Hydrographic changes during 20 years in the brine-filled basins of the Red Sea

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Abstract

Many of the deep basins filled by hot brines in the Red Sea have not been investigated since their discovery in the early 1970s. Twenty years later, in September 1992, six of these deeps were revisited. The temperature and salinity of the Suakin, Port Sudan, Chain B, and Nereus deeps ranged from 23.25 to 44.60°C and from 144 to 270‰. These values were approximately the same in 1972, indicating that the budget of heat and salt was quite balanced. We measured strong gradients of properties in the transition zone between brines and overlying seawater. The contribution of salinity to the density gradient was more than one order of magnitude higher than the opposite contribution of temperature across the seawater–brine interface. Therefore the interface was exemely stable, and the transfer of properties across it was considered to be controlled mostly by molecular diffusion. We calculate that the diffusional transport of salt from the brines to seawater cannot affect significantly the salinity of the brines over a 20 year period, which agrees with the observations. The brine pools can persist for centuries with no salt input. Therefore, the persistence of brines does not correspond to a steady balance between diffusional loss and continuous input of hydrothermal solutions. Deeps that experience only episodical hydrothermal brine supplies may persist for a long time with salt inherited from past inputs. The theoretical loss of heat by diffusion from the brine to seawater was higher than the observed decrease in temperature of the brine pool during the 20 year period of observation. We calculated that the heat flux out of the pools into the overlying seawater was compensated by a heat flux into the pools of about 250–600 mW/m². This range of values corresponds to bottom heat flow values that have been reported earlier for the axial zone of the Red Sea. In contrast to the other brine pools, the temperature and salinity of the Valdivia Deep

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brine increased by 4.1°C and 10‰, respectively, between 1972 and 1992, which is explained by present-day hydrothermal brine discharge. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The central axial zone of the Red Sea is marked by 0.02–60 km^2 basins located between 1500 and 2800 m deep (Fig. 1), which are filled with anoxic, dense, and hot brines (Bäcker and Schoell, 1972; Bäcker et al., 1975; Pautot et al., 1984). The Atlantis II Deep, which is the largest basin and which contains metal-rich sediments, has been visited many times between 1965 and 1997. Successive hydrographic measurements of the layered brine that has filled this basin show that the bulk heat and salt content of the brine increased regularly over time (Schoell and Hartmann, 1978; Anschutz and Blanc, 1996). The temperature reached 66°C and the salinity increased up to 270‰ (Blanc and Anschutz, 1995). From this observation it was possible to determine a range of the temperature, salinity, and fluid flow characteristics of the hydrothermal brines that supplied the Atlantis II Deep during the recent decades (Anschutz and Blanc, 1996). Unlike the Atlantis II Deep, the hydrographic properties of most of the deeps have not been studied since their discovery in the early 1970s. Even if most of these deeps were filled with brines, the temperature anomaly was not as spectacular as that of the Atlantis II Deep, and their metalliferous sediment content was lower. In order to determine a general pattern of the evolution of brine in the Red Sea, however, we have studied the changes of properties through time of several brine pools of different temperature, salinity, and size. In 1992, six deeps and the well-known Atlantis II Deep were re-investigated during the REDSED expedition of the R.V. Marion Dufresne. We present for the first time high-resolution profiles of temperature and salinity vs. depth for the brines of Suakin, Port-Sudan, Valdivia, Chain B, and Nereus deeps. We propose to quantify the exchanges of salt and heat between the brines and the overlying seawater and to define the impact of these exchanges on the persistence of brine pools. It is also possible to determine the actual evolution of the brine pool temperature and salinity between 1972 and 1992. Finally, we examine the influence of geothermal heat flow on the heat balance of the brine-filled basins.

2. Methods

Details of the methods were described previously (Blanc and Anschutz, 1995; Anschutz and Blanc, 1996). Briefly, continuous recording of temperature and conductivity was made at each station (Fig. 2) using a Bissett-Bermann bathyprobe modified for high temperature and salinity values. Temperature recordings were calibrated with digital thermometer readings. Salinities of brines were obtained, using a Golberg optical refractometer, from samples collected with Niskin bottles, and were compared to conductivity. A polynomial relationship between unitless conductivity-sensor data,
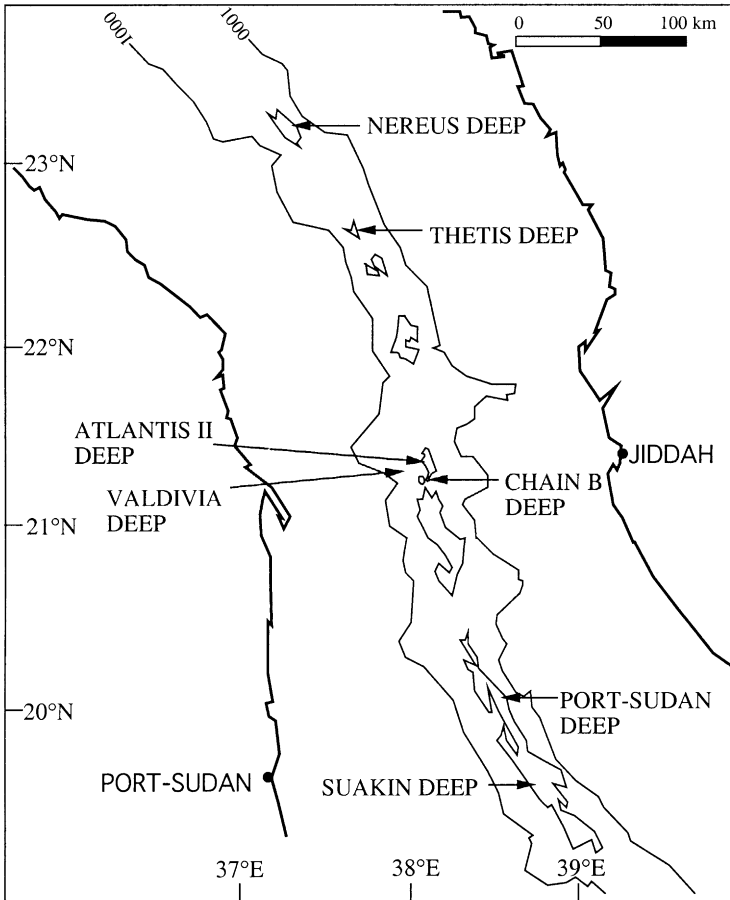
Fig. 1. Map of the central axial zone of the Red Sea and location of the Red Sea deeps investigated during the REDSED cruise of the R.V. Marion Dufresne in September 1992.

