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Thermal convection in the *Atlantis II* hot brine pool*

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Abstract—It is suggested from direct measurements of vertical motions in the intermediate hot brine layer of the *Atlantis II* deep, made in 1971, that at least two types of thermal convection are active: a primary small-scale convection responsible for the warming of the layer in recent years, and a secondary large-scale cellular convection driven by non-uniform horizontal heating which maintains vertical mixing in the layer.

INTRODUCTION

THE *Atlantis II* brine pool is the largest in area ($\approx$ 60 km²) of three pools found in small deeps midway along the rift portion of the Red Sea (DEGENS and ROSS, 1969). A remarkable feature of these pools is their thermal haline structure. Very hot saline water occurs in one or more horizontally uniform, well-mixed layers separated by very sharp vertical gradients of temperature and salt. Shown in Fig. 1 are the temperature and conductometric salinity from sea surface to the bottom of the *Atlantis II* deep as reported by MUNNS, STANLEY and DENSMORE (1967) from measurements made in 1965 and 1966. Two main brine layers are apparent; a deep layer extending from about 2040 m to the bottom (which has a maximum depth of about 2170 m) and an overlying lighter, cooler, and fresher intermediate layer about 30 m thick. The transition zone between these layers is very thin, of the order of 1–2 m in thickness. Above the intermediate layer is a second transition zone, about 50 m thick, separating it from overlying normal Red Sea bottom water. The temperature and salinity structure in this zone is step-like and irregular (MUNNS, STANLEY and DENSMORE, 1967; ROSS, 1972).

It is generally believed that the *Atlantis II* pool was caused by the venting of geothermally heated brine through the bottom of the deep and there is strong evidence that this process is still active. MUNNS, STANLEY and DENSMORE (1967) reported a temperature increase of 0·5°C for the deep layer over a period of 20 months between February, 1965, and October, 1966. In February, 1971, the temperatures of the deep and intermediate layers had increased 2·7 and 5·4°C, respectively over that reported in 1966 (BREWER, WILSON, MURRAY, MUNNS and DENSMORE, 1971). The salinity of the former had not changed significantly but there was an increase of 2·2‰ in the latter. Brewer (private communication) has computed the mean net heat and salt fluxes into the intermediate layer over the period from 1966 to 1971 to be

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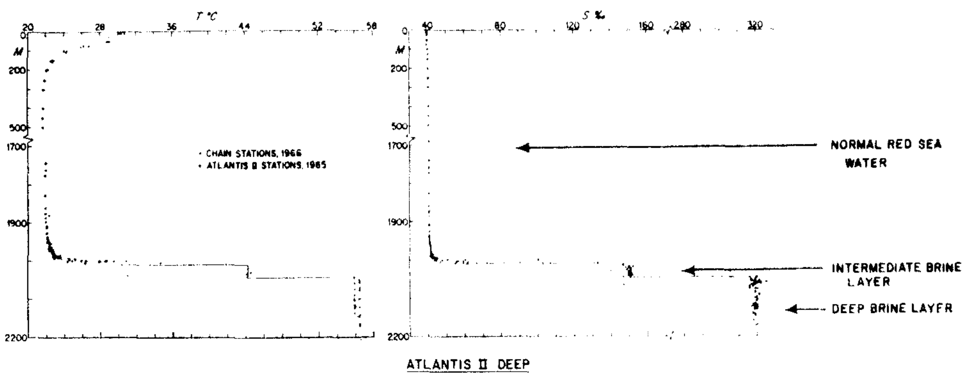

Fig. 1. Temperature and conductometric salinity as a function of depth in the *Atlantis II* deep after Munns, Stanley and Densmore (1967).

130 μcal cm^{-2}s^{-1} and 6 × 10^{-8}g cm^{-2}s^{-1}, respectively. Finally, the interface between the two layers had sharpened and risen 6–7 m, increasing the volume of the deep layer about 23%. All of this activity plus the persistence of the mixed layers within a confined deep suggests that they are maintained by thermal convection. Described here is an attempt on a cruise of *R.V. Chain* in February, 1971, to detect the convection by measuring directly vertical currents in the intermediate brine layer of the *Atlantis II* deep.

