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The Galapagos Spreading Centre: Bottom-Water Temperatures and the Significance of Geothermal Heating*

Robert S. Detrick, David L. Williams, John D. Mudie and John G. Sclater

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Summary

A detailed survey of bottom-water temperatures was conducted over a portion of the Galapagos spreading centre near 0° 48′ N, 86° 10′ W. A complex bottom-water temperature structure exists here with large thermal gradients both vertically and horizontally. Despite very detailed temperature measurements 50–200 m above the sea floor, no local temperature anomalies were observed which could be attributed to hydrothermal circulation. However, temperature measurements made less than 10 m from the bottom revealed local temperature anomalies of several hundredths °C which may have been caused by hydrothermal activity. The high geothermal heat flux associated with the Galapagos spreading centre is an important factor causing bottom-water renewal in the Panama Basin. Slightly higher regional bottom-water temperature observed near the Galapagos spreading centre may also be caused by geothermal heating.

Introduction

In plate tectonics oceanic crust is created by the intrusion of hot, molten magma which cools and contracts as it moves away from the centre of spreading. The mechanism by which this heat is released appears to be primarily a combination of conductive heat transfer and hydrothermal circulation (Langseth & Von Herzen 1971; Lister 1972; Williams & Von Herzen 1974; Williams 1974). Substantial amounts of heat are released during the spreading process. Simple calculations indicate that the total thermal output of a ridge spreading at 35 mm/yr is about 1100 cal s^{-1} cm^{-1} along the length of ridge crest or about 3.5×10^{10} cal/yr per cm of ridge length (Williams *et al.* 1974). While this is a substantial amount of heat very little is known about its effect on bottom-water temperatures.

This paper presents the results of a detailed bottom-water temperature survey of a portion of the Galapagos spreading centre. The purpose of this study was to determine the effect of geothermal heating on bottom-water temperatures at an active spreading centre. We were particularly interested in identifying bottom-water temperature anomalies which might be indicative of hydrothermal circulation. Close to 100 000 individual temperature readings were taken in a small area on the Galapagos spreading centre near 0° 48′ N, 86° 10′ W and along a roughly N–S line from

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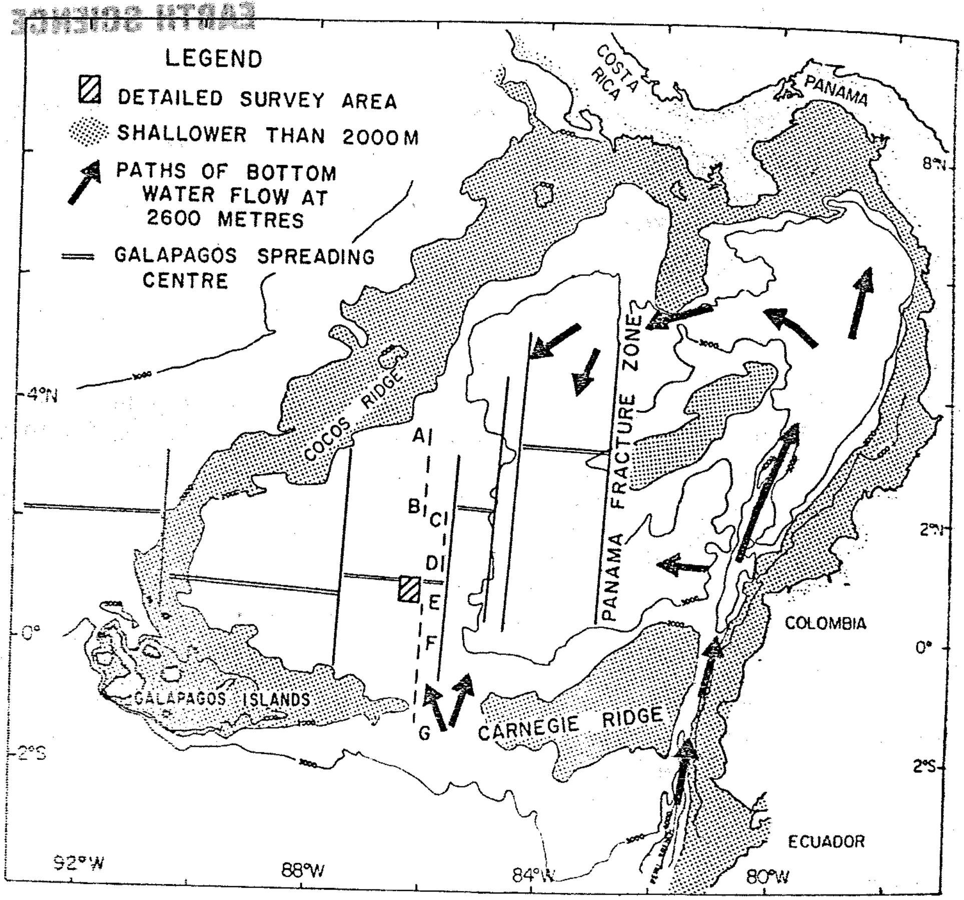


