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EXTREME DEEP-SEA ENVIRONMENT OF THE EASTERN MEDITERRANEAN ANOXIC BASINS: THE STATE OF THE ART

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Riassunto. I bacini anossici attuali del Mediterraneo Orientale sono stati di continuo studiati con un approccio multidisciplinare fin dal 1983, anno della loro scoperta. Questi bacini si formano in conseguenza della dissoluzione in ambiente profondo di evaporiti Messiniane sui fianchi di depressioni del fondo. L'anossia è causata dalla stratificazione di densità indotta dalle salamoie, che impedisce la circolazione al fondo. Presentiamo una breve sintesi delle conoscenze geologiche e geochimiche sinora ottenute, enfatizzando il bisogno di ulteriori indagini.

Abstract. Extant anoxic basins in the Eastern Mediterranean have been continuously studied with multidisciplinary approach since 1983, year of their discovery. They form after dissolution of Messinian evaporites on the flanks of deep-sea rimmed depressions. Anoxia is due to brine density stratification which prevents bottom water ventilation. The state of the art of the geological and geochemical knowledge is presented and the need for further investigation is stressed.

Introduction.

A few years ago two anoxic depressions of the seafloor were discovered in the Eastern Mediterranean (Jongsma et al., 1983; Scientific Staff of Cruise Bannock 84-12, 1985). They were named Tyro Basin and Bannock Basin after the two oceanographic vessels (Dutch and Italian, respectively) that discovered them. Both basins lay at more than 3000 m water depth, with an area of a few square kilometers and a negative relief of a few hundreds of meters with respect to the surrounding seafloor. The density stratification of the water column within the basins, which causes anoxia, is produced by a hypersaline brine derived from the dissolution of evaporitic rocks (Late Miocene Messinian halite, gypsum, and anhydrite) outcropping on the flanks of the depressions. Similar cases are known in two other small ocean basins only: the Gulf of Mexico and the Red Sea. The Red Sea hot brine lakes are the first to have been reported in the literature (Degens & Ross, 1969). They differ from the Mediterranean cases for the

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high temperature of the brine (56°C in Atlantis II Deep; Pugh, 1969) and the geological setting. The Gulf of Mexico brine lakes (Shokes et al., 1977; Rezak & Bright, 1981; Brooks et al., 1990) are "cold" like the Mediterranean ones, but the dissolving evaporites are much older, Jurassic versus Late Miocene.

From 1983 to 1990 ten multidisciplinary cruises have been dedicated to the study of the Eastern Mediterranean anoxic basins, and more than 50 cores have been raised only from the Bannock Basin area (Fig. 1). Two special issues of the journal Marine Geology (van Hinte et al., 1987 and Cita et al., 1991) and one of Marine Chemistry (van der Weijden et al., 1990) have been published. Three workshops were

