Reports

Red Sea Hot Brine Area: Revisited

Abstract. *A return expedition to the hot brine area of the Red Sea in 1971 found that the temperature of the brine had increased, indicating that the process that formed the underlying deposits rich in heavy metals is still occurring. About 0.346 cubic kilometers of water having a minimum temperature of 104°C has been added over the last 52 months. Calculations suggest that this water may have come from a relatively shallow depth; this result coupled with the fact that fracture zones are found north and south of the brine area indicates a relatively local source for the brine, rather than the Strait of Bab el Mandeb, as previously suggested.*

In March 1971 we returned on the R.V. *Chain* to the hot brine area of the Red Sea for a continuation of our previous studies (*1*). This area is unique in that hot, saline water (up to 56.5°C and 257 per mil salinity) was found in three deeps in the central rift portion of the sea. The deeps, Discovery, Atlantis II, and Chain, were named after the ships from which the initial discoveries were made (*2, 3*). The sediments underlying the hot brine are unusually enriched in heavy metals, such as copper, zinc, lead, and silver; the in situ value of the sediments underlying the Atlantis II Deep has been estimated at over $2 billion (*4*).

Continuous measurements of temperature and depth made in 1966 showed two distinct high-temperature water layers in the Atlantis II and Discovery deeps (*5*). In the Atlantis II Deep the upper layer had a temperature of 44.3°C and the lower 56.5°C. In 1965 the temperature of the lower layer was 55.9°C (*3, 6*); thus, there was reason to suspect that the temperature might be slowly increasing (specifically, an increase of 0.58°C in 20 months or 0.029°C per month). This increase in temperature is related to the origin of the brines. Although there is still some debate, it is generally thought that the brines are due to geothermally heated Red Sea water (*7*) being discharged into the Atlantis II Deep. Past overflows have spilled into the Discovery and Chain deeps. In 1971 the temperature of the lower layer in the Atlantis II Deep had increased from 56.5° to 59.2°C [2.7°C in 52 months, or 0.052°C per month, about a 1.8-fold increase in rate (*8*)]. An increase of about 0.08°C was observed over a 20-day period in March 1971, which suggests that an even higher rate of increase (0.12°C per month) may be typical of present conditions (*9*).

The general shape of the curves obtained by plotting temperature against depth for measurements made during 1966 and 1971 has also changed (Fig. 1). In this period (i) the level of the lower, hotter water rose 7 m; (ii) the separation between the upper and lower water masses decreased from 5 to 2 m; (iii) the temperature of the upper water unit increased from 44.3°C to about 49.7°C and is even higher near the bottom of the unit; and (iv) the temperature structure in the zone between the upper layer and the overlying normal Red Sea water (about 22°C) is presently more irregular. The first three points indicate a large and perhaps continuous input of hot, saline water. The salinity of the upper water increased slightly (*10*), whereas no salinity increase was noted in the lower (59.2°C) water. A simple calculation shows that the minimum input temperature of the brine is about 104°C (*11*). The increase of 7 m in the lower water level is equivalent to an input of about 0.346 km^3 of water or a 23 percent increase in the volume of the lower water unit. An input of 0.346 km^3 over 52 months is equivalent to about 2.6 m^3/sec or about 700 gallon/sec. For comparison, Old Faithful Geyser in Yellowstone National Park discharges about 10,000 to 12,000 gallons of water every 66 minutes, or about 1/200 of the Red Sea flow.

The presence of two well-mixed water layers separated by a sharp interface is characteristic of liquids stabilized by salt but made unstable by heating from below (*12*). The increase in heat in the water at 49.7°C has occurred mainly by diffusion from the water at 59.2°C;

