Metalliferous Sediments of the Seabed: The Atlantis-II–Deep Deposits of the Red Sea[1]

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INTRODUCTION

This paper deals with metalliferous sediments of the seabed occurring in the Red Sea, in particular, within the depression of the seafloor known as the Atlantis-II deep (A-II deep), which is named after the U.S. research vessel that engaged in the investigation of the area. The deep is in the central Red Sea, between Jeddah and Port Sudan (fig. 1).

The scientific and other literature on the A-II and related metalliferous deposits has increased in recent years to such an extent that it is difficult to cite all the references used for this paper. Instead only the more important publications will be quoted, those which, in turn, offer more detailed bibliographies for the reader interested in specific sectors. In addition, the Saudi-Sudanese Red Sea Joint Commission[2] is prepared to mail, upon request, a comprehensive bibliography on the subject.

DISCOVERY AND EARLY DEVELOPMENT (BEFORE 1974)

In 1948 the first indications of anomalous seawater conditions were recorded by the Swedish research vessel *Albatross*. In the late fifties and early sixties more evidence was found of increased temperatures and salinities in near-bottom water. Reflecting layers occasionally observed in deep echo soundings could not be interpreted at that time.

1. We wish to thank the Saudi-Sudanese Red Sea Joint Commission, Jeddah, and Preussag AG, Hannover, for permission to publish and also appreciate the help and criticism of our colleagues in the performance of the project. Our special thanks are due to H. E. Dr. Zaki Mustafa, Secretary General of the Red Sea Commission, for his outstanding role of guiding this project along its thorny road from the academic realm toward economic realization.

2. Saudi-Sudanese Red Sea Commission, P.O. Box 5886, Jeddah, Saudi Arabia.

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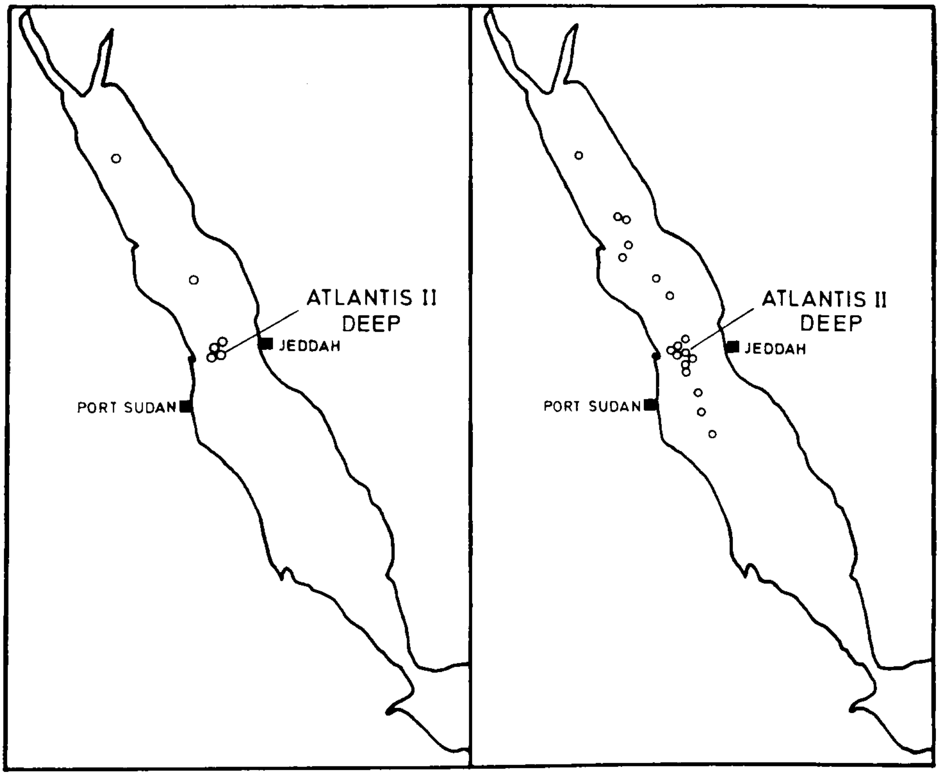

FIG. 1.—Red Sea overview—discovery of brine deeps and/or metalliferous sediments. Left, prior to 1969. Right, following 1969.

The sampling of sediments with R.R.S. *Discovery* in 1963 and the recognition of their metal enrichments probably constituted the actual discovery of the Red Sea metalliferous mud. In 1965 the research vessel *Atlantis II*[3] returned to the areas of anomalous conditions and surveyed, in more detail, the seabed depression which became later known as the Atlantis II deep. Several other ships were deployed in the following years, and by 1968 six deeps with brines and metalliferous sediments had been located (fig. 1). This history of discovery is an outstanding example of international cooperation and the rapid advancement of knowledge through joint efforts. Altogether, ships from the following countries and their research institutes were involved (in

3. Editors' note.—For specifications of this, and most of the other vessels mentioned in this chapter, see "Surface Research and Survey Vessels, by Country," Appendix table 2G, *Ocean Yearbook 2*, ed. Elisabeth Mann Borgese and Norton Ginsburg (Chicago: University of Chicago Press, 1980), pp. 645–70.

the order of first appearance): Sweden, United States, Great Britain, Federal Republic of Germany, and USSR.

Following the discovery of metalliferous mud, economic interest rose with the confirmation of metal-grade material, apart from iron and manganese, of zinc, copper, silver, and several others. These metals are present in concentrations that would make them interesting ores, if they occurred on land. The results of these investigations and an estimate of the overall metal contents and their value appeared first in 1967 and were revised in 1969.[4]

Those early investigators, speculating on the economics of the metalliferous mud contained within the A-II deep, arrived at a value in the range of 2.5–8 billion U.S. dollars for the metals *in situ*. Although the authors warned against an overestimation of the possibility of utilizing this mineral deposit in view of the absence of mining techniques and suitable metal extraction processes, their reports, nevertheless, caused widespread interest.

In 1968, the Democratic Republic of the Sudan issued licenses for further investigations, evidently on the assumption that the A-II deep would fall west of a median line if such a delineation would be introduced and agreed upon as legally binding. The licenses were awarded to a Sudanese private company, which, in turn, secured the partnership and technical expertise of American entity and Preussag AG of Hannover, Germany. In 1969, a cruise was carried out with the chartered vessel *Wando River*, mainly to conduct an advanced bathymetric survey of the deep and to obtain more sample material.

The government of the Kingdom of Saudi Arabia, also conscious of the economic implications of these discoveries in the Red Sea, sponsored an extensive research program through the Ministry of Petroleum and Minerals. Financed by the Saudis, geochemical investigations along the axis were undertaken by the Imperial College of Science and Technology, London, using the *Nereus*, in 1970 and 1971. Several deeps were investigated, including the previously unrecorded Nereus deep, but no mineralization—comparable to that of the A-II deep—was found. In 1971, magnetic and gravimetric surveys and continuous seismic profiling were financed by the Saudis and undertaken by Woods Hole Oceanographic Institution—using the vessel *Chain*. These geophysical investigations and the drilling subsequently undertaken by the *Glomar Challenger* eventually led to the concept of a two-stage seafloor spreading as the mechanism responsible for the formation of the Red Sea.[5] In 1972 the mining authorities of Saudi Arabia conferred prospecting rights for Red Sea minerals on Preussag.

4. J. L. Bischoff and F. T. Manheim, "Economic Potential of the Red Sea Heavy Metal Deposits," in *Hot Brines and Recent Heavy Metal Deposits in the Red Sea*, ed. Egon T. Degens and David A. Ross (Berlin: Springer-Verlag, 1969), pp. 535–41; Thomas N. Walthier and Clifford E. Schatz, "Economic Significance of Minerals Deposited in the Red Sea Deeps," in Degens and Ross, eds., pp. 542–49.

5. David A. Ross, "Results of Recent Expeditions to the Red Sea—'Chain,'

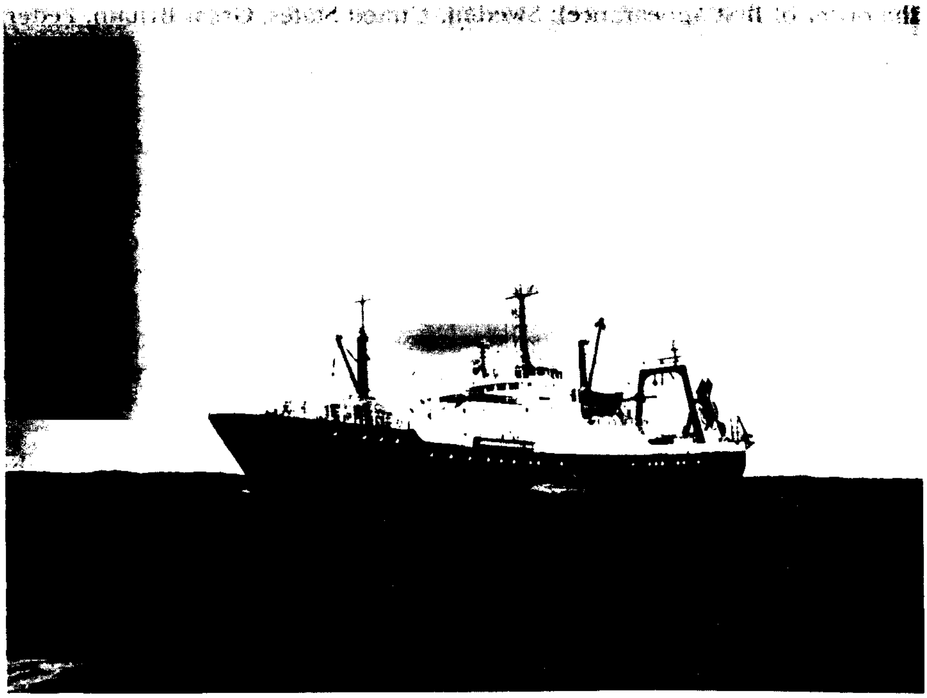

Fig. 2.—Research vessel *Valdivia II*

Preussag, with a long tradition and deep involvement in mining and processing nonferrous metal ores on land and in offshore activities, had decided toward the end of the sixties to become engaged in the reconnaissance and evaluation of seabed minerals, in general, and to prepare a highly sophisticated and especially equipped exploration system, in the form of a research vessel, for this purpose. A stern-trawler was acquired and converted to such a vessel. In remembrance of *Valdivia*, an ocean research ship used at the turn of the century, the newly converted vessel was named after her. With the financial support of the Ministry of Research and Technology of the Federal Republic of Germany and the participation of the Federal Geological Survey, members of university institutes, and other industrial firms, Preussag organized and operated two extensive cruises with *Valdivia II*. (For a view of the vessel and important technical data, see fig. 2 and table 1.) These surveys, performed mainly in the Red Sea and the Gulf of Aden in 1971 and in the central and southern Red Sea in 1972 to follow up in more detail the previous work, produced several results.