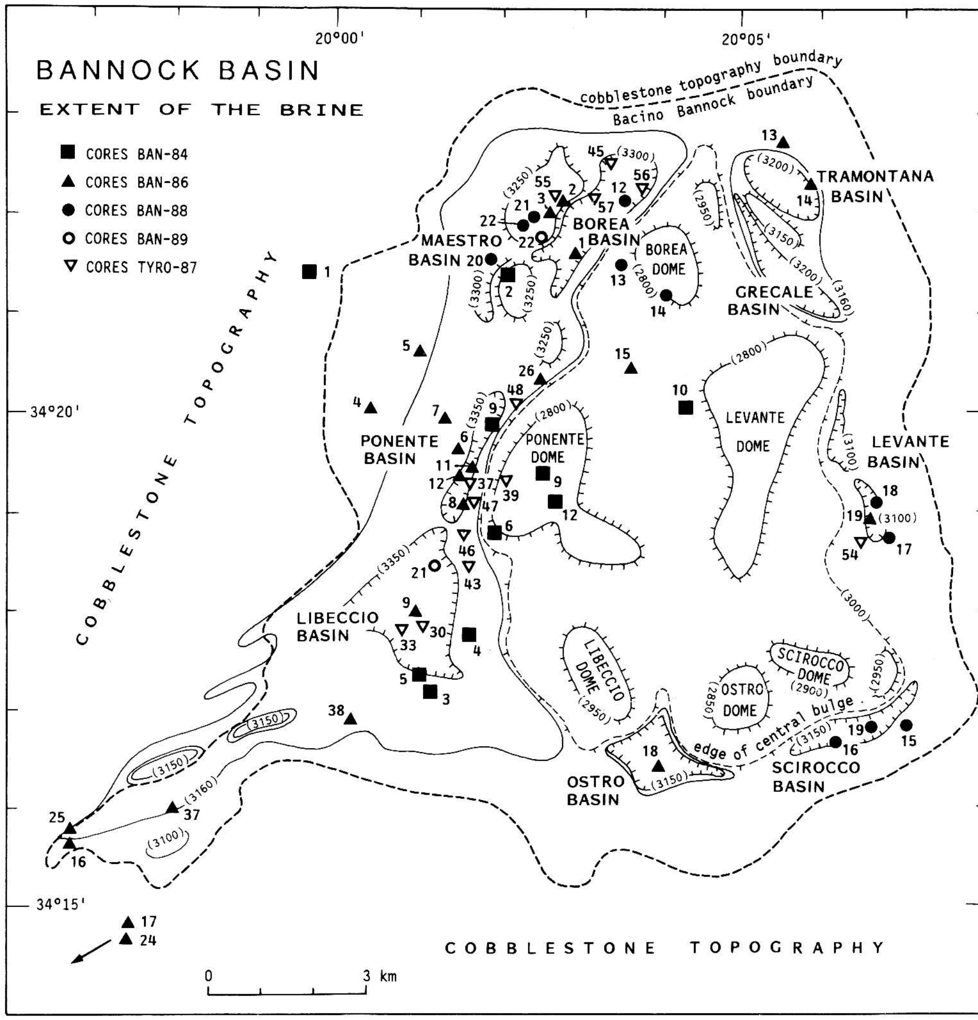

Fig. 1 - Location of all cores raised from the Bannock Basin area until 1990.

held in Bergamo (Italy) to coordinate the ongoing research (Cita et al., 1989) and a dedicated session of the 1990 Ocean Science Meeting in New Orleans reward our efforts.

In this short note we summarize the present knowledge of the geology and geochemistry of the Bannock and Tyro areas, with the purpose of attracting the interest of a broad audience to this fascinating topic.

Geological setting.

The two anoxic depressions discovered in the Eastern Mediterranean have different geological settings both related to the convergent relative motion between the African and European lithospheric plates: compressional tectonic style on an accretionary wedge (Bannock Basin on the Mediterranean Ridge) and transcurrent tectonic style along a deep-sea trough (Tyro Basin in the Strabo Trench within the Hellenic Trench system).

On the Mediterranean Ridge, the rimmed depressions that cause the so called Cobblestone Topography are due to the subsurface dissolution of Messinian evaporites (Camerlenghi, 1988, 1990) caused by folding and faulting of sediments related to the deformation of the accretionary wedge (Ryan et al., 1982; Camerlenghi & Cita, 1987; Cita & Camerlenghi, in press; Kastens et al., in press). These depressions become increasingly deeper and eventually evolve into deep sea brine lakes, like those forming the sub-basins of the Bannock Basin area, when the Messinian salt is exumed on their flanks.

In the Strabo Trench, pull-apart basins like Tyro, Kretheus, and Poseidon basins, are originated by left strike-slip motion along a non-linear fault plane (Jongsma, 1987; Camerlenghi & Cita, 1987). With analogy to the depressions of the Cobblestone Topography, these basins also deepen with time and eventually evolve into deep-sea brine lakes like the extant Tyro Basin.

In both cases, Messinian evaporitic deposits laying at shallow depth (100-200 m below seafloor) beneath Plio-Quaternary hemipelagic sediments outcrop on the flanks of the depressions whose bottom is filled by a dense brine flowing down slope like a cascade. In Bannock Basin area, salt diapirism is also involved in the formation of vertical relief (Camerlenghi & McCoy, 1990).

Morphology.

