Detailed Heat Flow Measurements Over the Juan de Fuca Ridge System

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Eleven detailed profiles of heat flow measurements have been completed over young oceanic crust of the Juan de Fuca ridge system. Individual measurements were spaced typically 0.4–1 km apart along multiple-penetration lines from 3 to 20 km in total length, and each measurement was located with respect to structural and sedimentary features by simultaneous seismic reflection profiling. In all cases, the average heat flow is well below that predicted by simple conductively cooled spreading models, even when the sediment cover is thick and the nearest basement outcrop is 15 km away. This disparity is attributed to ventilated convective circulation of water in the crust. Large heat flow variability is common along all profiles. Variations are present at two scales. Small-scale variations (from 1 km to a few kilometers between significant heat flow maxima), present in the younger profiles, probably reflect the influence of local venting and permeability variations on permeable layer cellular convection. Large-scale variations (10–20 km between significant heat flow maxima), present in all profiles, may reflect the influence of regional circulation driven by cold water recharge at isolated basement outcrops. Laboratory experimental data indicate that normal cellular convection can coexist with larger-scale bilateral flows, so that there is no simple way to extract the permeable layer thickness from the surface heat flow data. There is a considerable reduction in the amplitude of small-scale heat flow variability over the range of crustal age studied (0.1–12.5 m.y.). This is probably caused by the thermal filtering effects of the sediment cover which increases from about 50 m near the ridge crests to over 700 m on the flanks.

INTRODUCTION

It is now recognized that hydrothermal circulation plays an important role in heat transport through the sea floor. Strong evidence has been derived from a number of observations.

1. Heat flow variations in young oceanic crust are often large and cannot be explained by thermal refraction effects, by sediment deposition or erosion, or by bottom water temperature variations. They can be explained by the effects of seawater circulating in the oceanic crust [*Lister*, 1972; *Hyndman and Rankin*, 1972; *Sclater and Klitgord*, 1973; *Williams et al.*, 1974; *Sclater et al.*, 1974].

2. Weathering and low-grade metamorphism of rocks recovered from dredging [*Cann*, 1979], DSDP drilling [*Donnelly*, 1979], and ophiolite suites [*Salisbury and Christensen*, 1978; *Spooner*, 1979] demonstrate that seawater circulates through a large fraction of the oceanic crust, even at ridge crest locations.

3. There is a large disparity between the high mean heat flow predicted by any reasonable model of lithosphere accretion that satisfies topographic and gravity data, and the low mean heat flow measured over spreading ridge crests [*Langseth et al.*, 1966; *McKenzie*, 1967; *Sleep*, 1969; *Sclater and Francheteau*, 1970; *Parker and Oldenburg*, 1973; *Davis and Lister*, 1974]. Advection of heat from young lithosphere by circulation open to the sea can easily account for this disparity [*Lister*, 1972; *Sclater et al.*, 1976; *Davis and Lister*, 1977*a*].

4. Evidence for efficient fluid flow has been found in 16 m.y. old crust on the mid-Atlantic ridge where a highly permeable zone was penetrated by deep-sea drilling at a crustal depth of 324 m [*Hyndman et al.*, 1976*a*]. Seawater moving down the hole was carried away at a rapid rate.

5. Direct evidence for advective heat loss has now been found in a number of locations. Thermal anomalies in near-bottom seawater temperatures arising from emanations of warm water have been observed on the mid-Atlantic ridge [*Scott et al.*, 1974], on the East Pacific rise [*Crane and Normark*, 1977], and on the Galapagos spreading center (R. P. von Herzen et al., manuscript in preparation, 1979). At the last location, direct measurements from a submersible have been made of warm water vents with temperatures up to 15 K above bottom water temperatures and with flows of several liters per minute.