'Glomar Challenger,' and 'Valdivia' Expeditions," in *Red Sea Research 1970–1975*, ed. Directorate General of Mineral Resources (Jiddah), Bulletin 22-B (1977), pp. B1–B14.

TABLE 1.—RESEARCH VESSELS "VALDIVIA" AND "SONNE": TECHNICAL DATA

	Valdivia	*Sonne*
Description	Built 1960/61 as fishing trawler, converted to research vessel for exploring marine mineral resources in 1970, and renamed *Valdivia* after a vessel engaged in oceanographic work of the southern oceans in 1898–99	Built 1969 as fishing trawler, converted to research vessel for exploring marine mineral resources in 1977 (first phase), and 1978 (second phase)
Displacement	2,115 tons	3,865 tons
Measurements:		
Length	74 m	86.5 m
Beam	11 m	14.2 m
Draught	5 m	5.4 m
Gross registered tons (GRT)	1,317	2,607
Cruising speed	12 knots	13 knots
Accommodation	24 crew 17–19 scientific personnel	22–26 crew 23–25 scientific personnel
Hoisting gear	1 15-ton A-frame at the stern 2 booms 3 cranes 1 corer frame (18 m) 1 jibboom on starboard	1 hydraulic A-frame at the stern, SWL 12 tons 1 crane AK 6000 on the work deck 1 central crane, SWL 6–8 tons 1 derrick 1 jibboom up to 3 m, SWL 10 tons
Winches	1 hydraulic friction winch (10,000 m of 18-mm-diameter wire and 8,000 m of 18-mm Ø TV cable) 1 hydraulic winch (8,000 m of 4-mm Ø stainless steel wire) 1 electrical winch for bathysonde (6-mm Ø cable)	1 core frame, 24 m 1 deep-tow winch, hydraulic, with 8,000 m of 21-mm Ø cable, slack-line take-up mechanism, and wave compensator 2 fishing winch units (Shetland type) 1 ATLAS-net sounder winch Various auxiliary winches

In the Gulf of Aden no deposits similar to the metalliferous mud of the A-II deep were discovered. There were only rare signs of possibly hydrothermal activity; otherwise, only crusts on the seafloor, mostly iron and manganese enrichments with no base metals in interesting contents, were encountered. Contrary to this negative finding, more than a dozen new brine deeps and/or occurrences of metalliferous sediments were discovered in the

Red Sea (fig. 1).[6] Brines and sediments show a variety of physical and chemical characteristics. The brines exhibit different salt concentrations and temperatures; some are stratified with more concentrated and hotter layers underlying a less concentrated and cooler brine body. The predominant metals in most deeps are iron and manganese. In the Chain deep the manganese content averages 30%–40%.

Of all Red Sea deposits discovered, the A-II deep occurrence is the only interesting one from the economic viewpoint. At a water depth of approximately 2,000 m, the seawater is underlain by a 200-m thick layered body of brine (up to 25% NaCl and exceeding 60°C). The brine fills an elongated, northwest trending depression with steep walls, covering about 60 km^2 (figs. 3 and 4). At the bottom, the variegated, partly laminated deposits attain an average thickness of 11 m. The bright white, yellow, red, and grayish black colors correspond to the oxidic and sulfidic mineral facies and compounds of iron and manganese and the value metals: zinc, copper, and silver. The schematic sequence of units in the A-II deep is shown in table 2.

In general, the solid content of the mud varies between 8% and 13%; the rest is brine. The mud averages 2%–5% zinc, 0.3%–0.9% copper, and 60–100 ppm silver, on a dry, salt-free basis. The total solid substance contained within the deep weighs about 100 Mt. The shares of the value metals are: zinc, about 2 Mt; copper, 0.4 Mt; silver, 9,000 tons; gold, about 80 tons. The 30 Mt of iron are not of economic interest. Where the base of the metalliferous sediments is reached by core samplers, it is generally found to be geologically young basalt.

Metalliferous sediments of the A-II type are believed to originate as follows: seawater percolates through the tectonically active, highly fractured and fissured seafloor, consisting of Tertiary evaporites (mostly Miocene rock salt), along the flanks of the deep, and basalt, forming the bottom (fig. 4). As a result of the seafloor spreading, whereby the crustal plate with the Arabian Peninsula drifts away from the African plate along the central rift of the Red Sea, the emplaced basalt closes the gap and forms new ocean floor. More heat is conveyed to the seabed, where the upward movement of molten rock-material leads to volcanic activities. Under this highly increased heat flow the percolating seawater dissolves salt and metals from the host rocks. Where the heated water is discharged again in closed depressions of the seafloor, it may collect and form brine pools. (Some of the metals are also contributed from solutions rising from the magmatic sources of the earth mantle.) Upon contact

6. H. Bäcker and M. Schoell, "New Deeps with Brines and Metalliferous Sediments in the Red Sea," *Nature Physical Science* 240 (December 1972): 153–58; H. Amann, H. Bäcker, and E. Blissenbach, "Metalliferous Muds of the Marine Environment," *Preprints of the Offshore Technology Conference*, 5th Annual Conference of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Houston, May 1973, Paper no. 1,759 (Houston, 1973), 1:345–58; H. Bäcker, "2.2 Erzschlämme," *Geologisches Jahrbuch* D38 (1980): 77–100 and 192–96.

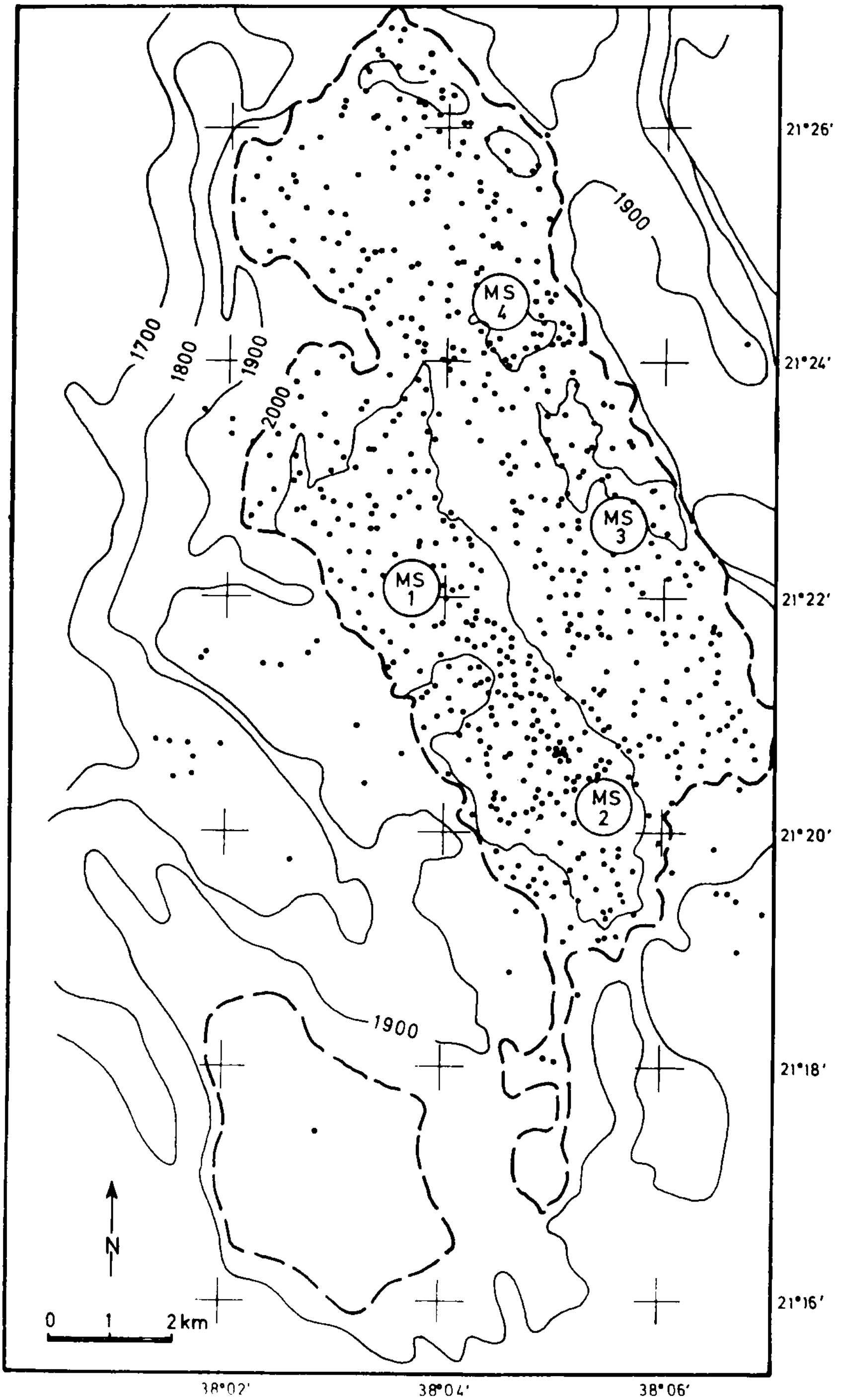

FIG. 3.—Atlantis-II deep: core stations and mining test sites (MS 1-4) of 1979; isobaths in meters.

