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Heat Flow Near a Fossil Ridge on the North Flank of the Galapagos Spreading Center

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Sixteen new heat flow stations plus a seismic reflection, bathymetric, and magnetic survey of the north flank of the Galapagos Spreading Center have provided additional data to further delineate a low heat flow zone approximately 50 km wide running from 85.5°W to 88°W. This anomalous, low heat flow zone appears to be related to a graben which is found as a continuous, fault-bounded trough, offset by fracture zones and trending parallel to the present spreading center. Thin sediment, symmetric magnetic anomalies, shoaling topography, and a topographic step between the graben and the present spreading center suggest that it is the central rift valley of a fossil spreading center which jumped to the south ~4 m.y. B.P. The low heat flow measurements appear to be a manifestation of our inability to measure convective heat transfer in this area of thin sediment cover. The thin sediment cover appears to be caused by (1) the youth of the fossil ridge crest relative to the surrounding sea floor and (2) burial by extrusive activity which might have continued after the major components of sea floor spreading jumped to the presently active ridge crest.

INTRODUCTION

The central portion of the Galapagos Spreading Center (originally identified and named the Galapagos Rift Zone by *Raff* [1968] and *Herron and Heirtzler* [1967]) is one of the most complex of the oceanic accreting plate boundaries. In the past few years an extensive collection of geophysical data on this ridge has been accumulated by vessels of the U.S. Naval Oceanographic Office, Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, and Lamont-Doherty Geological Observatory. Because it is an east-trending sea floor spreading ridge very near the magnetic equator, the magnetic anomalies generated by the Galapagos Spreading Center are of large amplitude and are easily correlated from profile to profile; however, correlation with the geomagnetic time scale is more difficult. The crestal sequence of anomalies 1 to 2′ is of classic shape and agrees in every detail with the theoretical shape generated by assuming symmetric sea floor spreading [*Sclater and Klitgord*, 1973; *Anderson et al.*, 1975]. The older anomalies, however, are another matter. To date the time scale correlation has been so difficult that *Sclater and Klitgord* [1973] interpreted a *Glomar Challenger* 16 profile as indicating that a segment of sea floor north of the ridge axis was missing, whereas *Hey* [1975] interpreted that same profile as requiring an additional segment of sea floor north of the ridge axis.

Other geophysical data present further confusing anomalies. The heat flow has been extensively sampled with more than 300 values now measured on the Galapagos Spreading Center. A portion of the crest has been mapped by a deeply-towed instrument package [*Klitgord and Mudie*, 1974], and a large set of heat flow measurements has been precisely navigated in relation to the bottom by using ocean bottom transponders [*Williams et al.*, 1974]. The resulting survey delineated an oscillatory heat flow pattern which varies systematically with distance from the crest. *Williams et al.* [1974] concluded that the heat flow pattern represented strong evidence for widespread circulation of seawater into the oceanic crust at the ridge crest. *Williams et al.* [1974] and *Ribando et al.* [1975] modeled the observed pattern and showed that it could be caused by cellular convection within the oceanic crust. On the north flank, *Sclater and Klitgord* [1973] and *Sclater et al.* [1974] reported a low heat flow zone which correlated with as yet unexplained local sediment thickness variations and possibly with a large trough on the southern border of the low heat flow zone. *Sclater et al.* [1974] suggested that the cause of the low zone is high 'effective permeability' which allows hydrothermal circulation and convective heat transfer to dominate the thermal regime of the flank in a manner similar to that proposed to occur on the crest. They attributed this renewed hydrothermal circulation to either (1) sediment thinning so that basement is in contact with seawater rather than blanketed by impermeable sediment as to the north and south [*Lister*, 1972] and/or (2) dehydration caused by heating from below [*Anderson*, 1972] which opens plugged cracks and allows renewed circulation to occur. The latter mechanism should be related to age from the crest, whereas the former should be related to sedimentation patterns.

In an attempt to determine the mechanism or mechanisms responsible for the low heat flow anomaly, we conducted a geophysical survey of the north flank of the Galapagos Rift Zone from 2°–3°N, 87°–88°W and attempted to map the two-dimensional extent of the low heat flow zone, the trough, and the thinned sediment region. We report 16 new heat flow measurements in addition to the results of that underway geophysical survey. Our results help to resolve the tectonic causes of the above-mentioned anomalous features of the Galapagos Spreading Center.

REGIONAL SETTING

The Galapagos Rift Zone is the central ridge segment of the Galapagos Spreading Center (Figure 1). The easternmost segment of the spreading center, the Costa Rica Rift [*Grim*, 1970], is bounded by the Panama fracture zone, a transform fault plate boundary between the Cocos Plate and the Panama Basin (which may be part of the Nazca Plate), and by the Ecuador fracture zone. To the west, a segment of the Galapagos Spreading Center runs from the Galapagos fracture zone to the Nazca-Pacific-Cocos triple junction at 2°N, 102°W (Figure 1). The crust generated by the Galapagos Rift Zone is disrupted to the north and south by the Cocos and Carnegie aseismic ridges, which are thought to be hot spot trails from the Galapagos Islands hot spot [*Morgan*, 1973; *Hey*, 1975; *Holden and Dietz*, 1972].

The crest of the Galapagos Rift Zone itself is marked by a distinct topographic peak [*Anderson et al.*, 1975; *Johnson et al.*, 1976]. The half spreading rate is ~3.1 cm/yr from anomalies 1 to 2' [*Anderson et al.*, 1975; *Sclater and Klitgord*, 1973]. The crustal magnetic anomalies have anomalously large amplitudes, possibly caused by Fe, Ti enrichment of crustal basalts from a geochemical anomaly centered roughly about the Galapagos Islands [*Vogt and Johnson*, 1973; *Anderson et al.*, 1975].

BATHYMETRY

Sclater and Klitgord [1973] presented a contour map of bathymetry on the Galapagos Rift Zone. Since the construction of that map, two major expeditions have greatly increased our knowledge of the bathymetry of the region: (1) *Sclater et al* [1974] mapped a deep trough on the north flank of the presently active ridge extending from 85°20'W to 86°W along 2°N latitude and (2) during expedition Cocotow, leg 4 (Figure 1), we mapped this trough as a continuous topographic feature extending from 86°W to its intersection with the Cocos Ridge at 88°W. We have recontoured the region from 1°S to 4°N and from 84°W to 88°W (Figure 2). The results of these two detailed surveys and additional Lamont-Doherty Geological Observatory lines in the area were used in the revision of the *Sclater and Klitgord* [1973] map. The major new feature of Figure 2 is the trough trending east-west from 2° to 3°N and offset in at least three places by fracture zones. The trough appears as a steeply walled graben with step-faulted sides as shown in the seismic reflection profile trending perpendicular to the trough along 87°W latitude (Figure 3). *Sclater et al.* [1974] conducted a deep-tow bathymetric and magnetic survey of the graben at 2°N, 86°W. They found basement exposed along the boundary scarps, stair step faulting on the southern flank, and a uniformly sedimented graben floor. The inferred fracture zones appear as shoal regions with little sediment cover connecting offset troughs. Tholeiitic pillow basalts recovered from the trough at ~2°30'N, 87°30'W are extremely fresh with little manganese and plentiful glass, possibly indicating that the trough is anomalously young for its present position relative to the Galapagos Rift Zone crest.

