Implications of Estimated and Measured Thermal Conductivity for Oceanic Heat Flow Studies

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Abstract. Heat flow data provide constraints on the thermal structure and evolution of the oceanic lithosphere. Because precise determination of the heat flux requires that both the thermal gradient and the thermal conductivity be well determined we have examined the thermal conductivities used in a new Pacific Basin heat flow data set. ~43% of the ~1600 heat flow determinations rely on values estimated by various methods, rather than directly measured. Although the measured and estimated conductivities have comparable means, the measured conductivities have a standard deviation ~50% larger than the estimated, suggesting that the estimated values underestimate the actual variation. We investigate the limitations of using such estimates by examining factors controlling the variations of measured conductivity values. We find that the variation between the closest adjacent sites increases with increasing separation, such that sites within 200 km are on average noticeably closer in conductivity than sites further apart. Contributing to this effect may be the variation of conductivity with lithology (with mean conductivity highest for carbonate oozes, intermediate for deep-sea clays, and least for siliceous oozes) and a possible trend of decreasing conductivity with increasing seafloor depth. Tests with the measured data suggest that the best method for estimating conductivity is using the mean value measured within 200 km. The mean of a larger geographical region is a somewhat poorer predictor, and using the oceanwide mean and the value at the nearest site are poorer still. Approximately 29% of the estimated values were not based on measurements from a reference site. For most others, the reference site was the nearest measurement from the same cruise, typically a large distance away. For those sites where conductivity was not measured, 78% had measured conductivity within 200 km and were reestimated using the local mean, whereas the remaining 22% were reestimated using the regional mean. The resulting change in the estimated conductivity averaged ~9% using the local mean and ~6% using the regional mean. We suggest that such a procedure be used to improve the utility of the heat flow data set, as an alternative to discarding the large fraction of the available data that does not incorporate measured conductivities.

Introduction

The heat flow inferred at the earth's surface is the negative of the product of the measured near-surface thermal gradient and the thermal conductivity of the near-surface material. The gradient is derived from a set of *in situ* temperature measurements. The conductivity, in contrast, is often estimated rather than directly measured. It is thus natural to explore the effects of using estimated conductivities on heat flow data. Our purpose in doing so is because uncertainties in the conductivity can pose difficulties in using heat flow for tectonic purposes. For example, the difference between the predicted heat flow for 20 and 31 Ma lithosphere, or for 50 and 78 Ma lithosphere, is only 20% (Parsons and Sclater, 1977).

The thermal conductivity can either be measured *in situ*, at the location of temperature measurements, or by subsequent measurements on a sample taken when the temperatures were determined. When a piston core (usually 5–10 m long) is taken, 3–10 thermal conductivity measurements are typically made. The average thermal conductivity for the site equals

$$\bar{k} = \left[1/N \left(\sum_{i=1}^{N} 1/k_i \right) \right]^{-1}$$

where N is the number of individual measurements along the core.

The conductivity of a sample is commonly measured using a needle probe (Von Herzen and Maxwell, 1959) with corrections for the differences in temperature and pressure from *in situ* conditions (Radcliffe, 1960). A comparison between *in situ* and needle probe conductivity determinations indicates only small discrepancies, within 5% (Hyndman *et al.*, 1979; Hutchison *et al.*, 1985; Detrick *et al.*, 1986; Hutchison and Owen, 1989; Jemsek and Von Herzen, 1989; Lister *et al.*, 1990). In the past, thermal conductivity was infrequently measured *in situ*,

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for example, using a modified Bullard-type probe (Vacquier *et al.*, 1966; Sclater *et al.*, 1969; Lister, 1970). Presently, using improved instrumentation, *in situ* measurements have become common, and provide a significant improvement of the heat flow measurements (Hutchison and Owen, 1989; Jemsek and Von Herzen, 1989; Wright and Fang, 1989). Given the few *in situ* measurements in our data set, we will treat values measured *in situ* and on a sample equivalently.

A few conductivity values have been inferred using an empirical relation between water content w and conductivity k, $k = (c_1 + c_2 w)^{-1}$ (Bullard and Day, 1961). However, the constants (c_1 and c_2) determined by Bullard and Day (1961) differ from those determined by other investigators (Lachenbruch and Marshall, 1966; Erickson and Simmons, 1968). Since the value of the conductivity as a function of water content appears to depend on the region, the sediment type, and also perhaps the pore structure (Zimmerman, 1989), in this paper we treat values inferred by this method as estimated.

Our goal in this paper is to explore the effects of using measured versus estimated conductivities in heat flow studies, using a data base larger than available to previous workers. First, we compare the distribution of estimated and measured thermal conductivities. Second, we examine how the measured conductivity varies spatially, due to factors such as the sediment type and seafloor depth. Third, we examine how the values can be best estimated from the measured data set. Fourth, we examine how the estimated values were derived, and for those derived using reference sites with measured conductivity, determine their distances from the reference sites. Finally, based on these results, we reestimate the thermal conductivity using more appropriate reference sites and determine how such changes might affect the calculated heat flow.

Data Set

We tabulated thermal conductivities for the Pacific Basin region studied by Berger *et al.* (1976) (Figure 1) using 566 published and unpublished values from the Lamont–Doherty Geological Observatory and 1017 additional values from a compilation by Louden (1989). 895 values were measured using *in situ* techniques, or on a sample using the needle probe or divided bar techniques, and 688 were estimated using values from other sites, water content, or other methods (Table I). Values listed as 'not specified' are included in the estimated category. The few sites with seafloor depths greater than 6300 m, all in trenches, were excluded. Most of the study area is reasonably well sampled, except south of about 40°S.

We examine the distribution of values for both the measured and estimated thermal conductivity data (Figure 2). Unfortunately, neither the Lamont data nor the Louden compilation include estimates of the uncertainty associated with individual conductivity measurements. Until recently, this issue has not been routinely addressed in reporting measurements. We thus are unable to assign uncertainties to individual values. The mean and standard deviations are 0.820 ± 0.117 W m^{-1} K^{-1} for the measured conductivities and 0.826 ± 0.079 W m^{-1} K^{-1} for the estimated set. It is interesting to note that the standard deviation of the measured conductivity is about 14% of the mean, whereas heat flow values for a given lithospheric age can be more variable, with standard deviation often approximately 40% of the mean (Sclater *et al.*, 1980).

Since the estimated conductivity values are based on measured ones, it is not surprising that the averages for the two sets are similar. However, it is noteworthy that the standard deviation of the estimated values is less than for the measured ones. This suggests that the estimated values may underestimate the range of thermal conductivities, especially for sites with values deviating significantly from the mean. Since the sites with both measured

TABLE I

Thermal conductivity for Pacific Ocean

Number	Percent	Code[a]	Method
835	52.7	N	Needle probe
43	2.7	Q	*In situ* method
17	1.1	A	Divided Bar
662	41.8	S	Estimated from nearby sites
15	0.9	O	Water content
2	0.1	R	Other methods
9	0.6	Z	Not specified

[a]Code describing conductivity measurements as used in Jessop *et al.*, (1975) and Louden (1989).

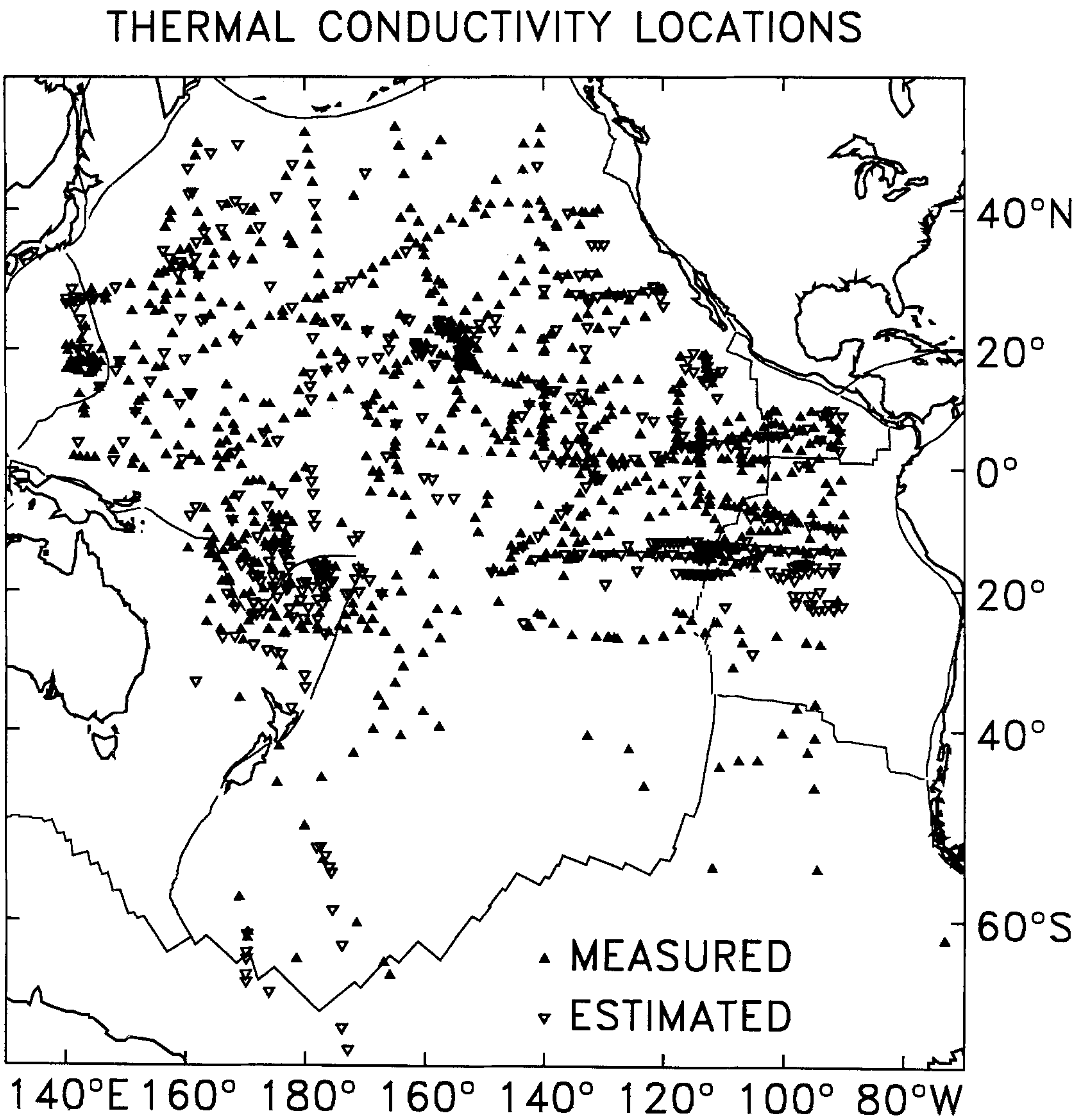

Fig. 1. Locations of measured and estimated thermal conductivity values used for this study. The thinner lines show the plate boundaries and the thicker lines show coastlines. Only conductivity data located in the Pacific Ocean area covered by Berger *et al.* (1976) study are included in this work.

