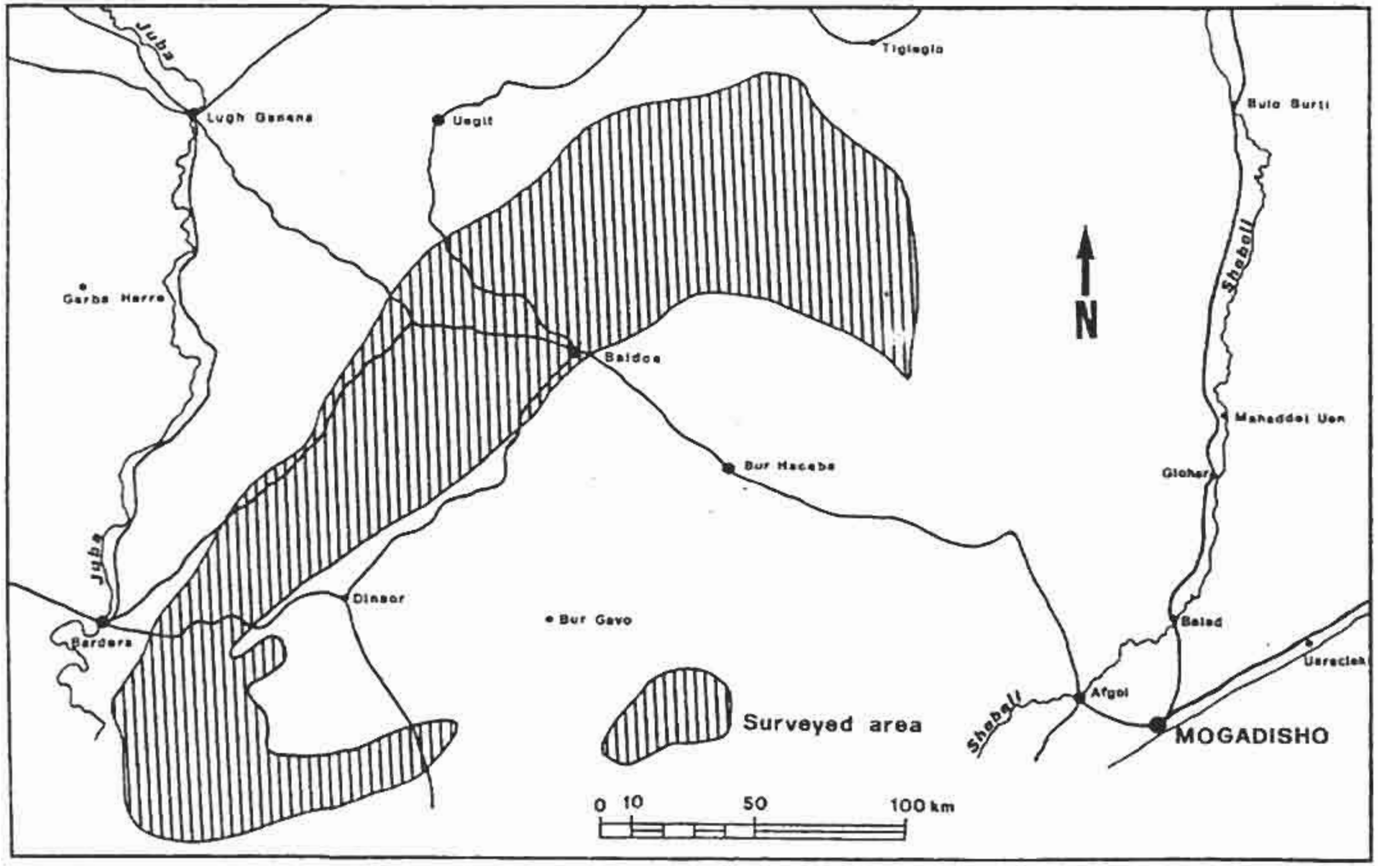

Fig. 1 - Sketch map for locating the studied area.

1922 to 1987 (Faculty of Agriculture of the National Somali University and Meteorologic Section of the Somali Ministry of Agriculture).

The mean annual rainfall is 581.5 mm, with a mean of 59 days of rain over two periods (April 10 - May 11 and October 5 - 31). The mean annual temperature is 26.3 °C, with a day/night temperature difference of about 5 °C.

The mean annual potential evapotranspiration, calculated using Thornthwaite's method, is about 1,700 mm a value which practically coincides with that measured by the Meteorologic Section of the Ministry of Agriculture applying Penman's formula. Effective evaporotranspiration, calculated using Turc's formula, turned out to be equal to the annual rainfall.

The outcrop area of the limestone complex (Fig. 1) which is completely peneplained, is about 17,000 sq/km. (excluding the part with a practically impermeable eluvial cover), so that the volume of water falling on the limestone is about 9,900,000 m^3/year. Considering the potential infiltration coefficent of the complex as equal to 100%, the almost flat topographic surface, the absence of any vegetal cover capable of holding rainwater to any conspicuous extent, and the existence of permanent groundwaters in the limestones, it is clear that effective infiltration is provided by an albeit minimal percentage of rainfall.

As 1% of the rainfall may be considered a conservative estimate of quantity of water managing to infiltrate the limestone to form water resources, the volume of available water should be about 100,000,000 m^3/year, giving a productivity about 0.7 m^3/hour/sq/km.

The available data for the most important springs and wells show that the volume of water flowing from the limestones may be estimated at about 8,500,000 m^3/year, which only represents 8.5% of the potential infiltration. It may therefore be deduced that the limestone complex contains moderate quantities of subterranean waters, although their types of accumulation and flow do not currently allow good water collection and its optimal management.

CONCLUSIONS

Although the available data are neither homogeneous nor continuous in time, they do allow a general estimate of the elements essential for an evaluation of the subterranean water reserves of the Baidoa Formation, which is the most important aquifer in the region, both as regards its permeability characteristics (fracturing and karstism) and its geometry. Previous studies have already defined the hydrogeologic importance of the carbonates, but until now the problem of estimating water reserves has not been faced.

This preliminary contribution also reveals that the annual regulating reserves of the hydrogeologic structure are greatly under-exploited. Further direct knowledge on the various elements making up the hydrogeologic balance is therefore necessary, for more precise evaluation allowing better exploitation of the subterranean water reserves.

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A GEOLOGICAL MODEL FOR GROUND WATER RESEARCH IN THE SHABEELLE VALLEY (SOMALIA)

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ABSTRACT

The authors were asked by U.N.H.C.R. to assess the possible presence, quality and potentiality of ground water in an area where a refugee settlement was being planned.

First of all, a geological investigation was carried out, aimed to define a geological model for the region. For this purpose, satellite images (MMS, Bands 5 and 7) and "False Colour Composites" (from Bands 4, 5 and 7) proved very useful, along with photogeological and field survey. In addition, the main lithological and geomorphological units (paleodunal sandy soils, paleochannels, loamy flood-plains etc.) were defined as a basis for the land-use study.

The model led to the important discovery of an ancient hydrogeological system, mainly consisting of buried paleochannels with a NW-SE direction, originating in the "Buur inselbergs region" and dating back to a time when the Shabeelle paleoriver did not the studied area, but flowed into Indian Ocean much further to the north. The upstream reaches of this paleodrainage still coincide partly with the present hydrographic network. Hence the paleochannels are possible aquifers recharged by the Buur drainage.

The paleochannels are still visible, in the satellite images, upstream of the area selected for the settlement. In this area, they are buried under the alluvium carried by the present Shabeelle after its diversion toward SE, and have been detected, localized and measured thanks to geophysical methods.

Three pilot wells have been drilled in the middle of the paleochannels.

The data collected from the wells and the petrographycal and mineralogical study of the samples confirmed the geological model and the foreseen location of the sands and gravel source-area in the Buur region: two catchment areas (3,500 km^2 and 3,800 km^2 wide) which recharge two different aquifers in the project area.

The third borehole has been drilled in the second aquifer (which is confined with static level at 4.5 m below ground) and turned out to be a production well with fresh water probably sufficient for the whole settlement.

The surprisingly good result of this study is due to the adopted method which supplied a geological model, reliable for a vast region where, according to previous researches, good water was extremely rare and available only by chance.

INTRODUCTION

The availability of fresh water in arid and semi-arid regions is the first prerequisite when planning any development project. In order to investigate the hydrogeological possibilities of an area in the Lower Shabeelle Region (Somalia) destined for the resettlement of refugees who fled to Somalia from Ethiopia, the Department of Geology of the Somali National University (S.N.U.) signed an agreement with the United Nations High Commissioner for Refugees (U.N.H.C.R.).

The study was carried out from November, 1985, to April, 1986, by some members of the S.N.U. staff. The group was co-ordinated by the senior geologist E. SOMMAVILLA; S. MARCHESI (Trento, Italy) conducted the geophysical research and G. MASÈ was chief geologist in charge of the drilling operations; the geological, geomorphological and hydrogeological study was carried out, in order, by IBRAHIM MOHAMED FARAH, ALI KASSIM and HUSSEN SALAD of the Geological Department of the Mogadishu University, F. INNOCENTI supervised the mineralogical study of the cuttings. All the work was carried out as a training course, and several recently graduated Somali geologists and last year students of the S.N.U. were provided with the valuable opportunity of an on-the-job training.

The zone in which the research was conducted, known as "Farjanno settlement area", is located in the Lower Shabeelle Region, west of the city of Barawe (Fig. 1).

A preliminary hydrogeological survey in the Farjanno area indicated that almost all the low depth aquifers are salty. The existing hand-dug wells have water with electroconductivity values ranging from 3.700 to 7.320 $\mu S\ cm^{-1}$, with the only exception of two wells, located in (or near) old river channels which seasonally recharge very small and short-lasting water-tables.

Only one deep aquifer of acceptable quality has been detected in a settlement area (Sablaale) located several kilometres away from the project area (see References, 6), and a recent study carried out for the Barawe water supply project stated, on the basis of test-wells, that the aquifer of Sablaale is the only exception in the whole region.

The conclusion of the preliminary bibliographic and field investigation was that the first 10-15 metres below ground level are useless for water research, as the small water tables connected with paleorivers are insufficient for the demand of the new settlement. The chance of finding more deeper acceptable water was, according to the previous studies, very little. Therefore a wider geological investigation was planned.

GEOLOGY AND GEOMORPHOLOGY

DATA

Based on the analysis of satellite imagery, as well as preliminary consideration of the general and structural geology of Middle Somalia and geomorphological history of the Shabeelle Valley, it was decided to extend the investigation to the northwest

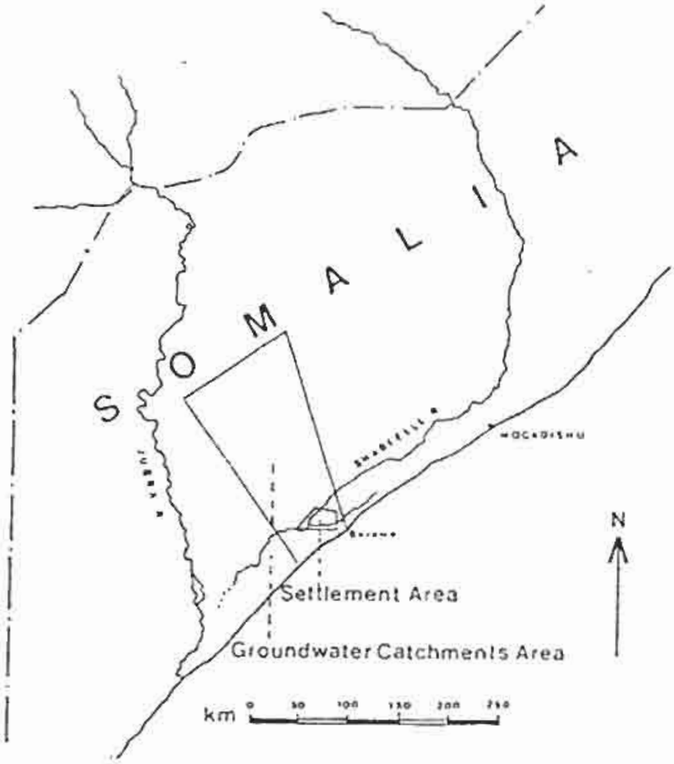


Fig. 1 - Area location.

including the "Buur", a region with numerous inselbergs consisting of magmatic and metamorphic rocks, located to a distance of 80-180 km from the settlement area.

A map of the main geological and geomorphological features was prepared in scale 1:200,000 for the whole area (about 1,600 km²) from the study of satellite images (LANDSAT MMS, Band 5, 6 and 7, and "False colour composite" from Band 4, 5 and 7). A simplified sketch of this map is represented in Fig. 2, showing the geological features which concern the hydrology (lithology, drainage patterns and faults that play a role in the succession of hydrogeological events). For the settlement area and surroundings, a more detailed geomorphological map at the scale 1:50,000 was produced using black and white aerial photos (1983/84 NTTCP project) along with field surveys. A series of topographical profiles and geological sections along with a geological block-diagram were drawn.

In the area between the Buur and the coastal dunes, three main zones, from NW to SE, can be distinguished from LANDSAT images (see Fig. 2; the drainage and the main water courses are indicated by "Y" marks):

1) a north-western zone, lying upstream, with clear NW-SE drainage ("Buur systems");
2) an intermediate zone with drainage gradually passing from NW-SE to NE-SW ("transitional system");
3) a flat north-eastern zone with NE-SW drainage ("Shabeelle system").

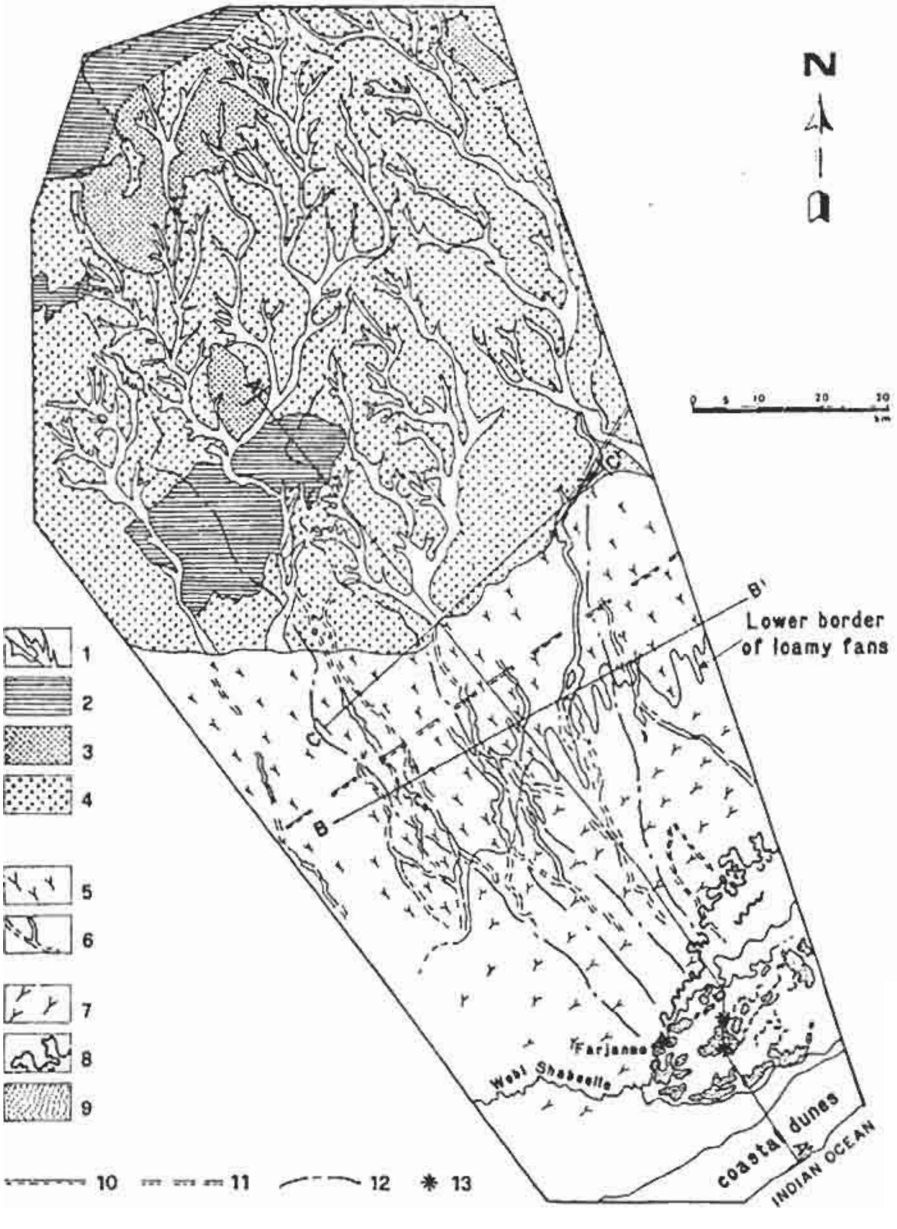
In the first zone two different features can be distinguished.

In the satellite images (MMS Band 5), the first feature consists of winding dark stripes ending toward SE with lobed shapes which clearly recall alluvial fans. Their pattern represent the continuation of the Buur region drainage toward the Shabeelle plain. The dark gray colour very likely corresponds to clayey or loamy terrains. These characteristcs lead us to identify the dark strips as river beds. They neither reach the Shabeelle nor its alluvial plain, but stop about 30 kilometres from the river. This hydrographic network is not interrupted or deformed even at the lower edge of the fans. In Fig. 2, only a line indicating the "lower border of loamy fans" of this network is shown.

The second feature is portrayed in Band 5 by white stripes, which by comparison between satellite images and known terrains should represent gravel or sand deposits. Hundreds of metres wide in the upstream reaches, the stripes get more and more narrow and gradually disappear towards SE. The white stripes are, in some points, partially shadowed or covered by the dark ones. In spite of these interruptions, they can be followed, in the satellite images, from the southern Buur border down to the very Shabeelle plain, for a length of 60 or 70 kilometres.

Like the dark stripes, the white ones also show a winding shape and originate from the Buur drainage. These data, along with the gravel-sandy composition, lead to the interpretation of the white stripes as outcrops of paleochannels belonging to a torrential drainage which probably reached the Indian Ocean at a time when the coast line lay to the north-west of the present position.

