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A major geothermal anomaly in the Gulf of California

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We have mapped a 3-km wide, high heat flow anomaly with a maximum value of 30 μcalorie cm $^{-2}$ s^{-1} within a zone of seafloor extension in the central Gulf of California. From seismic reflection data and thermal modelling we suggest that the anomaly is caused by a 1-km wide basaltic intrusion which is roughly 100 m deep and less than 18,000 yr old.

SEAFLOOR spreading associated with the East Pacific Rise can be extended to inside the mouth of the Gulf of California, by correlating magnetic lineations[1]. Further into the gulf the magnetic lineations are either disturbed by the thick sedimentary cover, or the lineations are weak or non-existent due to an intrusive or cooling mechanism that is unfavourable to their formation[2]. The San Andreas fault to the north is recognised as the major part of the boundary between two large plates—the Pacific and North American. The Gulf of California is a transitional region between predominantly seafloor spreading to the south and totally transform fault motion to the north. The lack of identifiable magnetic anomalies in the gulf makes it necessary to look for other evidence to support the idea of seafloor extension. The pole of rotation for the Pacific–North American plates is 50.9 °N, 66.3 °W (ref. 3). The trend of the gulf differs sufficiently from a small circle about this pole to require *en echelon* offset of the transform faults and thus requires some seafloor extension in the gulf. Large heat flow[4] and microseismicity[5] in the basins also suggest that the gulf is undergoing extension as well as transform fault motion.

Shepard[6] recognised the similarity between the Gulf of California and the Red Sea and mapped the *en echelon* strike–slip faults and rhombic nature of the basins. Rusnak, Fisher and Shepard[7] related the opening in the gulf to the strike–slip motion of the San Andreas fault and deduced a figure of 260 km of opening, with Cabo San Lucas originally near Banderas Bay, Sinaloa. They considered the central depressions in the Guaymas and Farallon Basins to be extensional features due to their perpendicularity to the strike–slip faults. Larson[1] deduced a half-spreading rate of 30 mm yr^{-1} by correlating magnetic anomaly patterns at the mouth of the gulf. Lawver *et al.*[4] reported on 13 new heat-flow measurements in the Guaymas Basin bringing the then total to 16, with three from Von Herzen[8]. Large values were found in the north-east central Guaymas Deep, >5 HFU (>200 mW m^{-2}) with the greatest being 7.2 HFU (300 mW m^{-2}) near a 160-m high mound in the deep.

Measurements and techniques

The most recent cruise, in October 1974, collected 58 new heat-flow measurements in the Guaymas Basin. Most of the work was concentrated in the north-east Guaymas Deep but some of the most interesting results came from the south-west Guaymas Deep (Fig. 1).

The thermal gradients were measured using the Woods Hole Oceanographic Institution multipenetration heat-flow probe[9]. It consists of a 2.5-m probe with three outrigger thermistor probes at 1-m intervals. Acoustically telemetered data were recorded on a precision depth recorder aboard the RV Agassiz of the Scripps Institution of Oceanography. Navigation consisted of radar fixes and depths later plotted on the satellite navigated bathymetric chart of G. F. Sharman (unpublished). The radar navigation was accurate to about 500 m, with relative positions between individual measurements being better (~250 m), see Fig. 2. The sediments in the Guaymas Basin are extremely uniform and consist almost solely of green hemipelagic mud. Thermal conductivities were assumed from measurements made on previous cruises[4]. The water content is very high in the near-surface sediments causing the conductivity in those shallower than 50 cm to be about 1.5×10^{-3} calorie °C^{-1} s^{-1} cm^{-1} (0.60 W m^{-1} K^{-1}). The conductivity below 50 cm is assumed to be reasonably constant, based on the findings of Lawver *et al.*[4] and is taken to be 1.71×10^{-3} calorie °C^{-1} s^{-1} cm^{-1} (0.71 W m^{-1} K^{-1}). The heat-flow values are shown on the diagram in Fig. 3 and listed in Table 1.

