Hot Brines and Recent Iron Deposits in Deeps of the Red Sea

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GSA

Contribution No. 1667 from the
Woods Hole Oceanographic Institution

added to [illegible]

This work was supported by Grant GP-821 from the National Science Foundation. Messrs. Miller, Densmore and Pocklington are members of the Department of Physical Oceanography and Dr. Degens and Mr. Jokela are members of the Department of Chemistry and Geology of the Woods Hole Oceanographic Institution. They were part of the scientific team aboard Atlantis II; Mr. Miller was chief scientist.

Mr. Hathaway and Dr. Manheim, members of the U. S. Geological Survey at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts made the laboratory mineralogical and chemical determinations. Mr. McFarlin, also a member of the Department of Chemistry and Geology, participated in the laboratory mineralogical work.

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Introduction

Sedimentary iron and heavy metal deposits of undetermined size have been found in the middle of the Red Sea some 2000 meters below the surface of the sea (Fig. 1). This discovery has been made from the Research Vessel *Atlantis II,* which is still at sea engaged in a series of oceanographic investigations which ultimately will end in November, 1965 after the ship has circumnavigated the globe. The discovery is significant because the environment and the processes controlling deposition of heavy metals are observable and appear to be still active.

The environment of the deposits can be briefly described as an isolated submarine pool of brine having a pH as low as 5.3, a temperature of $56^{\circ}C.$ and a salt content of about 310 grams per liter (at $20^{\circ}C$). Shipboard oxygen determinations and the indicated presence of H_2S, divalent iron and divalent manganese in the water suggest that the environment is anaerobic. This hot, dense brine is trapped in a local depression of the Red Sea median valley. (*Atlantis II*

Deep, Fig. 1). The iron deposits, consisting largely of hydrous iron oxides, are found in the same depression. Brines from the Discovery Deep (21°17'N, 38°02'E) (1), a few miles southwest of the Atlantis II Deep (21°21'N, 38°04'E), have a pH of 6.2 and a temperature of 44.7°C, and are also associated with iron-bearing sediments. The Discovery and Atlantis II brine pools both extend about 150 meters above the bottom. A few miles south of the Discovery Deep another depression of greater depth has been reported (2) containing essentially normal Red Sea water. Deeps several hundred miles to the north (Sta. 540) and south (Sta. 545) were investigated and contained no brine. One of these (Sta. 545) is known to contain normal sediments.

Geologic Setting

The Red Sea median valley is a ~~prominent~~ conspicuous trough structure, particularly well developed in the southern ~~portion~~ part, where it is associated with strong magnetic and positive gravity anomalies. It generally is thought to be a graben or rift structure, representing tensional forces acting normal to the Red Sea axis (3). The measured anomalies, plus seismic refraction studies, have indicated the presence of a long, narrow intrusive igneous body at a shallow depth below the median valley (4). The same studies suggest that a considerable thickness of sediments exists below the shelves on both sides of the valley. A hypothetical cross section of the Red Sea was constructed by Drake and Girdler (Fig. 2), who also cited borehole data indicating a section of more than 2000 meters of evaporites near Dahlak Island at 16°N latitude on the western shelf of the southern Red Sea (5). Continuous seismic profiles made more recently by the Woods Hole Oceanographic Institution confirm this general type of structure, though they show it to be somewhat more complicated (6). The probable age of the major Red Sea sedimentation sequence is Miocene to Recent (7).

Oceanographic History

The finding of the hot brines has an interesting history, as Table 1 shows. As much as 80 years ago ~~It was known to earlier~~ investigators (8, 9, 10) knew that below a few hundred meters, the Red Sea had a remarkably uniform mass of warm, unusually salty water. This feature was explained by the predominance of evaporation over precipitation, which caused downward movement and mixing of the saltier surface water layers. In the deepest water of the central Red Sea, small but anomalous increases in temperature (up to 3°c) and salinity (5‰) appeared in the data of the Swedish Albatross Expedition of 1947-48 (11) and the Atlantis Cruise 242 (12) of 1959. These increases were apparently consistent with the theory of downward mixing of warmer and saltier surface water. The features were reinvestigated by Atlantis II and Discovery in 1963, and were then recognised and pointed out by Miller (13) and by Charnock (14) as temperature and salinity anomalies. On

Discovery's return to the locations in 1964 a local bathymetric survey (Fig. 1) was made, showing at least two local depressions, each a mile or more across and separated by several miles. In one of these a remarkable hot brine was found (1). The new German research vessel Meteor visited the area in the fall of 1964 and confirmed the observations (2).

Shipboard Work

In February 1965, Atlantis II returned to do more detailed hydrography and to investigate the sediments of the hot water holes. Sediment samples were taken in conjunction with hydrographic casts. In each deep a gravity corer serving as a pilot weight collected a sediment section one to two meters long. In the Atlantis II Deep, a pipe dredge sample was recovered and a third core was taken by lowering a small gravity corer separately on the hydro wire. Attempts were made to lower a piston corer in both deeps, but owing to drift of the ship, only the side slopes were reached. On the slope of the Discovery Deep only fragments of basalt and limestone were obtained, whereas ~~while~~ on the slope of the Atlantis II Deep the corer hit hard rock below about two meters of iron-rich sediment.

Hydrography and Water Chemistry

Four hydrographic casts were made, two in the Atlantis II Deep and two in the Discovery Deep. Special high-range thermometers protected from deep sea pressures permitted measurement of the unusual temperatures. Hydrographic data for the Red Sea stations visited on this cruise are given in Table 2. The salt content of the anomalous water is given as chlorinity in order to permit a comparison with the surface and intermediate waters. Knudsen salinity tables or standard salinometer conversion tables cannot be used to calculate salinity for the brines, ~~since~~ because these waters differ from normal oceanic waters in their ionic ratios. Calibration curves relating salinometer readings to titration chlorinity have been prepared from mixtures of brines and intermediate waters, ~~since~~ as not all the brine samples are available for analysis at the present time.

Table 3 compares analyses of bottom water from the *Atlantis II* and *Discovery* Deeps with other types of water. It may be noted that the hot brines in *Atlantis II* Deep were clear when taken, but soon after brownish precipitates formed. The metal analyses refer to total water samples, the precipitates being redissolved by adding HCl.

Brine from the *Atlantis II* Deep is composed chiefly of sodium chloride, and has a total salt content about 10 times higher than normal sea water. The brine is markedly depleted in magnesium, sulfate, and bromine relative to total salt, and contains extraordinary concentrations of heavy metals. Zinc, copper, iron, and manganese are found in concentrations 1000 to more than 50,000 times higher than their estimated normal levels in sea water. Silica is present in amounts about 200 times greater than in normal Red Sea surface water.