The details of sea floor groundwater flow are poorly understood, but it appears that water circulates relatively freely through much of the oceanic crust, whereas flow is insignificant in all but the most permeable of marine sediments [*Pearson and Lister*, 1973; *Langseth et al.*, 1977]. It is not difficult to estimate the conditions for fluid flow in marine sediments: they are relatively homogeneous, they can be sampled, and the critical factor of permeability can be measured in the laboratory. This has been done with a variety of sediment types, and permeability values range from 10^{-20} to 10^{-15} m^2 [*Pearson and Lister*, 1973; *Bryant et al.*, 1974]. These values probably are representative of the large-scale average in situ values, so that fluid flow within the sediments generally should be negligible [e.g., *Lister*, 1972; *Pearson and Lister*, 1973; *Davis and Lister*, 1977*a*; *Anderson et al.*, 1977].

Conditions in the oceanic basement are much more com-

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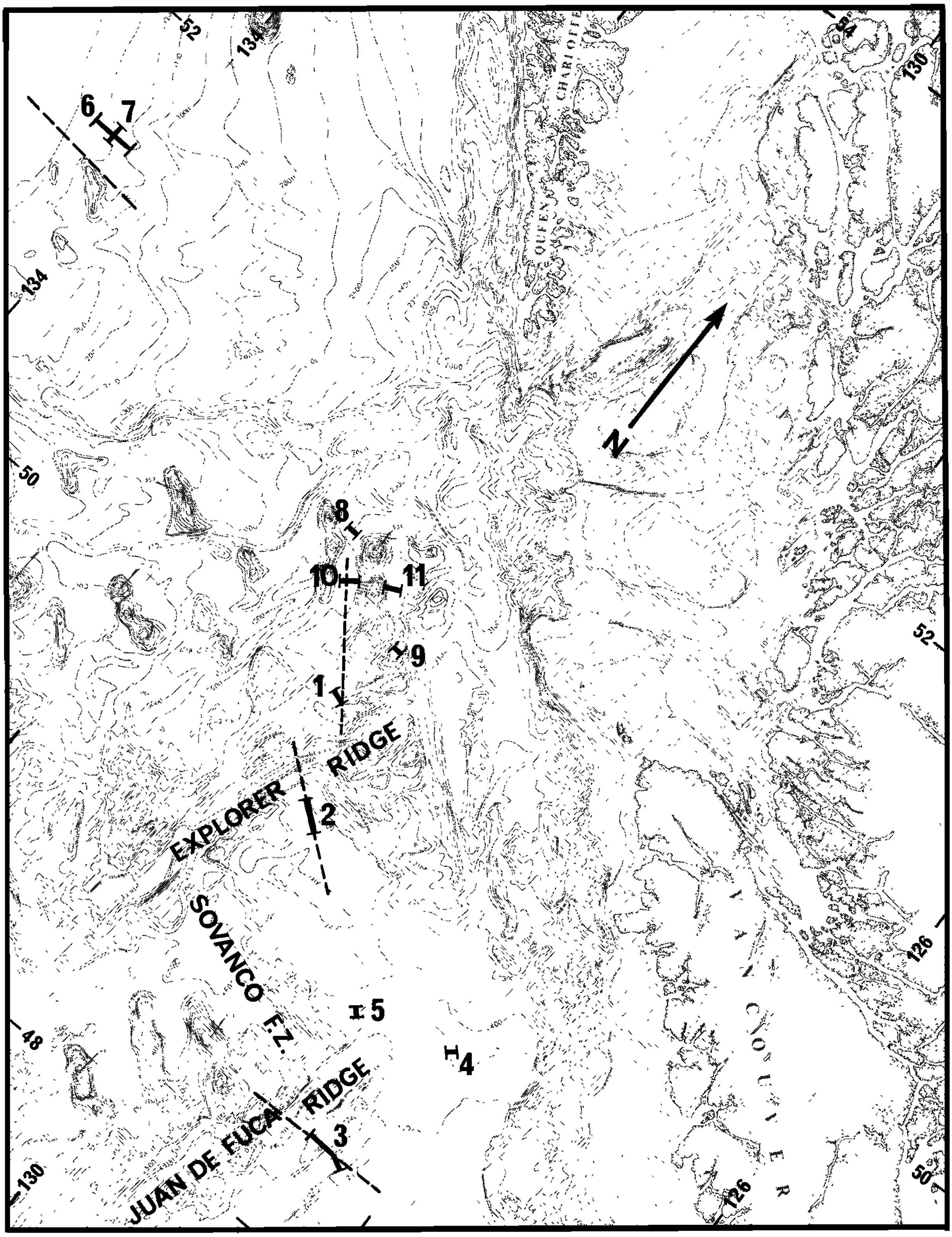

