The Red Sea: A Natural Geodynamic and Metallogenic Laboratory

by Yves Thisse, Pol Guennoc,
Georges Pouit and Zohair Nawab

As one of the youngest oceanic zones on Earth – an ocean in the making – the Red Sea is of enormous interest in understanding structural and tectonic phenomena related to ocean floor spreading and in reconstructing the history of the global tectonics. In addition, in the last twenty years metalliferous deposits have been discovered in the Red Sea. Their study should lead to a better understanding of processes of metal concentration and to useful guides in the exploration for new deposits, such as those associated with old oceanic formations.

Introduction

Separating the Arabian and Nubian plates, the Red Sea is an elongated, narrow depression nearly 2000 km long and averaging 300 km in width. It is relatively deep, exceeding 2000 m in the axial zone and almost closed in the south where only the shallow strait of Bab-el-Mandeb connects it to the Indian Ocean through the Gulf of Aden.

Although the history of investigation of the Red Sea goes back to the late 19th century, the mid-1960s mark the true beginning of its scientific exploration, with oceanographic studies increasing both in number and diversity (Table 1). The first major result was the demonstration of the basaltic nature of the axial rift and the conclusion that the Red Sea opened by a process of oceanic accretion (Chase, in Degens and Ross, 1969; Falcon *et al.*, 1970; Coleman, 1974). Of equal importance was the discovery of metalliferous sediments covered by hot brines at the bottom of depressions or deeps usually situated along the rift axis (Degens and Ross, 1969).

The scientific results, together with the potential mining value of certain of the Red Sea deposits, led in 1974 to the creation of the Saudi-Sudanese Red Sea Commission. The SSRSC then hired Preussag (F.R.G.) and BRGM (France) to verify the economic importance of the deposits and to study processes for eventual recovery and treatment of the metalliferous muds, as well as the ecological impact of such development. The mineral reconnaissance work very soon focussed on the Atlantis II Deep – opposite Jeddah – a site 60 km² in area and 220 m deep. With nearly 700 core samples, this is now one of the best-explored underwater zones in the world.

An Ocean in the Making

Morphologically, the Red Sea consists of a narrow continental shelf to the east and west, a wide central depression extending from 15°N to the tip of Sinai (28°N) and contained

between the 600 m and 1500 m bathymetric contours, and a narrow, clearly marked axial valley or rift from 15° to 24°N (Fig. 1). The latter is 30 km wide and up to 2000 m or more deep, and is characterized by irregular topography and stepped sides, similar to the Mid-Atlantic Rift. The axial zone of the Red Sea has a tholeiitic substratum and was formed by oceanic accretion. Magnetic lineations indicate

Table 1. Major Investigations of Red Sea Deepes

1881-83	Vityaz (U.S.S.R.)	}	First measurements of temperature and salinity in Red Sea deep waters	
1897	Pol (Austria)			
1898	Valdivia (Germany)			
1948	Albatross (S)	}	Discovery of anomalously high temperature and salinity values around 21°N	
1959	Atlantis (U.S.A.)			
1963	Atlantis II (U.S.A.)			
1963	Discovery (U.K.)			
1964	Discovery (U.K.)			
1964-65	Meteor (F.R.G.)	}	Discovery of the deeps, dredging, coring of metalliferous muds	
1965	Atlantis II (U.S.A.)			
1965	Meteor (F.R.G.)			
1966	Chain (U.S.A.)			
1966	AK.S. Vavilov (U.S.S.R.)			
1967	Discovery (U.K.)			
1967	Oceanographer (U.K.)			
1969	Chain (U.S.A.)			
1969	Wando River (U.S.A.)			
1970-71	Nereus (Saudi Arabia)			
1971	Valdivia (F.R.G.)	}	SSRSC program devoted to evaluation of the economic interest of muds and ecological impact of an exploitation	
1972	Glomar Challenger (U.S.A.)			
1976	AK. Kurchatov (U.S.S.R.)			
1977-78	Sonne (F.R.G.) - Commission I (SO-01)			
1977-78	Sonne (F.R.G.) - Meseda I (SOI-02)	}		
1979	Valdivia (F.R.G.) - Meseda II (Va22)			
1979	Sedco 445 (F.R.G.) - Pre Pilot Mining Test			
1980-81	Valdivia (F.R.G.) - Meseda III (Va29)			
1981	Marion-Dufresnes (France) - COMMAR I (MD29)	}	(U.S.S.R.) - study of 18°N axial area and diving in the Atlantis II area	
1979	Jean-Charcot (France) - MEROU - bathymetric survey (Seabeam)			
1980	AK. Kurchatov Pr. Chotkman BRS Agnarrante	}	(U.S.S.R.) - study of 18°N axial area and diving in the Atlantis II area	

