Mineralogy of Metalliferous Sediments from Atlantis II Deep – Red Sea

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ABSTRACT. Mineralogical composition of 295 samples of Atlantis II, Deep metalliferous sediments was studied by X-ray diffraction analysis. Various types of silicates, iron and manganese oxides, carbonates, sulfates, sulfides are the common mineral phases. The minerals exhibit systematic distribution pattern in the sediments cores and facilitate a facies and subfacies classification. Typical mineralogical sequence from bottom to top is: sulfides, silicates, siderite, Ca-Fe-Mn carbonate, rhodochrosite, iron oxides, manganese and amorphous silica, iron or manganese oxides. Mineralogical variations in the Atlantis II, Deep sediments are considered to be due to the presence of repeated depositional cycles related to fluctuation in temperature, pH and perhaps oxygen fugacity, during the mixing of magmatic hydrothermal solution and sea-water.

Introduction

The Red Sea metalliferous sediments have received wide attention since the discovery of the rich copper-zinc mineralization in the Atlantis II Deep in 1965. The economic significance of these deposits has been investigated by Guennoc et al. (1984). Based on the data accumulated from hundreds of cores, the estimated reserves are two million tons of contained zinc and half a million tons of contained copper, in addition to significant amounts of silver and gold, for the top 20 m of the sediments (Guennoc et al. 1984). Zierenberg and Shanks (1983) indicated a vertical zonation of the sediments, basing on the mineralogy which is dominated by anhydrite, talc, smectite, pyrite, sphalerite and chalcopyrite.
The recent Meso3 II Vez 29 coring program, undertaken in the top 10–20 m of the Atlantis II Deep metalliferous sediments, provided an excellent opportunity to extend the studies on the nature and origin of the deposits.

A total of 269 samples from 32 cores spread over the NS and EW sections of the Atlantis II Deep were selected for mineralogical and geochemical studies (Fig. 1). This paper presents the results of the mineralogical investigation on these studied samples. Vertical as well as lateral variations, which could be identified in terms of specific mineral faces and subfaces that reflect episodic depositional cycles under different physico-chemical conditions, are discussed.

A brief discussion of the preliminary results of these studies was presented at the Annual Meeting of the Geophysical Society of America (Glaze et al. 1983).

Methods of Investigations

Sample Collection and Preparation

The Atlantis II Deep metalliferous muds are laminated, and each lamina is characterized by a certain colour, and varies in thickness from a few millimeters to several meters. Occasionally, the source layered layers are characterized by different textures. Keeping in view these two variables, samples were collected from layers exhibiting different colours and textures.

From the samples, sodium chloride, which generally constitutes 0.25% to 0.75% of the bulk sediment by weight, was removed by washing with demineralized water. Since most of the mineral particles are less than 1 μm in diameter, as indicated by scanning electron microscopy, the sediments were washed through 0.45 μm membrane filters to prevent the loss of fine particles during washing. After drying, samples were ground and well mixed before analysis.

X-Ray Analyses

X-ray diffraction was used for identification of the minerals in the sediments. For the identification of the clay minerals, each sample was first analysed untreated, then glycolized and X-rayed, both after heating at 350°C for one hour, and subsequently after heating at 550°C for one hour (Lin et al. 1987).

Results

XRD studies indicated that each lamina is composed of a group of minerals, which appear to represent a certain range of temperature. Bischoff (1969a) divided the Red Sea, geothermal brine deposits into seven bedded and laterally correlative facies as follows: detrital, non-martinitic lutite, goethite-amorphous, sulfide, manganese, anhydrite and manganese. Zierzenberg and Shanks (1983) indicated that the mineralogy of the Deep is dominated by anhydrite, talc, smectite, pyrite, sphalerite and chlorapatite.