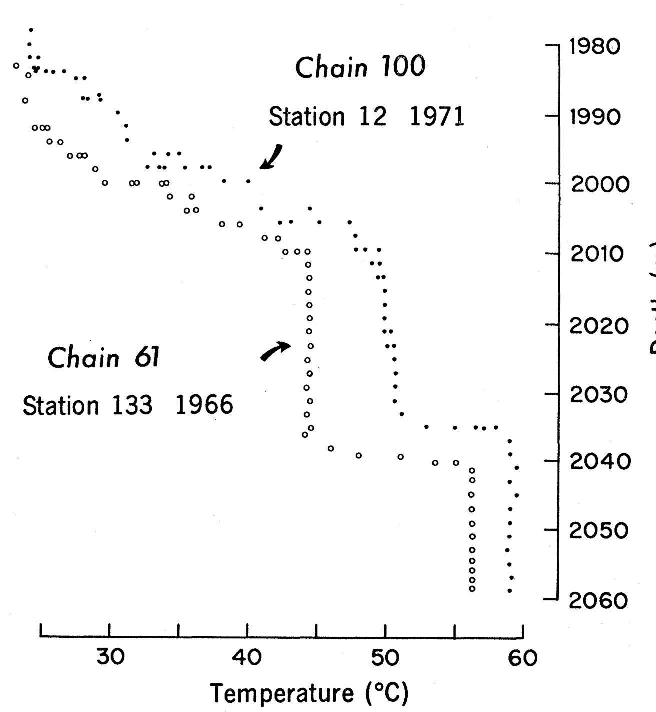

Fig. 1. The 1966 and 1971 temperature measurements made in the Atlantis II Deep. Both sets of measurements were continuous readings of temperature by means of a temperature telemetering acoustic device (*5*). The exact values of temperature were confirmed by conventional hydrographic techniques. The small temperature variations in the water at 59°C are probably instrumental in origin; temperatures measured by high-precision reversing thermometers indicated a more uniform temperature structure.

convection within each layer tends to remove the smoothing effects of diffusion at their contact. The increased irregularity in the water temperature between the upper layer and the normal Red Sea water may be indicative of internal wave activity.

From what depth below the surface are the brines originating? From the normal geothermal gradient of the deep sea (0.06°C per meter for a heat flow of 1.5 μcal/cm^2 sec) or a temperature gradient more typical of the Red Sea rift valley [0.16°C per meter for a heat flow of 4 μcal/cm^2 sec (*13*)], the calculated input temperature of the brines (104°C), and the water temperature at the bottom of the Red Sea (22°C), the depth at which the hot water originated can be estimated. The depths calculated with the two temperature gradients are about 1300 and 500 m, respectively; the lower value, based on the temperature gradients of Red Sea sediment, is the more probable. A calculation of this type is, of course, subject to numerous assumptions. For example, the geothermal gradient within basalts, for a similar heat flow, would be lower—perhaps only a third as high—because of the higher conductivity of the basalt. Thus, if the flow is in basalt, water at 104°C would be expected (from the conductive gradient) at a depth closer to 1500 m. In addition, in a convective system the above temperature could occur at shallower or deeper depths, depending on the characteristics of the system. The possibility that the brines originate at a relatively shallow depth presents some difficulties for the hypothesis that the source of the brine is at the Strait of Bab el Mandeb, 1000 km south of the brine area. The strait, at a depth of about 120 m, is the sill for the Red Sea. Between Bab el Mandeb and the brine area are numerous fracture zones (*14*); some of them cross and offset the central rift valley; others may extend across almost the entire Red Sea. The exact depth to which these fracture zones extend is unknown, but it is reasonable to assume that they extend at least throughout layer 2, which is generally at least 4 km below the surface in the Red Sea (*15*). If the brine originated at the Strait of Bab el Mandeb, it would indeed involve a complicated plumbing system for it to bypass or transit the numerous fracture zones between the strait and the known brine area. If the brines do travel at depths below the fracture zones, then considerable heat must be lost prior to discharge in the brine area.

The hypothesis that the Bab el Mandeb area is the source for the brine is largely based on the work of Craig (*7*), who noted that the present salinity at the strait (38.2 per mil) corresponds to the original salinity of the brine, as indicated by oxygen and deuterium isotope studies. Degens and Ross (*16*) have noted a cyclicity of increased activity in the brine area—twice within the last 25,000 years the Atlantis II Deep has overflowed. These overflows took place about 5000 years after a period of high salinity was abruptly followed by a rapid decrease in salinity in the entire Red Sea. The decreased salanities were caused by a rising sea level (due mainly to melting of Pleistocene glaciers and possibly to some local tectonic movements), which reestablished the normal water exchange between the Indian Ocean and the Red Sea. Before this reestablishment of circulation the Red Sea level had dropped because of evaporation to a fraction of its former size (*16*), and the above suggested source of the brine or any other possible source on the shelf or slope would have been well above sea level. With rising sea level a source area would have been submerged and the flow of the brine could again start. However, incoming Indian Ocean water (salinity of about 36.5 per mil) mixed with small amounts of more saline Red Sea water would dominate in the shallow areas of the Red Sea. It is almost impossible to determine what the salinities of any specific area were 5000 years ago. Likewise, the present salinity of any specific area probably bears little relationship to its salinity at the time when the connection between the Indian Ocean and the Red Sea was first reestablished. Thus, almost any shallow area could have had a salinity of 38.2 per mil at that time. Because flow into the brine area is proceeding at present, the calculated salinity value of 38.2 per mil just represents an average input into the brine area over the last several thousand years.