- Hackett, J.P. and Bischoff, J.L., 1973. New data on the stratigraphy, extent, and geologic history of the Red Sea geothermal deposits. *Economic Geology*, v. 68, no. 4, p. 553-564.
- Hall, S.A., Andreasen, G.E. and Girdler, R.W., 1977. Total-intensity magnetic anomaly map of the Red Sea and adjacent coastal areas, a description and preliminary interpretation. In: *Red Sea Research, 1970-1975*, Saudi Arabia, Directorate General of Mineral Resources, Bulletin no. 22, p. F1-F15.
- Hartmann, M., 1980. Atlantis II Deep geothermal brine system. Hydrographic situation in 1977 and changes since 1965. *Deep Sea Research*, v. 27, no. 2A, p. 161-171.
- Izzeldin, A.Y., 1982. On the structure and evolution of the Red Sea based on geophysical data from the central and northern parts. Ph.D. Thesis, Strasbourg, 165p.
- Länge, J., Bäcker, H. and Karbe, L., 1981. Erzschlamm im Atlantis II Tief-Lagerstätten und Umweltuntersuchung. International Conference on Ocean Mining, Düsseldorf, 1981, p. 91-102.
- Le Pichon, X. and Francheteau, F., 1978. A plate tectonic analysis of the Red Sea-Gulf of Aden area. *Tectonophysics*, v. 46, no. 3-4, p. 369-406.
- Lowell, J.D. and Genik, G.J., 1972. Sea-floor spreading and structural evolution of the Southern Red Sea. *American Association of Petroleum Geologists Bulletin*, v. 56, no. 2, p. 247-259.
- Lupton, J.E., Weiss, R.F. and Craig, H., 1977. Mantle helium in the Red Sea brines. *Nature*, v. 266, no. 5599, p. 244-246.
- Manheim, F.T., 1974. Red Sea Geochemistry. In: Whitmarsh, R.B., et al. (eds.), *Initial Reports of the Deep Sea Drilling Project*, v. 23, U.S. Government Printing Office, p. 975-998.
- Oudin, E., 1981. Étude minéralogique et géochimique des dépôts sulfurés sous-marins actuels de la ride Est-Pacifique (21°N). *Documents BRGM*, v. 25, 241p.
- Oudin, E., 1983. Minéralogie de gisements et indices liés à des zones d'accrétion océaniques actuelles (ride Est-Pacifique et mer Rouge) et fossile (Chypre). *Chronique de la recherche minière*, v. 470, p. 43-56.
- Oudin, E. and Thisse, Y., 1983. Fluides minéralisateurs de haute température dans la mer Rouge. *Géochronique*, v. 2, p. 5.
- Pottorf, R.J. and Barnes, H.L., 1978. The nature of hydrothermal sediments in the Atlantis II Deep of the Red Sea. *Geological Society of America, Abstracts with programs*, vol. 10, no. 7, p. 473.
- Pouit, G., Bigot, M., Delfour, J., Milesio, J.-P. and Picot, P., 1982. Les minéralisations actuelles et anciennes: l'exemple de la mer Rouge. *Documents du BRGM*, no. 52, 90p.
- Schoell, M. and Faber, E., 1978. New isotopic evidence for the origin of Red sea brines. *Nature*, v. 275, no. 5679, p. 436-438.
- Shanks, W.C., III, and Bischoff, J.L., 1980. Geochemistry, sulfur isotope composition and accumulation rates of Red Sea geothermal deposits. *Economic Geology*, v. 75, no. 3, p. 445-459.
- Thisse, Y., 1982. Sédiments métallifères de la fosse Atlantis II (mer Rouge). Contribution à l'étude de leur contexte morpho-structural et de leurs caractéristiques minéralogiques et géochimiques. Thèse Université Orléans et BRGM, 155p.
- Thisse, Y., Oudin, E. and Ramboz, C., 1983. Boiling fluids in the Red Sea metalliferous sediments. *Current European Research on Fluid Inclusions*, abstract.
- Weiss, H.M., Nöltner, T. and Stoffers, P., 1980. The occurrence of ilvaite in metalliferous brine muds from the Red Sea. *Neues Jahrbuch für Mineralogie Abhandlungen*, v. 139, no. 3, p. 239-253.
- Zierenberg, R.A. and Shanks, W.C., III, 1983. Mineralogy and geochemistry of epigenetic features in metalliferous sediment, Atlantis II Deep, Red Sea. *Economic Geology*, v. 78, no. 1, p. 57-72.

RECENT IUGS PUBLICATION

THE ORDOVICIAN SYSTEM IN SOUTHWESTERN EUROPE

(France, Spain and Portugal):

Correlation Chart and Explanatory Notes

by

W. Hammann, M. Robardet and M. Romano

with the collaboration of M.D. Gil, J.C. Gutierrez, P. Herranz, A. Marcos, J. Martin, J.R. Palaez, A. Perez-Estaun, M. Prieto, I. Rabano, M.A. de San Jose, J. Trujols, R. Vegas, L. Vilas, E. Villas and J. Villena.

IUGS Publication 11, 1982, 47 p., one map and one correlation chart. Sponsored by IUGS Subcommittee on Ordovician Stratigraphy. \$7.50 (U.S.).