HEAT FLOW MEASUREMENTS

Sixteen new heat flow stations were occupied in and near this graben on the north flank of the Galapagos Rift Zone (Table 1). All geothermal gradients were measured with a 4-m Bullard probe. Thermal conductivities were measured on a core within the trough at 2°30'N, 87°30'W by using the needle probe method of *Von Herzen and Maxwell* [1959]. Individual station conductivities were assumed by using both these new values and previous measurements within the survey area from *Langseth et al.* [1966], *Sclater and Klitgord* [1973], and *Sclater et al.* [1974]. All conductivity values from these independent sources were within 10% of each other. Each station was evaluated for instrumental performance, and the local environment of each was described in detail (Table 1*b*). In the

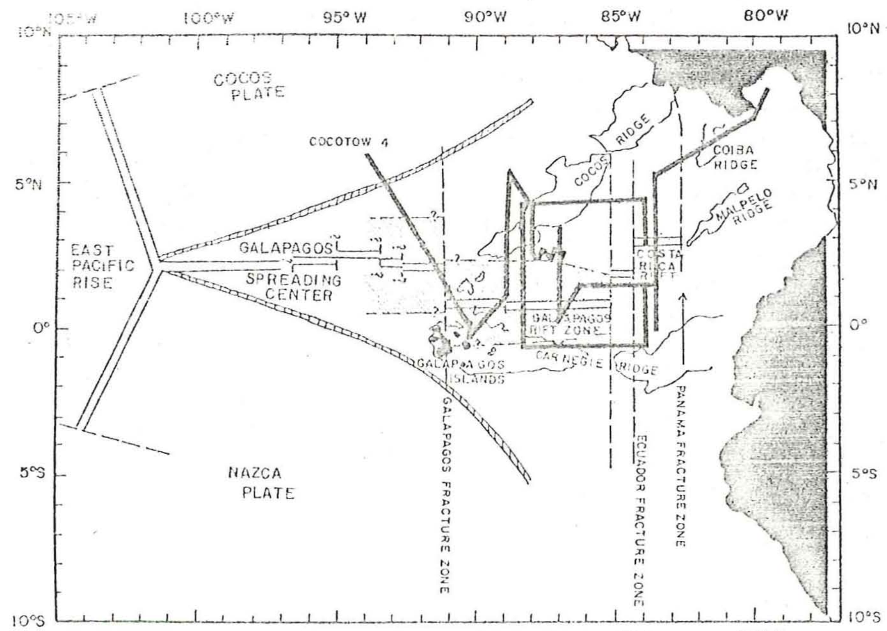

Fig. 1. Physiographic diagram of eastern equatorial Pacific. Double bar lines are spreading centers, dashed lines are fracture zones, and solid line is ship tracks of Cocotow 4 expedition of this report. Square delineates boundaries of bathymetric map of Figure 2.

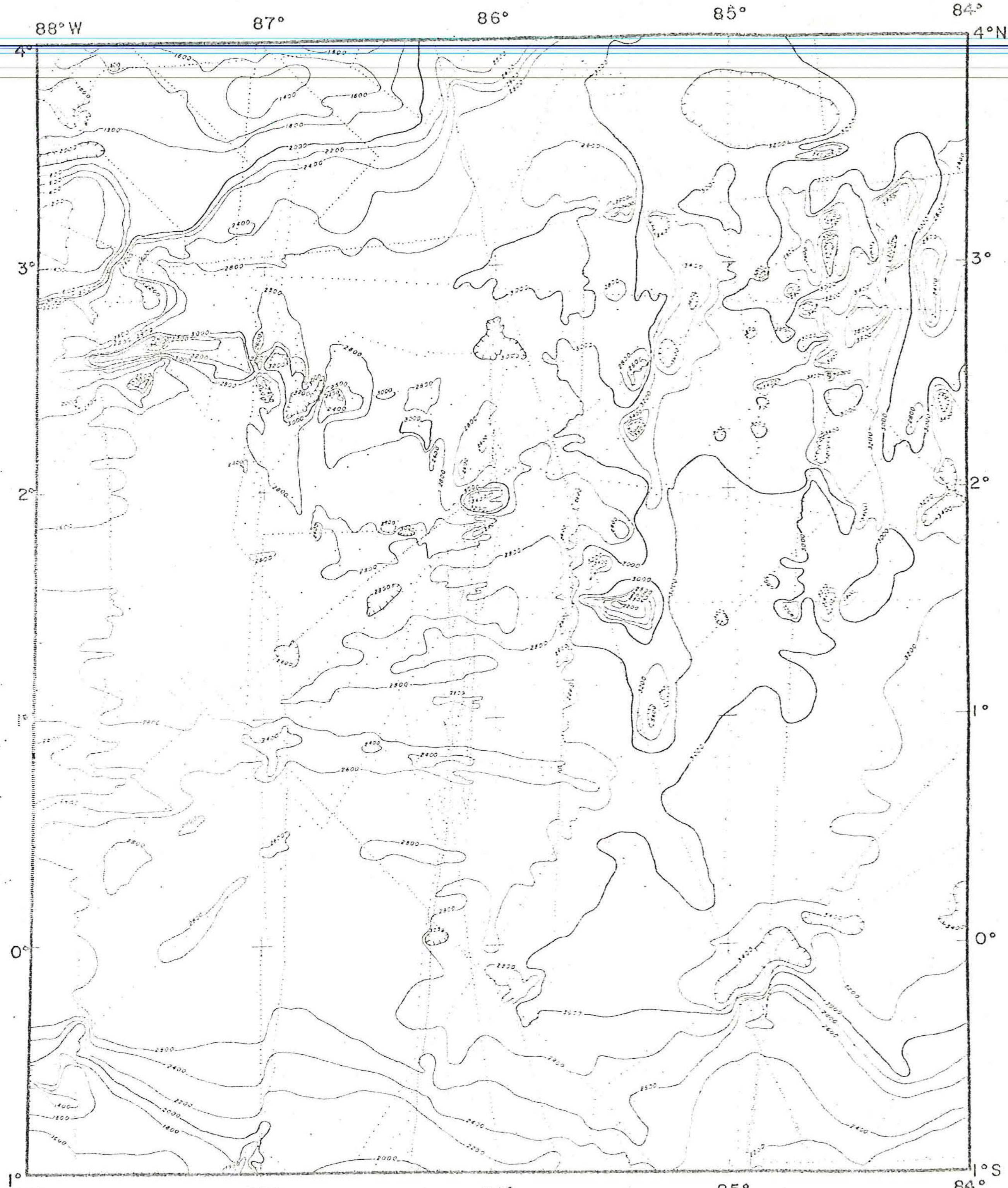

Fig. 2. Bathymetric map of Galapagos Rift Zone. Location is indicated in Figure 1. Dotted lines are ship tracks used for the map. Contours are in corrected meters.

majority of stations, four geothermal gradients were measured. These were evaluated for systematic variations both between and among individual data populations. All were linear over the entire measurement range to an accuracy of ±10% (appendix).