The average sedimentation rate in the central part of the Guaymas Basin is approximately 2.0 m per 1,000 yr (ref. 10). This high sedimentation rate depresses the surface heat flow, requiring approximately a +12% correction according to Fig. 9 of ref. 11. From the seismic reflection profiles in Fig. 5, the south-west Guaymas Deep seems to be underlain by basement which has intruded through older sediments, as evidenced by the apparent 0.8±0.2 s thick sediment to the north and 0.6±0.1 s thick sediment to the south. Later we show that the heat-flow anomaly is consistent with an intrusion of this geometry with an age of about 2×10^4 yr. For this model, the anomaly is completely dominated by the transient cooling of the intrusion and the sedimentation rate has a negligible influence. For purposes of discussion no corrections will be made to the recorded heat-flow values.

Interpretation

Nearly every other region of active seafloor generation is almost devoid of sediments making heat-flow measurements there possible only in isolated sediment ponds. The available heat-flow values from these regions are apparently depressed by hydrothermal circulation. The heat-flow values measured in the Gulf of California are significantly higher than those measured on other spreading centres. Henyey (unpublished) measured a

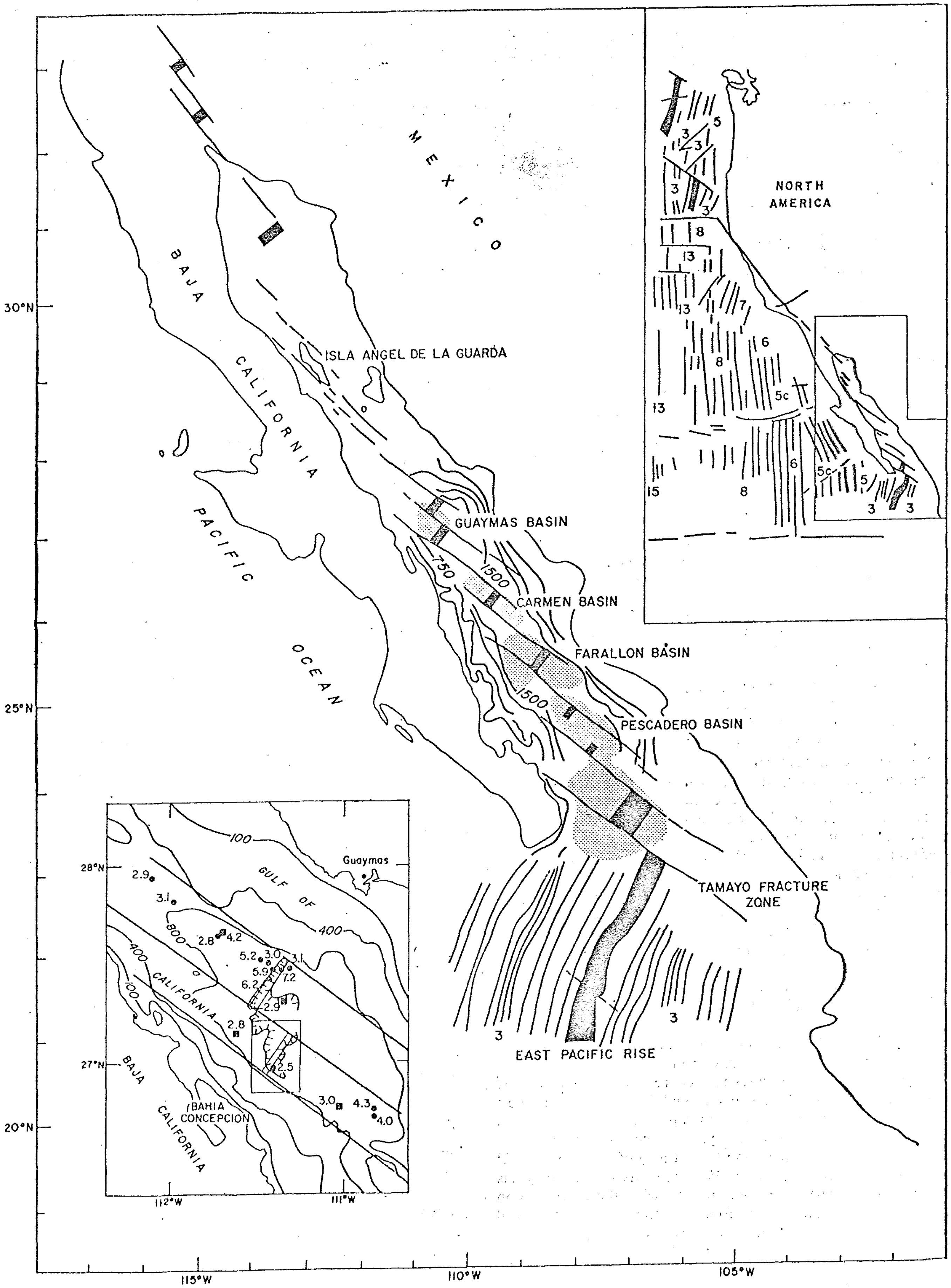


Fig. 1 Lineated magnetic anomalies at the mouth of the Gulf of California, from Larson[1]. Generalised bathymetric lines in gulf in metres. Upper inset map with magnetic anomaly numbers from Atwater[20]. The lower inset is a generalised diagram of the Guaymas Basin from Lawver *et al.*[4] showing heat-flow values, in µcalorie cm^{-2} s^{-1}. Squares indicate values from Von Herzen[8]. Circles from Lawver *et al.*[4]. Box shows area of detailed heat-flow measurements shown in Fig. 2. Heavy lines and stippled areas mark transform faults and areas of active generalised extension, respectively.