In the present study, the identified minerals are classified into facies; some of these facies are subdivided into subfacies according to the dominant mineral of the group (Table 1).
Fig. 1. Location map of the sediment cores in the Aghagii II Deep, Red Sea.
<table>
<thead>
<tr>
<th>Facies</th>
<th>Subfacies</th>
<th>No. of samples</th>
<th>%</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authigenic</td>
<td>Iron oxide,</td>
<td>9</td>
<td>5</td>
<td>Light brown</td>
</tr>
<tr>
<td></td>
<td>Manganese-oxide</td>
<td></td>
<td></td>
<td>Dusky yellowish brown,</td>
</tr>
<tr>
<td></td>
<td>Silicate</td>
<td></td>
<td></td>
<td>olive black, dark grey</td>
</tr>
<tr>
<td></td>
<td>Manganese</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonate</td>
<td>Goethite</td>
<td>71</td>
<td>24</td>
<td>Light brown</td>
</tr>
<tr>
<td></td>
<td>Hematite</td>
<td></td>
<td></td>
<td>Moderate yellowish brown</td>
</tr>
<tr>
<td></td>
<td>Lepidocrocite</td>
<td></td>
<td></td>
<td>Light brown, greyish-orange</td>
</tr>
<tr>
<td></td>
<td>Siderite</td>
<td>39</td>
<td>13</td>
<td>Dark yellowish brown</td>
</tr>
<tr>
<td></td>
<td>Antlerite-achroite</td>
<td></td>
<td></td>
<td>Dusky yellow, moderate</td>
</tr>
<tr>
<td></td>
<td>Volcanite</td>
<td></td>
<td></td>
<td>brown, light brown to</td>
</tr>
<tr>
<td></td>
<td>Aragonite</td>
<td>131</td>
<td>44</td>
<td>moderate, reddish brown,</td>
</tr>
<tr>
<td></td>
<td>Smetricite</td>
<td></td>
<td></td>
<td>olive, grey, yellowish</td>
</tr>
<tr>
<td></td>
<td>Chamosite</td>
<td></td>
<td></td>
<td>grey</td>
</tr>
<tr>
<td></td>
<td>Quartz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>Antlerite</td>
<td>25</td>
<td>8</td>
<td>Moderate yellowish brown</td>
</tr>
<tr>
<td></td>
<td>Gypsum</td>
<td></td>
<td></td>
<td>brown, olive grey,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>medium grey, white</td>
</tr>
<tr>
<td>Sulfide</td>
<td>Sphalerite</td>
<td>12</td>
<td>4</td>
<td>Light olive grey to</td>
</tr>
<tr>
<td></td>
<td>Pyrite</td>
<td></td>
<td></td>
<td>red, dark red, yellowish</td>
</tr>
<tr>
<td></td>
<td>Chalcopyrite</td>
<td></td>
<td></td>
<td>brown</td>
</tr>
<tr>
<td></td>
<td>Galite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total number of samples</td>
<td>296</td>
<td></td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

Sulfide Facies

Sulfide facies constitute the most important group in these sediments, since they contain the most valuable mineral deposits from an economic point of view. They mark the bottom horizon of each depositional cycle (Fig. 2 and 3), and are characterized by dominantly grey colour of micromassized appearance.

The sulfide minerals identified are mainly sphalerite and pyrite with minor chalcopyrite (Table 1). According to the dominant sulfide mineral present, this facies is further subdivided into a sphalerite-rich subfacies which represent the high temperature form of the sulfide facies and the lower temperature pyrite-rich subfacies with minor chalcopyrite.
Fig. 3. The vertical rotation in the N-S profile.
Sphalerite-rich subfacies generally occur as purplish to medium grey layer, varying in thickness from a few millimeters to several meters and extending along the two traverses for several kilometers as this indicated in cores 460, 284, and the lower sulfide layer of core 352 (Fig. 2) and cores 382, 449, 452, 458, 496 and 499 (Fig. 3). Sphalerite is a major constituent of about 88% of the samples of the sulfide facies and about 5% of the total number of the collected samples. It is mostly associated with nontronite, siderite and chalcopyrite and to lesser extent with anhydrite, Ca-Fe-Mg carbonate and barite.

Pyrite-rich subfacies occur as light olive gray to medium dark gray layers; a few centimeters thick. This layer occurs throughout the Deep as indicated in cores, 462, 426, 283 and the upper sulfide layer in core 352 (Fig. 2) and core 243 (Fig. 3).