Available from:

EPISODES
601 Booth Street
Room 177
Ottawa, Ontario
Canada K1A 0E8

or

IUGS
Maison de la Geologie
77, rue Claude Bernard
75005 Paris
France

NEW IUGS PUBLICATION

THE CAMBRIAN SYSTEM IN THE NEAR AND MIDDLE EAST

Correlation Chart and Explanatory Notes

by

R. Wolfart

IUGS Publication 15, 1983, 70p., one figure and one four-colour correlation chart. Sponsored by IUGS International Subcommittee on Cambrian Stratigraphy. \$10.00 (U.S.).

Available from:

EPISODES
601 Booth Street
Room 177
Ottawa, Ontario
Canada K1A 0E8

or

IUGS
Maison de la Geologie
77, rue Claude Bernard
75005 Paris
France

Figure 1: Schematic section of the Red Sea in the area 19° to 24°N, after El Tayeb *et al* (1979), Cochran (1981) and Izzeldin (1982). Basement structures not to scale. 1 - continental crust of the Arabo-Nubian Precambrian basement; 2 - mainly Miocene volcanics; 3 - proto-oceanic crust formed at a very slow rate under unit 6; 4 - Pliocene to Recent oceanic crust; 5 - Early Miocene (19-26 Ma) diabase dykes (Blank, 1977); 6 - Middle to Upper Miocene massive salt covered by stratified evaporites; 7 - Pliocene to Quaternary sediments; 8 - Miocene to Recent basalt plateaus.

that the spreading occurred between 5 and 6 Ma ago in the southern part and seems to be advancing from the south to the north (Drake and Girdler, 1964; Izzeldin, 1982)

The substratum under the other parts of the Red Sea is difficult to study because it is covered by a thick Miocene evaporite series, which extends down 3000 m or more in places. The top of this formation is marked by a strong seismic reflector similar to the one observed in the Mediterranean. Under the influence of salt tectonics, the evaporites have flowed over the newly formed crust, partly covering it, and, in the north where accretion has still not been effective, it occupies the entire width of the Red Sea.

The Red Sea is thus a geologically recent opening in the Afro-Arabian continent. Following a pre-rifting phase during the Oligocene, the central depression began to form only during the lower Miocene. A long and vigorous debate continues over the nature of the crust in the marginal regions. Is it continental material that has undergone large-scale stretching and thinning before opening in the early Pliocene (Lowell and Genik, 1972; Le Pichon and Francheteau, 1978), or does it represent an oceanic crust formed during the Miocene or even earlier (Hall *et al.*, 1977)? The latter alternative is supported by certain magnetic lineations, the thickness of the crust in these regions and the terrestrial volcanism in southern Arabia.

An explanation for many observations was put forward by Cochran (1981) for the Gulf of Aden and later for the Red Sea (1983), based on opening by continental stretching with associated basic intrusions. These models account for the clearly observable magnetic lineations, especially in the southern part of the Red Sea; these apparently correspond to terrestrial intrusions, particularly those of the Arabian Shield (Blank, 1977). Cochran's model also explains the presence of outcrops of Precambrian basement off the coastal areas, such as Zabargad Island (Bonatti *et al.*, 1981,) and similar inliers inferred elsewhere from seismic refraction velocities (Drake and Girdler, 1964). It also accounts for numerous indications of Miocene volcanism and for the existence of intrusions in the Miocene salt-bearing series (Lowell and Genik, 1972).

Indeed the opposing hypothesis of an oceanic crust covering the full width of the Red Sea implies an abrupt rupture of the continental crust which is very unlikely (Lowell and Genik, 1972). There is also the difficulty in attempting to recon-

struct the pre-opening period and of covering the continental masses to the south and north (Le Pichon and Francheteau, 1978).

Using aeromagnetic, multitrace seismic reflection and gravimetric data collected by the SSRSC between 18° and 24°N, Izzeldin (1982) supports the concept of stretching of the continental crust, combined with basic intrusions. Between 10 and 12 Ma ago this process led to the creation of a "diffuse oceanic" crust formed at a low expansion rate, at least in the area between 17° and 19°N. The complete rupture of the continental crust had to occur before true oceanic accretion appeared 5 to 6 Ma ago, accompanied by the gradual spreading out of the Miocene salt cover to outcrops in the axial regions of the oceanic crust.

The long debate is obviously not over yet, for deep drilling through the thick evaporites is still required. Nevertheless there is general agreement that spreading is advancing from south to north, with geomorphological and structural features that correspond to rather advanced stages of opening.

Mineralization – Cretaceous to the Pleistocene

In addition to the zinc, copper, silver and other deposits of the present axial deeps, a number of older occurrences (Fig. 2) have been found during exploration along the edges of the Red Sea (Pouit *et al.*, 1983).

The Late Cretaceous to Eocene pre-rifting period was characterized by tectonic instability due to regional uplift, by erosion of the cover and by alkaline magmatism. The latter comprises mainly alkaline basalt flows and annular complexes with nepheline syenites, essexites and carbonatites and trachytes, phonolites, rhyolites and pyroclastics. The lavas are found only in Yemen to the south, while the ring complexes are found in Sudan and Egypt, in places with a NNW alignment similar to that of the future Red Sea rift.