The 16 newly reported heat flow stations, which bring the total number of measurements from 2°–3°N, 86°–88°W to 43, are systematic enough to be contoured, a rarity with heat flow measurements (Figure 4). The low heat flow zone on the north flank of the Galapagos Rift Zone can be traced as a continuous feature from 85°30′W to 88°W. Low heat flow was consistently measured within and just to the north of the graben (Figure 3). Thirty values within the low-zone average 1.38 ± 1.13 s.d. HFU (1 HFU = μcal/cm^2 s, 1 HFU × 41.87 = 1 mW/m^2), whereas 13 from the flanks which have high heat flow average 4.72 ± 0.77 s.d. HFU. The thermal gradients of

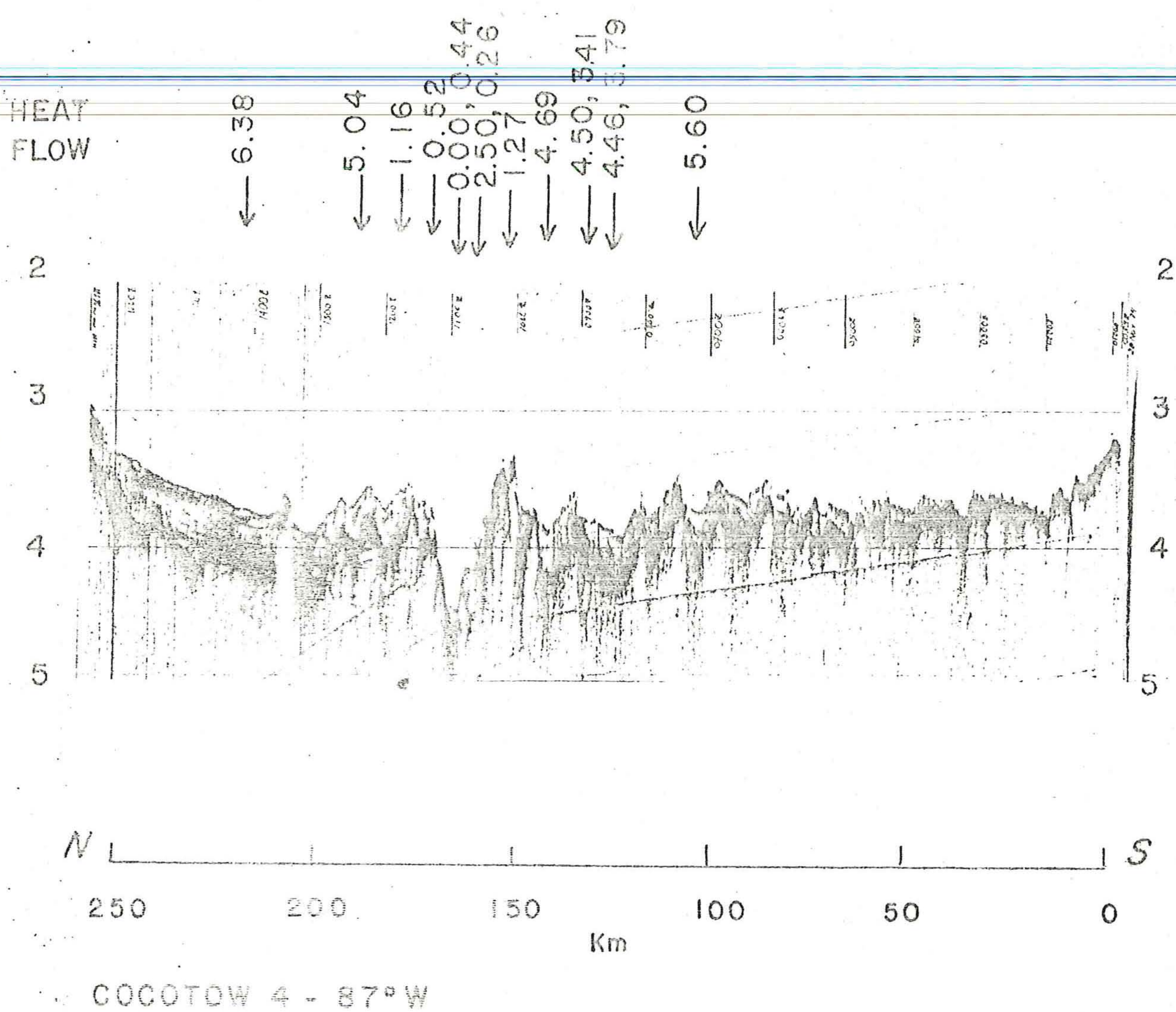

Fig. 3. Seismic reflection profile trending north along 87°W longitude from Cocotow 4. Location is indicated by long solid line within square of Figure 1. Heat flow values from Table 1 along this profile are shown in microcalories per square centimeter second.

TABLE 1a. Heat Flow Measurements on Cocotow 4

Station	Latitude	Longitude	Depth, m	Penetration, cm	$\Delta T/\Delta Z$	K	Q
27HF23	3°32.4′N	86°52.0′W	2136	440	0.87	1.84	1.57
28HF24	2°57.1′N	86°59.8′W	2870	320	3.54	1.84	6.38
29HF25	2°43.4′N	86°54.7′W	2690	440	2.8	1.84	5.04
30HF26B	2°29.5′N	87°00.3′W	2880	0	...	...	...
31HF27	2°09.1′N	87°01.3′W	2824	440	2.48	1.84	4.46
32HF28	2°02.1′N	87°03.3′W	2503	440	3.11	1.84	5.60
33HF29	2°18.3′N	86°50.1′W	2878	440	2.61	1.84	4.69
34HF30	2°30.2′N	86°51.1′W	3096	440	0.29	1.84	0.52
35HF31	2°41.5′N	86°52.9′W	2721	440	0.63	1.84	1.16
36HF32	2°40.3′N	87°11.4′W	3214	440	0.00	1.84	0.00
37HF33	2°32.0′N	87°13.3′W	2906	440	0.14	1.84	0.26
38HF34	2°20.4′N	87°15.2′W	2736	440	2.50	1.84	4.50
39HF35	2°33.3′N	87°26.4′W	2590	440	0.70	1.84	1.27
40HF36	2°38.9′N	87°29.8′W	1910	440	1.38	1.84	2.50
42HF37	2°21.5′N	87°35.1′W	2593	440	1.89	1.84	3.41
43HF38	2°19.7′N	87°44.5′W	2580	440	2.10	1.84	3.79
44HF39	2°34.1′N	87°52.6′W	2682	440	0.24	1.84	0.44
45HF40	4°00.2′N	87°44.1′W	1610	0	...	...	...
46HF41	5°16.3′N	88°37.8′W	3050	300	1.97	1.84	3.54

$\Delta T/\Delta Z$ is the thermal gradient in 10^{-4} °C/m, K is thermal conductivity in mcal/cm s°C, Q is heat flow in μcal/cm² s.