temperature and salinity allowed us to construct continuous salinity profiles. The depths were calculated from acoustic data. Sound velocities were determined for seawater and the convective brine layers. The sound velocities in the brines were deduced from the extrapolation of Matthew's corrections for salinity, temperature, and pressure.

3. Results

The deeps were filled with homogeneous brines, except the Thetis Deep, which was filled with normal Red Sea bottom water. Although the temperature of the brines was higher than that of seawater (Fig. 2), the salt contribution dominated the density
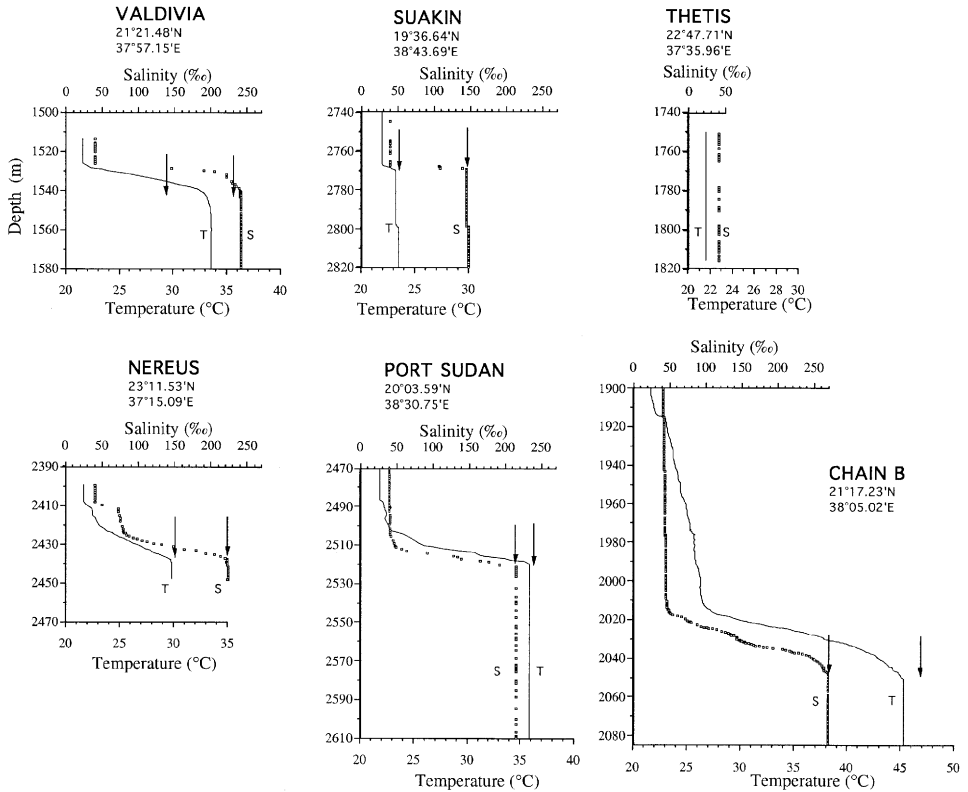
Fig. 2. Temperature (line) and salinity (dots) versus depth profiles of six Red Sea brine-filled deeps obtained from the REDSED cruise in September 1992. Results are presented on the same scale for all deeps. Arrows show the temperature and the salinity of the brines in 1972.

(Fig. 3). All brine-filled deeps had densities far higher than the density of the Red Sea bottom water and reached values up to 1197 kg/m^3 in the Chain B Deep. The brine pool of the Suakin Deep contained two layers. The upper one had a temperature of 23.25°C and a salinity of 145‰. It was separated from seawater by an interface less than 4 m thick. The lower brine was 0.26°C warmer and 4‰ saltier. Port Sudan Deep contained a brine of 35.9°C and 214‰ separated from seawater by a 34 m thick transition zone. An important temperature and salinity gradient occurred just above the hot brine. The Valdivia Deep had a brine of 33.68°C and 242‰ overlain by a 29 m thick transition zone characterized by an S-shaped temperature gradient. The salinity gradient was most pronounced at the top of this zone. The Nereus Deep brine registered 29.89°C and 222‰. The 32 m thick transition zone showed a step in the salinity and temperature profile at the top.