A further reason for observing the convective activity is the strong resemblance these pools have to the double diffusive systems studied theoretically and in the laboratory by numerous workers. When water with a stable salinity gradient is heated from below (Turner, 1965, 1968), a series of overlying mixed turbulent layers are formed separated by sharp diffusive boundaries. The system is maintained because the much larger molecular diffusivity of heat compared with salt allows the destabilizing heat to escape from the boundary to cause convective stirring in the layer while the salt is left behind to stabilize the boundary. The convective activity is mainly controlled by a layer stability number, $\left|\frac{\Delta\rho_S}{\Delta\rho_T}\right|$, where $\Delta\rho_T$ and $\Delta\rho_S$ are the separate contributions to the total density jump across the boundary due to temperature and salinity, respectively. The flux of heat and salt decreases as this number increases. Mancini and Loehrke (1973) suggest from their tank experiments that doubly diffusive convection ceases when the stability number exceeds a critical value for a water–salt system of around 14 or 15. For the boundary between the deep and intermediate layer in the *Atlantis II* deep this number was approximately 20 in 1971 (Brewer, private communication). Hence, it is of real interest to observe what motions do exist in the intermediate layer, which appears to be convectively stirred.

MEASUREMENT TECHNIQUE

Vertical motions in the intermediate layer were sensed with a special neutrally buoyant float using a technique developed by Webb and Worthington (1968) which works best in weakly stratified water. In normal use, such a float is ballasted to sink to the desired depth for the measurement. After it has reached its equilibrium depth, vertical water currents will continue to generate relative vertical flow past the instrument because its compressibility is less than that of the surrounding seawater. This relative flow acts on an array of tilted vanes mounted axially around the float in such a way as to rotate the float about its vertical axis. The resulting rotation is sensed relative to an internal magnetic compass and recorded internally as a measure of the vertical flow. The response of these vertical current meters, hereafter referred to as VCMs, has been discussed by Voorhis (1971).

In the Red Sea we were not able to ballast a VCM to drift freely *completely within* the 30 m thick intermediate brine layer because the *in situ* density of the layer was not known with sufficient accuracy. Instead, a double float arrangement was used as shown schematically in Fig. 2. The upper float was a 25·4-cm diameter hollow glass sphere. Suspended 15 m below this on a length of bathythermograph wire was the main instrument, a cylinder approximately 1 m in height and 15 cm in diameter, which contained batteries and the signalling and recording systems. The entire arrangement was ballasted so that it would drift with the main instrument in the middle of the intermediate brine layer suspended from the glass sphere which 'rode' on the large density gradient above the layer.

The vanes which sensed the vertical brine current are shown in Fig. 2 around the mid-length of the cylinder. The number of vanes and their pitch was such that approximately 1·2 m vertical flow of brine was required to rotate the instrument one turn. Brine temperature and pressure were also recorded internally on a chart recorder in addition to the float rotation.

Attached to the bottom end cap of the main cylinder was a 4 kHz pinger which transmitted a master and slave acoustic pulse every 4 s to the ship on the surface. The master pulse was used for locating and tracking the VCM. The time delay between

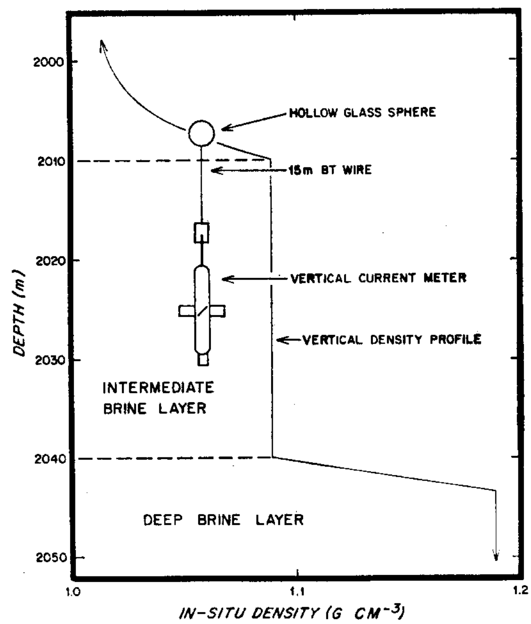

Fig. 2. Schematic diagram showing the position of the vertical meter as it drifted within the intermediate brine layer.

