New stratification in the hydrothermal brine system of the Atlantis II Deep, Red Sea

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ABSTRACT

Temperature and salinity records from the REDSED cruise (September 1992) reveal a new stratification in the hydrothermal brine system of the Atlantis II Deep. This stratification consists of the preexisting lower and upper convective layers (LCL and UCL1), with temperatures of about 66 °C and 55 °C, respectively, and two additional upper convective layers (UCL2 and UCL3) that formed more recently and have distinct temperature, salinity, and thickness. In accordance with the physical process that leads to the formation of brine layers (i.e., double-diffusive convection), a flow rate of about 200 L/s has been estimated for the hydrothermal discharge.

INTRODUCTION

The first actively forming deposit of sea-floor sulfides was discovered underlying metal-rich brine in the Atlantis II Deep (Miller et al., 1966; Degens and Ross, 1969). This 60-km^2-wide deep is located near 21°25′N in the axial rift of the Red Sea (Fig. 1). The bottom of the brine pool is 2200 m below sea level and is flanked by thick Miocene evaporite. Metalliferous sediments 10–30 m thick at the bottom of the pool overlie tholeiitic basalts (Bäcker and Richter, 1973; Bäcker et al., 1975). This hydrothermal deposit was formed within the past 25 000 yr (Shanks and Bischoff, 1980; Anschutz and Blanc, 1993). It remains the largest sulfide accumulation discovered on the sea floor.

Among the 18 deeps within the median valley of the Red Sea (Bignell et al., 1976; Pautot et al., 1984), the Atlantis II Deep is the one where hot brines are currently discharging onto the sea floor. Numerous studies have shown that the ~5 km^3 pool of brine is stratified into two distinct, dense, and convective layers of differing temperature and chlorinity (Turner, 1969; Bäcker and Schoell, 1972; Voorhis and Dorson, 1975; Schoell and Hartmann, 1973, 1978; Hartmann, 1980). This dense brine pool acquired its salt by leaching Miocene evaporite deposits (Shanks and Bischoff, 1977; Zierenberg and Shanks, 1986; Dupré et al., 1988). The two brine layers—the lower convective layer (LCL) and the upper convective layer (UCL)—provide a unique environment for the formation of a stratiform metalliferous deposit. This deposit is of much greater extent than deposits formed by buoyant-plume systems typical of mid-ocean ridges, such as the East Pacific Rise, because of much more efficient metal entrapment (Zierenberg and Shanks, 1986). Theoretical models and laboratory experiments suggest that the development of a submarine brine pool results from a high rate of heat diffusion relative to that of the dissolved components (Turner, 1969; Sato, 1972; Turner and Gustafson, 1978; Huppert and Linden, 1979). A local and still active influx of hot brines in the southwest basin was suggested by periodic surveys of the temperature and depth of the deep between 1965 and 1980 (Hartmann, 1980; Monin et al., 1981). The generally accepted hydrodynamic model of the Atlantis II Deep hypothesizes an injection of hot brines directly into the bottom of the southwest basin. This injection could induce a plume above the vents that would spread laterally at the brine interface into the nearby basins. Previous hydrologic observations suggested that the brine influx produced an increase in the volume of the LCL since 1965 (Hartmann, 1980). On the basis of the hydrologic pattern summarized above, Ramboz and Danis (1990) calculated spring temperatures and mass-flow rates for the time interval 1965–1979 and deduced a decrease in hydrothermal activity between 1976 and 1979.

Comparison of the present hydrographic structure of the Atlantis II Deep brine system with the results of earlier investigations allows us to define the changing hydrothermal activity more accurately and to estimate the mean salt flux leading to the formation of new brine layers.

SAMPLING METHODS

During the REDSED cruise (September 1992) on board the R/V *Marion Dufresne*, three sites were occupied for hydrographic investigations of the Atlantis II Deep. The sites B6, B3, and B4 are