Chain B Deep is a small and isolated topographic depression of the Atlantis II-Discovery-Chain Deep system. It is connected to the large Atlantis II Deep and the proximal Discovery Deep at depths shallower than 1990 m. Chain B Deep contained
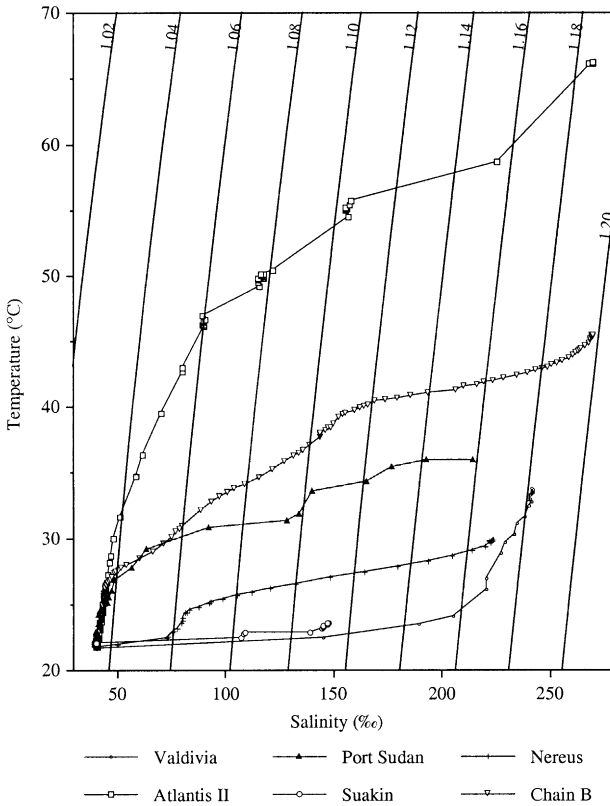
Fig. 3. Salinity versus temperature diagram of the transition zone between the hot and concentrated brines and seawater for the six studied Red Sea deeps in 1992. Isopycnal lines were calculated from densities of NaCl aqueous solutions at 200 bars computed from thermodynamic data given by Pitzer et al. (1984). Salinity and temperature in 1972 of the brine pools are shown. Salinities in 1972 were given in chlorinity (Bäcker and Schoell, 1972). We used the equation of Danielsson et al. (1980) in order to obtain salinities ($S = 1.67$ Cl $+ 4.02$).