the master and slave was controlled by a pressure transducer in the main instrument and was used to monitor the depth of the VCM.

RESULTS

The bathymetry of the *Atlantis II* deep after ROSS, HAYS and ALLSTROM (1969) is shown in Fig. 3. The deepest part, 2170 m, is the small basin lying in the southwest sector where the deep brine layer is approximately 130 m thick. The top of the intermediate brine pool, as defined by the 2000-m depth contour, is shown by the cross-hatched area.

The VCM, after a short trial to test its response to the rather bizarre conditions of the brine pool, was launched finally over the deepest part of the pool for a drift of 83 h. Shown in Fig. 3 are the times and positions of the VCM launch and recovery as well as the location of a moored radar buoy used to navigate the ship over the rather small area of the deep.

During its drift, the VCM moved a net distance of about 3 km out of the deep basin to the east-southeast with a mean speed of close to 1 cm s^{-1}. Positions of the VCM between launch and recovery could not be obtained because the *Chain* was working in other areas of the deep. Hence, the actual drift track is unknown. The bottom depth at the position of recovery was about 2055 m and the underlying deep brine layer was only 15 m thick.

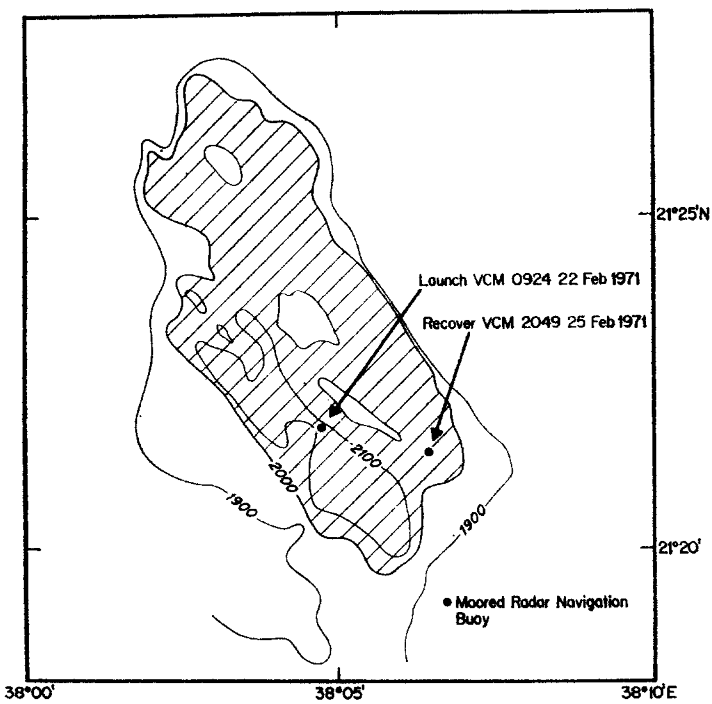

Fig. 3. The bathymetry of the *Atlantis II* brine pool after ROSS, HAYS and ALLSTROM (1969) showing the upper surface of the intermediate brine layer (cross-hatched area) and the launch and recovery position of the vertical current meter.

