VOL. 81, NO. 26 JOURNAL OF GEOPHYSICAL RESEARCH SEPTEMBER 10, 1976

THERMAL CONDUCTION ACROSS FRACTURE ZONES AND THE GRAVITATIONAL EDGE EFFECT

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Abstract. We solve the two-dimensional time-dependent heat flow equation across an idealized fracture zone boundary, which includes the process of lateral heat conduction across an initially abrupt temperature contrast. From this solution we can calculate the temperature field for any initial offset and at any sequential time. We can use this to calculate a theoretical free air gravity anomaly across the fracture zone given an assumed density variation with temperature. Results for a 30 m.y. initial offset show that both the amplitude and the shape of the anomaly are significantly altered by lateral heat conduction across the fracture zone even during the first few million years. Assumptions of a sharp density contrast across fracture zones are therefore only valid in very restricted regions close to the ridges. We also find that the theoretical anomaly is small in comparison to observations of free air gravity anomalies. These results add significant complications to attempts at finding unique models for the structure of the lithosphere from gravity anomalies across fracture zones.

Fracture zones in ocean basins form a unique asymmetrical contact between separate sections of the same lithospheric plate, which can have substantially different ages and thermal structures. Recently, several authors have suggested using the gravity anomaly across fracture zones as a means of measuring changes in the density structure associated with the cooling of an oceanic plate [Le Pichon et al., 1973; Sibuet et al., 1974; Dorman, 1975]. The edge effect produced by such a sharp discontinuity can reduce the nonuniqueness inherent in modeling the density distribution, which is an especially difficult problem in the interpretation of long-wavelength features such as mid-ocean ridges. However, all of these studies have neglected the effect of heat flowing laterally across the fracture zone, which tends to spread out the transition between the two thermal regimes. In this report we summarize some early results of our theoretical investigation into this process and point out possible difficulties in simple approaches to the direct modeling or inversion of the gravity data. We find that the gravitational edge effect associated with deep thermal structure may be small in comparison with that caused by shallow crustal differences, which might include topographic and structural variations; that the wavelength of the anomaly is greatly increased by lateral conduction even during the first few million years; and that even without lateral conduction the analysis of observed free air gravity anomalies across fracture zones can only hope to yield a poorly constrained minimum value for the thickness of the plate.

Figure 1 depicts the idealized geometry of the problem. Two ridge segments (I and II) spreading with a velocity v are offset a distance y_0 by an active transform fault. A section of crust that is formed on ridge I comes in contact with newly forming crust on ridge II after a time t_0. From then on it remains fixed in relation to this younger crust, and heat will flow horizontally across the fracture zone from the hotter (younger) to the colder side. At any point far away from the fracture zone we assume that the thermal history can be described as the cooling of an infinite half space. Near the fracture zone we combine this vertical cooling with the lateral conduction of heat across the fracture zone boundary.

Such a two-dimensional analysis cannot adequately model the temperature structure in the active transform portion of the fault zone. The more complicated boundary conditions within this region probably necessitate an iterative numerical model. In this paper we avoid such difficulties by assuming that the thermal structure of the older lithosphere at section A-A' (Figure 1a) is unaffected by having previously been in contact with another plate. Justification for this is based on the symmetry of the geometry within the region of the transform fault.