in 1992 a 45.33°C brine as saline as the Atlantis II Deep lower brine. Fig. 4 focusses on the transition zone of the vertical temperature profile. The irregular temperature gradients and lateral variations can be explained by the topography and the influence of the adjacent Discovery Deep and Atlantis II Deep. For example, the sharp gradient at about 1910 m was created by an overflow of waters across a sill at 1903 m, which marked the top of the system (Anschutz and Blanc, 1996). This sill was located in the southern end of the system, i.e. close to the Chain B Deep. The perturbation of the profiles around 1980 m occurred at the depth where the Chain Deep and the neighbouring Discovery Deep were connected. Fig. 4 also shows a profile of temperature of the transition zone located above the Atlantis II Deep (Blanc and Anschutz, 1995). This profile was approximately parallel, but with higher values, to the Chain B Deep profile for depths shallower than 1980 m. This suggests that the properties measured
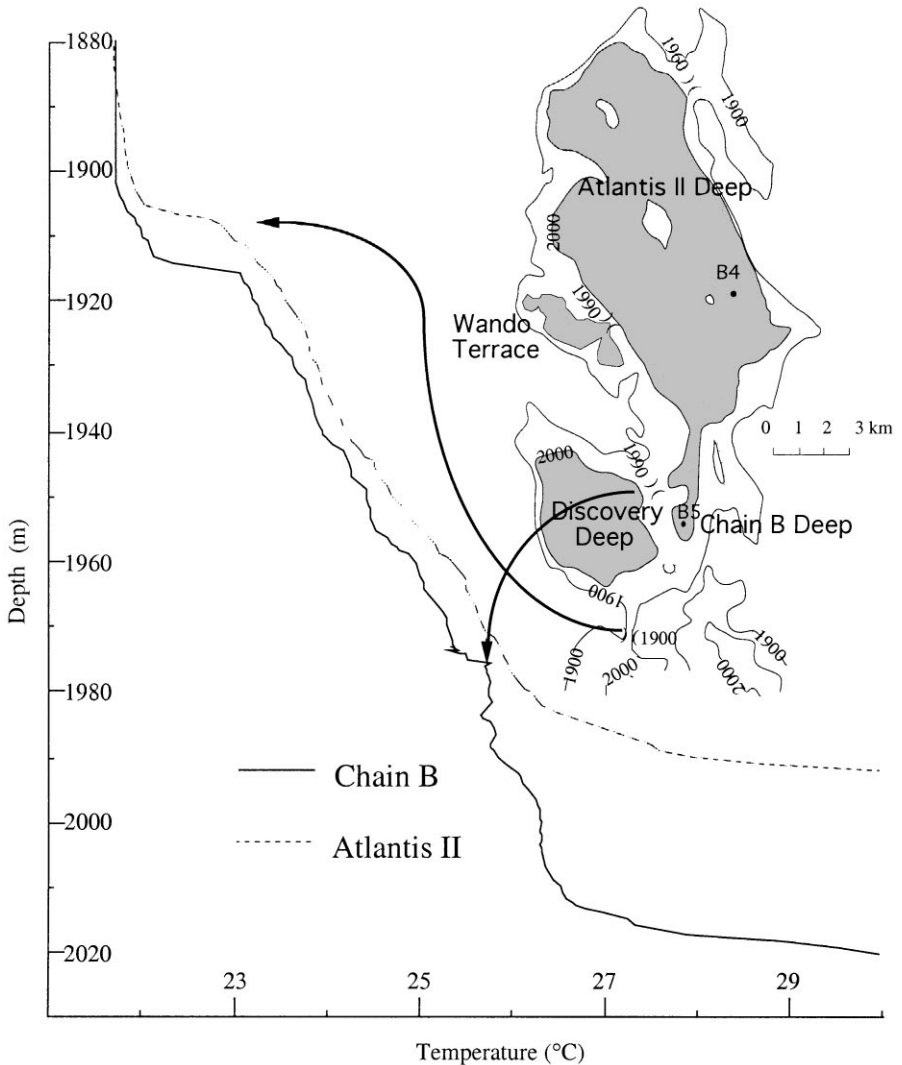
Fig. 4. Detail of the upper transition zone for the temperature versus depth profile of the Chain B Deep. The profile is compared to that measured at station B4 of the Atlantis II Deep. Both transition zones are connected at depths shallower than 2000 m. Irregularities in the profiles are ascribed to the topography, and more specifically to the depth of sills (arrows). The remoteness of the Chain B Deep from the Atlantis II Deep shifted both T and S profiles to lower values in the upper transition zones. The 2000 m contour line delimits the area covered by concentrated brines (grey area) and corresponds approximately to the bottom of the transition zone of the Atlantis II Deep. The 1900 m contour line represents its top, and also the maximal extent of the Atlantis II Deep hydrothermal system, including Chain B Deep and Discovery Deep. The maximum depths of the sills that separate the different basins of the area are indicated.

at these depths in the Chain B Deep result mostly from the lateral scattering of properties that diffuse from the Atlantis II Deep. The observed shape of the transition zones of the Suakin, Port Sudan, and Valdivia deeps, and especially the sharp gradient at the top of the Nereus Deep, must also depend on the topography, but maps as precise as that for the Atlantis II Deep (Bäcker and Richter, 1973; Pautot, 1983) are not available.

4. Evolution of brine properties from 1972 to 1992

From 1972 to 1992, the temperature and salinity of the Valdivia Deep increased by 4.1°C and 10‰. Intermediate values were documented in 1980 (Monin et al., 1981). The change in properties cannot be explained by the dissolution of outcropping salt from the Miocene evaporite of the Red Sea (Whitmarsh et al., 1974), since this is an endothermic reaction. Therefore, the increase of temperature and salinity of the Valdivia Deep must be linked with present-day hydrothermal brine supplies as in the Atlantis II Deep (Anschutz and Blanc, 1996).

The temperature of the Suakin, Port-Sudan, Chain B, and Nereus deeps decreased little between 1972 and 1992, whereas their salinities remained constant within measurement precision (Fig. 2). In order to estimate whether the relative constancy of properties was due to low exchange of heat and salt with overlying seawater or was due to heat and salt inputs that compensated upward losses, we have to calculate the magnitude of fluxes across the brine–seawater interface. For that, the mechanism of heat and salt transfers must be known.

The deeps are steep-sided basins (Bäcker et al., 1975) isolated from the Red Sea general circulation; therefore we exclude the mixing of brine with seawater driven by a surface stress. The gradient of properties in the transition zones can result from molecular diffusion and advective mixing of brine and overlying seawater. We examine below the relative proportion of each process. The mixing process is important when the upper interface of the brine pool becomes unstable (Crapper, 1975). The stability depends on the ratio between the stabilizing effect on the density gradient (salinity) and the destabilizing effect on it (temperature). This density ratio, $R\rho$, is expessed as $R\rho = \beta \Delta S / \alpha \Delta T$, where α is the coefficient of thermal expansion, and β is the coefficient of salinity contraction (Turner, 1979). Experiments and numerical simulations showed that when this ratio was close to 1, the interface was unstable and the fluxes were governed by turbulent convective mixing (Turner, 1968; Fernando, 1987; Kelley, 1990; Molemaker and Dijkstra, 1995). Griffiths (1979) showed experimentally that for values of $R\rho < 3$, penetrative convection produced interfacial waves. These waves became large enough when $R\rho < 2$ to break and cause mixing of the two layers.

