Reports

Geothermal Convection Through Oceanic Crust and Sediments in the Indian Ocean

Abstract. *Closely spaced heat flow surveys at four sites on the flanks of the Central Indian Ridge and the Southeast Indian Ridge delineate a pattern of oscillatory heat flow which can only result from cellular convection of oceanic bottom water through the oceanic crust and overlying sediment. These cells have a wavelength of 5 to 10 kilometers and are presently active in sea floor 18 × 10⁶, 25 × 10⁶, and 45 × 10⁶ years old of the Crozet Basin and in sea floor 55 × 10⁶ years old of the Madagascar Basin. The precise measurement of nonlinear temperature profiles makes it possible to calculate the conductive and convective heat transfer components through the sea floor. Even in the oldest sites, geothermal convection is still a major component of heat transfer through both the crust and sedimentary layers. These observations coupled with the results of earlier oceanwide geothermal studies indicate that more than one-third of the entire surface area of the world's ocean floor contains presently active geothermal convection that is cellular in plan form.*

The heat content of the oceanic lithosphere at any given age is thought to be known since theoretical models which calculate the thermal contraction of the lithosphere can be used to accurately predict the observed subsidence of the sea floor away from the intrusion zones of midoceanic ridges (*1*). Yet recent marine geothermal studies have shown quite conclusively that surface heat flow near midoceanic ridges is controlled not by conductive processes but by convective heat loss due to seawater circulation between the crust and the ocean (*2*, *3*). An observed transition from convective to conductive geothermal regimes is believed to be due to the capping or isolation of this crustal convection system from the oceanic bottom water by a sedimentary layer much less permeable than the crust or by the loss of permeability within the oceanic crust as cracks are sealed by metamorphic precipitates, or both. For example, in the eastern Pacific the transition occurs in sea floor 10×10^6 to 15×10^6 years old: crust younger than this has lower conductive heat flow than that predicted by theoretical plate models, and older crust has mean conductive heat flow in general agreement with the predictions (*4*).

Seawater convection within the oceanic crust is removing a substantial part of the geothermal heat near ridge crests, so that earlier experiments designed only to measure the conductive heat transport through the sea floor have not measured this convective component. The result is anomalously low heat flow observations. The flanks of all midoceanic ridges are characterized by such low conductive heat flow (*5*). Sufficiently detailed sampling programs have rarely been made so that the form of the convective heat loss remains obscure. Only at one ridge axis do we have such detail. Williams *et al.* (*2*) mapped an oscillatory variation in heat flow on the Galápagos spreading center that must be attributable to cellular convection of seawater through a porous medium, the oceanic crust.

We report here the first detailed heat flow measurements on the old flanks of a midoceanic ridge system. We have discovered oscillatory heat flow patterns caused by geothermal convection in Crozet Basin sea floor 18×10^6, 25×10^6, and 45×10^6 years old and in Madagascar Basin sea floor 55×10^6 years old in the Indian Ocean (Fig. 1). The spacing of our measurements has been sufficiently close to give a more representative look at the way the flanks of midoceanic ridges cool; the picture is quite different from the simple plate tectonic concept of monotonic cooling away from midoceanic ridge axes. By carefully measuring the nonlinearity of temperature profiles, we have calculated both the conductive and convective components of the total heat flow at the sea floor. Significant convective heat transfer is occurring through the crustal and sedimentary layers even at the oldest (55×10^6 years) experimental site.