Fig. 2 - Main geological features of the Farjanno settlement area. *NW-SE Buur hydrogeological system*: 1 = gravelly and sandy alluvial deposits of recent torrents; 2 = outcrops and bedrock of limestones (Jurassic Series); 3 = outcrops and bedrock of quartzite, epimetamorphic schists and calk-silicates rocks; 4 = outcrops and bedrock of granite-migmatite (Basement Complex); 5 = pediment with eluvium and recent riverbeds; 6 = outcrops of older gravelly-sandy channels partially covered by recent rivers. *NE-SW Shabeelle hydrogeological system*: 7 = transitional zone between the NW-SE and NE-SW systems: eluvium and older Shabeelle alluvium; 8 = paleo-channels of Shabeelle river; 9 = sands of old dunes partially resedimented by the older Shabeelle river. 10 = fault; 11 = buried fault; 12 = divide; 13 = boreholes location.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The hydrographic network of the Buur region, which has been already mapped in previous works (see maps CITECO, 1974; FAILLACE and FAILLACE, 1986 and IDROTECHNECO, 1976), as well as the catchment basins approximately correspond to both the older and recent system (the river beds of the Buur area actually appear too large for the present hydrological regime). In fact, the hydrographic feature do not undergo considerable changes due to energy reduction of the regime.

Therefore, as a result of the satellite images study, an older, partially buried hydrological system was identified, which coincides only in part, and within the Buur area only, with the recent hydrological network.

The limit between the north-western zone (1) and the transitional one coincides with a break-of-slope, clearly visible in all the NW-SE topographic profiles in this area, where the mentioned fans are located, the torrents corresponding to the white stripes show a braided pattern. The break-of-slope line is parallel to the Jalalaqsi fault, which lies, buried under Tertiary and Qaternary sediments, a few kilometres to the NW. All these features are likely to be linked, as it will be seen later.

Moving further to the SE, the satellite images show indistinct remains of paleocourses of the Shabeelle, along with stretches of the NW-SE oriented paleochannels narrowing and vanishing toward SE, as it has been said before. In this area, there are some large, whitish, S-shaped patches which correspond to sandy alluvial deposits eroded from the old torrents beds and resedimented by the earliest streams of the NE-SW "Shabeelle system". Hence, the transitional character of this zone results, due to the fact that the NW-SE and NE-SW systems are mixed.

The north-eastern zone consists of Shabeelle alluvium and is crossed by the present river course and very recent paleochannels. The designated settlement is located in this zone.

In this zone four main features can be distinguished on the satellite images:

- clean-white patches with lobed shapes forming two principal NE-SW oriented rows;
- gray-white patches which show less lobed margins, and whose major length is oriented approximately in NE-SW direction;
- very dark winding stripes, also with prevailing NE-SW direction;
- dark-gray zone which encompass all the above mentioned features.

Geomorphological considerations and field surveys led to a classification of these feature as follows:

- remains of old coastal dunes;
- sands or sandy loam resedimented along with some fines by the "Shabeelle system" rivers; the source of the sand is mainly dunal in the south-eastern sector and torrential ("Bur system") in the north-western part of this zone;
- paleochannels of the "Shabeelle system", with clayey soils, sometimes flooded by recent alluvial events;
- flood with clayey and loamy terrains, frequently overflooded in the rainy seasons.

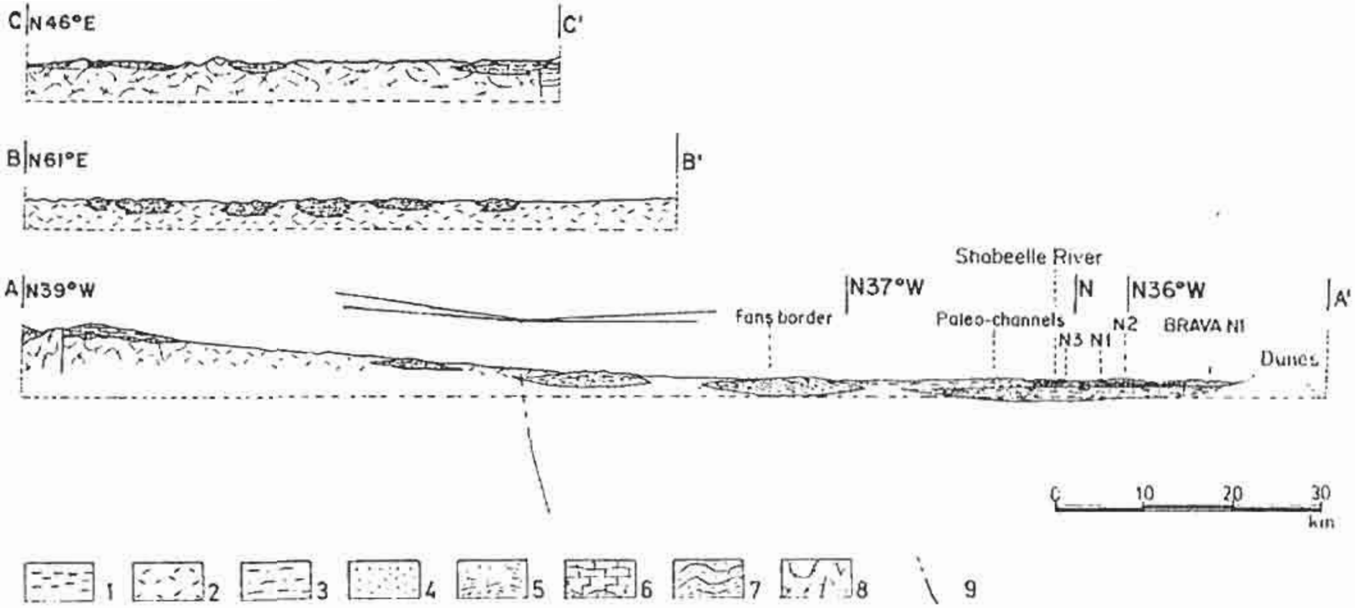

Fig. 3 - Geological sections
1 = recent alluvium; 2 = recent and old eluvium/alluvium; 3 = old Shabeelle alluvium; 4 = remains of old eolian dunes; 5 = NW/SE old channels system; 6 = Jurassic limestones/Adigrat Sandstones; 7 = quartzites; 8 = migmatites/granites; 9 = fault.

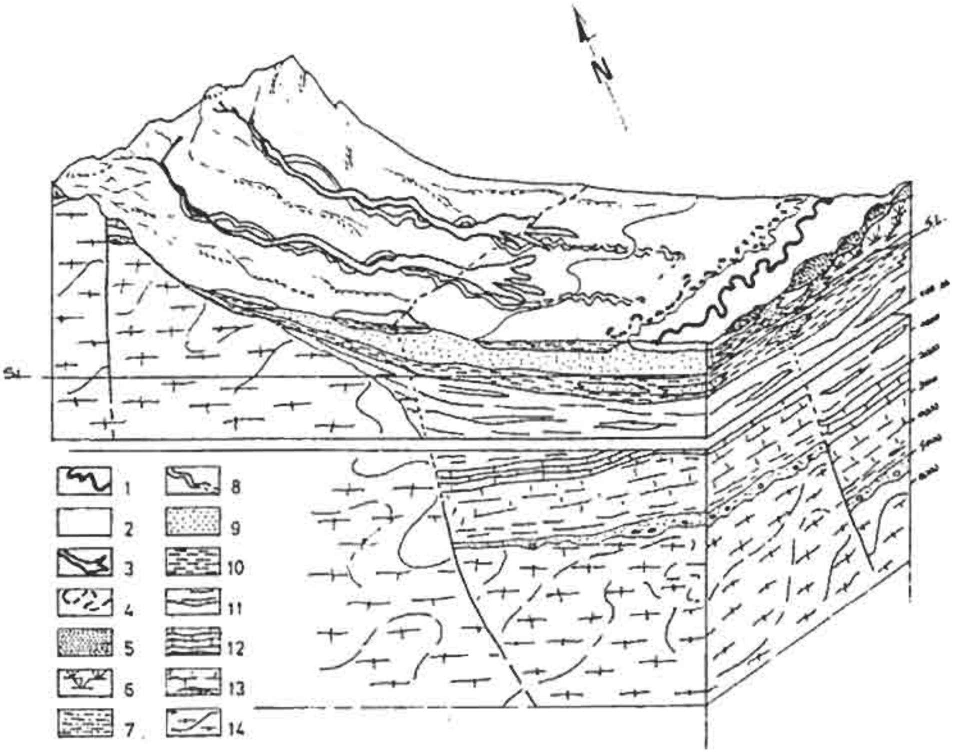

Fig. 4 - Geological block-diagram of the ground water catchment area.
1 = Shabeelle River; 2 = recent flood-plain; 3 = recent alluvial beds and fans; 4 = old Shabeelle River; 5 = old and recent coastal dunes; 6 = uplifted recent reefs; 7 = eluvium and older Shabeelle alluvium; 8 = older channels outcrops; 9 = older channels gravel and sand; 10 = older fine alluvium-eluvium; 11 = Tertiary; 12 = Cretaceous; 13 = Jurassic (with transitional deposits at the base); 14 = Migmatite and Granite.

CONCLUSIONS

From the above-discussed data, the following succession of geomorphological and hydrogeological events can be inferred.

1. A former torrential regime, with a much higher energy than the present one, eroded the Buur mountain region with a pattern oriented from NW to SE, i.e. perpendicular to the coast. The streams reached the coast, which was located at a still unknown distance NW of the present shore-line (the Indian Ocean is in a regressional stage).

2. Later, the first water courses arrived from N and NE in a north-western area of the present Shabeelle plain. The energy of this regime was lower than that of the above mentioned streams, but higher than the energy of the present Shabeelle, as indicated by the sandy deposits.
3. Later on, the regimes in both the "Buur" and "Shabeelle" systems suddenly became weaker. The sudden nature of this change suggests a tectonic cause rather than a climatic one.

   The tectonic event is also supported by the following data:

- the break-of-slope, the loamy fans and the braiding of the paleochannel of the "Buur system" are located in a zone where the "Jalalaqsi fault system" passes;
- rows of dunal remains, lying parallel to the coast up to tens of kilometres from the present shore-line, testify to important see withdrawals, hardly an acceptable circumstance without supposing new-tectonic, coastal up-lifts;
- there is evidence, on the coasts of Middle and Southern Somalia, of the uplifting of coastal sedimentary rocks up to tens of meters from see level, the event is probably of tilting type, since it is caused by isostatic movement centred in the Indian Ocean. The Jalalaqsi system could have easily worked as a "hinge" for the rotation;
- the angle of the supposed rotational movement, providing that the "hinge" is in the above-mentioned zone, corresponds exactly to that or the break-of-slope;
- on the satellite images, river captures have been observed, apparently due to the rejuvenation of a fault of the Jalalaqsi system.

The coastal uplifting along with the rotational movement could, first of all, explain the diversion of the Shabeelle from its natural flow toward the Indian Ocean to the present course, parallel to the coast. The coastal dunes are usually considered as the cause of such a diversion, but a dunal field, large and high enough to dam the outlet of the Shabeelle into the see, is very hard to explain without an uplift aiding the formation of the dunes. The rotational movement transformed the coastal belt into a semi-graben and the pediment which linked the mountains of the Buur region to the coast, become a less sloping or possibly a counter-sloping surface, helping the Shabeelle drainage to find its new way toward the south-west. This is probably why the NE-SW courses formed, at first, in a more internal zone near the Jalalaqsi fault system. These relatively high energy streams reworked the upper sandy alluvium of the Buur system. The change of slope reduced the energy of the streams coming from NW and gradually transformed them into the small, low energy rivers with the loamy fans. After having filled the depression formed by the tilting movement, the new Shabeelle drainage also evolved toward the present condition. Now, in the lower reaches, sand is no longer transported and clay is carried and deposited only during floods. A climatic change, that probably took place not long after the tectonic movement, was a factor, but not the only cause of this hydrological evolution.

In the course of these events, the shore-line withdrew from a former, still unknown position, to the present one, as an obvious consequence of the uplifting of coastal blocks. Three or four rows of paleodunal remains testify to this event. They are lobed morphological rises consisting of sand or sandstone in an early stage of lithification, with typical cross-bedding. The lobed shape is due to the erosion operated by the Shabeelle drainage. In the geomorphological study, four orders of paleochannels were distinguished in addition to the present course of the Shabeelle river, and some more or less recent flood plains were identified, consistent mainly of clayey or silty loam. These features have been mapped in scale 1:50,000, as a basis for the pedological, agronomic and town-planning study. The sandy morphological rises are probably the most suitable areas for settlement because the drainage is very good, and the soil is well adapted for foundation of small houses.

As far as the main purpose of this research is concerned, the most interesting conclusions are as follows:

- the gravelly and sandy paleochannels are possible aquifers;
- remains of their catchment basins, as well as links between the catchments and the lower reaches of the paleochannels, are still preserved and, as a consequence, the aquifers have a high recharging potential;
- in the settlement area, the paleochannels are buried under recent alluvium of the Shabeelle system;
- taking in account all the geological findings, the possible depth of the paleochannels top should not exceed, in the settlement area, few tens of meters.

GEOPHYSICAL INVESTIGATION

A geophysical research was planned in order to reconstruct the stratigraphy and structures in the project area, giving particular attention to the possible water bearing strata. A geoelectrical survey consisted of 46 resistivity soundings with maximum AB lenght of the Schlumberger quadripole ranging from 40 to 1,000 m.

According to the calibration soundings carried out near a Sablaale well (BH_3), a preliminary two-phase interpretation of the data was performed consisting of:

- a qualitative evaluation based on the isoresistivity papers appearing to AB = 20,300 and 600 m;
- a quantitative phase in which the method of comparison with the theoretical curves, as calculated by numerous authors, was applied to the soundings at 3 layers, whereas for the soundings at 4 or more layers the auxiliary point method was used.

On the basis of the results of the preliminary interpretation, a test-well was drilled on the spot where the electrical sounding no. 17 had been obtained. In this well, a spontaneous potential log was performed, and the electrical conductibility was measured.

Finally, the electrical soundings were once again interpreted on the basis of the data obtain din the test-well.

The final interpretation led to the following conclusions:

a) clayey alluvial deposits similar to the surface sediments are always present down to 15-25 m;

b) underneath the clayey soils, coarser sediments (sandy or gravelly) occur in the area with variable thickness from few metres to 50 m;

c) the points where coarse sediments of considerable thickness (some tens of metres) were spotted by geophysical soundings, are aligned along two winding stripes approximately N-S oriented;

d) The coarse alluvial deposits are likely to be saturated in fresh water; only those of limited thickness may be dry.

These results made it possible to spot the paleochannels that, according to the geological study, must lie under the recent alluvial sediments of the Shabeelle river. Thus the geological model was confirmed.

The location of two other test bore-holes was established, of which at least the last one turned out to be productive with high yield and good water.

The most promising areas and the most appropriate drilling depth were also defined.

HYDROGEOLOGY

On the basis of the dimensions of the buried channels obtained from the geophysical investigation and geomorphological data, three points were selected for drilling test bore-holes. In the hope that some test hole would become a producing well, the holes were located, wherever possible, on the sandy rises since these are the most appropriate locations for new settlements.

The chosen locations are as follows:

	coordinates	ground elevation
- well no. 1	N 01° 12' 45" - E 43° 48' 33"	45.7
- well no. 2	N 01° 11' 16" - E 43° 48' 40"	45.7
- well no. 3	N 01° 11' 01" - E 43° 13' 21"	45.5

The SOMALI DRILLING COMPANY, equipped with a Failing 250 rig, executed the pilot holes during the month of February 1986. The first diameter of the boreholes was 8-5/8" and the subsequent enlargement diameter was 12-1/4". The drilling mud was made up of local clays, except in well no. 3, where some bentonite was used. The supervision of drilling operations included recording of drilling velocity, continuous sampling, measurement of temperature and electroconductivity of the drilling mud and control of fluid losses.

The depth reached in the three wells is 55 m, 52 m and 78 m below ground level respectively.

Most of the cuttings were classified as medium to coarse sands; fine gravel and fine sands are also present. Numerous rhythmic point bar sequences have been encountered with graded bedding ranging from gravel or coarse sand to fine sand. The thickness of the sequences varies from 0.5 m to several metres. At the top of the sequences the presence of clay was usually inferred from drilling velocity and absence of cutting; in several cases duricrusts, *caliche*, were detected both from drilling restraints and from cutting.

The sediments encountered are fluvial; their composition clearly shows a granitic source; the maturity degree and morphometry fit perfectly in with the distance of the Buur and exclude any further source (see next chapter).

The pilot holes were equipped with a 6" plastic casing and Pruessag type filters. The string of casing and screens and the gravel pack granulometry were designed on the basis of the logs obtained during the drilling operations. For gravel packing, clean quartz gravel and sand with a gradation of between 10 and 0.84 mm were brought from the Buur torrential beds. Grouting was performed in order to isolate the salty aquifers localized in the Shabeelle alluvial deposits.

Development of the wells was accomplished by air surging with a 2" drop pipe inside the screen. The submergence was 59.5% for well no. 1, 49.5% for well no. 2 and 87.5% for well no. 3. Surging and pumping were continued until the water was clear and free of sand.

Well no. 1 and 2 are localized in the same paleochannel with a catchment area of 3,800 km^2; the aquifer is unconfined and the water level lies at 16.3 and 20.2 m respectively from the surface. The channel in which well no. 3 was drilled corresponds to a catchment of 3,500 km^2, adjacent to the former, the aquifer is confined, with a water level 4.5 below ground.

Mean annual rainfall in the catchment basins can be estimated around 600 mm.

The transmissivity, specific yield and storage of the aquifers were approximately estimated from grain size analyses:

- well no. 1:	$T = 1.35 \times 10^{-4} m^2 min^{-1}$	sp. yield = 0.28
- well no. 2:	$T = 8.25 \times 10^{-5} m^2 min^{-1}$	sp. yield = 0.26
- well no. 3:	$T = 4.25 \times 10^{-5} m^2 min^{-1}$	storage = 2.3×10^{-4}

Due to difficulties in finding proper equipment to run pumping tests in the wells, the true aquifer parameters are yet not known. Anyway, on the basis of present data, it is possible to state, that the water of well no. 3 has very good quality and quantity. The water of well no. 1 and no. 2 had, after development, a high salt content which is not compatible with hydrogeological considerations. This may be due to improper grouting. In fact the cement used was very old and probably did not harden, and, as a consequence, salty aquifers and the salt component of the cement may have leaked into the gravel pack. In well no. 3, over the gravel pack, instead of a sand bridge, a seal 2 m thick of bentonite pellets was used, and then grouting was made up to the surface.