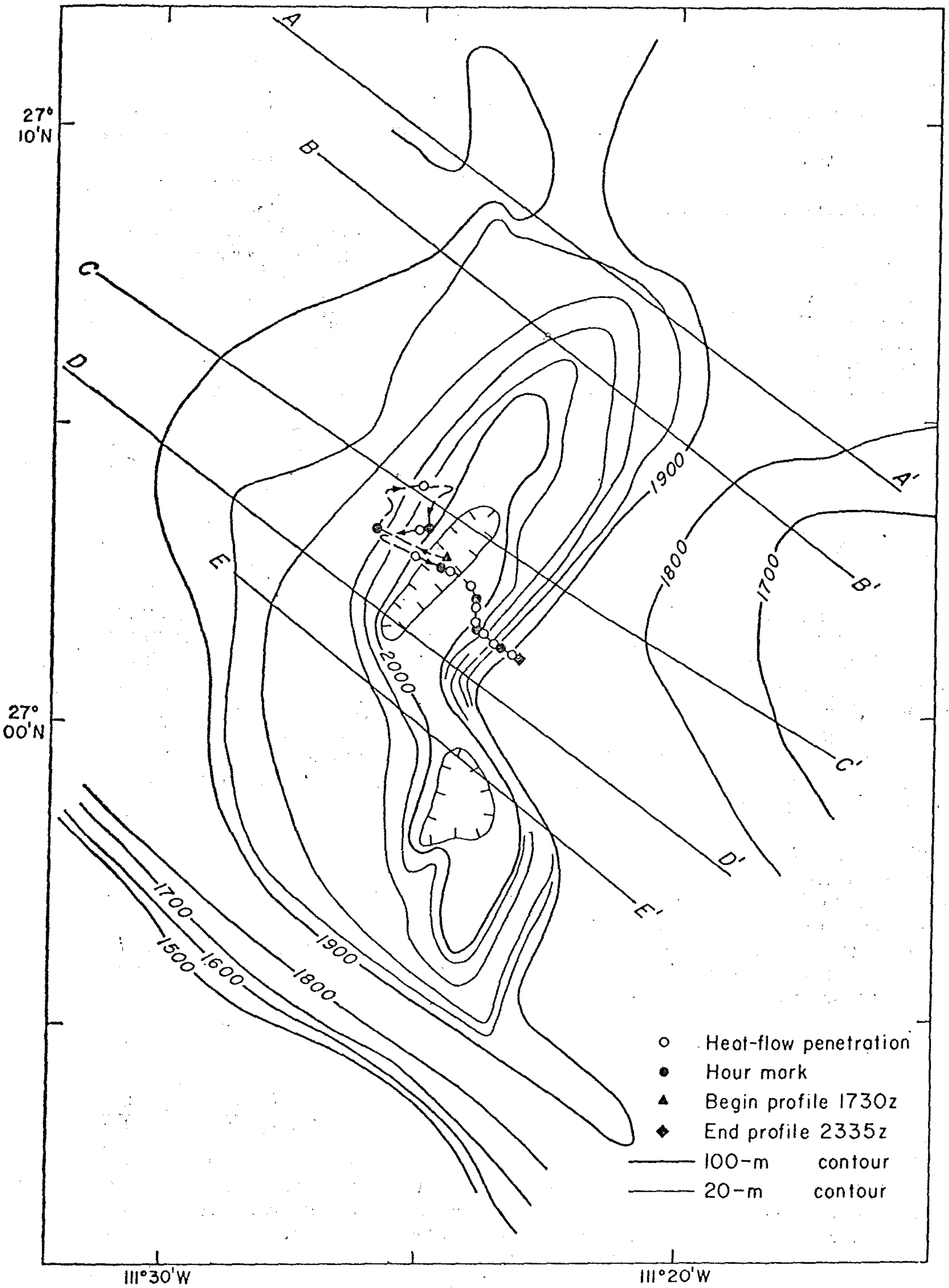


Fig. 2 Detailed chart of heat-flow survey of the south-west Guaymas Deep in corrected metres. Bathymetry from G. Sharman (unpublished). The values progressed from the north-west side of the depression to the south-east side. Seismic reflection profiles A–A′ to E–E′ indicated by solid lines are shown in Fig. 5.

value of 35.8 HFU (1,450 mW m^{-2}) in the Ballenas Channel in the northern gulf but this may be an isolated hot spring.

The heat release associated with lithospheric creation for a spreading rate equivalent to that of the gulf is estimated to be at least 330 calorie s^{-1} per cm of ridge length within 35 km of the spreading centre[12] or an average heat flow of 47 HFU. At most oceanic spreading centres the rate is presumed much higher near the centre due to the faster cooling produced by hydrothermal circulation (compare ref. 12). The Gulf of California is different because the actively spreading zone may be losing heat through the sea floor to a greater extent by conduction because of its unusually thick and continuous sedimentary cover.

Figure 4 shows all the 26 published and new heat-flow values in the Guaymas Basin plotted against distance from the presumed most recent spreading centre. Additional heat-flow values in the Guaymas Basin to be discussed in a subsequent paper reinforce the basic shape of the curve in Fig. 4. It is unusual that the background heat flow for the Guaymas Basin is remarkably regular at 3.4 ± 0.5 HFU for the total length of the basin. The central deep coincides with a higher heat-flow zone less than 20 km wide.