The observations presented below are characterized by (i) a spatial oscillation (Fig. 1) similar to that observed on the Galápagos Ridge crest and (ii) a predominance of nonlinear temperature profiles (Fig. 2). Such explanations for the cause of this nonlinearity as fluctuations in the bottom water temperature, internal heat sources, or variations in the thermal conductivity can be ruled out. Kolla *et al.* (*6*) have shown that Antarctic bottom water from the Weddell Sea covers the sea floor of the two basins where our measurements were made, the Crozet and Madagascar basins. This bottom water mass is one of the coldest and most stable in all of the oceans. It is unlikely that significant fluctuations in the bottom water temperature occur in these Indian Ocean basins. Major temperature variations over a few kilometers of flat sea floor would be required to explain the contrasting temperature profiles measured at adjacent stations. The low organic content of the predominantly clay sediments in these basins rules out internal heat generation due to chemical reactions in the surface sediments. We made detailed thermal conductivity measurements in each of our survey areas (Fig. 3). With the exception of one manganese layer 5 cm thick in one of the cores, the thermal conductivity never ranges more than 10 to 15 percent about the mean. Even in the thin manganese layer, the thermal conductivity increases by less than 50 percent (Fig. 3, core C140). Furthermore, there is no systematic variation with depth which could account for the nonlinearity in temperature profiles (Fig. 2). We know of only one physically realistic mechanism which can account for the intermixing over a few kilometers of convex, linear, and concave temperature profiles (Fig. 2): predominantly vertical convection of fluid through the surface sedimentary layer. We thus interpret the degree of nonlinearity to directly reflect the velocity of flow of convecting fluid through the upper surface of the sedimentary layer. Since the aspect ratio (width divided by depth) of the crustal convection system is thought to be near unity (*7*) (indeed, the wavelengths we observe are 5 to 10 km) and since our measurements of the variation of temperature with depth are only spot samples of the upper 5 m of the top surface of the convection system, we can choose a one-dimensional model to interpret each individual temperature profile. For a uniformly permeable porous medium with fluid convecting through it at a mass flux (v), the temperature (T) varies with depth (z) as (*8*)

$$\frac{T(z) - T_0}{T_L - T_0} = \frac{e^{\beta z/L} - 1}{e^{\beta} - 1} \qquad (1)$$

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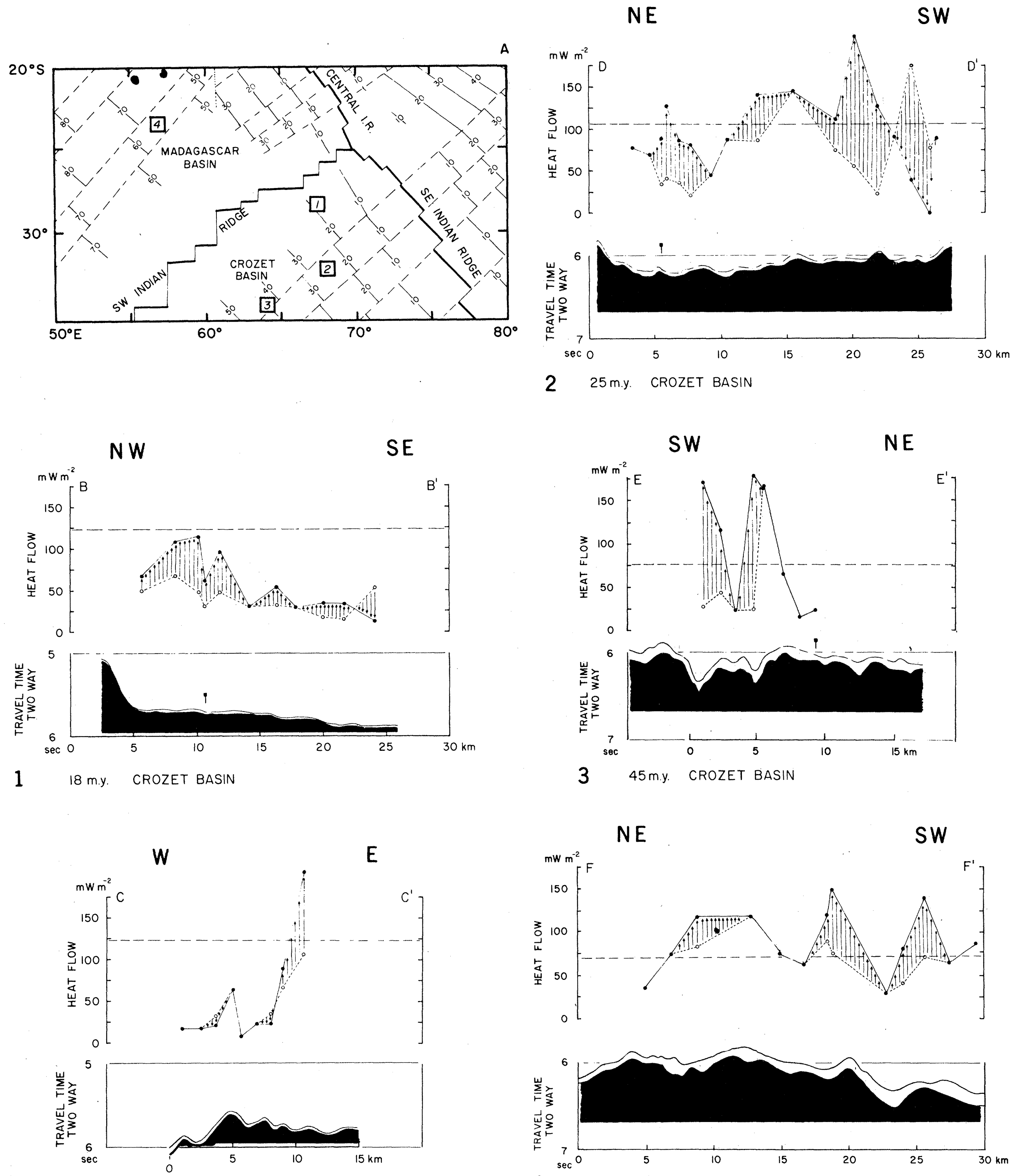