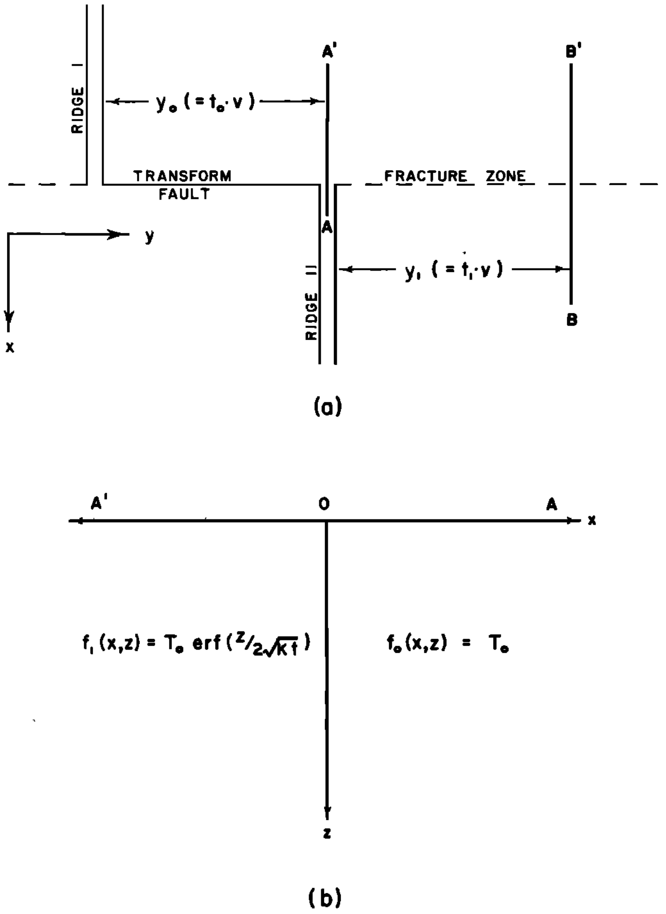

Fig. 1. (a) Schematic diagram of a ridge offset in plan view. The thermal model developed in the text pertains to the fracture zone region, $y_1 \geq 0$. (b) Cross section of line A-A' in (a). T = 0 at the surface z = 0. The functions $f_1(x,z)$ and $f_0(x,z)$ represent the initial temperature distribution in the two regions ($x < 0$ and $x > 0$, respectively) of the half space $z > 0$ when $t_1 = 0$. The right side is at the ridge crest and has a constant temperature $T_0 = 1300°C$; the left has cooled vertically for t_0 m.y. from this initially constant temperature.

We know that one side is younger than the other for half of the time and older for the other half. Thus we can assume that the net heat flow across the entire transform fault is zero. If the time history of the heat flow is also symmetric about the midpoint of the transform fault, the thermal structure at A-A' will return to an exact step discontinuity. Second-order effects, such as frictional heating by the two plates sliding past each other, would affect the accuracy of this assumption but are not treated in this paper.

In the region outside of the active transform faults we solve the two-dimensional heat flow equation,

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{K}\frac{\partial T}{\partial t} \tag{1}$$

where K is the thermal diffusivity which is assigned a value of 10^{-2} cm^2 s^{-1} on the basis of experimental values for typical mantle minerals [e.g., Kanamori et al., 1968]. The generalized solution to (1) for a half space with any initial temperature distribution f(x, z) and T = 0 at the surface z = 0 is given by

$$T(x, z, t) = 1/4\pi Kt \int_0^\infty dz' \int_{-\infty}^{\infty} f(x', z')P(x', z')\, dx' \tag{2}$$

where [Carslaw and Jaeger, 1959],

$$P(x', z') = \exp\{-[(z - z')^2 + (x - x')^2]/4Kt\} - \exp\{-[(z + z')^2 + (x - x')^2]/4Kt\}$$

At any later time t_1 (section B-B' in Figure 1a) we can solve (2) for initial temperature distributions $f_1(x, z)$, when $x < 0$ and $f_0(x, z)$ when $x > 0$, as given in Figure 1b, and obtain the complete temperature structure of the half space. An example when t_0 = 30 m.y. and t_1 = 10 m.y. is shown in Figure 2. Instead of a step function in temperature at the fracture zone, the transition spreads out over several tens of kilometers. The temperature at any depth vertically below the fracture zone is an average of the two temperatures at infinity for that same depth. The difference between this model and a one-dimensional model which con-