Two kinds of mineral deposits were formed during this period, but only in the northern part of the Red Sea region. First, there are marine phosphates of Upper Cretaceous (Egypt and Saudi Arabia) to Eocene age (Saudi Arabia), but set back from the Red Sea itself. These are likely to be related to special palaeoclimatic conditions which existed from Morocco to Syria, but the morphology of the basin at this pre-rift stage probably provided a trap for the deposits. Secondly, in association with the ring complexes there are rare earths, U,

Figure 2: Regional Setting and Tertiary to Recent Mineral Deposits of the Red Sea.

Ni, Ta and other related minerals, together with Al which may one day be of economic interest.

During the Oligocene, the Red Sea began following its own special path of development. This is marked by an absence of marine deposits, by intense erosion with formation of conglomerates (in places very coarse-grained) and other detrital deposits, and by the start of extensive volcanism, especially in Ethiopia and Yemen. Oligocene deposits rest unconformably on the basement rock or in a few places on Cretaceous-Eocene rocks. Horsts and grabens are particularly evident along the Arabian margin and seem clearly controlled by older structures in the basement.

The associated mineralization is of two kinds. First there are red beds with copper or Pb-Zn which seem to be mutually exclusive. The metals in stratiform deposits, found especially in northwest Saudi Arabia, impregnate colourless detrital horizons interstratified with red formations. Oolitic iron deposits comprise the second group. Large concentrations (50 Mt at 44%-50% Fe) are observed in the Wadi Fatima graben east of Jeddah. Oolitic iron occurs at two levels in the Shumargi Formation (Eocene to the Oligocene) which consists of red detrital deposits, cherts, tuffs and basic lavas.

In the Miocene, the separation between Africa and Arabia became more pronounced and the Red Sea depression was formed. Mineralization was common along both sides of the northern half of the Red Sea, particularly in the earlier reactivated grabens where differentiated sediments such as

marls, evaporites and reef deposits are found. Occurrences have been recorded of Mn, Ba and/or Pb-Zn (with Ba, Cu and Ag), the latter sometimes dubiously assigned to the "Mississippi Valley" type.

This Miocene mineralization seems to be penecontemporaneous with the deposition of the host sediments but with a source from deep hydrothermal solutions. Deposits range from concordant to cross-cutting and are localized in certain Miocene reef and conglomeratic facies, strictly controlled by modern tectonics. Found are diffuse impregnations, blobs, peneconcordant pockets and veinlets sometimes (as at Umm Ghaeig in Egypt) constituting cross-cutting bodies along faults and peneconcordant interdigitations. In all cases there is an apparent direct or indirect structural control. Yet the discordant mineralizations are not primary and certainly cannot be due to later remobilization. A hydrothermal-sedimentary origin seems therefore likely.

Several deposits are related to the opening of the southern Red Sea between 5 and 6 Ma ago. These include horizons of black shales drilled by the Glomar Challenger in the post-evaporite marine sediments, which are slightly enriched by several hundred ppm of Cu and Zn (Manheim, 1974) and concentrations of manganese found in brownish reef limestones. The Mn-Fe (Ba) deposit (Bonatti et al., 1972) of the east edge of the Afar rift, separated from the Red Sea by an outlier of continental crust (the Danakil horst), was formed 200 000 years ago on oceanic crust covered by a basal conglomerate composed of volcanic clasts. The deposit is two meters thick with iron at the base and manganese at the top. It has a gangue of opal and barite and extends over several square kilometers, representing several million tonnes of ore.

These deposits and many other shows found in the Afar depression are located at the edge of oolitic reef limestones, and their origin is certainly hydrothermal-sedimentary. Moreover, hydrothermal activity is present throughout the whole region, as shown by numerous hot springs (50°C to 100°C+), the hot brines of Lake Giuletti in the Afar depression (comparable to those of the Atlantis II Deep), and by high temperatures and precipitates of massive sulphides (e.g. galena) recorded in drill holes on the shores of Lake Asal, Djibouti.

Recent to Present Day Metalliferous Sediments

The key to the origin of the older deposits undoubtedly lies in the presence along the rift axis of troughs containing Recent to modern-day metalliferous sediments usually covered by hot brines. The most significant example of these is the Atlantis II Deep.

The first true temperature and salinity anomalies in the deep water of the Red Sea opposite Jeddah were revealed in 1948 by the Swedish ship Albatross. Other measurements taken in this area confirmed these anomalies and led to the discovery of metalliferous sediments at the bottom of depressions along the rift axis. Of the 24 troughs with mineralized sediments and/or hot brines discovered to date (Table 2), only the Atlantis II Deep which is the most heavily mineralized, has been studied in detail (Guennoc and Thisse, 1982).

Atlantis II Deep – Morphology and Structure

The Atlantis II Deep (Fig. 3) appears at 21°N as a 2200 m deep trough, 14 km x 5 km in area, trending in the general direction of the axial valley. Its outer contours are limited mostly to the 2000 meter isobath, which corresponds to the top of the hot brines that fill it. Bäckér and Richter (1973) subdivide the deep into four basins joined by thresholds or "passes", which are gaps between blocks of rock emerging from the brines. The largest of these is the Central Sill.