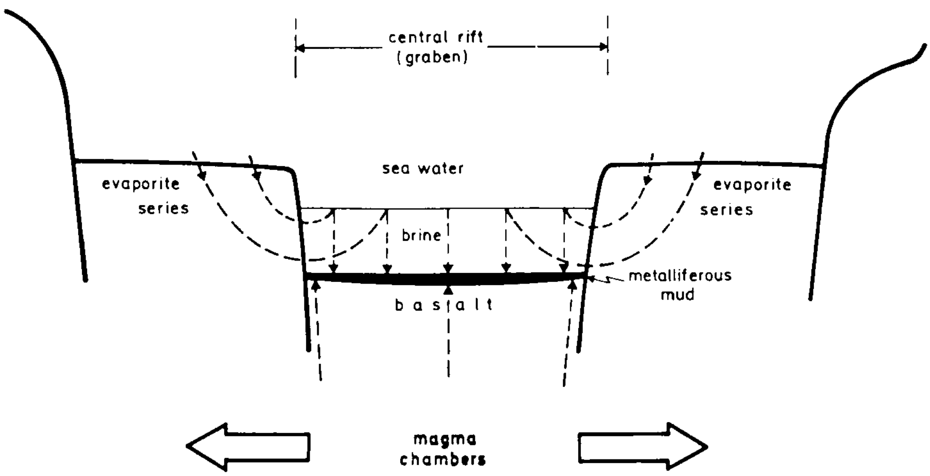

FIG. 4.—Atlantis-II deep: schematic cross-section and principles of origin of metalliferous sediments (hypothetical flow of solutions and seafloor spreading).

TABLE 2.—SEQUENCE OF ZONES IN ATLANTIS II DEEP (from Top to Bottom)

Zone	Thickness (m)	Description
AM	2–4	Amorphous siliceous facies; greenish to brown; spongy consistency; up to 97% interstitial brine; semiliquid
SU_2	2–4	Upper sulfide facies with economically interesting sulfides of zinc, copper, lead, and silver; grayish purple; monosulfide laminae contain as much as 20% zinc (dry weight)
CO	.5–11	Central oxidic facies; mostly common limonite with an iron content of approximately 50% (dry weight); vivid red and orange colors
SU_1	1–4	Lower sulfide facies, similar to SU_2
DOP	1.3–6	Detritic oxidic-pyritic facies of little or no economic interest; sulfide intercalations within upper parts not sufficiently known

SOURCES.—H. Bäcker and M. Schoell, "New Deeps with Brines and Metalliferous Sediments in the Red Sea," *Nature Physical Science* 240 (December 1972): 153–58; H. Amann, H. Bäcker, and E. Blissenbach, "Metalliferous Muds of the Marine Environment," *Preprints of the Offshore Technology Conference*, 5th Annual Conference of the American Institute of Mining, Metallurgical and Petroleum Engineers, Houston, May 1973, Paper no. 1759 (Houston, 1973), 1:345–58; H. Bäcker, "2.2 Erzschlämme," *Geologisches Jahrbuch* D38 (1980): 77–100 and 192–96.

of the dissolved brine constituents with normal (cooler, oxygenized) seawater, precipitation of certain metallic compounds takes place. These resulting chemical sediments collect at the bottom of the deep to form metalliferous mud. The sedimentation rate is relatively high, around 1 mm/year—considerably higher than for normal deep-sea deposits, about 100,000 times more than for the Pacific manganese nodules.[7]

In recent years, it has become increasingly evident that a number of ore deposits, some of considerable economic importance, were originally formed in a way similar to that of the A-II mud (although a closer or identical relationship would require the presence of ophiolites and/or mafic or ultramafic rocks formed as new oceanic crust). Prominent ore deposits include lead-zinc suppliers, such as the Pre-Cambrian Mt. Isa (1.6 billion years old) of Australia and the Devonian Rammelsberg mine (300 million years old) of West Germany. A thorough knowledge of the origin of those ore deposits could help to locate still undiscovered extensions or neighboring (sister) occurrences.

ADVANCED DEVELOPMENT (SINCE 1974)

Saudi Sudanese Agreement and Foundation of Red Sea Joint Commission (RSC) 1974–75

Meetings between the governments of Saudi Arabia and Sudan started as early as May 1968 for the purpose of reaching a suitable agreement with regard to the exploitation of Red Sea minerals. Later that year, the Royal Decree No. M-27 established the Saudi ownership over mineral resources of the seabed adjacent to the Saudi continental shelf.

Progress for an international agreement on possibly disputed boundaries of adjacent or opposite states was slow, in spite of Saudi Arabian efforts to call for a meeting of all riparian states in July 1972. Following action by the Sudan, a new round of negotiations with Saudi Arabia was opened in 1973 and resulted in a bilateral agreement in 1974. Under this agreement, the bed of the Red Sea between the two countries is divided into three zones (beyond the coastline and the adjacent zone of full sovereignty): (1) a zone extending westward from the Saudi coast to a line where the water depth is continuously 1,000 m; (2) a zone extending eastward from the Sudanese coast to a line where the water depth is continuously 1,000 m; and (3) a common zone lying between the two zones, as defined above, and including all the known deeps. Each country has exclusive sovereign rights over the area between its coastline and the common zone, in which both countries have exclusive and equal rights.

7. Editors' note.—For an extended discussion of interactions between sea water and oceanic crust, see A. T. Anderson's contribution, "The Ocean Basins and Ocean Water," in this volume.

The agreement gave to the Saudi-Sudanese Red Sea Joint Commission (RSC) in 1975 a corporate status and an independent legal personality; the RSC was to consist of three members from each country, each side being headed by the minister responsible for mineral resources in his country. Funding of commission activities is provided by the government of Saudi Arabia, which will recover such funds from the expected revenues of production from the common zone in a manner to be agreed upon between the two countries.

The RSC chose the Bureau de Recherches Géologiques et Minière (BRGM), a French public body, as its technical consultants. On the basis of its previous experience Preussag was designated as general contractor for the implementation of a feasibility study, covering both the economic and the technological aspects of developing the mineral resources lying within the A-II deep.

Contract with Preussag (1976)—Atlantis-II–Deep Mineral Development Project

The negotiations with Preussag were successfully concluded in August 1976. The contract was based on cost reimbursement without profit elements in favor of the general contractors. It left open the possibility of Preussag's marketing the metals produced and of obtaining a certain percentage of the production.

The purpose of the project consists in assessing of the economic utilization of the A-II deep mineral deposits and in acquiring the knowledge necessary to decide whether or not commercial exploitation is to be initiated. The program was conceived in two subsequent steps of several years each: a prepilot phase and a pilot phase. In view of the very new and unique nature of this type of work, a concise program could only be drafted for the first phase. The prepilot phase would comprise comprehensive studies and tests in the following fields: sampling and evaluation of the mineral deposit, establishing environmental factors and assessing possible impacts of exploitation, mining methods, and selecting and developing methods to extract the metals from the metalliferous mud. This first phase was to culminate in a prepilot mining test (PPMT). After its conclusion and subsequent metallurgical studies, the prerequisites for entering into the second phase were expected to be available and to allow detailed planning of that phase in 1980.

Program including Prepilot Mining Test (PPMT) 1979

The first major operation under this program was the exploration cruise with the newly commissioned R/V *Sonne* (fig. 5, table 1) in fall 1977. Most of the

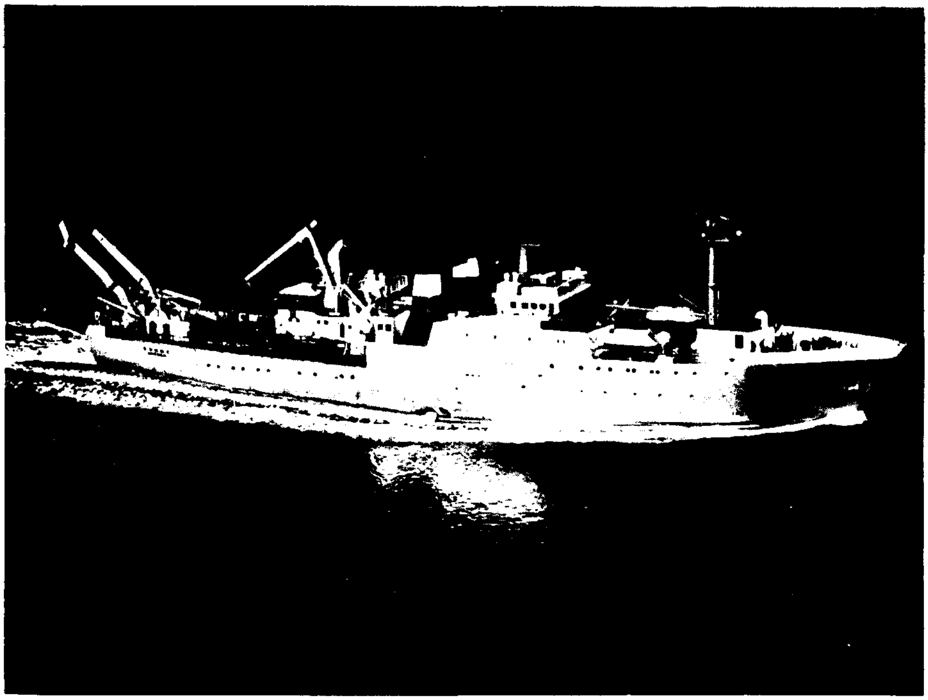

FIG. 5.—Research vessel *Sonne*

survey concentrated on further mapping and sampling of the A-II deposits and on environmental studies. It was felt from the very beginning of the project that every precaution must be taken to ensure that a future mining operation would not endanger the ecosystem of the Red Sea through pollution. A wide range of studies, with the participation of scientists from renowned university institutes, were initiated. This included physical oceanography to establish the systems of currents—horizontally and vertically, seasonally, etc. It was found that new instruments had to be developed in order to record the parameters required, for example, a drift buoy for the seawater/brine interface. Another large sector of work consisted of the study of the biosphere: a baseline inventory of flora and fauna, their distribution and habits, and the contents of metals in their bodies. (It turned out that a good deal was known about marginal areas, such as reef populations, but little about critical issues, such as currents in the central Red Sea and its bottom-dwelling fauna.)