This distribution of conductive heat flow does not fit the theoretical models for a conductively cooled lithosphere (see ref. 13). As can be seen in Fig. 4, the observed heat-flow values average less than half of the predicted value. Two factors, prevalent in the Gulf of California, would tend to make the measured values lie below the theoretical curve. First, the theoretical models assume continuous intrusion whereas in the Gulf of California there is evidence that the location of spreading centres changes discontinuously with time. This idea was first advanced by Bishoff and Henyey[14] on

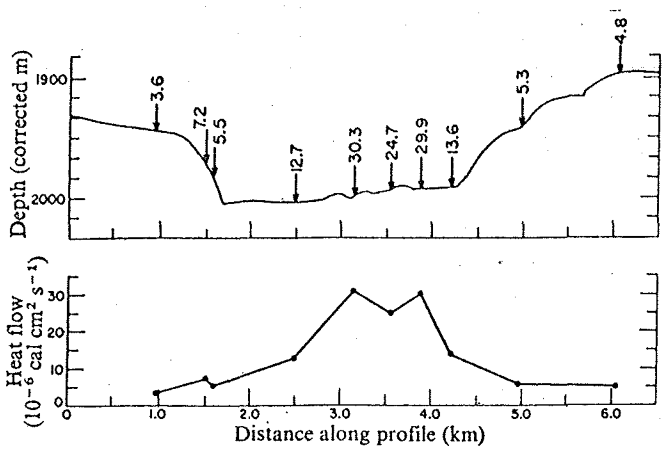


Fig. 3 Profile across the Guaymas Deep showing the heat-flow (HFU) values and the shape of the anomaly found.

the basis of seismic reflection profiles. It is supported by our heat-flow measurements and the reflection profiles shown in Fig. 5. At (*a*) on profile D–D′ (Fig. 5), there is a slight depression which has not been completely filled with sediment; it has an uncertain age relationship to the central intrusion. Probably the depressions are in fact grabens caused by the pulling apart of the basement, resulting in an intrusion and a thinning of the overlying sediment (Fig. 3, ref. 21). The weight and shear strength of the sediments compared with water may cause the intrusion to slow and stop before it reaches the surface. This effect of the sediment may even cause the site of intrusion to change discontinuously rather than remaining fixed as at a normal spreading centre. The second factor that may affect the heat flow is that the ratio of the widths of spreading centres to the length of transform faults is much less in the Gulf of California than in more normal oceanic spreading areas. This could lead to significant lateral heat transfer. Although these factors redistribute heat to the flanking regions and away from the actively spreading locations, the total heat loss remains approximately the same and thus will not explain the great discrepancy between the predicted and observed heat flows.