The east and west sides of Atlantis II are bounded by stepped fault scarps (Fig. 3), which recall the morphology of another slow-spreading ridge, that of the Mid-Atlantic. To the south and north, the axial zone has a maximum depth of 1500

Table 2.
CHARACTERISTICS OF THE BRINES AND METALLIFEROUS
SEDIMENTS OF THE MAIN AXIAL DEEPS
from Bäckér and Schoell (1972) and Bignell *et al.* (1976)

NAME	DEPTH	Thick in m	BRINES		METALLIFEROUS MUDS				Fig-2 Ref.
			Temp. in °C	Cl %	Approximate content of Fe % Mn % Zn ppm Cu ppm				
SUAKIN	2850	54-74	24	86	10	3	700-3000	70-300	1
VOLCANO	2050-2400	no brines			traces				2
PORT SUDAN	2830	322	36.2	125	5	0.3	360	70	3
ERBA	2396	19	28	86.5	traces				4
SHAGARA	2496	8	?	113	3.5	3.0	200	70	5
ALBATROSS	2133	72	24.4	143	5	0.3	300	70	6
A	2072	83	52	154	12	35	12000	200	7
CHAIN B	2130	140	46.5	146	12	35	12000	200	
C	2165	167	44.5	154	no metalliferous sediments				
DISCOVERY	2224	209	45	155	10	1.3	1400	100	
VALDIVIA	1500-1673	123	30	145	5	0.4	250	80	
ATLANTIS II	2200	200	50-64	92-188	28	5	34000	13000	
HATIBA	2300				20	0.6	850	2500	8
HADARBA	2200				3.5	0.6	300	70	9
THETIS	1970	no brines			23	9	4200	750	10
NEREUS (E Basin)	2458	39	30	165	10	2	1500	150	11
VEMA	1611	no brines			5	0.3	250	70	12
GYPSUM	1196	no brines			20	0.3	900	200	13
KEBRIT	1573	107	23	153	3	0.3	250	70	14
OCEANO-GRAPHER	1528	>100	?	160	1.11	0.4	87	24	15

meters and a low relief. Here the oceanic crust and the central channel disappear under several hundred meters of evaporites and marls for a distance of about 40 km. Beyond this new rift sections reappear with basaltic crust rock and mineralized troughs.

The deep is marked by a number of transverse fractures (Bäckér, 1973; Bäckér *et al.*, 1975; Bignell *et al.*, 1976). Between 20° and 21°30'N, three such discontinuities have been discovered, extending nearly to the coastline (Garson and Krs, 1976) and even to land. The accretion axis at the centre of the positive axial anomaly is, in some instances, offset by these faults. This situation, together with magnetic and gravimetric data, indicates clearly that these are transform faults (El Tayeb *et al.*, 1979; Izzeldin, 1982).

Hot Brines and Mineralized Sediments

The importance of the Atlantis II Deep comes from the existence of a double layer of brines nearly 200 m thick covering the sediments and screening them from the waters of the Red Sea. It was these brines that led to the discovery of the underlying mineral deposits.

The lower brine (Fig. 3) is nearly 150 m thick with a temperature approaching 65°C in 1983, high salinity (33% NaCl equivalent) and a slightly acidic pH (5.6). This brine is lacking in oxygen, and relative to normal Red Sea water it is rich in Na, Cl and Ca, and low in Mg and SO⁴, with metal concentrations as high as a thousand times that of sea water. Such properties characterize this brine as hydrothermal and comparable to the fluids from the hydrothermal vents of the East Pacific Rise. There is a transition in less than a meter to the 30 m-thick upper brine, which has a composition intermediate between that of the lower brine and sea water.

Measurements taken over the last twenty years in the lower brine have shown that its temperature – and that of the geothermal system – has risen from 50°C in 1965. The main thermal discharge zone is located in a sector several square kilometers in area in the centre of the SW basin (Brewer *et al.*, 1971; Hartmann, 1980).

The metalliferous sediments beneath the brines, which were cored first in 1965, are 10-15 m thick and represent about 100 Mt (million metric tons) in dry weight. Among other metals these sediments contain 3.5 Mt of zinc, 0.5 Mt of copper and 9000 t of silver (Länge *et al.*, 1981), comparable to a sulphide deposit of above average size. As shown in Figure 3, the sediments comprise five lithologic units (Bäckér and Richter, 1973), characterized by a diversity of colours associated with fine bedding. They are virtually saturated (nearly 85% weight) by saline water with physico-chemical parameters similar to those of the lower brine. The solid fraction has a very small range in grain-size, with about 65% of the material less than or equal to two microns (Fletcher and Mustafa, 1980).

The basal unit is a biomechanical zone dominated by marls and contains several horizons of iron oxides and pyrite. This zone rests on the basalts and has been dated at 25000 B.P. at its base (C¹⁴ on microfossil tests) and 11000 B.P. at the top (Pleistocene-Holocene transition: Shanks and Bischoff, 1980).