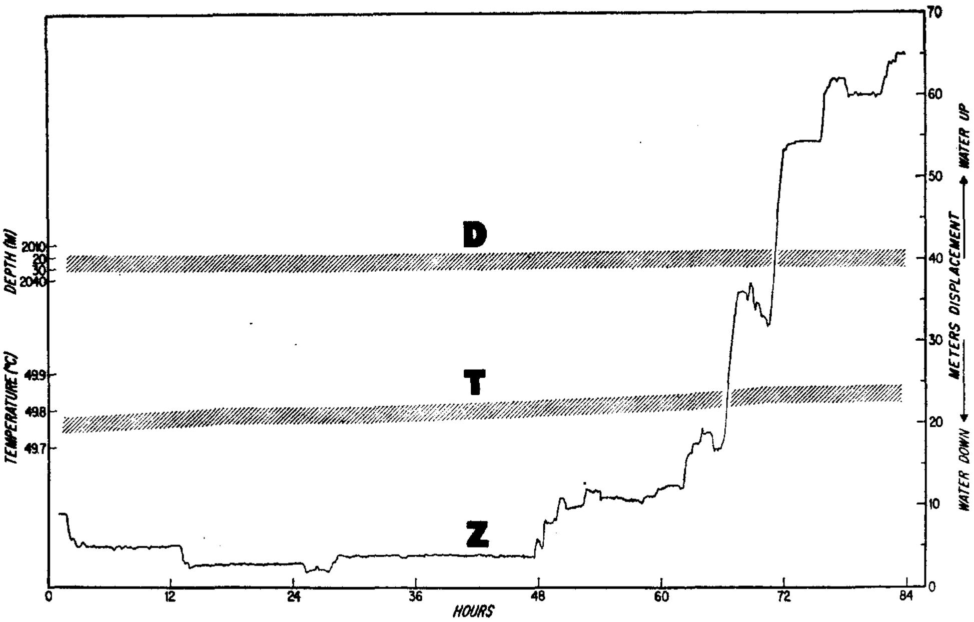

Fig. 4. Depth (*D*), brine temperature (*T*), and vertical brine displacement (*Z*) recorded by the vertical current meter during its drift.

The data recorded by the VCM as it drifted in the intermediate brine layer are summarized in Fig. 4. Shown is the instrument depth, the brine temperature, and the vertical displacement of the brine relative to the instrument as it drifted.

The mean depth of the VCM, although it decreased slightly from 2025 to about 2020 m, shows that the instrument was fairly well centered in the intermediate layer. The main temperature increased slightly by about 0·1°C during the drift. The cross-hatched width of the depth and temperature curves in Fig. 4 indicates the resolution of the measurements.

The recorded vertical brine displacement is extermely interesting and varied, roughly speaking, on at least three time scales. On the longest scale Fig. 4 shows that there is a net sinking of about 5 m of brine during the first 48 h followed by a net rising of 60 m of brine over the remainder of the drift. These displacements, however, did not occur gradually. The first 48 h is characterized by long periods of no net motion separated by small, abrupt, up and down displacements of less than 5 m. Thereafter, the brine activity increased markedly and the net flow occurred mostly in three or four large upward bursts of as much as 15 m of brine which occurred at intervals of approximately 4 h. The maximum vertical brine velocity in these bursts was about 0·5 cm s^{-1}. After a burst there was sometimes a subsidence of as much as 5 m of brine which occurred either abruptly or more gradually.

Although barely visible in Fig. 4 there were also small, high frequency brine motions which occurred more or less uniformly throughout the drift. These can be seen clearly in Fig. 5, which is a photograph of a portion of the rotation record. They appear as rapid up and down motions of amplitude less than 1 m and with a repetition rate more rapid than once every 5 min.