Fig. 1. (A) Isochrons [ages in 10^6 years (*m.y.*)] in the central Indian Ocean (*5*). Boxes denote heat flow survey areas. Heavy lines are ridge axes. Dashed lines are fracture zones. The two black spots at the top are Mauritius and Réunion Islands. (B and C) Survey 1. Line B–B′ is parallel to the 18×10^6 year isochron and bears an oblique relation to line C–C′. The open circles are conductive components of the total heat flow (closed circles). The arrows indicate the quantity and direction of the convective heat loss calculated from the fit to nonlinear gradients (Fig. 2). The dashed line represents the predicted heat flow value for this age from theoretical plate models. Obviously, heat is missing from this survey area. The double line at the bottom is the sedimentary thickness from seismic reflection profiling and 3.5-kHz echo sounder records over the survey area. The black area is the basement depth. The piston core (TG27) location is shown above the topography. (D) Survey 2. Symbols are the same as above. The profile is perpendicular to the isochrons. Little heat is missing in this area, but convection is still occurring through the sedimentary layer. The piston core (TG25) location is shown. (E) Survey 3. This survey was cut short by engine failure at 35°S in the Crozet Basin, an area of excessively rough seas. The piston core (TG26) location is shown. (F) Survey 4. No heat flow is missing in this area but cellular convection in the crust and sediments is evident. In fact, the total heat flow appears to be slightly greater than the theoretical predictions. Piston core (C140) was taken along this profile.

where T_0 and T_L are, respectively, the top and bottom temperature measurements. The Peclet number (β) is $v\rho c L/K$, where ρ is the density, c is the specific heat of the convecting fluid, L is the length over which the temperatures are measured, and K is the thermal conductivity of the water-saturated porous medium. At any z, the total heat flow is

$$q = -K \left.\frac{dT}{dz}\right|_z + v\rho c\, T(z) \qquad (2)$$

From Eq. 1

$$\frac{dT}{dz} = (T_L - T_0)\,\frac{v\rho c}{K}\left(\frac{e^{\beta z/L}}{e^{\beta} - 1}\right) \qquad (3)$$

and

$$q = v\rho c\left(T_0 - \frac{T_L - T_0}{e^{\beta} - 1}\right) \qquad (4)$$

Thus, if β is measured, then the total heat flow can be calculated. For the experiments presented below, we have developed a special probe (5 m long) with five discrete temperature sensors plus a "surface probe" which measures the precise sedimentary gradient between the bottom water and a depth of 10 cm into the sedimentary layer. By using this surface probe, we have verified that the temperature gradient at the sea-floor interface is indeed that calculated from a β-curve fit to the deeper temperature measurements (Fig. 2).

By fitting a value of β to each nonlinear temperature profile, we have calculated both the conductive and total heat flow at each measurement site from Eq. 4. We estimate the accuracy of the total heat flow value calculated in this way to be ± 15 percent (this estimate is based upon an analysis of the error in the goodness of fit of the β curve to the discrete temperature points along each nonlinear temperature profile. We estimate an accuracy of ± 5 percent for the determination of q where $\beta = 0$ (linear temperature profile) (9).

A value for β of 1.0 corresponds to a fluid flux of about 5×10^{-8} m sec^{-1} for deep-sea clays typically found in our Indian Ocean survey areas.

We have conducted four detailed surveys in the Indian Ocean (Fig. 1) in order to delineate the convection pattern in the Crozet and Madagascar basins.