TABLE 1*b*. Evaluation of Heat Flow Measurements on Cocotow 4

Station	Instrumental Performance	Rating	Local Environment
27HF23	4 good gradients	8	On top of 366-m hill. Well sedimented.
28HF24	2 gradients, partial penetration, 30° tilt	6	Station at base of 183-m gentle slope. No clear cause of tilt or partial penetration.
29HF25	4 good gradients	8	Half way up 110-m scarp. Well sedimented. Low, rolling hills.
30HF26B	bounced	0	On side of large scarp of trough wall.
31HF27	4 gradients	8	Flat terrain; > 36-m sediment.
32HF28	2 gradients, 2 offscale because of high heat flow	7	On top of 183-m hill. Well sedimented. Generally flat relief.
33HF29	4 gradients	8	On top of small 91-m hill. Well sedimented.
34HF30	4 gradients	8	At base of 1100-m scarp in trough floor. > 36-m sediment.
35HF31	4 gradients	8	Gentle, well-sedimented flat terrain.
36HF32	4 linear gradients, full penetration	8	On top of hill (183-m high). 72-m sediment.
37HF33	4 gradients	8	On scarp, 183-m sediment. Just off 36-m deeper floor of valley and 110-m shallower hill.
38HF34	4 gradients	8	Gently undulating, well-sedimented sea floor.
39HF35	4 gradients	8	Half way up 183-m scarp. 18-m sediment. 72-m relief.
40HF36	4 gradients	8	At bottom of 512-m scarp in trough. Rock scarp. 36-m sediment. 72-m relief.
42HF37	4 gradients	8	At base of 183-m hill. Flat to south. > 36-m sediment.
43HF38	4 gradients	8	Flat, gentle terrain. At base of 366-m hill.
44HF39	4 gradients	8	In trough floor. Well-sedimented 183-m scarps on both sides.
45HF40	bounced	0	On top of Cocos Ridge. Hard bottom. Shallow.
46HF41	30° tilt, 2 gradients, partial penetration	6	Flat, well sedimented. No indication why there is tilt or partial penetration.

Rating is from 0 to 10 depending upon instrumental performance, tilt, penetration depth, and whether the thermal conductivity was estimated or assumed. Local environmental descriptions are from 3.5-kHz echo sounder and seismic reflection records in area of each station. All are two-dimensional only.

the 43 stations represent measurements from instruments of three institutions (Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, and Lamont-Doherty Geological Observatory) and from heat flow probes of three fundamentally different designs (the 4-m Bullard probe from Scripps, a 2-m outrigger short probe from Woods Hole, and outrigger probes on Ewing piston corers from Lamont-Doherty and Woods Hole). Thus it is highly unlikely that the low heat flow values are due to experimental error, and further, the low heat flow zone and the graben appear to be

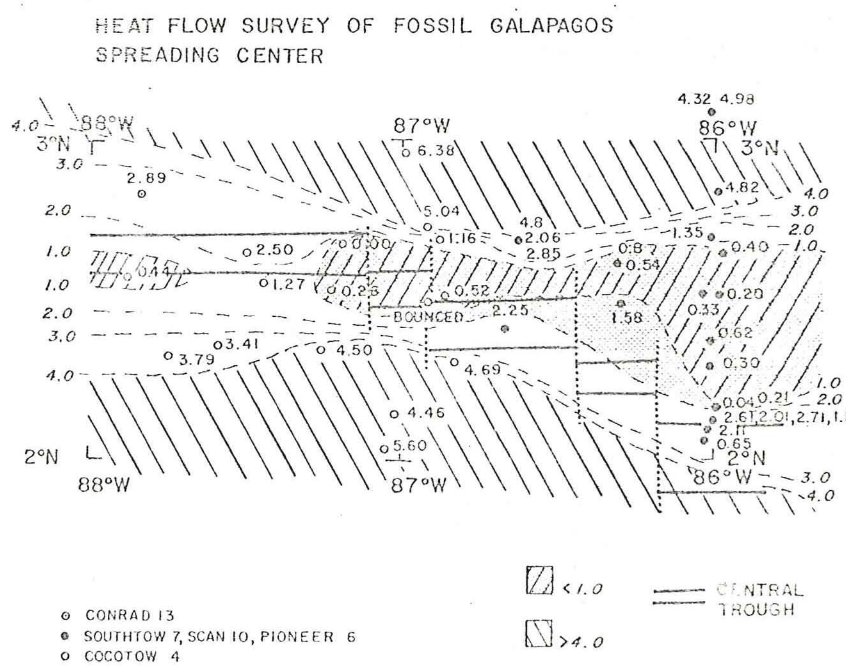

Fig. 4. Heat flow values from *Sclater and Klitgord* [1973], *Sclater et al.* [1974], *Langseth et al.* [1966], and this paper. Double bar lines are central graben of fossil ridge system. Dashed lines are fracture zones. Contour interval is 1.0 μcal/cm^2 s.

causally related. Below, we will attempt to test causality by examining other geophysical parameters of the graben system.

MAGNETIC ANOMALIES AND A FOSSIL RIDGE CREST

As mentioned earlier, *Sclater and Klitgord* [1973] interpreted the magnetic anomalies from the *Glomar Challenger* 16 profile (Figure 5*a*) as indicating to them that a section of sea floor was missing north of the Galapagos Rift Zone. *Hey* [1975] proposed alternatively that the *Glomar Challenger* 16 profile might be interpreted as representing the magnetic anomalies from a fossil ridge system on the north flank of the presently active ridge crest. The Cocotow survey has provided magnetic profiles which confirm this latter interpretation. The Cocotow 4/Tripod combined profile at 87°W (Figure 5*a*) shows repetition of anomaly 3, a pattern which is diagnostic of anomalies about a fossil ridge crest [*Herron*, 1972]. Furthermore, this repeated anomaly 3 sequence appears to be symmetric about the trough (Figure 5*a*). This suggests that the trough is a fossil