Assuming that seafloor spreading applies in the gulf, the most plausible explanation for the discrepancy is hydrothermal heat loss even though there is a thick sediment cover. The existence and importance of hydrothermal convection in the basement have been discussed by numerous investigators (see reference lists in refs 12 and 15). The porosity and permeability would be related to dike contacts, the dissolution of minerals by thermal waters, the horizontal component of thermal contraction, and faulting. In the gulf the evidence is not as compelling as it is at other spreading centres. There is no evidence of numerous low heat-flow values and the large scatter in observed values that have supported previous hydrothermal circulation hypotheses. We made approximately 50 km of near-bottom horizontal water temperature profiles (see ref. 12) in the north-east Guaymas Basin but failed to detect any temperature anomalies that might be associated with hydrothermal vents. Evidence for sediment that was more metalliferous than normal was found only in the southernmost basin of the gulf (P. Wilde, personal communication). Since this basin is nearest to the East Pacific Rise and has a much thinner sediment cover[16] it is more likely to be subject to hydrothermal discharge through the sediment surface. In the heavily sedimented Guaymas Basin, where the sediments are assumed to be relatively impermeable and there is very little expression of faulting in the surface sediments, it is hard to imagine the free convection that Williams *et al.*[12] found on the Galapagos spreading centre.

Thermal modelling

With the line drawings of seismic reflection profiles crossing the south-west Guaymas Deep (shown in Fig. 5), available as control, the heat-flow data were inverted under the assumption of conductive cooling. We first used Horai's model[17] for a dike intruded instantaneously and remaining at a constant temperature for infinite time. This model yields a 1.6-km wide intrusion with a depth to its top of 220 ± 30 m, using a background heat flow of 3.4 ± 0.5 HFU. But this gives either an unacceptably high surface thermal gradient (5 °C cm^{-1}) or a temperature too low for molten rock (400 °C). This result implies that the measured heat-flow values are not due to a constant temperature intrusion but rather to a transient cooling process. Therefore, we used Simmons'[18] method for modelling the transient cooling of a dike, which is a variation of that given by Carslaw and Jaeger (ref. 19, p. 256). The temperature for a dike is given as:

$$T(x,y,z,t)=(S/8)\ E(x,x_1,x_2)E(y,y_1,y_2)\{E(z,z_1,z_2)+ +E(z,-z_1,-z_2)\}$$

where S=source strength, which for a three-dimensional source is simply the temperature at the time of the intrusion, here assumed to be 1,100 °C; x_1 and x_2 are coordinates defining the width of the dike; y_1 and y_2 give the lateral extent of the dike; z_1 and z_2 are the depths to the top and bottom respectively and E is a dimensionless function defined as:

$$E(\xi,\ \xi_1,\ \xi_2) \equiv \text{erf}\frac{\xi-\xi_1}{(4kt)^{1/2}} - \text{erf}\frac{\xi-\xi_2}{(4kt)^{1/2}}$$

where t is the time after intrusion and k is thermal diffusivity. If one assumes y_1 and y_2 are large, greater than $3(4kt)^{1/2}$, then $E(y,y_1,y_2)$ is two. For a time of 10^4 yr the absolute value of y_1 or y_2 would have to be larger than 0.8 km. Using Figs 2 and 5, it seems that $y_1=-2.0$ km and $y_2=6.0$ km. z_2 is the