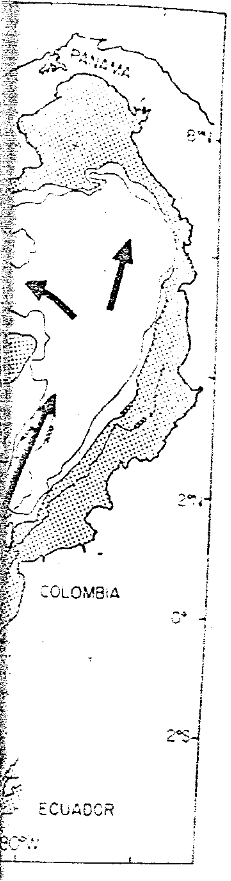
Fig. 1. Panama Basin showing location of detailed survey area on the Galapagos spreading centre. Labelled dashed lines indicate location of temperature profiles in Fig 6. Contours in uncorrected metres from van Andel *et al.* (1971). Paths of bottom-water flow from Laird (1971) and Lonsdale & Malfait (*in press*).

the equator to 3° N (Figs 1 and 2). This work was part of a near-bottom geophysical study and heat-flow survey of the Galapagos spreading centre near 86° W (see companion papers: Klitgord & Mudie 1974; Sclater *et al.* 1974; Williams *et al.* 1974).

Instrumentation

Three different techniques of measuring bottom-water temperatures were employed in this study:

Vertical temperature profiles were measured at all heat-flow stations of Scripps Institution of Oceanography (SIO) and Woods Hole Oceanographic Institution (WHOI). The thermistor sensors used in the SIO instruments have an absolute accuracy of ±0·01 °C and a relative accuracy of ±0·005 °C (Chung *et al.* 1969) while those in the WHOI instruments have an absolute accuracy of ±0·01 °C and a relative accuracy of ±0·003 °C. All these thermistor probes have thermal time-constants of only a few seconds. Location of station positions was accomplished by a combination of satellite navigation, acoustic transponders and dead reckoning (see Williams *et al.* 1974). The water depth at each station was determined either from a surface ship echo-sounder or from a deep-tow bathymetry chart for this area (Klitgord & Mudie 1974). The height of the instrument above the bottom was measured