In 1979, the survey of the mineral deposit and the environment was continued with a cruise of the R/V *Valdivia*, which also assisted in the preparation and execution of the PPMT. For this cruise, a buoy-mounted transponder system was used for positioning. Together with satellite navigation and miniranger, this system permitted isobath charting of four PPMT sites at

1-m contours (fig. 3). During the two cruises of 1977 and 1979, about 220 sediment cores were recovered from the deep (in addition to the 130 cores taken previously). The new samples allowed an updated and more accurate assessment of the metal values. Because the results were still insufficient, another voyage with *Valdivia* was undertaken in 1981, producing core samples from 443 more stations.

The total of almost 800 cores from the deep may appear high, being equivalent to an average of about 13 samples per square kilometer. It must, however, be recognized that the distribution of samples is not as uniform as desired statistically, nor did the coring equipment always penetrate the entire sequence of metalliferous sediments. It should also be borne in mind that mineral deposits of comparable origin on land must be sampled at a much closer spacing before allowing a reasonably reliable deposit evaluation; such figures are commonly in excess of 50 samples per square kilometer prior to commercial exploitation.

The selection of a mining system for the PPMT was preceded by a thorough study of the flow behavior of the mud (from earlier expeditions) in order to establish friction coefficients and analyze such properties as abrasion. As a result of tests performed by a German university institute, an easy and cheap alternative (the use of plastic pipe for pumping up the mud) had to be discarded. Steel pipe had to be provided instead, leading to heavier loads and the necessity of using a much larger and more expensive test ship.

Another important sector of the program consisted of tests to extract the value minerals—zinc, silver, and copper—from the mud. The metal compounds are only a small percentage of the mud; therefore it is necessary to effect a concentration of the solid phase on the ship—prior to further treatment.

One method of concentration is flotation, whereby air is injected into a cell containing metalliferous mud. With the addition of special reagents, the metallic compounds collect on the surface of the rising bubbles and form a concentrate which can be skimmed off as a foam. Lab tests had shown that, in spite of the unfavorable, extremely small particle size of the mud with more than 80% below 2 μ (0.002 mm), a flotation concentrate could be formed. However, because such an operation would have to be carried out on board a vessel, it remained to be tested whether the ship's movements would allow this method to be applied. In a British laboratory, flotation-at-sea conditions were simulated. The effectiveness of the procedure was not much inferior to the one under stable land conditions.

With regard to the recovery operation, it was thought best to fluidize the mud with a specially designed mining head and pump it to the surface through a length of steel pipe. A six-stage centrifugal pump was eventually chosen (flow rate up to 100 m^3/hour; with a 535-kw electric motor). The mining head was furnished with a vibration mechanism and water under pressure for breaking up the mud. High-quality oil-field drill pipe of 5 inches diameter was

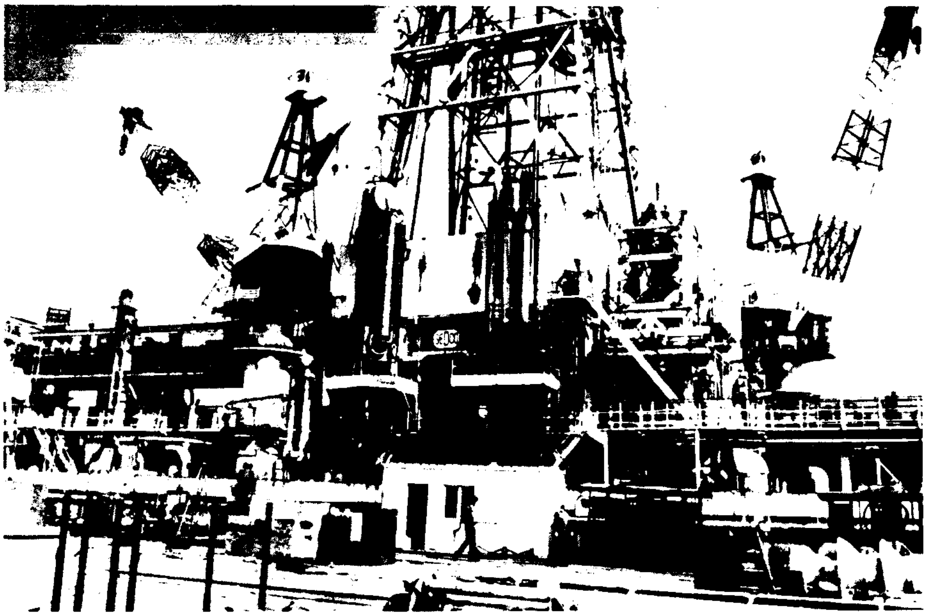

FIG. 6.—Mining test vessel *Sedco 445* in Marseille port for conversion

selected for the vertical transport. The mining head plus pump were connected and tested once, in shallow water in a Scottish fjord in 1978.

In March 1979, the chartered vessel *Sedco 445* (of a U.S. contractor), normally employed for offshore oil drilling, arrived at Marseilles, where she was converted into a mining ship (fig. 6). By mid-April she was at the A-II deep, where navigational aids had been previously set by *Valdivia* for the dynamic positioning of the ship, because the depth of more than 2,000 m would not allow anchoring. The dynamic positioning, whereby the vessel can remain above a given point with the aid of computer-controlled thrusters, worked without fault, and the ship could move in any given direction at low speed, in spite of heavy seas, currents, and wind.

The mining head, pump, and other mining equipment, including a large number of instruments for measuring temperature, flow speed, density, movement of pipe, thickness of sediments below the mining head (in order to avoid collision with the rugged basaltic bedrock), etc., were lowered through the moon pool, the mid-ship opening (fig. 7). Several days passed with the inevitable debugging of equipment. On May 1, 1979, the first flow of mud from such a depth was achieved—a spectacular breakthrough similar to the test mining of manganese nodules from the deep Pacific seabed the previous year.[8] After the tanks were filled with mud under varying mining conditions,

8. Zaki Mustafa and Hans M. Amann, "The Red Sea Pre-Pilot Mining Test 1979," *Proceedings of the Offshore Technology Conference*, 12th Annual Conference of the Ameri-

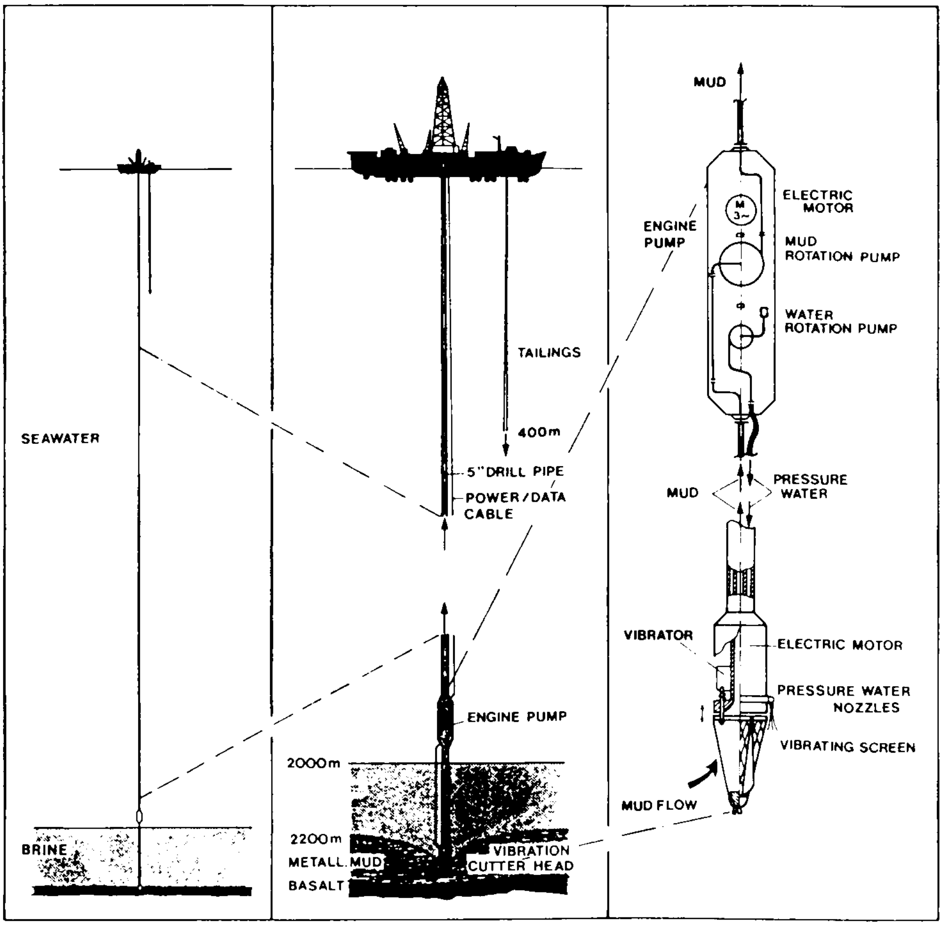

FIG. 7.—Atlantis-II deep: prepilot mining test of 1979. Left, true-to-scale relation of water depth to mining vessel. Center and right, details of mining test equipment.

the flotation tests began. Difficulties arose which were overcome, the concentration started to work, and, through changes of conditions, it gave improved results. Three subsequent test sites, previously selected as areas representative of the varying properties of the A-II deposits, were mined (fig. 3).

One of the major remaining tasks was the disposal of the flotation tailings. They were ejected through a 400-m long vertical pipe at the bow of the ship (fig. 7). That depth was chosen because it lies below the richer sea life layer (fig. 8). Through several methods of monitoring (tracers, direct observation of

can Institute of Mining, Metallurgical, and Petroleum Engineers, May 1980, Paper no. 3874 (Houston, 1980), 4:197–210; Zohair Nawab and Klaus Lück, "Test Mining of Metalliferous Mud from the Red Sea Bottom," *Meerestechnik mt* 10 (December 1979): 181–87.