Survey 1, Crozet Basin sea floor 18 × 10^6 years old. This survey area is located on magnetic anomaly 6 in the northern Crozet Basin (Fig. 1A) in an area of 10 to

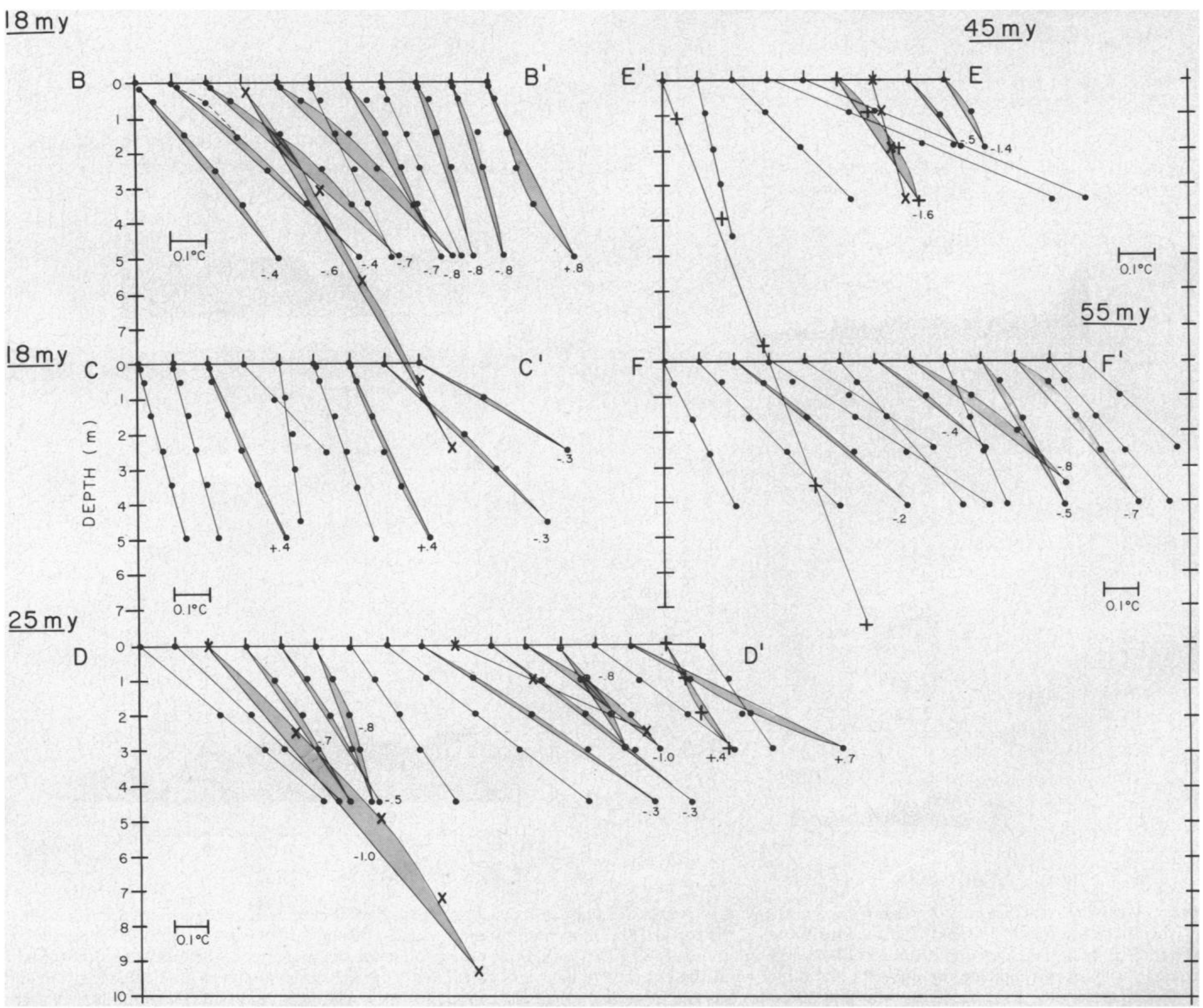

Fig. 2. Temperature profiles measured in each survey area of Fig. 1. Shaded curves with numbers are nonlinear β-curve fits. Different symbols represent different profiles. A positive β indicates downward water flow. With this type of presentation, the shaded area under the β curve for any value of β increases as the slope of the thermal gradient increases. Linear gradients are least-squares fits. For nonlinear temperature profiles, the two heat flow values plotted in Fig. 1 are the β-curve corrected total heat flow (closed circles) and the heat flow assuming a more traditional conduction-only model (open circles). These latter values were obtained from least-squares linear fits. Piston core measurements extend to greater depths (up to 15 m) than the digital heat flow measurements (5 m) and so cross from one profile to the next below. The depth scale remains constant and continues from profile to profile. Abbreviation: *my*, million years.