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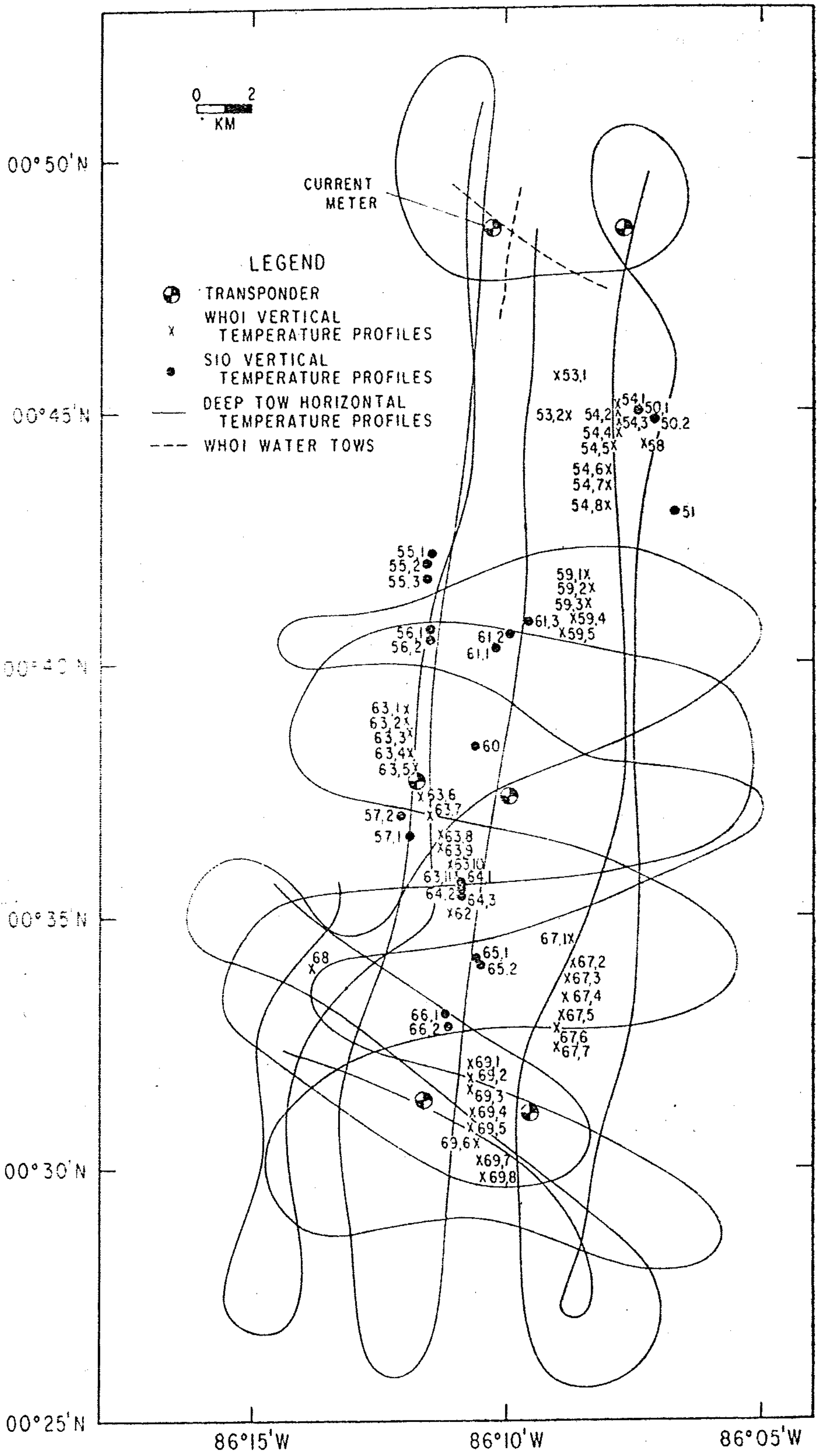


FIG 2. Detailed survey area showing location of SIO and WHOI vertical temperature profiles, WHOI water tows and deep-tow track coverage.

in all cases with an acoustic pinger attached either to the probe (WHOI) or about 100 m above the probe (SIO). The uncertainty in the depth data depends on the accuracy of the bathymetry and navigation at each station as well as the height of the probe above the bottom. Generally, the overall error in depth is probably less than 20 m, although it may be as great as 100 m.

Horizontal temperature profiles close to the sea floor were obtained by two different methods. The Marine Physical Laboratory's near-bottom geophysical instrument package (Spiess & Mudie 1970; Spiess & Tyce 1973) is equipped with an oscillating quartz crystal temperature probe which has a relative accuracy of 0·001 °C, an absolute accuracy of 0·005 °C and a thermal time constant of about 5 s (Detrick 1972; Spiess & Tyce 1973). An up-and-down-looking sonar system on the instrument package and an acoustic-transponder navigation system determine the depth of the probe to within 2 m and the relative position to within 20 m. Throughout a 10-day geophysical survey of the Galapagos spreading centre, temperatures were taken every 10 s at heights generally ranging between 50 and 200 m above the sea floor. Two additional horizontal temperature profiles, generally less than 10 m above the sea floor, were obtained using a modified WHOI heat-flow instrument described by Williams *et al.* (1974).

