An Evaluation of Methods for Estimating Regional Heat Flow

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Abstract

We look at 3 methods for estimating the regional heatflow: a simple mean of all heat flow measurements, the heat flow at the regional median depth, and the mean of gridded heat flow measurements. We find that the simple mean is the least accurate method: simple means estimate the average heat flow at the median water depth of the heat flow survey and are often significantly biased. The heat flow at the regional median depth is more accurate, but can be biased by the spatial distribution of the heat flow survey. The mean of gridded heat flow data produces the most accurate estimate of the regional heatflow. However, the value of the gridded mean is influenced by the grid spacing, and other methods of gridding should be evaluated.

Introduction

The existing models for the thermal evolution of the oceanic lithosphere use simple means of heat flow versus age[*Parsons and Sclater,* 1977; *Stein and Stein,* 1992] to estimate the mean heat flow which is coming from the cooling plate. These models assume that, once the oceanic crust is covered by thick sediment cover and hydrothermal circulation slows or stops, the heat flow is not correlated to basement topography. Therefore, the mean of the heat flow in an area of well-sedimented oceanic crust will approximate the average heat flow derived from conductive cooling of the lithosphere.

Several different studies of hydrothermal circulation suggest that convection often continues beneath areas that are completely covered by sediment and that the convection cells are topographically controlled[*Embley,* 1983; *Fisher et al.,* 1990]. If the convection is topographically controlled, it follows that heat flow patterns will correlate with the basement topography. Therefore, it may not be safe to assume that a simple mean of a regional heat flow survey is the most accurate estimate of the heat flow from great depth.

Our long term interest in this study is to evaluate the extent of crack filling in the oceanic crust, and the relative effects of topographic relief and the permeability of layer 2A on hydrothermal circulation. However, we have found that there is as yet no agreement on the heat flow coming from great depths through simple conductive cooling of the oceanic lithosphere. Because the intensity of hydrothermal circulation is sometimes assessed by looking at the heatflow deficit between the "expected" heat flow derived from simple conductive cooling, and the "observed" heat flow derived from measurements in sediment ponds, it is crucial to assess first the "expected" heat flow and then to assess the best methods of measuring the heat flow deficit in areas of open convection. This paper addresses these issues, but finds that many more detailed heat flow surveys are needed to fully answer these questions.

Methodology

We use heat flow data from a well surveyed area on ~ 5 m.y. old crust in the Equatorial Pacific [*Hobart et al.,* 1985; *Langseth et al.,* 1988] (Figure 1). This area has one of the highest densities of marine heat flow measurements in the world, over 300 measurements in an area 10 km high and 12 km wide. Most of the measurements are in a grid pattern, with a minimum spacing of 1 km between measurements. The spreading direction is basically due North-South. The crests of abyssal hills run East-West. The survey area encompasses one abyssal hill wavelength, and runs from the crest of one line of hills to the crest of a second line of hills[*Langseth et al.,* 1988].

Most detailed heat flow surveys involve far fewer measurements, usually one or two lines which run perpendicular to the spreading direction. We are interested in the local variability in the heat flow estimate from a detailed survey with only one or two lines of heat flow measurements which run perpendicular to the spreading direction. For this reason, we divided the area into six boxes (A to E), each of which contains one abyssal hill wavelength and two major North-South lines of heat flow measurements (Figure 2).

In each box, we found the regional heat flow using three different methods. The first method was to take the simple mean of all the individual heat flow measurements within the boundaries of the box. The second method used the trend of heat flow versus topography to calculate the heat flow at the 3 different median depths: the median depth of the heat flow survey, the median depth of the local survey, and the median depth of the entire survey area. The third method involved gridding the heat flow data to remove any spatial bias in sampling and then taking the mean of the heat flow grid.

The first method, taking the simple mean, assumes that heat loss is randomly distributed in space and that all of the heat flow measurements are randomly distributed. It also assumes that the distribution of heat flow values is Gaussian (normal). The survey pattern shows that the heat flow measurements are not randomly distributed (Figure 2). A histogram of the heat flow data shows that the measurements are skewed toward low values [*Langseth et al.,* 1988].