The Bannock Basin area (Fig. 2b) has been studied in great detail with the aid of Sea Beam, 3.5, and 33 kHz echosounding devices. The shape of the area is unique in the marine environment. Its morphology is dominated by a large, rounded bulge around which is a narrow and continuous depression. A local vertical displacement of the seafloor exceeding 800 m creates slopes up to 78° and possibly overhanging. Avera-

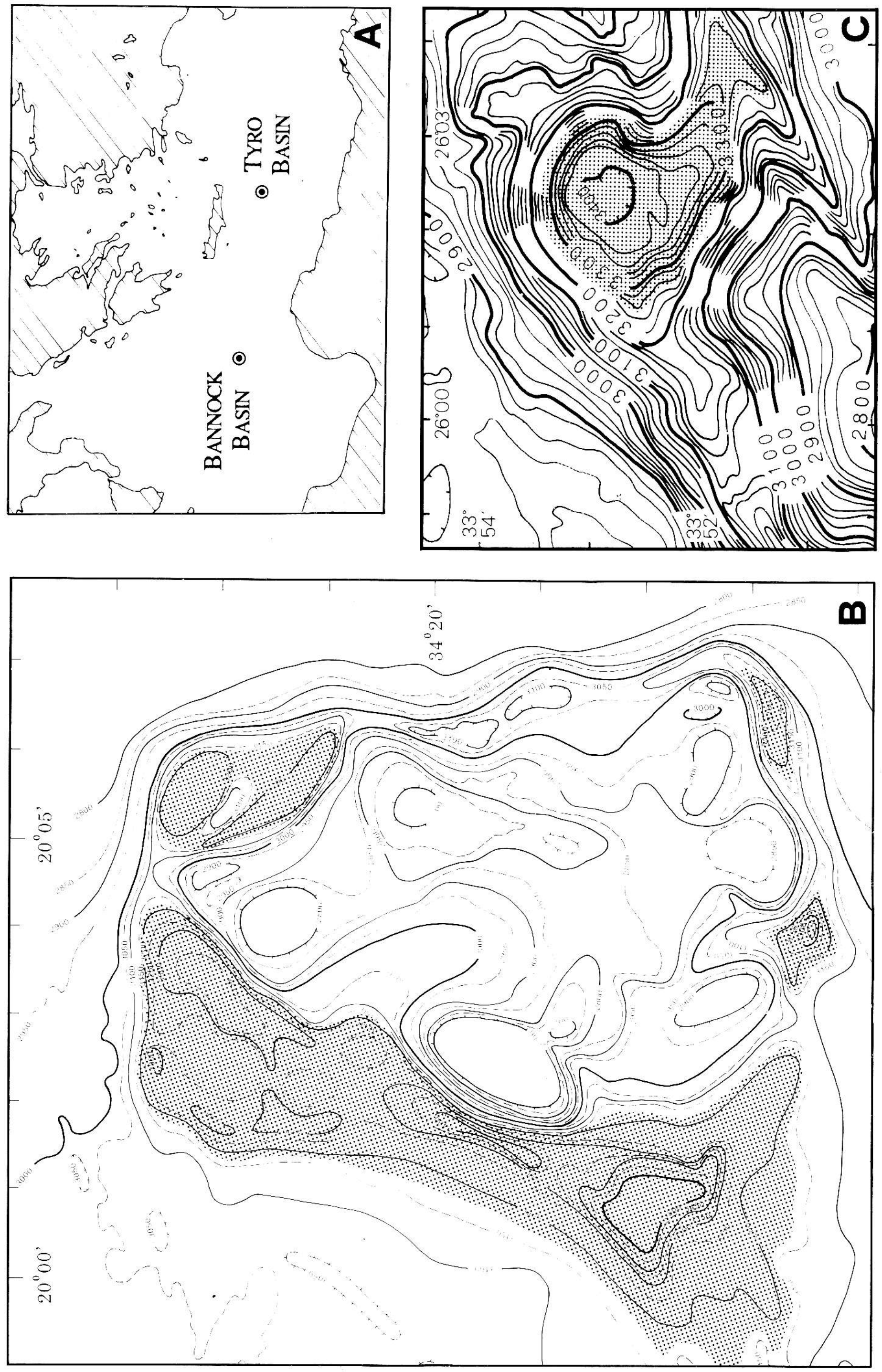

Fig. 2 - Index map (a), bathymetry of Bannock Basin area (b) and Tyro Basin (c). The two basins are portrayed at the same scale for comparison. The brine lakes are outlined by the gray tones.