Fig. 1. Bathymetric index map (depths in meters) of the northern Juan de Fuca ridge system showing the location of representative seismic reflection profiles of Figure 4 (dashed lines) and the location of the multiple penetration heat flow lines discussed in the text and shown in Figure 5.

plex and difficult to estimate; in particular, the physical properties of laboratory specimens are not representative of large-scale bulk properties. This fact is borne out clearly where determinations of seismic velocity of DSDP core samples can be directly compared with velocity determinations by seismic refraction [e.g., *Hyndman et al.,* 1976*b*; *Hyndman and Drury,* 1976; *Salisbury et al.,* 1979]. A large discrepancy exists between specimen velocities of upper crustal material, which average 5.9 km/s, and bulk seismic refraction velocities measured for layer 2, which range from 2.8 km/s (layer 2*a*) to 5.0 km/s (layer 2*b*). This difference is best explained by the presence of large-scale fractures and voids (volcanic, thermal, or tectonic) in the crust.

In the same way that valid conclusions about seismic velocities in the crust cannot be made from measurements on laboratory rock specimens, conclusions about permeability of the crust cannot be made from measurements on single-rock specimens. The same large-scale fractures in the crust which affect its bulk seismic properties will have an even stronger influence on the effective permeability permitting efficient flow of groundwater through the oceanic crust. Estimates have been made of the regional permeability in certain land areas; for the Wairakei geothermal system in New Zealand, *Elder* [1965] estimates the permeability at 10^{-14} m^2; in Iceland, a region perhaps more analogous to the oceanic crust, *Palmason* [1967] estimates permeabilities up to 10^{-8} m^2. All values are well above those measured for sediments and are by theory and by field observation high enough to allow hydrothermal circulation.

Thus the existence of hydrothermal circulation in the oceanic crust is well established. However, several questions remain regarding the details of this circulation. Three have been considered in the field study reported here: (1) What is the nature of the circulation; is the circulation limited to tectonic fractures, or is it widespread in a generally permeable crust? (2) How deep into the crust does the circulation penetrate? (3) As the crust ages and the sediment cover thickens, how long does circulation persist? Each of these questions has been approached theoretically and through detailed heat flow measurements by a number of investigations [e.g., *Lister,* 1974; *Anderson and Hobart,* 1976; *Williams et al.,* 1974; *Davis and Lister,* 1977*a*], but significant uncertainties remain. The detailed suites of heat flow measurements reported here were gathered with the goal of gaining information about the nature of hydrothermal circulation in oceanic basement of various ages and sediment covers, and with different degrees of fracturing.

The northeast Pacific is an excellent region for studying these problems. An active, medium spreading rate (3 cm/yr) ridge crest is in some areas blanketed by continuous turbidite sediments. The coverage that these sediments provide may allow conductive heat flow measurements to be made right to the ridge crest, and the pronounced, initially horizontal layering in the sediments provides an excellent tectonic reference for delineating the normal faults which often accompany spreading at medium and slow spreading rates [see *Davis and Lister,* 1977*b*]. In this article, linear profiles of closely spaced heat flow measurements are presented for a variety of environments and over a range of ages from about 0.1 to 12 m.y. (Figure 1). A total of about 150 measurements are reported. Some of the values and a brief discussion of measurements were given in a preliminary article [*Hyndman et al.,* 1978].