The second method, calculating the heat flow at the median topographic depth, does not require that all heat flow measurements be randomly distributed in space. However, this method assumes that the heat flow is significantly correlated to the topographic relief. The median depth was selected because half of all of the surface area is above the median depth and half of all the surface area is below the median depth. If the heat loss of the area is also equally distributed about the median depth, this method will produce a reasonable estimate of the regional heat loss.

The third method, calculating the heat flow of a gridded data set, is roughly equivalent to calculating the mean heat flow per unit area. The gridding method does not require either that heat flow is correlated to the topographic relief, or that the heat flow measurements are randomly distributed. We have tested the method by using different gridding intervals and found that the estimated mean regional heat flow decreases by 3 mW/m^2 when we change the gridding interval from 1 km (the average distance between heat flow measurements) to 0.25 km (Table 1). Our gridded mean for a 1 km gridding interval is the same as that of [*Langseth et al.,* 1988].

All of the methods have an uncertainty which is associated with the pattern of heat flow variability and the shape of the heat flow distribution. The survey spacing was adjusted to make more measurements in areas of high heat flow variability. Nevertheless, there is still some uncertainty which is difficult to estimate from the individual methods and which is perhaps best assessed by a combination of detailed flow modeling (beyond the scope of this paper) and a comparison of the results from the different methods of assessing the local heat flow.

Results from Surveys A to E

Each of the methods of calculating the heat flow yielded different results, both within individual survey areas and between individual survey areas (Tables 1, 2). The simple mean is higher than the gridded mean within 5 out of 6 survey areas. Within two out of the 6 areas (B and E), the simple mean is significantly different from the gridded mean; e.g. their estimated error limits do not overlap. The heat flow at the local median depth is sometimes closer to the gridded mean than the simple mean, but is significantly different within two areas (A and E). Overall, the heat flow at the local median depth does not seem to be a particularly good predictor of the gridded mean of the local heat flow.

For purposes of comparison, we also used the relationship of heat flow versus topography to calculate the heat flow at the median water depth of the heat flow survey (Table 1). Interestingly, the heat flow at the median survey depth is nearly identical to the simple heat flow mean.

The differences between areas are also large. Although adjacent areas have gridded heat flow means which are not significantly different, areas which are separated by one or two other areas are significantly different. For example, the gridded mean for area A is significantly different from Area C, and Area C is significantly different from Areas E and F. Simple means and heat flow at the local median depths are even more variable, in that spatially adjacent areas are quite often significantly different (for example areas B and C). Overall, there is a regional pattern of higher heat flow to the west, with decreasing heat flow as one moves to the east.

A final disturbing pattern is that the correlation of heat flow with topography does not have a uniform regional slope. Heat flow correlates positively with topography (high heat flow on topographic highs) in 4 areas (Table 2). Heat flow correlatives negatively with topography (low heat flow on topographic highs) in 2 areas. Therefore, there is not a regionally consistent pattern of heat flow versus topographic relief.

Evaluating the Regional Heat Loss

Our overall interest is in evaluating the regional heat loss with the most accuracy in the most efficient manner. We therefore evaluated the regional heat loss using two different survey patterns. The first survey pattern used the entire heatflow data set. The second survey pattern used the heat flow values from the edge of the heat flow box and two cross sections running from opposite corners of the box (Figure 3). Both of these survey patterns can be reliably gridded, but the X survey pattern uses one third as many measurements.

We found that the gridded heat flow data sets from both survey patterns produced identical estimates of the mean regional heat loss (Table 1). The two estimates differ only in their standard errors, which are slightly higher for the X survey. In contrast, the simple means and the heat flow at the local median depth are significantly different between each of the two survey patterns. Most disturbing is that the simple mean for the entire survey is significantly different from the gridded mean for the entire survey. The other methods and survey patterns do not produce significantly different estimates of the mean regional heat loss.