ge slopes are also very steep for marine sediments (35°). In the ring-shaped depression 9 sub-basins can be identified, 8 of which are brine-filled, forming 4 distinct brine lakes whose total areal extent is 47.5 km^2. The sides of the depression are characterized by the alternation of escarpments and benches than can be related to normal faulting occurring in response to upward (diapirism) and downward (collapse due to dissolution) vertical movements (Camerlenghi & McCoy, 1990).

Tyro Basin has been investigated during a dedicated Sea Beam survey (Huchon et al., 1982) (Fig. 2c). Unpublished Sea-Marc data of neighboring segments of the Strabo Trench are also available (Kastens, pers. comm., 1984). The shape of the basin is subrounded, no sub-basins are present, and a single brine lake with an area of 20 km^2 has developed at the bottom of the depression. The local vertical displacement of the sediments is of about 600 m. The basin is located along a SW-NE trending narrow trough and is sided by two other rimmed depressions: Kretheus Basin to the SW which is presently oxygenated but shows to have been anoxic in the past (Erba, Parisi, et al., 1987; Troelstra, 1987) and Poseidon Basin to the E, which has been discovered very recently, still anoxic but lacking geological investigation (Erba, 1989).

Sediments.

More than 50 cores have been collected from the Bannock Basin area and 17 from the Strabo Trench. Tyro and Bannock basins floor is filled by sediments sliding from the steep side walls as turbidity currents, debris flows, and slumpings at a rate calculated as up to 14 cm/1000 years in Bannock Basin (Cita et al., 1988). The anoxic portion of the sediment column is also characterized by typically soupy marls and muds, dark-green to black in color, with high concentration of Corg (up to 6.08% t.w.), strong odor of H_2S, and often displaying faint lamination. Siliceous plankton (diatoms, radiolarians, and silicoflagellates) is unusually abundant in the anoxic mud.

Crusts and slabs of indurated carbonate sediments, usually referred to as hardgrounds, were dredged along the east wall of Ponente Basin and cored in Borea Basin. Some slabs are impregnated by Fe-Mn oxides and borings occur in several samples. Oxygen isotope data suggest that lithification takes place within cold and hypersaline brines. Carbon isotope data reflect a contribution of methanogenic CO_2 to the hypersaline brine (Aghib et al., 1991).

A unique characteristic of the anoxic sediments from the Eastern Mediterranean basins is the occurrence of "mucillagineous pellicles" (Fig. 3a; Jongsma et al., 1983; Erba & Parisi, 1987; Erba, Rodondi et al., 1987; Rodondi & Andreis, 1989; Erba, 1991). These pellicles are included in the sediments, either laying parallel to the bedding planes or folded at the base of turbidites. They consist of coal-like amorphous organic matter of bacterial origin foliating into undulating and anastomosing micrometric laminae entrapping planktonic debris and minerals. The formation of the pellicles is thought to occur at the interface between brines and normal seawater (surface of the brine lakes) where enhanced bacterial activity produces organic mats floating on the brine and being slowly loaded by falling sediments. They reach the basin floor either by sinking or by capture by turbidity currents (Erba & Parisi, 1987; Corselli & McCoy, 1989; Erba, 1991).

The age of the onset of anoxia in the basins can be calculated from the transition between oxygenated and anoxic sediments. The oldest transition recovered in Bannock Basin is dated to about 180,000 years before present (*Emiliania huxleyi* nannofossil Zone; Parisi et al., 1987), while in Tyro Basin such a boundary has been inferred to be approximately 70,000 years old (Erba, Parisi et al., 1987).