In some cases, sphalerite and pyrite occur as mixed layers as in the upper sulfide layers of cores 448, 455, 457 and 369 (Fig. 2) and cores 443, 274, 198, 557, 559 and 338 (Fig. 3).

Chalcopyrite could be observed only as a minor constituent associated with sphalerite and pyrite in cores 351 and 369 (Fig. 2).

**Sulfate Facies**

The sulfate minerals in the Atlantic 11 Deep metaliferous sediments are mainly anhydrite with minor gypsum and barite. The latter represents the highest temperature form of the sulfate facies. The appearance of gypsum in many anhydrite samples is suggested to be due to recrystallization of anhydrite during core storage. In general, the anhydrite and gypsum subfacies occur as discontinuous beds or lenses of variable thickness or as discordant and discordant vein in the margin of the sulfate facies, associated with nontronite and pyrite. On the other hand the barite occurs as accessory mineral disseminated in the sphalerite subfacies.

**Silicate Facies**

In the Red Sea metaliferous sediments, the silicate mineral constitute the major mineral facies. In the 295 investigated samples, 131 are silicate minerals. Nontronite, Mg smectite, and chamosite are the common silicate minerals according to Baker and Richer (1975), Bischoff (1966a) and Ziescheberg and Shanks (1983). However, the present detailed X-ray diffraction studies and chemical analyses indicate that nontronite, glauconite and mixed-layer glauconite/nontronite, are the most common silicate minerals with minor amounts of Fe-rich chlorite, possibly chamosite and glass shreds (Lin et al. 1987).

**Carbonate Facies**

The carbonate minerals noticed in the carbonate facies are siderite, rhodochrosite, calcite, and minor aragonite. The presence of aragonite is indicated by the characteristic 3.4 Å, 1.98 Å and 3.2 Å peaks. Transitional X-ray diffraction patterns between siderite and rhodochrosite are also common in the analyzed samples. These transitional forms have been loosely called Ca-Fe-Mg carbonates.
In the carbonates’ facies, sidereite represents the high-temperature hydrothermal carbonate and calcite, the lowest temperature variety. The presence of nanofossils, including "Gephyrocapsa oceanica" and "Helicocapsa carteri" may suggest the low temperature of formation of these subfacies (21°C to 23°C) (Tan et al. 1987).

According to the dominant carbonate mineral in the samples, this facies is further subdivided into sidereite subfacies about 5-14mm thick layers, Ca-Mg-Mn carbonate- rhodochrosite subfacies, calcite subfacies ranging from 2cm-4mm thick layers and argonite subfacies as thin layers about 2-10mm thick. Sidereite subfacies is mostly associated with nontronite and goethite, Ca-Mg-Mn carbonate subfacies with nontronite goethite, calcite subfacies mostly with nontronite and quartz, and to lesser extent with pyrite, hematite, and argonite subfacies with calcite and quartz.

Iron Oxide Facies

The iron oxide facies consist of goethite subfacies, hematite subfacies and lepidocrocite subfacies. Magnetite has not been detected in the investigated cores, but was reported in some recrystallized cores (Hacken and Bischoff 1973, Zierenberg and Shanks 1983). Goethite is the most abundant iron oxide. Hematite and goethite occur in alternating laminae or layers of variable thickness, which extend for several kilometers across the Atlantis II Deep. Hematite is generally deposited at the bottom, whereas goethite on the top of the depositional sequence. Lepidocrocite generally occurs as thin laminae, which are apparently continuous for several kilometers.

According to Bischoff (1989b), the hematite in the Red Sea brine is formed at a temperature near 55-120°C or higher, whereas goethite is formed at a lower temperature. Lepidocrocite is believed to form at a temperature lower than that for goethite in the Red Sea environment, because lepidocrocite-rich laminae generally overlie goethite-rich laminae.

The hematite is commonly associated with goethite and nontronite and to lesser extent Ca-Mg-Mn carbonate, whereas the goethite with hematite, montmorillonite and to lesser extent with Ca-Mg-Mn carbonate and maganumite.