Discussion

Our results clearly show that the standard error of a heat flow mean derived by any one of the 3 methods is not necessarily a reliable guide to its true uncertainty. The extent to which a given heat flow survey samples the regional variability in heat loss must be considered. Spatial biases in the pattern of heat flow measurements must also be considered. If the heat flow is uniformly correlated to topography in a given area, the heat flow at the median regional depth (Table 2) gives results which are comparable to the results of gridding the data. This is true even though the fit of topography versus heat flow is for a subset of the data (done separately for each area A to E) whereas the topographic median depth is for the entire area. However, if the correlation of heat flow to topography varies from positive to negative within a region (results from entire region and X survey in Table 2), the heat flow at the regional median depth will give results which do not necessarily match the results from gridding the heat flow data.

It is somewhat disturbing that the results from gridding the heat flow data vary with the size of the gridding interval. We believe that this is because the present gridding algorithm linearly extrapolates between heat flow data points. However, we know that the actual heat flow pattern is skewed and that heat flow does not change linearly with distance, suggesting that other extrapolation methods for gridding should be carefully examined, for example krieging [*Morin et al.,* 1991]. The most desirable method of gridding would produce results that did not change with the gridding interval.

Conclusions

Simple means of all heat flow measurements are the least reliable method of evaluating the regional heat loss. The heat flow at the regional median depth is a more reliable method of evaluating regional heat loss, but will only work well in areas where heat flow is strongly and uniformly correlated to topographic relief. The best method of evaluating regional heat loss is to grid the heat flow data at several different grid spacings ranging from the mean spacing between heat flow measurements to the minimum spacing between heat flow measurements. The range in the mean heat flow values at the different gridding intervals provides an estimate of the reliability of the gridded mean.

Some heat flow data sets are not suitable for gridding and have notable biases in their pattern of spatial sampling. In these cases (if the heat flow is significantly and uniformly correlated to the topography), calculating the heat flow at the regional median depth can provide an estimate of the reliability of the simple mean. In our study area, the heat flow at the regional median depth (206±6 to 224±9 mW/m^2) is usually closer to the gridded regional mean (213 to 216 mW/m^2) than is the simple mean (200 to 259 mW/m^2). The heat flow at the regional median depth (calculated for each individual survey A to E) also has much less variability than the simple mean.

The regional heat flow can be evaluated most efficiently by making measurements on the edges of a roughly square box which encompasses one topographic wavelength of the abyssal hills. The edge survey should be followed by two diagonal surveys which connect the opposite corners of the box. If the regional, along-strike variability of the heat flow is unknown, more than one of these surveys may be necessary to adequately evaluate the regional heat loss.

All of these methods of evaluating the regional heat flow depend upon adequate sampling of regional heat flow variability and of topographic relief. If the heat flow survey does not include enough surface area and reliable depth measurements, none of these methods will produce a reliable estimate of the mean regional heat flow.

Our data set is the best available for young, fully sediment covered oceanic crust. There is no other comparable data set for somewhat older, fully sedimented oceanic crust. We found it somewhat disturbing that the simple means changed dramatically from east to west, and that there was no indication that even one wavelength of the ridge parallel heat flow pattern was fully sampled. Hence, more heat flow measurements are needed, both in this area, and in other areas of relatively young (<40 m.y.) areas of fully sedimented oceanic crust. These measurements will help us to evaluate the alternative models for the thermal evolution of the oceanic crust and thereby allow us to return to studying the relative effects of topographic relief, sediment thickness, basement permeability (cracking) and basal heat flow upon submarine hydrothermal circulation.

Acknowledgments

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Figure Captions

Figure 1. Location map of the study area.

Figure 2. Map of the heat flow pattern within the study area. Cross: heat flow < 200 mW/m2. Square: heat flow from 200 to 250 mW/m2. Plus: heat flow over 250 mW/2. North-South lines represent the boundaries between the subareas: A through E.

Figure 3. Locations of heat flow data used in X survey with outlines of local highs superimposed. The water depth is shallower than 3400 meters inside the contour lines.

Bibliography

Embley, R. N., Anomalous heat flow in the northwest Atlantic: A case for continued hydrothermal circulation in 80 m.y. old crust, *J. Geophys. Res., 88,* 1067-1074, 1983.