An extraordinary discovery was made during the geological exploration of the Bannock Basin area. Hundreds of small sized and two large (40 cm) gypsum crystals were dredged from the east wall of Ponente Basin (Fig. 3b). Gypsum crystals have been also recovered in piston and gravity cores (Fig. 3c). Four different morphologies of the crystals have been identified and related to genetic processes (Corselli & Aghib, 1987). The age of gypsum growth is very young, as suggested by the inclusion of recent planktonic foraminifera and pteropods in several crystals (Scientific Staff of Cruise Bannock 1984-12, 1985; Cita et al., 1985) and by stable isotopic data (Friends of Gypsum, 1989). Some of the crystals (tabular to lenticular) form within the sediments, whereas interlocked euhedral prismatic and twinned crystals grow near the brine/normal seawater interface. Modern gypsum precipitation suggests that the brine reaches the saturation with respect to gypsum. This phenomenon has not been documented in Tyro Basin. The scientific community presently working on Bannock Basin nicknamed the gypsum outcrops on the eastern wall of Ponente Basin "Gypsum Crystal Garden".

Water column.

The surface of the brine lakes is characterized by a sharp interface which separates normal seawater (above) from extremely salty and dense waters (below). The physics and chemistry of these brines have been studied in great detail in the Bannock Basin area, where four different brine lakes have developed. On the other hand the Tyro Basin area, where only one lake exists, has been investigated to a lesser extent.

In the Bannock Basin area the brine/normal seawater interface is marked by a sudden increase in water density which reaches the extreme value of 1.21 gms/cm^3 (Cita et al., 1985). This corresponds to the highest salinity ever measured in deep

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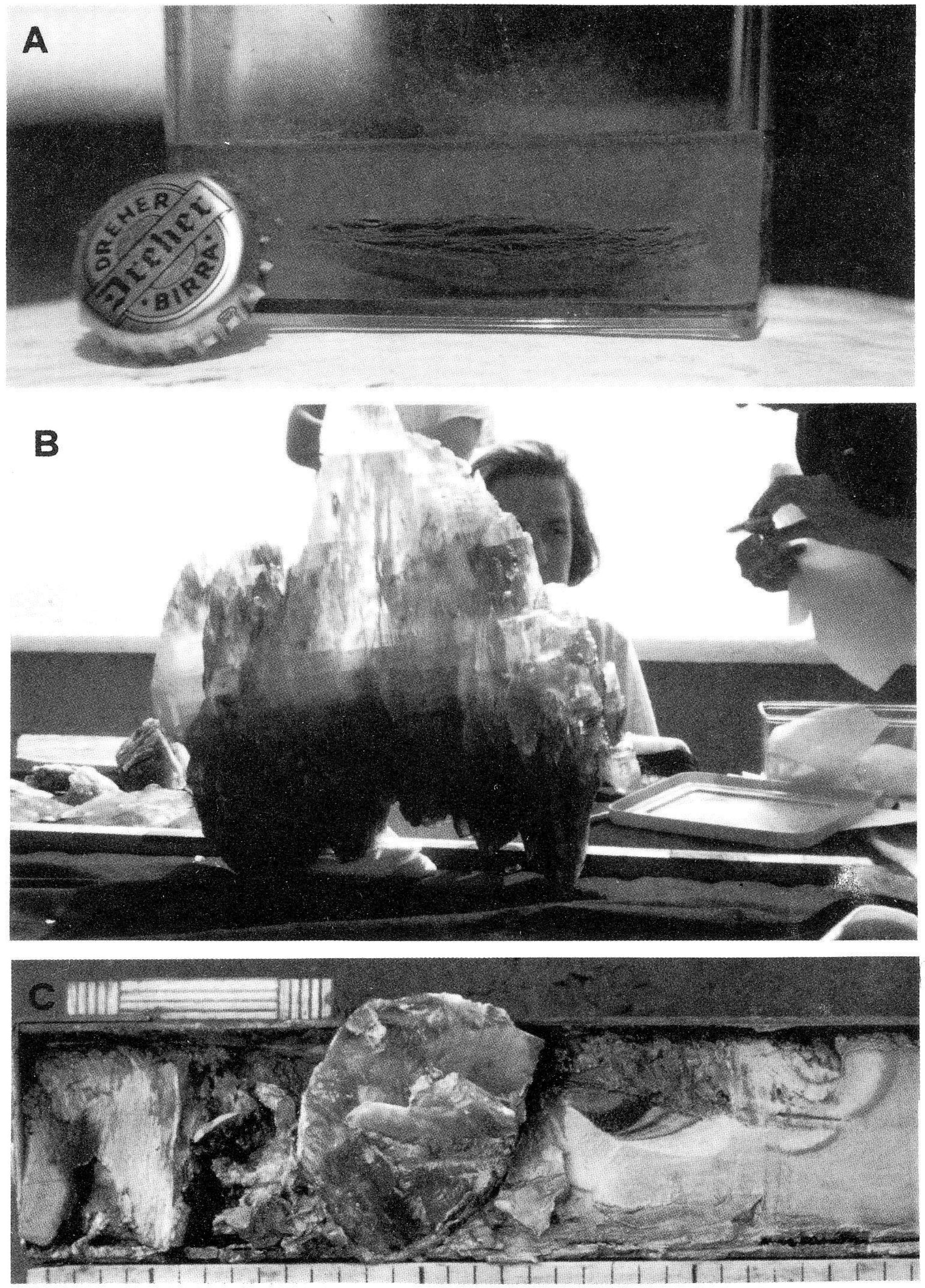
Fig. 3 - (a) Bacterial mats are common within the anoxic sediments and at the sediment surface. (b) Maria B. Cita still does not believe what dredge BAN-84/07-D brought to the surface from the Bannock Basin seafloor. The giant gypsum crystal, precipitated by the gypsum saturated brine is more than 40 cm wide and weighs about 18 kg. It is now exposed at the Natural History Museum in Bergamo (Italy). Hundreds of smaller crystals were later recovered from the basin. Some of them seem to grow within the sediment column as documented by core BAN-86/15-GC (c).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ocean water (approximately 325 ppt; Bregant et al., 1988). The ionic ratio of the brines differs from that of normal seawater, being the brine greatly enriched in ions such as Cl, Na, K, Mg, and SO_4 (Bregant et al., 1990; de Lange et al., 1990). In contrast, certain elements such as Ca have almost the same concentration as in average seawater.