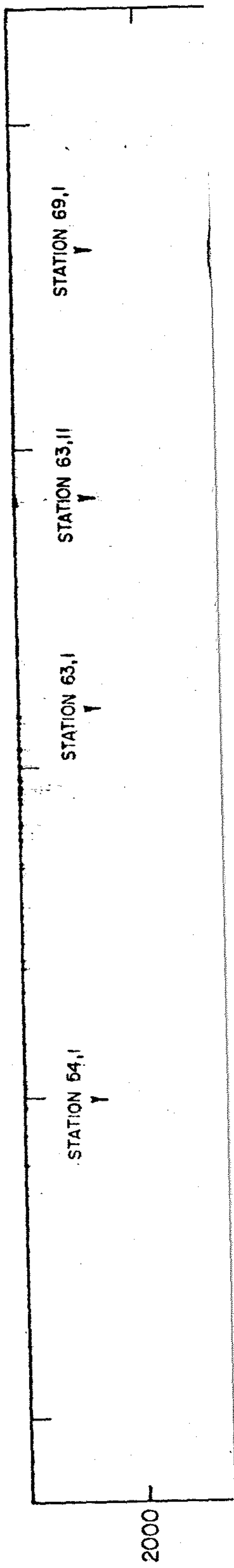
All three instruments were independently calibrated and the relative error between the thermistors was less than 0·02 °C. These temperatures agree to within ±0·01 °C with bottom-water temperatures compiled by the National Oceanographic Data Centre from Nansen bottle casts in this area. All temperatures presented in this paper are potential temperatures, calculated from *in situ* temperatures using the equation of Fofonoff (1962) and assuming a constant salinity of 34·7 per mil for abyssal waters of the Panama Basin (Laird 1971).

Bottom-water temperatures

Galapagos spreading centre

Closely spaced, vertical temperature profiles near the Galapagos spreading centre indicate the presence of a complex bottom-water temperature structure with steep thermal gradients both vertically and horizontally (Figs 3 and 4). A well-stratified mass of water with thermal gradients ranging from 0·025 to 0·040 °C/100 m overlies a more homogeneous layer with very small thermal gradients (0·003–0·012 °C/100 m). Separating these two layers is water with relatively large thermal gradients (0·060–0·110 °C/100 m). This deep thermocline extends over the entire detailed survey area (0° 30′ N–0° 48′ N). It is between 70 and 160 m thick and is somewhat deeper on the ridge flanks (2400–2500 m) than at the ridge crest (2200–2300 m). In the immediate vicinity of the ridge crest it is consistently 100–150 m shallower on the northern edge of the ridge. There is considerably less variation in the depth of this thermocline parallel to the ridge crest. Individual potential temperature isotherms usually vary less than 50 m in depth over the width of the survey area. In general, the depth of the thermocline appears to be significantly influenced by the underlying topography, resulting in a local shallowing of potential temperature isotherms in the immediate vicinity of the ridge crest and relatively little variation in the depth of isotherms parallel to the ridge crest.

A free-vehicle current meter (Isaacs *et al.* 1966; Schick, Isaacs & Sessions 1968) deployed near the ridge crest (Fig. 2) indicated the presence of strong, partially tidally induced currents. The meter was located about 185 m above the sea floor within the thermocline described above. Twenty-three days of readings were obtained and over this period there was a net northward flow of water at 2·4 cm s^{-1} (Fig. 5). Superimposed on this general northward flow was a strong, semi-diurnal tidal component oriented primarily E–W, parallel to the ridge crest, resulting in