HEAT FLOW MEASUREMENTS

Previous measurements in the region of the northern Juan de Fuca ridge [*Davis and Lister,* 1977*a*] demonstrated clearly that the heat flow station spacing of much less than 10 km is necessary if the continuous variation is to be outlined. Very near the ridge crest, even 2 km proved to be too coarse, but further reduction in scale was restricted by heat probe instrumentation and navigation limitations. Further refinement of the scale of sampling required the use of a multiple-penetration instrument; two instruments with this capability were used in the work reported here. One was developed by C. R. B. Lister and briefly described by *Hyndman et al.* [1978]; the second is conceptually similar and largely follows the design of the first. A summary description of both is given here. Temperature information is digitized to 1 and 2 mK precision for the two instruments, respectively, and telemetered to the ship in real time via frequency shift keyed acoustic transmission. The probes are 2 and 2.5 m long and use a 'violin bow' design; thermistors are placed in a thin steel tube (9- and 6-mm diameter) held under tension by a heavy strength member. The strength members are strong enough to resist bending during skew pullouts, while the sensors are in tubes small enough to equilibrate rapidly with the sediment. The sensor string in the first instrument consists of three thermistors for gradient measurement, interspersed by two groups of nine series-parallel thermistors used in the thermal conductivity measurement to determine mean thermal resistivities for the gradient intervals [see *Lister,* 1970*a*]. The second instrument has simply five equally spaced thermistors with no averaging sections. A resistance wire runs the full active length of the sensor tubes of both instruments to provide a heat pulse whose decay is used for the thermal resistivity determination [cf. *Lister,* 1979; *Hyndman et al.,* 1979]. With the small diameter sensor tubes, a gradient can be determined in just 3–5 min, and the sediment conductivity in an additional 10 min.

The station suites were measured by steaming or drifting the ship slowly across features of interest and dropping the probe into the bottom at suitable intervals. The instrument was raised about 100 m off the bottom between penetrations. The minimum penetration interval is a complex function of in-bottom time, drift speed, instrument and wire weight, depth, and wire drag. It was found that with a drift speed of about 1 kn ($\frac{1}{2}$ m/s) and an in-bottom time of 3–5 min, a station spacing of 700 m was possible in 3 km of water. The maximum duration of a profile was dependent upon instrument limitations (36 hours for the first instrument, 6 hours for the second), but in practice, lowerings were often limited more by the patience of the operators or crew. Typical profiles lasted from 4 to 12 hours, and allowed up to 30 penetrations.

Shipboard navigation was accomplished with satellite fixes and dead reckoning (1976) (excellent if ship drift was consistent) or with Loran-C (first available in 1977). The latter was found invaluable as a real time navigational aid, both for maintaining a desired drift speed with respect to the bottom, and for maintaining drift courses when they were at awkward angles to the winds or currents. Shipboard acoustic profiling operated simultaneously with the pinger soundings from the probe allowed excellent navigation of the instrument relative to the ship, and aided in positioning stations accurately with

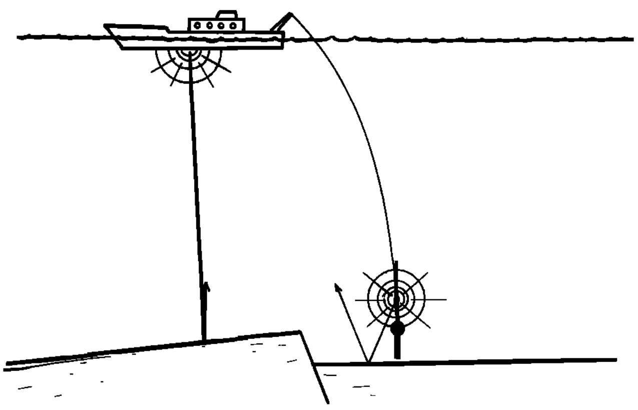

Fig. 2. Cartoon of the method used to determine the position of the heat flow probe with respect to the ship. With the tow speed and other parameters given in the text, typical lag of the instrument was about 0.6 km.