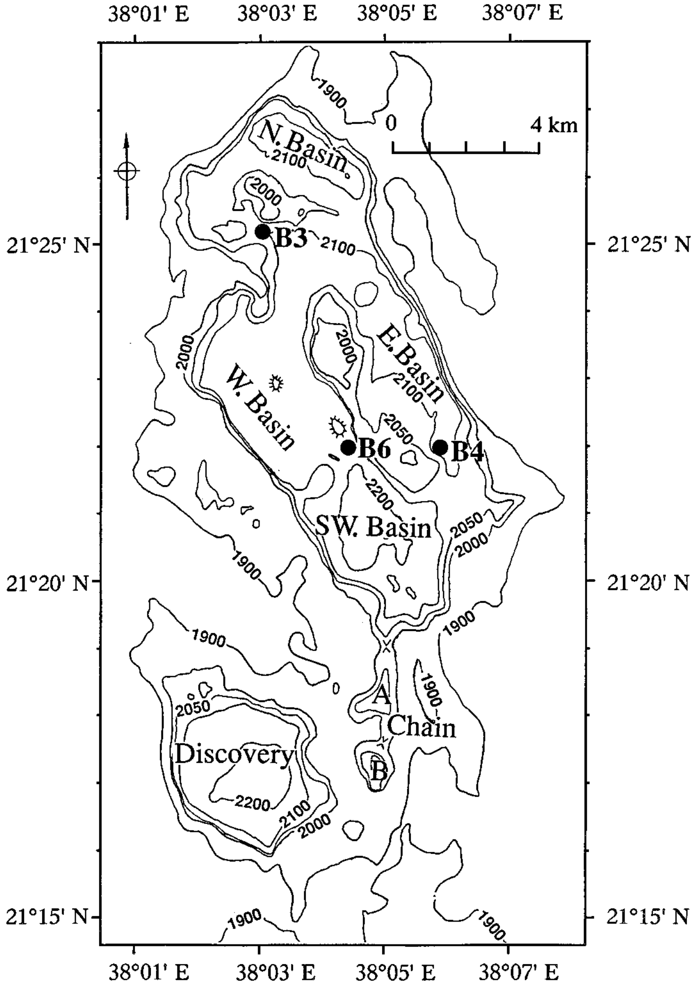

Figure 1. Location of Atlantis II Deep area, including Discovery and Chain deeps, showing sites of bathysonde recordings and hydrographic samplings.

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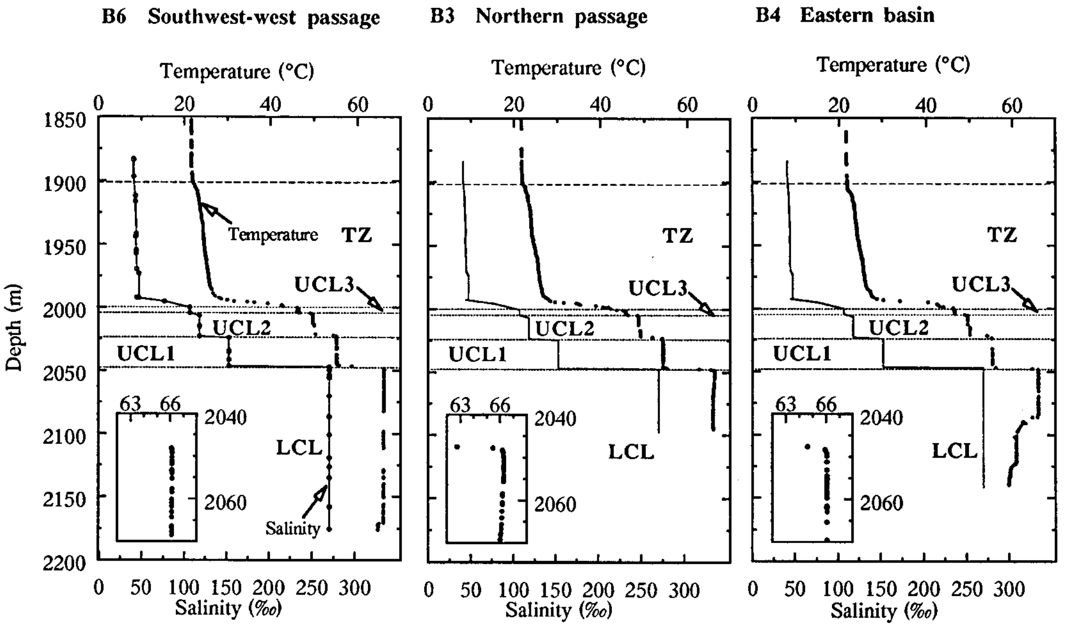

Figure 2. Salinity and temperature profiles for each hydrographic station (B3, B4, B6). TZ is transition zone, UCL is upper convection layer, and LCL is lower convection layer.