Above the basal zone are two sulphide zones each averaging 2 m in thickness. These have iron, copper and zinc sulphides associated with clays of the montmorillonite type and sometimes with anhydrite horizons. Between these two zones is an oxidized unit, 5-6 m thick, of iron and/or manganese oxyhydroxides and argillaceous silicates. At the top of these muds is a delicate semi-liquid zone that can only be sampled as one unit. It is 2-3 m thick and consists of ferriferous nontronite associated with partially crystalline iron sulphides and oxyhydroxides. These sediments may be forming as rapidly as one meter in several thousand years (Bischoff, in Degens and Ross, 1969; Bäckér and Richter, 1973; Hackett and Bischoff, 1973; Bäckér, 1973; Bignell *et al.*, 1976; Bignell, 1978).

The SW portion of the Atlantis II Deep is somewhat different, with many epigenetic characteristics resulting from recent upwellings of mineralizing fluids (Bäckér and Richter, 1973; Zierenberg and Shanks, 1983). These features include resedimentation structures, breccias and numerous fine veinlets filled with anhydrite (with crystals to 1 cm) and associated with talc and some sulphides. Among the latter are pyrrhotite, chalcopryrite and chalcopryrrhotite (CuFe₂S₃). This combination indicates high-temperature circulation (Pottorf and Barnes, 1978; Weiss *et al.*, 1980; Thisse, 1982; Oudin, 1983) and is comparable to that described from high-temperature (350°C) chimneys of the East Pacific Rise (Oudin, 1981; 1983). The host sediment is locally metamorphosed, as

Figure 3: Schematic E-W section through the southern Atlantis II Deep (modified from Bäckér, 1973 and Bignell, 1978). 1 - lower brine; 2 - upper brine; 3 - Red Sea water; 4 - Pliocene to Quaternary marls; 5 - Miocene evaporites; 6 - oceanic basement; 7 - Fe-Mn oxides; 8 - oxide zone; 9 - amorphous silicate zone; 10 - sulphide zones; 11 - biogenic-detrital marls.

indicated by the presence of magnetite, amphibole of the actinolite type and an Fe-Mn skarn silicate ilvaite (Weiss *et al.*, 1980; Oudin, 1983).

Studies of the fluid inclusions in the anhydrite along the sides of these secondary veinlets were recently undertaken at BRGM on material provided by the SSRSC. We have found two populations of inclusions characterizing the hydrothermal fluids. The first yields a temperature of about 340°C for a salinity equivalent to 22% NaCl, while the second and later group (in places found in halite crystals) indicates temperatures of 400°C with a salinity equivalent to 33% NaCl. At the location sampled, the initial fluid appears to have been boiling, possibly as a result of decompression during fracturing of the pre-existing sediments due to volcanic-tectonic activity periodically affecting these deeps. The boiling would have modified the physico-chemical characteristics of the fluid and induced the precipitation of many elements, especially metals (Thisse *et al.*, 1983).

Origin and Development of the Brines

The Red Sea brines were first interpreted as coastal evaporite deposits flowing as dense brines to the sea floor, or as the result of leaching of submarine salt-bearing outcrops. Brewer *et al.* (in Degens and Ross, 1969) rejected these hypotheses and advocated a connate origin for the super-saline water, recirculated by geothermal phenomena. On the basis of isotopic data, Craig (in Degens and Ross, 1969) argued for a correspondence between the brines and the water in the southern part of the Red Sea; however, the long distance implied gives this model little credibility.

Bäcker (1973) and Manheim (1974) were the first to propose a lateral convective flow by which Red Sea water infiltrates and descends into the sides of the rift, heats up as it approaches the ascending magma, dissolves salts and metals and finally rises by ordinary convection to deposit some of its dissolved elements on the sea floor. This mechanism has received much direct and indirect support, particularly through the study of accretion zones and recent discoveries of hydrothermal activity in the eastern Pacific.

The following sequence is now believed to apply to the metalliferous deposits in the Atlantis II Deep. The hydrothermal fluid could be fossil water from the Red Sea, as the isotopic data of Schoell and Faber (1978) indicates an age of 5000 B.P. This fluid is either set in motion by tectonic phenomena related to oceanic expansion, or it percolates very slowly and steadily through the fractures associated with the rift. The salinity of water is due to leaching of the anhydrite and halite which cover most of the floor of the Red Sea.

The heating of this water to several hundred degrees, due to the presence of magma not far below the axial zone results in a number of changes confirmed by laboratory experiments. These changes include lowering of magnesium and sulphate content, acidification and, especially, metal enrichment by leaching of newly formed basalts. Sulphur isotope measurements (Shanks and Bischoff, 1980) indicate additions to these fluids from great depths in the crust and possibly also direct additions from the mantle. Evidence of the latter is provided by helium isotope ratios which show an excess of He^3 , a typical mantle marker (Lupton *et al.*, 1977) also found systematically at active hydrothermal locations in the Pacific, where they serve as a guide to exploration. In addition to these deep sources, there may also be a leaching of earlier sediments like those found by the Glomar Challenger (Manheim, 1974) — shale horizons interstratified with or overlying the evaporites and bearing rather high contents of metals such as Zn, Mo and V.

The hot, concentrated fluids rise along fractures by simple convection to emerge in the bottom of the trough where abrupt changes in physico-chemical conditions (especially the drop in temperature) cause the precipitation of a number of

metals. The reducing conditions and the absence of oxygen in this environment favour the formation and preservation of sulphide.