Oxygen isotope (O^{18}/O^{16}) ratios have been measured on normal Red Sea water and on the anomalous brines. The values are given in Table 4, along with values for several reference waters. O^{18} enrichment for a normal Red Sea sample (1480 m, Table 4) is consistent with values for other ocean waters of similar salinity, such as water from the Grand Bahama Banks (22). Highly evaporated sea water should be appreciably enriched in O^{18} relative to mean ocean water, but the Red Sea deep brines do not show such enrichment. It should be emphasized, however, that precise prediction of ultimate δO^{18} values for sea water bodies which have been greatly reduced by evaporation cannot be made because of the variable molecular exchange between water and water vapor during evaporation (25). Most fresh waters are highly enriched in O^{16}, and δO^{18} values from -5 to -15 are frequently encountered (26). Many Oil field brines, on the other hand, are similar in δO^{18} to normal sea water, although they may have high salt concentrations (23). The slight shift into the positive range of δO^{18} (Table 4) may be explained by slight evaporation at the time of deposition, or by isotope exchange with the surrounding rock formations during diagenesis. Some petroleum brines are known to be enriched in O^{16} (23). However, this enrichment is generally matched by a decrease in salinity, suggesting mixing effects with "light" meteoric waters.

During the preparation of this paper, the German research vessel Meteor re-visited the brine area and made several further observations. One of the authors (A. Jokela) was transferred in the Gulf of Oman from the Atlantis II to the Meteor, and was generously allowed to accompany the ship on her return trip through the Red Sea. It is noteworthy that Meteor scientists observed a water temperature slightly higher than reported here (27) and a bottom sediment temperature ~~appreciably~~ about 5°-10°C higher than that of the associated brines. Precise differences in temperature between waters and sediments cannot be presented, as measurements of the sediment temperature were made only after the samples were hoisted aboard ship. Thus the differences in place are probably higher.

Lithology and Paleontology

The sediment collected from the Atlantis II Deep was a megascopically homogeneous black ooze which gradually turned sepia-brown up on drying or storage. The sediment did not respond to a hand magnet in the fresh state, but became highly magnetic on drying in air at 60°C. Sediment recovered with a piston core from a slope about 130 m above the bottom of the deep was finely laminated and looked more compact than the deeper sediments, but it still consisted largely of iron oxides. The upper part of the gravity core from Discovery Deep was fine brown ooze at the time of collection whereas the basal 60 cm of the core contained brittle, fossil-bearing carbonate fragments.

The material collected by pipe dredge from Atlantis II Deep (Sta. 543) was examined for microfossils. Well-preserved planktonic foraminiferal species were found as follows (28):

Globigerinoides ruber (d'Orbigny)
Globigerinoides tribobus (Reuss)
Globigerinoides sacculifer (Brady)
Globigerinella aequilateralis (Brady)
Globigerinita glutinata (Egger)

All of these species range from Miocene to Recent, and would fit in with the present Red Sea surface environment. Only a few possible fragments of benthonic Foraminifera were noted and preliminary examination of the sediment showed no pollen, spores or microplankton (29).

Mineralogy

The minerals in the samples obtained from the Red Sea Deeps were determined by X-ray diffraction analysis, by examination with the petrographic microscope and by comparison with the chemical analyses given in the section on chemistry below. Table 5 lists the minerals found in each sample. The pipe dredge sample from Sta. 543 had been dried on shipboard and showed about 60% halite in laboratory analysis. Therefore, this sample and others from the deeps were washed with distilled water to remove the large amounts of NaCl dissolved in the interstitial water.

Most of the iron in the samples seems to occur as hydrous, amorphous oxides in yellow to brown spherical aggregates 5-10 microns in diameter, such as those shown in Fig. 3. The dried and unwashed pipe dredge sample was magnetic; it yielded diffuse X-ray diffraction maxima and showed optical properties that suggested poorly crystallized maghemite. ~~However,~~ no reflections for any known iron oxide mineral were observed in the material that had been preserved wet, nor did the material respond to a hand magnet. A small amount of pyrite and possibly marcasite occurred in the upper part of the gravity core from the Atlantis II Deep (Sta. 543), but not enough to account for the large amount of iron present.

The X-ray diffraction patterns for the gravity core from Sta. 543 are shown in Fig. 4. Sphalerite is present in all the samples studied in the less than 2 micron fraction. The sample from the 0-15 cm section of the core contains a small amount of sphalerite (about 3%, calculated from the ZnO value given in Table 7); the sphalerite increases to 7-8% in the section from 43-51 cm and decreases to 2-3% at 2 meters depth in the core.

A carbonate mineral with a cell size between that of siderite ($FeCO_3$) and rhodochrosite ($MnCO_3$) occurs in the sample from 2 meters, and it is confined largely to the size fraction greater than 2 microns. A calculation of the composition of the carbonate based on a comparison of six of its interplanar spacings with the corresponding spacings of siderite and rhodochrosite suggests that it contains about 70 mol percent $MnCO_3$ to 30 mol percent $FeCO_3$ assuming that no Ca++ and Mg++ are ~~is~~ present ~~in~~ the structure. As the average index of refraction of the mineral lies appreciably above 1.70, large amounts of Ca++ and Mg++ are not likely to be present. These elements would tend to lower the index toward 1.60; thus huntite is excluded in spite of its almost identical pattern. However, as little as 14 mol percent of $CaCO_3$ in siderite could produce the spacings observed in the X-ray patterns, and because only 1.3% MnO is reported in the chemical analysis (Table 7), it is likely that the ratio of Mn++ to Fe++ in the mineral is somewhat less than 70:30. Siderite has not been synthesized with a $CaCO_3$ content higher than 5 mol percent (30), but natural siderite is reported with $CaCO_3$ concentrations up to 23 mol percent (31). Calcite is present as foraminiferal shells and their fragments.

Anhydrite occurs in all of the samples from the core but only reaches appreciable quantities in the sample from 2 meters. Much of the original anhydrite was leached from the samples of Fig. 4 by washing the samples with distilled water.

The only clay mineral in any of the *Atlantis II* Deep samples was dioctahedral montmorillonite. A d_{060} spacing of about 1.51 rather than 1.52 suggests that nontronite is not the principal montmorillonite group mineral present, in spite of the large amount of iron available in the sample. The absence of "normal" marine clay minerals (32) of the type found in nearby localities suggests that little terrigenous detrital material is present.

Although about 10% (leached basis) amorphous silica was found in a dredge sample that had been dried on board the ship, none was detected in the wet sample.

The piston core from the slope adjacent to the Atlantis II Deep contained only dioctahedral montmorillonite and an iron-bearing mineral amorphous to X-rays.

The mineralogy of the core from the Discovery Deep (Fig. 5) is substantially different from that of the Atlantis II. The major component of the limestone fragments in the basal section is magnesian calcite with about 10 mol percent $MgCO_3$. Normal calcite and a small amount of dolomite with about 10 mol percent excess $CaCO_3$ (based on a spacing of 2.901 Å for d_{104}) are also present. The dolomite may be similar to the protodolomite of Goldsmith and Graf (33). The sediment matrix contains abundant "protodolomite" in euhedral rhombs 20-30 microns in diameter (Fig. 6), and calcite and magnesian calcite. At least some of the iron is in the form of hematite, but amorphous hydrated iron oxide also seems to be present. Quartz, plagioclase feldspar near the composition of labradorite, chlorite, mica and possibly some of the montmorillonite in the sample are probably detrital. Some sphalerite may be present although an anomalously strong feldspar line may be responsible for the peak indicated by a question mark in Figure 5.