Calculated $R\rho$ values for the Red Sea brines are presented in Table 1. Values of α and β were computed from density calculations of NaCl aqueous solution after Pitzer et al. (1984). In 1992, $R\rho$ values were 165, 22.2, 40.3, and 19.4 for Suakin, Port Sudan, Nereus, and Chain B Deeps, respectively. This shows that the salinity contribution to the density difference is much more important than the opposite

Table 1
Values of the density ratio $R\rho$ between seawater and the underlying brines of the Suakin, Port Sudan, Nereus, and Chain B Deeps, and parameters used for the calculations

Deep	S (‰)	T (°C)	Density (kg/m³)	C_p J/kg/°C	α	β	$R\rho$
Seawater	40.19	21.97	1034.8	3937	0.000315	0.000706	165.0
Suakin brine	144.3	23.25	1110.9	3552	0.000438	0.000759	
Seawater	40.9	21.93	1038.0	3935	0.000315	0.000706	22.2
Port Sudan brine	214	35.89	1158.0	3368	0.000520	0.000789	
Seawater	40.8	21.7	1038.0	3935	0.000315	0.000706	40.2
Nereus brine	222	29.89	1167.4	3345	0.000515	0.000804	
Transition zone	44.6	25.87	1040.0	3923	0.000340	0.000708	19.4
Chain B brine	269.5	45.33	1197.6	3233	0.000576	0.000831	

temperature contribution. All the interfaces, then, were very stable. In fact, these $R\rho$ values were one or two orders of magnitude higher than values where mixing was experimentally observed. Because of the high stability of the investigated Red Sea brine interfaces, it is likely that molecular processes alone determined the exchanges across them. To our knowledge, values of $R\rho$ of the same order of magnitude in a natural environment have been considered only for the Atlantis II Deep ($10 < R\rho < 20$) (Turner, 1969; Anschutz et al., 1998). In this basin, Anschutz et al. (1998) showed that the upward flux of properties across the interface during the last 30 years could be attributed solely to molecular diffusion. The creation of new layers in the Atlantis II Deep during this period did not correspond to interface instabilities, but arose from inputs of new brine flowing down into the Deep from above. For other deeps where $R\rho$ was higher, the dominant mechanism of heat and salt transport from the homogeneous brine pools to seawater must have been molecular diffusion across the transition zones.

This hypothesis was tested and compared to the actual evolution of the brines (Table 2). For flux calculations across the interfaces of Suakin, Port Sudan, Nereus, and Chain B deeps, we used the maximum gradients of heat and salt registered between the homogeneous brine and seawater. Diffusive salt flux is expressed by Fick's law as

$$F_S = D(\Delta C/dz),$$

where D is the diffusion coefficient of salt and $\Delta C/dz$ is the vertical concentration gradient across the brine–seawater interface. The calculated diffusive loss of salt across the transition zone of the Suakin, Port Sudan, Nereus, and Chain B deeps over a period of 20 years (Table 2) is F_S (in kg/m²/20 years):

$$F_S = 20D(S_{Bottom}\rho_{Bottom} - S_{Top}\rho_{Top})/(z_{Bottom} - z_{Top})1000),$$

where the subcripts Top and Bottom refer to the measured or calculated properties at the limit of the brine interval where the maximum gradient of salinity was observed.

Table 2
Calculated diffusive fluxes of heat and salt across the maximum gradient of salinity and heat of the Suakin, Port Sudan, Nereus, and Chain B deeps over a period of 20 years, and parameters used for the calculations.

Deep	Depth of the maximum gradient[a] (m)	S (‰)	T (°C)	Density (kg/m³)	C_p J/kg/°C	Salt Flux kg/m²/20 yr	Calculated decrease of salinity ‰	Heat flux mW/m²	Calculated decrease of temperature (°C)	Observed decrease of temperature (°C)
Suakin	2767.47	40.19	22.01	1034.8	3937.5	84.02	1.55			
	2768.14	106.98	22.44	1084.0	3677.0					
	2769.10	138.89	22.86	1106.2	3571.8			539	1.72	0.1
	2769.50	144.85	23.17	1110.5	3553.6					
Port Sudan	2516.19	134.30	31.82	1098.8	3596.2			1329	2.15	0.3
	2517.04	140.10	33.52	1107.0	3578.8					
	2517.04	140.10	33.52	1107.0	3578.8	27.23	0.24			
	2517.89	165.63	34.27	1121.0	3500.9					
Nereus	2432.50	163.99	27.38	1123.1	3500.5	16.79	0.74	250	2.02	0.3
	2433.37	179.31	27.79	1134.8	3456.5					
Chain B	2030.79	147.42	38.29	1105.6	3559.7			436	2.03	1.0
	2031.27	150.28	38.65	1107.5	3551.1					
	2033.89	173.93	40.27	1124.4	3480.7	22.16	0.55			
	2035.32	206.58	41.21	1149.4	3389.0					

[a]The maximum gradient of temperature was not always at the same depth than the maximum gradient of salinity.