Table 1 Heat-flow data

Station no.	Latitude (°N)	Longitude (°W)	Water depth (corrected m)	T	P	N	K	Q
12.1	27°04.0′	111°24.4′	2,004	2.82	2.7	3	1.71 (0.72)	5.5 (230)
12.2	27°03.6′	111°24.9′	1,988	2.82	2.7	3	1.71 (0.72)	7.2 (301)
12.3	27°03.1′	111°25.8′	1,955	2.82	2.7	3	1.71 (0.72)	3.6 (151)
12.4	27°02.6′	111°24.6′	2,024	2.83	2.7	2	1.71 (0.72)	12.7 (531)
12.5	27°02.4′	111°24.3′	2,020	2.82	2.7	1	1.71 (0.72)	30.3 (1268)*
12.6	27°02.2′	111°24.0′	2,014	2.82	2.7	1	1.71 (0.72)	24.7 (1033)*
12.7	27°02.0′	111°24.0′	2,012	2.82	2.7	1	1.71 (0.72)	29.9 (1251)*
12.8	27°01.8′	111°23.9′	2,010	2.82	2.7	3	1.71 (0.72)	13.6 (569)
12.9	27°01.5′	111°23.7′	1,952	2.83	2.7	3	1.71 (0.72)	5.3 (222)
12.10	27°01.3′	111°23.4′	1,898	2.83	2.7	3	1.71 (0.72)	4.8 (201)

T is bottom water temperature (°C); P is estimated sediment penetration (m) of the lowermost probe used in gradient measurements; N is the number of thermistors used for sediment temperature gradient measurements; K is the thermal conductivity in 10^{-3} calorie °C^{-1} cm^{-1} s^{-1} (W m^{-1} K^{-1}) (All values are assumed); Q is the heat flow in 10^{-6} calorie cm^{-2} s^{-1} (10^{-3} W m^{-2}).
*Only one thermistor on scale.

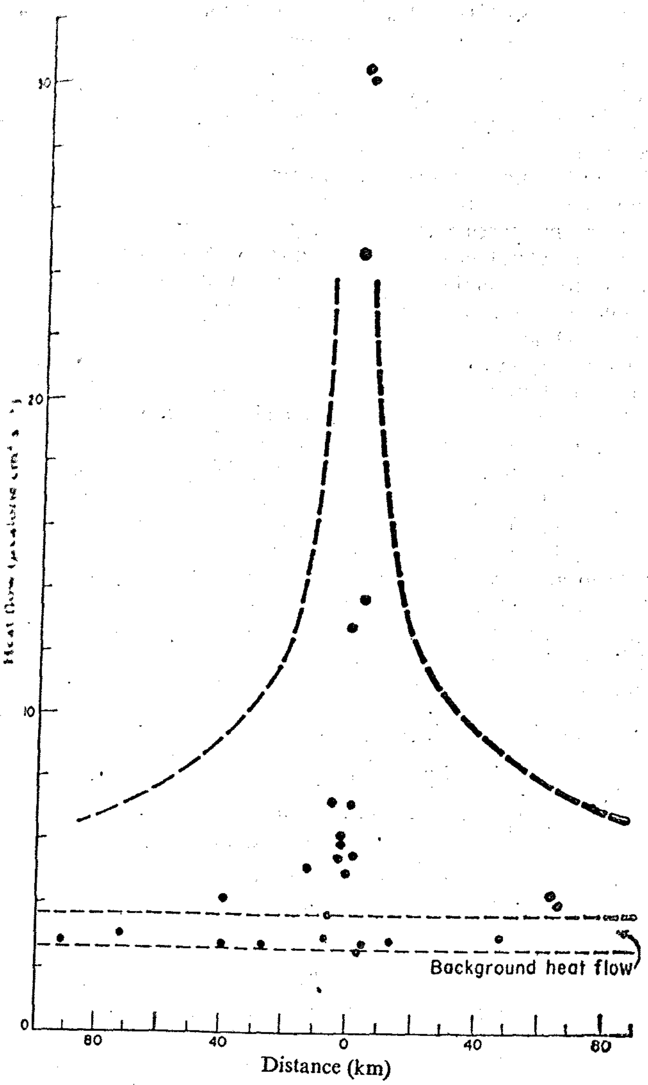


Fig. 4 Summary of the previous published values and the ten new values. The background heat flow is roughly 3.4±0.5 HFU (135±20 mW m^{-2}). The heat flow anomaly is strikingly regular directly over the depressions confirming them as the locus of present intrusive activity.

depth to the base of the dike which we assume is large in comparison to z_1. If z_2 is just twice z_1, it affects Q_z only 2%.