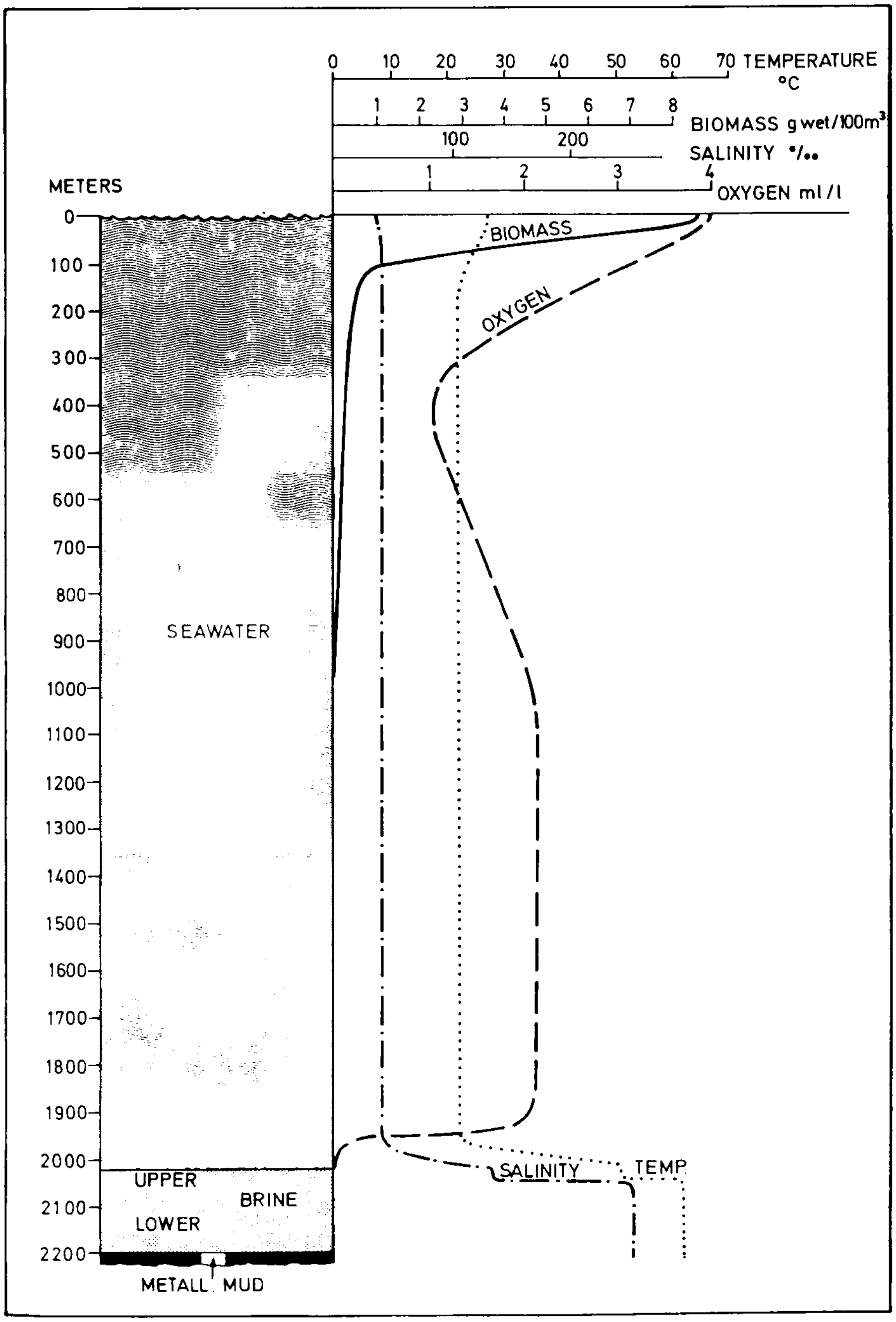

FIG. 8.—Atlantis-II deep: schematic cross-section through water column and bottom, including water layering, salinity, temperature, oxygen, and biomass (zooplankton).

plume by echosounder, light attenuation probe, drift buoys in plume, etc.) the disposed tailings could be followed by *Valdivia*.[9] From the point of discharge they sink to a depth of about 1,200 m in a short time, probably as a result of jet flow and gravity.

Careful base-line studies were conducted to establish the status of the Red Sea ecosystems. Two examples may serve to illustrate the extraordinary results obtained in the course of environmental base-line studies. Crustacea from the water column and the seabed in the vicinity of the A-II deep were found to exhibit mercury contents of several parts per million. These rates are a full order of magnitude in excess of the WHO and FAO limit for human consumption. Had such a finding been made following the beginning of ocean mining, it would undoubtedly have been attributed to that activity. Another unusual finding is the presence of water gyres as recorded by current measuring devices along vertical profiles. The base-line studies have also confirmed oceanographers' previous findings that the Red Sea is a very poorly populated water space, apart from the reef zones whose rich life is erroneously taken by the general public as representing the average. (With reference to metazoa smaller than 1 mm per unit bottom surface, the Red Sea communities amount to only one-third of the number of organisms on the Mediterranean seabed, and only to one-seventh to one-eighth of their numbers in the east Atlantic and the Norwegian Sea; for other categories of metazoa, the discrepancy is even larger.)

Samples of mud and tailings were secured in order to test their effect on specific members of the ecosystem, in dilated form and in short- and long-term experiments. Although a final evaluation of the environmental studies is not yet available, it appears that there is no detrimental influence to be feared from commercial mining if these principles of discharge are followed. Altogether it appears that the environmental studies, performed with the international cooperation of scientists and renowned institutes, form the most comprehensive investigation ever undertaken to assess the effects of future ocean mining (table 3). (Because of the exemplary nature of such investigations they received the financial support of the Federal Republic of Germany, Ministry of Research and Technology.)

9. H. Bäcker and L. Karbe, "Environmental Research Accompanying a Deepsea Mining Project in the Red Sea," *Conference Report of the Intermaritec '80*, ed. C. Kruppa and G. Clauss (Hamburg: Messe & Congress, 1980), pp. 543–52; J. Lange, "Control of Environmental Pollution by Mining Wastes (Metalliferous Mud, Red Sea)," *Proceedings of the 4th International Symposium on Environmental Biogeochemistry and Conference on Biogeochemistry in Relation to Mining Industry and Environmental Pollution*, Canberra, August/September 1979 (in press); J. Lange, H. Bäcker, J. Post, and H. Weber, "Plans and Tests for a Metal Concentration and Tailing Disposal at Sea," *Proceedings, Symposium on the Coastal and Marine Environment of the Red Sea, Gulf of Aden and Tropical Western Indian Ocean*, January 1980, ed. Y. B. Abu Gideiri (Khartoum: University Press, in press [with more references on this subject]).

TABLE 3.—ENVIRONMENTAL STUDIES AND RESEARCH INSTITUTIONS

A. PROGRAMS

Baseline studies: inventory of organisms; toxic constituents in water and organisms
Experimental studies: tests with original tailings
Computer simulation: currents around A-II deep
Monitoring influence during prepilot mining test, 1979: recording of tailings plume
Monitoring changes following mining test, 1979–80
Synoptic environmental assessment
Monitoring in connection with pilot mining test (scheduled for 1983): study of long-term effects

B. STUDIES AND INSTITUTIONS

Area of investigation	Methods employed and phenomena studied	Operator[a]
Physical oceanography	Eulerian and Lagrangian current measurements; bathysonde; multisonde (among others)	ARGAS, Preussag
Chemical oceanography	Water sampling with Niskin and Nansen samplers; major, minor, and trace elements (among others)	IHF, GKSS, Preussag
Biological oceanography	Phytoplankton; zooplankton; nekton; benthos	IHF
Ecotoxicology	Natural toxic substances; threshold values of tailings toxicity (among others)	IHF
Reef ecosystem	Tests in selected reef environments	OIP, IHF, Preussag
Numerical current models	Current systems; tailing plume movement; sedimentation	ICL, IMH
Tracer investigations	Iridium as activated tracer	CKSS, Preussag
Isotope geochemistry	Concentration gradient of natural isotopes (C^{13}, C^{14}, He^{3}, Ar^{39}, among others)	IUH

[a]ARGAS: Arabian Geophysical and Surveying Company, Jeddah; GKSS: Forschungszentrum Geesthacht, Federal Republic of Germany; ICL: Imperial College, London; IHF: Institut für Hydrobiologie und Fischereiwissenschaften, Hamburg; IMH: Institut für Meereskunde, Hamburg; IUH: Institut für Umweltphysik, Heidelberg; OIP: Oceanographic Institute, Port Sudan.

During the 3-month test period in 1979, about 15,000 tons of mud/brine mixture were mined. From 2,000 tons of mud 4 tons of concentrate were produced with zinc contents of 25%–40%, in addition to copper and silver. The concentrates were then used for processing tests, with the participation of some of the world's leading companies in extractive metallurgy, to select the most appropriate process. Since conventional metallurgical processes require the prior removal of salt, present to a high degree in the concentrates as a brine residue, recently introduced alternative methods were investigated. They require the presence of salt and use cupric or ferric chloride as a lixiviant or a high-temperature oxygen pressure leach. Several of the results from a 6-month test period of these methods were most encouraging, and two of them were selected for further studies. They have been elaborated to a degree where the first, sound estimates of these processes could be presented and incorporated among the preliminary feasibility data.[10] (E.g., the capital expenditure per annual ton of zinc is estimated to remain below U.S.$2,000 with operating costs of U.S.$350, as order of magnitude.)

Pilot Operation and Commercial Production

The development work undertaken to date does not yet allow assessment of the project's overall technical and economic feasibility, in spite of many encouraging findings and the absence of any prohibitive results. Before a final decision on commercialization is reached, it is necessary that a longer-term test of mining and metal production on a pilot scale be successfully performed. This operation, lasting from 200 to 300 days, would also give the working experience necessary for designing the commercial plants.