and estimated conductivities appear to have a similar spatial distribution, it is unclear why the standard deviations should differ. This problem will be examined later in this paper.

Measured Thermal Conductivity Variability

To examine the utility of previously estimated thermal conductivity values, we investigated the variation in measured thermal conductivity as a function of various factors. Langseth and Von Herzen (1970) computed average values for 5° by 5° regions in the Pacific and found relatively uniform average conductivities ranging from 0.753–0.941 $W\,m^{-1}\,K^{-1}$ (1.8 to 2.25 $mcal\,cm^{-1}\,s^{-1}\,C^{-1}$) over large regions. For our 75% larger data set, 120 values exceed 0.941 $W\,m^{-1}\,K^{-1}$; 266 measurements are less than 0.753 $W\,m^{-1}\,K^{-1}$, and 509 measurements are between these values. The intermediate range determined by Langseth and Von Herzen (0.753–0.941 $W\,m^{-1}\,K^{-1}$) spans the same approximately range as one standard deviation about the mean for our values of the measured conductivity (0.705–0.937 $W\,m^{-1}\,K^{-1}$).

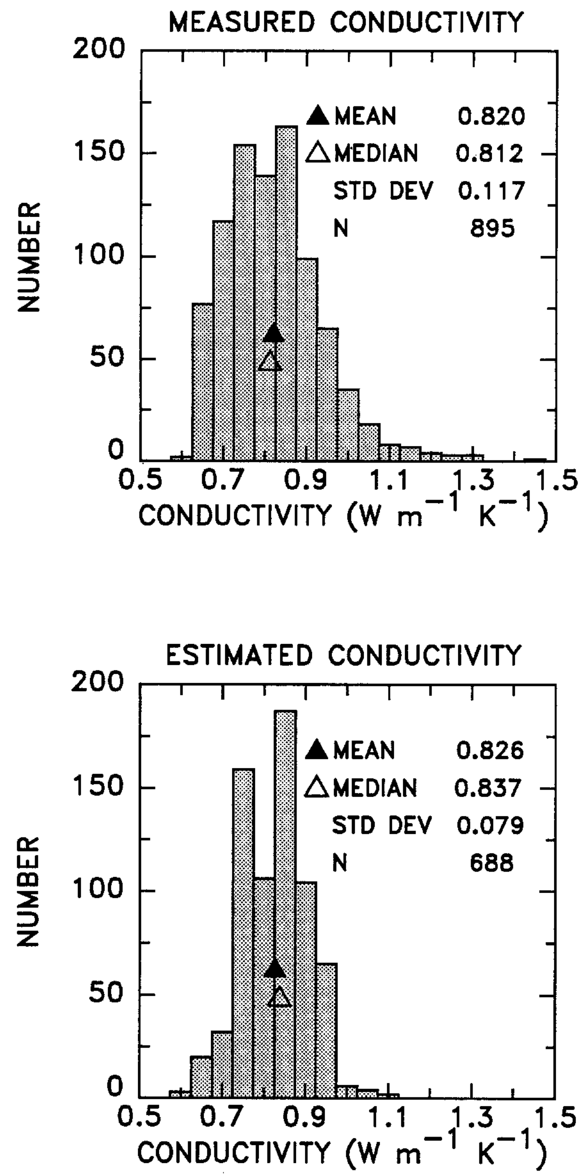

Fig. 2. Histograms showing the distribution of measured (top) and estimated (bottom) thermal conductivity. Although the means and medians are about the same for both categories, the estimated have a smaller standard deviation than the measured conductivities. The bin width is 0.05 W m^{-1} K^{-1}.

We found a spatial variation in conductivity (Figure 3) that is generally in agreement with the results of Langseth and Von Herzen (1970). On average, the conductivity is somewhat higher in the eastern equatorial Pacific, a region of seafloor below the zone of high productivity which may have more carbonate sands. A broad region of the central Pacific south of about 10°N is characterized by values generally lower than the mean of the data set. Seafloor in this area has deep-sea clay and some siliceous sediment (Davies, 1985). To explore such effects, we examined variations in conductivity as functions of sediment type, distance between nearby sites, seafloor depth, and geographic region.

SEDIMENT TYPE DEPENDENCE

To examine whether the regional variation in thermal conductivity reflects different sediment types, we grouped the measurements by sediment type (calcareous ooze, deep-sea clay, siliceous ooze, terrigenous sediment, and glacial sediment) using the distribution from Davies (1985). Both in terms of mean and median values (Table II) calcareous oozes have higher values than deep-sea clays, and deep-sea clays have higher values than siliceous oozes (Figure 4). The variation in conductivity for calcareous oozes seems somewhat greater than for the clays and siliceous oozes, given the somewhat larger standard deviation and difference between the mean and median values. The higher average conductivity for calcareous oozes agrees well with the work by Matsuda and Von Herzen (1986) for the variation of conductivity with $CaCO_3$, H_2O, and SiO_2 content within a piston core. They found that for increasing carbonate content, the conductivity increased and the water content decreased. But, for increasing SiO_2 content, the conductivity decreased and the water content increased. A meaningful comparison with terrigenous and glacial sediments is impossible because of the small number of measurements.

LOCAL VARIABILITY

Given that the conductivity varies with sediment type, one might expect conductivity to vary locally less than oceanwide. To examine this possibility, we compared each measurement to the value measured

TABLE II

Measured thermal conductivity (in W m^{-1} K^{-1}) for the Pacific Ocean

Sediment type	Number sites	Mean	Standard deviation	Median
All data	895	0.820	0.117	0.812
Carbonate	322	0.853	0.127	0.837
Deep-sea clay	423	0.808	0.105	0.800
Siliceous	144	0.780	0.105	0.776
Terrigenous	5	0.882	0.131	0.808
Glacial	1	0.649	–	–