It seems more reasonable to me to assume a more local source, perhaps along the shallow areas of the Saudi Arabian or Sudanese coasts, especially since a survey made on the 1971 cruise showed distinct bathymetric and magnetic patterns indicating displacements of the central rift valley in the hot brine area (*17*). These displacements, probably fracture zones, structurally isolate the brine area and may explain why the present brine area is found in such a relatively small region of the sea floor. The relationship of the hot brine deposits to recent sea-floor spreading in the Red Sea is compelling.

Sediment deposits enriched in iron and copper were also found on the eastern flank of the rift valley, buried below several meters of normal calcareous sediments. These deposits indicate ancient brine activity.

The main implications of the above studies are that the deposition of these potential ore deposits is a dynamic process that is still occurring and that similar, older deposits may be found. Indeed, cores from holes drilled along the Atlantic continental margin of the United States (*18*) contain deposits similar to those of the Red Sea.

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References and Notes

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9. Measurements by Brewer *et al.* (*8*) in the latter part of February 1971 indicated an average temperature of 59.21°C, while our measurements in early March averaged 59.29°C. There is a possibility that the increase may not be real since only two measurements were made in March (ten were made in February with none over 59.24°C) and the accuracy of our thermometers is about ± 0.05°C.
10. The conductometric salinity of the water at 49.7°C has increased from 151.5 to 154 per mil, which is equivalent to an increase in true (gravimetric) salinity of 2.2 per mil (*8*).
11. An estimate of the temperature increase can be made from the following relationship:
$$t = [(\theta_L' C_L V_L' + \theta_U' C_U V_U') - (\theta_L C_L V_L + \theta_U C_U V_U)]/C_L V''$$
where t is the temperature of the incoming water, θ is the temperature of the water, the subscripts U and L indicate the upper and lower water units, the superscript ′ indicates the present condition, V is the volume of the water unit, V'' is the volume of the new water added ($V + V'' = V'$), and C is the specific heat of the brine units. For estimates of specific heat, Brewer *et al.* (*8*) have extrapolated the results of Gucker and Rubin [F. T. Gucker, Jr., and T. R. Rubin, *J. Amer. Chem. Soc.* **57**, 78 (1935)] for sodium chloride solutions and those of Bromley *et al.* [L. A. Bromley, W. S. Gillan, F. H. Coley, *J. Chem. Eng. Data* **12**, 202 (1967)] for sea water and obtained values of 0.86 for the upper water and 0.80 for the lower, more saline water. Solution of the above equation indicates a minimum input temperature of 104°C. In this calculation it is assumed that (i) no heat is lost to surrounding rocks, sediments, or water; (ii)

no water escapes to yet undiscovered deeps; and (iii) no heat is being supplied other than that of the incoming water. Since the first assumption is probably incorrect the 104°C is clearly a minimum value. Brewer *et al.* (*8*) made a similar calculation based on changes in water depth rather than volume and estimated a minimum value of the input brine temperature as 113°C. B. Fournier (personal communication) estimates an input temperature of about 120°C based on the SiO_2 content of the brine.
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19. The 1971 expedition to the Red Sea was sponsored by the U.S. Geological Survey as part of its regional mineral program that is being conducted on behalf of the Saudi Arabian Ministry of Petroleum and Mineral Resources. Many people participated in the expedition and supplied data that are used in this report. In particular, I would like to thank Stanley Abbot, Gordon Andreasen, Ameen Basalamah, Peter Brewer, Alan Driscoll, Robert Fournier, John Hackett, John C. Hathaway, Ali Kettani, J. B. Lassiter III, Donald Mabey, John Mahoney, F. T. Manheim, J. D. Milliman, R. Munns, Thomas O'Brien, A. J. Petty, Roger Searle, Earl Young, Robert Young, and the officers and crew of R.V. *Chain*. K. O. Emery, A. J. Erickson, and J. R. Heirtzler reviewed this manuscript. Woods Hole Oceanographic Institution contribution 2783.

5 January 1972; revised 11 February 1972 ■

Magnetic Noise Preceding the August 1971 Summit Eruption of Kilauea Volcano

Abstract. *During the course of an electromagnetic survey about Kilauea Volcano in Hawaii, an unusual amount of low-frequency noise was observed at one recording location. Several weeks later an eruption occurred very close to this site. The high noise level appeared to be associated in some way with the impending eruption.*

During July 1971, we made an electromagnetic survey of the summit area of Kilauea Volcano, Hawaii, to study the internal structure of the volcano.