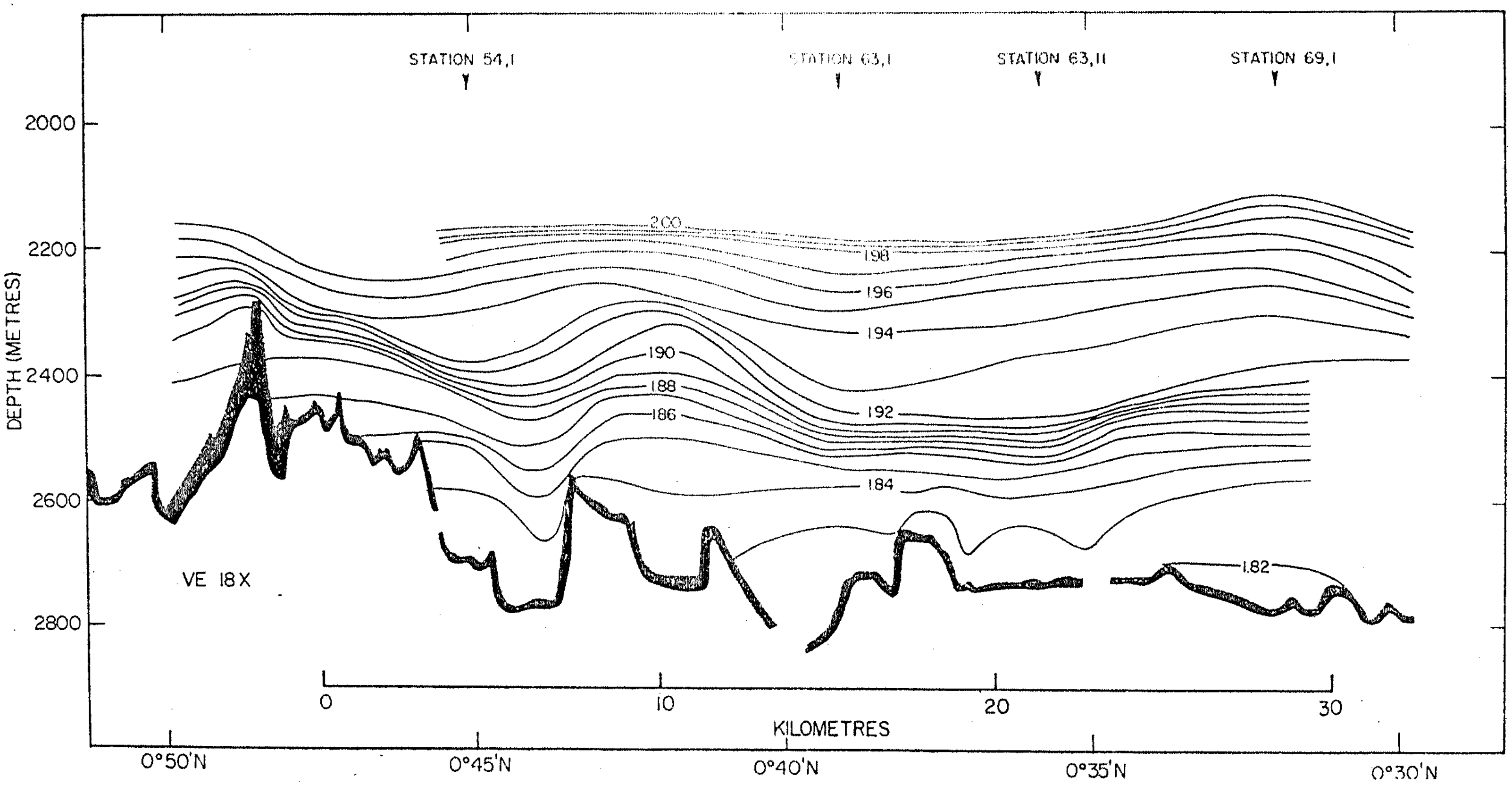


FIG 3. Potential temperature isotherms along a N–S section within the detailed survey area. Compiled from 71 vertical temperature profiles and extensive horizontal temperature measurements in this area (see Fig 2). Individual data points are not shown. Temperatures at the four labelled stations are plotted versus depth in Fig 4. Bathymetry taken from near-bottom observations in this area. Distance in kilometres is from the inferred centre of spreading (Klitgord & Mudie 1974).

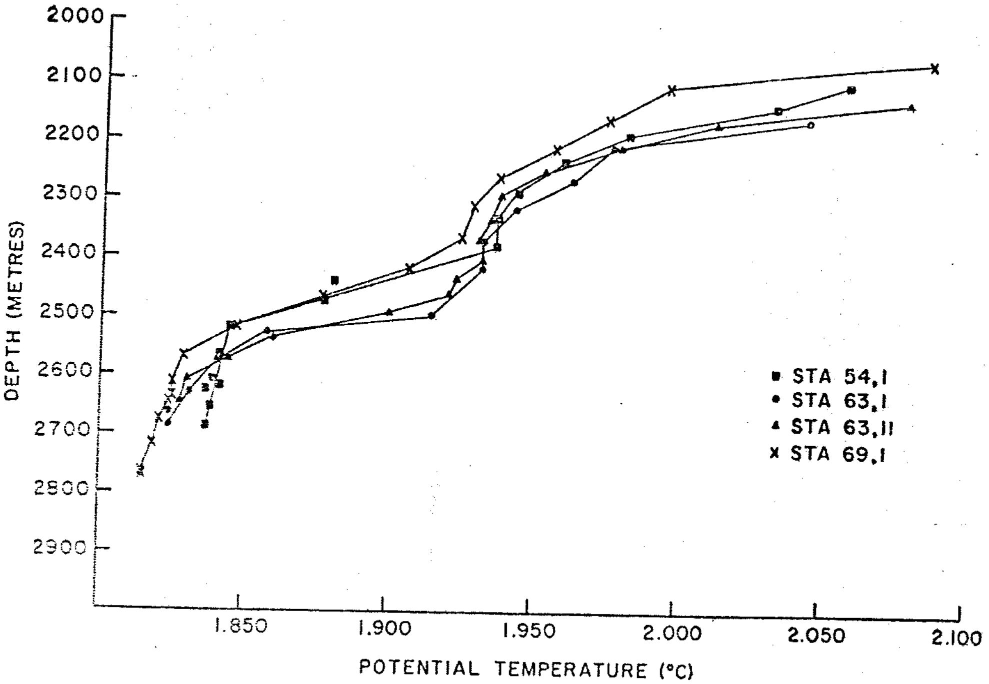


FIG 4. Potential temperature versus depth at various distances from the ridge crest. Location of individual stations shown in Figs 2 and 3. Note layered water structure and the presence of a deep thermocline between 2400 and 2550 m.