located in the southwest-west passage, the northern passage, and the east basin, respectively (Fig. 1). A Bissett-Berman modified Ollivier bathysonde equipped to measure temperature, conductivity, and hydrostatic pressure allowed continuous recording while it was lowered to the bottom of the brine pool and raised to the sea surface. Niskin bottles with 12 L capacity were used to collect water samples during the ascent of the bathysonde. Digital thermometers gave additional temperature readings for all sections of the brine system. Temperature recordings of the bathysonde probes were calibrated according to the deep-sea thermometer readings. Accuracies were estimated to be ±0.2 °C. Salinities were determined by using a Golberg optical refractometer that measured the total dissolved solids. We used an iterative method for density correction of the diluted samples to determine salinity (‰). Reproducibility of the IAPSO seawater standard was ±1%. Precision, as determined from duplication of the sample dilutions, never exceeded 2%. Chlorinity was deduced by using the calibration curve given by Danielsson et al. (1980). Sound velocities were determined for the seawater and for the convective brine layers. Precise sound-velocity data obtained during the MEROU cruise were useful to calibrate the measurements (Beauverger et al., 1984). These data were recorded above the Atlantis II Deep during the same season as those obtained on the REDSED cruise. The sound velocities in the convective brine layers were calculated by extrapolation of Matthews's corrections for salinity and temperature. The positions of the water samples and the interface depths between brine layers were calculated by means of the sound velocities, the bathysonde readings, and the position of a pinger from the bottom. An electronic contact-breaker placed 10 m below the bathysonde was used as a reference position for the sampling and the electronic recordings.

RESULTS

The salinity profile (Fig. 2) includes the salinity measurements on all samples collected at the three hydrographic stations (Table 1). The scattering of values around the profile line is insignificant; thus, we can infer a homogeneous hydrographic structure throughout the entire basin. Temperature vs. depth profiles of each hydrographic station (Fig. 2) confirm the homogeneity of the major hydrographic structure of the Atlantis II Deep and emphasize the striking temperature differences. The hydrographic data for the Atlantis II Deep are given in Table 2. Below 2047 ± 3 m, the LCL yields a salinity of 270‰ ± 3‰ and a sound velocity of 1885 ± 15 m/s. In the upper zone of the LCL, the temperature averages 66.14 ± 0.09 °C for a large depth range. However, at station B4, two temperature gradients are noticeable: one from 2085 to 2101 m and one from 2120 to 2126 m. Between these gradients, the temperature averages 60.90 ± 0.01 °C. Below 2126 m, temperatures ranging from 59.60 and 59.15 °C were recorded. At station B6, a minimum temperature of 64.67 °C was measured near the brine-sediment interface. Above the LCL, the surprising feature of the Atlantis II Deep is the presence of three UCLs, which we named UCL1, UCL2, and UCL3 (Fig. 2). The three UCLs show characteristic temperatures, salinities, sound velocities, and thicknesses (Table 2) and appear to be present over the entire surface of the Atlantis II Deep. Between UCL3 and normal Red Sea Deep Water (RSDW), two distinct temperature and salinity gradients define a lower transition zone (LTZ) and an upper transition zone (UTZ). The gradients of the LTZ are much higher than those of the UTZ.

DISCUSSION

The results presented here indicate that the hydrographic structure of the brine system of the Atlantis II Deep is different from that previously described. Since the last bathysonde recordings in November 1977, two additional brine layers (UCL2 and UCL3) have been discovered, and the temperatures of the preexisting LCL and UCL1 increased significantly by 4.64 and 4.99 °C, respectively. The temperature change since 1977 indicates an average increase of 0.31 °C/yr for the LCL, similar to that determined between 1972 and 1977 (0.29 °C/yr) (Schoell and Hartmann, 1978). However, the mean value of the heating rate—0.30 °C/yr—between 1972 and 1992 is lower than that in the 1966–1972 period (0.62 °C/yr). The increased temperature in the LCL was previously interpreted as resulting from the injection of hot brines into the system (Turner, 1969; Schoell and Hartmann, 1973, 1978; Hartmann, 1980; Monin et al., 1981; Ramboz and Danis, 1990). The maximum temperature in the LCL profile was found just beneath the interface with the upper