Fisher, A. T., K. Becker, T. N. Narasimhan, M. G. Langseth, and M. J. Mottl, Passive, Off-Axis Convection Through the Southern Flank of the Costa Rica Rift, *J. Geophys. Res., 95,* 9343-9370, 1990.

Hobart, M. A., M. G. Langseth, and R. N. Anderson, A geothermal and geophysical survey on the south flank of the Costa Rica Rift: Sites 504 and 505, in *Init. Rept. DSDP, 83,* edited by R. N. Anderson, J. Honnorez and K. Becker et al., pp. 379-404, U.S. Govt. Printing Office, Washington, 1985.

Langseth, M. G., M. J. Mottl, M. A. Hobart, and A. Fisher, The distribution of geothermal and geochemical gradients near Site 501/504: Implications for hydrothermal circulation in the oceanic crust, in *Proc. ODP, Init. Rpts., 111,* edited by K. Becker and H. S. e. al., pp. 23-32, Ocean Drilling Program, College Station, 1988.

Parsons, B. A., and J. G. Sclater, The analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res., 82,* 803-827, 1977.

Stein, C. A., and S. Stein, A model for the global variation in oceanic depth and heat flow with lithospheric age, *Nature, 359,* 123-129, 1992.

Embley, R. N., Anomalous heat flow in the northwest Atlantic: A case for continued hydrothermal circulation in 80 m.y. old crust, *J. Geophys. Res., 88,* 1067-1074, 1983.

Fisher, A. T., K. Becker, T. N. Narasimhan, M. G. Langseth, and M. J. Mottl, Passive, Off-Axis Convection Through the Southern Flank of the Costa Rica Rift, *J. Geophys. Res., 95,* 9343-9370, 1990.

Hobart, M. A., M. G. Langseth, and R. N. Anderson, A geothermal and geophysical survey on the south flank of the Costa Rica Rift: Sites 504 and 505, in *Init. Rept. DSDP, 83,* edited by R. N. Anderson, J. Honnorez and K. Becker et al., pp. 379-404, U.S. Govt. Printing Office, Washington, 1985.

Langseth, M. G., M. J. Mottl, M. A. Hobart, and A. Fisher, The distribution of geothermal and geochemical gradients near Site 501/504: Implications for hydrothermal circulation in the oceanic crust, in *Proc. ODP, Init. Rpts., 111,* edited by K. Becker and H. S. e. al., pp. 23-32, Ocean Drilling Program, College Station, 1988.

Morin, R. H., R. Gable, and J. P. Chiles, Defining heat transfer processes through the southern flank of the Costa Rica Rift from geostatistical correlation of bathymetry and heat flow, *EOS, 72,* 265, 1991.

Parsons, B. A., and J. G. Sclater, The analysis of the variation of ocean floor bathymetry and heat flow with age, *J. Geophys. Res., 82,* 803-827, 1977.

Stein, C. A., and S. Stein, A model for the global variation in oceanic depth and heat flow with lithospheric age, *Nature, 359,* 123-129, 1992.