current directions that generally varied between NW and NE. The tidally induced currents averaged about 4·5 cm s^{-1}, over twice the average non-tidal flow. Total current velocities in excess of 20 cm s^{-1} and tidally induced currents as great as 9 cm s^{-1} were measured over periods of several hours near the ridge crest. Significant, non-tidal variations in current direction were also observed over periods up to several days in length (e.g. between the first and fourth day of the record).

Despite very detailed temperature measurements, 50–200 m above the sea floor, no temperature anomalies were observed which could be attributed to hydrothermal circulation. However, temperature measurements made less than 10 m from the bottom revealed water temperature anomalies of several hundredths °C which may have been caused by hydrothermal activity (see discussion in Williams *et al.* 1974). The absence of any large temperature anomalies more than a few metres above the sea floor is not entirely unexpected since normal dilution, aided by the strong currents and topographically disturbed flow near the Galapagos spreading centre, will rapidly disperse any heat released by hydrothermal activity. Temperature measurements within a few metres of the sea floor are apparently necessary in order to detect these temperature anomalies before they are dissipated.

Regional variations

The east–west trending Galapagos spreading centre is located within the Panama Basin, an area bounded on the north-west by the Cocos Ridge and on the south by the Carnegie Ridge (Fig. 1). Bottom-water temperatures in the Panama Basin below 3000 m range from 1·6 °C near the coast of Ecuador to over 1·8 °C in the north-western portion of the basin, the water presumably being heated by vertical mixing and geothermal heat flow as it moves through the basin (Laird 1971).

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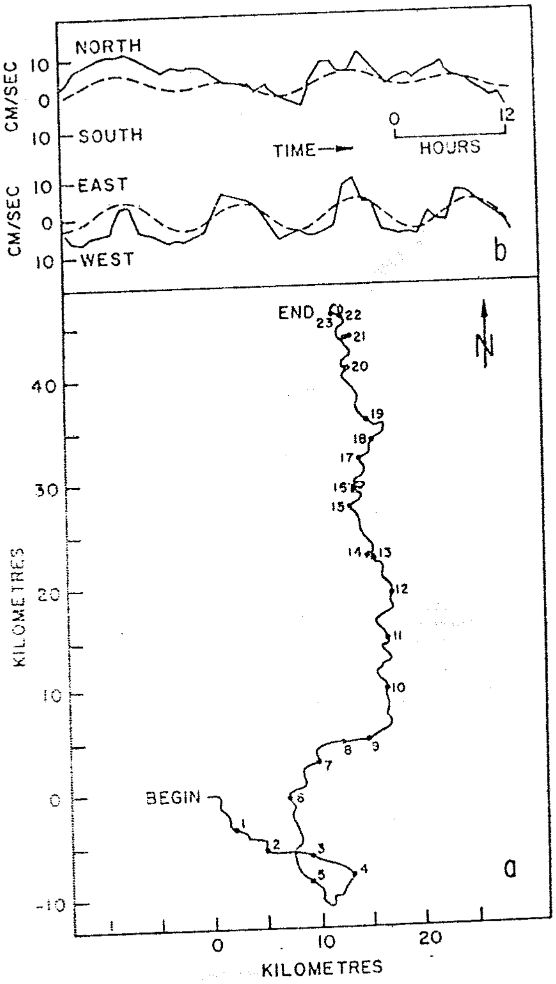

FIG 5. Current meter results. (a) Vector plot of the motion of a parcel of water during the 23 days of current meter observations at the Galapagos spreading centre. Individual days are labelled. Current meter location shown in Fig 2. (b) Observed N-S and E-W current components (solid line) and estimated tidal components (dashed line) plotted versus time. E-W component almost entirely tidal in origin.