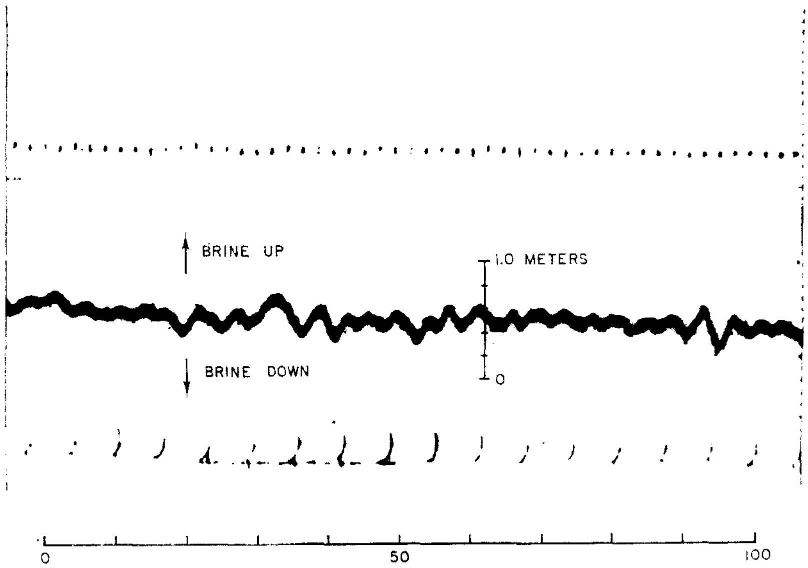

Fig. 5. Photographic enlargement of a portion of the vertical current meter record, showing small amplitude vertical brine motions.

DISCUSSION

Brine plumes

The most dramatic features of the brine activity are the abrupt vertical displacements, particularly those in the last half of the record in Fig. 4. We believe these are rising and sinking brine plumes which are generated at the lower and upper interfaces, respectively, of the intermediate pool. The upward plumes are larger because the net heating of the pool is from below. One or two of the upward plumes observed in the latter half of the record probably rose through the entire thickness of the pool (30 m).

An interesting question is whether these plumes are the dominant mechanisms responsible for heating the intermediate pool 5·4°C from November, 1966, to February, 1971. Our guess is that they are not because of the low frequency of these events in our sample. If one assumes an upward brine velocity of 0·5 cm s^{-1} (approximate observed value) in a plume at pool mid-depth, one can compute, for example, from the experimental analysis of BAINES and TURNER (1969) that the mean horizontal plume spacing, assuming steady convection, should be 1–10 m in order to convect the required net heat flux of about 100 μcal cm^{-2} s^{-1} into the pool.* Over a drift of 3 km one should expect the VCM to encounter hundreds of these plumes if they are the principal mechanisms of the heat transfer. Clearly, this did not happen. We realize, of course, that very few of these events were observed so that our statistics are poor, and perhaps biased because the currents associated with a plume could either aid or hinder the advection of our VCM into a plume.

*This is true whether these are circular or line plumes. An estimate of the temperature drop from the center of the plume to the pool environment gives 10^{-4} to 10^{-3} °C at pool mid-depth. This is clearly less than our measurement resolution.

Large-scale secondary convection

A plausible interpretation of the brine plumes is that they provide the vertical circulation in large-scale, unsteady, convection cells within the intermediate pool. The greater plume activity and increased net upward brine movement in the latter half of the record in Fig. 4 suggests that the VCM had drifted into an up-draught region of such a cell. These cells could be driven by horizontally non-uniform heating from below. Although the temperature within the intermediate pool is surprisingly uniform in the horizontal, it is not perfectly so. An examination of temperatures measured in various locations in the pool by reversing thermometers show horizontal variations of 0·1–0·2°C over distances of several kilometers. This agrees with the temperature increase in Fig. 4 over a drift distance of 3 km. The effect of non-uniform heating would be to set up convection cells (ROSSBY, 1965) within the intermediate layer with brine rising in the warmer regions and sinking in the cooler. Horizontal currents would be generated to conserve mass flow. The general motion of the brine suggests that the VCM was drifting within a single large convection cell with a horizontal scale greater than 3 km. Presumably, the vertical scale of the cell was comparable to the layer thickness, 30 m.