To completely define the parameters of the aquifers, it is necessary to conduct pumping tests and over pump well no. 1 and no. 2 to see if the water became less saline.

MINERALOGY OF THE CUTTINGS

The mineralogical study of the cuttings fraction retained on sieve no. 200, pointed out the presence, in order of frequency, of the following minerals:

- quartz grains from subangular to angular,
- calcite spatic and concretional (cement of caliche),
- feldspar rounded or subrounded,
- dark mica in flakes,
- amphibole subrounded,
- ore minerals and heavy minerals,
- sepiolite,
- fragments of calcite and lithics.

From the mineralogical parameters, it is possible to draw the following conclusions:

1. Outcrops of the basement are the only possible source of the examined minerals, both the less rounded and the reworked ones with desert environment characteristics.
2. The presence and relatively high quantity of feldspar and femic minerals, as well as the degree of roundness of most of the grains, clearly indicate a low degree of maturity of these fluvial sediments. As a consequence, the source area must be relatively close. It is apparent that the only possible rocky complex that could supply the sampled minerals is the Buur region. Other basement outcrops lie in the upper Shabeelle basin, at a distance absolutely incompatible with the modal composition and morphometry of the grains. The geological model is therefore confirmed also by the mineralogical analysis.
3. The sands sampled in boreholes no. 1 and no. 2 are very similar. Hence, both geological and geophysical evidence of a unique channel and catchment basin for the aquifer of these two wells is confirmed by mineralogical parameters. In the cuttings of well no. 3, the content in calcite is much higher and two different minerals are present: quartz of quartzite type and tremolite-actinolite. These differences confirm the subdivision, already made in the geological model, of the possible source area in two basins. In the basin foreseen for the channel of well no. 1 and no. 2, only granitoidal rocks are present; in the basin foreseen for the channel of well no. 3, quartzite, tremolite-actinolite bearing rocks (epimetamorphic) and limestones are outcrop along with granitoids, and their areal ratio fits in well with the results of the modal analysis of the well no. 3 samples, taking in account the different degree of erodibility and alterability.

HYDROCHEMISTRY

Water samples were collected in the pilot holes before and after development, and water quality was determined by chemical and physical analyses.

Chemical and physical parameters of ground and surface waters are presented in Table 1.

Table 1

N°	T °C	E.C. µS/cm	pH	N^+ ppm	K^+ ppm	Ca^{++} ppm	Mg^{++} ppm	^-Cl ppm	$^{--}SO_4$ ppm	$^-HCO_3$ ppm	Langelier Index	SAR
1	32	3910	7.6	655	5.5	312	118	338	1540	291	1.2	8.1
2	-	3120	-	520	13	240	83	369	1100	308	-	7.4
3a	-	1980	-	200	5.6	240	39	149	689	351	-	3.1
3b	-	1530	-	122	4.5	200	44	123	460	339	-	2.0
4	29	800	7.8	-	-	-	-	-	-	-	-	-
5	30.3	743	8.3	-	-	92	22.3	-	-	-	-	-

no. 1 - pilot-hole no. 1
no. 2 - pilot-hole no. 2
no. 3 a - pilot-hole no. 3 before development
no. 3 b - pilot-hole no. 3 after development
no. 4 - surface waters of Webi Shabeelle
no. 5 - surface waters of Webi Goof.

The Langelier Index indicates that aggressive CO_2 is not present. The SAR (Sodium Adsorption Ratio) values mean that there is no danger of accumulation of exchangeable Sodium in the soil, and therefore, there are no restraints for using these waters for irrigation.

Well no. 3 has a very good water quality compared with the standards accepted in Somalia both for drinking and irrigation purposes. The salinity of the waters in well no. 1 and no. 2 became very high following the development. As has already been said, the simplest explanation could be the salt leakage in the gravel pack from the weathered cement used during the grouting operations. It was not possible to wash these salts with over pumping because the equipment was not available. In addition, the cement may not have hardened and salt may have been washed away from the high saline sediments present above the aquifer by the development operation.

CONCLUSIONS

The geological approach proved to be very appropriate in this water research in the Lower Shabeelle plain. The obtained geological model was a determining factor in achieving the results of this study. At least one of the three test boreholes, located near the Farjanno village, turned out to be a productive well with a huge amount of very good water, probably sufficient for the whole settlement. The other two pilot-holes are likely to become productive wells after cleaning operation of the slurry cement that probably penetrated into the gravel pack without hardening.

The aquifer in which well no. 3 was drilled can be exploited even by hand-dug wells, provided that the upper, brackish aquifer is isolated. Several of those wells equipped with hand-pumps can support the needs of local settlers.

The hydrogeological model is valid beyond the area of the Farjanno settlement, and its results may be extended to vast areas where the existing hydrogeological literature had only indicated the possibility of finding, by chance, scarce amounts of very poor quality ground water. These areas are: Lower Shabeelle, part of Middle Shabeelle and part of Middle Jubba.

In the light of these results, new prospects for the development of these regions seem possible, as a huge amount of water can be obtained from paleochannels for domestic uses and as irrigation support in the dry seasons both for existing and new settlements.

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ASPECTS OF ETHIOPIAN HYDROGEOLOGY

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ABSTRACT

A first inventory of the main productive water bearing formations in the various Ethiopian provinces under different climatic conditions and peculiar geo-petrographical environments, is here proposed, in order to contribute to the fulfilment of the present and future water needs of populations, agriculture and industry, as well as to the social and economic improvement of the country.

The copious geo-petrographical literature together with an excellent mapping, the specific technical reports mostly unpublished compiled by local Agencies and International Organizations, and finally the Author's own field experience acquired during several ground water research programs carried out in various geological environments of Ethiopia, have allowed to point out in the present paper the main hydrogeological characteristics and the research hypotheses regarding the diverse successive rock formations from the Precambrian to the Quaternary, which have given rise to its well-known complex geological structure.

INTRODUCTION

One of the most important issues for government decision makers in developing countries is the proper solution of water supply problems through the implementation of studies and research programs on surface and underground water in order to satisfy present and future needs of populations, agriculture and industry.

This statement becomes more significant when referred to nations characterized both by a great extension and a wide heterogeneity of climate and environmental conditions:

- high mountain areas, highlands, lowlands, wide depressions, piedmont or coastal areas, etc., characterized by a climate ranging from very wet to extremely arid and correspondingly from diverse luxuriant to very scattered, rare or no vegetation at all;
- outcrops of pervious or impervious solid rocks, fossil or actual river beds consisting of thick horizons of alluvial deposits, sandy or clayey soil layers deriving from weathering of country rocks, alluvial fans along the escarpments, salt deposits in depression areas, etc.;
- wide ranges of variation among the main factors of the water budget; i.e. rainfall rate, runoff coefficient, actual and potential evapotranspiration and infiltration rate;
- big differences among the various hydraulic parameters of the rocks and soils, i.e.

porosity, permeability, transmissibility, storage coefficient and infiltration capacity.

It may therefore be observed that this complete heterogeneity acts as a conditioning and limiting factor for whatever hydrogeological research program is to be carried out.

Such hydrogeological research programs are especially useful in nations which are periodically affected by severe drought and famine, such as Ethiopia (VERNIER et al., 1987).

The aim of the present paper is to point out the ground water potentiality of Ethiopia, not only in relation to the various geological units, but also to the different changeable climatic and environmental conditions over the whole territory. The reason for this being that the conditions favouring the formation of important aquifers are often invalidated by peculiar environmental limiting factors.

HYDROGEOLOGY OF ETHIOPIA

GENERALITIES

One of the fundamental conditions for the growth and development of a nation like Ethiopia is certainly the progressive fulfilment of its most urgent water needs, of whatever kind and from whatever source.

Past and recent studies in this field have shown that the most suitable solution to this problem is undoubtedly the rational utilization of surface waters. As a matter of fact, due to the great extent of the territory, which is characterized by the well-known morphological aspects and especially by the peculiar rainfall distribution in time and space, the solution is a proper regimen control of the rivers by means of the construction of appropriate dams, from which the water can be continuously tapped, depending on local requirements.

This could give a final solution to the problems of the most populated urban areas, which are normally characterized by the most important agricultural and industrial activities.

Unless disproportionate funds are provided, this kind of general intervention is not suitable for the rural areas, which are randomly scattered over the territory and generally affected by periodical nomad migrations (VERNIER, 1987).

These local problems, which sometimes lead to extreme emergency situations (drought, famine, etc.) may be definitely solved by means of a proper utilization of ground water.

In recent years these suggestions have finally been adopted by the Ethiopian Government who have included the problem of water supply among the main items of their socio-economical planning, acting directly through their Local Agencies and at the same time promoting aid and technical cooperation programs on the part of Foreign Countries and International Organizations.

The investigations carried out at the different scales in various parts of the country, have attained the double effect of relieving the people's distress as far as possible and contributing to a better knowledge of the main hydrogeological characteristics of the various geological units.

Referring to the general principles of hydrogeology and on the basis of the results obtained, we here propose a first inventory of the best productive aquifers to be found in the various Ethiopian provinces in well defined climatic zones and peculiar geo-petrographical environments.

The geology of Ethiopia taken from several maps (AZZAROLI et al., 1959; MOHR, 1963; BARBERI et al., 1970; KAZMIN, 1973; MERLA et al., 1973) can be traced back from the Precambrian up to the present day as follows:

- Precambrian metamorphic rocks with associated intrusives forming the "Old Basement"; 23 % of the total Ethiopian surface;
- Palaeozoic and Mesozoic sediments; 25 %;
- Early Tertiary volcanics; 23 %;
- Late Tertiary volcanics; 12 %;
- Quaternary sediments and volcanics; 17 %.

Fig. 1 - Ethiopian Administrative Province.

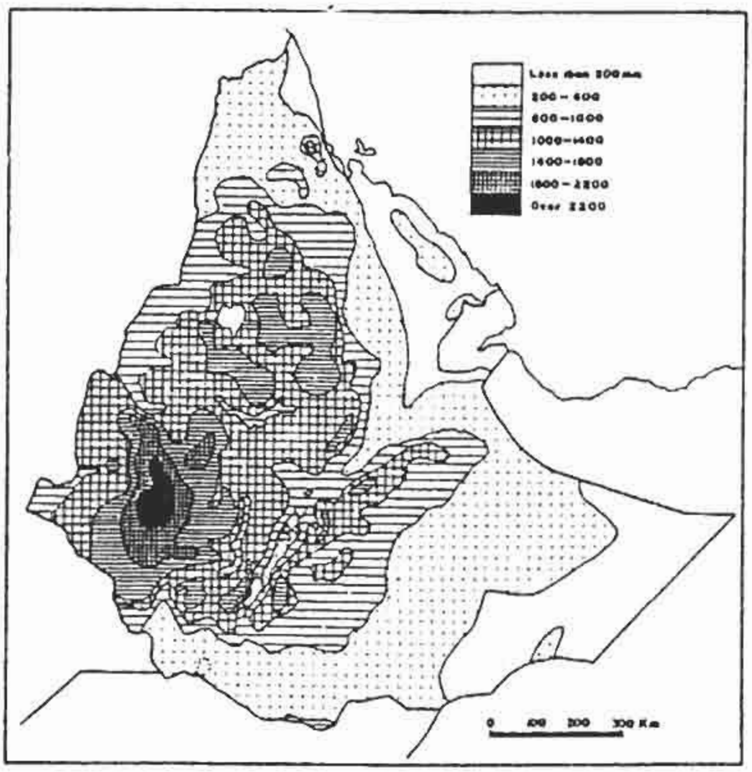


Fig. 2 - Areal distribution of mean yearly rainfall.

The Ethiopian Provinces, the areal distribution of the mean yearly rainfall depths and of the various lithotypes of different ages, are respectively represented in Figs. 1, 2, 3.

PRECAMBRIAN ROCKS

The main water bearing formations of the Precambrian age are found to be present within the structural discontinuities of the various crystalline rocks occurring mainly both in the Lower Complex (high grade gneisses, banded migmatites, granulites and metamorphic granitoids) and in the Upper Complex (syn-tectonic and post-tectonic granitoids).

It is well known that discontinuities in metamorphic and intrusive rocks have to be referred to deformations in plastic as well as post-crystalline solid state.

On the basis of this theory and by means of peculiar structural analyses at the large and small scale, the following hydrogeological principal remarks aimed at localizing economical aquifers can here be briefly outlined:

metamorphic rocks

- intersection of the main regional tectonic structures;
- tectonic lineaments following the contact with the Middle and Upper Complex younger belts;
- occurrence of post-crystalline tensile and shear fractures in gneissan synclinal and anticlinal structures as relics of S-tectonites formed by compressive stresses along the deformation plane;
- structural heterogeneity due to the occurrence of banded migmatites and granulites in a gneiss groundmass;
- occurrence of quartz and pegmatite dikes;
- occurrence of post-crystalline tensile and shear fractures in the metamorphic granitoid rock bodies considered as B-tectonites characterized by rotational movements around the fold axis.

Syn-tectonic granitoids

- evidence of strong foliation of the rocks along the margins;
- occurrence of massive bodies cut by a wide pattern of post-crystalline tectonic discontinuities;
- occurrence of numerous veins and dikes of quartz of secondary recirculation into the open fractures of the massive granodiorites;
- occurrence of pegmatite and aplite dikes in the granitic massifs;
- sharp contact with metasediments and metavolcanics marked by very important tectonic lineaments;
- occurrence of thick overburden of soils and pervious weathered materials;

post-tectonic granitoids

- occurrence of oval and round shaped bodies without evidence of tectonic activity but strongly affected by weathering processes;
- occurrence of large massive batholiths cut by a severe tectonic pattern;
- occurrence of linear springs along the contact with surrounding metamorphosed rocks;
- wide differences in composition, structure and texture, and corresponding variability of hydraulic parameters;
- occurrence of acidic and mafic dikes.

As seen in Fig. 3a, the Precambrian occurs in many areas of Ethiopia, more precisely:

- in the South (Sidamo, Gemu Gofa, Kaffa)
- in the West (Wollega, Gojam, Gondar)
- in the North (Eritrea, Tigrai)
- in the East (Hararghe)

Unfortunately, the data regarding productivity of the most suitable aquifers in the different areas are incomplete, especially in those where the climate, particularly the high rainfall rates, could provide fairly high values. This is because the main ground water investigations have so far been carried out in most unfavourable areas with low rainfalls and periodical drought events, often due to incipient progressive desertification (Eritrea, Tigrai, Wollo, Hararghe). Only recently, and in order to favour the resettlement policy, have some investigations involved the potentially most productive areas with excellent results (Gondar, Gojam, Wollega, Kaffa, Gemu Gofa, Sidamo).

PALEOZOIC AND MESOZOIC DEPOSITS (Fig. 3b)

The Ethiopian Palaeozoic formations occurring only in South Eritrea and North Tigrai are not very important from the hydrogeologic point of view, mainly because of their limited areal extent. They are essentially constituted of two well defined horizons, both classified as glacial deposits: Edgà Arbì Tillites and Enticho Sandstones. While the former constitute a very heterogeneous morenic sediment with chaotic granulometric distribution and such a strong silty-clayey cement to make them completely tight, the latter, a coarse calcareous arenaceous complex, may give rise to good aquifers within the more conglomeratic horizons or when adequately thick and highly reworked by weathering.

The aquifers of the Mesozoic formations are much more important, especially when they occur in the more favourable climatic areas. This is exactly the case of the Mesozoic, which outcrops in the central-northern Ethiopian Plateau (Blue Nile basin and Tigrai), giving rise to a stratigraphical series of remarkable thickness and good continuity, even though at times hidden by the overlying vulcanites of later date. This is a transgressive series which starts with an arenaceous-type formation (Adigrat Sandstones), goes on to calcareous-dolomitic levels, very often fossiliferous and poorly marly towards the top (Abai beds, Antalo Limestones), to reach the levels where the marl component tends to predominate over the calcareous (Agula Shales), and finally the upper horizon once more arenaceous-conglomeratic (Amba Aradam Sandstones).

With reference to the different horizons of this complex mesozoic series, the following hydrogeological remarks can be made:

- interesting aquifers may be found in the Adigrat Sandstones within the most superficial horizons notably weathered and significantly reworked, or within more distinctly conglomeratic intercalations at different depths; deep aquifers or peculiar highly productive springs may be found at the contact between these sandstones and the impervious Palaeozoic glacial deposits;
- important aquifers occur also in the Antalo limestones and Abai beds both within

the karstic circuits deeply affecting the carbonatic rock, and along the main tectonic lineaments, and also at the contact with the formation of the Adigrat Sandstones. This contact, which is more clearly visible in the deepest gorges of the Blue Nile Valley, gives rise to a series of highly productive springs, which constitute the primary water sources of such areas;

- multilayer aquifers may be found in the complex formation of the Agula Shales, within the less compact carbonatic intercalations, which are fractured, often highly laminated, curled and karstified. As far as regards exploitation of these aquifers, it is important to note that utilization of this ground water must be restricted to the deeper levels, since the more superficial waters are very often characterized by a certain degree of salinity, due to the presence of frequent intercalations of salt and gypsum. These aquifers are confined by the more marly levels and often also by quite compact magmatic horizons, made up of tertiary dolerite sills (Makallé Dolerites), which are present at different depths in this formation. Possible abundant ground waters that may also be found in these basaltic sills are mainly due to their severe local fracturing, which can be attributed to the action of the principal tectonic alignments that sometimes upset the whole stratigraphical series.
- Aquifers of the Amba Aradam Sandstones are on the other hand totally insignificant from an economical point of view, since they are moderately thick and not very extended.

In spite of their great areal extent, the Mesozoic calcareous-marly-arenaceous sediments occurring in the north-east (Danakil Horst) and in the south-east (Sidamo, Bale, Hararghe, Ogaden) of Ethiopia seem to be far less significant hydrogeologically. This is to be attributed to different factors:

- most of the involved areas are scarcely populated and difficult to reach due to the lack of transport facilities;
- the areas are very often characterized by an arid or semi-arid climate with very low rainfall rates;
- the most productive horizons are almost always interbedded with frequent layers of salt and gypsum, that make the water practically unusable.

Costly operational investigations carried out in these areas by LOCAL AGENCIES or INTERNATIONAL ORGANIZATIONS have attained only fair results, except in some areas (Bale, Sidamo) characterized by remarkable deep karstic circulation.