The coefficient of diffusion D is given in m^2/yr. It was calculated by using the tracer diffusion coefficient of NaCl D^o (Li and Gregory, 1974) corrected for kinematic viscosity, temperature, and mutual electrostatic effect of the brines. The effect due to pressure is negligible for the values corresponding to the depth of the deeps (Oelkers and Helgeson, 1988). The estimation of D in a concentrated solution (D^c) depends on the viscosity of the solution (Salvinien and Brun, 1964), i.e.

$$D^c/D^o \approx v^c/v^o,$$

where v^c and v^o are the viscosity of brine and water, respectively. The dependance of the diffusivity on the temperature in the range 0–100°C is given by the Stokes–Einstein relation (Simpson and Carr, 1958):

$$(D^o_{T_1}/T_1)v^o_{T_1} = (D^o_{T_2}/T_2)v^o_{T_2},$$

where T_1 and T_2 are the absolute temperatures (K). By combining the last two equations, and considering that the second remains viable in saline waters in the range of the Red Sea brines, i.e.

$$v^o_{T_2}/v^o_{T_1} = v^c_{T_2}/v^c_{T_1},$$

we obtain the diffusion coefficient of a chemical species in a concentrated solution at a given temperature, that is

$$D^c_{T_2} \approx D^o_{T_1}(T_2/T_1)((v^o_{T_1})^2)/v^o_{T_2}v^c_{T_1})).$$

For an aqueous solution containing charged species, the actual diffusion coefficient of an ion is dependent on the diffusivity of the other ions, since the electroneutrality of the solution must be conserved everywhere. For the case of a solution containing a dilute amount of one salt, the mutual diffusion coefficient is (Li and Gregory, 1974):

$$D = ((|Z^+| + |Z^-|)D_+D_-)/((Z^+D_+) + (Z^-D_-)),$$

where Z^+ and Z^- are the charges of the cation and anion. As the concentration increases, D can also vary according to a thermodynamic term, which can become important. However, for the Red Sea brines, which are highly dominated by dissolved Na and Cl, the overall effect of this term is small (Lasaga, 1979). Values of D calculated for in situ conditions ranged between 0.031 and 0.041 m^2/yr for the four considered transition zones. Numerical values of density ρ were computed for the temperature and salinity of the brines using data for NaCl aqueous solutions (Pitzer et al., 1984). The decrease in salinity is

$$\Delta S = F_S/((\rho_{Brine}/1000)d),$$

where ρ_{Brine} is the density of homogeneous brine pool and d is its mean thickness (50, 100, 20, and 35 m for the Suakin, Port Sudan, Nereus and Chain B deeps, respectively). Calculated F_S values are reported in Table 2. F_S was maximal (84 $kg/m^2/20$ yr) in the Suakin Deep interface, where the salinity gradient was the most important. However, the decrease in salinity of the Suakin Deep brine deduced from our flux calculation corresponds only to 1.55 g/kg in 20 years, which is only about 1.5% of the salinity anomaly of the brine relative to seawater (105 g/kg).

Therefore, if we consider a constant salt flux, the loss of half of the salinity anomaly (the half-life of the brine) by diffusion needs 680 years. In the same way the diffusive loss of salt in other basins from 1972 to 1992 has been negligible in comparison with the reserve of dissolved salt. The half-life of the brines is 7160, 2460, and 4160 years for the Port Sudan, Nereus, and Chain B deeps, respectively.

The diffusive thermal flux is

$$F_H = K(\Delta(\rho C_p T)/\mathrm{d}z),$$

where K is the thermal diffusivity and $\Delta(\rho C_p T)/\mathrm{d}z$ is the vertical gradient of heat, K is $0.16 \pm 0.02 \times 10^{-6}$ m^2/s. Numerical values of heat capacity C_p were calculated for the temperature and salinity of the brines using data for NaCl aqueous solutions (Pitzer et al., 1984). The numerical value of the heat loss (Table 2) is F_H (in W/m^2):

$$F_H = K((\rho C_p T)_{\mathrm{Bottom}} - (\rho C_p T)_{\mathrm{Top}})/(z_{\mathrm{Bottom}} - z_{\mathrm{Top}})).$$

The temperature decrease of the brine during 20 years (6.3×10^8 s) was deduced from the calculated maximum heat flux across the brine–seawater interface, i.e.,

$$\Delta T = 6.3 \times 10^8 F_H/d(\rho C_p)_{\mathrm{Brine}}.$$

The results show that the maximum gradients of heat at the different interfaces support heat fluxes ranging from 250 mW/m^2 for the Nereus Deep to 1329 mW/m^2 for the Port Sudan deep. When these heat losses from the brine pools are converted into temperature decreases, which takes into account the mean thickness of the brines, the results are relatively similar. The heat loss from the brine pools for the last 20 years should correspond to a decrease in temperature of about 2 degrees for the four pools (Table 2). The actual decreases of temperature from 1972 to 1992 were 0.1, 0.3, 0.3, and 1.0°C for the Suakin, Port Sudan, Nereus, and Chain B deeps, respectively. These lower values suggest that the loss of heat at the top of the brines was partially balanced by a flux of heat from the bottom of the basins. This flux can be attributed to the bedrock geothermal gradient.