Chemistry

A partial chemical analysis of the sediment from the dredge sample, dried on board ship is given in Table 6; quantitative spectrochemical analyses of sediments from the gravity and piston cores from Atlantis II Deep are given in Table 7. A semi-quantitative spectrochemical analysis of the dredge sample is given in Table 8. All ~~of~~ the analyzed samples were leached free of sodium chloride, but retained most of the anhydrite noted in the mineralogical analyses.

Aside from the major component iron, the sediments of Atlantis II Deep contain silica and extraordinary amounts of heavy metals. Zinc, for example, reaches 6.2% as ZnO in one sample (Table 7), compared with an average concentration on the order of 0.01% in marine sediments. Carbonate was not determined quantitatively on the sediment, but lack of effervescence on treatment of the sediment with hot HCl indicated that little was present in the surface layers. In the lower part of the gravity core, some effervescence was noted, which corresponds to manganese-iron carbonate phases found by the X-ray work, and to the higher amounts of manganese in the bottom part of the gravity core (Table 7). Qualitative examination also indicated a relatively small amount of sulfide, which, on the basis of the X-ray work, appears to be bound chiefly with zinc, rather than with iron, although traces of ~~FeS~~ pyrite/marcasite were found.

The large proportion of interstitial water in the iron-rich bottom sediments is remarkable, even where the sediment appears firm and compacted, as in the piston core in Table 7. The dredge sample of Table 6, dried at 60°C without leaching out NaCl, contained over 60% readily water-soluble matter (primarily NaCl obtained during evaporation) and only 21.6% Fe_2O_3; one sediment sample in Table 7 (gravity core, 43-51 cm) contained 93.4% interstitial water as a percent of original bulk weight.

Discussion

Before summarizing the evidence bearing on the origin of the Red Sea brines and metal deposits, one should point out that (a) the abnormal, iron-rich sediments have been found only on the floors and sides of the ~~in~~ hot brine ~~zones~~ reservoirs while other deep areas of the Red Sea contain only carbonate-rich sediments; (b) unusually high concentrations of the metals enriched in the sediments are also found in high concentration in the brines; (c) the sediments are gel-like, containing a large amount of brine, which suggests that a major part of the sediment has been precipitated from free solution; and (~~d~~e) a temperature ~~even~~ greater by about 5 to 10°C than those determined for the brines has been observed in a sediment sample. Hence, it appears that the brines and metalliferous sediments have a common origin, and any theory of origin of one must explain the other.

Three principal hypotheses can be advanced to account for the temperature and salinity of the brines:

1) Basinward flow of brines concentrated by local surface evaporation and solar heating (14).

2) Basinwide evaporation during a former isolated stage of the Red Sea (34).

3) Submarine discharge of brine.

(d) the very high temperatures of the brine reservoirs demand some special source of heat to compensate for the heat lost upward by conduction and perhaps, by multi-cell convection;

The first two hypotheses would take advantage of the great regional excess of evaporation over precipitation and stream runoff to directly account for the brines and the high temperatures by surface processes. In the first hypothesis, concentrated, hot brines would flow down Red Sea basinal slopes and collect in the deeps, retaining their heat for an appreciable length of time. In the second hypothesis, the brines would represent residues of much larger volumes of original Red Sea water, which evaporated during an earlier glacial period or periods. At such times, sea levels dropped close to or below the depth of the sill between the Arabian and the Red Sea, restricting or completely cutting off the supply of ocean water. Subsequent inflow of sea water could submerge the residual brine pools.

Whereas both of the above hypotheses offer plausible theoretical mechanisms for the emplacement of concentrated brine under essentially normal sea water, the present evidence against them is strong:

1) Neither mechanism offers any explanation for the source of the metals.

2) If the brines are due to earlier evaporation of large volumes of Red Sea water, we should expect all deep areas to contain brine. Yet, comparable deeps only few miles away from the brine pools contain only ordinary Red Sea water.

3) A selective mechanism by which descending brines seek out certain pockets in the central Red Sea and not others nearby, has yet to be found. There appear to be no evaporating pans which would supply such brines.

4) If the brines are direct residua after solar evaporation of either sea water or mixed continental-sea waters, we should expect concentration of highly soluble constituents such as magnesium and bromine. In contrast, both of these elements, as well as sulfate, are greatly depleted in the brines.

5) The fact that the sediments are hotter than the brines indicates that the source of heat is from below.

6) O^{18}/O^{16} ratios in the brines are similar to surface Red Sea waters or other sea waters which have been slightly concentrated by evaporation. However, the ratios do not favor the possibility that evaporated residues of normal Red Sea waters are involved.

In that case, much higher ratios would be expected.

The position of the brine pools in zones of tectonic activity and near great thicknesses of sedimentary strata could provide both large volumes of interstitial waters and mechanisms for introduction of the waters into the sea through fissures and faults. It is notable that concentrated oilfield brines often are enriched in iron and heavy metals, and normally have temperatures as great or greater than the brines under discussion. The Red Sea brines may be related to oilfield brines in mechanism of formation, or may be produced through subsurface circulation and leaching of evaporites by formation waters of near-normal oceanic salinity. The proximity of an intrusive igneous body also may be effective as a source of heat and possibly of volatile materials. However, it is not necessary to postulate hydrothermal or magmatic activity to account for the metals or the temperatures noted. In the Imperial Valley of southern California, an area similar in geologic characteristics to the Red Sea, a deep geothermal well tapped a brine considerably higher in temperature (~300°C) but of similar chemical composition. A magmatic origin for the water was propos (White et al. 1963)(3

We recognize that the brine may have changed in composition during passage through the Red Sea substrata and may reflect a number of consequent influences. For example, the presence of "protodolomite" in the Discovery Deep core suggests that dolomitization of pre-existing carbonate rocks may be partly responsible for the depletion of magnesium in the brines. Although the oxygen isotope data support submarine discharge of water of some unknown origin ~~as the origin of the brines~~, they do not provide conclusive evidence for influence from either hydrothermal or formation water in their genesis. Juvenile ~~Hydrothermal~~ waters are assumed to be enriched in O^{18} by a few per mil relative to mean ocean water (35, 36), but the same can be true of formation waters. A study of the deuterium/O^{18} relation~~ship~~ may be revealing, as ~~since~~ hydrothermal waters show a characteristic "oxygen isotope shift" into the positive range relative to deuterium, owing ~~due~~ to oxygen isotope exchange with the bedrock (37).

The Red Sea deeps may be considered a natural laboratory where information on a number of significant geochemical problems can be obtained. For example, hydrated forms of $CaSO_4$ are stable configurations in hypersaline surface environments; thus causing anhydrite in the present sediments to appear anomalous. Perhaps high salinity, hydrostatic pressure, and high temperature, or all three, are responsible for the presence of anhydrite instead of gypsum or bassanite. Other problems which profitably may be investigated in the Red Sea deeps include the formation and diagenesis of syngenetic sulfides; of siderite, rhodochrosite, and dolomite; of authigenic silicates such as montmorillonite; and of sedimentary iron ore. The problem of iron ore formation is of particular interest because of the controversy on the origin of Precambrian iron ore formations. The controversy is chiefly caused by the lack of recent counterparts to these deposits. Studies of the Red Sea deposits may, therefore, ~~help~~ shed light on the environmental conditions that existed in Precambrian seas.