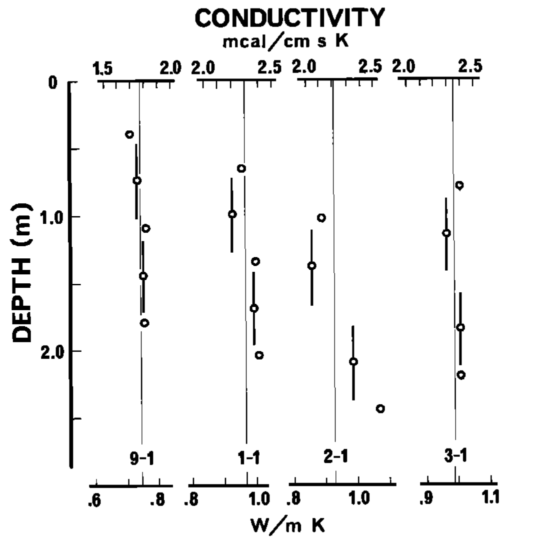

Fig. 3*a*. Conductivity versus depth measured in situ at four sites in the survey area. Measurements are made at three point and two averaging sensors over an active length of 1.4 m; values are shown about the weighted harmonic mean of the five values for each pentration.

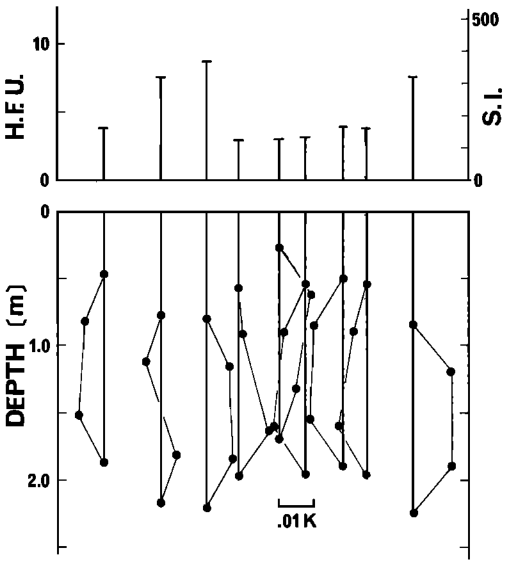

Fig. 3*c*. Nonlinearity of gradient along a section of profile 3. Nonlinearity is typically about 5% of the overall gradient values.

respect to bottom structure. A cartoon depicting the situation is shown in Figure 2. With this scheme, absolute positioning of the ship varies from about 100 to 500 m, whereas the positioning of the heat flow stations with respect to the ship, and consequently to local sea floor features, is thought to be better than 100 m.

A list of the data for all station suites with their beginning and end point coordinates is given in Appendix 1.[1] At most stations the heat flow values have been calculated from the measured gradients, and the conductivity values estimated from the nearest measurement. Real heat flow variations in young areas are large compared to variations in sediment conductivity, and since high absolute accuracy is not important to the goals of this study, a trade-off was made between more conductivity measurements (longer station times) and more stations (fewer conductivity measurements), generally in favor of more stations. At least one conductivity measurement was made on most profiles. Conductivity averaged over the upper 2 m of turbidites in this region has been found previously to vary by about 10–20% over distances of a few kilometers. Without a conductivity measurement at each station, individual heat flow values may be in error by this amount. Variation of conductivity with depth at individual heat flow stations also can be large in turbidite sediments. On a small scale this variation can be enormous (greater than a factor of 2 in cores reported in *Kasameyer et al.* [1972] and in *Davis and Lister* [1977*a*]); when conductivity is averaged over the intervals of measured gradients (tens of centimeters), values typically vary by 10–20%. Values measured at four stations are given in Figure 3*a*, and the effects of conductivity variations with depth on the gradients are shown in Figure 3*b*. In nearly every case the nonlinearity in temperature-depth profile corresponds to the conductivity-depth variation so that the heat flow variation with depth is small (<5%) and comparable to instrument resolution over the short intervals.