The importance of geothermal heating on bottom-water temperatures in the Panama Basin can be estimated by calculating the total geothermal heat flow into the basin and comparing this with the total amount of heat required for complete bottom-water renewal. Using this technique, Laird (1971) estimated a residence time of about 220 years for bottom water in the Panama Basin. This estimate, however, does not take into account the high and extremely variable heat flow near the Galapagos spreading centre or the possible existence of other heat transfer mechanisms such as hydrothermal circulation. We have therefore recomputed the total geothermal heat flux of the Panama Basin using the theoretical heat flow of Sclater & Francheteau (1970). This type of calculation approximates the total geothermal heat being released by conductive cooling, hydrothermal circulation and other mechanisms of heat transfer. We assume that all portions of the basin lying below 2300 m (the height of the ridge crest) and west of the Panama fracture zone were produced by spreading at the Galapagos spreading centre. All portions of the basin east of Panama fracture

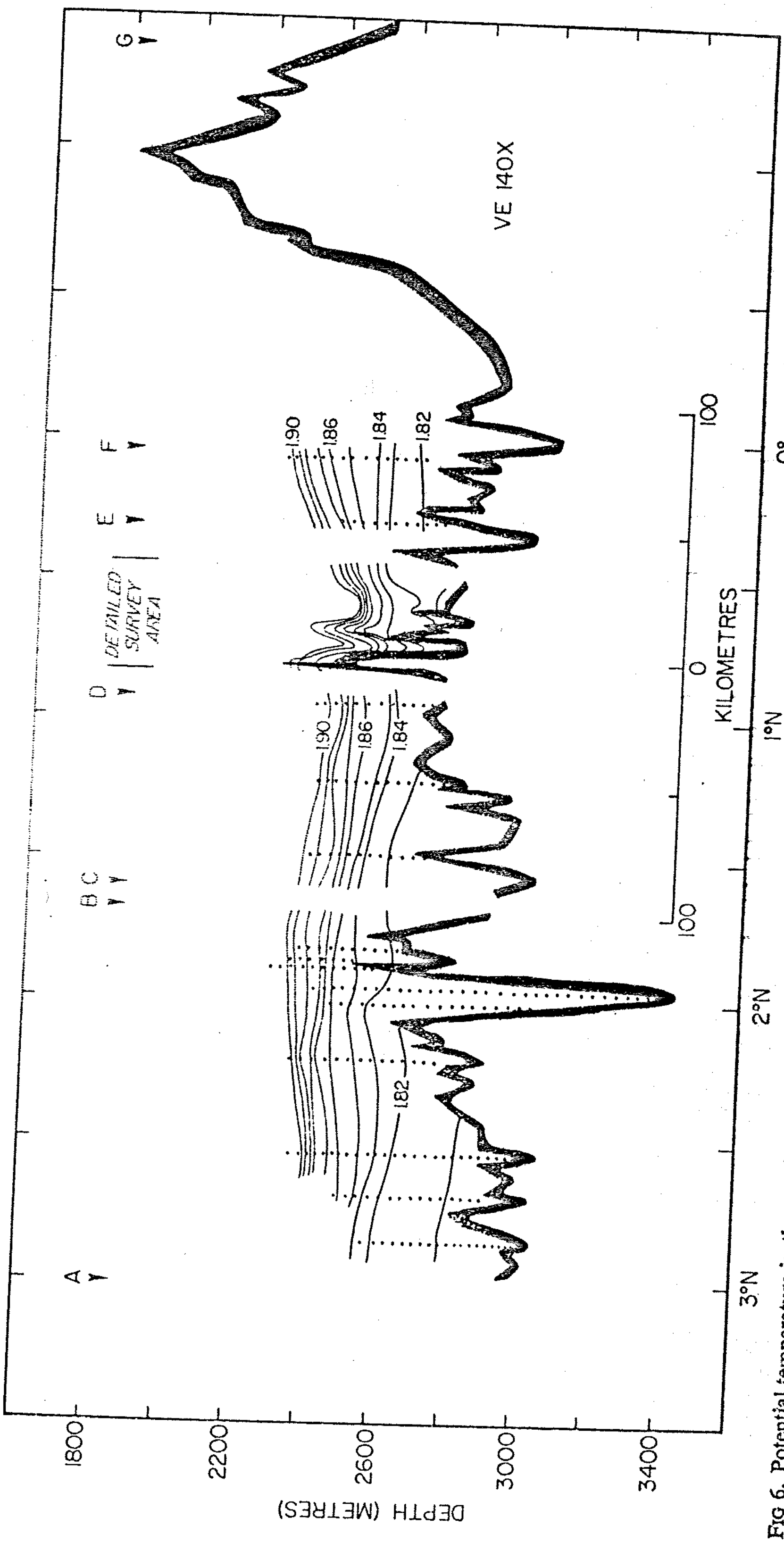

Fig 6. Potential temperature isotherms along N–S section from the equator to 3°N. All stations have been projected onto 86° 10′ W. Locations of labelled sections shown in Fig 1. Individual data points are only shown outside of the detailed survey area. Bathymetry taken from surface ship and near-bottom observations in this area. Distance in kilometres is from inferred centre of spreading (Klitgord & Mudie 1974).