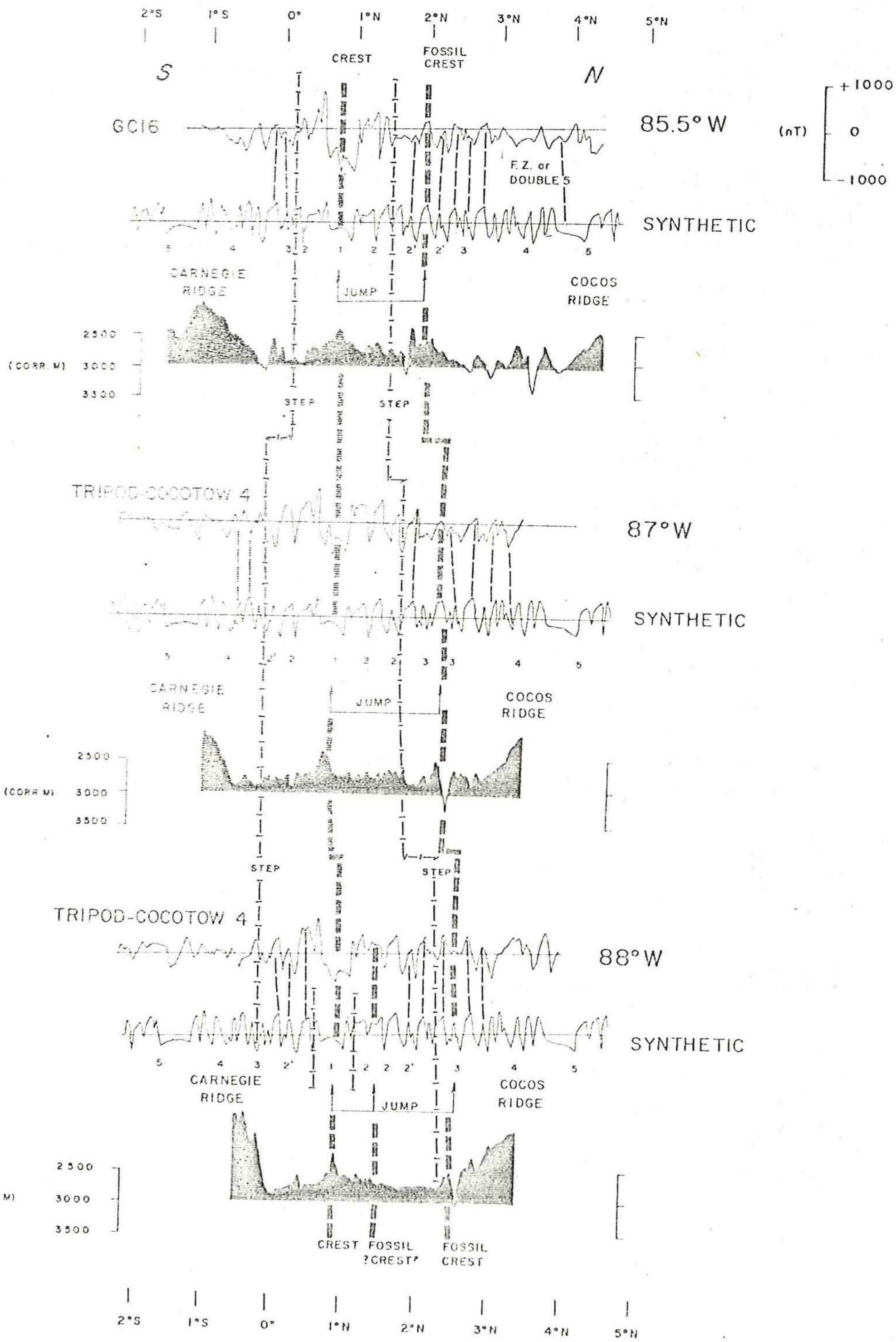

Fig. 5*a*

Fig. 5. Magnetic anomalies and topographic profiles on Galapagos Spreading Center. Profiles are compared to synthetic anomalies generated by assuming that fossil ridge jumps exist to the north of the present crest.

central rift valley. The jump in spreading occurred prior to anomaly 2′ time (3–4 m.y. B.P.) and after anomaly 3 time (6 m.y. B.P.). Furthermore, we can correlate anomalies over the entire northern flank of the Galapagos Rift Zone from the crest to the intersection with the Cocos Ridge and from 85.5°W to 88°W (Figure 5*a*). On the *Glomar Challenger* 16 profile at 85.5°W, the fossil ridge is delineated by repeated anomalies 2′, indicating to us that the ridge became inactive more recently than at 87°W. (A possible repeated anomaly 5 sequence to the north indicates an older fossil ridge or the crossing of a fracture zone. We have no further data on this segment of sea floor.) At 88°W the Cocotow 4/Tripod profile (Figure 5*a*) shows that two fossil ridges might have existed, the older showing symmetry about anomaly 3 and the younger showing symmetry about anomaly 2 (Figure 5*a*). Though a small 'jog' exists near the double 2 symmetry on the Tripod profile, the possibility of the generation of the extra anomaly 2 by the crossing of a fracture zone can be eliminated because of the missing anomaly 2 on the south flank (Figure 5*a*). Cocotow 4 profiles at 89°W and 92.5°W also show anomaly 2 symmetry about a fossil ridge which became inactive at that time (Figure 5*b*). One can therefore conclude from the magnetic data that the Cocos-Nazca accreting boundary has had a very complex recent history with a well-developed older fossil ridge system extending from 85.5°W to 88°W which became extinct ~4 m.y. B.P. (Figure 6) and a younger fossil ridge system extending from 88°W to at least 92.5°W which became extinct ~2 m.y. B.P. (Figure 6).

Topographic Evidence of the Older Fossil Ridge

Vogt et al. [1969], *Sclater et al.* [1971], and *Anderson and Sclater* [1972] have demonstrated that a fossil ridge produces a distinct topographic signature, since subsidence from the ridge crest is a function of age only [*Sclater et al.*, 1971]. Any age discontinuity should produce a topographic discontinuity. The fossil rift valley on the north flank of the Galapagos Rift Zone is at the crest of the anomalous shoaling in topography noted by *Sclater and Klitgord* [1973] (Figure 5*a*, *Glomar Challenger* 16 profile). Further, on the Cocotow 4 profile at 87°W, a distinct topographic step exists to the south of the fossil crest marking the boundary between crust generated at the fossil ridge and that generated at the presently active Galapagos Rift Zone crest (Figure 5*a*). A companion step in topography which should exist to the south of the present crest is obscured by the Carnegie Ridge. Similar topographic and magnetic patterns have been identified on the flank of the Galapagos Spreading Center between 91°W and 93°W [*Tréhu*, 1975; *Hey*, 1975]. The present crest of the active Galapagos Rift Zone has a topographic peak, whereas the fossil ridge has a graben or central rift valley. The change in topography might indicate that the cessation of spreading on the fossil ridge took place over a finite time in which the spreading rate dropped slowly to

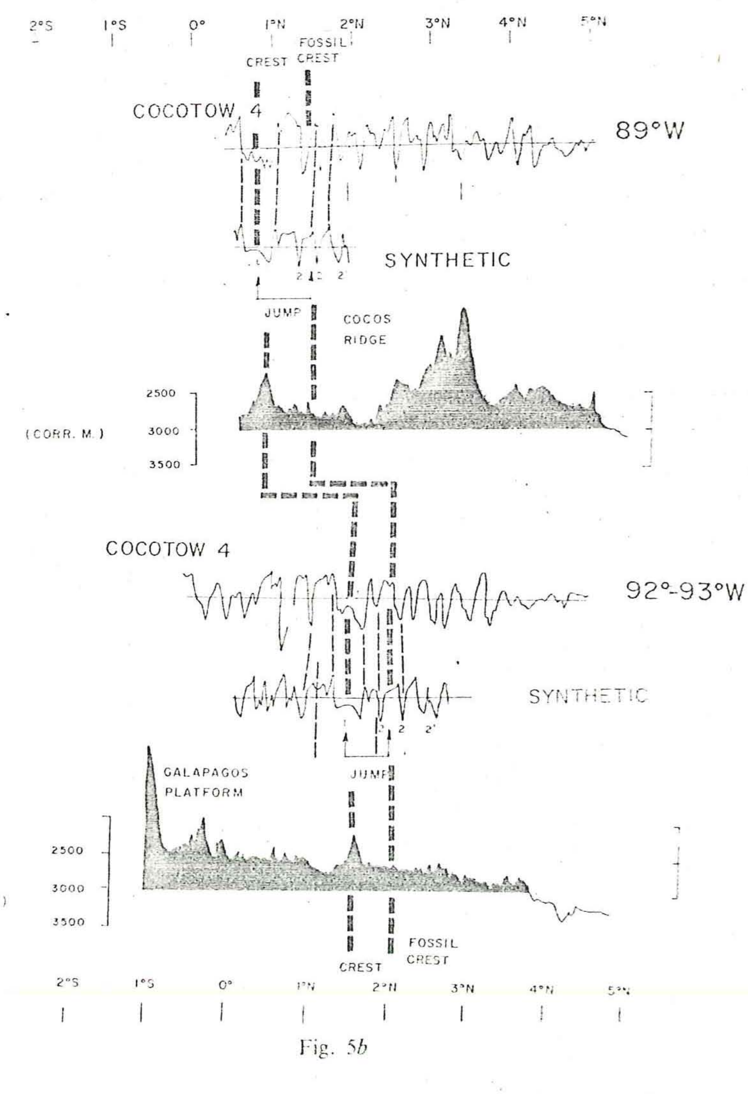

Fig. 5*b*

ro, producing crestal topography characteristic of very slow spreading ridges [cf. *Anderson and Noltimier*, 1973].