Summary and Conclusions

(1) Hot, weakly acidic brines concentrated in heavy metals and silica are present in central Red Sea deeps at depths of about 2000 meters. Interaction of the anoxic brines with the oxidizing, weakly alkaline Red Sea waters promotes deposition of metal oxides and sulfides, anhydrite and silica. More than 6% ZnO (mainly as ZnS) and nearly 1% CuO in a dominantly hydrous iron oxide matrix have been observed. Diagenetic reorganization and formation of such phases as dolomite, magnesian calcite, siderite-rhodochrosite, sphalerite and possibly montmorillonite occurs in the sediment.

(2) Geologic, chemical and oxygen-isotope data point to submarine discharge ~~as the probable mode of origin of the brines~~ of some deep thermal water of unknown origin. Sedimentary-evaporitic strata underlying the Red Sea offer a promising source for the concentrated brines. Whatever the ultimate origin of the brines, it seems clear that their discharge appears to be associated with the tectonic history of the Red Sea. Tectonism and rifting may have opened migration paths for the passage of solutions. Other areas in the Red Sea - East African Rift Zone region, or elsewhere, which combine rift activity and thick stratigraphic sections containing abundant water may be considered as potential sites for similar phenomena. Examples of such areas might include the Gulf of Aden, the Gulf of Aqaba and the Gulf of California.

Table 1. Maximum temperatures and salinities recorded in Red Sea stations:

Depth(m)	T°C	S (‰)	Location		Date, Vessel, Station and Reference	
600	21.6	40.4	21°N	38°E	1881-3	*Vityaz*, sta. 200 (8)
1852	21.5	40.6	20°41'N	38°07'E	1897	*Pola*, sta. 294 (9)
>2000	21.5	> 40.0	21°N	38°E	1898	*Valdivia* (10)
1930	24.5	45.0	21°10'N	38°09'E	1948	*Albatross*, sta. 254 (11)
1914	----	42.5	21°22.5'N	38°05'E	1959	*Atlantis*, sta. 5639 (12)
1931-78	25.8	43.2	21°21.5'N	38°04.5'E	1963	*Atlantis II*, sta. 42 (13)
2350	21.9	40.8	21°07'N	38°10'E	1963	*Discovery*, sta. 5247 (14)
2190	44.0	271*	21°17'N	38°02'E	1964	*Discovery*, sta. 5580 (1)
2167	56.0	261**	21°20.5'N	38°03.5'E	1965	*Atlantis II*, sta. 543 (This report)

* Calculated from salinometer readings using tables for normal sea water

** Calculated from chemical analysis

Table 2. Hydrographic data for Red Sea Deep stations. Chlorinities less than 23.5‰ are calculated directly from salinometer measurements using standard tables. The last decimal in the oxygen and temperature values has been retained although the figures do not necessarily represent absolute accuracy. Empirical calibration curves were used to relate the shipboard salinometer readings (on diluted water) to chlorinity in the case of the high chlorinities. These values should be regarded as approximations. The phosphate, nitrite, nitrate, oxygen and silicate values for the brines are given without taking into consideration possible influence of the abnormal character of the water on the shipboard determinations. However, an "F" factor was estimated for silicate using evaporated surface water.

Depth(m)	T°C	Cl (‰)	O_2 (ml/l)	NO_2-N (μgA/l)	NO_3-N (μgA/l)	PO_4-P (μgA/l)	P (μgA/l)	SiO_3-Si (μgA/l)
a. Station 540. 25°28'N-25°22.5'N, 36°10'E-36°08.5'E, Maximum depth 1945m								
0-1	22.87	22.20	4.95	0.03	0.08	0.03	0.18	-
100	22.88	22.26	4.66	0.07	0.66	0.08	0.21	-
199	21.86	22.40	3.06	0.00	7.7	0.48	0.57	-
398	21.68	22.43	1.03	0.00	15.0	0.99	1.03	-
594	21.73	22.445	1.46	0.00	13.3	0.90	0.95	-
786	21.73	22.45	1.86	-	13.4	0.75	0.82	-
986	21.75	22.45	2.16	-	10.8	0.72	0.78	-
1147	21.78	22.45	2.31	-	10.8	0.65	0.71	-
1343	21.84	22.455	2.38	-	9.8	0.61	0.67	-
1540	21.87	22.455	2.61	-	9.3	0.57	0.64	-
1737	21.90	22.455	2.62	-	9.7	0.59	0.64	-
1880	22.07	22.455	2.62	-	9.7	0.57	0.66	-

Table 2 (Continued)

Depth(m)	T°C	Cl (‰)	O_2 (ml/l)	NO_2-N (μgA/l)	NO_3-N (μgA/l)	PO_4-P (μgA/l)	P (μgA/l)	SiO_3-Si (μgA/l)
b. Station 541 (Discovery Deep) 21°17'N, 38°00'E; Maximum depth 2089m								
951	21.75	22.45	1.18	0.01	11.1	0.72	0.75	11.4
1149	21.78	22.45	2.10	0.01	12.3	0.70	0.75	10.5
1443	21.87	22.46	2.28	0.01	12.6	0.64	0.71	11.6
1706	21.95	22.465	2.27	0.00	12.0	0.62	0.70	12.0
1800	21.99	22.475	2.14	0.01	11.7	0.50	0.67	13.0
1847	22.01	22.47	2.22	0.00	11.7	0.57	0.67	12.4
1894	-	22.47	2.17	0.01	11.2	0.62	0.72	12.1
1940	22.06	22.50	2.13	0.02	11.6	0.66	0.72	12.4
1987	24.47	24.985	1.33	0.01	12.6	0.52	0.56	36.2
2044	44.72	154.	0.1	0.00	0.01	(-0.13)	0.12	(672.)
c. Station 542 21°17'N, 38°05'E; Maximum depth 2067m								
1165	21.79	22.45	2.10	-	-	-	-	-
1553	21.90	22.46	2.26	-	-	-	-	-
1843	22.03	22.47	2.13	-	-	-	-	-
1891	22.04	22.49	1.87	-	-	-	-	-
1939	-	22.475	2.17	-	-	-	-	-
1986	23.22	-	2.20	-	-	-	-	-
2005	24.72	-	1.92	-	-	-	-	-
2034	27.89	-	2.04	-	-	-	-	-

Table 2 (Continued)

Depth(m)	T°C	Cl (‰)	O_2 (ml/l)	NO_2-N (µgA/l)	NO_3-N (µgA/l)	PO_4-P (µgA/l)	P (µgA/l)	SiO_3-Si (µgA/l)
e. Station 544, 21°19.5'N, 38°06.5'E; Maximum depth 2156 m								
1878	21.99	-	-	-	-	-	-	-
1976	22.07	22.005	2.58	-	-	-	-	-
1997	-	37	-	-	-	-	-	-
2017	-	78	-	-	-	-	-	-
2064	55.92	155	(0.1)	-	-	-	-	-
2108	55.91	156	(0.1)	-	-	-	-	-
2141	55.94	155	(0.1)	-	-	-	-	-
f. Station 545, 16°34'N, 38°03'E; Maximum depth 1981. Sediment: normal Red Sea type								
0-1	25.89	20.895	4.81	-	-	0.26	0.51	-
197	21.87	22.415	0.93	-	-	0.80	0.94	-
640	21.72	22.455	1.27	-	-	0.31	0.44	-
1129	21.81	22.455	1.68	-	-	0.16	0.33	-
1570	21.90	22.455	1.92	-	-	0.11	0.27	-
1870	21.91	22.46	1.80	-	-	0.05	0.26	-
1910	21.94	22.455	-	-	-	0.70	0.75	-
1970	-	22.465	1.76	-	-	0.55	0.61	-

Table 3. Chemical composition of waters. Values in grams/liter at 20°C. Note that these values are in g/l, whereas those in Table 2 are in g/kg (standard hydrographic unit). The difference is particularly marked for the high Sp.G. ~~B~~rines. l.c.