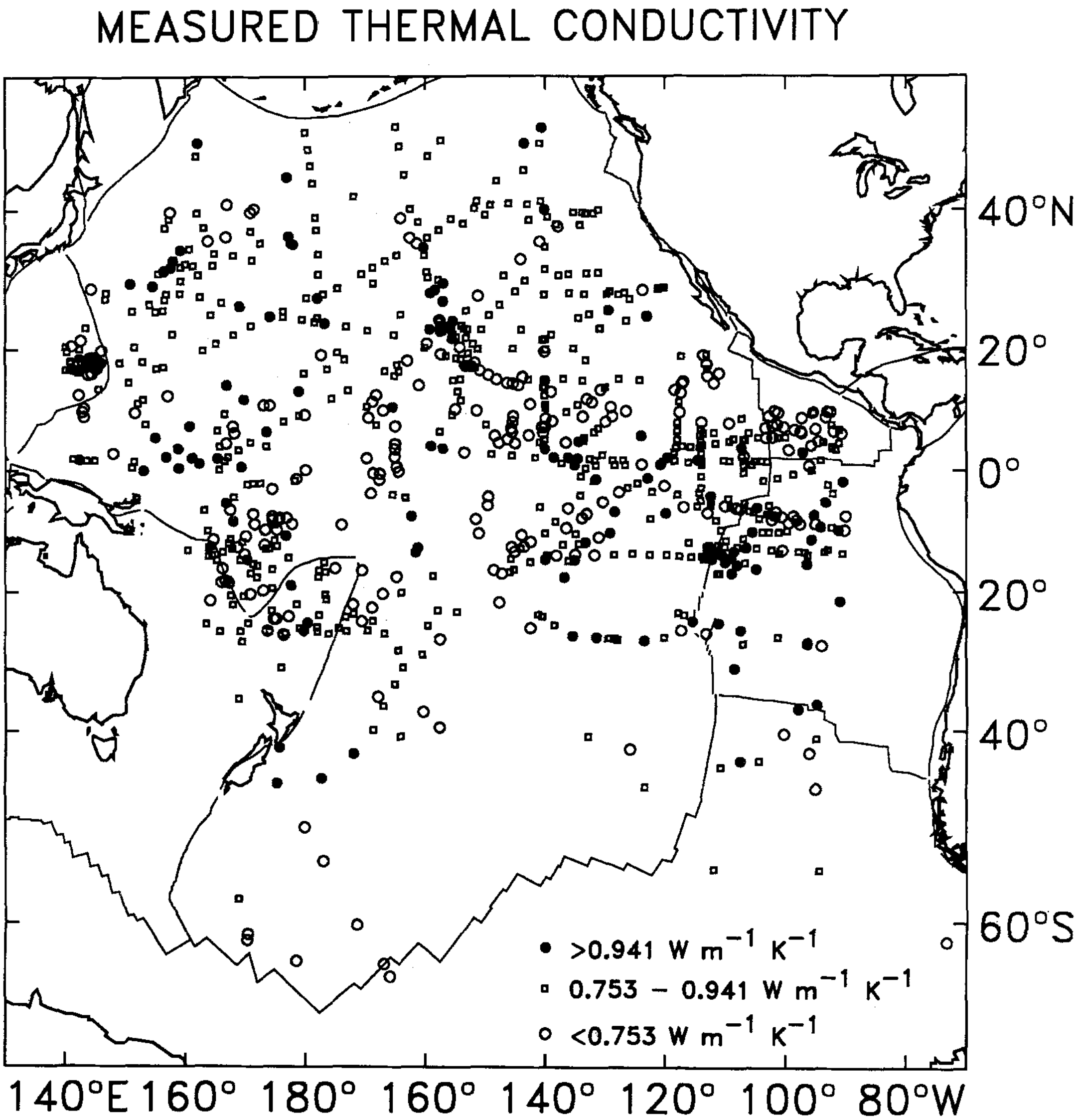

Fig. 3. Locations of measured thermal conductivity values. Values are grouped into three ranges following Langseth and Von Herzen (1970), $>0.941\ \mathrm{W\,m^{-1}\,K^{-1}}$ ($2.25\ \mathrm{mcal\,cm^{-1}\,s^{-1}\,C^{-1}}$), $<0.753\ \mathrm{W\,m^{-1}\,K^{-1}}$ ($1.8\ \mathrm{mcal\,cm^{-1}\,s^{-1}\,C^{-1}}$), and $0.753-0.941\ \mathrm{W\,m^{-1}\,K^{-1}}$.

at the nearest other site. For each measurement site pair we computed the separation distance, difference in conductivity, absolute value of the difference in conductivity, percent difference in conductivity, difference in ocean depth and absolute value of the difference in depth change. Means, medians and standard deviations for these data are shown in Table III. The average distance between the site pairs is ~160 km and the absolute change in the conductivity is ~10%. The mean of the absolute difference in conductivity for the site pairs, $0.083\ \mathrm{W\,m^{-1}\,K^{-1}}$, is about 71% of the standard deviation of the entire measured conductivity data set, $0.117\ \mathrm{W\,m^{-1}\,K^{-1}}$. It thus appears that the local variation of conductivity is less than for the whole data set.

Figure 5 (top) shows the absolute value of the conductivity difference between the nearest measurement pairs as a function of their separation, for distances up to 600 km. The difference in conductivity generally increases with the separation (Table IV). The mean and standard deviation for the absolute value of the difference between conductivity measurements separated by less than 200 km ($0.073 \pm 0.075\ \mathrm{W\,m^{-1}\,K^{-1}}$) are significantly smaller than for measurements 200–400 km apart ($0.110 \pm 0.118\ \mathrm{W\,m^{-1}\,K^{-1}}$). However, the larger

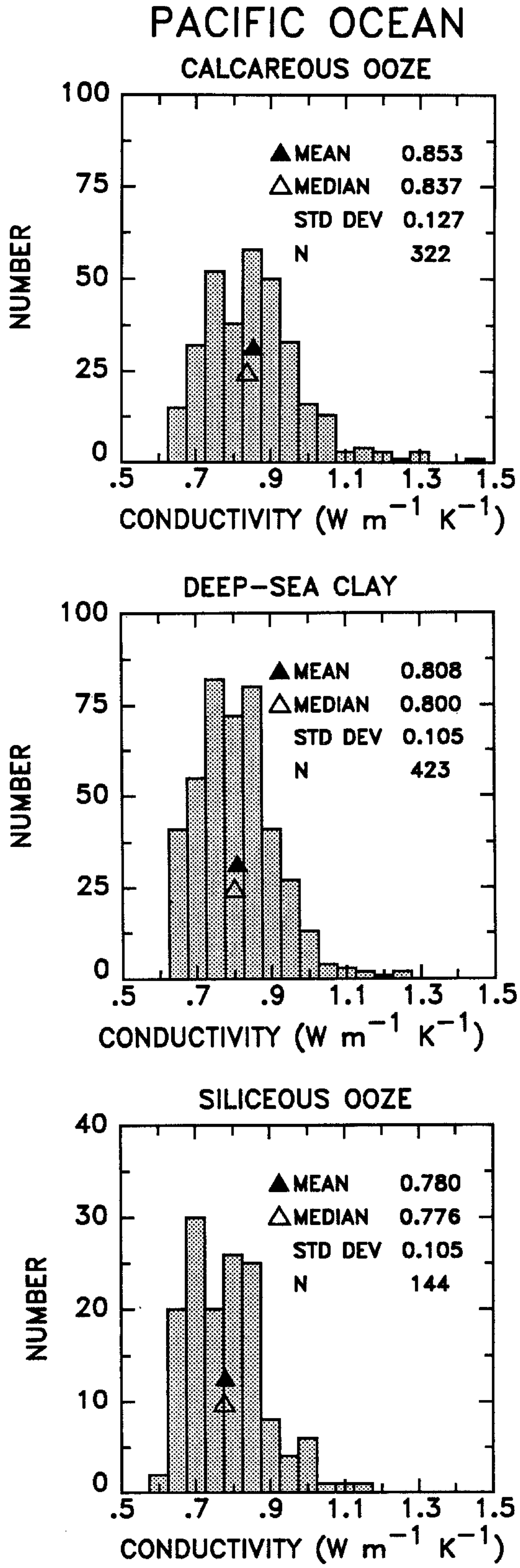

Fig. 4. Thermal conductivity distribution by sediment type. Conductivity is highest for calcareous oozes, intermediate for deep-sea clays, and least for siliceous oozes. The bin width is 0.05 W m^{-1} K^{-1}.

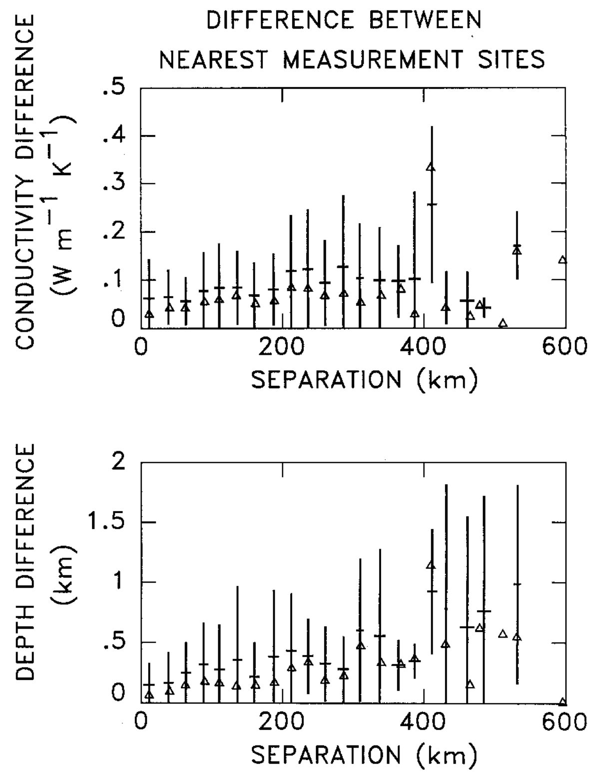

Fig. 5. Absolute value of the difference in conductivity and depth between the closest measured sites as a function of separation, averaged over 25 km bins. Means and medians are shown by tics and triangles. Error bars are one standard deviation. The differences in conductivity and depth increase with distance, especially for separations greater than 200 km. The large scatter in the data at distances greater than 400 km results from the few number of data points. Data for separations greater than 600 km are not shown.

standard deviation for the group with the larger separation distances maybe somewhat due to the fewer data points (Table IV). Presumably the fact that the conductivity difference increases with distance reflects the fact that the greater the distance between sites, the larger the difference in depth (Figure 5, bottom) and lithology.

Also, we can test if the variation between conductivity values increases with increasing separation distances by comparing the difference between a measured conductivity value to an average of all measured values within a given radius (Figure 6). As the radius increases the number of other measurements within that radius and the number of sites with other measured conductivity values within that radius increases (Figure 6, top and middle). We

TABLE III

Spatial variations for adjacent sites with measured thermal conductivity for the Pacific Ocean

Data	Mean	Median	Standard deviation
Separation distance (kilometers)	154	128	113
Conductivity change ($W\ m^{-1}\ K^{-1}$)	0.004	0.000	0.123
Absolute ($W\ m^{-1}\ K^{-1}$)	0.084	0.054	0.090
Percentage conductivity change	−0.65%	0.00%	14.40%
Absolute percentage	9.96%	6.72%	10.42%
Depth change (meters)	19	3	537
Absolute (meters)	318	155	433