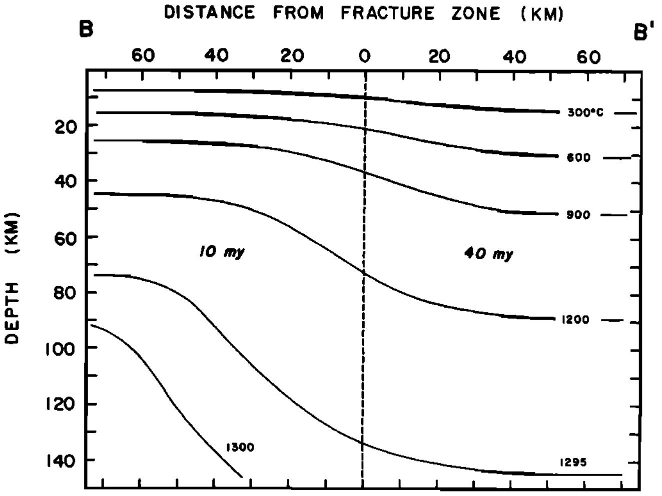

Fig. 2. Isotherms as a function of depth and distance from the fracture zone for t_0 = 30 m.y. and t_1 = 10 m.y. The right side represents the older lithosphere. Lateral conduction of heat across the fracture zone has diffused an initially sharp thermal contrast at the fracture zone into one that is spread out over 70 km.

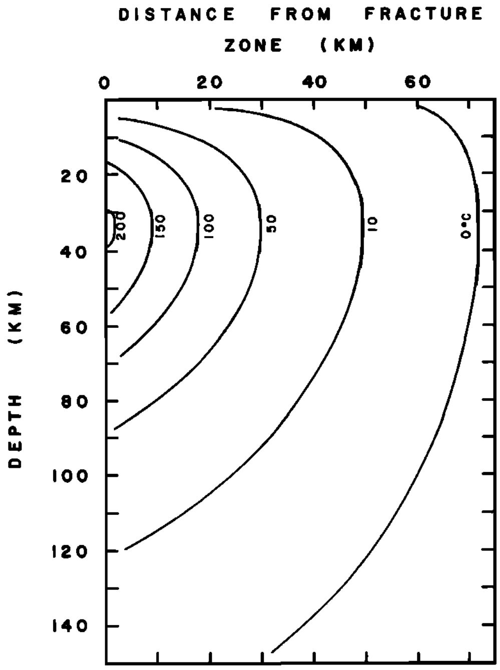

Fig. 3. The difference for one side of the fracture zone between the temperature field in Figure 2 and one with similar ages which allows only vertical heat conduction. The temperature difference on the other (younger) side of the fracture zone is identical but of opposite sign. Temperature changes of 100°C extend nearly 20 km from the fracture zone and to a depth of 70 km.

siders only vertical conduction is shown in Figure 3. After 10 m.y. the horizontal conduction of heat alters the temperature field as far as 70 km from the fault and increases the temperature by more than 100°C within a substantial area of the old lithosphere.

To estimate the influence of the lateral conduction of heat on the gravitational edge effect, we construct a two-dimensional structural model in which the densities are controlled by the temperature field. The assumption of two dimensionality is a good approximation if the spreading rate is fast enough to sufficiently spread out the variation in density with age along the strike of the fault. We assume a constant density $\rho_o(z)$ at the ridge crest, where the temperature is independent of depth (T_o = 1300°C) and then calculate the density for any other temperature $T(x, z)$ from the equation,

$$\rho(x, z) = \rho_o(z)\{1 + \alpha[T_o - T(x, z)]\} \quad (3)$$

where α is the coefficient of thermal expansion. Temperatures were calculated on a 2 km x 2 km grid, and therefore an average density could be calculated for each 2 x 2 km^2 region. As the lithosphere cools and contracts, density increases are isostatically compensated by increasing the depth of the water layer, at the expense of mantle material, so that each vertical column from the water surface to the bottom of the half space (i.e., where $T(x, z) = T_o$) has equal mass. The water depth is a function of temperature structure (which depends on the age) and the value chosen for α. Using a value for α of 3.0 x 10^{-5} °C^{-1} yields a depth versus age relationship which matches the observed bathymetric data of Sclater et al. [1971], at least up to 50 m.y., where the finite thickness of the plate becomes important.