Thermal measurements in the sediments of the deeps have never been performed. This prevents any accurate estimation of the heat flux at the brine–bottom interface. Bottom heat flow measurements have been made in the axial zone of the northern part of the Red Sea (Martinez and Cochran, 1989). Values ranged typically between 300 and 400 mW/m^2, and occasionally up to 600 mW/m^2. These values are of the same order of magnitude as the heat loss we calculated across the brine–seawater interface. Therefore, if we consider that the bottom heat flow in the axial zone of the middle part of the Red Sea was equivalent to that of the northern Red Sea, it appears that heat loss above the brines was compensated simply by the geothermal heat flux, and this explains the low temperature decrease during the 1972–1992 period. In other words, there was no advective hydrothermal heat input in the four deeps during this period.

The heat gradient above the brine pool, and the corresponding heat flux, was the highest in the Port Sudan Deep (1329 mW/m^2). This corresponds to a calculated temperature decrease of 2.15°C during the 20 years, whereas the actual decrease was only 0.3°C. This indicates that the bottom thermal flux was the highest in the Port

Sudan Deep, and this implies that a part of this flux could have come from a hydrothermal fluid input. Another hypothesis, however, can explain the important heat input into the deep, and this depends on the topography of the basin. The area of the brine–seawater interface is about 5 km^2 (Bäcker and Schoell, 1972). Although the Port Sudan Deep is an elongated, steep sided, and deep basin, the surface area of the bottom and sides in contact with the brine is at least 1.5 times larger than that of the interface. Therefore the high upward heat loss is compensated by a somewhat smaller heat flux acting over a larger surface.

5. Discussion and conclusion

In conclusion, we have shown that the brine–seawater interfaces of Suakin, Port Sudan, Chain B, and Nereus deeps were extremely stable and that the property transfers were mostly governed by diffusive processes. The salinity of the brines remained the same or decreased little from 1972 to 1992. This agreed, however, with the slow diffusive exchanges of salt through the transition zone between seawater and brines. These brine pools were therefore not supplied by hydrothermal salty fluids during the 1972–1992 interval. Rather, they lost by diffusion a small proportion of their salt inherited from past inputs. A salinity anomaly can be present for centuries with no additional salt input. Consequently, the brine-filled basins do not need to be continuously fed by hydrothermal brines to persist over the course of hundreds of years.

The calculated diffusive exchanges at the top of the brine pools also showed that a temperature anomaly relative to seawater temperature could persist for many decades. Over the long term, the heat loss at the top is, in fact, partly balanced by the geothermal heat flux. Of the six brine pools investigated two were hydrothermally active (Atlantis II and Valdivia deeps) and four were inactive. However, the thermal anomalies recorded in the four inactive basins suggest that hydrothermal activity must have occurred previously.

The Thetis Deep contained no brine in 1992 or in 1972. However, the sediment blanketing the basin contained layers consisting of iron and manganese oxides (Scholten et al., 1991). This suggests that the Deep was filled in the past by a brine layer, which dissipated. The disappearance of a brine pool occurs when mixing at the interface between the brine and seawater becomes important, that is when the density ratio $R\rho$ decreases to values down to 2, where penetrative convection produces interfacial waves. $R\rho$ decreases when the salinity decreases or when the temperature increases without a corresponding addition of salt. We showed that the loss of salinity was slow as long as $R\rho$ was high. Therefore the dissipation of a brine pool must result mostly from an addition of heat. For example, the value of $R\rho$ would reach a value of 2 in the Suakin and the Port Sudan Deep at constant salinity if the temperature of the brine reached 80 and 150°C, respectively. This should occur in periods of extreme heat flux in the Red Sea axial trough, as for example during periods of volcanic activity and basaltic discharge. Such events already have been detected for the Holocene period in the Atlantis II Deep (Blanc et al., 1998).

Comparison of modern sediments deposited under the hypersaline waters and under normal Red Sea water shows that the brines represent an environment of mineral precipitation. For some deeps, such as Atlantis II, it has been shown clearly that the major source of chemical elements that compose the authigenic material, such as sulfide minerals or metal oxides, silicates and carbonates, was of hydrothermal origin (Zierenberg and Shanks, 1986; Anschutz and Blanc, 1995). In other areas, such as the Suakin, Nereus or Port-Sudan deeps, the chemistry and mineralogy of Holocene and Late-Pleistocene sediments are similar to those of the background detrital and biogenic sediments of the Red Sea. However, some horizons are enriched in metals such as Fe, Mn, or Zn (Bäcker and Schoell, 1972). Such enrichments can reflect two different histories: (1) hydrothermal fluid episodically flowed into an established brine pool; or (2) a brine pool was present only during the periods of metal deposition, but not during the deposition of intervening non-metalliferous sediments. Our study supports the first hypothesis.

Acknowledgements

References

Anschutz, P., Blanc, G., 1995. Chemical mass balances in metalliferous deposits from the Atlantis II Deep (Red Sea). Geochimica et Cosmochimica Acta 59, 4205–4218.

Anschutz, P., Blanc, G., 1996. Heat and salt fluxes in the Atlantis II Deep (Red Sea). Earth and Planetary Science Letters 142, 147–159.

Anschutz, P., Turner, J.S., Blanc, G., 1998. The development of layering, fluxes through double-diffusive interfaces, and location of hydrothermal sources of brines in the Atlantis II Deep: Red Sea. Journal of Geophysical Research 103 (C12), 27809–27819.

Bäcker, H., Richter, H., 1973. Die rezente hydrothermal sedimentäre Lagerstätte Atlantis II Tief in Roten Meer. Geologische Rundschau 62, 697–740.