It is probable that there is little or no variation of heat flow with depth in the remaining stations where no conductivities were measured; temperature-depth nonlinearities are usually about 10% or less (Figure 3*c*), comparable to expected conductivity variations. Gradients decrease with depth in the majority of cases, but in a few, gradients increase with depth, and the sense of nonlinearity is often consistent over a horizontal distance of a few stations. There is no consistent relation between heat flow values and the sense of nonlinearity; regions of both high and low relative heat flow possess gradients which increase and decrease with depth. Since there is no regional pattern in the sense of nonlinearities, it is unlikely that the nonlinearities are due to recent bottom water temperature variations. Since there is no clear relationship between heat

[1] The appendix is available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N. W., Washington, D. C. 20009. Document J79-007; $1.00. Payment must accompany order.

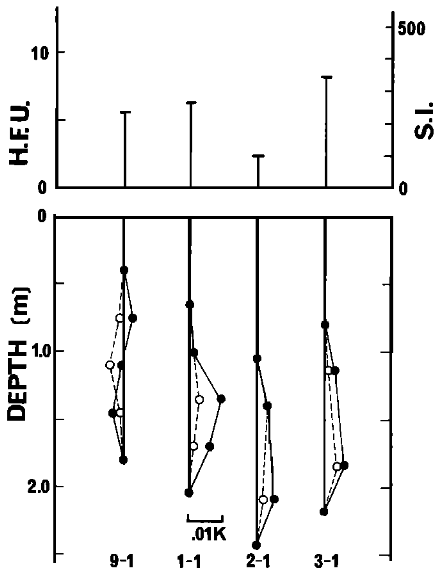

Fig. 3*b*. Nonlinearity of gradients for the stations shown in Figure 3*a*. Measured temperatures are shown with the gradient from upper to lower sensor removed. Dashed values have been corrected for measured conductivity variations; remaining nonlinearity is about 2% (typical gradients = 250 mK m^{-1}).

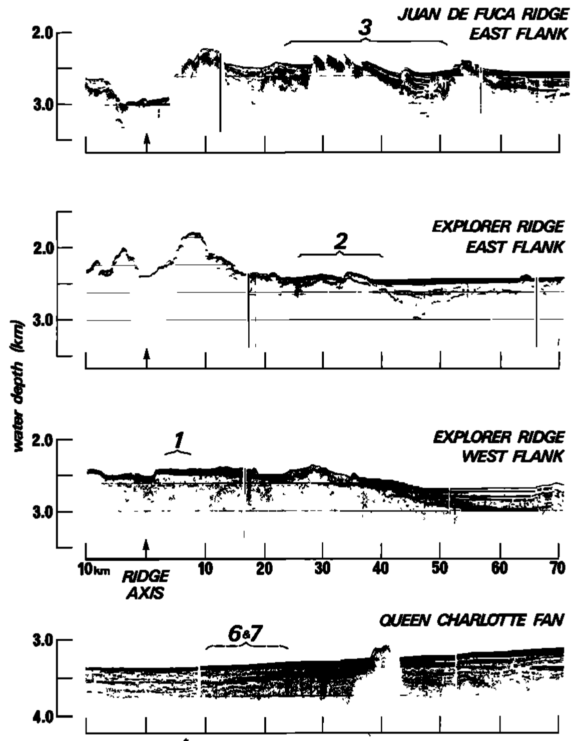

Fig. 4. Representative regional profiles across the Juan de Fuca ridge, Explorer ridge, and Queen Charlotte abyssal fan, along which five of the heat flow profiles are located. Seismic reflection profiles shown here and in Figure 5 were taken with a 200-Hz electromagnetic attraction-type pulser designed and built by C. Lister.

flow level (or basement temperature) and the sense of nonlinearity, it is unlikely that the nonlinear temperature profiles are caused by fluid migration in sediments. The most probable cause of the nonlinearities is variations of conductivity with depth in the turbidites. Gradients typically decrease with depth by an amount consistent with typical depth dependence of conductivity. Gradients which increase with depth require decreasing conductivity; a shallow concentration of sandy layers could easily cause the observed sense and magnitude of nonlinearity.