TABLE 1. DATA FOR ALL HYDROLOGIC SAMPLES FROM THE ATLANTIS II DEEP

Sample	Depth (m)	Temp. (°C)	Salinity (‰)	Chlorinity (‰)
Northern passage				
B3/11	1883.5	21.71	41	22
B3/10	1912.0	23.12	43	23
B3/9	1944.0	24.25	43	23
B3/8	1954.7	24.94	44	24
B3/7	1973.1	25.80	47	26
B3/6	1995.2	34.45	77	44
B3/5	2014.6	48.67	118	68
B3/4	2034.4	54.31	150	87
B3/3	2053.5	66.26	268	158
B3/2	2070.1	66.00	267	157
B3/1	2087.1	66.00	271	160
bottom	2091.9			
Eastern basin				
B4/11	1896.9	21.83	41	22
B4/10	1941.7	24.25	44	24
B4/9	1969.6	25.64	44	24
B4/8	1990.3	27.63	47	26
B4/7	2015.3	50.05	119	69
B4/6	2035.1	55.29	153	89
B4/5	2049.9	66.06	271	160
B4/4	2086.4	64.59	271	160
B4/3	2101.0	60.92	271	160
B4/2	2119.4	60.90	268	158
B4/1	2135.1	59.21	271	160
bottom	2139.8			
Southwest-west passage				
B6/11	1916.3	23.42	43	23
B6/10	1957.4	24.89	44	24
B6/9	1992.4	28.13	44	24
B6/8	2006.4	49.7	107	62
B6/7	2024.0	55.1	152	89
B6/6	2041.3	55.16	154	90
B6/5	2055.8	66.12	268	158
B6/4	2086.3	66.06	270	159
B6/3	2126.3	66.04	270	159
B6/2	2158.1	65.98	270	159
B6/1	2175.5	64.67	270	159
bottom	2179.6			

TABLE 2. PRESENT-DAY CONDITIONS IN THE ATLANTIS II DEEP

	Temperature (°C)	Salinity (‰)	Salinity (g/l)	Sound velocity (m/s)	Upper interface depth (m)
RSDW	21.64 ± 0.03	40.6	41.8	1548 ± 2 *	
TZ	21.9 to 45.8			1590 ± 10	1903 ± 3
UCL3	46.30 ± 0.30	107 ± 2	115	1685 ± 10	2000 ± 3
UCL2	49.52 ± 0.50	118 ± 1	128	1701 ± 10	2005 ± 3
UCL1	54.92 ± 0.43	153 ± 2	170	1748 ± 10	2023 ± 3
LCL	66.14 ± 0.09	270 ± 3	326	1885 ± 15	2047 ± 3
Bottom					
B3	65.98				2091.9 ± 3
B4	59.15				2139.8 ± 3
B6	64.67				2179.6 ± 3

Note: RSDW = Red Sea Deep Water, at 1850 m; TZ = transition zone; UCL = upper convective layer; LCL = lower convective layer.

* Averaged sound velocity from 0 to 1903 m.

brine (Schoell and Hatmann, 1973, 1978). This temperature peak was observed only in the western part of the deep, and it was the most pronounced in the southwest basin. This zone of elevated temperature was related to spreading of hot brines from a localized source in the southwestern basin (Pugh, 1969; Schoell and Hartmann, 1973). However, this temperature peak is not detectable on the B6, B3, and B4 temperature-depth profiles. The almost-constant heating rate, the disappearance of the temperature peak at the top of the LCL, and the presence of two additional UCLs confirm a change in the hydrothermal activity since 1972, as previously suggested by Schoell and Hartmann (1978).

The brine system is now characterized by four layers separated by relatively thin interfaces in which there are strong gradients in properties. Temperature and salinity are fairly uniform in each layer, suggesting that each is convectively mixed. The development of such a system has been experimentally obtained and has been quantitatively described by numerical models (Turner and Stommel, 1964; Turner, 1979; Huppert, 1971; Huppert and Linden, 1979). This phenomenon—called double-diffusive convection—has found numerous applications in the Earth sciences (Huppert and Turner, 1981). When heat is applied at the bottom of a stable salinity gradient, a series of layers with uniform temperature and salinity is formed. New layers form at the top of a growing convection region while lower adjacent layers merge. Turbulent convection maintains the uniformity throughout each layer while both heat and salt are transferred by molecular diffusion through the thin interface separating the layers.