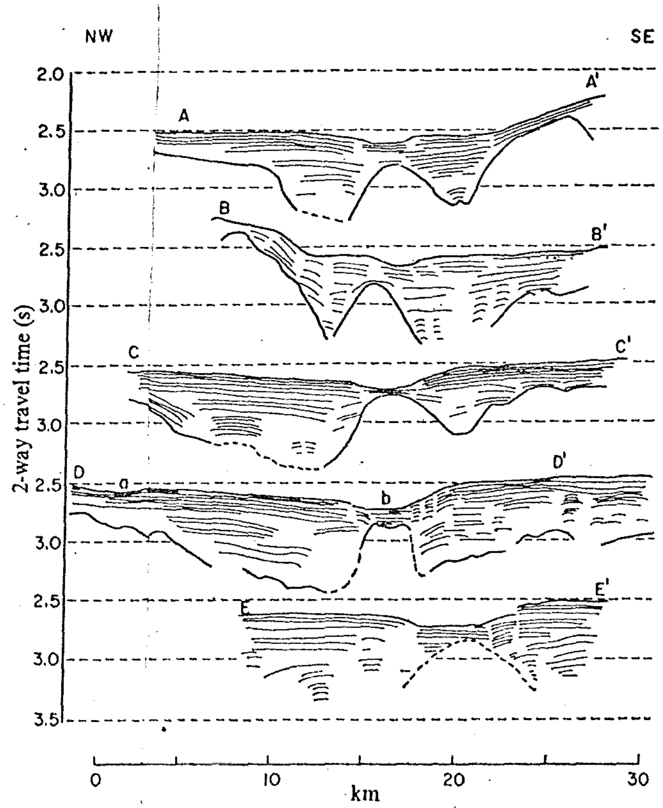
Simmons (ref. 18, equation 17) gives the surface heat-flow distribution as:

$$Q_z|_{z=0} = \frac{-KS}{2(\pi k t)^{1/2}} E(x,x_1,x_2)[\exp(-z_1^2/4kt)-\exp(-z_2^2/4kt)]$$

In this model, the same thermal properties are assumed for the dike as for the material into which it is intruded. We assume the thermal properties of sediments to be more realistic because the cooling is probably dominated by the insulating properties of the sediment. But the igneous body should be able to release heat faster, and should be younger than our solutions indicate. In Fig. 6 however, we show that both sediment and igneous rock thermal properties can be made to match the data. We have taken a conductivity, K, of 2×10^{-3} calorie $°C^{-1}$ s^{-1} cm^{-1} (0.83 Wm^{-1} K^{-1}) and diffusivity, k, of 2.35×10^{-3} cm^2 s^{-1} to approximate a slightly compacted sediment column[20]. Even greater values might be expected considering the probable metamorphism of the sediments directly above the intruded body. From the seismic reflection profile D–D′ shown in Fig. 5, it seems that the anomaly is due to an intrusion that is directly underneath the depression. From Fig. 5 the intrusion seems to be present and approximately the same shape on profiles A–A′ through D–D′ and is vague but present on E–E′. The intrusion seems to extend from one transform fault to the other. On profile D–D′, closest to the profile of heat-flow stations, the depth to the top of the intrusion seems to be about 120–200 m. Figure 6 shows that using a depth of 200 m and removing the background heat flow, our anomaly is closely matched with a width of 1.3 km, and an age of 17,000 yr. For this model a maximum heat flow of 53 HFU would be reached at about 2,700 yr after the emplacement of the intrusion. The observed heat-flow maximum of 30 HFU is found twice for any model that assumes $z=200$ m, once at about 1,000 y and again at 17,000 yr. The earlier time value seems unacceptable because it produces a very steep-sided anomaly as shown in Fig. 6, unlike the profile measured. If one assumes a depth to intrusion of 100 m, then an age of 18,000 yr very nearly models the observed anomaly. A greater depth to the intrusion is more difficult to model with thermal properties of sediments, although the thermal properties of the intrusive rock will fit the observed curve for a depth to intrusion of slightly greater than 500 m.

The seismic reflection profile indicates that the base of the intrusion may be 4 km in width, equivalent to about 65,000 yr of spreading at the half-rate of 30 mm yr^{-1}. It seems plausible to assume that the most recent intrusion is simply the latest in a continuing series of recent intrusions now totalling 4 km. If the most recent intrusion was emplaced into an older intrusion not at thermal equilibrium then our model would be less representative and much more recent ages of intrusion are possible. A 1.3 km wide intrusion would account for 21,000 yr of spreading. Since we have more than 42 m of sediment (2 m per 1,000 yr for 21,000 yr), we assume that the intrusion has always been covered. Hydrothermal cooling which might account for removal of about half the heat would be roughly equivalent to doubling the thermal conductivity (similar to the conductivity

Fig. 5 Line drawings of seismic reflection profiles. Line of profiles shown on Fig. 2. In profile D–D′, a indicates a possible depression that is either just forming or is being filled and b indicates the area of the main heat-flow anomaly.