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The regional deepening of potential temperature isotherms across the Galapagos spreading centre (Fig. 6) may also be a result of geothermal heating. Vertical temperature profiles taken along a roughly N–S line extending from the equator to 3° N indicate that potential temperature isotherms deepen almost 100 m between the equator and the crest of the Galapagos spreading centre (0° 48′ N), while to the north of the ridge crest, between 1° N and 2° N, they shallow by 50–100 m. Temperatures at 2600 m are 0·02 °C higher near the ridge than they are 100 km either to the north or south and temperatures at 2400 m are over 0·01 °C higher near the ridge crest. This warmer water present near the Galapagos spreading centre may be the result of abyssal circulation patterns in the Panama Basin, unrelated to variations in geothermal heat flow. On the other hand the higher bottom-water temperatures may be a direct result of the higher geothermal heat flow near the Galapagos spreading centre. The total geothermal heat flux within 35 km of the Galapagos spreading centre is over an order of magnitude higher than the average oceanic heat flux and it may have a significant effect on bottom-water temperatures.

Relatively warm bottom water has also been reported from other active spreading centres. Knauss (1962) found higher bottom-water temperatures at the East Pacific Rise between 20° S and 30° S which he attributed to geothermal heating. Warren (1973) noted a regional deepening of potential temperature isotherms across the East Pacific Rise at 28° S and 43° S and a similar feature is apparent on temperature profiles across the Mid-Atlantic Ridge near 48° N, 36° N, 32° N, 24° N, 16° N and 24° S (Fuglister 1960). In at least some cases (e.g. 28° S on the East Pacific Rise and 36° N and 16° N on the Mid-Atlantic Ridge) there is no corresponding change in salinity. The presence of warmer bottom water at spreading centres in widely-separated portions of the world's oceans supports the suggestion that these higher bottom-water temperatures may be related to the higher geothermal heat flux at active spreading centres. The spreading process is one of the major mechanisms by which the Earth releases heat (Williams & Von Herzen 1974) and it appears that, in at least some cases, this heat may have a significant effect on bottom-water temperatures.

Summary and conclusions

(1) Closely spaced, vertical temperature profiles near the crest of the Galapagos spreading centre indicate the presence of a complex bottom-water temperature structure with significant local variations in the depths of individual potential temperature

FIG 6. Potential temperature isotherms along N–S section from the equator to 3°N. All stations have been projected onto 86°10′W. Locations of labelled sections shown in Fig 1. Individual data points are only shown outside of the detailed survey area. Bathymetry taken from surface ship and near-bottom observations in this area. Distance in kilometres is from inferred centre of spreading (Klitgord & Mudie 1974).

isotherms. A thermocline 70–160 m thick and less than 200 m from the bottom separates a nearly isothermal layer of water from the warmer water above. A current meter located in this thermocline recorded strong, partially tidally induced currents at times greater than 20 cm s^{-1}.

(2) Despite detailed bottom-water temperature measurements 50–200 m above the sea floor, no local temperature anomalies were observed which could be attributed to hydrothermal circulation. However, local temperature anomalies of several hundredths °C which may have been caused by hydrothermal activity were observed within a few metres of the bottom. Any heat gained through hydrothermal activity is quickly dispersed into surrounding bottom water.

(3) The high geothermal heat flux associated with the Galapagos spreading centre is an important factor causing bottom-water renewal in the Panama Basin. Our calculations indicate that geothermal heating alone can produce renewal in 100 years or less. The large amount of heat released during the spreading process may also be responsible for higher bottom-water temperatures observed at the Galapagos spreading centre.

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R. S. Detrick and J. D. Mudie:
Marine Physical Laboratory of the Scripps Institution of Oceanography,
La Jolla, California 92037.

D. L. Williams:
Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts 02543.

J. G. Sclater:
Earth and Planetary Sciences,
Massachusetts Institute of Technology,
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