SEDIMENT THICKNESS ON THE GALAPAGOS RIFT ZONE

Further evidence for the existence of the fossil ridge at ~3°N is found from an examination of the variation in sediment thickness to the north of the presently active crest. Sediment thicknesses at ~2-km intervals were determined by using the Cocotow 4 seismic reflection profile at 87°W (Figure from the crest of the Galapagos Rift Zone at 0°50′N to the Cocos Ridge at 3°30′N (Figure 7). Sediment thickness increases linearly with distance from the crest to ~2°N; it then thins to the fossil graben and then thickens again to the Cocos Ridge. A sedimentation rate of 40 m/m.y. was determined from anomalies 1 to 2′ on the presently active crest. Extrapolation of this rate to the north produces an age for the fossil crest of ~4 m.y. B.P. and an age distribution in general agreement with the magnetic anomaly identifications of Figures 5*a*, and 6. We feel that the correlation between these various types of geophysical data is definitive evidence for the existence of a fossil ridge centered on the graben mapped in Figure We then constructed a plot of heat flow versus distance north of the presently active crest of the Galapagos Rift Zone (Figure 7). The 100 heat flow measurements (for sources, see Figure 7) show a gross correlation with sediment thickness. Heat flow increases from the crest as sediment thickness increases, decreases as sediment thickness decreases to the fossil ridge, and then increases again as the sediment thickness increases from the fossil ridge to the Cocos Ridge (Figure 3).

A similar correlation was first reported by *Lister* [1972] on the Juan de Fuca Ridge and attributed to the sealing of convective heat transfer from hydrothermal circulation by the deposition of an impermeable sediment cover which draped all basement relief. *Williams et al.* [1974] and *Sclater et al.* [1974] found the same correlation at 86°W on the Galapagos Rift and *Anderson and Hobart* [1976] found a similar correlation on the Costa Rica Rift.

We postulate that the sediment thickness variations of the Galapagos Rift Zone are caused by the existence of the fossil ridge. Thus the conclusion of *Lister* [1972] and *Sclater et al.* [1974] that low heat flow is measured on the north flank of the Galapagos Rift Zone because we measure only the conductive heat transfer with present techniques appears valid. A significant percent of the total heat transfer through the water–sea floor interface appears to be by convective heat transport when the sediment cover is not sufficiently thick to blanket basement relief.

Sclater et al. [1974] classified the local environment of each heat flow station which they occupied north of the Galapagos Rift Zone. They attributed the low heat flow measurements in the region to local outcropping of basement caused by sediment thickness variations. We propose here that a further effect of sediment thickness variations is also evident in the heat flow distribution on the north flank of the Galapagos Rift Zone. Low measurements were recorded by us not only in sediment ponds near rock outcrops but also in areas with flat relief (Table 1, station 35HF31) (Figure 3) and no outcropping rock (Table 1, station 27HF23). These low measurements still correlate with sediment thickness, however, in that although the sediment cover is uniformly draped over the basement, it is thin (generally <150 m thick). Perhaps convective transfer of heat by hydrothermal circulation is possible through a uniform sediment cover as long as it is thin [*Anderson and Hobart*, 1976], as seen on the south flank of the Galapagos Spreading Center where high heat flow is found in >50 m of sediment cover [*Williams et al.*, 1974]. Though the sedimentary cover required to prevent convective heat transfer on the south flank is less than that on the fossil ridge, the topographic relief is also less, and as *Anderson and Hobart* [1976] point out, it is probably this ratio which controls the heat transfer mechanisms.

The variation in the sediment cover appears to be tectonically controlled. But why there is so little sediment in the fossil rift valley remains problematical. If an instantaneous ridge jump had occurred in this region, the sediment cover would not thin on the fossil crest but would be similar to that at the jump boundary. The lack of sediment in the graben suggests that extrusive activity might not have ceased when the accreting plate boundary jumped to the south. A possible explanation for the existence of the above-mentioned fresh basalts in the graben is that subsequent volcanic extrusions occurred after the ridge jump. This volcanic activity might have covered

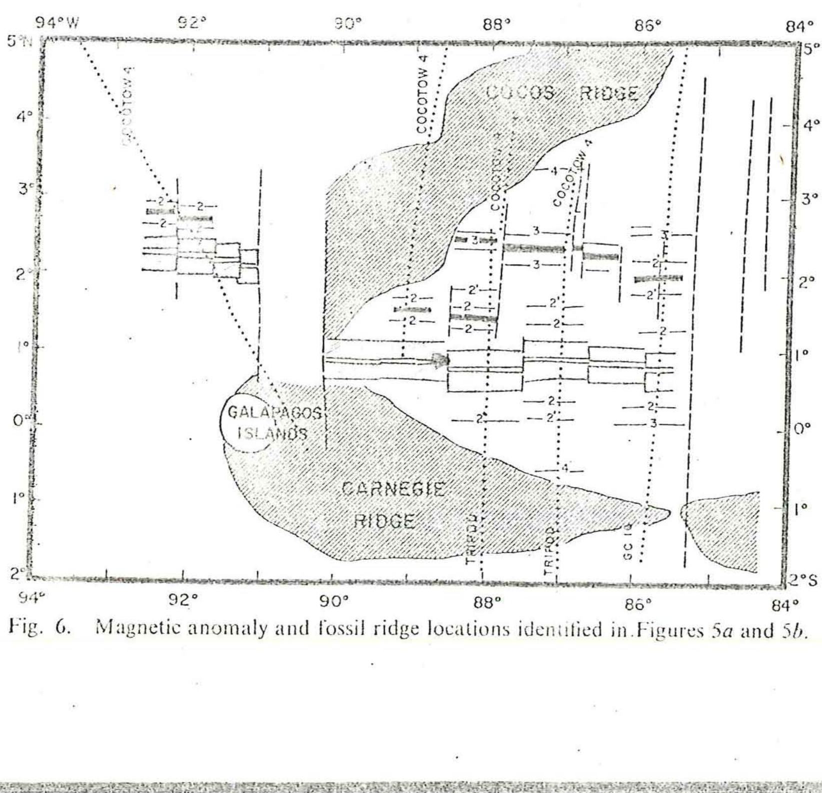

Fig. 6. Magnetic anomaly and fossil ridge locations identified in Figures 5*a* and 5*b*.