TABLE IV

Data for Figure 5

Bin boundaries		Pairs	Conductivity difference		Depth difference	
Minimum km	Maximum km	Number	Mean $W\ m^{-1}\ K^{-1}$	Standard deviation $W\ m^{-1}\ K^{-1}$	Mean m	Standard deviation m
0	25	83	0.062	0.080	147	183
25	50	71	0.065	0.056	174	261
50	75	71	0.054	0.047	242	252
75	100	104	0.079	0.080	324	345
100	125	110	0.084	0.092	276	376
125	150	73	0.084	0.076	356	614
150	175	59	0.069	0.068	218	287
175	200	65	0.081	0.074	385	549
200	225	33	0.119	0.116	433	474
225	250	43	0.123	0.123	389	309
250	275	47	0.095	0.089	327	309
275	300	35	0.127	0.149	281	272
300	325	21	0.104	0.113	604	591
325	350	24	0.099	0.110	555	721
350	375	13	0.098	0.075	315	209
375	400	11	0.102	0.180	349	143
400	425	3	0.257	0.163	926	515
425	450	6	0.064	0.055	782	1034
450	475	3	0.057	0.060	629	919
475	500	5	0.043	0.020	764	958
500	525	1	0.009	–	570	–
525	550	6	0.171	0.071	988	826
550	575	0	–	–	–	–
575	600	1	0.140	–	11	–

compute the error,

$$\frac{1}{N}\sum_{i=1}^{N}(k_i-\bar{k})^2,$$

for the misfit between the measured value k_i and $\bar{k}$, the average of all sites within a given radius, where N is the number of sites with at least one measurement within that given radius (Figure 6, bottom). Although the error is at a minimum for a radius of 50 km, only 9.7% of the measured conductivity sites have values within that distance, compared to 71.1% within 200 km. For distances greater than about 200 km, the error is larger. It thus appears that conductivity can be most

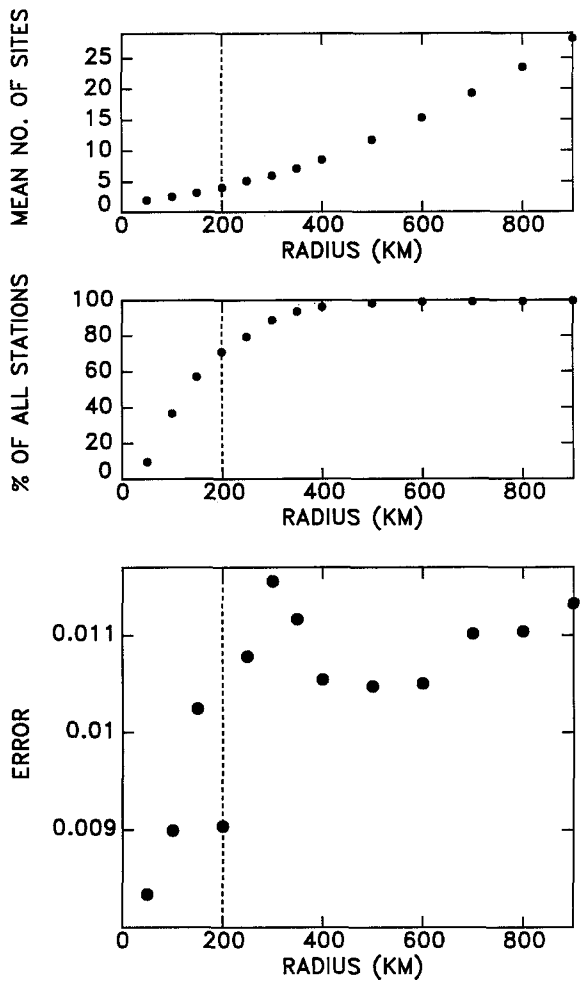

Fig. 6. Tests with measured thermal conductivity data as a function of distance from the measurement sites. (*top*) The mean number of conductivity measurements within a given radius of each measurement site increases as the radius around the site increases. (*middle*) The percentage of all sites with nearby measurements within a given radius measurements increases as the radius increases. (*bottom*) The errors between the measured conductivity value and the average value of the measured conductivity for a given radius is shown. Although the minimum error is at 50 km, only a small percentage of stations have measured values within that distance. For a radius of 200 km (dashed lines) the error is relatively small and 71.1% of the sites have measurements within that distance.

usefully estimated from nearby measurements within ~200 km.

Depth dependence

Previous work indirectly suggests that seafloor depth, in addition to sediment type and water content, has an effect on thermal conductivity. Data for the Arctic show generally higher conductivities for shallower areas (Lachenbruch and Marshall, 1966). Piston cores in the Indian Ocean have higher conductivities near shallower spreading ridges compared to adjacent deeper basins, probably due to a change from coarse-grained carbonate to finer grained clays in the deeper areas (Anderson *et al.*, 1977). DSDP Legs 26 and 60 data show higher conductivity for sediments deposited above the carbonate compensation depth (CCD) than for those on deeper seafloor, perhaps due to calcite content differences (Hyndman *et al.*, 1974). Horai (1981) proposed that the decrease is due to a gradual depletion of calcite, a high conductivity mineral, with depth from the lysocline until the CCD where the calcite is completely lost. However, although the conductivity decreased with depth, different trends were found for the data from the Mariana arc and Trough compared with the Mariana Trench.

A plot of the measured conductivity versus seafloor depth for our study area (Figure 7, left), shows a slight trend of decreasing conductivity with depth. A linear fit to the data has slope -1470 ± 251 m^2 K W^{-1}, with a correlation coefficient of -0.19. This correlation is significant, provided that the customary assumption of uncorrelated parent distributions is valid (Bevington, 1969). Given that this assumption may not be appropriate, the large scatter in the data, and that the linear fit was derived assuming that all data had equal uncertainties, we regard the trend as suggestive but not compelling. A similar plot for the estimated values shows no significant variation with depth, perhaps because only a limited range of conductivities are chosen when making estimates (Figure 7, right).

Regional variations

Because conductivity varies with lithology and nearby sites are generally similar in conductivity, it seems natural to compare the standard deviation of the entire data set (Figure 2) to that for subsets of data in individual regions. Moreover, the fact that the entire data set shows at best a weak correlation between depth and conductivity may reflect the fact that data from different regions are combined. To examine this possibility, we grouped the data in 25 regions (Figure 8) chosen by Berger *et al.*, (1976) to minimize the scatter of carbonate versus depth, taking into account the productivity, carbonate preservation, and topography.

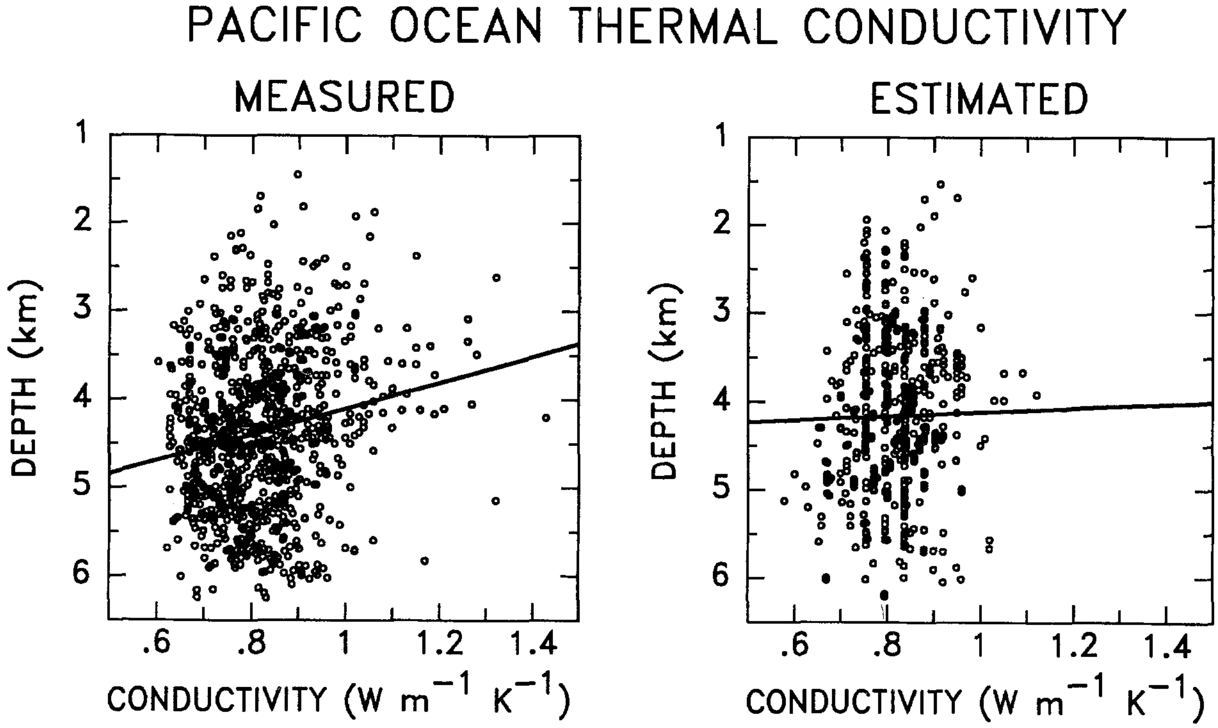

Fig. 7. Thermal conductivity versus seafloor depth. The measured data (left) shows a slight trend of decreasing conductivity with depth. The estimated data (right) shows no trend of decreasing conductivity with depth.

Table V shows the number of measurements, and the mean, median, and standard deviation for the conductivity in each region. For 16 of the 25 regions, the standard deviation is less than that for the entire data set (0.117 W m^{-1} K^{-1}). As a result, the mean of the regional standard deviations is also less than for the entire data set. Hence, as expected, the conductivity varies less within regions than oceanwide.

Furthermore, when the measured values are plotted by region, a trend of conductivity decreasing with increasing depth is somewhat more apparent (Figure 9). For 19 of the 25 regions a least squares fit to the data suggests such a relationship, with varying degrees of confidence. The different slopes and intercepts (Table V) presumably reflect differences in sediment type and CCD. For these 19 regions, the slope of the fit varies from -0.0152 to -13.3 km^2 K W^{-1} with a median value of -2.26 km^2 K W^{-1}. Six regions (3, 5, 9, 13, 19, and 24) do not show a trend of decreasing conductivity with depth. Region 24 has too few values over a large distance (110° in longitude) to be considered significant. The data thus generally suggest a trend of decreasing conductivity with increasing depth, but are inadequate to characterize the trend beyond the simple linear fit. There is also a slight suggestion that conductivity changes with depth more slowly beneath the CCD than above it.