Bäcker, H., Schoell, M., 1972. New deeps with brines and metalliferous sediments in the Red Sea. Nature Physical Science 240, 153–158.

Bäcker, H., Lange, K., Richter, H., 1975. Morphology of the Red Sea central Graben between Subair Islands and Abul Kizaan. Geologische Jahrbuch D 13, 79–123.

Blanc, G., Anschutz, P., Pierret, M.C., 1998. Metalliferous sedimentation into the Atlantis II Deep: a geochemical insight. In: Purser, B.H., Bosence, D.W.J. (Eds.), Sedimentation and tectonics of rift basins: Red Sea-Gulf of Aden. Chapman & Hall, London, pp. 505–520.

Blanc, G., Anschutz, P., 1995. New hydrographic situation in the Atlantis II Deep hydrothermal brine system. Geology 23, 543–546.

Crapper, P.F., 1975. Measurements across a diffusive interface. Deep-Sea Research 22, 537–545.

Danielsson, L.G., Dryssen, D., Graneli, A., 1980. Chemical investigations of Atlantis II and Discovery brines in the Red Sea. Geochimica et Cosmochimica Acta 44, 2051–2065.

Fernando, H.J.S., 1987. The formation of a layered structure when a stable salinity gradient is heated from below. Journal of Fluid Mechanics 182, 525–544.

Griffiths, R.W., 1979. The transport of multiple components through thermohaline diffusive interfaces. Deep-Sea Research 26, 383–397.

Kelley, D.E., 1990. Fluxes through diffusive staircases: A new formulation. Journal of Geophysical Research 95, 3365–3371.

Lasaga, A.C., 1979. The treatment of multicomponent diffusion and ion pairs in diagenetic fluxes. American Journal of Science 279, 324–346.

Li, Y.H., Gregory, S., 1974. Diffusion of ions in sea water and in deep-sea sediments. Geochimica et Cosmochimica Acta 38, 703–714.

Martinez, F., Cochran, J.R., 1989. Geothermal measurements in the Northern Red Sea: implications for lithospheric thermal structure and mode of extension during continental rifting. Journal of Geophysical Research 94, 12239–12265.

Molemaker, M.J., Dijkstra, H.A., 1995. Layer formation in a salt stratified liquid cooled from above. Double-Diffusive Convection. Geophysical Monograph 94, 97–104.

Monin, A.S., Plakhin, E.A., Podrazhansky, A.M., Sagalevich, A.M., Sorokhtin, O.G., 1981. Visual observation of the Red Sea hot brines. Nature 291, 222–225.

Oelkers, E.H., Helgeson, H.C., 1988. Calculation of the thermodynamic and transport properties of aqueous species at high pressures and temperatures: aqueous tracer diffusion coefficients of ions to 1000°C and 5 kb. Geochimica et Cosmochimica Acta 52, 63–85.

Pautot, G., 1983. Les fosses de la Mer Rouge: approche géomorphologique d'un stade initial d'ouverture océanique réalisée à l'aide du Seabeam. Oceanologica Acta 6, 235–244.

Pautot, G., Guennoc, P., Coutelle, A., Lyberis, N., 1984. Discovery of a large brine deep in the northern Red Sea. Nature 310, 133–136.

Pitzer, K.S., Peiper, J.C., Busey, R.H., 1984. Thermodynamic properties of aqueous sodium chloride solutions. Journal of Physical Chemistry Reference Data 13, 1–102.

Salvinien, J., Brun, B., 1964. Mesure des coefficients de self-diffusion des constituants (ions et solvant) de solutions salines entre de larges limites de concentrations. Comptes Rendus de l'Académie des Sciences, Paris 259, 565–567.

Schoell, M., Hartmann, M., 1978. Changing hydrothermal activity in the Atlantis II Deep geothermal system. Nature 274, 784–785.

Scholten, J.C., Stoffers, P., Walter, P., Plüger, W., 1991. Evidence for episodic hydrothermal activity in the Red Sea from the composition and formation of hydrothermal sediments. Thetis Deep. Tectonophysics 190, 109–117.

Simpson. J.H., Carr, H.Y., 1958. Diffusion and nuclear spin relaxation in water. Physical Review, 1201–1202.

Turner, J.S., 1968. The behaviour of a stable salinity gradient heated from below. Journal of Fluid Mechanics 33, 183–200.

Turner, J.S., 1969. A physical interpretation of the observations of the hot brine layers in the Red Sea. In: Degens, E.T., Ross, A.D. (Eds.), Hot Brines and Recent Heavy Metal Deposits in the Red Sea. Springer, Berlin, pp. 164–173.

Turner, J.S., 1979. Buoyancy Effects in Fluids. Cambridge University Press, Cambridge, 367 p.

Whitmarsh, R.B., Weser, D.E., Ross, D.A. et al., 1974. Initial Reports of the Deep Sea Drilling Project, Vol. 23. U.S. Government Printing Office, Washington, DC.

Zierenberg, R.A., Shanks, W.C., 1986. Isotopic constraints on the origin of the Atlantis II, Suakin, Valdivia brines. Red Sea. Geochimica et Cosmochimica Acta 50, 2205–2214.