20 m of red clay draping a smooth basement (Fig. 1). Areas of unusually smooth topography were chosen for each survey so that controlled experiments might be carried out in which the effect of increasing sedimentary thickness could be evaluated. Measurements in survey 1 were made both along and across isochrons in an only partially successful attempt to test for possible three-dimensionality of the convection pattern. Nine heat flow measurements, each with a penetration of 5 m, were made at approximately 1-km spacing across isochrons (C-C′ in Fig. 1), yielding an oscillatory convection pattern with an approximately 5-km wavelength. Four temperature profiles were nonlinear; two were convex, indicating areas of fluid discharge, and two were concave, indicating areas of recharge (Fig. 2). All of the heat flow values except one were below the theoretically predicted heat flow value for sea floor of this age (*1*). Conductive heat flow was determined by a least-squares linear fit to the temperature points (Fig. 1). Thus, these heat flow values compare with those reported in earlier regional surveys in the Indian Ocean (*5*).

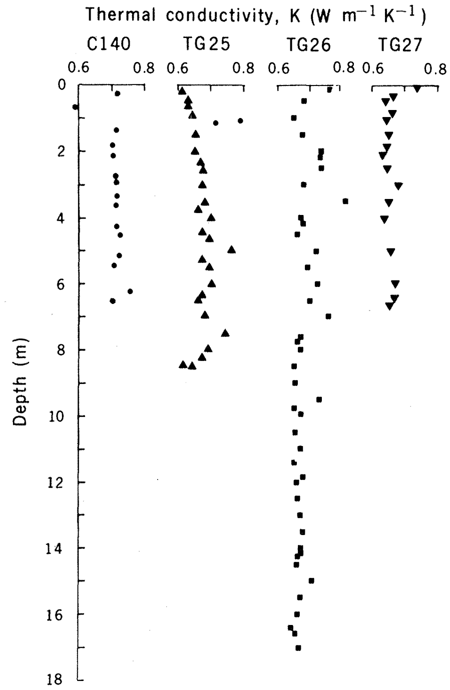

Fig. 3. Thermal conductivity (K) measurements by the needle-probe method from cores in survey areas 1 (TG27), 2 (TG25), 3 (TG26), and 4 (C140). The high K values of core C140 are from a manganese micronodule layer 5 cm thick. The K values just above and below this thin layer are close to the mean for the whole core. The nonlinearity of Fig. 2 obviously cannot be caused by a variation of K with depth. Regionally, K remains uniform over large portions of the Indian Ocean sea floor [see (*5*) for a contour map of K].

An additional profile in survey 1 was made along the strike of both the topographic relief and the isochrons (B-B′ of Fig. 1). As in the earlier case, an oscillatory pattern was measured but the wavelength was approximately 20 km. The longer wavelength may indicate that this profile crossed a convection cell at an oblique angle. From our limited data we cannot tell whether the heat flow pattern is two- or three-dimensional. Nine of 11 temperature profile measurements were nonlinear (Fig. 2); eight have convex upward shapes and one curvature is clearly concave, indicating a flow of water downward in a convective recharge area (Fig. 2). Concave thermal gradients should be observed only where the sediment is sufficiently thin so that our lowermost temperature point is within the thermal boundary layer at the sediment-rock interface. If the sediment is sufficiently thick, the recharge areas should be characterized by linear but very low thermal gradients and no concave gradients should be measured. As in the earlier case, the total heat flow in this area is well below the predicted or theoretical value. No correlation was observed between areas of upwelling and downwelling fluids and topographic highs and lows (*2*).