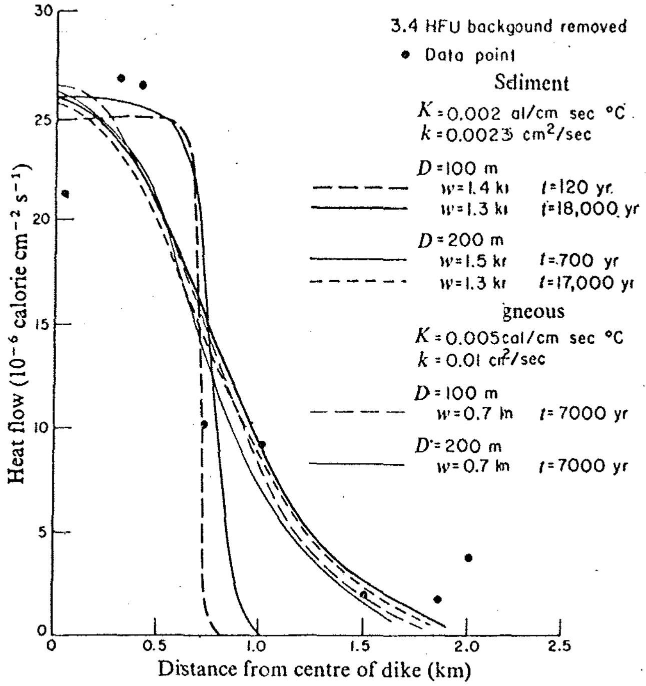


Fig. 6 Results of Simmon's[18] model for heat-flovproduced by a cooling intrusion.

of the intrusive rock). Although there are manyvariable parameters not defined by our data, the results from he model can be summarised as indicating an intrusion approxmately 1.0 km wide, beneath 150±100 m of sediments and less:han 18,000 yr old.

Conclusions

Our findings allowed us to use heat-flow measurenents to model a reasonably young intrusion, something that is nrely achieved. It does seem reasonably certain from our result that the gulf is not being opened by a continuing constant ntrusion as is presumed at most oceanic spreading centres. Discontinuous and episodic intrusions into a thick sedimentar cover would explain the lack of magnetic anomalies in the gulf. Apparently the intrusion is continuous between transform faults and is believed contemporaneous.

The Gulf of California has an average sedinent depth of about 1 km (ref. 16). This, coupled with the high background heat flow, suggests that temperatures of 200 °C should generally be found near the sediment-rock interface. This is in addition to large areas where the thermal gradient is several times as high. If the upper regions of the basement are as porous and permeable as we believe, the Gulf of California would be one of the Earth's most important geothermal resources. This theory, though, can only be tested by drilling.

More measurements are needed in this area to trace the assumed lateral extent of the anomaly. Since the intrusion seems to be continuous between the transform faults, one would hope that the heat flow remains uniformly high in this region. Other sites in the Guaymas Basin and particularly the Farallon Basin to the south may be undergoing current intrusion and should be investigated.

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Three-dimensional model of purple membrane obtained by electrcn microscopy

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A 7-Å resolution map of the purple membrne has been obtained by electron microscopy of tilted, unstained specimens. The protein in the membrane contains seven, closely packed, α-helical segments which extend roighly perpendicular to the plane of the membrane for mos of its width. Lipid bilayer regions fill the spaces betweei the protein molecules.

THE purple membrane is a specialised part of the cell membrane of *Halobacterium halobium*[1]. Oesterhelt and Stoeckenius[2] have shown that it functions *in vivo* as a light-driven hydrogen ion pump involved in photosynthesis. It contains identical protein molecules of molecular weight 26,000, which make up 75% of the total mass, and lipid which makes up the remaining 25% (ref. 3). Retinal, covalently linked to each protein molecule in a 1:1 ratio is responsible for the characteristic purple colour[3]. These components together form an extremely regular two-dimensional array[4].

We have studied the purple membrane by electron microscopy using a method for determining the projected structures of unstained crystalline specimens[5]. By applying the method to tilted specimens, and using the principles put forward by