There are several possible causes for non-uniform heating in the intermediate layer. Probably the most important is that approximately 1/20 of its volume does not overlie the deep brine layer and is, therefore, not subject to direct heating. This is the part around the edges of the layer on the flanks of the deep. TURNER (1973) has pointed out that large-scale convection can be induced by such edge effects. It is perhaps significant that the VCM drifted towards the edge of the intermediate layer. Another possible cause for non-uniform heating is that the geothermal heat flux into the bottom of the deep pool may itself be non-uniform. There is some evidence for this from the measurements of thermal gradients in the bottom sediments (ERICKSON and SIMMONS, 1969).

It can be argued that the magnitude of the VCM drift speed is additional evidence for large-scale convection motions. If the observed motion is not due to convection, one might assume it was caused either by horizontal pressure gradients or by frictional drag induced by motions in the overlying Red Sea bottom water. In either case, one can argue that an induced net speed of 1 cm s^{-1} over 83 h is unrealistically large for a small confined region in a deep which is isolated from above by an extremely large density contrast. The expected coupling due to pressure gradients has been estimated by P. Rhines (personal communication). The ratio of brine speed to the overlying bottom water speed is given approximately by $(L/L_p)^2$ where L is the horizontal scale of the bottom water motion and

$$L_p = \frac{1}{f}\left(g\,\frac{\Delta\rho}{\rho}\,H_p \right)^{\frac{1}{2}}$$

is a Rossby radius of deformation for the brine pool.

Here f is the local Coriolis parameter, g acceleration due to gravity, $\Delta\rho/\rho$ the fractional density decrease from brine to normal water, and H_p the pool depth. For the *Atlantis II* brine pool one finds that $L_p \approx 200$ km. On the horizontal scale of the pool, approximately 10 km, one requires geostrophic motions with speeds of the order of 400 cm s^{-1} in the overlying bottom water to induce the observed drift speed. This seems unreasonable. The effect of frictional drag is more difficult to assess. A rough calculation indicates that the thickness of the transition zone above the brine pool is of the order of ten times the vertical scale of the Ekman frictional boundary layer. This suggests that the pool is pretty well isolated from motions above.

Small-scale primary convection

If the brine plumes are not the primary convectors of heat, what is? It is our belief that the bulk of the upward heat flux is carried by small-scale motions which, although poorly resolved, generated the small vertical displacements seen in Fig. 5 throughout the drift of the VCM. This record suggests that the intermediate pool is rather densely filled with thermally driven turbulence having a length scale of the order of a meter which generates small sinking and rising motions with speeds less than 1 cm s^{-1}. The turbulent elements could be similar, except for scale, to the ribbon-like thermals which rise from a heated horizontal surface as observed by SPARROW, HUSAR and GOLDSTEIN (1970).

If the above picture is true it is intriguing to speculate as to why the primary convecting scale is so small. One might expect the heat flux through the rather uniform interface at the bottom of the layer to be carried by a statistically steady spectrum of motions having scales from a few millimeters up to the thickness of the layer (30 m). Yet, there are periods of 12 h or more during the first half of the drift when no vertical brine displacements over 20–30 cm were observed. The answer may lie in the very large stability ratio between the intermediate and deep layer. Although destabilizing heat does escape through the lower boundary, there may be simply too much salt from the deep layer to allow convecting elements to coalesce beyond a certain size as they sweep brine from the boundary and rise into the layer.

The above picture is meant to be suggestive, and further measurements with smaller sensors having a faster time response are required before the origin of the small fluctuations is determined. An alternative explanation, for example, to the one we have given is that these fluctuations are caused by internal waves propagating along the large density gradients separating the brine layers. ERICKSON and SIMMONS (1969) suggest this as an explanation for temperature fluctuations of similar period observed by them within the deep layer. The minimum possible internal wave period is determined by the buoyancy gradient between layers and is of the order of 6–15 s, beyond our resolution. Simple theory indicates that free internal waves with periods similar to that resolved in Fig. 5, that is, from 2 to 5 min, have wave lengths from 600 to 2000 m. The brine density interfaces, with these wavelengths would have to move vertically about 2 m to generate the observed *relative* displacement of 20 cm at the VCM, with the arrangement in Fig. 2. It is difficult to find convective processes within the brine pool with sufficient energy on this scale to produce such displacements. High frequency processes outside of the pool can be ruled out because of the weak stratification of the overlying Red Sea bottom water.