In particular, the pilot operation should mine metalliferous mud with a newly designed mining head, stronger pumps, and (probably) 9⅝-inch pipe, to allow the production of about 10 tons/day of concentrate, in the course of simultaneous flotation on board the pilot mining ship and/or a support vessel. The concentrate could be periodically transported by a shuttle boat to the metallurgical pilot plant on shore, which may become part of the future commercial processing plant (fig. 9). The residues (tailings) will be discharged at 800 m. It is likely that the site of the processing plant will be the development project of Yanbu, 300 km northwest of Jeddah, where a large petrochemical industry, based on the oil and gas supplied by pipeline from the Arabian Gulf fields, is being erected (fig. 10). The processing of the A-II concentrates would be the first mineral resource project in this complex.

The annual commercial production envisaged would amount to about

10. H. Weber, K. Pretzsch, C. Barbery, and A. W. Fletcher, "Metallurgical Treatment of Red Sea Concentrates," *Conference Report Interocean '81*, ed. H. G. Stalp (Düsseldorf: Düsseldorfer Messegesellschaft, 1981), pp. 116–22.

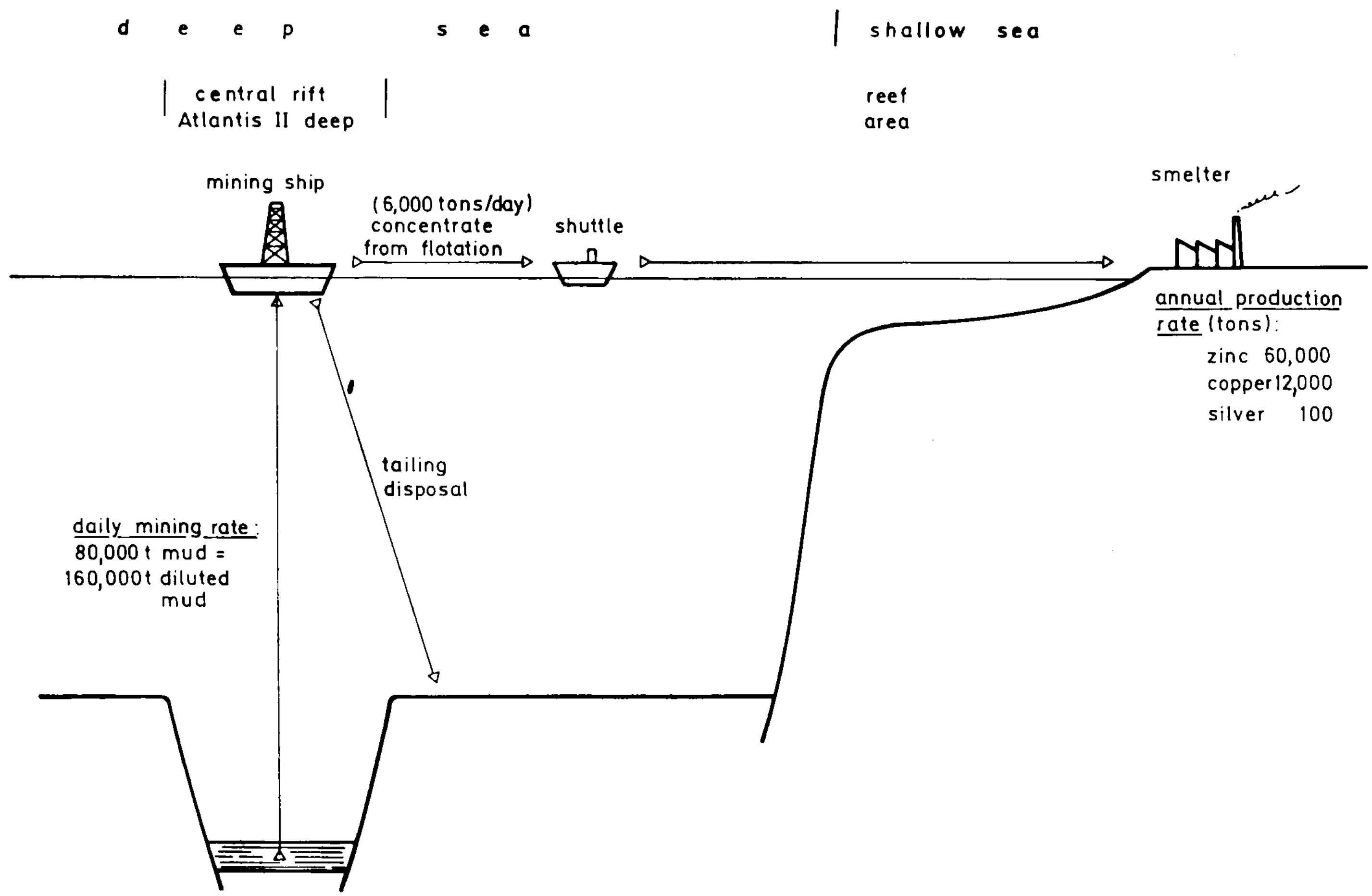

FIG. 9.—Atlantis-II deep: schematic of commercial extraction

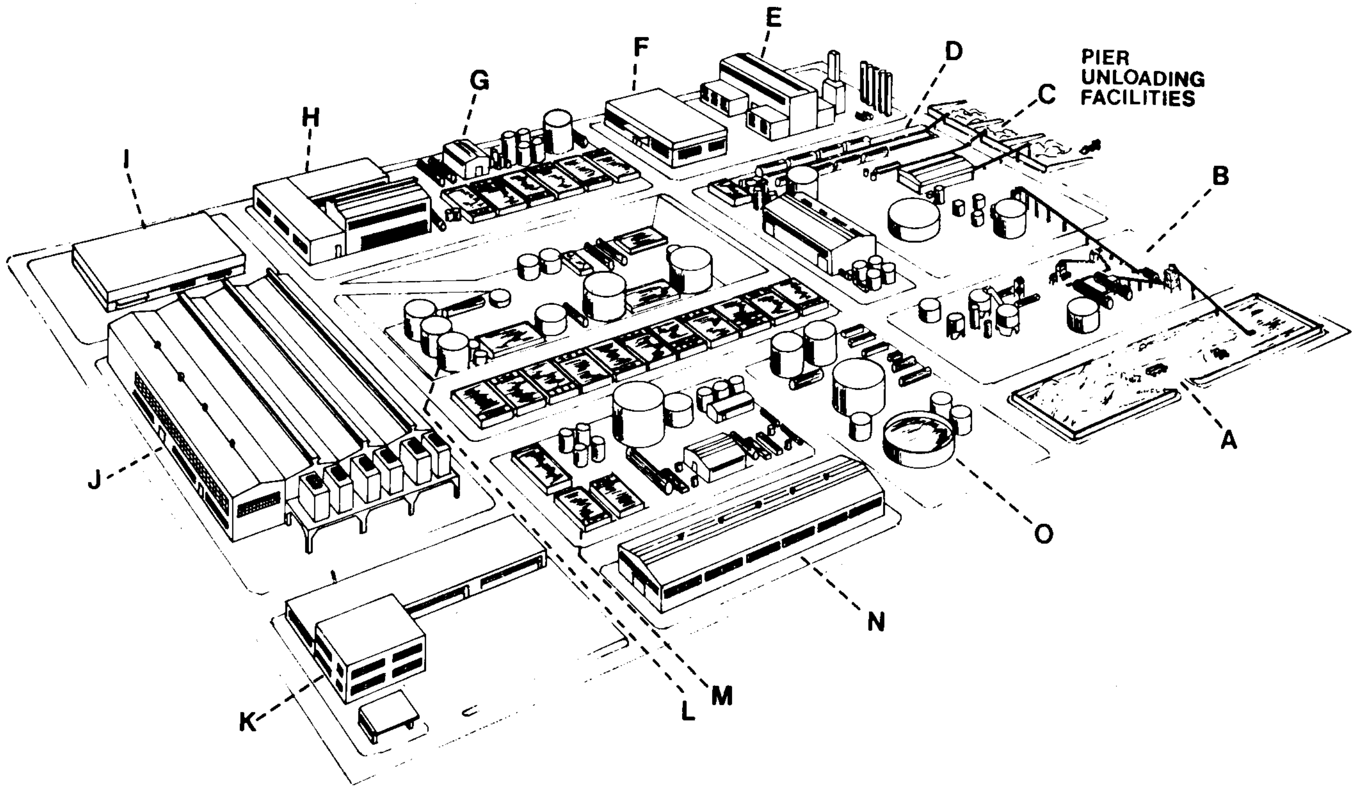

Fig. 10.—Yanbu metallurgical plant (artist's impression, after Tecnicas Reunidas, Madrid). Groups of buildings and functions: *A*, limestone storage; *B*, milk of lime preparation; *C*, residues; *D*, pressure leaching and neutralization; *E*, oxygen plant; *F*, motor control center; *G*, silver cake production; *H*, copper electrolysis; *I*, electrical substation; *J*, zinc electrolysis; *K*, administration and laboratories; *L*, solvent extraction; *M*, cobalt and cadmium production; *N*, product storage and workshops; *O*, waste storage.

60,000 tons of zinc, 12,000 tons of copper, 100 tons of silver, and, possibly, cadmium, cobalt, some gold, and by-products of the processing stages, such as gypsum. Although the zinc production would be only 1%–2% of the world's total, it would, nevertheless, be a valuable contribution to the economies of the countries involved in this project. Given a beginning of pilot operations by 1983, the commercial plant could be built and become operational within the second part of this decade.

RELATED ISSUES

One of the crucial issues, before making any concise commercialization plans for the A-II deep mineral deposit, was the question of ownership. What state or states or any other organization (there has been an application to the United Nations) can claim rights, or can anyone explore and mine under one of the freedoms of the high seas? It had been apparent that most arguments for rights and ownership would favor the two riparian states: the Kingdom of Saudi Arabia and the Democratic Republic of the Sudan. This was further supported by the fact that both states had decreed rights over the continental shelf adjacent to their coastal zones of sovereignty. In 1971 there was an attempt by a representative of the industrial party already engaged in exploration to present a sharing and participation model.[11] The subsequent development (Saudi-Sudanese agreement of 1974 and the forming of the RSC in 1975) has already been discussed.