This is the same mechanism as conceived for the active hydrothermal vents of the East Pacific Rise. However the comparison does not extend beyond the similarities in temperatures and mineralogy. The growth of hydrothermal vents in the Red Sea is inhibited by the mass of sediments trapped in the trough, while in the East Pacific they can develop freely at the basalt-seawater interface. The difference in evolution of hydrothermal indicators is thus due to contrasts in the morphological and tectonic environments of these two oceanic accretion zones: the Red Sea is characterized by an early stage of slow opening with deep bathymetry, while the East Pacific Rise is a subject to more rapid and mature spreading.

Comparison with Fossil Deposits Elsewhere

There are many analogies between the modern deposits of the Red Sea and major Pb-Zn-Cu-Ag-Ba deposits elsewhere, especially those found in rifts or abortive grabens of the Proterozoic, such as McArthur River, Mt. Isa and Pegmont in Australia, the Sullivan in British Columbia, and Gamsberg in South Africa. The similarities include the association with ferriferous (banded iron) formations and sulphides with vertical and lateral zoning, lateral changes to Mn, and the existence of siliceous deposits capping the sulphides. In common also are many other aspects typical of exhalative deposits, such as talc deposits, chlorite sometimes altered to cordierite and horizons rich in anorthite. In addition brines typically deposit metals in the deepest parts of their basins.

However, not all aspects of the Red Sea deposits are matched elsewhere, for two main reasons arising from their basically hydrothermal and sedimentary nature. First, the composition and the nature of the hydrothermal solutions and deposition processes vary from one trough to another in the Red Sea, as they do in fossil mineral deposits elsewhere. Second, hydrothermal deposits can form in various geological and structural environments, as shown particularly well by DSDP Leg XI drilling in the marine Cretaceous of the North Atlantic. Thus, just as there is no one model for veins in a single environment, deposits of the Red Sea type, although of sedimentary origin, vary widely from one geological environment to another because of their basically hydrothermal nature.

Comparison with Old Rifts

There are also similarities between the Red Sea and other rift-based deposits in terms of evolution and geodynamic setting. The most typical examples were formed during the opening of the North Atlantic and of Tethys in the Permian-Triassic and Lower Jurassic and during the opening of the South Atlantic in the Cretaceous. In both cases, (e.g. in Morocco, the Benue Trough and Angola) a succession of mineral deposits associated with hyperalkaline carbonate complexes was followed by Cu, Pb, Zn, Mn and Ba mineralizations of the Red Bed and/or Mississippi Valley type. These deposits occur in adjacent basins in "herringbone" fashion along the rifts. Finally, oolitic iron deposits are also often observed in old rifts such as the Proterozoic Labrador Trough and the Benue deep in Nigeria.

Summary

Study of the mineral associations in secondary veinlets and of the metamorphism of the host sediment has demonstrated the circulation of very hot (350°) saline fluids in the metalliferous sediments of the Atlantis II Deep. For the first time, microthermometric studies on fluid inclusions in sulphates have made it possible to characterize the temperature and salinity variations in these ascending mineralizing fluids.

There are remarkable similarities between the parageneses observed in the Red Sea veinlets and those in the high-

temperature chimneys of the East Pacific Rise, as well as in their formation temperatures. The different maturity levels of these two accretion zones can explain the specific differences in their hydrothermal deposits.

Mineralization associated with the oceanic ridges and ancient rifts provide most of the basis for comparison with fossil deposits. The Red Sea is of special interest and importance because of its economic significance and the variety of types present at different evolutionary stages of the rift. A close relation has now been demonstrated between geodynamic evolution and the development of the mineralization. The existence of similar mineral variations in older deposits may thus provide a key to their geodynamic setting.

Finally, the studies on the Tertiary mineral deposits along the Red Sea margin have led to a better understanding of the

basic characteristics of certain deposits whose origin is still very much a matter of debate. These include red beds, oolitic iron ores and especially deposits of the Mississippi Valley type.

Acknowledgements

The authors wish to thank the officials of the Saudi-Sudanese Red Sea Joint Commission. With their assistance, BRGM was able to conduct scientific studies on six core samples taken from the Atlantis II Deep. The first results of this work, together with the re-examination of earlier studies, have already provided a fuller understanding of the process of formation of mineral deposits associated with the Red Sea rift.

ABOUT THE AUTHORS:

Yves Thisse joined the Marine Geology Department of BRGM (B.P. 6009, 45060 Orléans Cedex, France) in 1982, after completing his thesis at University of Orléans, on the metalliferous oozes of the Atlantis II Deep. His work on the Red Sea metalliferous deposits continues in collaboration with Elisabeth Oudin.

Pol Guennoc has been with the Marine Geology Department of BRGM since 1978 and is in charge of its Centre Océanologique de Bretagne at Brest. His main fields of activity are in submarine geology and the study of recent and ancient hydrothermal deposits.

A mining geologist specializing in mineral deposits, **Georges Pouit** has worked and studied in Africa, Europe and North America. He is now on the staff of the BRGM Mineral Deposits Department at Orléans. His interests include volcanic-sedimentary ore deposits, in the Red Sea and elsewhere.