Manganosite Facies

Manganosite occurs as black laminae varying in thickness from few millimeters to several centimeters overlying goethite layers and extending for several kilometers. Fe- and Mn-oxides overlying iron-rich sulfide deposits have been widely used as one of the most reliable guides to sites of active deep weathering. Bischoff (1986a) attributed the Atlantis II Deep manganese oxides to possible local “weathering” products of preexisting manganese-oxide beds. Manganite layers have also been found on top of Zn-Cu-Pb mineralization in Kuroko deposits, where they are associated with chert (Ishihara 1974).

Amorphous Facies

Amorphous material in the Atlantis II Deep metaliferous sediments constitute
the upper-most part of the succession. It is characterized by a reddish colour without obvious textures and with no X-ray diffraction pattern.

However, this facies has not been previously described in detail. The authors have found, according to chemical data (in preparation) that the amorphous material, which forms about 70% of this facies, is mostly amorphous iron oxide, amorphous silica and amorphous manganese oxide. They are mostly associated with nontronite, goethite, and manganite, and to lesser extent with Ca-Fe-Mn carbonate and anhydrite.

Discussion

The present investigation on the Atlantis II Deep metalliferous sediments indicates a complicated mineral composition, deposited in laminar or layers of variable colours and thicknesses. Each lamina/layer is composed of an assemblage of minerals, and they are grouped as different mineral facies. Most of these facies can again be subdivided into subfacies. The sulfide facies is characterized by sphalerite-rich subfacies and pyrite-rich subfacies with minor amounts of chalcopyrite. The sphalerite subfacies represent the high temperature hydrothermal sulfide, whereas pyrite the lower temperature. It is deposited over the sphalerite in the depositional sequence. The sulfide facies is characterized by anhydrate subfacies, minor barite subfacies. The silicate facies consists mainly of nontronite and glaucohe and with mixed layer of glaucohe and nontronite. The carbonate facies consist mainly of siderite subfacies, the high temperature form of the carbonate facies, rhodochrosite, Ca-Fe-Mn carbonate, celestite and aragonite subfacies. The iron oxide facies are characterized by hematite subfacies, goethite subfacies, and lepidocrocite subfacies. The manganite facies is composed mainly of manganite. The presence of manganite over goethite and lepidocrocite indicates temperature of formation lower than of goethite but still higher than the temperature to form aragonite. The amorphous facies, which only exist in the upper-most part of the sediments consists of amorphous iron oxide, amorphous silica and amorphous manganese oxide.

Vertical mineral zonation indicates that the precipitation of muds took place in different cycles. Five major cycles could be identified. Each complete cycle begins with a high temperature sulfide facies followed by sulfate, silicate, carbonate, iron oxide, manganite and ends with amorphous facies or fossils composed of aragonite and calcite which indicates the lowest temperature. It is not necessary, however, that a cycle shows all the mineral sequence (Fig. 2 and 3). Stamps and Broderick (1980) indicated that facies variations are related to rate of brine influx and size of the brine pool rather than to changes in temperature or bulk composition of the incoming brine. However, in the present study the investigators believe that the geochemical zonation of the Red Sea metalliferous sediments may be governed by many factors, including temperature, and mixing of hydrothermal solution with sea water. The temperature of the Red Sea metalliferous sediments was approximately 150-230°C, indicated by the oxygen isotopes of the associated nontronites studied by the
investigators (in preparation) following the Yeh and Savin's methods (1977). This
temperature range is apparently lower than the formation temperatures 200-350°C,
of the cubanite-chalcocpite-pyrrhotite assemblage of the Red Sea sediments iden-
tified by Potter and Barnes (1983). The cubanite and pyrrhotite associations are be-
lieved to be a rare high-temperature assemblage in the Red Sea metaliferous sedi-
ments, which has not been found in the investigated samples. The isotopic study also
indicates that the silicate facies was deposited at temperatures between 70 and 170°C.
This temperature is, in general, lower than the temperature of the formation of sul-
fide facies, which is as high as 230°C and encompass the range of the temperatures
of the formation of hematite, which is 115-120°C (Bischoff 1969b). Cole et al. (1983)
distinguished between 3 ranges for the temperature of formation of smectites in re-
cent marine sediments: 90-140°C for smectites associated with sulfide and Fe-rich
material, (80°C) for smectite associated with carbonate and Fe-oxide, and (140-
200°C) for smectite associated with anhydrite and sulfates. The range determined by
the investigators includes apparently the three ranges of Cole. The temperature of
the boundary between hematite and goethite was calculated as 115°C by Bischoff
(1969b), who postulated that the temperature of the Atlantic II brine of 56°C was
favorable for the deposition of goethite and too low for hematite. The deposition of
goethite is possibly completed at temperature near 50°C because most iron in the hot
brine has been deposited, but manganese remained in the water at 44°C (Brewer and
Spencer 1969). The iron content decreases more than 80% from 52 to 25°C (Bebnow
et al. 1977). The manganese is believed to be deposited as manganese at a tempera-
ture between 44 and 25°C, and close to 35°C. The final tannin zone indicates a temper-
ature near 21-23°C according to the fauna found by this study (Tan et al. 1987). The
amorphous facies is believed to be deposited in a relatively short period, resulting in
an amorphous form.