Tertiary and Quaternary Volcanites

As can be seen from Figs. 3 c and 3 d, the volcanic rocks and their accessories cover a good part of the Ethiopian territory and can be chronologically referred to three phases of volcanic activity starting in the Early Tertiary, Late Tertiary and Quaternary respectively, and due to the well known episodes of tectonization and crustal deformation which led first to the uplift of the pre-Tertiary peneplain, then to the formation and progressive opening of the Rift system and finally to the outcropping of the Mantle

Rock. This succession of events gave rise to a thick series of volcanites, variously distributed over the Ethiopian territory and characterized by an extremely variable mineral content and chemism.

Laccolithes and basaltic sills within Mesozoic sediments, old basalt flows associated with silicified lacustrine deposits, columnar basalt flows alternate with agglomerates and tuffs, sequences of thin mafic and acidic lavas deeply weathered and tectonized, lenticular basalts and scoriaceous lava flows filling ancient river beds cut in typical medium-coarse grained paleosoils, silicic lavas, domes and old volcanic centres, are the main volcanic units (Trap Series), which characterize the Ethiopian Central Plateau and the north-west margin of the Rift escarpment.

Partially overlying the Trap Series of the Ethiopian Plateau and mainly along the central and southern margins of the Rift, more acidic lavas, such as rhyolites, trachytes, trachy-basalts, etc., are commonly present together with tuffs, ignimbrites, agglomerates and interbedded basaltic flows and reworked paleosoils (Magdala Group).

Fissural basalt flows, silicic massifs and lavas, domes, young volcanic centres, ash spatter cones, thick pyroclastic sediments, constitute the main petrographic environments of the Rift floor and Danakil lowlands (Afar Group and others).

The complex spatial and temporal distribution of these volcanic rocks, their different reciprocal stratigraphic relationships, their changeable contacts with ancient and recent rocks, their great compositional, structural and textural variability, their different level of tectonization and weathering, the clear heterogeneity of their hydraulic characteristics, are all factors which highly complicate the possibility of standardizing hydrogeological research methodologies in these geological formations. Operational investigations carried out in apparently similar lithological areas could give very different results depending on unforeseen local heterogeneity factors.

All this was confirmed by several hydrogeological investigations carried out in some areas of Ethiopia (Wollo, Showa, Arussi, Bale, etc.) with extremely different results, which can be attributed not only to foreseen climatic causes.

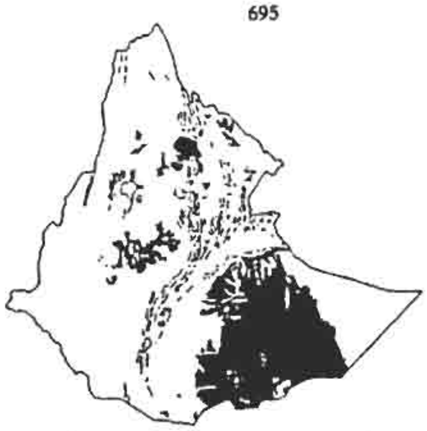
Even though the factors conditioning the research work are so imponderable, and all possible work hypotheses are made aleatory, a few precise hydrogeological evidences seem to be generally confirmed as far as regards recognition of important productive aquifers within the various volcanic units.

These evidences are briefly listed:

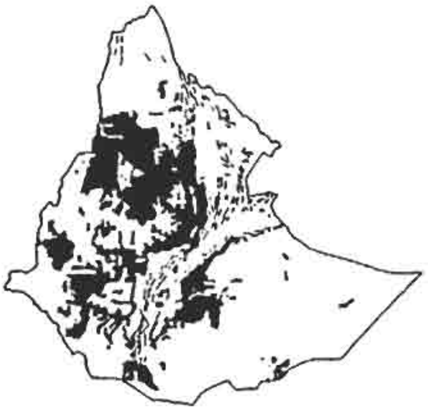
- occurrence within the basaltic flows of thick horizons of paleosoils constituted by coarse alluvial and eluvial sediments probably due to various stagnation phases of the volcanic activity, when erosion and transport processes normally play an important role;

Fig. 3 - Areal distribution of Ethiopian Geological Units.

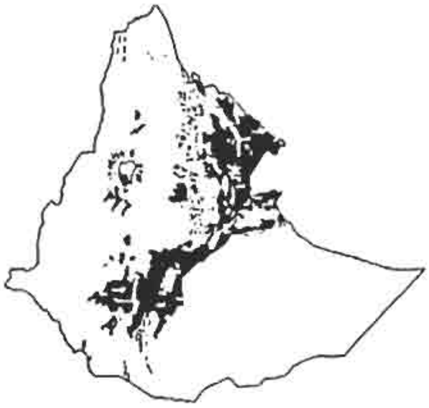
3a. Precambrian Rocks



3b. Paleozoic and Mesozoic Sediments



3c. Tertiary Volcanites



3d. Quaternary Volcanites

3e. Tertiary Sediments

3f. Quaternary Sediments

- occurrence within the mafic and acidic lava flows of interbedded loose pyroclastic materials and reworked agglomerates or breccias, when the finest clayey elements have been totally removed;
- occurrence of structural discontinuities within the Mesozoic sediments due to the presence of extremely fractured tertiary laccolithes and dolerite sills;
- occurrence of structural discontinuities due to the sharp contacts between lava flows and massive volcanic apparatus, such as big volcanos, domes etc.;
- occurrence of peculiar openings and significant patterns of vertical and horizontal joints within rather thick lava flows;
- occurrence of thick residual soils as products of the strong weathering of the more silicic volcanics;
- occurrence of contact and overflow springs due to the sequence of pervious and impervious layers;
- occurrence of fracture and fault springs along the main tectonic lineaments.

It would be interesting at this point to spend a few words on important circulation of hydrothermal waters that is often found in such volcanic formations, especially in the most recent ones, and which is due to the intense tectonic activity that always accompanies events of crustal deformation. But due to its importance, complexity, and practical implications, it will be the subject matter of a specific next paper.

TERTIARY AND QUATERNARY DEPOSITS (Figs. 3e; 3f)

Variegated quartzose sandstones (Yessoma Sandstones), biogenic massive limestones (Auradu Series), anidrites, gypsum, dolomites, cherty limestones and clays (Taleh Series), fossiliferous limestones with marly and clayey intercalations (Karkar Series), are the main tertiary sediments present in the Ogaden desertic area (Hararghe), quite close to the Somalian border.

The absolute lack of hydrogeological information together with the peculiar climatic conditions of the whole area, make these sediments quite insignificant from the hydrogeological point of view, even if some geological features could give rise to limited ground water storages during the wettest periods. Sporadic low production wells, tapped with hand pumps or more traditional rudimental methodologies, are said to be present and utilized by the rare local population.

Similar conclusions can be made regarding the tertiary sediments occurring in the Afar desert lowlands (Wollo and Eritrea): marly and biogenic limestones, often corraline, with subordinate coarse sandstones and conglomerates, marly and clayey sediments interbedded with thick horizons of evaporites. These last salt formations and the almost absolute lack of resident population, due to the precarious environmental life conditions, render the occurrence of possible local aquifers even less usable and significant.

The Quaternary sediments occurring along the coastal area of Eritrea may be considered in the same way: conglomerates, sands, silts, clays and reef limestones.

In addition these formations are often affected by a heavy marine salt water encroachment.

On the other hand, the piedmont alluvia recent formations present along the most populated areas close to the Rift Escarpment may seem to assume much greater importance. Good aquifers may therefore be found, which are mainly fed by the abundant rivers coming from the Highlands and tending to penetrate the alluvial deposits after a more or less long path.

Numerous groundwater investigations carried out in such areas have attained good productions, allowing both the setting of intensive crop cultures and the fulfilment of the water needs of the nomad populations.

Even though the recent alluvial sediments of the Ethiopian Plateau along both sides of the larger river beds have not been represented in the text figures, they deserve special mention. For most of the year these permeable formations are characterized by a significant ground water circulation which sometimes gives rise to abundant aquifers, even if conditioned by the rainfall and runoff variable regimens.

As far as regards the recent undifferentiated alluvials occurring along the Western border of the Ethiopian territory, no precise data are available due to the fact that they occur in very remote areas, scarcely populated, affected by copious rainfalls and characterized by strictly swampy or tropical forest environments.

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CHEMICAL FEATURES OF SPRINGWATERS FROM THE EAST AFRICAN RIFT. A RECONNAISSANCE STUDY

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ABSTRACT

The chemical features of 40 springwaters from the East African Rift Valley (most from Ethiopia) have been described. The waters are mainly alkaline in pH and all characterized by the dominance of sodium among cations. On the contrary bicarbonate is predominant in the waters from the Ethiopian and Kenyan Rift Valley, and chloride is characteristic of the waters from the Afar Depression. Springwaters from Uganda, that locally show a high sulphate content, appear to have an anionic composition intermediate between the two above groups.

Hypotheses for the origin of the springwaters are discussed. As the waters derive salinity mainly from leaching rocks through which they circulate, the different regional chemical patterns likely reflect differences in the rock suites.

The fluoride content of most springwaters studied is notably high and for a half of the samples fluorite deposition is theoretically predictable. Despite this, no evidence of fluorite precipitation has been so far reported. Possible explanations of such behaviour are proposed.

INTRODUCTION

A relatively large number of chemical analyses are now available from the literature for spring and lake waters from the East African Rift area. However, unlike for lake water analyses (e.g., CERLING, 1979), there is no critical geologic evaluation of the data for springwaters. Therefore in this paper we have accomplished with a critical assessment review of published data and have also carried out some new analyses of springwaters from Ethiopia. From this region comes most of the available data, as the Ethiopian section of the East African Rift (EAR) was extensively studied in the seventies by volcanologists, who dealt with the problem of the Rift formation and related magmatism.

GEOLOGIC SETTING

Locations of the analysed water samples are listed in the Appendix along with references and sketchly indicated in Fig. 1, 30 out of 40 samples are from Ethiopia (spring number prefixed by E), 8 from Uganda (prefix U) and 2 from Kenya (prefix K). The uppermost of the Ethiopian springs occurs in the Rift Valley Area, including under this term also the Afar Depression, and mainly in the Rift bottom, only a few being located at the escarpments.

The Ethiopian Rift Valley formed in the Late Tertiary; it trends roughly NE-SW and is filled up with a variety of volcanic rocks, mainly basic in character. Acidic volcanites also occur, whereas intermediate rocks are strongly subordinate. Beneath the volcanic terranes a variety of sedimentary formations ranging from the Mesozoic to the Tertiary, underlain by Precambrian and Lower Paleozoic metamorphic and granitic rocks, occurs. Evidence of these rocks is found on the flanks of the Rift Valley.

The Ethiopian Rift continues southwards to Kenya, where it is called Gregory Rift and trends roughly N-S. It is filled up with Caenozoic volcanics, that are in general distinctly more alkaline and/or undersaturated than the coeval Ethiopian ones (BROTZU et al., 1984). The Gregory Rift Valley is flanked by rocks of the crystalline basement and is locally blanketed, as well as the Ethiopian Rift, by Quaternary sediments of continental origin.

Finally, the Ugandan Rift represents a distinct branch (or W Rift) of the EAR system trending roughly NE-SW. It is filled up by Neogene sediments (sand, clay and conglomerate) (ARAD and MORTON, 1969). Precambrian rocks, mainly represented by granitic gneisses, crop out on the Eastern flank of the Rift; these rocks, which extend over most of Uganda, are lacking in the southern-eastern part, where the Buganda-Toro System (slates, phyllites and mica-schists with subordinate quartzites and amphibolites) and the overlying Karagu-Ankolean System (argillaceous rocks with a lower grade of regional metamorphism) crop out.

As shown in Fig. 1, the East African Rift Valley hosts several lakes, the waters of which are generally alkaline in character. A few of them lie down salts (e.g. lake Natron, lake Magadi).

According to CERLING (1979) the EAR has been sufferring a dramatic change of climate since the late Pliocene to a less humid character and thus the present-day chemistry of springwaters from this area does not reflect the past climate features.

RESULTS AND DISCUSSION

Table 1 lists the chemical analyses herein considered and includes both new data and those from the literature.

Despite the springwaters are scattered through about 2,500 km (from the Red Sea coast to Western Uganda) only few chemical patterns are exhibited. To make the discussion simpler the Ethiopian springwaters can be splitted into two groups with respect to their geologic setting: Group-A waters (i.e. samples E-1 to E-15) occur throughout the Main Rift Valley, while Group-B waters (samples E-16 to E-30) in the Afar Depression. The two springwaters from the Kenyan Rift Valley are considered akin to those of Group-A.

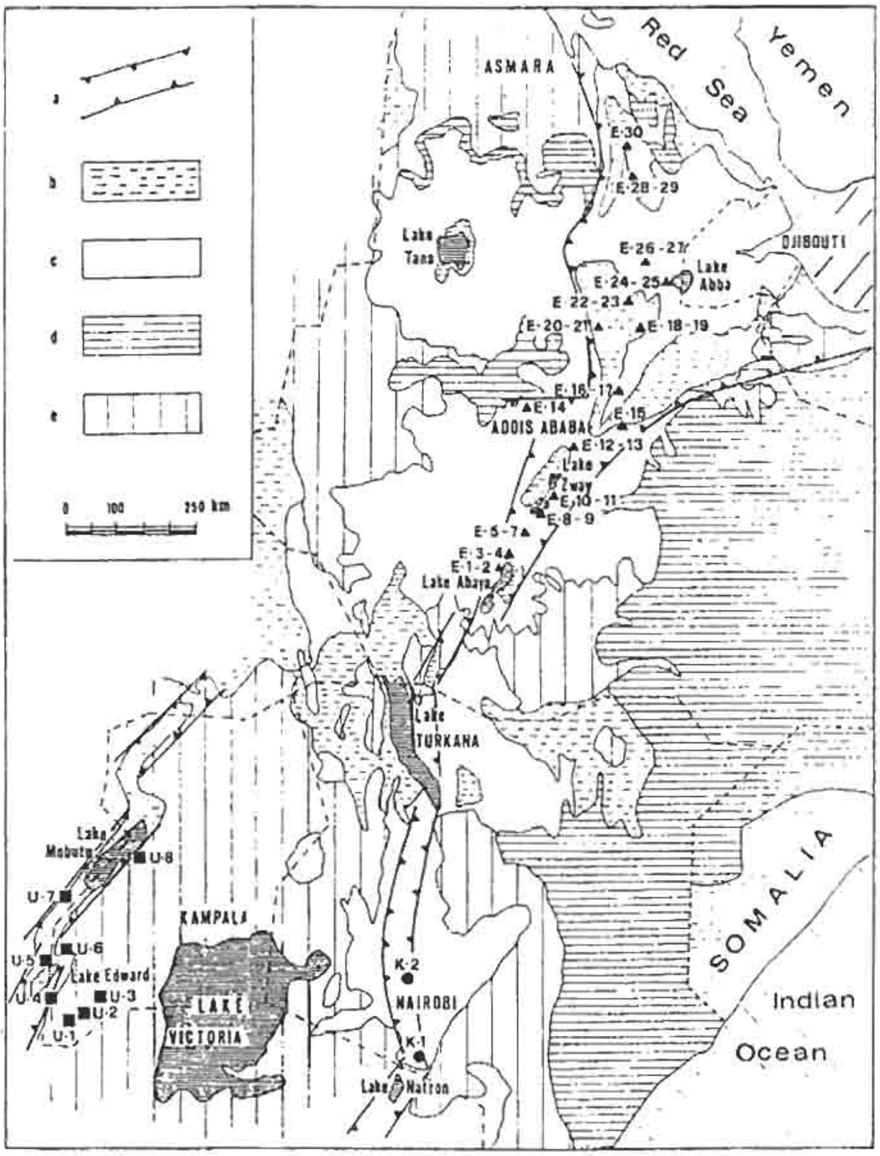

Fig. 1 - Geologic sketch map of East Africa with locations of the watersprings studied (E = Ethiopia; K = Kenya and U = Uganda). a = main tectonic outlines of the East African Rift; b = Neogene to the present sediments; c = Tertiary and Quaternary volcanics; d = Mesozoic sedimentary sequences; e = Precambrian and Lower Paleozoic metamorphic and granitic terranes.

Table 1 shows that neither pH, ranging from 6.4 to 9.6 and from 6.5 to 8.9 for Group-A and Group-B, respectively, nor total dissolved solids (TDS), ranging from 325 to 9.066 ppm and from 256 up to 47.522 ppm for Group-A and Group-B respectively, distinguish among the two groups of springwaters. Based on both pH and TDS values even the two Kenyan springwaters fall into the two corresponding Ethiopian groups; hence these parameters are useless for regional distinction.

Waters of Group-A differ from those of Group-B for the dominant anion, viz., bicarbonate (hereafter we use the operational term "bicarbonate" to include all the carbonic species in solutions) and chloride, respectively. However, three springwaters of Group-B (i.e., E-17, E-20 and E-21) are significantly richer in bicarbonate rather than in chloride and thus are included in Group-A, despite of being located in the Afar Depression, but however next to the Main Rift Valley. Such apparently arbitrary assignment does not affect the previous conclusion about the significance of both pH and TDS, which still fail in discriminating between the two groups of springwaters.

Unlike the prevailing anion, the dominant cation (Na) is not a distinctive character amount the waters.

Waters of Group-A are of sodium-bicarbonate character, their Na and carbonate contents totalling from 62% (E-20) up to 91% (E-13) of TDS. Such a feature could reflect their meteoric origin, in agreement with the few isotopic data (CRAIG, 1977). As the increased Na levels are not matched by those of chloride, it is likely that the aquifers of Group-A waters are represented by volcanic and/or terrigenous sediments. The low Ca content of these waters does not support any significant circulation through carbonate rocks.