Oxygen concentration drops to zero across the sharp interface between normal seawater and dense brines, pH decreases to 6.3-6.4, and total alkalinity rises to 4.2 mM. Sulphide ion (SH^-) concentration reaches 2.97 mM in Bannock Basin brine thus demonstrating that this is one of the most sulfidic bodies of water known in the marine environment (Luther III et al., 1990).

In the Tyro Basin, the salinity of the brine is almost identical to the one of the Bannock Basin area. However, the Tyro brine is characterized by a relatively higher

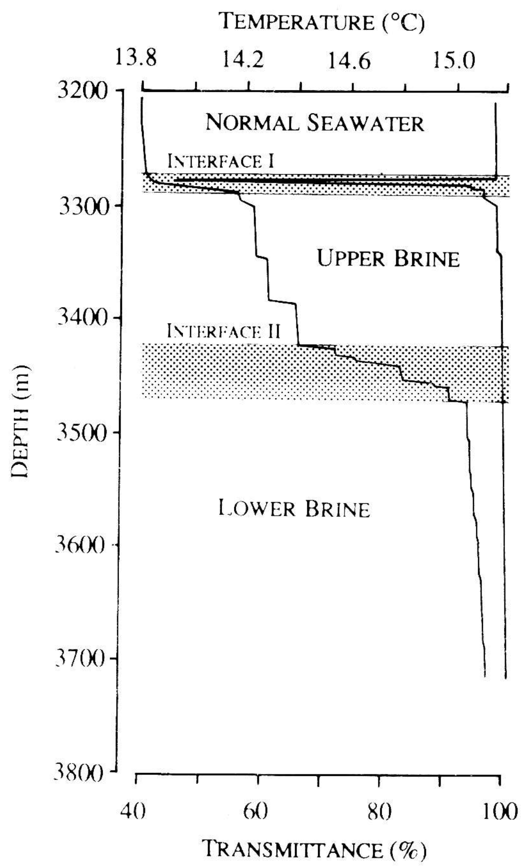

Fig. 4 - Vertical profiles of temperature and transmittance in the Bannock Basin brine. A sharp interface (I) separates normal seawater and upper brine. A second interface (II) devides the brine body in two parts with different temperature and chemical composition. The accumulation of suspended matter at interface I reflects the sharp density increase from normal seawater to brines.