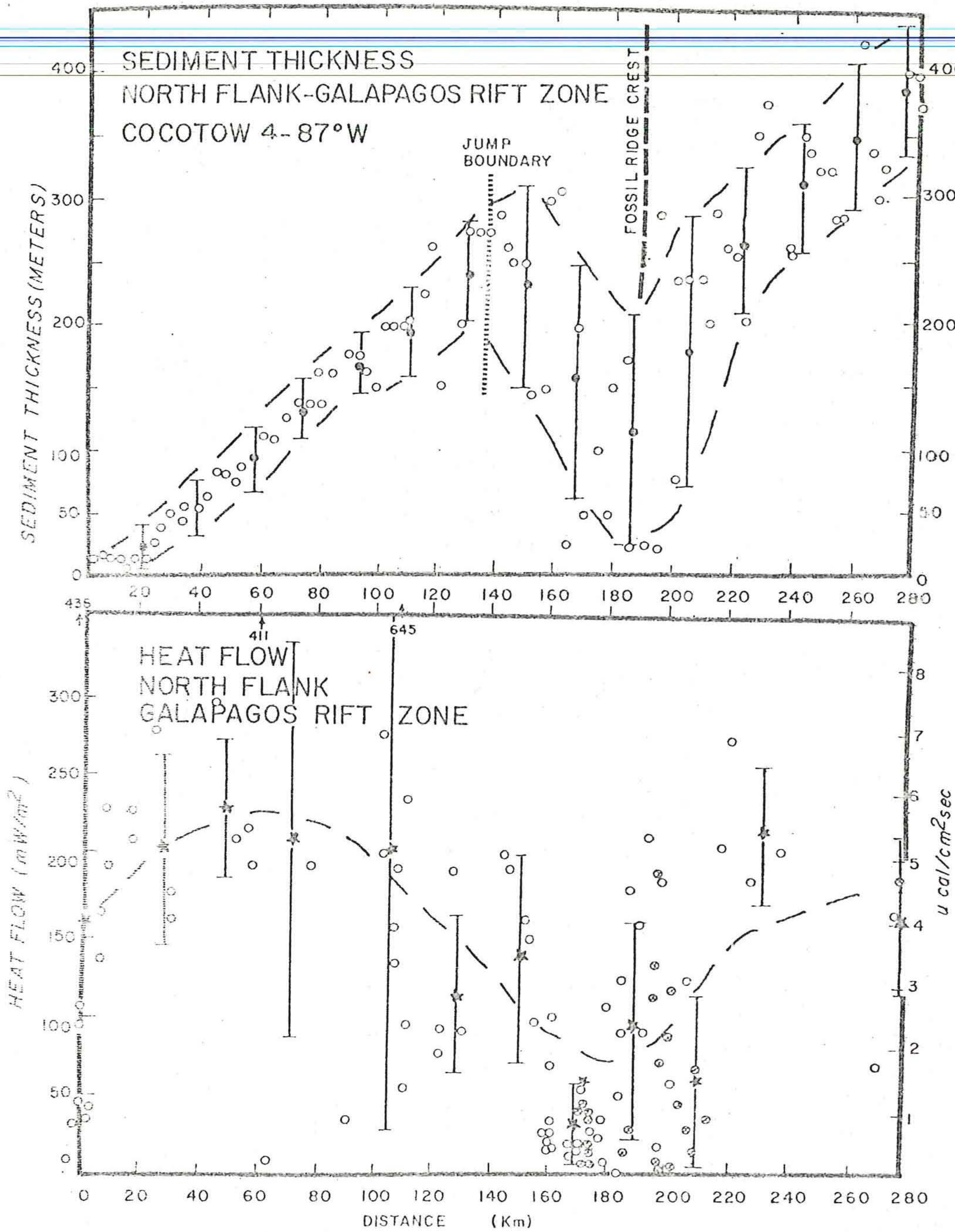

Fig. 7. (Top) Sediment thicknesses derived at 2-km intervals from seismic reflection profile of Cocotow 4, track along 87°W longitude (Figure 3), plotted versus distance from crest of the Galapagos Rift Zone. (Bottom) Heat flow values plotted versus distance from crest of Galapagos Rift Zone. Sources are this paper, *Sclater and Klitgord* [1973], *Sclater et al.* [1974], *Von Herzen and Anderson* [1972], *Langseth et al.* [1966], *Von Herzen and Uyeda* [1963], and *Anderson and Hobart* [1976].

the floor of the graben, burying sediment. If this is true, then the original graben must have been much deeper than it is now.

The existence of the low heat flow zone, its correlation with thin sediments, and the correlation of this environment with hydrothermal circulation on active ridges (*Lister*, 1972; *Williams et al.*, 1974] suggest that the convective hydrothermal activity on the fossil ridge continued long after the major component of sea floor spreading jumped to the presently active center.

TECTONIC IMPLICATIONS OF THE RIDGE JUMP

Sclater and Klitgord [1973] reported that the Carnegie Ridge truncates crust of anomaly 2′ time from 88°W to 86°W, whereas the Cocos Ridge truncates anomalies 4 to 5 from 88°W to 86°W. They concluded that since the Cocos Ridge was 'age progressive' from southwest to northeast, whereas the Carnegie Ridge appeared to be 3-4 m.y. old over the same geographic interval, the two ridges were tectonically unrelated and therefore could not be hot spot trails formed as the Cocos and Nazca plates moved over the Galapagos hot spot. *Hey* [1975] suggested that this geometric dilemma could be resolved if a fossil ridge existed to the north of the present crest. Then the Carnegie Ridge would be truncating older aged crust than that proposed by *Sclater and Klitgord* [1973]. Our mapping of the fossil ridge north of the Galapagos Rift Zone has removed the *Sclater and*

TABLE 2. Averages of the Departures of the Individual Interval Thermal Gradients From the Average Gradient at Each Station From Table 1*a* and From Additional Heat Flow Stations in the Area From *Anderson and Hobart* [1976, Table 1]

	d = 70	*d* = 190	*d* = 290	*d* = 390
Average algebraic departure from mean gradient, %	0.2	−3.8	5.4	0.3
Average absolute value of departure from mean gradient, %	5.8	6.3	9.0	4.2

d is depth in centimeters.

Klitgord [1973] objection to the hot spot trail origin for Cocos and Carnegie ridges.

It is interesting to note that the present ridge from 95°W to 95.5°W is the only segment of the Galapagos Spreading Center exhibiting topographic, magnetic, and petrologic characteristics of the Galapagos hot spot geochemical anomaly [*Vogt and Johnson*, 1973; *Anderson et al.*, 1975]. That is, shoal topography, anomalously high magnetic anomaly amplitudes, and extremely high FeO* and TiO_2 concentrations have been mapped over this segment of the Galapagos Spreading Center. Hey [1975] suggests that the ridge jumped to the south to remain near the hot spot. This appears to be a quite reasonable conclusion, since only that portion of the ridge now showing the geochemical effects of proximity to the hot spot jumped to the south.

SUMMARY

We have established that the low heat flow zone on the north flank of the Galapagos Rift Zone is a linear feature parallel to the present strike of the ridge, that it is causally related to a graben, that the graben is the crest of a fossil midocean ridge system which jumped to the south ~4 m.y. B.P., and that the low heat flow zone correlates with sediment thinning related to the existence of the fossil ridge.