Group-B waters are of sodium-chloride type, their Na and Cl contents accounting for 61.7% (E-16) up to 88.1% (E-27) of TDS. Thus, despite these waters circulates through volcanites chemically comparable to those of the Ethiopian Rift Valley (Fig. 1), their mineralization pattern rather mirrors groundwater interaction with salt deposits and/or mixing with confined brines. Filed evidence supports this inference only for springwaters E-28 and E-30, which outpour where salt deposits are known. Generally speaking, however, the occurrence of either salt deposits or brines at depth cannot be ruled out. In particular brines may be expected, for the local geothermal anomalies likely produced convective cells of hydrothermal waters. Interaction with salt deposits and/or mixing with brines is in agreement with the order of abundance of the main constituents of the springwaters, i.e.:

$$Cl > SO_4 > HCO_3 \quad . \text{ and } \quad Na > Ca > K.$$

Springwaters from Uganda can be classified into two groups according to aquifer lithology. In particular Group-C comprehends waters U-1 to U-3 from the Precambrian shield and Group-D (samples U-4 to U-8) those from the graben of the Rift Valley, i.e., U-4 to U-8. As for the Ethiopian springwaters, pH does not discriminate between the two Ugandan groups of waters, this further showing that such parameter is not

SAMPLE	Na	K	Mg	Ca	HCO$_3$	CO$_3$	Cl	SO$_4$	F	pH	TDS
U-1	9.13	0.51	0.82	1.99	2.78	n.d.	3.10	4.16	n.d.	6.5	542
U-2	20.00	0.61	2.38	3.34	14.42	n.d.	5.36	7.70	n.d.	6.7	2,020
U-3	8.30	0.25	0.66	1.59	1.30	0.33	1.69	7.49	n.d.	7.7	780
U-4	7.83	0.13	0.16	0.59	1.32	0.36	2.06	4.26	n.d.	8.5	564
U-5	304.48	23.57	1.64	0.23	39.33	90.00	141.04	74.95	n.d.	8.2	21,725
U-6	177.98	2.04	0.82	0.75	44.25	5.00	78.98	68.70	n.d.	8.5	13,085
U-7	247.93	4.60	0.41	0.35	50.30	6.00	110.01	82.24	2.00	8.4	17,060
U-8	70.43	5.12	1.60	2.50	0.98	n.d.	71.42	2.50	0.31	7.1	4,576
K-1	468.02	38.87	24.68	0.39	201.63	112.33	144.14	3.37	6.68	8.9	33,387
K-2	344.38	2.27	0.74	0.69	28.18	n.d.	8.99	1.20	3.84	6.8	3,334
E-1	2.09	0.33	0.79	0.55	4.50	n.d.	0.09	0.18	0.08	6.4	392
E-2	51.41	5.80	0.10	0.04	17.87	19.30	22.70	1.94	2.52	9.6	4,025
E-3	8.92	0.79	0.32	0.65	8.37	0.70	0.59	0.19	0.79	7.0	830
E-4	17.62	0.39	0.07	0.90	8.93	2.00	0.93	0.85	1.89	8.4	1,139
E-5	18.05	0.92	0.31	0.78	14.25	1.20	1.01	1.92	0.95	8.3	1,534
E-6	29.56	1.82	0.75	0.99	23.28	n.d.	3.80	3.12	0.16	8.0	2,488
E-7	2.60	0.31	0.27	0.32	2.98	1.27	0.17	0.31	0.03	7.3	325
E-8	30.20	1.40	0.70	0.56	16.72	10.20	10.20	0.37	1.32	9.7	2,300
E-9	119.61	2.43	0.28	0.39	78.50	n.d.	36.81	0.64	4.32	3.0	9,066
E-10	4.48	0.40	0.92	1.04	6.31	n.d.	1.15	0.94	0.09	8.0	625
E-11	39.30	2.31	0.67	0.95	26.24	n.d.	11.84	1.00	1.63	8.1	3,132
E-12	27.40	0.95	1.25	0.95	22.30	n.d.	4.50	2.40	0.47	7.5	2,344
E-13	10.43	0.39	0.30	0.45	10.08	n.d.	0.76	0.39	1.10	8.3	974
E-14	37.84	0.43	0.10	20.70	29.20	n.d.	1.55	8.50	1.26	7.0	3,572
E-15	17.18	0.64	0.12	0.21	11.52	n.d.	4.65	1.71	0.15	8.2	1,429
E-16	52.85	1.80	0.25	0.95	11.14	n.d.	31.03	13.75	0.37	7.5	3,753
E-17	11.30	0.28	0.17	0.33	5.73	n.d.	3.07	1.67	0.05	8.0	859
E-18	39.67	1.28	1.56	4.44	1.30	n.d.	33.85	7.50	0.16	6.5	2,649
E-19	23.92	0.26	0.08	2.74	2.08	n.d.	22.99	2.89	0.10	6.6	1,674
E-20	10.35	0.40	2.30	3.00	7.73	n.d.	2.57	4.89	0.10	7.5	1,134
E-21	1.52	0.13	1.25	0.49	2.11	n.d.	0.28	0.37	0.10	8.9	256
E-22	22.18	1.79	0.08	0.99	1.61	n.d.	21.16	4.48	0.04	8.4	1,737
E-23	20.88	1.04	0.58	2.39	0.90	n.d.	16.61	7.25	0.16	7.3	1,571
E-24	35.01	1.81	1.23	3.44	2.13	n.d.	27.89	7.28	0.05	7.7	2,403
E-25	41.32	0.54	0.16	1.90	1.19	n.d.	31.31	8.26	0.10	8.4	2,576
E-26	23.70	1.35	0.42	2.84	1.00	n.d.	21.15	6.23	0.31	8.0	1,751
E-27	86.34	4.80	1.00	6.75	1.40	n.d.	92.43	5.81	0.10	8.0	5,927
E-28	254.46	9.97	2.00	136.00	0.60	n.d.	393.51	8.20	0.10	7.2	23,599
E-29	34.36	1.56	6.99	10.08	3.52	n.d.	45.27	3.60	0.21	8.2	3,047
E-30	561.98	15.40	47.31	186.64	0.62	n.d.	805.70	24.57	0.10	7.4	47,522

Table 1 - Analyses of springwaters from the East African Rift. (Except for TDS, given in mg/l, result are meq/l, ND= not determined)

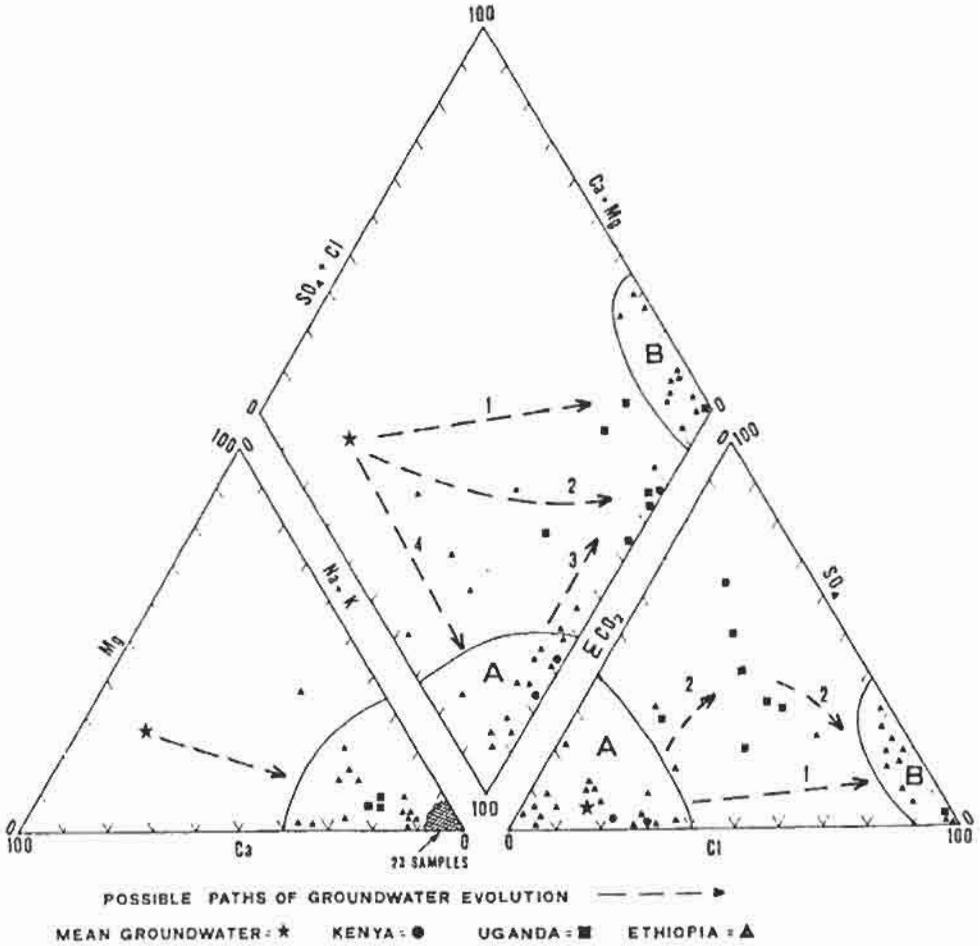

Fig. 2 - PIPER (1949) plot for the studied springwaters. The meaning of the arrows is discussed in the text.

lithology-dependent. By reverse, unlike for the Ethiopian springwaters, TDS distinguishes between Group-C (542-2.000 mg/l) and Group-D (4.576-21.725 mg/l), except for sample U-4, whose low TDS fits in the Group-C range. As the low TDS of springwater U-4 suggests that its aquifer comprehends some Precambrian shield terranes, this spring is included in the Group-C despite its location.

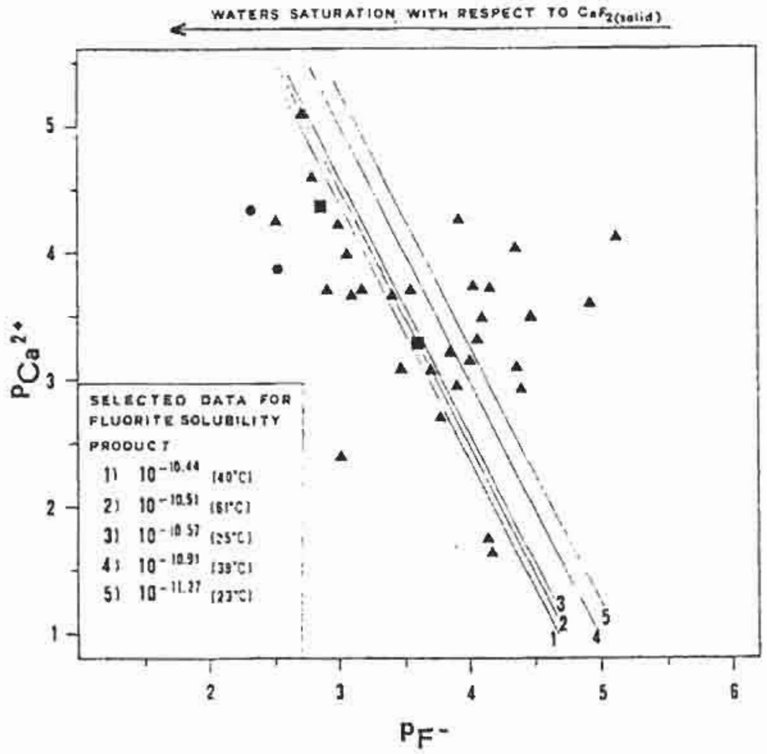

Fig. 3 - P_{Ca}^{2+} vs. P_F^- diagram for the studied springwaters. The fluorite solubility product (straight lines) result from data after HEM, 1970 (1), ALLMANN and KORITNIG, 1978 (2-4-5); SILLEN and MARTELL, 1971 (3). Symbols as in Fig. 2.

The chemical features of the two groups of Ugandan waters discriminated by TDS are quite distinct from those of the Ethiopian groups. Though Na predominates either in the Ugandan and Ethiopian waters, neither chloride nor bicarbonate represent the most abundant anions in Group-C springwaters as in the Ethiopian waters. On the contrary 3 out of 4 waters of Group-C are characterized by a major content of sulphate, suggesting that these waters circulate mainly through crystalline rather than volcanic terranes.

Concerning Group-D waters, their overall chemical pattern is comparable with that of Group-B waters, although these latter show far higher chloride contents. Further marked chemical differences between the two groups of waters suggest that Group-D includes waters transitional between the chloride and sulphate type. This is in agreement with the fact that the Ugandan and the Ethiopian sectors of the EAR are represented mainly by Precambrian shield terranes and volcanites, respectively.

Considering Group-D waters, high bicarbonate coupled with low Ca contents rule out any major TDS input from circulation through carbonate rocks, that are indeed rare or lacking at all throughout the Ugandan Rift. The source of bicarbonate, which is too high for a typical groundwater and however lower relative to Group-B waters, could be volcanic (CO_2) and/or biogenic (organic matter decay).

Fig. 2 shows that the uppermost of the waters, regardless of their provenance, are characterized by a marked predominance of the alkalis over the alkaline-earths. By reverse in the anion triangle the Ethiopian springwaters are splitted into two groups, only a few samples (including all except one from Uganda) being scattered around the plot centre. A starlet represents the mean for waters from the Ethiopian Plateau near the escarpment.

Of interest is arguing about chemical evolution of the studied springwaters from the composition of "typical" groudwaters. In this respect the arrows in Fig. 2 show the viable evolution paths for groundwater to trend towards the studied springwaters. It appears that in the cation triangle, there is only one pathway for determining enrichment in alkali-metals, whereas as in that of anions two possible evolution paths are shown. Path 1 links directly "typical" groundwater through several Group-A samples to Group-B waters, this trend indicating chloride enrichment paralleled by bicarbonate dropping. However, lack of waters intermediate between Group-A and Group-B makes unrealistic such evolution pathway for the EAR springwaters. By reverse, the waters that fall along Path 2 support this trend of increasing chloride and, subordinately, sulphate contents. In this view it is noteworthy that Group-B waters display almost constant bicarbonate, while chloride and sulphate (from 70 to 90% and from trace to 30%, respectively) show an indirect relationship. Most of waters in the middle of the anion triangle refers to Ugandan springwaters, thus supporting further that they are transitional between Group-A and Group-B.

Finally, in the diamond-shaped plot the possible evolution of "typical" groundwater towards Group-A waters through Path 4 is shown. As said for Path 1 in the anion plot, evolution of "typical" groundwater through Path 1 towards Group-B waters is hardly realistic. As a result, the data of Fig. 2 are in line with two possible evolution trends, one being represented by Path 2 and the other by Path 4 coupled with Path 3. Thus the Ugandan springwaters may derive from a "typical" groundwater either directly through Path 2 or, stepwisely, by Paths 4 and 3.

Appendix - Location of the springs and type of country rocks. B = basalt; G = granitic gneisses; S = sediments; V = volcanic tuffs; I = Ignimbrite; R = rhyolite Data credit: 1) UGANDA GEOLOGICAL SURVEY (1969); 2) ARAD A. and MORTON W.H. (1969); 3) MC CONNEL R.B. and BROWN G.M. (1954); 4) BAKER B.H. (1958); 5) STEVENS J.A. (1946); 6) UNITED NATION (1973)

Spring	Location site	Country rock	Reference
	<u>UGANDA</u>		
U-1	Rubabu	G	(1)
U-2	Minera	G	(2)
U-3	Kikagata	G	(2)
U-4	Inimbo	S	(2)
U-5	Katwe, N of Lake Edward	V	(1)
U-6	Bugoye	G	(3)
U-7	Buranga	S	(3)
U-8	Kibero, SE of Lake Mobutu	S&G	(1)
	<u>KENYA</u>		
K-1	near Lake Magadi	unknown	(4)
K-2	near Lake Elmenteira	unknown	(5)
	<u>ETHIOPIA</u>		
E-1	Chokore,NW coast of	I	this work
E-2	Lake Abaya		
E-3	N of Lake Abaya,	S	this work
E-4	near Bilate River		
E-5	E of Lake Awasa	R	this work
E-6	Wendo Genet	S	this work
E-7	SE of Wendo Genet	I	this work
E-8	E of Lake Shala	S	this work
E-9	SE of Lake Shala	R	this work
E-10	NE of Lake Langeno	B	this work
E-11	N of Lake Langeno	S	this work
E-12	Sodore (mean of 5 springs)	R	this work
E-13	Hippo Pool & Gargadi (mean)	S	this work
E-14	Filweha (Addis Abeba)	B	this work
	(mean of 5 springs)		
E-15	Filweha (NE Fanta'Ale)	B	(6)
	(mean of 5 springs)		
E-16	Meteka (Gewane)	B	(6)
E-17			
E-18	Teo Graben	S	(6)
E-19			
E-20	Kombolcha Graben	S	(6)
E-21			
E-22	Tendaho Graben	S	(6)
E-23			
E-24	W shore of Lake Abe	S	(6)
E-25			
E-26	Dobi Graben	S	(6)
E-27			
E-28	W shore of Lake Afrera	S	(6)
E-29			
E-30	S shore of Lake Asele	S	(6)
	(Erta'Ale Range)		

Of interest are the fluoride contents of the EAR springwaters which range from 0.8 ppm (E-22) up to 82 ppm (E-8). This generally high fluoride content causes fluorosis, a highly debilitating desease, widespread amount the inhabitants of the Rift Valley. The fluoride content discriminates between Group-A waters, which are significantly enriched (F = 18.0 ppm), and Group-B waters, which show low levels (F = 3.3 ppm). Such feature likely reflects to some extent both the water-rock interaction and lithological differences of the aquifers. In particular high fluoride suggests circulation through volcanic terranes, while low fluoride may indicate the occurrence of sedimentary aquifers.
The high F levels found in most of the studied waters bring about implications on fluorite formation. Although this process is governed by many interdependent variables, it is critical to determine whether the springwaters are saturated relative to fluorite. In this respect Fig. 3 shows five curves of the solubility product of fluorite over the temperature range of 23-61 °C, thus representative of the thermality at which the waters are issued. The activities of the ion pair involved in the solubility equilibrium of fluorite are used rather than their analytical concentrations. From Fig. 3 it is apparent that there are data falling both in the filed of undersaturation (right side of the diagram) and in that of oversaturation. Group-A waters exhibit the largest spread and include both the most undersaturated (E-7) and oversaturated (E-14) water samples. Both Kenyan springwaters and the two Ugandan of known fluoride content are oversaturated with respect to fluorite. Thus, as in a number of springwaters the product of F^- and Ca^{2+} activities exceeds the solubility product of fluorite, the precipitation of CaF_2 could be expected. This theoretical prediction, however, contrasts with field evidence because sedimentary fluorite has never still reported throughout the study area. A possible explanation is that in waters theoretically oversaturated with respect to fluorite the free fluoride ions are lacking, likely for being involved in coordination processes. This can cause such a dramatic dropping of F^- activity to prevent fluorite precipitation. However, though the analytical data are too incomplete for discussing in detail the chemical fluoride-bearing species, the complexation of silica by fluoride ion as well as the dissociation of HF and $(HF)_2$ which affect the fluoride activity only at acidic pH values (ROBERSON and BARNES, 1978), can be ruled out, the pHs of EAR being neutral or alkaline.