A. Average composition of sea water. Major composition recalculated from (15). Fe, Mn, Zn, Cu estimated for oceanic bottom water by (16). Ba from (17), (18) and (19).

B. Red Sea, Atlantis II Deep. Preliminary data for Na, K, Mg, Ca and Cl determined flame photometrically and chemically by a commercial firm; Br by X-ray fluorescence by Quality of Water Laboratories, U. S. Geological Survey, Denver, Colorado: others by solution-spark technique on the Woods Hole Oceanographic Institution direct-reading emission spectrometer. Specific gravity determined by pycnometer

C. Red Sea, Discovery Deep, brine transition zone. Determinations ~~as in B.~~ made at Woods Hole, except Br (Quality of Water Laboratorie

D. Na-rich oilfield brine from Miocene strata (2,550 m depth, bottom hole temperature 87.5°C), Louisiana. Analysis reported in (20).

E. Dead Sea. Analyses reported in (21). Major elements are an average for the entire sea. Trace elements refer to water from 310 m depth (stagnant zone).

F. Geothermal brine well, Imperial Valley, California (1,595 m depth, bottom hole Temperat ~300°C (38, 39)

Element	A	B	C	D	E	F
Sp. G	1.027	1.196	1.141	1.153	1.23	1.264
Na	10.8	105	-	73.7	39.1	64.5
K	0.39	3.61	-	1.00	7.26	31.6
Mg	1.30	0.95	-	1.23	40.6	.92
Ca	0.411	6.44	-	10.6	16.9	50.6
SO_4	2.72	1.14	-	0.18	0.47	.071
Cl	19.5	195	127.6**	143.0	212.4	233
Br	0.066	0.083	0.086	0.45	5.12	.185
B	0.0047	0.013*	0.008*	0.011	0.022	.657
Fe	1×10^{-6} ~~0.001×10^{-3}~~	0.070	< 0.001	0.058	< 0.002	4.04
Mn	1×10^{-6} ~~0.001×10^{-3}~~	0.086	0.022	0.035	0.004	2.53
Zn	5×10^{-6} ~~0.005×10^{-3}~~	0.003	< 0.001	0.006	< 0.02	1.23
Cu	2×10^{-6} ~~0.002×10^{-3}~~	0.001	< 0.001	0.005	< 0.0002	.013
Ba	15×10^{-6} ~~0.0015×10^{-2}~~	0.0011	< 0.0004	0.020	0.022	.25

* Approximate values only.

**Gravimetric titration calibrated with pure NaCl.

per mil deviation relative to Standard Mean Ocean Water. The Red Sea and Great Bahama Bank depths refer to sea level. Others refer to earth surface.

Locality	Depth (in meters)	Temperature (°C)	Chloride g/l at 20°C	δO^{18} (‰)	Reference
Red Sea					
Sta. 543	1480	21.9	23.3	+2.3	This report
Sta. 544	1997	>30.0	~ 40	+2.2	This report
Sta. 543	2016	>30.0	~ 88	+2.0	This report
Sta. 544	2047	55.9	~ 188	+1.4	This report
Sta. 544	2141	55.9	~ 188	+1.4	This report
Great Bahama Bank	Surface		23.0	+2.3	22
			23.1	+2.4	22
			23.1	+2.1	22
Great Salt Lake (Utah)	Surface		220	-7.0	23
Fresh Water entering Great Salt Lake	Surface		0.5	-17.0	23
Western Egyptian Desert (Artesian Water)	652	38.0	0.47	-11.5	24
		n.d			
Oil-field Brines (marine rocks)	990 (Cambrian)	n.d	206	-1.8	23
	1730 (Ordovician)	n.d	262	-0.1	23
	1350 (Devonian)	n.d	132	-0.5	23
	1220 (Pennsylvanian)	n.d	269	+2.1	23
	1700 (Tertiary)	n.d	104	+3.3	23

Station Number #	Type of Sample	Laboratory or other Treatment	Minerals Present	Estimated amounts % *	Remarks
	2 meters	leached with distilled water	Amorphous iron oxide	60	Some anhydrite was removed in leaching
			Siderite-rhodochrosite	10	
			Montmorillonite (dioctahedral)	10	
			Sphalerite	2-3	
			Calcite	< 5	
			Anhydrite	~5	
			Quartz	tr	
Discovery Deep 541	gravity core limestone fragments from basal 60 cm ~~2 feet~~	hand picked from sediment	Magnesian calcite	90	
			Calcite	10	
			Dolomite	tr	
			Quartz	tr	
			Feldspar	tr	
	Sediment mixed 0-60 cm ~~2 feet~~	leached with distilled water	Hematite Amorphous iron oxide	40	
			Magnesian calcite	15	
			Calcite	15	
			Dolomite	10	
			Feldspar (near labradorite)	5-10	
			Montmorillonite	5-10	
			Chlorite	5-10	
			Quartz	< 5	

*These estimates are not intended to give more than a general indication of the relative amounts of the various minerals present.

Table 6. Partial chemical analysis of bottom sediment dredge sample from *Atlantis II* Deep. Values are in weight per cent of NaCl-free material, dried at 120°C. *Includes Co, Ni, Cu, Pb and part of Mn, but not most of the Zn. Iron was determined gravimetrically after separation in ammoniacal tartrate solution.

HCl-insoluble	14.3
Fe_2O_3*	56.6
Ignition loss (1,000°C)	14.6
Remainder	14.5
	100.0

Table 7. Quantitative spectrochemical analysis of NaCl-free sediment (dried at 120°C). The values refer to aqua regia soluble matter, determined on a Jarrell Ash direct-reading emission spectrometer by a capillary electrode-high voltage spart technique (weight %).

Element	Gravity Core Sta. 543 (*Atlantis II* Deep)			Piston Core (slope of *Atlantis II* Deep)
	0-15 cm	43-51 cm	2 m	97 cm
Dry Matter (as % of bulk wet sample)	10.8	6.6	13.8	13.5
Fe_2O_3 (tot)	major	major	major	major
MnO (tot)	0.23	0.74	1.3	0.13
CoO	0.017	-	< 0.004	0.02
ZnO	2.4	6.2	1.8	0.025
CdO	0.02	0.04	≤ 0.01	< 0.01
CuO	0.36	0.57	0.28	0.74
BaO	0.024	0.045	< 0.0025	~ 0.002

Silver appeared to be present at the hundredths of a per cent level but these analyses are still uncertain because of possible interference from manganese.

Table 8. Semiquantitative spectrographic analysis of dredge sample, sta. 543. Analyses by the Spectrographic Services and Research group, U S. Geological Survey, Washington, D. C.. These results are reported to the nearest number in the series 1, 0.7, 0.5, 0.3, 0.2, etc; which represent approximate midpoints of group data on a geometric scale. The assigned group for semiquantitative results will include the quantitative value about 30% of the time. The sample is the same as in Table 2.