In order to quantify the effect of double-diffusive convection in the Atlantis II Deep, we calculated the amount of salt transferred at the interface between the LCL and UCL1 between November 1977 and September 1992. We first evaluated the salt loads, expressed in g/L equivalent NaCl in a water column with a planar section of 1 × 1 m and with a height defined by the thickness between the top of the LCL (2047 m) and 2000 m, which was the depth of the top of the UCL3 in 1992. The salt load in the corresponding column in 1977 was deduced from the chlorinity data given by Hartmann (1980). The calculations show that the upper convective layers sampled in 1992 contained a salt concentration of about 6770 kg/m^2, whereas the salt content was about 6100 kg/m^2 in 1977 within the corresponding brine column. Thus, the salt content of the upper brines increased by 670 kg/m^2 between November 1977 and September 1992 (14.8 yr). Considering the double-diffusive phenomenon, this salt gain could be derived from a mass transfer by molecular diffusion at the interface between the LCL and UCL1. According to the first Fick's law, the salt flux F_S per unit area through the interface, across which there is a compositional difference $\Delta S = S_{LCL} - S_{UCL1}$, is

$$F_S = K_S \cdot \Delta S/\Delta x.$$

F_S is an average salt flux for the 1977–1992 period; K_S is the average of the mutual diffusion coefficient of Na and Cl, estimated at 18.4×10^{-10} m^2/s from Li and Gregory (1974) and viscosity corrections. ΔS is the average of the compositional (i.e., salinity equivalent NaCl) difference deduced from the salt loads of the LCL and UCL1 determined in 1977 and 1992; $\Delta S = 159.2$ g/L. Δx is the thickness of the interface separating the LCL and UCL1. The formula for the interface thickness calculation is derived from calculations of the heat flux across the interface and the accompanying salt flux given by Huppert and Sparks (1980). The interface thickness can therefore be expressed as

$$\Delta x = (\beta \Delta S)^3 (\alpha \Delta T)^{-10/3} (g/\nu)^{-1/3} (K_S)^{1/2} (K_T)^{-1/6} (1/0.32),$$

where $\Delta T = T_{\mathrm{LCL}} - T_{\mathrm{UCL1}}$ is the positive difference of temperature, β is the proportional density change produced by a unit salinity change, and α is the coefficient of thermal expansion, given by De Marsily (1981, p. 202). Gravity is indicated by g, ν is the kinematic viscosity, K_{S} is the molecular diffusion coefficient of salt, and K_{T} is the thermal diffusivity. K_{T} can be estimated as $\lambda/\rho c$ (De Marsily, 1981), where λ is the mean thermal conductivity, ρ is the mean density, and c is the mean specific heat of the LCL-UCL1 brines. Calculations indicate that the interface thickness was about the same in 1977 and 1992, with an average Δx value of 19.2 ± 4.0 cm. Indeed, we calculated an average salt flux of $1.53 \pm 0.30 \times 10^{-6}$ $\mathrm{kg \cdot m^{-2} \cdot s^{-1}}$ at the LCL-UCL1 interface. This salt flux indicates that 712 ± 140 $\mathrm{kg/m^2}$ of salt was transferred by upward molecular diffusion through the LCL-UCL1 interface in 14.8 yr. This result agrees with our mass-balance calculation showing that 670 kg of salt/$\mathrm{m^2}$ were gained by the upper brines over this period of time. Therefore, the amount of salt supplied into the LCL from the brine influx seems to have been mostly lost by an upward-diffusive salt flux, which contributed to the formation of new brine layers such as UCL2 and UCL3. The salt input needed to balance the salt lost by upward diffusion must be at least equal to this salt output. If the mean surface area of the lower brine interface equals 43.5 $\mathrm{km^2}$ (Hartmann, 1980) and the brine flowing into the LCL has a salt load equal to that of the LCL (327 ± 4 g/L), then a flow rate of about 200 L/s for the inflowing brine can be estimated. This flow rate is similar to 150 ± 60 L/s determined for venting of the hydrothermal fluid onto the sea floor at lat 21°N on the East Pacific Rise (Converse et al., 1984), and it backs up the assumption that double-diffusive convection is the main physical process leading to the merging of new brine layers within the Atlantis II Deep.

CONCLUSIONS

Our hydrographic investigations, including the discovery of two additional layers in the brine system, confirm that the hydrothermal activity of the Atlantis II Deep provide a unique natural laboratory where double-diffusive convection can be tested. A new stratification with four brine layers provides a new chemical environment that must be considered for better understanding the genesis of the hydrothermal massive sulfide ore deposits at the Red Sea spreading center.

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