ACKNOWLEDGMENTS

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GROUNDWATER INVESTIGATIONS, DEVELOPMENT AND USE IN THE ATHI BASIN, KENYA

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ABSTRACT

The Athi River basin forms one of the five major surface drainage basins in Kenya. It drains the southern part of the country discharging its waters as Sabaki River into the Indian Ocean at Mambrui, near Malindi.

In its upper course the Athi drains young volcanic terrain of the highlands around Nairobi. In its middle course, it traverses Precambrian metamorphic terrain, while in its lower course it passes thorough Mesozoic and Cenozoic rocks before entering the Indian Ocean.

In each of the three rock formations (units), great influence is exerted on the quality and quantity of groundwater for development purposes as the amount of surface water availability is limited.

Attempts are hereby made to identify factors controlling aquifer characteristic. Recommendations have been suggested for water use and for future groundwater development.

INTRODUCTION

Kenya is divided into five hydrological basins, namely, Lake Victoria, Rift Valley, Athi, Tana and Northern Ewaso Nyiro as shown in Fig. 1.

The Athi Basin which is the subject for this paper is approximately 68,000 km^2 and is bounded by latitudes 0° 4' and 4° 45' S and longitudes 36° 35' and 40° 10' E. About 80% of the basin falls within the arid and semi-arid lands (ASAL) of Kenya.

Great importance has been attached to groundwater in the ASAL because it is the key to any tangible integrated development of these lands as the availability of surface water is extremely limited. The integrated development in the ASAL is the other way of easing the population pressure in the arable lands in the western and central parts of Kenya. The development of these would areas would also ensure higher food production which is required for the fast growing population. This would also be a measure to prevent the encroachment of desertification.

It will be appreciated that groundwater like any other natural resource has to be well understood if its development and utilization have to be optimized. It is with this view that this study has been undertaken.

The geology of the basin has been reviewed with particular emphasis on factors that

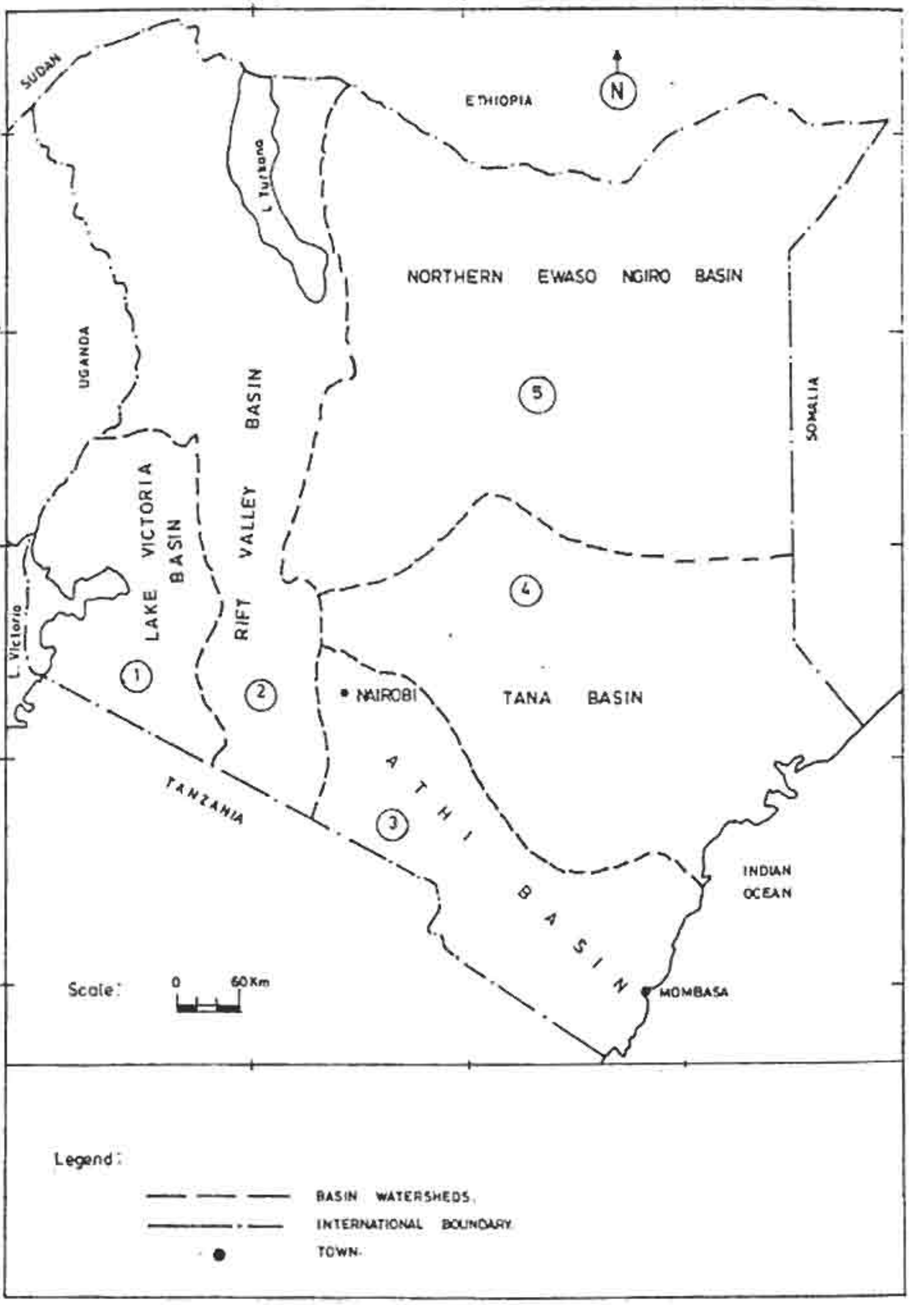


Fig. 1 - Hydrological Basin of Kenya. (Modified from Survey of Kenya, 1970).

control the groundwater occurrence. Borehole lithological logs have proved quite useful in bridging some of the geological gaps.

Borehole yields, depths at which water is struck, and groundwater flow have been analysed in an attempt to evaluate the characteristics and the distribution of the aquifers. Groundwater quality and level of development and utilization have been assessed and recommendations for the future proper management have been made.

GEOLOGICAL SETTING

The geology of the Athi Basin is characterized by three main rock types, namely, the metamorphic, volcanic and sedimentary rocks as shown in Fig. 2.

Metamorphic Rocks

The metamorphic rocks belong to the Mozambiquean Belt of the Precambrian, Pan-African Orogeny. These rocks outcrop in the central part of the area and constitute above 50% of the Athi Basin. They mainly comprise of gneisses, migmatites, schists, marbles and quartzites. Their general strike is more or less north-south. To the west of the area, the outcrop is associated with recumbent folding and extensive faulting. The main rocks are quartzites and marbles (JOURBERT, 1957; MATHESON, 1966). To the east, the outcrop is associated with symmetrical folding and occasional faults associated with gneisses and migmatites. Granitoid gneisses associated with peripheral concentric foliations are also observed (SEARLE, 1954; SAGGERSON, 1962, 1963).

Volcanic Rocks

Volcanic rocks are widely scattered with the largest outcrop in the north-western region of the Athi Basin.

Other significant outcrops are associated with the Yatta Plateau, Chyulu Ranges and the eastern slopes of Kilimanjaro Mountain. The oldest volcanic flows are represented by the phonolites and trachytes of the Tertiary Period. These mainly outcrop in the north-western region and along the Yatta Plateau. The younger volcanic flows are represented by trachytes and volcanic sediments of the Quaternary Period. They overlie the Tertiary volcanics in the north-western region. The Chyulu Ranges and the Kilimanjaro slopes are associated with these young volcanic rocks. Faulting is common in the volcanic rocks and the faults appear to be associated with the rift valley faulting and are oriented more or less north-south (WILLIAMS, 1972; WILCOCKSON, 1956).

Sedimentary Rocks

The sedimentary rocks of the Athi Basin may be broadly divisible into four types, namely, Permo-Triassic, Jurassic, Tertiary and Quaternary rocks.

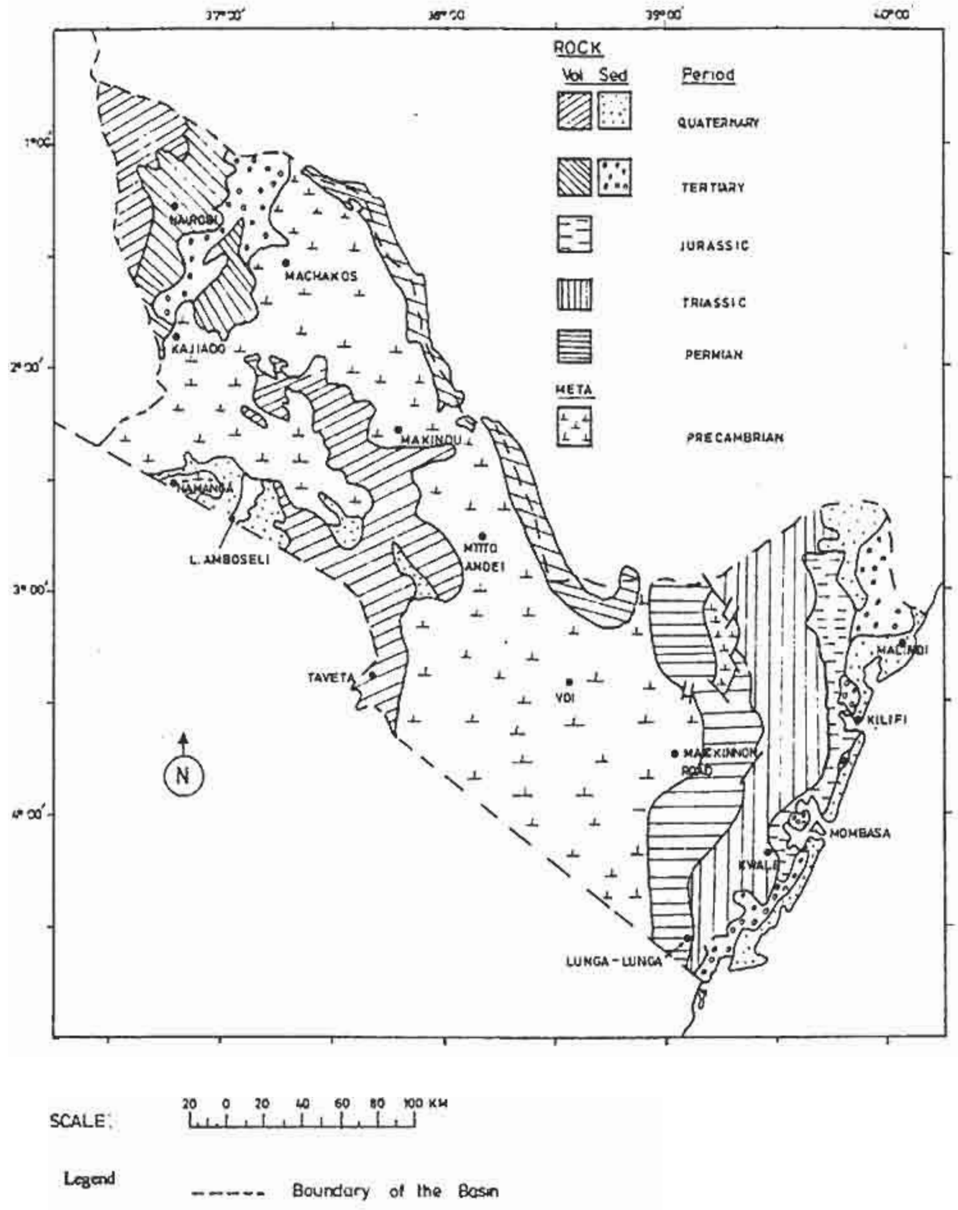


Fig. 2 - The geology of the Athi Basin.

The Permo-Triassic rocks are mainly consolidated sandstones and shales. These older rocks were deposited in deltaic environment and they are mainly grits, flaggy sandstones and shales. The younger rocks were deposited in continental environment and they comprise mainly of massive coarse sandstone.

The Jurassic rocks mainly comprise of limestones and shales of marine origin. They outcrop in a ragged topography which forms the boundary between the lowlands and the coastal plain (CASWELL, 1953, 1956; MILLER, 1952).

The Tertiary sediments outcrop along the coast where they overlie the Jurassic rocks, and inland where they overlie the Tertiary phonolites (Fig. 2). The coastal Tertiary sediments comprise mainly of loose sands with intercalations of clay. They are locally called Magarini sands. Their easterly extent overlain by Quaternary sediments.

The inland Tertiary sediments mainly comprise of volcanic sediments with intercalations of limestones and gypsum which are suggestive of lacustrine depositional environment (THOMPSON, 1950; FAIRBURN, 1963; WILLIAMS, 1962).

The Quaternary sediments along the coast are broadly divisible into three, namely the lagoonal sands, coral reef and sand dunes. The lagoonal sands are contemporaneous with the coral reef. The latter outcrops near the coastline and the former outcrop to the west where it overlies the Tertiary sediments. The sand dunes overlie the coral reef at isolated areas. Unlike the sand dunes, the coral reef and the lagoonal sands are continuous and extensive outcrops along the coastal plain (CASWELL, 1953; 1956).

HYDROGEOLOGY

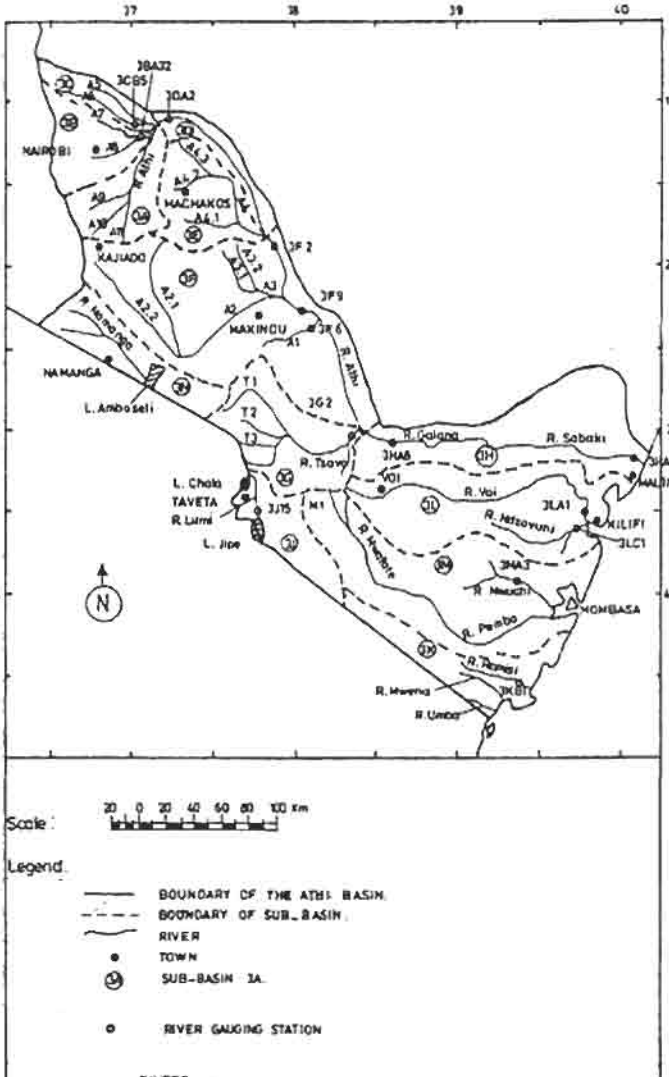
SURFACE WATER

The meteoric groundwater which we use for most practical purposes is mainly contributed by surface water. Consequently, before groundwater is discussed a mention of surface water in the Athi Basin is considered worthwhile.

For the purpose of surface water management, the Ministry of Water Development has divided the Athi Basin into thirteen sub-basins with code numbers from 3A to 3N. The number stands for Athi Basin and the letters stand for the sub-basins (Fig. 3).

It has been observed that the sub-basins underlain by metamorphic rocks drained by ephemeral rivers. Examples of these are 3D, 3F, 3L, and 3N. The sub-basins underlain by volcanic rocks are drained by perennial rivers. Examples of these are 3A, 3B, 3G and 3J.

This indicates that groundwater discharge to surface water is more significant in the areas underlain by volcanic rocks that areas underlain by the metamorphic rocks. The high permeability enhanced by faulting, jointing and expansive permeable volcanic sediments that separate impermeable volcanic flows facilitates higher groundwater discharge to surface water in areas underlain by volcanic rocks than in areas underlain by metamorphic rocks. However quantitative analysis of the relationship between surface water and groundwater in the basin is inhibited by limited river data.



RIVERS

CODE	NAME	CODE	NAME	CODE	NAME
M1	BURA	A2.2	OL KAJIADO	A4.3	KATHAANA
T1	LOLTURESH	A3	KIKUU	A5	KONU
T2	MAGOINE	A3.1	MUOONI	A6	NDARUGU
T3	NGARE LEN	A3.2	KWANGI	A7	RUIRU
A1	KIBWEZI	A4	THWAKE	A8	NAIROBI
A2	KIBOKO	A4.1	KAITI	A9	KISERIAN I
A2.1	SELENGAI	A4.2	IKIWE	A10	KITENGELA
				A11	STONEY ATHI

Fig. 3 - Hydrological map of the Athi Basin.

GROUNDWATER

In this context groundwater is discussed in three sub-headings namely, investigation, development and use.

Investigation

Groundwater exploration not only in the Athi Basin, but also in Kenya as a whole has not received much attention. This is clearly demonstrated by the borehole drilling records which show that 95% of the boreholes have been drilled for production purposes and only 5% have been drilled for exploratory purposes. The reason for the small percentage of exploratory boreholes is that the priority has been given to the production boreholes as a result of financial and trained manpower constraints (MAILU, 1983).

Microgeophysical surveys have been carried out in order to select drill sites of about 30% of the boreholes drilled in the Athi Basin since early 1950's. Unfortunately the micro surveys have not been synthesised for regional geophysical maps or models.

In this investigation much attention has been focused on borehole data to evaluate aquifer characteristics and hydrogeochemistry.

Aquifer Characteristics

The aquifer characteristics that have been considered in this investigation include aquifer types, depths, yields and groundwater flow.

Borehole lithological logs of 400 boreholes from metamorphic, volcanic and sedimentary rocks have been analysed in an attempt to classify the aquifers (Table l).

The fractured zones are mainly a result of faulting, columnar jointing, and fracturing. In metamorphic rocks, fractured zones are mainly associated; with faulting and differential rock resistance within the peripheries of intrusive granitoid gneisses. In volcanic rocks they are associated with faulting and columnar jointing.