Si	10
Al	0.7
Fe	major
Mg	0.7
Ca	0.5
Na	0.3
Ti	0.03
Mn	0.3
Ag	0.02
B	0.007
Ba	0.1
Cd	0.03
Co	0.03
Cr	0.001
Cu	0.5
Ga	0.002
Mo	0.02
Ni	0.005
Pb	0.15
Sc	0.0001
Sn	0.003
Sr	0.015
V	0.01
Y	0.005
Yb	0.0005
Zn	>2.6
Zr	0.005

The following elements were not detected:

K, P, As, Au, Be, Bi, Ce, Ge, Hf, Hg, In, La, Li, Nb, Pd, Pt, Re, Sb, Ta, Te, Th, Tl, U, W.

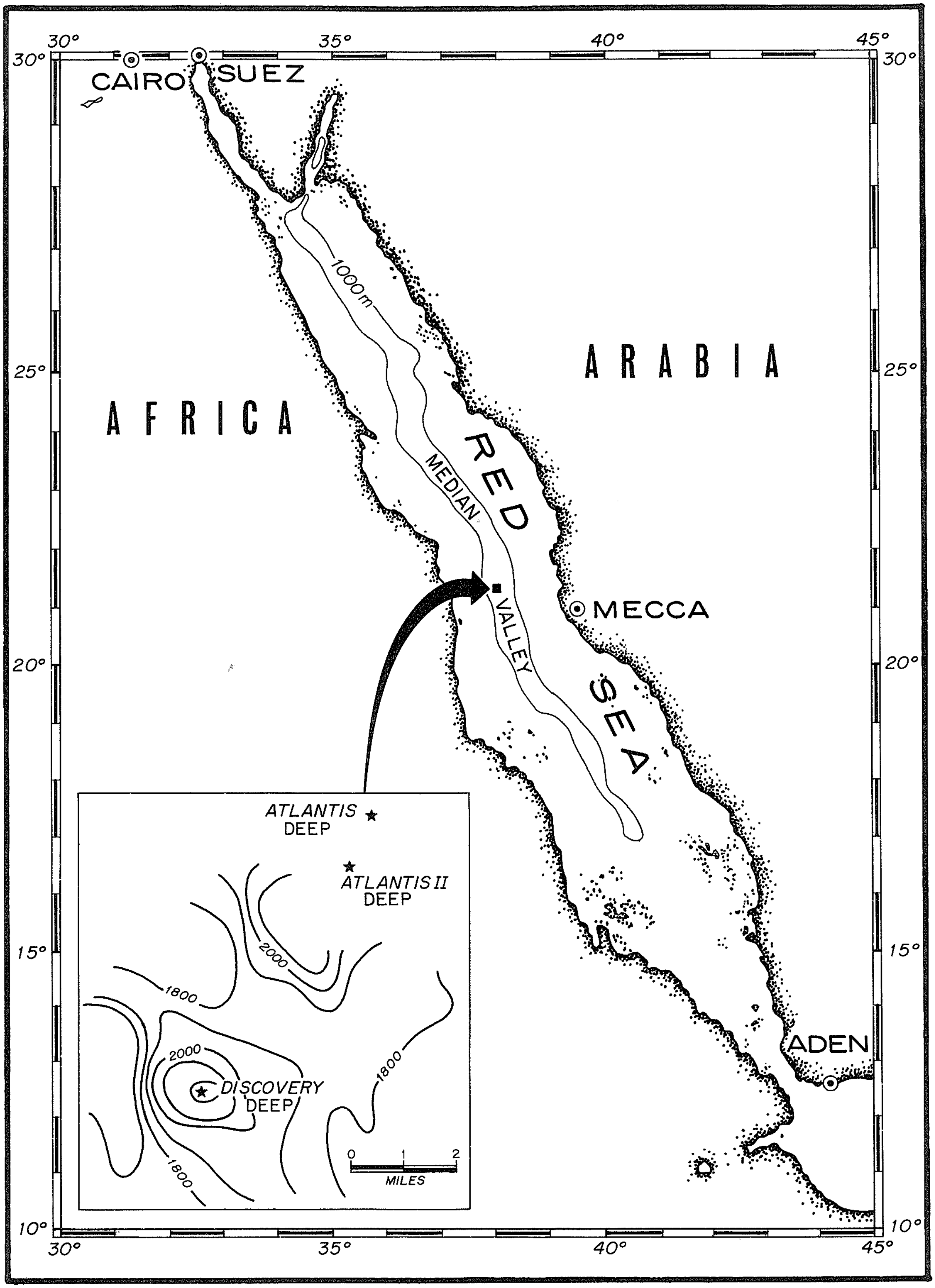

Fig. 1 Location of the Discovery and Atlantis II Deeps. Depth contours in meters, modified after Swallow and Crease, 1965 (1).