Some of these complexities may reflect factors controlling the variation of conductivity with lithology in addition to carbonate content (Bullard and Day, 1961). A decrease in grain size correlates with an increase in porosity (Horn *et al.*, 1968), whereas increased water content correlates with decreased conductivity (Bullard and Day, 1961). Hence, a decrease in grain size may correlate with a decrease in conductivity. Thus if grain size decreases with increasing depth of deposition on the seafloor, a grain size effect might contribute to the observed decrease in conductivity with depth. Also, it is possible that the distribution of fine-grain clays, especially montmorillonite (commonly found in areas of low sedimentation or near volcanic sources (Windom, 1976; Kennett, 1982) may be an important factor. Further work, beyond our scope here is required to determine how the percentage of carbonate, sediment type, water content, porosity, and grain size

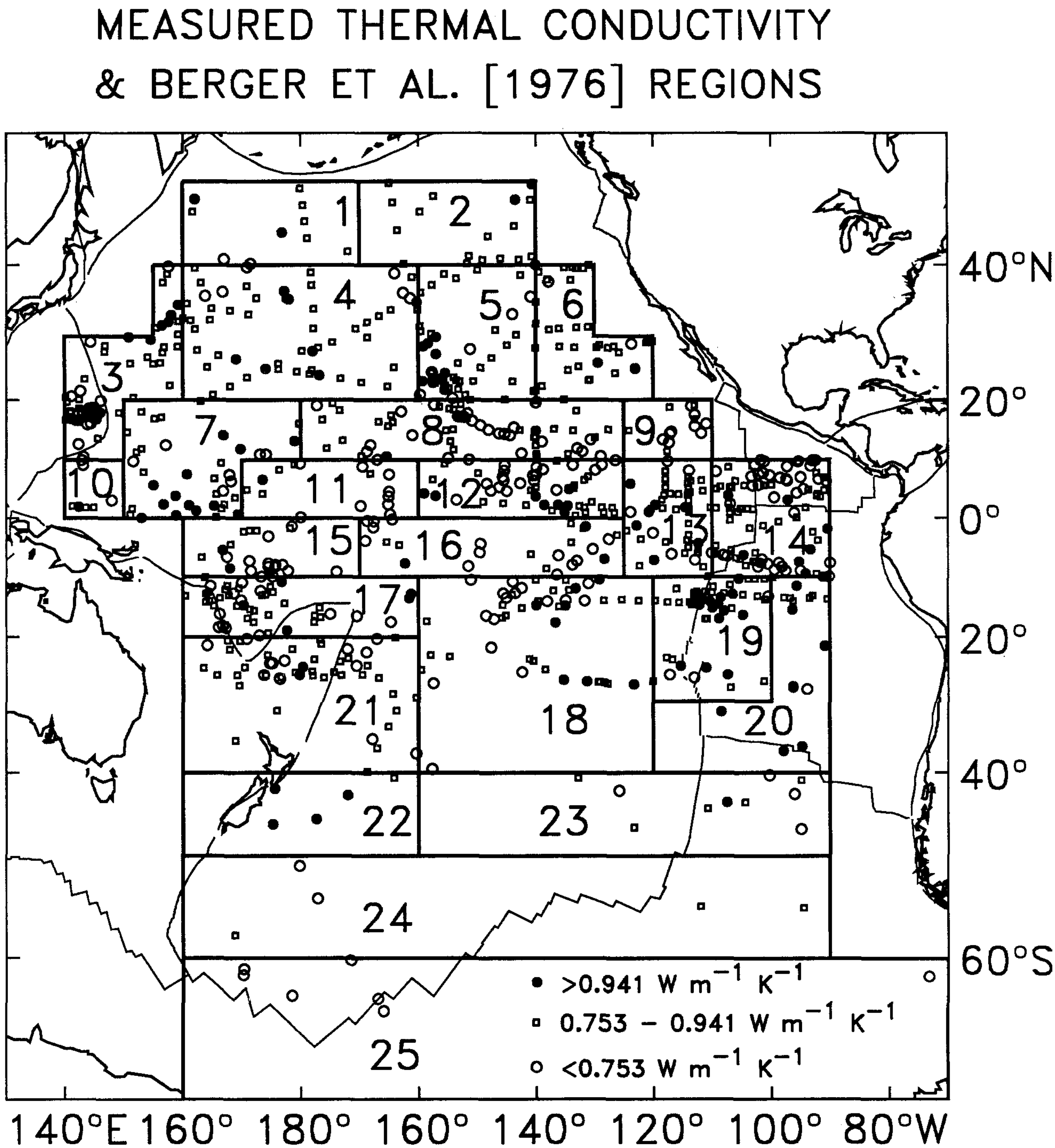

Fig. 8. Locations of measured thermal conductivity values in the 25 regions from Berger *et al.* (1976). Symbols same as for Figure 3.

correlates with thermal conductivity variations within a region and with seafloor depth.

Test of Estimation Methods

Given that our goal is to make better estimates of the conductivity at the sites where measurements are not available, we explored several methods for doing so. To compare various possible methods, we asked how well the conductivity at any measurement site could be predicted from the full set of measured values, for four different predictors:

(1) the overall data set mean $\bar{k}$,
(2) the value at the nearest other site,

TABLE V

Statistics for individual regions

Region		Conductivity		Linear fit			
Region	Sites	Mean $W\,m^{-1}K^{-1}$	Median $W\,m^{-1}K^{-1}$	Standard deviation	Slope $m^2\,K\,W^{-1}$	Y-Intercept m	Correlation coefficient
1	10	0.830	0.794	0.116	−152	5710	−0.04
2	17	0.859	0.850	0.074	−1440	6092	−0.21
3	75	0.787	0.775	0.123	584	4031	0.08
4	56	0.856	0.864	0.086	−3445	8232	−0.41
5	59	0.845	0.842	0.086	631	4438	0.10
6	39	0.845	0.846	0.057	−984	5495	−0.15
7	38	0.922	0.877	0.173	−3133	7618	−0.60
8	64	0.764	0.760	0.071	−2256	6764	−0.33
9	14	0.737	0.731	0.039	4693	413	0.45
10	7	0.827	0.850	0.120	−4329	7642	−0.82
11	16	0.774	0.725	0.102	−1595	6435	−0.44
12	53	0.805	0.779	0.124	−1970	6263	−0.75
13	53	0.847	0.833	0.114	120	3975	0.05
14	96	0.800	0.791	0.114	−326	3877	−0.10
15	21	0.778	0.733	0.115	−6021	9392	−0.88
16	26	0.768	0.722	0.120	−2054	6256	−0.56
17	51	0.800	0.766	0.082	−3715	6531	−0.31
18	50	0.831	0.792	0.138	−2098	5862	−0.43
19	51	0.888	0.904	0.121	464	3014	0.13
20	18	0.918	0.921	0.150	−1264	4844	−0.46
21	54	0.792	0.793	0.078	−6538	9318	−0.42
22	5	0.990	1.020	0.129	−6870	9959	−0.59
23	10	0.802	0.802	0.113	−4764	7937	−0.85
24	5	0.766	0.758	0.034	3183	2459	0.17
25	7	0.670	0.680	0.025	−17340	15420	−0.55

(3) the regional mean value for the geographic region (Figure 8),

(4)the local mean for the other sites within 200 km.

To test each approximation, we formed a total error indicating how well each method predicted all of the values in the data set. For the first method,

$$s_1^2 = \frac{1}{N-1} \sum_{i=1}^{N} (k_i - \bar{k})^2$$

where N = is the number of measurements, k_i are the individual measurements, and $\bar{k}$ is the mean (Figure 2) for the data set. For the nearest site method,

$$s_2^2 = \frac{1}{N} \sum_{i=1}^{N} (k_i - k_n)^2$$

where k_n is the value at the nearest other measured site. For the regional mean method

$$s_3^2 = \frac{1}{N-25} \sum_{i=1}^{N} (k_i - \bar{k}_j)^2$$

where $\bar{k}_j$ is the mean for region j, which contains point i. Finally, for the local mean method

$$s_4^2 = \frac{1}{N} \sum_{i=1}^{N} (k_i - \bar{k})^2$$

where $\bar{k}$ is the mean for all the sites within 200 km.

We applied these techniques to all 636 of the sites which have at least one other measurement site within 200 km. The minimum error ($s_4^2 = 0.00904$) is for the local mean method. The regional mean and overall mean yielded the second and third best estimates ($s_3^2 = 0.00962$, $s_1^2 = 0.01096$), and the neighbor method gave the largest error ($s_2^2 = 0.01099$). It thus appears that the best predictor of conductivity is the mean of the nearby sites, which for our data set averaged four sites within 200 km. Both this method and use of the mean for the appropriate geographic region are better predictors than the overall data set mean. We interpret the poor performance of the nearest site method as reflecting the large scatter in the data, which is somewhat smoothed out by using a local average.