For many years, especially since the Third United Nations Conference on the Law of the Sea (UNCLOS) was convened in 1973, controversy marked the discussions among states, individuals, and other groups regarding seabed minerals and deep ocean mining. The developing countries (a large majority at UNCLOS, numbering more than a hundred) attempted to play the leading role in future resource management within the international area, seaward of the coastal states' zones of full or partial control. Their claim rests on the "one state-one vote" principle of the UN organization, together with the "common heritage of mankind" idea presented by Arvid Pardo, Maltese ambassador in 1967. Their goal is the eventual establishment of a new economic order, also a subject of discussion within UNCTAD, UNIDO, and other fora.

On the other side, the industrialized states technically and financially capable of bringing mining of the deep seabed to life argued that, for contributing technology and funds for realizing ocean mining, they should have an appropriate share of the benefits. As a fair solution, in their view, they

11. E. Blissenbach, "Metalliferous Deposits of the Red Sea Bottom and Development Aspects," *World Law Review*, Belgrade World Conference on World Peace through Law and the 3d World Assembly of Judges, 1971 (Washington, D.C.: World Peace through Law Center, 1972), 5:135–42.

suggested a "parallel system" allowing the enterprise, dominated by developing countries, to undertake exploitation under the same conditions as private and state companies from the industrialized world. This is hardly the place to go into more detail about this controversy, but it should be stated that the opposite views could not be reconciled, especially concerning the so-called technology transfer, in spite of remarkable compromises in other important sectors of law of the sea affairs.[12]

The model of cooperation between Saudi Arabia and the Sudan, as represented by the RSC and a company from the industrialized world, may serve as an example for many other cases, where the prerequisites could be different but the underlying principle, nevertheless, applicable. In the example discussed, states and companies share whatever they are able to contribute: the Sudan offers its mineral rights and some trained personnel; Saudi Arabia contributes mineral rights and the project funding; BRGM as consultants and Preussag as principal contractor contribute know-how and the expertise of others retained as subcontractors. It has been the concern of the RSC to engage the most proficient parties in the project. As a result, subcontractors from the following countries have been involved: several from the United States, United Kingdom, France, the Federal Republic of Germany, and at least one from Norway and Spain, in addition to companies and institutes from Saudi Arabia and the Sudan.

Because the RSC believes that know-how does not only lie in patented formulae but, much more, in human beings, it has been one of its major concerns to bring about the training of Saudi and Sudanese students within the professional sectors of the project. Since the beginning of the project work, in 1976, more than 80 of their geoscientists, engineers, and technicians underwent theoretical and practical instruction. Most of them have also trained on board the research vessels *Valdivia* and *Sonne* and the mining ship *Sedco 445*.

The issue of technology transfer, which has been so controversial in the United Nations, is easily dealt with in the project work between the RSC and its general contractor. The contract provides not only for an adequate sharing of the new technologies but also foresees their joint application wherever feasible. The unique role played by the RSC as an active factor in the maturing of ocean mining has led to recognition, such as the award of an observer status at UNCLOS. The RSC is aware of its responsibilities for furthering the training of other developing countries' representatives, under the sponsorship of the International Ocean Institute (IOI), Malta, and is acting accordingly. Preussag has also contributed to the practical training programs of the IOI.[13]

12. For a more detailed discussion, see Elisabeth Mann Borgese, "The Draft Convention," and related documents from UNCLOS in this volume.

13. Editors' note.—See "IOI Report" in Appendix A of this volume.

GLOBAL MINERAL POTENTIAL

It had long been recognized that the formation of the Red Sea metalliferous sediments is a phenomenon associated with hydrothermal activities, increased heat flow, the additional supply of metals from magmatic sources, and all such features as they are observed and associated with the rift areas of diverging crustal plates. Since the Red Sea rift is part of a large tectonic system, the global system of ocean ridges, it was logical to continue the search for metallic enrichments into neighboring areas of related tectonic activity. The exploration focused on promising sites, with anomalies of increased heat flow, hot and mineralized springs, etc. Apart from the unsuccessful search for hydrothermal, metalliferous mud in the Gulf of Aden in 1971 with the *Valdivia*, the exploration also included several East African lakes.[14] Positive indications for noncommercial metallic enrichments (with increased heat-flow values) were found in Lakes Kivu (zinc) and Malawi (iron); no concentrations were found in Lakes Shala (in Ethiopia) and Tanganyika, which had little or no increased heatflow. The Carlsberg Ridge in the Indian Ocean showed interesting metal-forming trends, which were also recorded during the French-American FAMOUS Project, performed with the aid of deep-diving manned vessels in the Atlantic.[15]

By far the most encouraging signs, however, came from the East Pacific rise, in particular the Galapagos rift, the area closer to the Mexican coast, and that extending into the Gulf of California.[16] Some of these investigations resulted in the discovery of new strange worlds at water depths of several thousand meters, where plants and animals, so far unknown, live around geothermal springs in an environment devoid of oxygen. Some of the vents of those sources were found to consist of high-grade precipitates of zinc (up to 20%) and copper (up to 6%).

Because of these favorable indications, Preussag, with the participation of the Saudi-Sudanese Red Sea Commission and several national and international scientific institutions, performed a reconnaissance cruise in 1980, Geothermal Metallogenesis East Pacific (GEOMETEP 1), focusing on selected

14. E. Blissenbach, "Continental Drift and Metalliferous Sediments," *Conference Papers Oceanology International '72*, Brighton, England, March 1972 (London: BPS Exhibitions, 1972), pp. 412–16; E. Blissenbach and R. Fellerer, "Continental Drift and the Origin of Certain Mineral Deposits," *Geologische Rundschau* 62 (November 1973): 812–40.

15. C. Riffaud and X. Le Pichon, *Expedition "Famous": 3000 Meter unter dem Atlantik* (Frankfurt: Fisher Taschenbuch, 1980). (Original title: *Expédition "Famous": A trois mille mètres sous l'Atlantique* [Paris: Editions Albin Michel, 1976], highly recommended for both technical and nontechnical readers.)

16. J. Francheteau, H. D. Needham, P. Choukroune, T. Juteau, M. Séguret, R. D. Ballard, P. J. Fox, W. Normark, A. Carranzy, D. Cordoba, J. Guerrero, C. Rangin, H. Bougault, P. Cambon, and R. Hekinian, "Massive Deep-Sea Sulphide Ore Deposits Discovered on the East Pacific Rise," *Nature* 277 (February 1979): 523–28.

areas along the rise, from the Easter Island to the Galapagos Archipelago (fig. 11).[17] The results were encouraging enough to justify the planning of a second cruise for 1982.

It was concluded that the rifts and connected fault zones of the major ocean ridges are the preferential site of origin of metalliferous sediments where and when certain prerequisites combine in an optimum way. It may be that the early crustal opening in the forming of an ocean basin, as in the Red Sea, represents the most favorable conditions. Even if mineral deposits should be less likely and concentrated during later spreading stages, there still remains the possibility of locating the richer deposits of earlier spreading—probably covered by near-shore shelf sedimentation. Mining of a large mineral accumulation through overburden is not an altogether unrealistic endeavor. Recovery methods do exist. Drilling is at an advanced stage; frac operations by hydraulic or nuclear power are standard methods or at least experimentally tested; and solution mining is practiced successfully on land. It follows that the ocean floor, in particular in the vicinity of the central rift of the ridges, holds great promise for supplying metals in the future. In order to better comprehend the processes at work on the Red Sea floor, it is necessary to review the geological history of the area.

GEOLOGICAL HISTORY (FROM 25,000 B.P.) AND OUTLOOK

Our summary starts with the state of the Red Sea at around 25,000 B.P., the approximate age of the oldest of the fill of the A-II deep (fig. 12 and table 2). (The basic form of the Red Sea area had been achieved in the course of the previous movements of crustal plates, having taken place mostly in pre-Miocene and Pliocene times.)[18] We may assume that the morphologic shape was very similar to what it is now, although the central trench could have been somewhat less expanded. The water level was probably lower, as that time corresponds to the last climax of glaciation. This also affected the higher elevations of neighboring Ethiopia and East Africa, and, probably, the South Arabian highlands which were partially glaciated. The climate and its consequences for sedimentation in the Red Sea area are relevant because the period of circa 20,000–12,500 B.P. is considered an intertropical cold, dry phase.[19] The deposition around the Red Sea was characterized by high sediment yield—corresponding to a period of maximum aridity, minimum water yield,

17. E. Blissenbach, "Mineral Prospection on East Pacific Rise," *Meerestechnik mt* 11 (June 1980): 103–6.

18. Ross.

19. D. A. Adamson, F. Gasse, F. A. Street, and M. A. J. Williams, "Late Quaternary History of the Nile," *Nature* 288 (November 1979): 50–55 (also useful for other references to paleoclimatic data of the area).