Survey 2, Crozet Basin sea floor 25 × 10⁶ years old. This survey was carried out in an area of subdued topography (D-D′ of Fig. 1) with 20 to 40 m of predominantly deep-sea clay with minor components of marl. Seventeen measurements along a 25-km profile across the isochrons show an oscillatory pattern of heat flow of varying wavelengths (5 to 10 km), with the mean of all of the measurements approaching but still below the theoretical prediction for this age of sea floor. Thus, the convection pattern at first glance appears closed to the convective exchange of heat between the oceanic crust and the bottom water. Yet, ten nonlinear profiles (eight convex and two concave) indicate that a significant volume of circulating fluid is discharging through the sedimentary layer (Fig. 2). We interpret the results from this survey area as indicating the presence of a uniform blanket of clay isolating the oceanic crust from the oceanic bottom water. All of the heat transfer, both conductive and convective components, is occurring through the sedimentary layer. There is a consistent variation in thermal gradients across the convective cell width and a gradual transition from convex to concave temperature profiles across the convection cells (Fig. 2). Here, as in survey 1, the zones of upwelling and downwelling do not appear to correspond to topographic highs or lows.

Survey 3, Crozet Basin 45 × 10⁶ years old. This is an area of rougher topographic relief near anomaly 17 in the central Crozet Basin (E-E′ of Fig. 1). The sedimentary cover consists of 100 m of clay blanketing all of the basement relief. The convection pattern outlined by this small survey of nine measurements, although not as definitive as in the other areas, has a mean value slightly greater than the theoretical for sea floor of this age and a wavelength of approximately 5 km. The three nonlinear gradients recorded at this site were associated with sea-floor depressions (Figs. 1 and 2).

Survey 4, Madagascar Basin 55 × 10⁶ years old. This oldest survey area (F-F′ of Fig. 1) is also the roughest and the most thickly sedimented (Fig. 2). More than 100 m of deep-sea clay blanket the basement completely. The heat flow values have a mean value higher than the theoretical and vary with a wavelength of 5 to 10 km. Here, out of 13 measurements, five were nonlinear temperature profiles (Fig. 2). There appears to be no diminution of the convective pattern at this old site compared to that at the younger sites, and fluid is still convecting through the sediments. The mean value of β for the nonlinear measurements at this site is 0.75. This corresponds to a flow velocity of about 3×10^{-8} m sec^{-1}. Thus, convecting fluid is passing com-

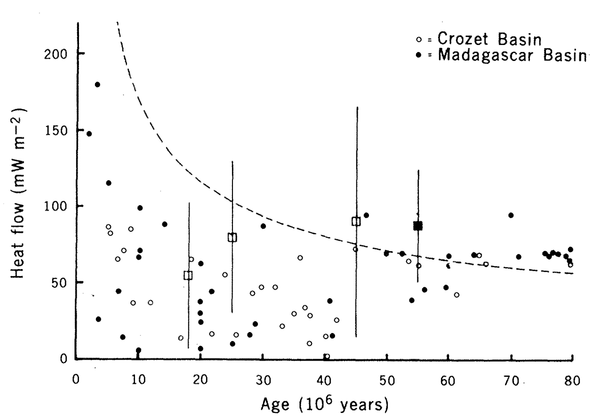

Fig. 4. Regional heat flow values in the Crozet and Madagascar basins (*5*). The boxes represent the total mean heat flow values of surveys 1 through 4 from this report. The vertical lines are the standard deviations. The dashed curve is the average theoretical heat flow curve which predicts monotonic cooling away from the axes of midoceanic ridges (*5*). Means of survey areas 2 and 3 approach the theoretical curve at a younger age than the regional values would predict.

pletely through the sedimentary layer in approximately 300 years.

A total of 59 measurements yielded 31 nonlinear temperature profiles (the rest are remarkably linear, to 0.005°C). Of these 31, 23 are in the survey areas 18×10^6 to 25×10^6 years old. Although the number of nonlinear temperature profiles appears to decrease with age, the flow rates through the sediments remain similar since the flow parameter β does not decrease with age. In addition, the amplitude of the heat flow pattern varies both between and within the survey areas. Since several hundred meters or more of insulating mud would be required to damp the temperature variation caused by the convection pattern in the oceanic crust, we conclude that the amplitude as well as the wavelength varies from cell to cell.