The pH of normal Deep Red Sea water is generally near 6.5, but it is 7.9 at a depth
of 2000 m in the Atlantic II Deep. The pH decreases to 6.6 abruptly below a depth of
2,050 m accompanied by an increase in temperatures from 25°C at 2000 m to 52°C at
2,100 m (Bebnow et al. 1977; Dantchow et al. 1980). The original outflow of the hy-
drothermal solution of the Atlantic II brine pool is estimated at 140-280°C by
Flaxman (1980) and the pH of the outflow should be much lower than 6.6. Potter and
Barett (1983) estimated a pH of 4.6 ± 0.5 for the deposition of a rare cubanite-
chalcocpite-pyrrhotite assemblage. However, the fractionation association of uderite
and sulfide facies should not be much lower than 6.0 according to the Eh-pH diagram
of Garret and Christ (1965).

Acknowledgement

This work was financed by King Abdulaziz University and the Saudi-Sudanese
Red Sea Joint Commission. The authors wish to thank Dr. A.R. Drysdale, Dr. R.
Divi and Dr. A. Hashud for their critical reading of the manuscript. A. Hakiz provided
valuable assistance in selecting the samples. Due thanks are also for S. Ali for assistance
in the computer calculations of the data. The analytical assistance of H. Sokle,
M.S. Tashkiand, I. Nator and M. Ramadan are gratefully acknowledged.
References


مدنية الروابط الغزيرة من منتحف الأنثروبولوجيا

2 - الحجر الأحمر

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منتحفًا. أُقررت دراسة على الترمث المعلمي 329، عينة من الطين المعدن
المستخرج من منتخفيض الأنثروبولوجيا_footer، فقد تم تطوره.
على أن يكون من الممكن استخدام الطين المعدن في المقاولات البلاستيكية، وأعددت الكتيبات والملاحظات
والجدول الزمني، وجزاءد الكتيبات والملاحظات. وقد قام برؤية هذه الملاحظات
متطلباته في المشهد، كما وُجِّح على تفتيشه بعدها، وقد تبين أن
العنوان المثير من أصل إلى أجل مبكر إعداد صناعات - سبيل - نموذج
المكسير، وتحديثًا، وتطوير - 19 - مختصرات - المجلة العالمية للمدنية - مبيعات وعلوم
مميزة للمقاولات البلاستيكية، وإعداد المخطط، وقد تم إعداد هذا النموذج
معروض في معرض مكونة الثقافة والحياة في جدة، وتم إجراء ثلاث مراكز
رسومات جلد الأحذية 11 إلى تفكيك فلاح علاج المدن في جدة
الحرارة والأذخ، حيث أظهر (1999)، ودورة الأساتذة بالنشاط الاقتصادي في اليمن، أثناء
الاستثناء أثناء العمران الساخنة بسلاج البحر.