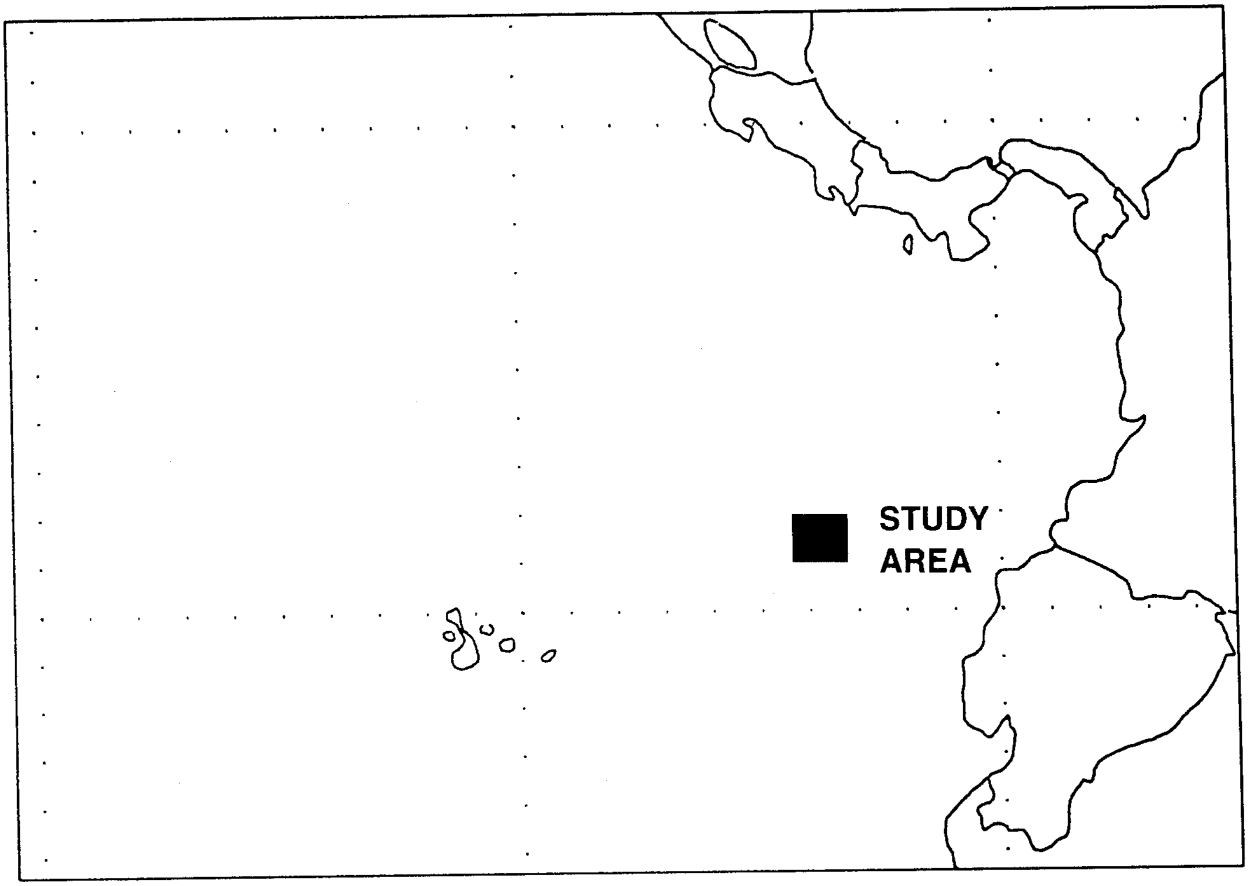

Figure 1

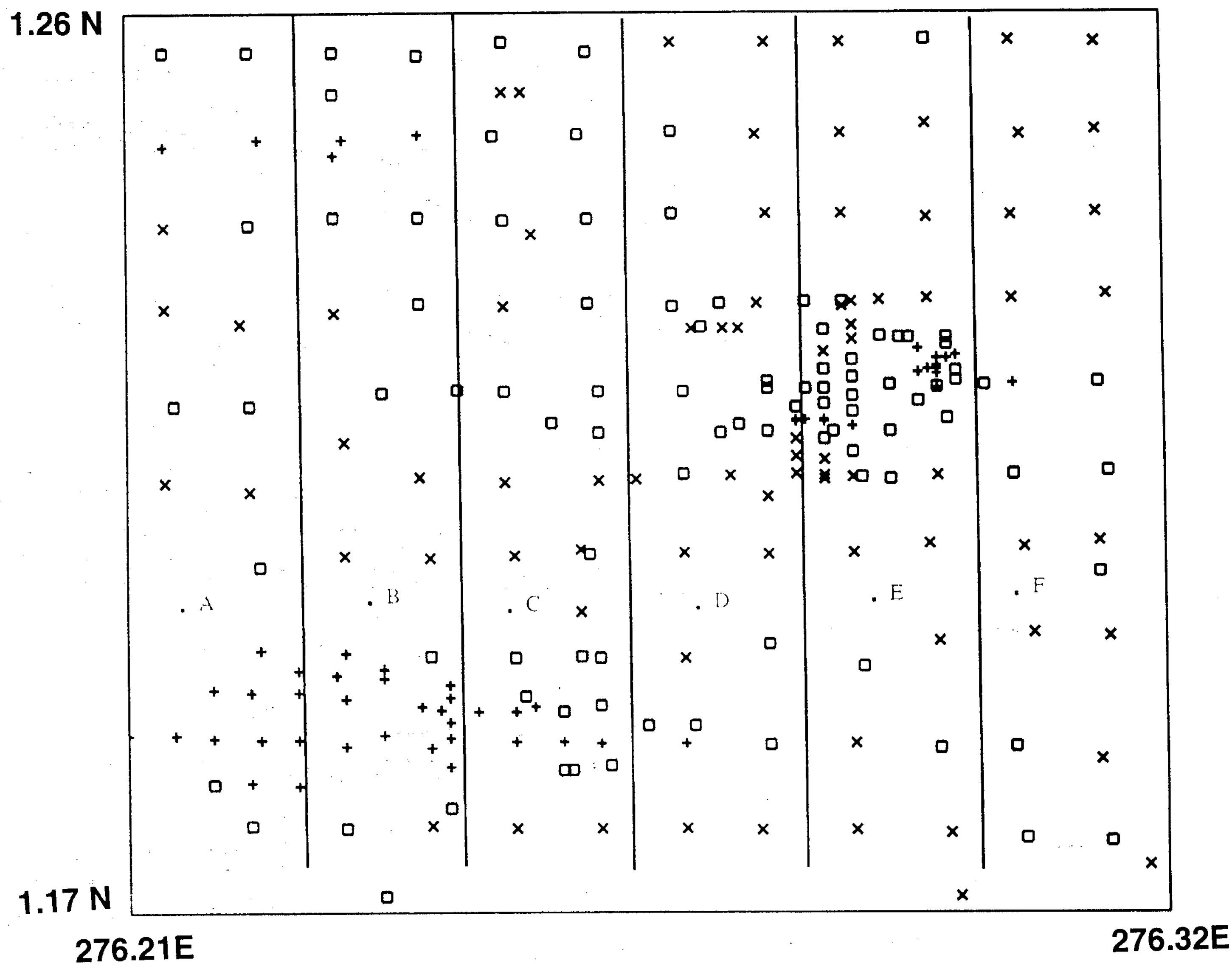

Figure 2

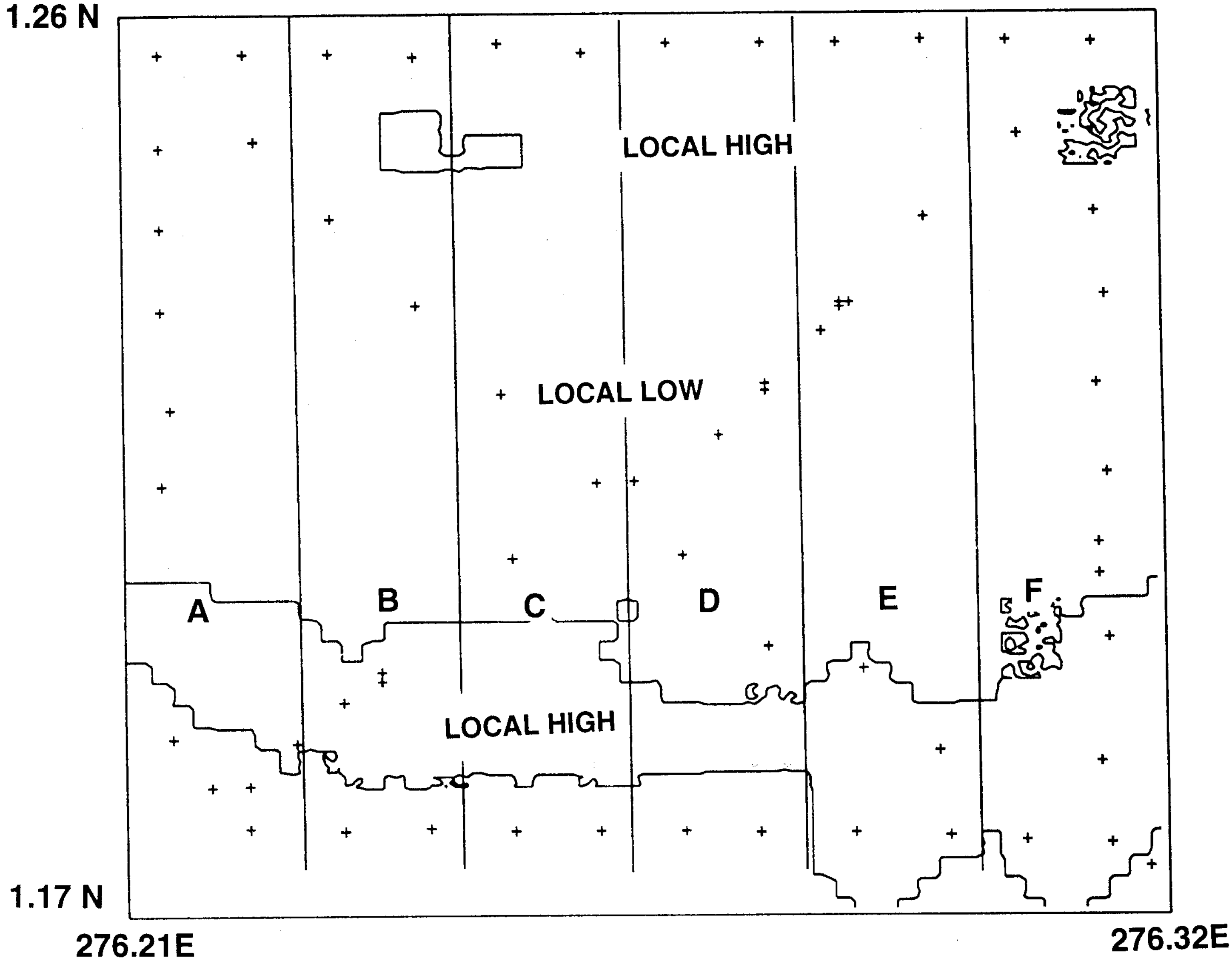
1.26 N
LOCAL HIGH
LOCAL LOW
A
B
C
D
E
F
LOCAL HIGH
1.17 N
276.21E
276.32E

Figure 3

Hf-Table 1

Table 1. Predictions of Subregion Heat Flow

Area Name	N	Gridded Mean 1 Km Grid	Gridded Mean 1/4 km Grid	Heat Flow at Local Median Depth	Simple