At the ridge crest the initial structural model has a water depth of 2.8 km and two layers representing the crust and the upper mantle. The first layer, with ρ_o = 2.8 g cm^{-3}, has a thickness of 6 km; the second, with ρ_o = 3.3 g cm^{-3}, includes the remainder of the half space. As the lithosphere cools with age, the thickness of layer 1 remains constant, but the water depth and mantle densities increase. Theoretical free air gravity anomalies are calculated for this two-dimensional structure by using formulae for horizontal and vertical sheets given by Talwani [1973]. These formulae are approximations that become inaccurate when the depth of the sheet becomes less than its cross-sectional dimensions. In our case, anomalies produced by the uppermost portions of our half space are calculated to within 1% by these formulae. Calculations of the gravity anomaly across a fracture zone with a 30-m.y. initial offset are shown in Figure 4 for several sequential times (t_1 = 0, 5, 10, and 20 m.y.). We chose a 30-m.y. offset in order to compare our results with those of Sibuet et al. [1974] for the Mendocino fracture zone.

There are two major points that these curves emphasize. The first is that the amplitude of the anomaly is small, even before horizontal conduction takes place, and that such conduction will decrease it still further at later times. The maximum peak-to-peak difference for a 30-m.y. offset is 58 mGal when t_1 = 0. After 5 m.y. the amplitude difference (21 mGal) is about half of what it would be without horizontal conduction (40 mGal), and after 20 m.y., no significant anomaly remains. These anomalies are small in comparison with observations such as those of Cochran [1973] in the equatorial Atlantic or Sibuet et al. [1974] across the Mendocino fault, where one often sees values several times as large. The observations must therefore include more than this edge effect. Indeed, in some cases refraction and reflection studies show large variations in crustal structure and accumulations of sediment within the fracture zone in addition to large topographic fluctua-