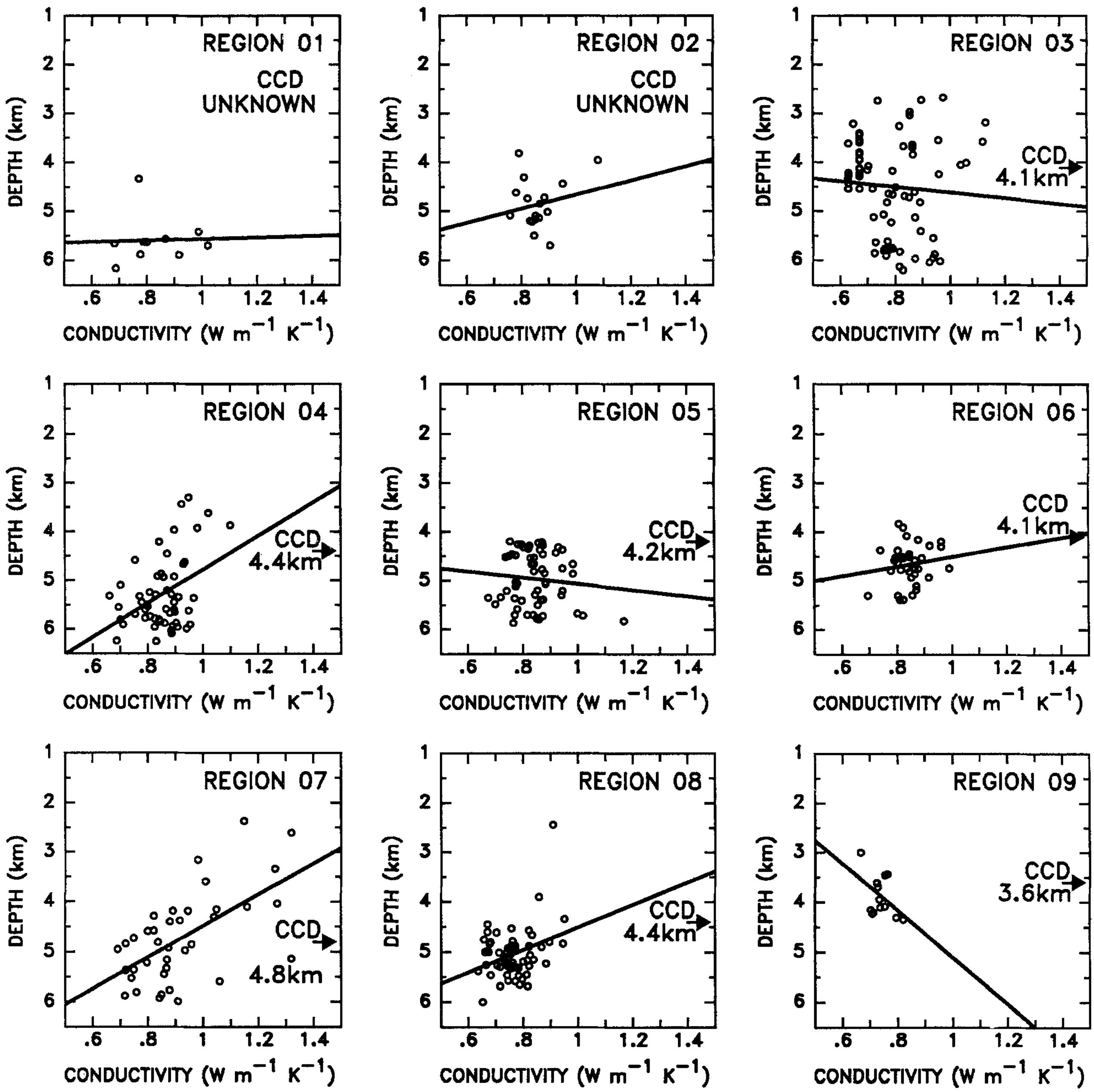

Fig. 9a. Least squares fit of conductivity versus depth for regions 1–9.

This result is useful in estimating conductivity at sites for which measured values are not available. We thus examine how previous estimates were derived, and illustrate the utility of reestimating the conductivity.

Estimated Thermal Conductivity

It is curious that the standard deviation of the estimated conductivity values is less than for the measured conductivities (Figures 2 and 7), since the estimated conductivities are in some way derived from the measured values. To investigate this discrepancy, we considered the data sources for the estimated values. We also examined the distance between the site at which the conductivity was estimated and the site of the measured value used for the estimate.

At first glance it appears that most of the 688 estimated values are based on measured data from

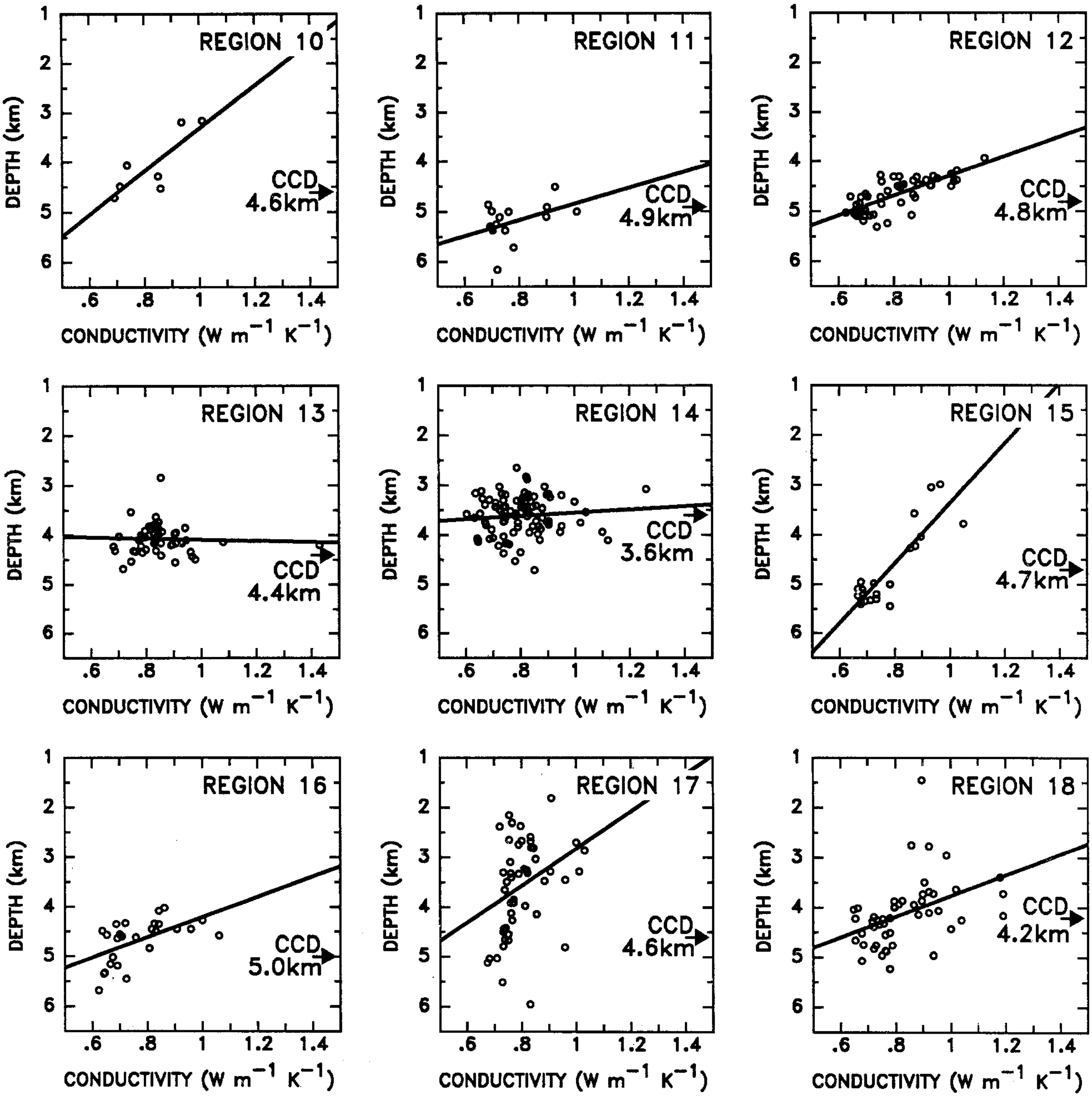

Fig. 9b. Least squares fit of conductivity versus depth for regions 10–18.

nearby sites, since 96% are listed in the '*S*' category (Table I). However, based on an examination of the published literature and unpublished reports, we have been unable to determine the measured site used for 29% (198) of the estimated values (Figure 10, top). Many or these values are suspiciously rounded (i.e. 0.800 W m^{-1} K^{-1}) as illustrated by the frequency of these values compared to the measured data set (Figure 7). 69% (475) are based on nearby measurements with 273 based on one site, 158 based on an average of two sites, and 44 based on weighed averages between two sites. Surprisingly, the distributions of the 475 estimated values with known sources (Figure 11, top) and the 198 values with unknown sources (Figure 11, bottom) are remarkably similar. We excluded the 15 values based on water content in this examination.