CONCLUSIONS

Our data suggest that at least two convective processes occur in the intermediate brine layer of the *Atlantis II* deep. Most of the vertical heat flux is transported by small-scale (1 m or less) thermal turbulence throughout the layer which was poorly resolved by our instrumentation. It was suggested that the maximum scale for this turbulence is limited by the large stability of the density boundary between the intermediate and the deep layers. Superimposed on this small-scale process are large horizontal scale (3 km or more), unsteady, convection cells. The vertical flow in these cells occurs in the form of intermittent plumes which can penetrate the full depth of the layer. This large-scale convection is probably generated by non-uniform heating around the flanks of the brine pool where the intermediate layer does not overlie the deep layer.

It is interesting to speculate on the role of the large-scale convection. Because of the large layer stability number between intermediate and deep layers, discussed in the introduction, we suggest that it is responsible for vertical mixing in the intermediate layer. Or, to put it another way, it is a new scale of motion required to maintain doubly diffusive convection when the layer stability becomes large.

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REFERENCES

BAINES W. C. and J. S. TURNER (1969) Turbulent buoyant convection from a source in a confined region. *Journal of Fluid Mechanics*, 37, 51–80.

BREWER P. G., T. R. S. WILSON, J. W. MURRAY, R. G. MUNNS and C. D. DENSMORE (1971) Hydrographic observations on the Red Sea brines indicate a marked increase in temperature. *Nature*, 231, 37–38.

DEGENS E. T. and D. A. ROSS (1969) *Hot brines and recent heavy metal deposits in the Red Sea*, E. T. DEGENS and D. A. ROSS, editors, Springer-Verlag.

ERICKSON A. J. and G. SIMMONS (1969) Thermal measurements in the Red Sea hot brine pools. In: *Hot brines and recent heavy metal deposits in the Red Sea*, E. T. DEGENS and D. A. ROSS, editors, Springer-Verlag, pp. 114–121.

MANCINI T. R. and R. I. LOEHRKE (1973) Layered double-diffusive convection of heat and salt. Department of Mechanical Engineering, Colorado State University. (Unpublished report.)

MUNNS R. G., R. J. STANLEY and C. D. DENSMORE (1967) Hydrographic observations of the Red Sea brines. *Nature*, 214, 1215–1217.

ROSS D. A., E. E. HAYS and F. C. ALLSTROM (1969) Bathymetry and continuous seismic profiles of the hot brine region of the Red Sea. In: *Hot brines and recent heavy metal deposits in the Red Sea*, E. T. DEGENS and D. A. ROSS, editors, Springer-Verlag, 82–97.

ROSS D. A. (1972) Red Sea hot brine area revisited. *Science*, 175, 1455–1457.

ROSSBY H. T. (1965) On thermal convection driven by non-uniform heating from below: an experimental study. *Deep-Sea Research*, 21, 9–16.

SPARROW E. M., R. H. HUSAR and R. J. GOLDSTEIN (1970) Observations and other characteristics of thermals. *Journal of Fluid Mechanics*, 41, 793–800.

TURNER J. S. (1965) The coupled turbulent transports of salt and heat across a sharp density interface. *International Journal of Heat and Mass Transfer*, 8, 759–767.

TURNER J. S. (1968) The behavior of a stable salinity gradient heated from below. *Journal of Fluid Mechanics*, 33, 183–200.

TURNER J. S. (1973) *Buoyancy effects in fluids*, Cambridge University Press, Chapter 8.

VOORHIS A. D. (1971) Response characteristics of the neutrally buoyant float. *Technical Report. Woods Hole Oceanographic Institution*, Ref. 71–73. (Unpublished manuscript.)

WEBB D. C. and L. V. WORTHINGTON (1968) Measurements of vertical water movement in the Cayman Basin. *Deep-Sea Research*, 15, 609–612.