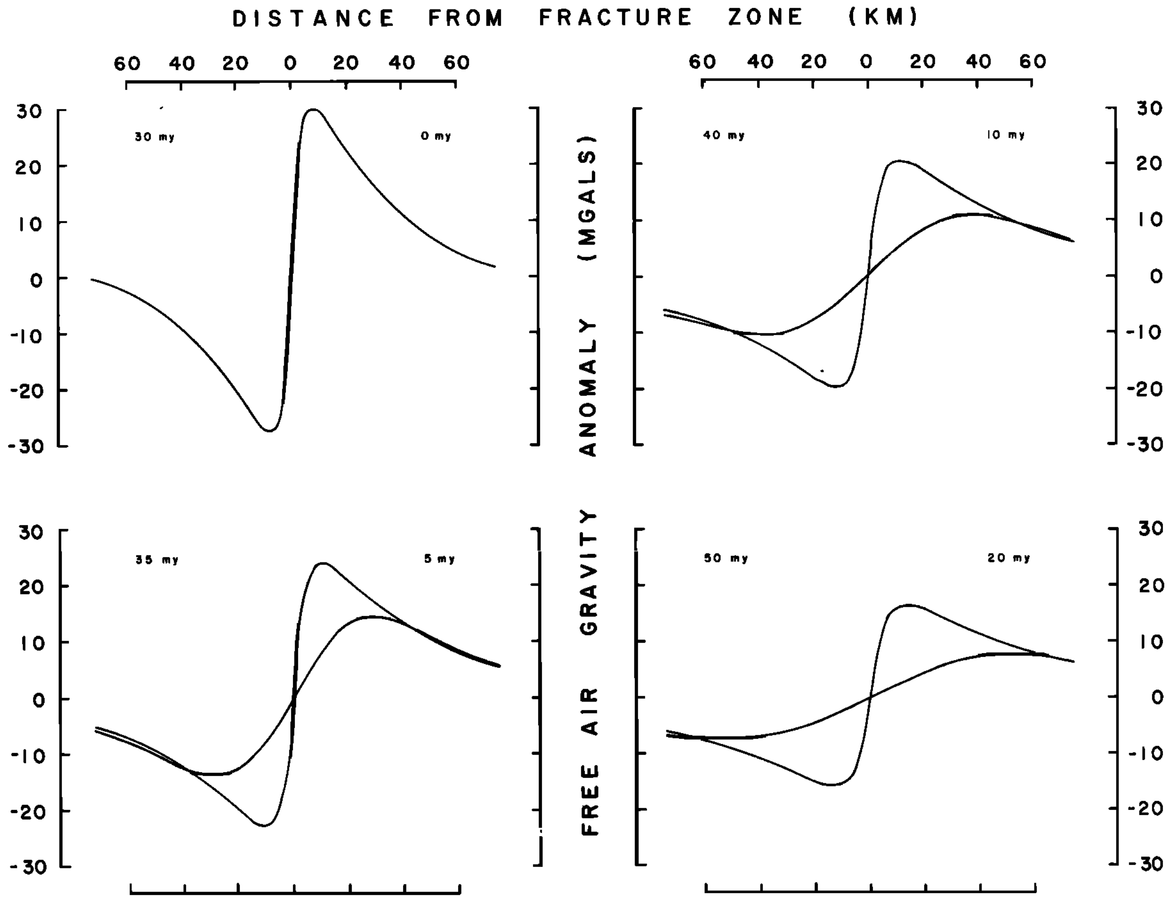

Fig. 4. Computed free air gravity anomalies across an isostatically compensated fracture zone for cases of both one- and two-dimensional conduction. The initial offset t_0 of the fracture zone is 30 m.y. Graphs represent curves for t_1 equal to 0, 5, 10, and 20 m.y. By 5 m.y. the shape of the anomaly is significantly different when heat is conducted laterally across the fracture zone. By 20 m.y. there is only a very small anomaly remaining. The anomaly is arbitrarily set to zero at the fracture zone.

tions. This creates the possibility that the edge effect could be completely dominated by shallow heterogeneities. To remove the crustal effects, either very complete seismic reflection and refraction results must be available, or many profiles from a wide variety of locations must be used to average out these shallow complications. Also, any observational program should be concentrated near the ridge crest, where the anomaly will not yet have decayed.

The second point is that the horizontal conduction of heat alters the frequency spectra of the gravity anomaly. As can be seen in Figure 4, the spreading out of the thermal transition zone between the two lithosphere sections removes the high-frequency part of the signal from the anomaly. The long-wavelength anomaly remaining would normally be interpreted as being produced by a deep-seated density contrast with a sharp transition, rather than by relatively shallow structure with a diffuse transition. Thus inversion techniques which employ the Fourier transform of the gravity field, such as that developed by Dorman [1975], would produce density models with contrasts consistently deeper than those actually producing the anomaly. Either a correction must be made for the diffusion of the temperature transition, or only measurements very close to the ridge crest should be used. The curves in Figure 4 show that there is a significant change in the sharpness of the anomaly even after only 5 m.y.

The inversion technique of Dorman [1975] describes the shape of the thermal transition zone as a Heaviside unit step function. Part of the process of finding the effect on the gravity field of a density contrast associated with the change in temperature involves convolving this step function with the gravity field of an infinitely long wire. The inversion technique can be approximately corrected for the diffusion of the thermal transition zone by replacing the step function with a function of the form of

$$h(x, t) = \operatorname{erfc}\,[-x/2(Kt)^{1/2}] \tag{4}$$

where

$$\operatorname{erfc}(x) = 1 - 2/(\pi)^{1/2} \int_0^x \exp(-y^2)\,dy$$

The function h(x, t) is a description of the form of the temperature field in an infinite solid with an initial step in temperature at x = 0, t = 0 [Carslaw and Jaeger, 1959]. After convolving with this altered description of the transition, inversion can proceed as before.