Except for about half a dozen values, the data for the estimated values are based on thermal

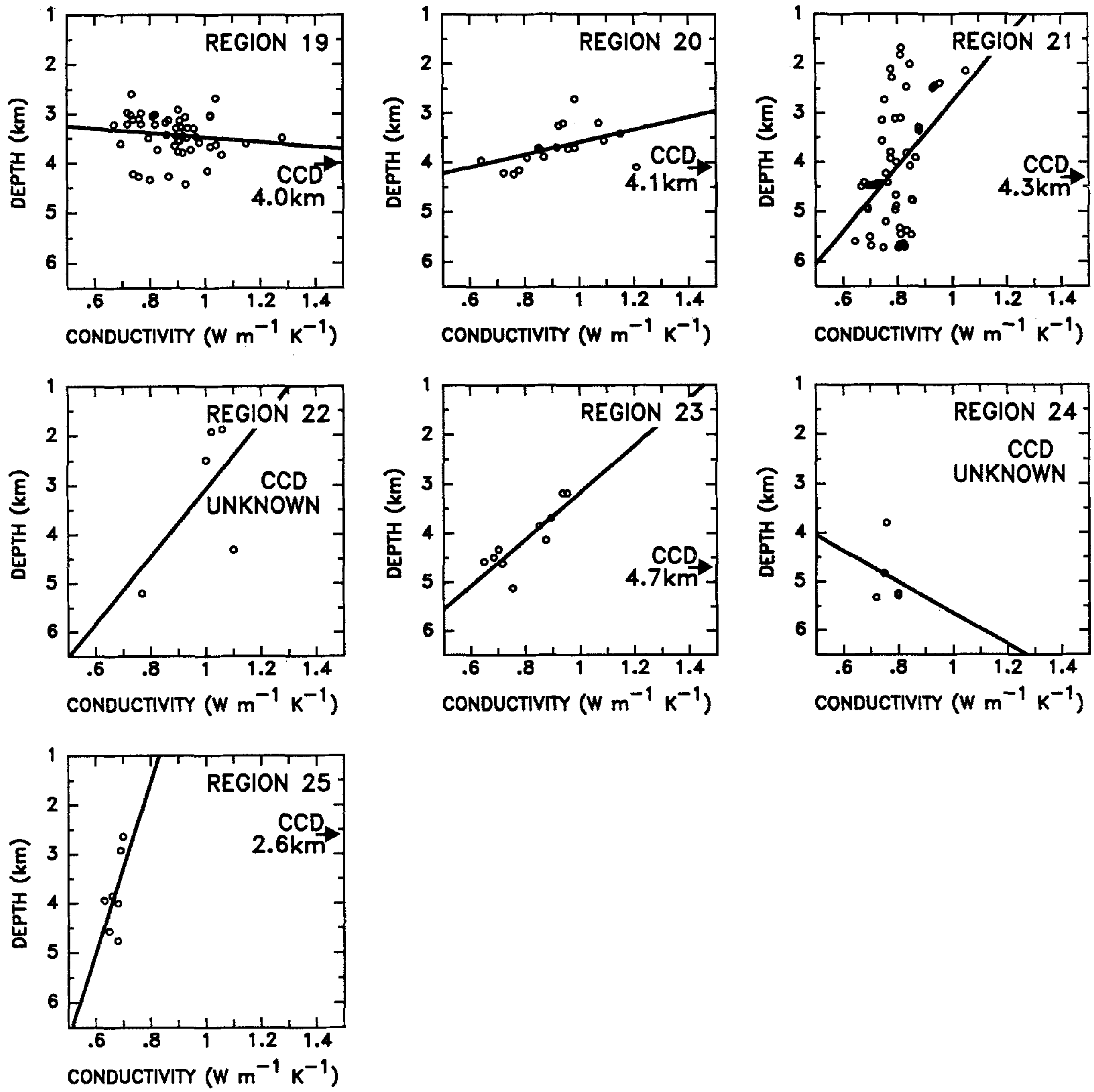

Fig. 9c. Least squares fit of conductivity versus depth for regions 19–25.

conductivity measurements for the same cruise. For the values estimated from one measurement, the separation between the measured and estimated sites is 135 ± 183 km. However, 105 of these sites are from 'pogo' heat flow surveys, where typically 3 to 10 temperature gradients were measured within about 20 km. These 'pogo' estimated stations average about 9 km away from the conductivity measurement site. For the remaining values estimated from one point, the separation between the measured and estimated sites is much higher, 215 ± 195 km, (Figure 12, top). These values are comparable to those for the stations with estimated values based either on an average of measurements, or some weighted average, whose average separation is 205 ± 213 km (Figure 12, bottom). These separation distances may pose some difficulties, given that it appears that conductivity estimates based on sites separated by 200 km or less are significantly better than for larger separations.

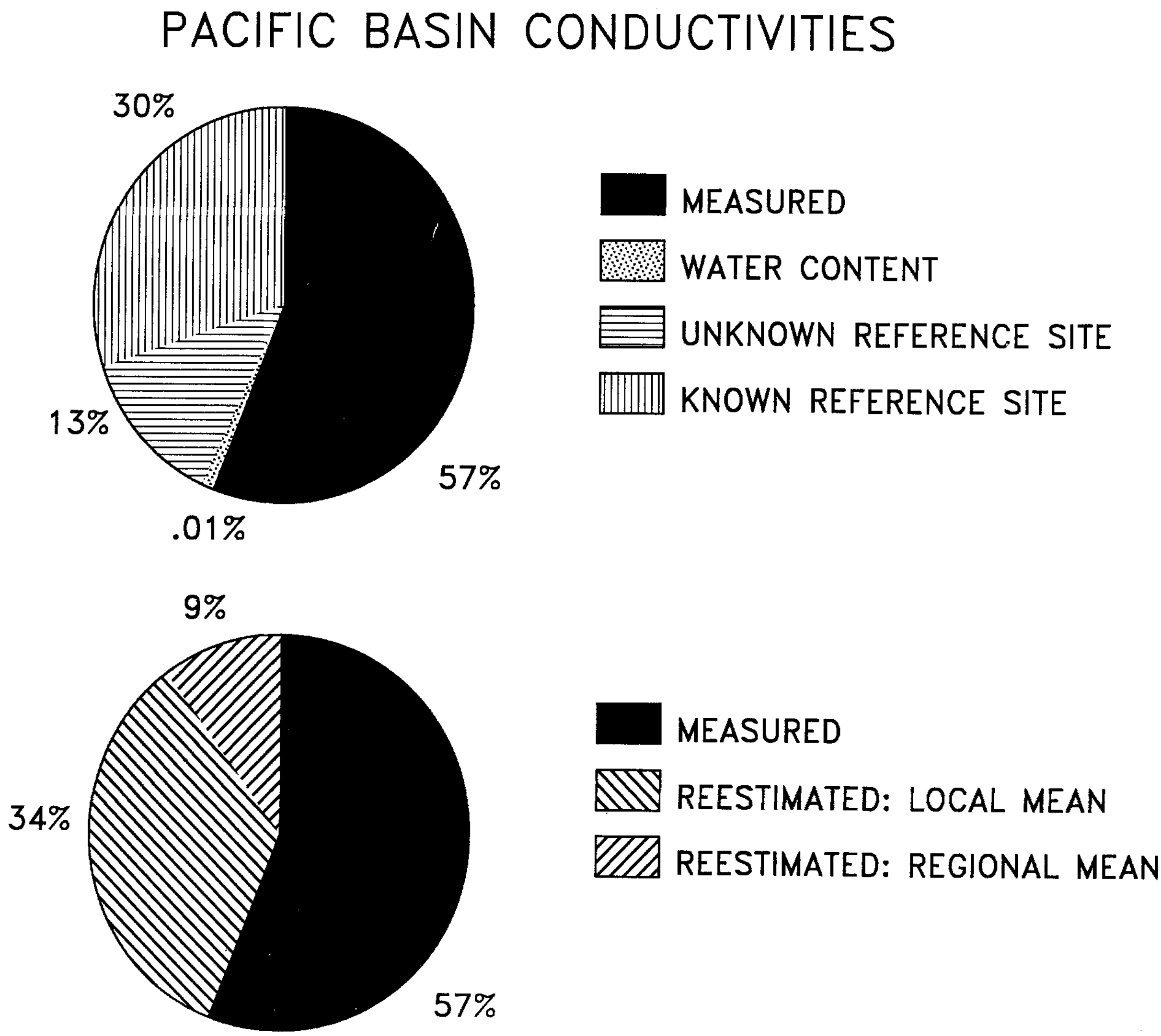

Fig. 10. Distribution of conductivity values for the Pacific Basin. (*top*) Showing percentage of measured values and those estimated by water content, using reference sites where conductivity was measured, and these without known reference sites. (*bottom*) Percentage of measured values and values reestimated by the local mean (within 200 km) and regional mean approach.

Reestimation of Thermal Conductivity

Using these results, we assigned new values to the sites with estimated thermal conductivities based on the average of the measurement sites within 200 km, and examined the change in inferred conductivity.

Many of the 688 sites with estimated thermal conductivities can be better reestimated (Figure 10, bottom). For the 198 values that are not apparently based on specific measured sites, we found measurements within 200 km for 144, and reestimated the conductivity from their mean. We did the same for the 391 of the 470 sites with conductivities estimated from reference sites at which our data set includes measurements within 200 km. These were generally closer to the site than the original reference value. The 138 remaining sites were reestimated using the regional means. Finally, we compared the conductivity values estimated from water content to the measured conductivity data.

Figure 13 shows the resulting change in the estimated conductivities. As might be expected, the average difference resulting from re-assigning values for sites with known references has a somewhat smaller change than for the sites with unknown references. After reestimating the conductivity for those sites based on reference sites we determined that on average

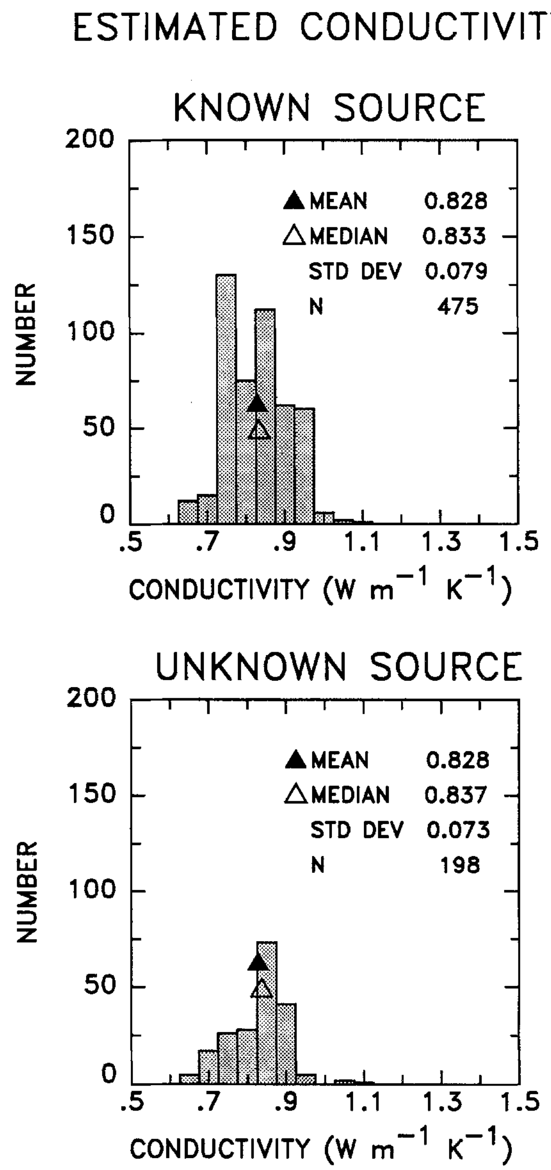

Fig. 11. Histogram of estimated thermal conductivity values. The distribution of values estimated from one or more nearby measurements (*top*) is similar to those estimated from an unknown source (*bottom*). The bin width is 0.05 W m^{-1} K^{-1}.