Aquifers due to fractures are usually rare in sedimentary rocks particular in areas underlain by Quaternary sediments. Wherever available such aquifers are mainly encountered at depths greater than 100 metres.

The aquifers associated with the weathered overburden occur at the top of the fresh parent rock which is overlain by the in-situ weathered material. The aquifers are common in the metamorphic rocks. Their depths rarely exceed 50 metres. However, in the volcanic areas underlain by trachytes depths of up to 100 metres have been recorded.

Aquifers associated with permeable sediments are commonly associated with sedimentary rocks. They are occasionally encountered in volcanic rocks where volcanic sediments have been sandwiched between impermeable lava flows of different ages. The depths of the aquifers associated with these sediments depend on the thickness of

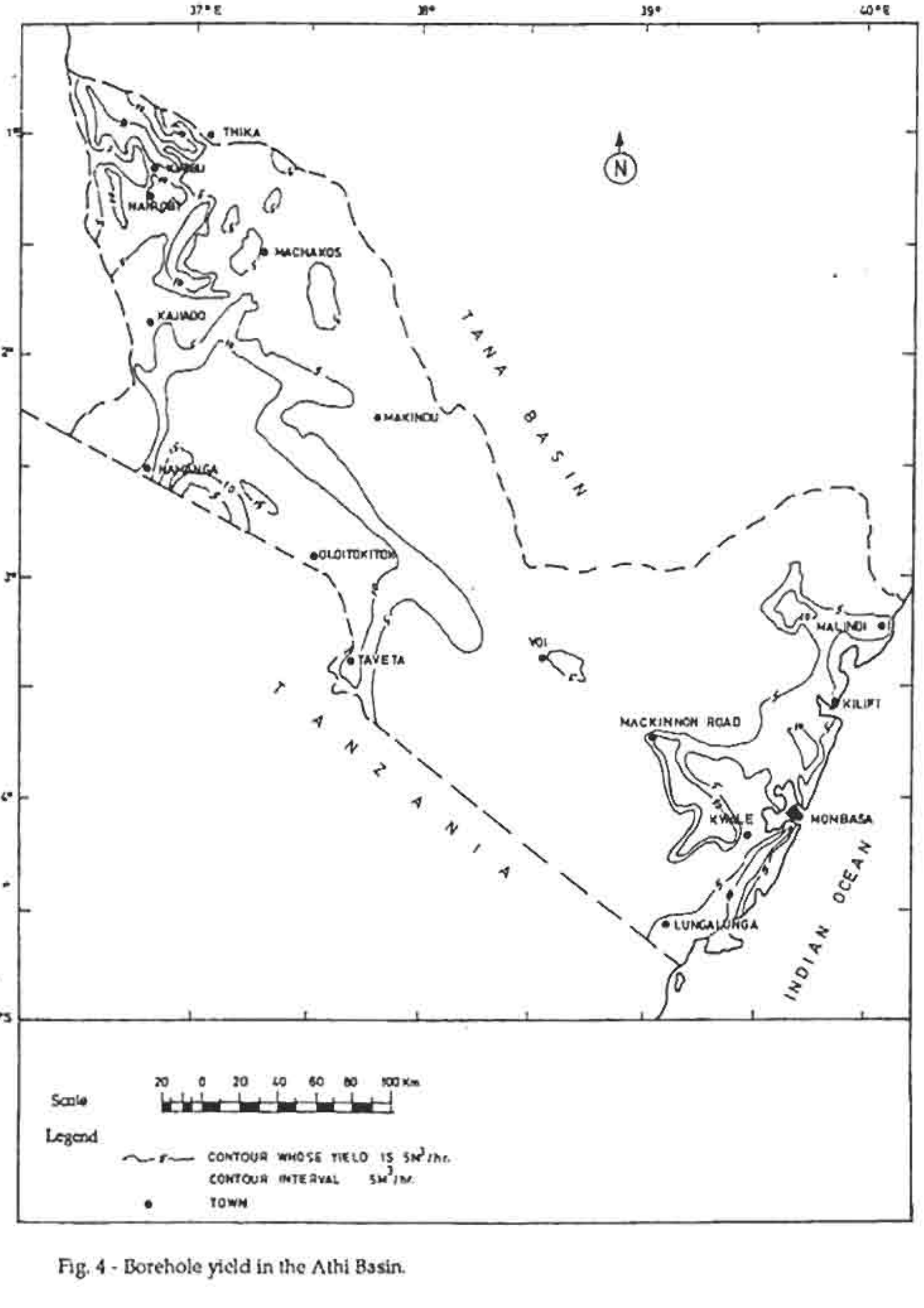


Fig. 4 - Borehole yield in the Athi Basin.

the overlying strata. They have not been encountered in metamorphic rocks in the Athi Basin.

The aquifer yields are based on analysis of pump tests of 1,500 boreholes radomnly selected from metamorphic, volcanic and sedimentary terrains. The results of the analysis are presented in Fig. 4.

It will be noted that the boreholes with yields below 5 m^3/hr are mainly found in the metamorphic rocks and are commonly associated with the weathered overburden. Isolated pockets of higher yields are associated with fractured zones.

Yields between 5 m^3/hr and 10 m^3/hr are common in volcanic and sedimentary rocks. They are mainly associated with permeable sediments. Widespread pockets of yields above 10 m^3/hr are common in both rock types.

Water rest levels of 700 boreholes have been reduced to mean sea level to facilitate the construction of the groundwater flow map as shown in Fig. 5. It will be noted that the groundwater divides more or less coincide with the surface water divides. The Athi-Galana-Sabaki River sub-basin forms the major groundwater discharge area. This is followed by the coastal plain in magnitude.

Table 1 - Aquifer types in the Athi Basin.

Aquifer Type	% Boreholes		
	Metamorphic Rocks	Volcanic Rocks	Sedimenatry Rocks
Fractured Zones	35	20	10
Weathered Overburden	65	26	0
Permeable Sediments	0	54	90
%Total	100	100	100
Sample size	150	140	110

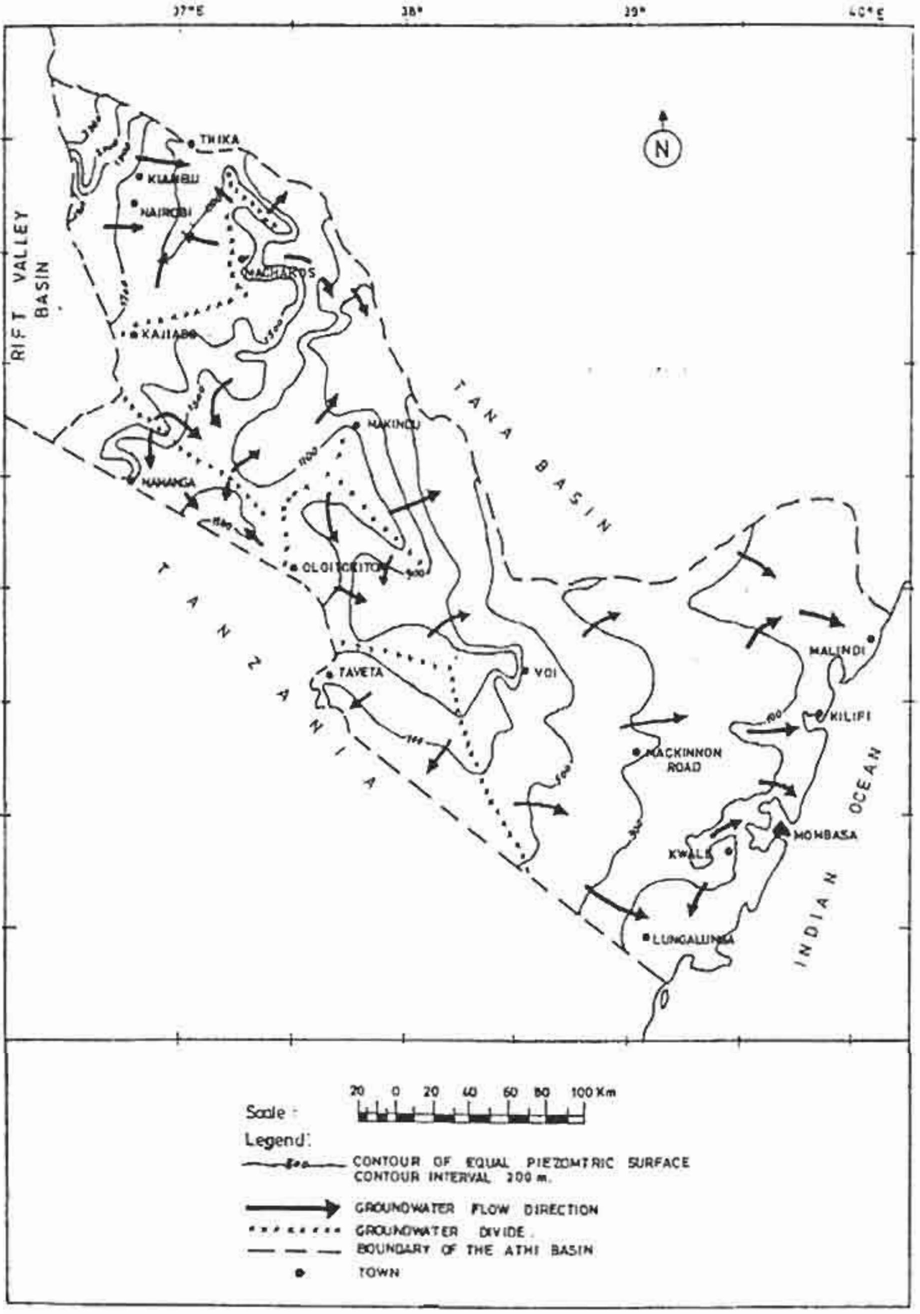


Fig. 5 - The groundwater flow in the Athi Basin.

Hydrogeochemistry

The usefulness of any water largely depends on its quality and that is why great importance has been attached to the hydrogeochemistry in this investigation. The mineral constituents of groundwater is plotted on trilinear diagrams (Figs. 6; 7; 8). From these it can be observed that waters in volcanic terrain are sodium carbonate-bicarbonate waters. Those in metamorphic terrain are mixed waters with significant ions of HCO_y, SO_4 and Cl while waters from the sedimentary terrain are mostly sodium chloride waters indicating marine influence. Other parameters considered and used in the determination of suitability or use include total dissolved solids (TDS), fluoride content and sodium adsorption ratio.

For total dissolved solids, 2000 samples were used to construct the distribution map. (See Fig. 9).

Table 2 - Classification of water based on TDS. (After GOORRELL, 1958).

Type of Water	TDS (mg/l)
Fresh	< 1000
Brackish	1,000-10,000
Salty	10,000-100,000
Brine	> 100,000

It will be observed from Fig. 9 that about 75% of groundwater in the Athi Basin is fresh and 25% is brackish. Cases of salty water and brine have not been observed in the basin. Water tapped from the volcanic rocks and lagoonal sands has values commonly below 500 mg/l. Consequently the water is suitable for most purposes.

The U.S. PUBLIC HEALTH SERVICE (1962) has recommended 1.5 mg/l as a safe maximum concentration of fluoride in water for human consumption. The recommendation has been adopted by the WHO (1984). Higher concentration may cause fluorosis.

Results of fluoride concentration from 300 groundwater samples were used to construct the map on the distribution of fluoride concentration in the Athi Basin as shown in Fig. 10.

It has been observed from the map that values above the recommended level are common in volcanic rocks. Such high values occur in isolated pockets associated with faulting in the metamorphic and sedimentary rocks. It is worth noting that although the water tapped from the volcanic rocks may be the best in terms of TDS, it may not be suitable for domestic purposes in the same areas particularly those underlain by phonolites of the Tertiary Period.

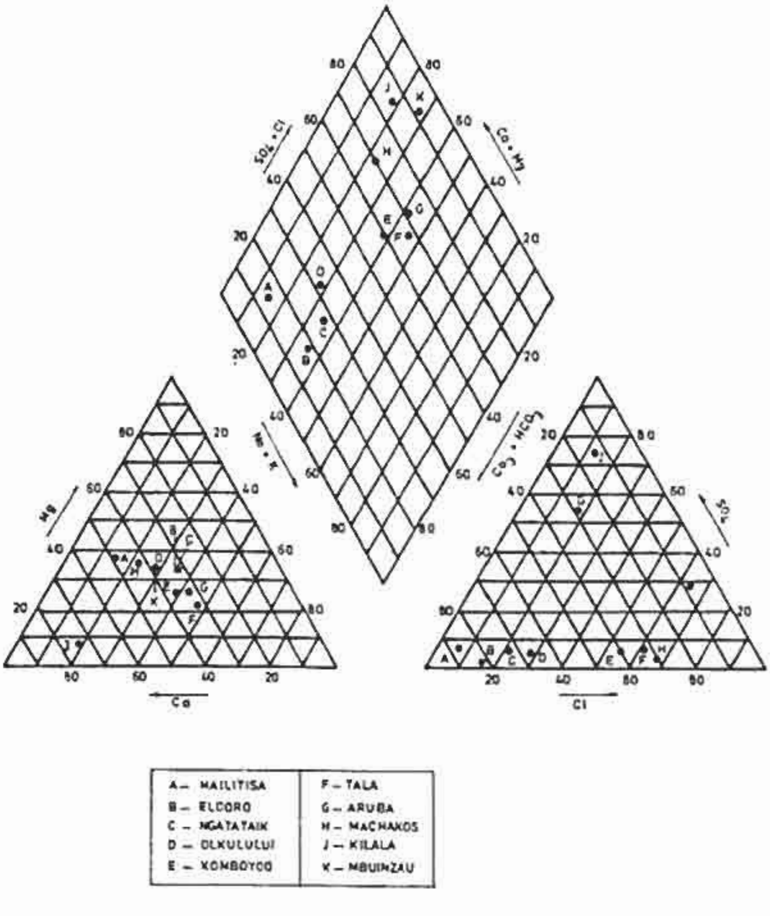


Fig. 6 - Piper diagram plot of groundwater quality of Metamorphic rocks in the Athi Basin. (Modified from MAILU, 1983).

Consideration of salinity and sodium hazards is very important for water used for irrigation. The U.S. SALINITY LABORATORY STAFF (1954) prepared a diagram for use in the classification of water on the basis of the salinity hazard as indicated by the electrical conductivity and sodium hazard as indicated by sodium adsorption ratio of the water. The sodium adsorption ratio is defined by the equation shown below:

$$\frac{Na^{+}}{\sqrt{\frac{Ca^{++} + Mg^{++}}{2}}}$$

Where Na^{+}, Ca^{++} and Mg^{++} represent the concentrations in milliequivalents per litre of the respective cations. The electrical conductivity is reported in micro siemens per centimetre (ms/cm) at 25°C.

This method was adopted for the classification of the water in the Athi Basin as shown in Fig. 11.

Development

The history of groundwater development in the Athi Basin dates back to late 1920's when drilling of the first boreholes commenced. By the end of 1986 more than 2500 boreholes had been drilled in the Athi Basin.

Before 1975 most boreholes were drilled by percussion rigs, but after this year, rotary rigs were used by both the Ministry of Water Development and drilling contractors. Currently there are more than 65 percussion and 25 rotary rigs which are being deployed for groundwater development.

The central region and some parts or the coastal region depend almost entirely on groundwater. However, in the north western and the Chyulu-Kilimanjaro regions, groundwater is developed to augment the surface water. Of late the north-western region has by far surpassed the other regions in groundwater development. In fact, about 50% of the boreholes drilled in the Athi Basin area in the north-western region. The high agricultural and industrial development in the region has brought about a situation where surface water demand is higher than supply, hence the need to resort to groundwater sources.

The groundwater development in and around Nairobi city is so high that conservation measures are being taken to avoid over-pumpage of the aquifers. Similar measures are imminent along the coastal plain to prevent sea water intrusion.

The central region which is underlain by Precambrian metamorphic and Permo-Triassic sedimentary rocks is underdeveloped in terms of groundwater although it almost entirely depends on groundwater. The reason for this anomaly is that the economic returns of the region are far much lower than those of the north-western region and hence they cannot justify the high cost of intensive drilling that is taking place in the north western region.

Use

Groundwater in the Athi Basin is mainly for domestic, agricultural and/or industrial purposes. Table 3 shows the level of groundwater use in the basin. Boreholes drilled for exploratory purpose have also been included.

Table 3 - Level of groundwater use in the Athi Basin.

Purpose	Boreholes	
	No.	%
Agricultural	377	49.5
Domestic	275	36.1
Industrial	65	8.5
Exploratory	45	5.9
Total	762	100.0

The usefulness of water for any given purpose depends very much on the quality of water. The quality will, therefore, be considered in dealing with each purpose separately.

Table 4 - TDS upper limits for liverstock water. (After the Officiers of the Department of Agriculture and Gouvernement Chemical Laboratories of Western, Australia, 1952).

Livestock	TDS Upper Limit (mg/L)
	> 2860
Poultry	2860
Pigs	4290
Horses	6435
Cattle (Dairy)	7150
Cattle (Beef)	10,000
Adult Sheep	12,900
	< 2,900

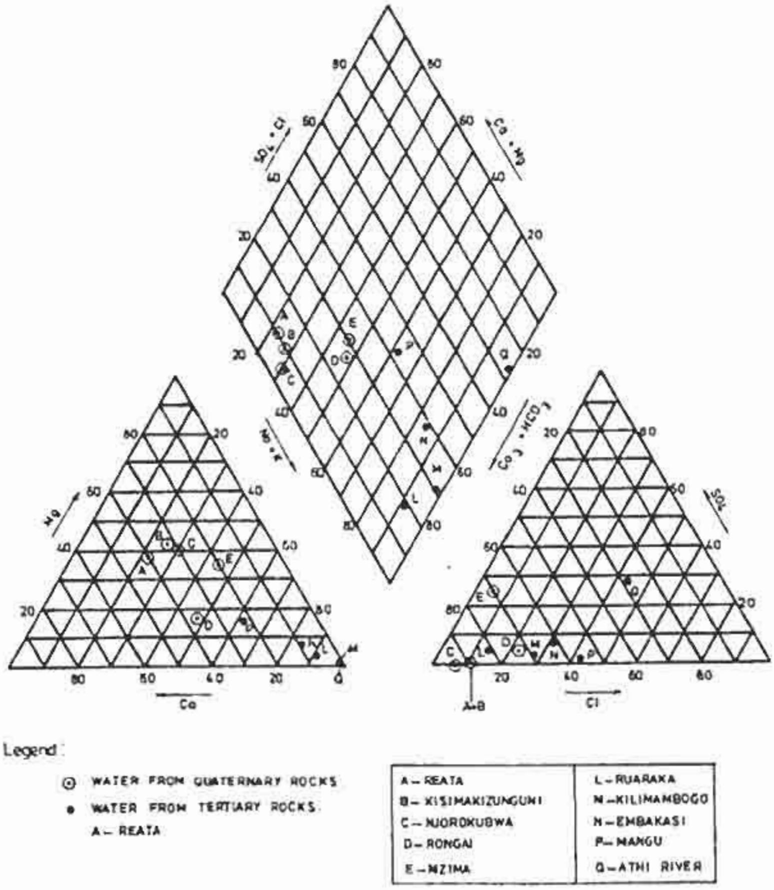


Fig. 7 - Piper diagram plot of groundwater quality of Volcanic rocks in the Athi Basin. (Modified *from* MAJLU, 1983).