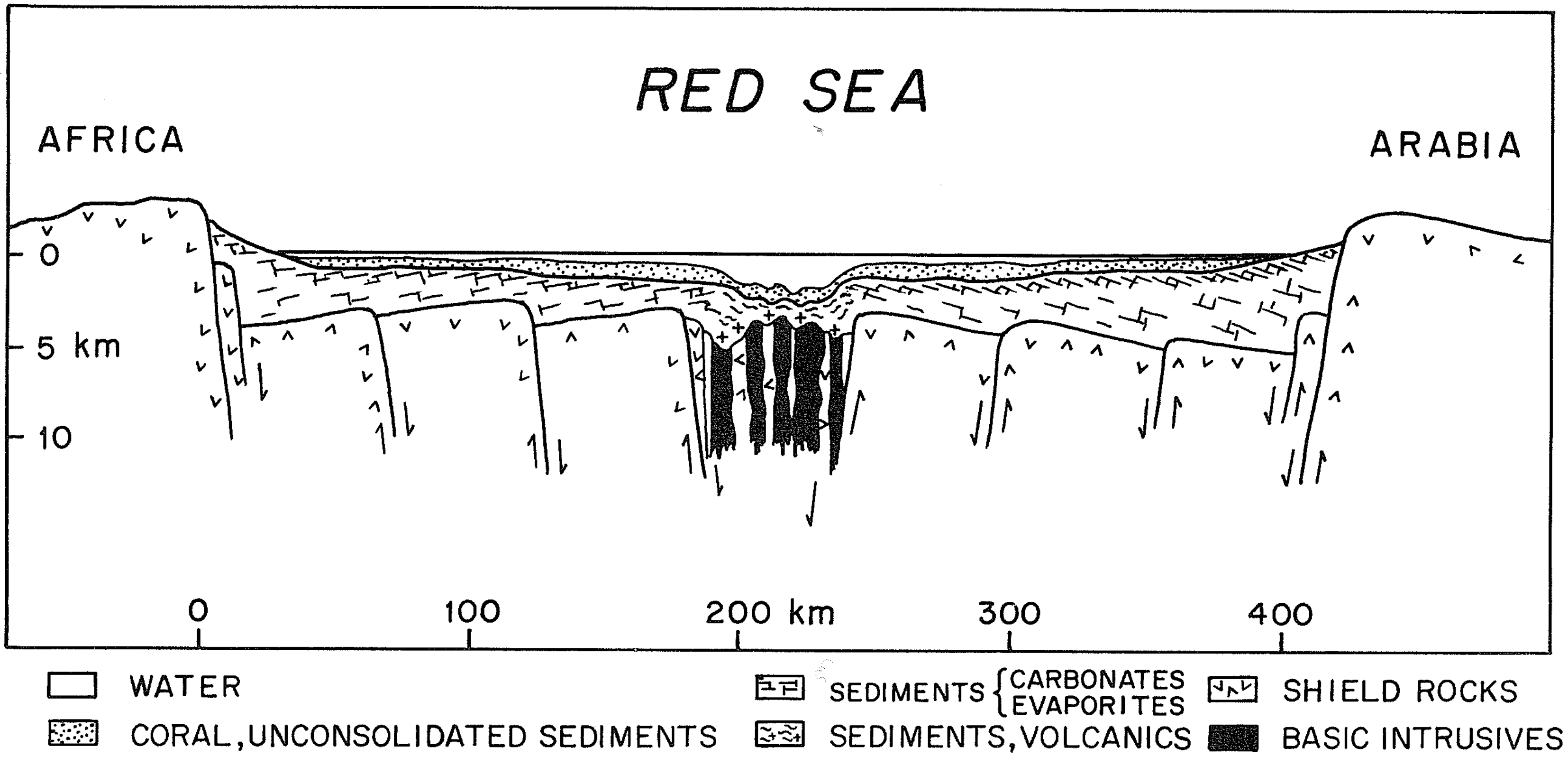

Fig. 2 Geologic cross-section of the Red Sea (schematic) modified after Drake and Girdler, 1964

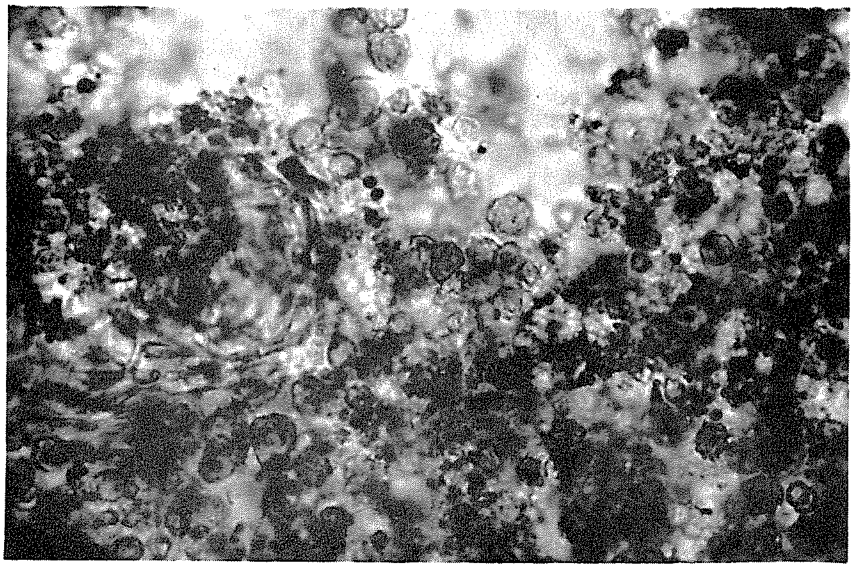

Fig. 3 Photomicrograph of iron bearing material from 0-15 cm section of core from Atlantis II Deep; diameter of spherical aggregates is about 5-10 microns.

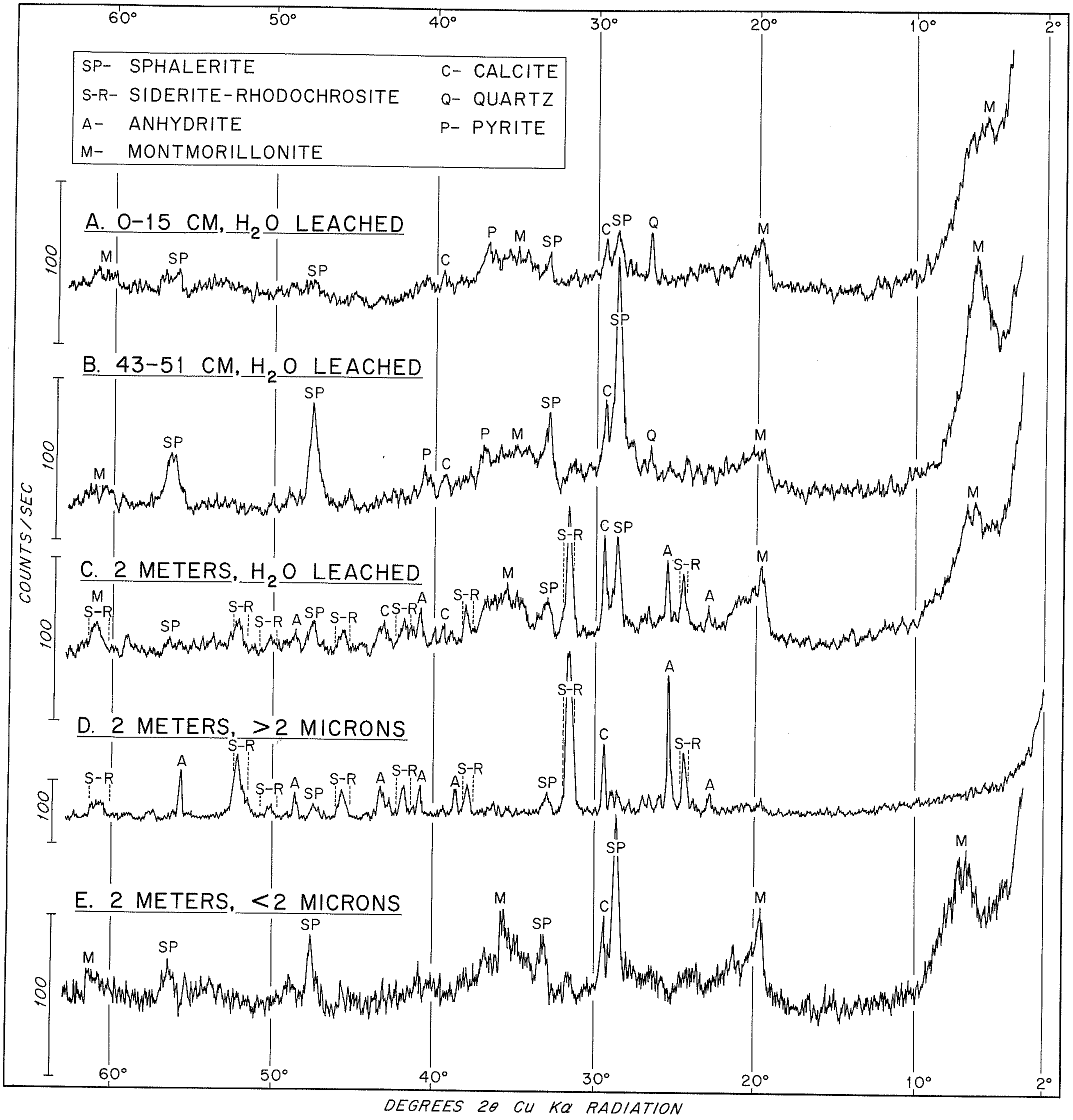

Fig. 4 X-ray diffractometer traces of samples from core taken in the Atlantis II Deep. Ni filtered CuK radiation, L = 1.5418 Å, 40 KVP 40 MA, 20/min scanning speed, scale in counts/sec as shown; time constants in seconds; A-2.0, B-2.0, C-1.0, D-2.0, E-1.0.