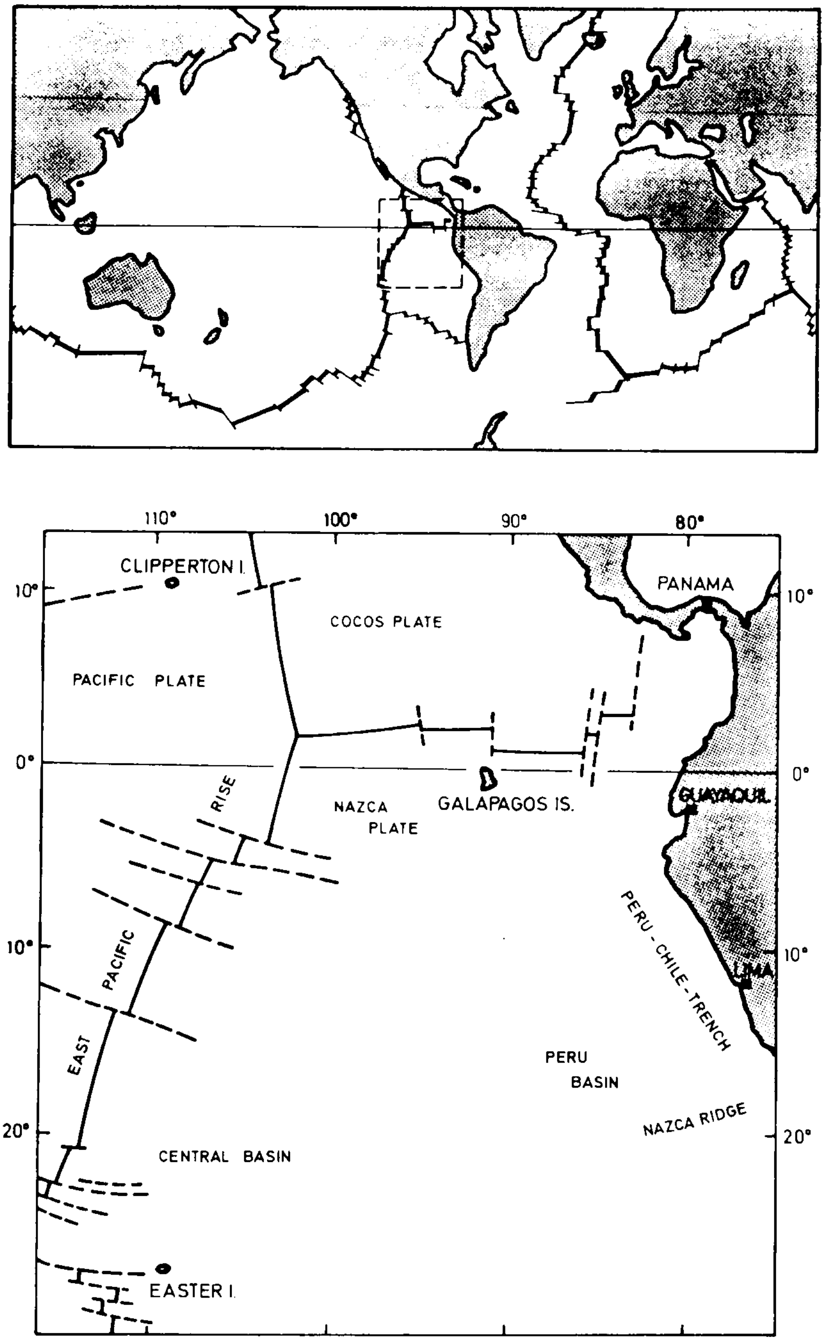

FIG. 11.—Top, global central rifts of ocean ridges. Bottom, area of GEOMETEP cruises 1980/82. (Taken with permission from *Meerestechnik mt* 11 [June 1980]: 104.)

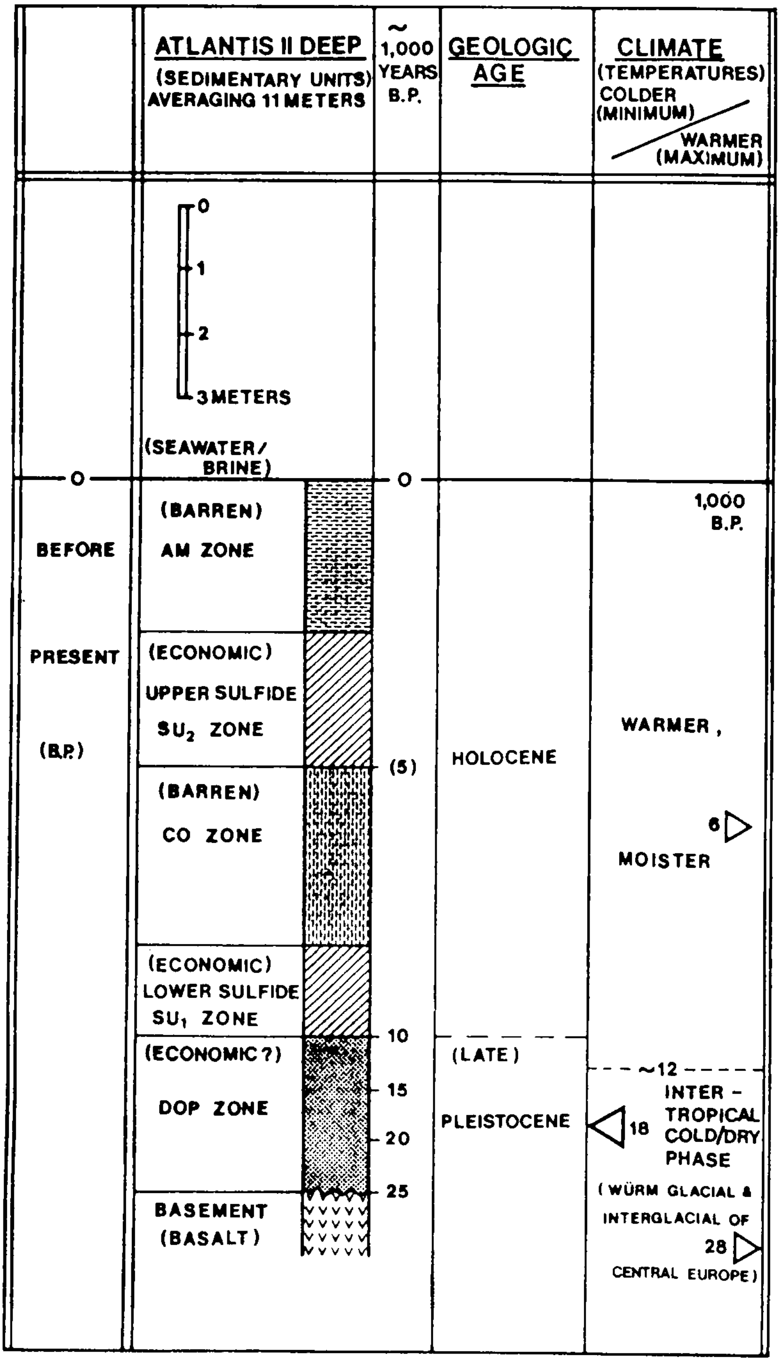

FIG. 12.—Geological history of Atlantis-II deep sedimentation

and highly seasonal runoff. We may assume that large volumes of clastic material also accumulated along the slopes descending to the Red Sea as recorded in the adjacent Nile basin.

This scenario fits well the findings in the A-II deep, where the lowermost sedimentary unit (DOP zone) consists predominantly of clastic deposits, which could be more easily swept into the depression with a large supply of detritus along the shores, strong seasonal runoff, and shorter transport distance due to a lower sea level. Also, eolian transport of fine-grained clastic material could have played a certain role. Volcanic activity, probably in connection with continued seafloor spreading, is indicated by the presence of basalt fragments in this zone.[20] In addition to some biogenic deposits, layers of iron oxides and pyrite were formed. This could point to the existence of brines.

A profound change took place during the period of about 12,500–10,000 B.P. within the sedimentary section of the A-II deep, when clastic sedimentation graded into chemical precipitation under anaerobic conditions with the formation of sulfide layers (the lowermost of the economically interesting metalliferous sediments [SU_1 zone]). The reason for the change is partly based on the beginning of a warmer and moister terminal Pleistocene to Holocene phase with less sediment yield and a rising sea level. In other words, there was less clastic material available along the Red Sea shores, and it ceased to be transported over the longer distance to the central area. Apart from the increased temperatures, there must have been still another cause: the uniform and widespread presence of chemical (sulfide and sulfate) precipitates within the SU_1 zone indicates the increased influence of brines. They, in turn, may imply stronger heat flow and leaching of the deep's flanks, probably in connection with ongoing or intensified seafloor spreading and local faulting.

For several thousand years, the deposition of mostly chemical precipitates continued within the A-II deep and possibly other deeps. Elsewhere in the Red Sea, normal pelagic sediments accumulated. It is noteworthy that during that time a sapropelitic unit was deposited on the Nile cone, according to the cores from a *Glomar Challenger* drill site. (There had been two previous sapropelitic phases there, at about 25,000 and 40,000 B.P.) The similarity between the Nile sapropelite and the lower A-II deep sulfide zone was due to higher water level, restricted water exchange, and the absence of high energy transport and clastic sedimentation.

The sulfide phase was followed from about 10,000 B.P. to 5,000 B.P. by mixed sedimentation in the A-II deep resulting in the CO zone, with pre-

20. Vulcanism has been an important and characteristic feature in the forming of the Red Sea. Prior to the separation of the crustal plates, the effusive flows of the Ethiopian and South Arabian trap basalts and their vast areal coverage, in Tertiary times, accompanied the beginning of the rifting process. Volcanic activity has always been recorded along the margins of the rift system and, also, within the evolving center of the crustal opening, where large volcanoes have risen from the seafloor—in several cases to form prominent islands such as the Zubeir Islands and Gebel Tair.

dominant oxidic deposits (mostly limonite-hematite). At its base and higher up in the section further volcanic activities are shown by the presence of basalt. Tectonic events during the time of sedimentation of this zone are also indicated by slump structures. They are especially common in the southwest part of the deep, from where the metal-bearing liquids are thought to have spread. Thereupon another sulfide series (SU_2) was laid down.

In the A-II deep, the deposition of the sulfides accompanied by montmorillonitic minerals and, locally, carbonate layers continued and may have graded into amorphous siliceous sediments (AM zone) at a time more or less 3,000 years ago. The upper layers, consisting mostly of brine and little solid substance, are more a combined emulsion/solution than a sediment, in its normal sense. The top layers and the brine interfaces of the A-II deep bear witness that modern men navigated 2,000 m above by the presence of minute fragments of paper and fuel coal.

There is every reason to believe that the precipitation of chemical sediments continues in the deep and will do so until significantly strong changes in conditions occur. Having arrived at the present, the question may well be asked, What are the major benefits of the activities described above for exploiting the A-II metalliferous sediments? Apart from the obvious benefits to the two supporting states and the general contractor, the world as a whole will benefit from the economic recovery of metals from the floor of the Red Sea through the technologies developed. Also, the principles of cooperation practiced by the RSC and its contractor and the way in which the problem of technology transfer, highly disputed elsewhere, has been handled can be applied in other conflict areas of ocean mining. A novel approach to open up new resources in the sea has been linked to a determination to exploit without leaving a trail of poisonous rubbish lining mankind's footsteps along this new route.