Agricultural Use

For the purpose of this investigation, the agricultural use is considered under two sub-heads, namely, irrigation and livestock.

It is noted from Fig. 11 that the water has generally low sodium hazard, but has high salinity hazard. Consequently if it has to be used for irrigation purposes it should be applied to well drained soils and salinity control measures should be instituted. In any case, crops which have high salinity resistance should be planted.

The Officers of the DEPARTMENT of AGRICULTURE and GOVERNMENT CHEMICAL LABORATORIES of Western Australia (1950) recommended, the TDS upper limits for various animals as shown in Table 4.

It has been observed that most of the groundwater quality in the Athi Basin is mainly fresh to brackish. Hence it can be used for livestock development without any injurious effects.

Table 5 - Recommended TDS for industrial use. (After MOORE, 1940).

Industry	Recommended upper limit of TDS (Mg/1)
1. Confectionary	100
2. Clear, uncoloured plastics and high grade light paper	200
3. Pulp	300
4. Light beer	500
5. Carbonate Beverage	850
6. Dark beer	1,000

Domestic Use

As far as the quality in terms of total dissolved solids is concerned, the groundwater from most aquifers in the Athi Basin is suitable for human consumption. This is true on the basis of the WHO (1984) recommendation that the upper limit of TDS of water for human consumption is 1.500 mg/l. On the other hand, water from some pockets in the Tertiary volcanic rocks has levels of fluoride concentration above the recommended upper limit of 1.5 mg/l.

Industrial Use

Different industrial uses require varied qualities of water. MOORE (1940) has attempted to establish the upper limits of TDS concentrations for a number of

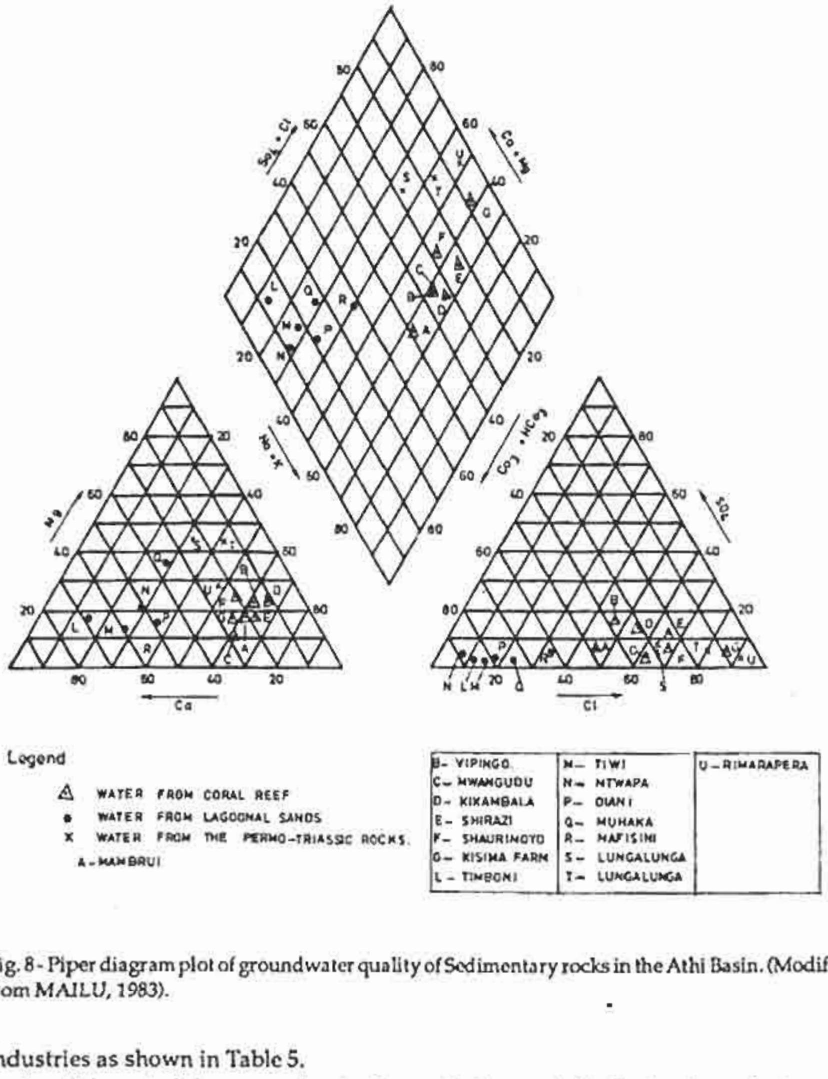


Fig. 8 - Piper diagram plot of groundwater quality of Sedimentary rocks in the Athi Basin. (Modified from MAILU, 1983).

industries as shown in Table 5.

It will be noted that groundwater for confectionery is limited and may be tapped from some pockets in the volcanic rocks of the Quaternary Period and the lagoonal sands of the same period. Water for high grade light paper, light beer and pulp is common in the foregoing volcanic rocks and the lagoonal sands. The water for carbonate beverage and dark beer is available almost everywhere in the Athi Basin.

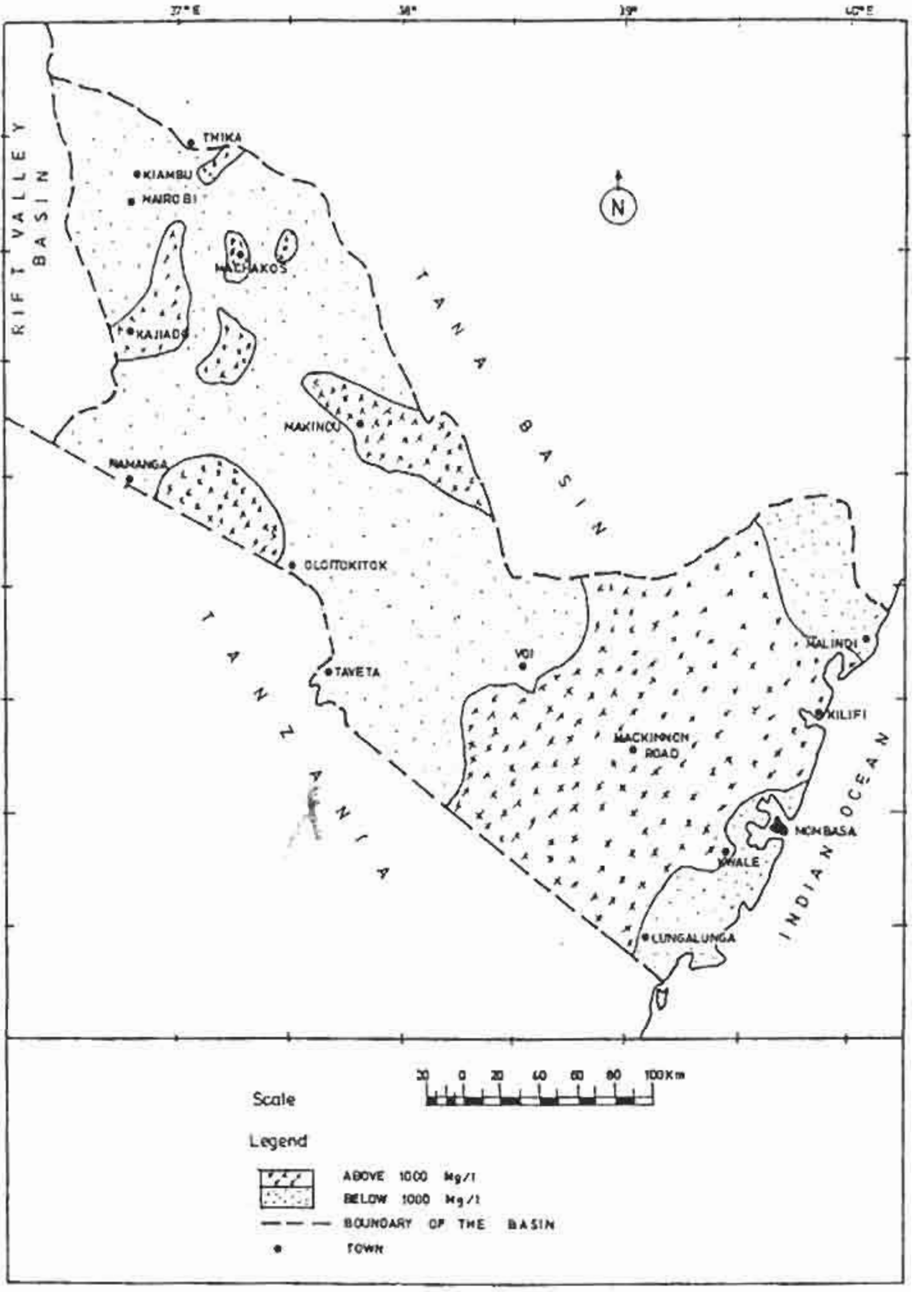


Fig. 9 - The total dissolved solids concentration of the groundwater in the Athi Basin.

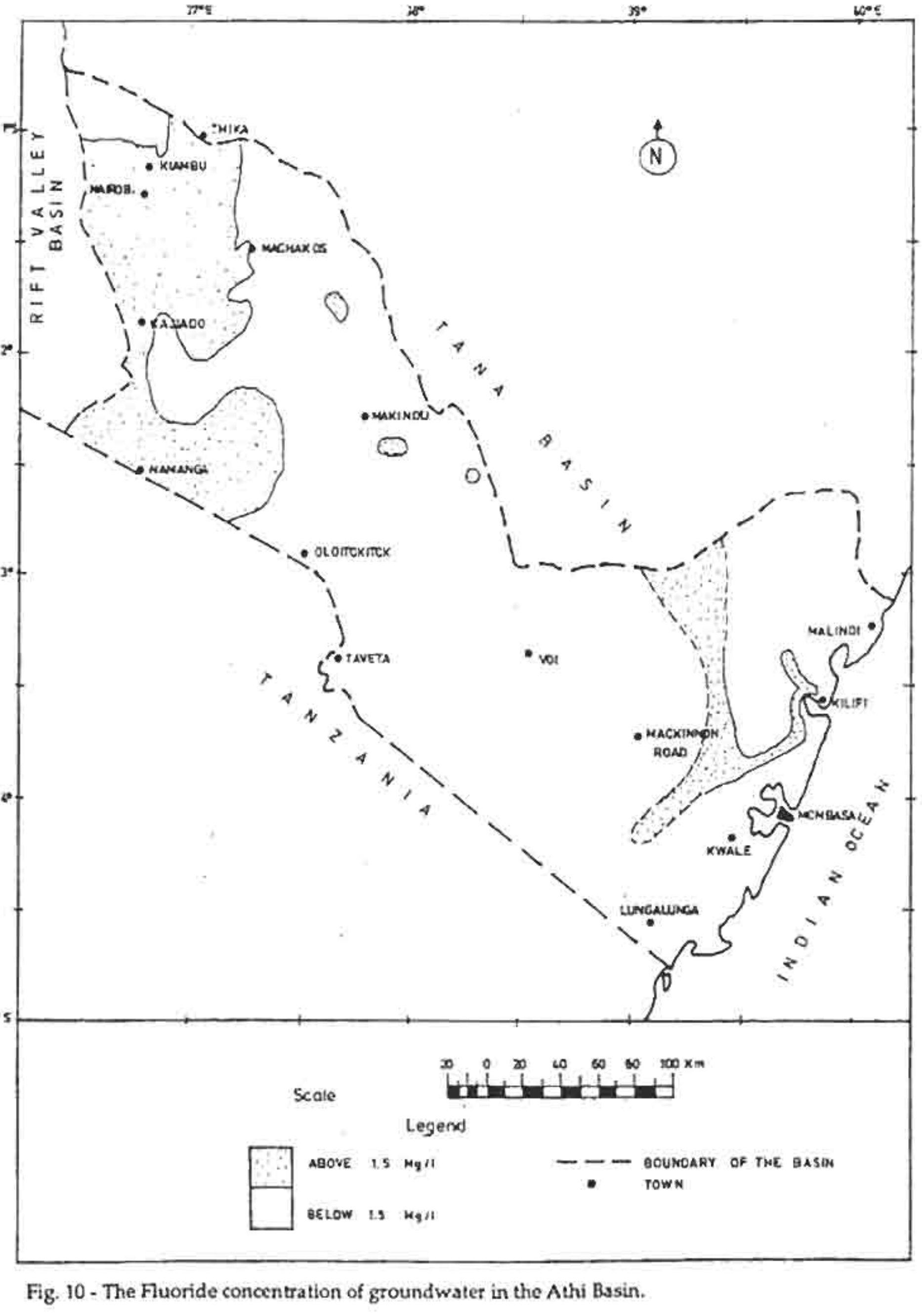


Fig. 10 - The Fluoride concentration of groundwater in the Athi Basin.

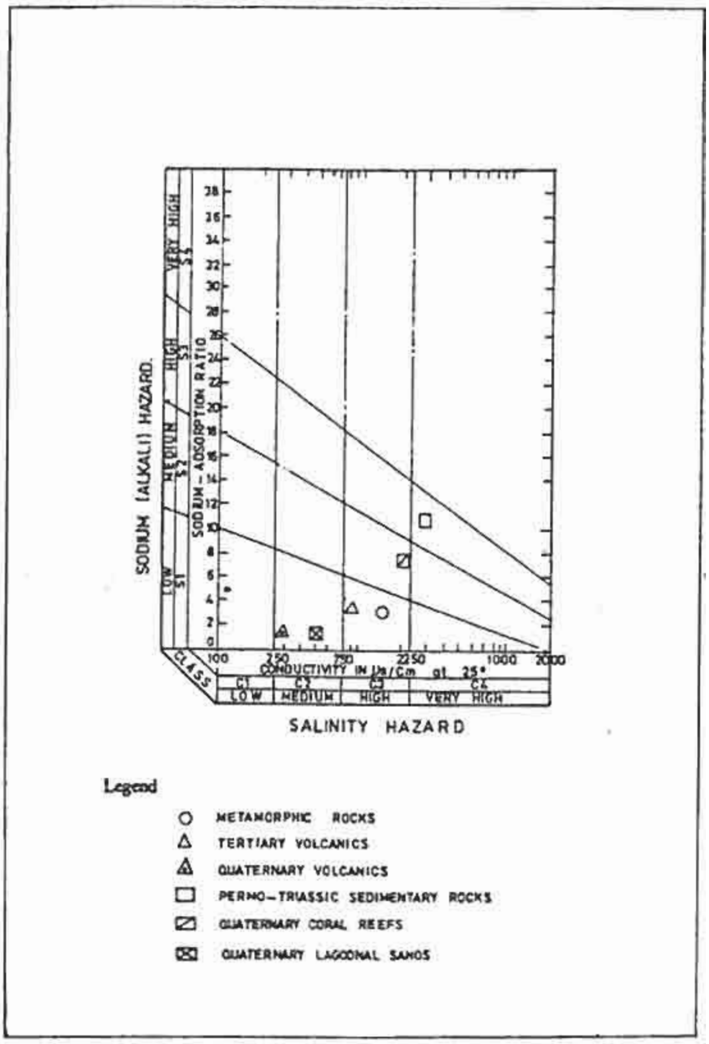


Fig. 11 - Sodium and salinity hazards of groundwater in various rock types in the Athi Basin. (Modified from US. Salinity Laboratory Staff, 1954).

CONCLUSIONS AND RECOMMENDATIONS

The occurrence of groundwater in the Athi Basin is strongly controlled by the geology. It has been observed that the aquifers are mainly associated with fractures and weathered overburden in the consolidated rocks. In the volcanic rocks and the young sedimentary rocks, the aquifers are associated with primary permeability of certain strata. The aquifers associated with fractures are usually deeper and more productive than the aquifers associated with overburden. The aquifers associated with primary permeability have variable depths depending on the overlying strata and they are generally the most productive.

The general direction of flow of the groundwater is to the south east on a regional scale, but it is quite variable on a micro scale.

The quality of the water is good with more than 75% showing values below 1000 mg/l of total dissolved solids. Consequently the water is useful for most purposes.

The heavy groundwater development in the Athi Basin is concentrated in the north-western region underlain by volcanic rocks and the coastal region underlain by lagoonal sands. There are fear of over development of the water in the two regions.

In fact, Nairobi area and its suburbs have been declared a conservation area and measures to restrict groundwater development are being enforced.

Similar enforcement is imminent in the coastal area.

On the basis of the foregoing conclusions the following recommendations have been drawn to ensure proper management of the groundwater development and utilization in the basin.

DATA BANK

The borehole data in the Athi Basin are scattered in various departments in their raw form. It is recommended that a data bank be established for the analysed data which can be efficiently stored, retrieved and reviewed from time to time depending on the need. Complementary hydrogeological models and maps should be processed at scales which are meaningful to the groundwater planners.

EXPLORATION

There is no sufficient data analysis to establish the level at which groundwater in the north-western and the coastal region is being over-developed. It is therefore recommended that exploration should be mounted to establish the quantitative capacity of each aquifer in order to rationalize further development or restriction of the water. Experiments on sea water intrusion should be carried out along the coast in order to establish the optimum development which will not cause sea water intrusion.

WELLS AND SPRINGS

Although wells and springs in the basin are important water supply sources, their records have not been properly documented. There is immediate need to quantify their supply and analyse their water quality if a total groundwater perspective of the basin has to be appreciated.

SUB-SURFACE DAMS

Where borehole drilling is not viable, particularly in certain areas underlain by metamorphic rocks, possibility of tapping water from sub-surface dams should be investigated particularly where river beds are laden with thick deposits of coarse sands.

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