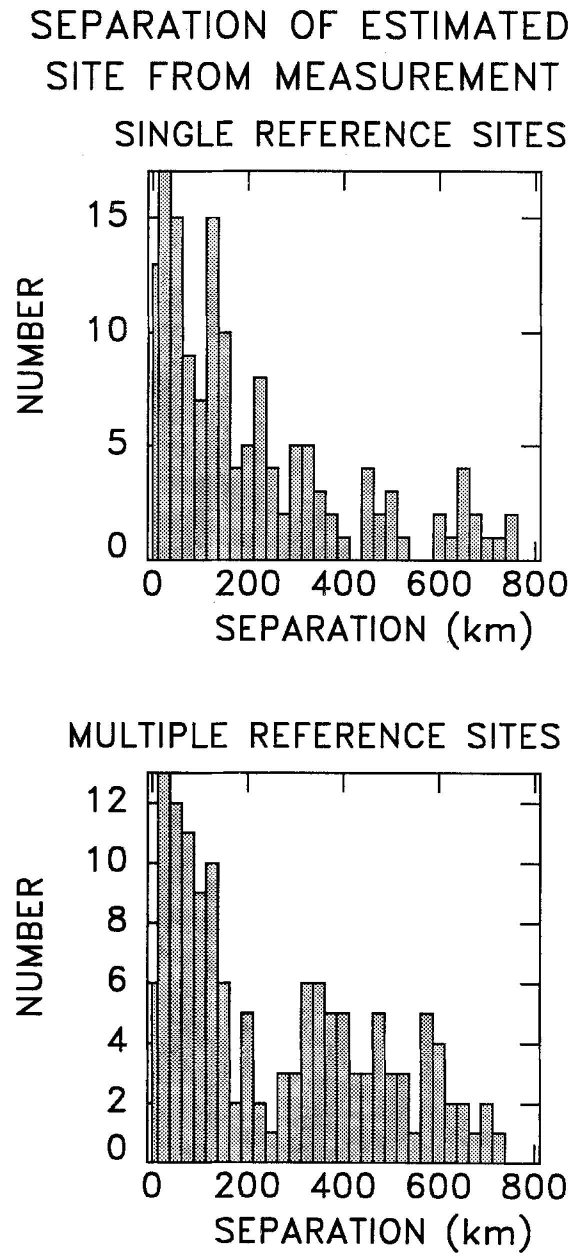

Fig. 12. Histograms of the separation between sites at which conductivity was estimated and the reference site. (*top*) Data for the sites with conductivity estimated from one measurement, excluding the 'pogo' sites. (*bottom*) Data for the sites at which conductivity was estimated from multiple sites. Note that the separation often exceeds 200 km. The bin width is 25 km.

they differed by -0.002 ± 0.062 W m^{-1} K^{-1}, or 0.046 ± 0.042 W m^{-1} K^{-1} ($5.58 \pm 5.16\%$) in absolute value. After reestimating the conductivity for those sites not based on reference sites we determined that on average they differed by -0.001 ± 0.100 W m^{-1} K^{-1}, or 0.069 ± 0.071 W m^{-1} K^{-1} ($8.52 \pm 9.08\%$) in absolute value.

Fifteen of the conductivities were estimated from the water content. Only 5 of the 15 have measured data within 200 km of the sites where conductivity was estimated from the water content. Compared to the conductivities estimated from our local and regional approach, 11 of the 15 original estimated values have lower conductivities. The values differ from the oriaginal estimates by 0.064 ± 0.061 W m^{-1} K^{-1}, or 0.113 ± 0.090 W m^{-1} K^{-1} ($16.4 \pm 14.1\%$) in absolute

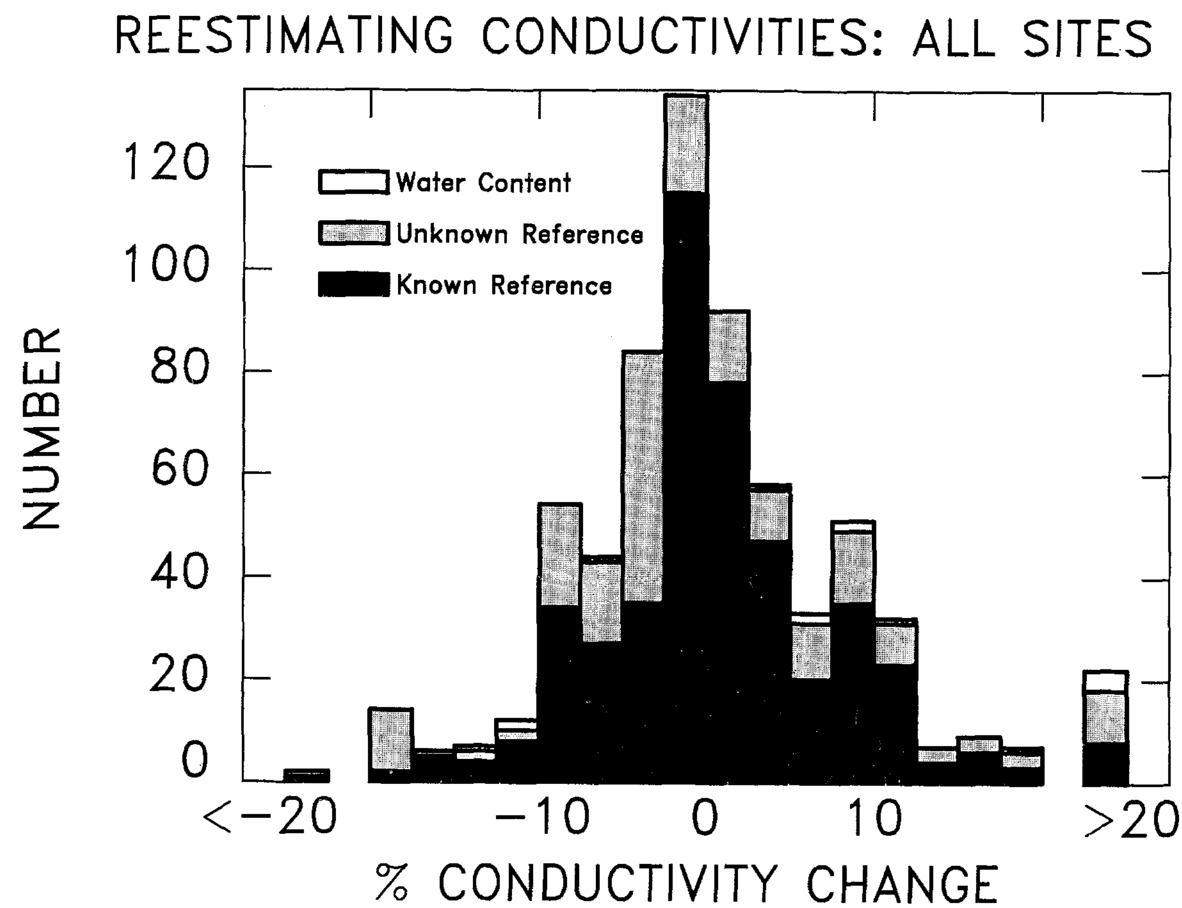

Fig. 13. Histograms showing the conductivity changes resulting from reestimation at all 688 sites without measured values. 540 are reestimated using the local mean within 200 km and 148 using the regional mean. The bin width is 2.5%.

value. Given the small number of measurements within 200 km of these sites, it is difficult to determine if there is any systematic bias from the water content approach relative to other measurement techniques.

We have used these results (Stein and Abbott, 1991) to reestimate thermal conductivities for sites with estimated conductivities, as part of a study of heat flow for the Superswell and Darwin Rise regions. These large areas of shallow bathymetry and low effective elastic thicknesses, relative to that expected for their age, perhaps result from widespread lithospheric reheating and thinning and dynamic uplift due to mantle flow (McNutt and Fisher, 1987; McNutt and Judge, 1990).

Conclusions

Analyses of the measured thermal conductivities demonstrate the variation in conductivity with ocean depth, site lithology, and distance between sites. There is a trend of decreasing conductivity with seafloor depth. We find conductivity variations associated with sediment type, with conductivity generally largest for carbonates, intermediate for deep-sea clays, and lowest for siliceous oozes. The difference in conductivity increases with the distances between sites, such that sites within 200 km of each other have similar values whereas more distant sites differ more.

It thus appears useful to reestimate estimated thermal conductivities using the mean measured value within 200 km or the regional mean. Obviously, given the variation in measured conductivity with distance, reestimation is less accurate than actual measurement. A resolution of 10% in the heat flow is important for many tectonic problems, especially for trying to understand the small variations of predicted heat flow for older oceanic lithosphere. We thus consider reestimation a useful alternative to discarding the large fraction of the heat flow data (43% for the Pacific) taken at sites without measured conductivity values, at least until such geographical coverage is available at sites with measured thermal conductivity.

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