APPENDIX: VARIATION OF TEMPERATURE GRADIENT FROM THE SURFACE TO 390-CM DEPTH

Temperature gradients reported in this paper and in the work by *Anderson and Hobart* [1976] from Cocotow, leg 4, Scripps Institution of Oceanography, were calculated at average depths of 70, 190, 290, and 390 cm from thermistor sensors located at 0, 140, 240, 340, and 440 cm from the surface of the sediment when the 4.5-m probe achieved full penetration. The total number of such stations was 27 (Table 1 and *Anderson and Hobart* [1976, Table 1]. Table 2 gives the average of the departures of the individual gradients from the average gradient at each station with regard to sign in the first row and without regard to sign in the second. The small values in the first row show that there is no measurable bias with respect to depth: i.e., the sum of positive and negative departures from the average gradient is close to zero at all the depths. The average absolute values of the departures for the four depths, namely, 6%, 6%, 9%, and 4%, do not indicate any trend but rather give us a measure of the accuracy of the measurements. The instrumental contribution to these errors is believed to be much smaller. It is presumed that these errors are principally caused by variations in thermal conductivity existing naturally in the sediment or produced by the mixing of the sediment by penetration of the probe. An attempt was made to investigate this latter hypothesis by assuming that the deepest gradient (g_{390}) was the true one, since it is least disturbed, and calculating the average differences between this gradient and the shallower ones (g_{290}, g_{190}, and g_{70}) in percent of the deepest one. Table 3 shows again that the differences balance well with regard to sign and that the absolute values of the departures are on the average 9.0, 9.4, and 6.8%, or about the same as when the gradients at the different depths were considered. These results confirm that the 2-m probe with which most of the Scripps Institution of Oceanography and Japanese heat flow stations have been taken penetrates the ocean mud far enough to yield reliable temperature gradients.

TABLE 3. Calculation of the Average Differences Between Deepest Measured Thermal Gradient (340–440 cm) and Shallower Gradients in Percent of Deepest Gradient

Depth *d*, cm	Algebraic Differences, %	Absolute Value Differences, %
70	−0.5	9.0
190	−1.1	9.4
290	2.7	6.8

The following equation was used to derive the algebraic and absolute value differences: $\frac{100}{27} \sum_{i=1}^{27} (g_i)\, d - (g_i)\, 390/(g_i)\, 390$.

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REFERENCES

Anderson, R. N., Petrological significance of low heat flow on the flanks of slow spreading midocean ridges, *Geol. Soc. Amer. Bull.*, *83*, 2947, 1972.

Anderson, R. N., and M. A. Hobart, The relation between heat flow, sediment thickness, and age in the eastern Pacific, *J. Geophys. Res.*, *81*, in press, 1976.

Anderson R. N., and H. C. Noltimier, A model for the horst and graben structure of midocean ridge crests based upon spreading velocity and basalt delivery to the oceanic crust, *Geophys. J. Roy. Astron. Soc.*, *34*, 137–147, 1973.

Anderson, R. N., and J. G. Sclater, Topography and the evolution of the southeastern Pacific, 5°S–20°S, *Earth Planet. Sci. Lett.*, *14*, 433, 1972.

Anderson, R. N., K. D. Klitgord, D. A. Clague, R. K. Nishimori, and M. Marshall, Magnetic and petrologic variations along the Galapagos spreading center and their relation to the Galapagos melting anomaly, *Geol. Soc. Amer. Bull.*, *86*, 613, 1975.

Grim, P. J., Connection of the Panama Fracture Zone with the Galapagos Rift Zone, eastern tropical Pacific, *Mar. Geophys. Res.*, *1*, 85, 1970.

Herron, E. M., Cenozoic evolution of the eastern central Pacific, *Geol. Soc. Amer. Bull.*, *83*, 1671, 1972.

Herron, E. M., and J. R. Heirtzler, Sea-floor spreading near the Galapagos, *Science*, *158*, 775, 1967.

Hey, R. N., Tectonic evolution of the Nazca-Cocos Rise, Ph.D. thesis, Princeton Univ., Princeton, N. J., 1975.

Holden, J. C., and R. S. Deitz, Galapagos gore, *NAZCOPAC* triple junction and Carnegie/Cocos ridges, *Nature*, *235*, 266, 1972.

Johnson, G. L., P. R. Vogt, R. N. Hey, J. Campsie, and A. Lowrie, Morphology and structure of the Galapagos Rift Zone, *Geol. Soc. Amer. Bull.*, in press, 1976.

Klitgord, K. D., and J. D. Mudie, The Galapagos spreading center: A near-bottom geophysical survey, *Geophys. J. Roy. Astron. Soc.*, *38*, 563, 1974.

Langseth, M. G., Jr., X. Le Pichon, and M. Ewing, Heat flow through the floor of the Pacific Ocean, *J. Geophys. Res.*, *71*, 5321, 1966.

Lister, C. R. B., On the thermal balance of a mid-ocean ridge, *Geophys. J. Roy. Astron. Soc., 26*, 515, 1972.
Morgan, W. J., Plate motions and deep mantle convection, studies in earth and space physics: Memoir to H. H. Hess, *Geol. Soc. Amer. Mem., 132*, 7, 1973.
Raff, A. D., Sea-floor spreading: Another rift, *J. Geophys. Res., 73*, 3699, 1968.
Ribando, R. J., and D. L. Turcotte, Numerical models for hydrothermal circulations in oceanic crust (abstract), *Eos Trans. AGU, 56*, 381, 1975.
Sclater, J. G., and K. D. Klitgord, A detailed heat flow, topographic, and magnetic survey across the Galapagos Spreading Center at 86°W, *J. Geophys. Res., 78*, 6951, 1973.
Sclater, J. G., R. N. Anderson, and M. L. Bell, The elevation of ridges and the evolution of the central eastern Pacific, *J. Geophys. Res., 76*, 7888, 1971.
Sclater, J. G., R. P. Von Herzen, D. L. Williams, R. N. Anderson, and K. Klitgord, The Galapagos Spreading Center: Heat flow low on the north flank, *Geophys. J. Roy. Astron. Soc., 38*, 609, 1974.
Tréhu, A., Depth versus age$^{1/2}$; a perspective on mid-ocean rises, *Earth Planet. Sci. Lett.*, 1975.
Vogt, P. R., and G. L. Johnson, Marine telechemistry of oceanic crust, *Nature, 245*, 373, 1973.
Vogt, P. R., O. E. Avery, E. D. Schneider, C. N. Anderson, and D. R. Bracey, Discontinuities in sea-floor spreading, *Tectonophysics, 8*, 285, 1969.
Von Herzen, R. P., and R. N. Anderson, Implications of heat flow and bottom water temperature in the eastern equatorial Pacific, *Geophys. J. Roy. Astron. Soc., 38*, 587, 1972.
Von Herzen, R. P., and A. E. Maxwell, The measurement of thermal conductivity of deep-sea sediments by a needle-probe method, *J. Geophys. Res., 64*, 1557, 1959.
Von Herzen, R. P., and S. Uyeda, Heat flow through the eastern Pacific Ocean floor, *J. Geophys. Res., 68*, 4219, 1963.
Williams, D. L., R. P. Von Herzen, J. G. Sclater, and R. N. Anderson, The Galapagos spreading center; lithospheric cooling and hydrothermal circulation, *Geophys. J. Roy. Astron. Soc., 38*, 587, 1974.

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