Na content and relatively low Br/Cl ratio (de Lange et al., 1990).

The temperature profile across the brine/normal seawater interface shows an increase in both Bannock and Tyro basins (Fig. 4). In Bannock Basin the temperature increases with a characteristic step-like profile which divides the brine body into two main layers called Upper Brine and Lower Brine. The Upper Brine shows a temperature increase from 13.61°C to 14.40°C, the Lower Brine from 14.40°C to 15.14°C. The two brines contrast also in chemical composition, because the Upper Brine has slightly higher concentration of Ca and Sr, and lower concentration of Mg, S, and SO_4. In Tyro Basin the temperature of the brine body is constantly 14.13°C (Boldrin & Rabitti, 1990).

Preliminary calculations of the heat fluxes across the brine body of Bannock Basin suggest that the temperature increase may be due to the geothermal heat flow from the sediments which cannot be dispersed by convection in the whole water column because of the density stratification. The step-like temperature profile is related to double-diffusion of heat and salt.

The interface between brines and normal seawater acts as a sediment trap. The settling velocity of both organic and inorganic debris is slowed down by the increasing density of the water so that an anomalous accumulation of suspended matter occurs at the surface of the brine lakes (Henneke & de Lange, 1990). Particulate and dissolved organic carbon profiles clearly show this process in both areas of the Eastern Mediterranean. In Tyro Basin unusual particulates rich in Fe, Cu, Zn, S, and P have been observed by Van der Sloot et al. (1990) whose formation may be related to biological activity at the interface.

Finally, a high microbial growth has been observed on culture media prepared from water samples collected at the interface of the Bannock brine lakes, while samples from the brine body showed a progressive growth of anaerobic colonies (De Domenico & De Domenico, 1989).

Conclusions.

The Bannock and Tyro areas of the Eastern Mediterranean seafloor can be considered as an extraordinary example of the influence of geological processes on the marine ecosystems. They are two very uncommon examples of extreme marine environment where aerobic organisms cannot survive local salinity and anoxic conditions, and biological activity is dominated by anaerobic bacteria. The anoxic environment is originated by a purely physical process: the formation of a density stratification in proximity of the bottom.

The recent discovery of chemosynthetic communities in a brine filled pockmark near Orca Basin in the Gulf of Mexico (Brooks et al., 1990) emphasizes that deep sea brine lakes, as indicators of fluid circulation within sedimentary sequences, can be useful natural laboratories for the understanding of several sedimentological and biological processes in the deep sea. As opposed to the pockmarks in the Gulf of Mexico, where methane venting has been observed, Bannock and Tyro basins have not yet revealed evidence of surface gas expulsion. This may be due to the limited areal coverage of the conventional techniques so far adopted for investigations (coring, dredging, in situ CTD measurements, and water sampling). Nevertheless, concentrations of hydrogen sulphide are extremely high in the brine lakes (whose areal extent is several square kilometers), recent carbonatic hardground formation has been identified within the Bannock Basin sediments (Aghib et al., 1991), and methane and other hydrocarbons have been recently detected by us in samples from mud volcanoes on the Mediterranean Ridge (Camerlenghi et al., in press), thus suggesting that fluid circulation is a regionally widespread phenomenon in the area. In our opinion Bannock and Tyro deep-sea brine lakes may still reserve other surprises for oceanographers.

During the first phase of investigations conducted in seven years since the discovery of the first deep-sea brine pool (Jongsma et al., 1983) the effort was concentrated exclusively on stratigraphic, sedimentological, geological, and geochemical problems, which resulted in a spontaneous multi-disciplinary international cooperation among marine scientists from The Netherlands, Italy, the United States of America, and Great Britain, led by the enthousiastic work of M.B. Cita. Only limted work was devoted to the microbiological implications. We believe that it is now necessary to strengthen national and international cooperation and try a different approach to these brine lakes, which involves costly direct observation of the seafloor through deep-sea cameras, ROVs or manned vehicles which only can provide a mean of investigation of deep-sea ecosystems.

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