Sibuet et al. [1975] in their analysis of the free air anomaly across the Mendocino fracture zone have avoided the problem of thermal diffusion by placing greatest emphasis on their profile closest to the ridge (t_1 = 0.3 m.y.). They attempt to place constraints on the thickness of the lithospheric plate by finding the value in the thermal model of Sclater and Francheteau [1970] that produces a best fit to the gravity anomaly. The problem with this method is that the effect of varying the thickness of the plate is very small in comparison with the total anomaly across the fracture zone. For instance, their results show a 10-mGal difference between a 75- and a 100-km-thick lithosphere, while the total peak-to-peak anomaly is 150 mGal. Figure 5 shows a similar result when we compare the gravity anomaly produced by our half space model (for t_o = 30 m.y. and t_1 = 0 m.y.) to that produced from thermal models of Sclater and Francheteau [1970] for plate thicknesses of 50 and 100 km. One can also see that the thinner the plate is, the greater is the effect of a small perturbation in thickness. Unless the plate is about 50 km thick or less, such an analysis can only yield a minimum value for the thickness of the lithosphere.

The two important parameters to be considered are the plate thickness and the difference in ages across the fracture zone. The thicker the plate, the greater must be the age offset for the size of the anomaly to be sensitive to the bottom of the plate. If the lithosphere is approximately 100 km thick, our results show that the offset across the fracture zone must be larger than 30 m.y. to produce a 15-mGal difference when the thickness is changed by 25 km.

These difficulties still do not negate the possible importance of a more complete analysis of transform fault and fracture zone regions. But care must be taken to consider both the theoretical and the observational limitations to any particular method of analysis. The work presented in this paper considers the quantitative effects on the gravitational edge effect anomaly of both thermal diffusion and age differential across the fracture zone boundary. Our results show that these should be considered when structural models are constructed from observed gravity anomalies across fracture zones.

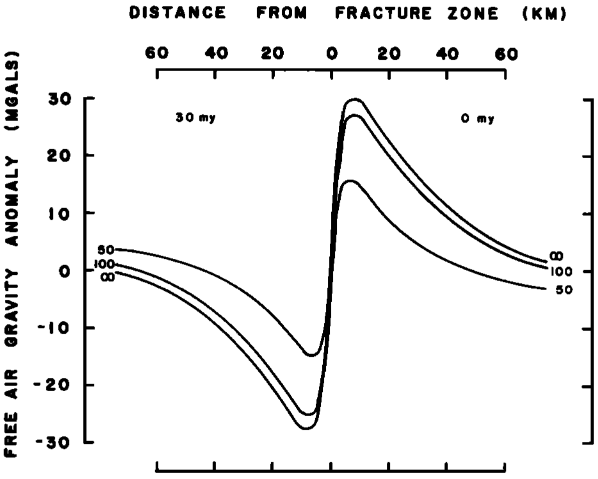

Fig. 5. Computed free air gravity anomalies across a fracture zone with a 30-m.y. offset. Curves are calculated for a half space model (same as in Figure 4) and the lithospheric plate model of Sclater and Francheteau [1970] with thicknesses of 50 and 100 km. The difference of 5 mGal between results for a half space and a 100-km-thick lithosphere is too small to be easily observable.

Acknowledgements. This work has been supported by the Office of Naval Research contract N00014-75-C-0291, by the Earth Sciences Section of the National Science Foundation, NSF grant EAR75-21788, and by the Woods Hole Oceanographic Institution. We would like to thank John Sclater for his continuing interest in this work and Carl Bowin, Richard Von Herzen, Jim Cochran, Roger Anderson, and Bob Detrick for their helpful reviews of this paper. Lamont-Doherty Geological Observatory contribution 2355. Woods Hole Oceanographic Institution contribution 3784.

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(Received October 28, 1975;
revised May 7, 1976;
accepted May 10, 1976.)