Mean of Heat Flow	Predicted Heat Flow at Median Depth of Survey
A	23	247±11	238±11	204±13	254±12	248±9
B	38	235±10	230±10	234±7	259±8	257±6
C	40	222±8	213±8	210±5	217±5	217±4
D	42	207±4	202±4	212±5	212±5	211±5
E	66	197±5	196±5	218±6	226±5	227±5
F	21	197±5	197±5	206±6	200±5	200±5

Hf-Table 2

Table 2. Predictions of Heat Flow for the Entire Region

Area Name	Sign of Slope	Slope of Heat Flow vs Topography	Gridded Mean 1 km grid	Gridded Mean 1/4 km grid	Predicted Heat Flow at Regional Modal Depth	Simple Mean of All Heat Flow
Entire Region	+	0.5±.1	216±3	213±3	222±3	228±3
A	+	1.8±.3	NR	NR	214±12	NR
B	+	1.0±.2	NR	NR	224±9	NR
C	+	0.4±0.1	NR	NR	209±5	NR
D	+	0.3±0.2	NR	NR	213±5	NR
E	-	0.7±0.2	NR	NR	220±5	NR
F	-	0.5±0.2	NR	NR	206±6	NR
X_survey	+	0.5±0.1	216±5	213±5	207±5	214±5