A. Whole sediment; 0-15 cm
B. Whole sediment; 43-51 cm
C. Whole sediment; 2 meters
D. 2 meter sediment; fraction 2 microns
E. 2 meter sediment; fraction 2 microns

All samples were leached with distilled water to prevent precipitation of halite from included brine.

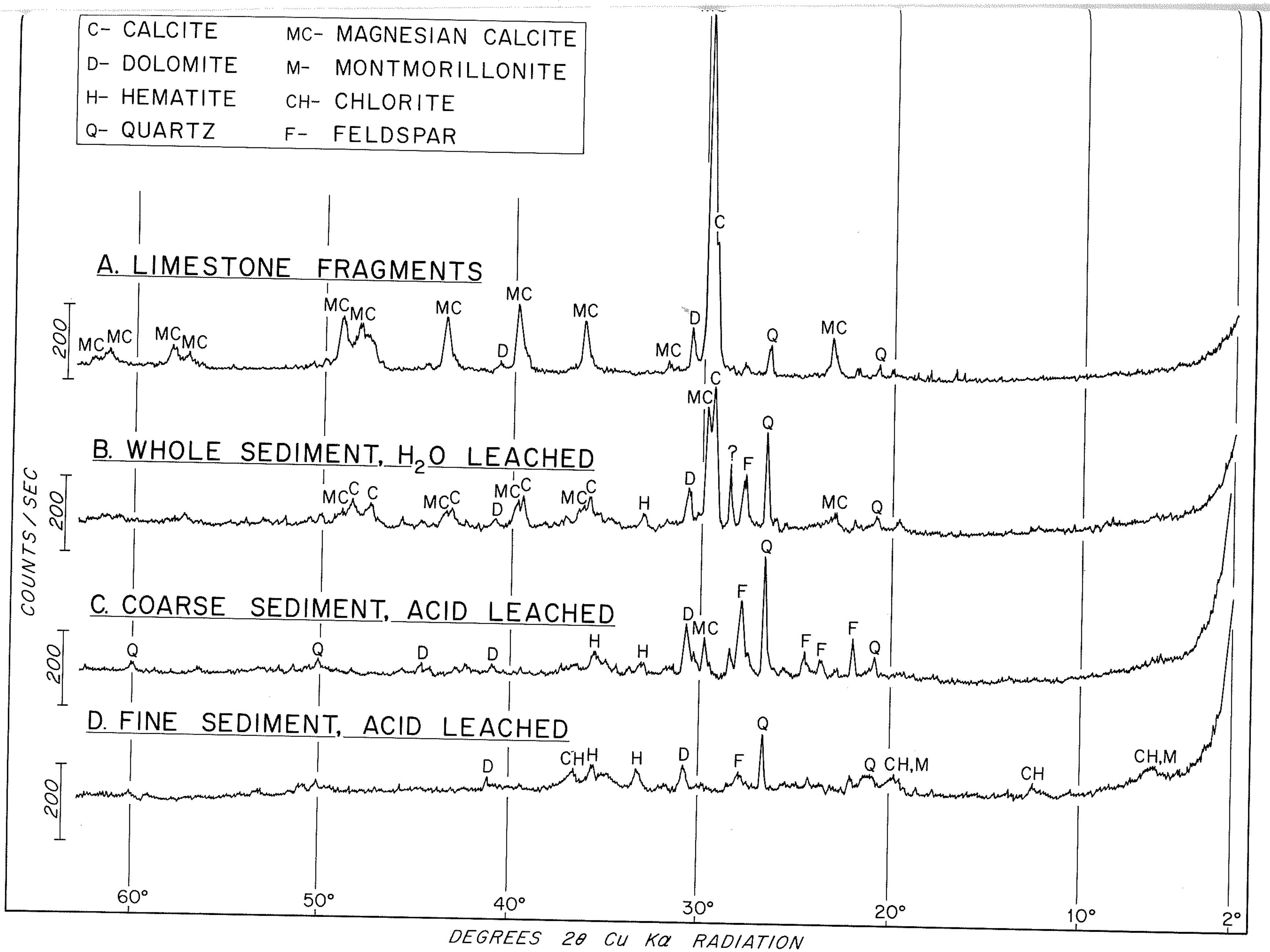

Fig. 5 X-ray diffractometer traces of samples from core taken in the Discovery Deep. Ni filtered CuK$_\alpha$ radiation, L = 1.5418 Å; 40KVP 40MA, 2°/min scanning speed, scale in counts/sec as shown; time constant 0.5 second. a. Limestone fragments. b. Whole sediment, leached with distilled water. c. Acetic acid insoluble residue, coarse fraction (>2 micron). d. Acetic acid insoluble residue, fine fraction (<2 micron).

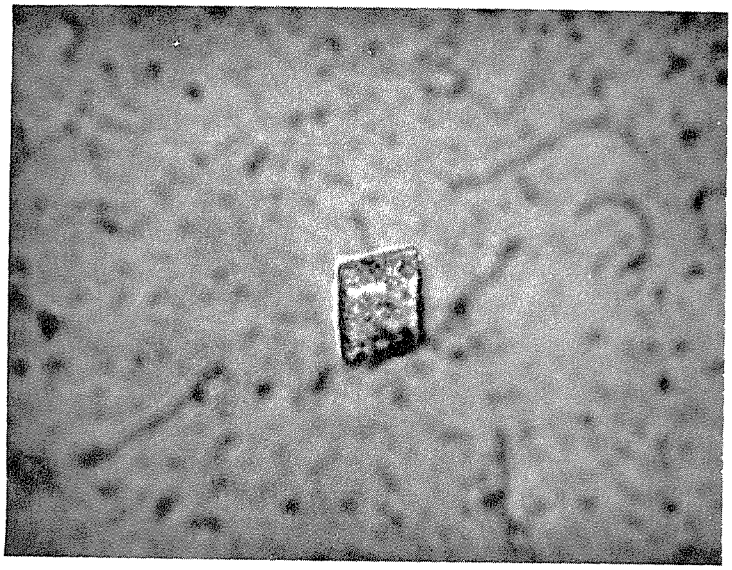

Fig. 6 Photomicrograph of dolomite crystal from Discovery Deep; diameter of crystal is about 25 microns.

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~~38~~ 40. Research grants from the Office of Naval Research and the National Science Foundation are acknowledged. We owe gratitude to K. O. Emery, S. Epstein, F. J. Flanagan, A. W. Helz, J. Hülsemann, M. L. Lindquist, R. H. Meade, C. J. Reynolds, M. Skougstad, and G. Thompson for discussion, criticism or help in the present work. This paper has been submitted to Geochimica et Cosmochimica Acta for publication and is now under review. Authorization for publication has been requested from the Director, U. S. Geological Survey.

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