It had earlier been thought that convection within the oceanic crust might stop at ages corresponding to the transition from low to normal heat flow on the flanks of midoceanic ridges (*5*). This transition occurs in sea floor 40×10^6 to 60×10^6 years old in the Crozet and Madagascar basins (Fig. 4). Our heat flow measurements show large-amplitude, small-scale geothermal variations that can only be explained as the result of vigorous convective heat transfer in the oceanic crust. This circulation continues beyond the age of the transition from low to high heat flow. The presence of nonlinear temperature profiles in all of our survey areas is best explained as a result of convective heat transfer through the sediments in addition to vigorous convection in the oceanic crust. Convection between the crust and the ocean continues even when a uniform blanket of sediments 100 m thick is draped over the oceanic basement. This pervasive geothermal circulation through the sediments and within the oceanic crust will have major implications for the chemistry of the oceanic crust, sediments, and the ocean itself (*10*).

The mean heat flow, well below theoretical predictions, observed at the survey site 18×10^6 years old perhaps indicates that much of the convective heat transfer in the younger crust is being channeled through "chimneys" of rock outcropping through the irregular sedimentary cover and thus is bypassing the areas where we can measure the heat flow. These chimneys would be subject to more prolonged and intense alteration than the adjacent sea floor. This rather ad hoc hypothesis may also provide a good explanation for the striking local variability in the grade of metamorphic alteration of the oceanic crust at International Program of Ocean Drilling sites 417 and 418 in the Atlantic Ocean (*11*); hole 417A possibly drilled into an old chimney.

There appear to be two types of convective heat transfer occurring through the sea floor of the Indian Ocean. Type 1 probably implies the convective exchange of heat from the geothermal circulation system in the oceanic crust directly to the water column, perhaps by chimneys of outcropping basement. Until we develop new techniques to measure heat flow on exposed rock, areas characterized by type 1 convection will continue to be recognizable only because the total observed heat flow will be low relative to predictions from theoretical models. Our results suggest that type 1 convection is sealed by the deposition of a uniform sedimentary blanket sufficiently thick to cover all basement outcrops; a thickness of 40 m appears to be sufficient in survey area 2. Oceanic heat flow measurements in the sedimentary layer directly detect only type 2 convection, that occurring in the oceanic crust and flowing through the sedimentary layer. Type 2 convection can only be recognized when closely spaced and sufficiently detailed temperature profiles are obtained so that nonlinearity can be identified, β values determined, and horizontal variability mapped. Even then, only discharge areas of upwelling fluids will ordinarily have measurable β values (very thin sediments being required to show curvature in downwelling or recharge areas). Despite the fact that regional heat flow analyses in the past have not been able to measure either type 1 or type 2 convection (*5*), the predominance of low heat flow on the flanks of all midoceanic ridges suggests that geothermal convection similar to that shown above is presently active beneath one-third of all of the world's ocean floor.

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12. We thank Capt. P. Cunningham and the officers and crew of the R.V. *Vema* for making these observations possible under the most adverse conditions. This work was supported by NSF grants OCE 76-21794 and INT 76-82960. Lamont-Doherty Geological Observatory Contribution No. 2828.

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Stratospheric Wave Spectra Resembling Turbulence

Abstract. *Pollution effects on ozone raise the question of the significance of turbulence in vertical transport in the stratosphere. The aircraft in situ measurements of velocity fluctuations previously employed to estimate turbulence transport were, it is hypothesized, due to atmospheric waves, despite their classical turbulence spectrum. This new hypothesis implies that previous turbulence estimates are invalid. Experimental tests are suggested.*

The current international concern about stratospheric pollution (as well as oceanic pollution) gives practical importance to the question of vertical transport due to turbulence in stratified fluids. Turbulence in such media, which is due presumably to the Kelvin-Helmholtz shear instability (*1, 2*), takes the form of thin, horizontal pancake-shaped layers. In the stratosphere these have a vertical thickness of order 200 m [see (*3*), temporarily omitting the last entry] and a horizontal extent of tens of kilometers.

One method of estimating vertical transport due to turbulence makes use of the power density spectrum of the turbulent velocity fluctuations (*4*). Figure 1 shows such spectra obtained by means of an instrumented U-2 aircraft flying through what was presumed to be a turbulent layer in the stratosphere (*5*). The shape of these curves roughly fits the well-known $-5/3$ law predicted by Kolmogorov (*6*). His theory, which is based on dimensional analysis, predicts that $\phi = \alpha\epsilon_0{}^{2/3}k^{-5/3}$ for the steady-state "inertial subrange" of turbulence where it acts like a conservative cascade; that is, "big whirls have little whirls that feed on their velocity, and little whirls have less-