Zohair A. Nawab is the Deputy Secretary-General of the SSRC (Box 5886, Jeddah, Saudi Arabia) and a member of the Saudi Arabian National Committee for Marine Sciences. After studying at Riyadh University and at Dhahran, Saudi Arabia, Dr. Nawab obtained his Ph.D. in geology from the University of Western Ontario in 1978.

References

- Bäcker, H., 1973. Rezente hydrothermal-sedimentäre Lagerstättenbildung. *Erzmetall*, v. 26, no. 11, p. 544-555.
- Bäker, H., Lange, K. and Richter, H., 1975. Morphology of the Red Sea central graben between Subair Islands and Abul Kizaan. *Geologisches Jahrbuch*, D. 13, p. 79-123.
- Bäker, H. and Richter, H., 1973. Die rezente hydrothermal-sedimentäre Lagerstätte Atlantic-II-Tief im Roten Meer. *Geologisches Rundschau*, v. 62, no. 3, p. 697-740.
- Bignell, R.D., 1978. Genesis of the Red Sea: Metalliferous sediments. *Marine Mining*, v. 1, no. 3, p. 209-235.
- Bignell, R.D., Cronan, D.S. and Tooms, J.S., 1976. Red Sea metalliferous brine precipitates. *Geological Association of Canada, Special Paper 14*, p. 147-179.
- Blank, H.R., Jr., 1977. Aeromagnetic and geological study of tertiary dykes and related structures on the Arabian margin of the Red Sea. In: *Red Sea Research, 1970-1975*, DGMR Bulletin No. 22, p. G1-G18.
- Bonatti, E., Fisher, D.E., Joensuu, O., Rydell, H.S. and Beyth, M., 1972. Iron-manganese-barium deposit from the northern Afar rift (Ethiopia). *Economic Geology*, v. 67, no. 6, p. 717-730.
- Bonatti, E., Hamlyn, P. and Ottonello, G., 1981. Upper mantle beneath a young oceanic rift: peridotites from the island of Zabargad (Red Sea). *Geology*, v. 9, no. 10, p. 474-479.
- Brewer, P.G., Wilson, T.R.S., Murray, J.W., Munns, R.G. and Densmore, C.D., 1971. Hydrographic observations on the Red Sea brines indicate a marked increase in temperature. *Nature*, v. 231, no. 5297, p. 37-38.
- Cochran, J.R., 1981. The Red Sea: implications for the early development of Atlantic-type continental margins. *EOS*, v. 62, no. 17, p. 407.
- Cochran, J.R., 1983. A model for development of Red Sea. *American Association of Petroleum Geologists Bulletin*, v. 67, no. 1, p. 41-69.
- Coleman, R.G., 1974. Geologic background of the Red Sea. In: Whitmarsh, R.B., Weser, O.E., Ross, D.A. et al. (eds.), *Initial Reports of the D.S.D.P.*, v. 23, p. 813-819. U.S. Geology Survey, Menlo Park, CA, U.S.A.
- Degens, E.T. and Ross, D.A., 1969. Hot Brines and Recent Heavy Metal Deposits in the Red Sea, a Geochemical and Geophysical Account. Springer Verlag, New York.
- Drake, C.L. and Girdler, R.W., 1964. A geophysical study of the Red Sea. *Geophysical Journal of the Royal Astronomical Society*, v. 8, p. 473-495.
- El Tayeb, M., Izzeldin, Y., Horn, R. and Tixeront, M., 1979. Les données géophysiques de la mer Rouge centrale (entre 18° et 24°N): leur traitement par la technique SIGMA. In: *Scolari, G. (ed.), Ressources Minérales Sous-Marines*, Colloque GERMINAL, 23-27 October 1978, Documents du BRGM, no. 7, p. 367-379.
- Falcon, N.L., Gass, I.G., Girdler, R.W. and Laughton, A.S., 1970. A discussion on the structure and evolution of the Red Sea and the nature of the Red Sea, Gulf of Aden and Ethiopia rift junction. *Philosophical Transactions of the Royal Society of London*, A 267, no. 1181, 417p.
- Fletcher, A.W. and Musta Fa, Z., 1980. Progress on the exploitation of metalliferous sediments of the Red Sea. *Proceedings of Conference on National and International Management of Mineral Resources*, May, 1980, Institution of Mining and Metallurgy, London, 16p.
- Garson, M.S. and Krs, M., 1976. Geophysical and geological evidence of the relationship of Red Sea transverse tectonics to ancient fractures. *Geological Society of America Bulletin*, v. 87, no. 2, p. 169-181.
- Girdler, R.W. and Styles, P., 1982. Comments on "the Gulf of Aden: Structure and evolution of a young ocean basin and continental margin" by J.R. Cochran. *Journal of Geophysical Research*, v. 87, no. B8, p. 6761-6763.
- Guennoc, P. and Thisse, Y., 1982. Genèse de l'ouverture de la mer Rouge et des minéralisations des fosses axiales. *Synthèse bibliographique*. Documents du BRGM, no. 51, 112p.