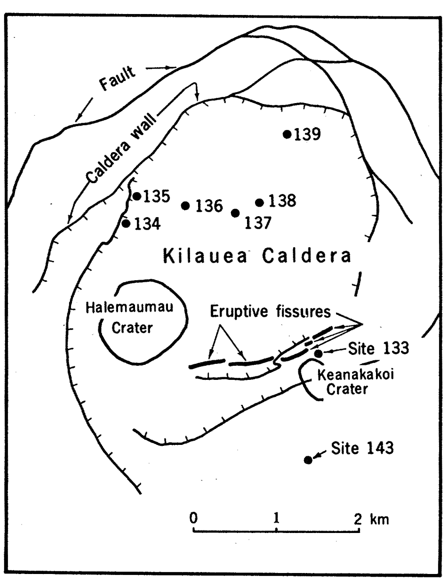

Fig. 1. Map of the summit of Kilauea Volcano showing the location of the eruption of 14 August 1971 and several sites at which electromagnetic field records were made. Other recording sites lie off the map, and site 133 was the only location at which the unusual magnetic noise was recorded. Caldera faults are as indicated by Peterson (*1*).

In so doing, we generated an electromagnetic field by passing current steps through a long grounded wire located several kilometers northwest of Kilauea Caldera. We detected the electromagnetic field by recording the voltage output from a coil of wire lying on the ground. From these measurements, the electrical conductivity distribution of the rocks within the caldera and to the south and west was mapped. Typically, the coil of wire consisted of 26 turns, with a perimeter of 305 m. On the afternoon of 22 July, we attempted to record the electromagnetic field at a site on the north lip of Keanakakoi Crater, a crater which is located only a few hundred meters from the southern rim of Kilauea Caldera (Fig. 1). However, we found that the coil produced relatively large background noise voltages, amounting to several tens of microvolts at frequencies less than 0.1 hz (Fig. 2A). The noise level was higher by at least an order of magnitude than that which had been observed at any of the preceding 32 recording sites (see Fig. 2B for an example), and the attempt to obtain a record was abandoned. At that time, we felt that the high noise level was caused by a faulty recording system.

On the next day, however, the survey was resumed with observations being made successfully at several additional recording sites before we returned to the Keanakakoi site. Again, we recorded a high level of noise characterized by a long period. It was then evident that this noise was characteristic of the site and not an instrument fault. However, no further effort was made to explain the phenomenon.

Twenty-three days later, on 14 August Kilauea Volcano erupted close to the Keanakakoi recording site (*1*). Lava fountained from a series of fissures along a 60°N–70°E trend extending from near the southeastern edge of Halemaumau Crater toward Keanakakoi Crater (Fig. 1). The Keanakakoi recording site (site 133) lies about 150 m from the closest fissure. The next closest recording site (site 143) lies almost 1.5 km south of the fissures. It is difficult to escape the impression that the unusually high noise level at recording site 133 was in some way associated with the impending eruption.

As with any fortuitous observation of this sort, the association cannot be very convincing unless some reasonable explanation can be put forward. One explanation would be that slow movement of magma into the incipient fissure zone would generate magnetic noise because the magma would behave as conductive material moving in the earth's magnetic field. In fact, a relatively high level of seismic activity had been ob-

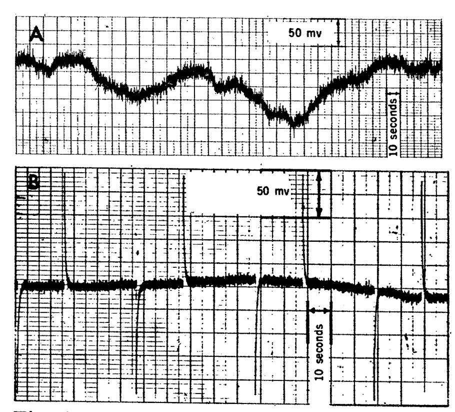

Fig. 2. Sections of records of the voltage produced from a vertical-axis induction loop with an effective area of 151,000 m^2. (A) At recording site 133, on the edge of Keanakakoi Crater. The record was obtained at approximately 1530 hours H.S.T., 22 July 1971, and exhibits an unusually high noise level. (B) At recording site 115, on 16 July 1971. This record shows typical background noise levels. The spikes with alternating polarity are the transient electromagnetic signals transmitted from the grounded-wire source and are not related to the phenomenon being discussed here.