Heat Flow Profiles

The heat flow profiles were made over both clearly faulted and generally unfaulted crust, and over crust ranging in age from about 0.1 to about 12 m.y. The variety of environments is exemplified in Figure 4, where seismic relection profiles are shown across the Explorer ridge, the Juan de Fuca ridge, and across the older crust produced at the Juan de Fuca ridge system, where five of the heat flow profiles are located. All profiles are shown on the reference map (Figure 1), and most are shown relative to the underlying sediment and basement structure in Figure 5. Heat flow values are given in mW m^{-2} (1 mW m^{-2} (SI) = 0.024 μcal cm^{-2} s^{-1} (HFU)), gradients in mK m^{-1}, and conductivities in W m^{-1} K^{-1} (1.0 W m^{-1} K^{-1} = 2.4 mcal cm^{-1} s^{-1} K^{-1}).

The profile of measurements over the youngest crust was completed very near the crest of the Explorer ridge (profile 1). The basement is unusually smooth and is covered by a uniform 50-m blanket of sediment. A single normal fault step with a throw of about 15 m is visible at the northwest end of the profile. Evidence of nearby volcanic outcrops is provided by side reflections, as observed at the location of the fault and about 1 km to the southeast. Heat flow values are high, but are certainly not unusual for a ridge crest location (see Figure 6). There is a tendency for values to increase near the fault and the volcanic outcrops. The variability is high and occurs on a scale of several hundred meters.

Profile 2 (Figure 5) crosses somewhat older crust on the Explorer ridge. Here sediment thickness varies considerably, and the crust is tectonically distrubed on a fairly fine scale, of the order of 1 km. One large normal fault is present on the profile; its presence seems to have no influence on the distribution of heat flow. Values along the profile vary by a factor of about 2 on a scale of about 2 km.

Normal faulting is dramatically displayed along profile 3 on the east flank of the Juan de Fuca ridge, where six major normal faults are crossed by the suite of measurements. The turbidite sediment cover is about 50 m thick, whereas the fault displacement is typically 100 m, and oceanic crust is exposed at four of the fault scarps. The age of crust sampled by this group of measurements spans from about 0.1 m.y. to slightly greater than 1 m.y. Heat flow variability is high, with values often changing by a factor of 2–3 in a distance of 1 km. There is a tendency for high values to occur near the bases of normal fault scarps. In addition, there is a general decrease in magnitude of small-scale variability from younger to older and more thickly sedimented crust. In particular, the large sediment-filled valley at the east end of the profile (East Valley) has nearly constant heat flow.

This age or sediment cover dependence of the nature of variability appears to continue in measurements of profiles 4 and 5 (appendix only, on microfiche) over crust 5–6 m.y. in age. Previous measurements in the region were too far apart to draw any conclusions about small-scale variability, but significant variations (a factor of 2–3) were seen at a scale of 10–20 km [*Davis and Lister,* 1977*a*]. The measurements of profiles 4 and 5 were taken with about 0.5-km spacing, and they display very low magnitude variability over their lengths of a few kilometers (193–205 mW m^{-2} in 2 km, profile 4; 176–226 mW m^{-2} in 5 km, profile 5).

A large region of even older crust was sampled in detail along profiles 6 and 7. These are located on crust about 12 m.y. in age, where 0.5–0.7 km of terrigenous sediments of the Queen Charlotte abyssal fan have covered relatively smooth basement. Occasional small seamounts outcrop above the sediment surface. Heat flow variation along the two crossed profiles is striking. Values vary smoothly by a factor of 5 over a distance of about 10 km, and the variation is clearly three-dimensional. Values peak at about 100 mW m^{-2}.

Four short profiles were completed over relatively young crust at the bases of seamounts in the Delwood Knoll region northwest of the Explorer ridge (Appendix 1 (on microfiche), Figure 1). Of these, two (profiles 10 and 11) are shown in Figure 5. Values tend to be very low for this young crust (0.5–2.3 m.y.), and vary by as much as a factor of 3 in a few hundred meters. In one case the nature of the variation (along profile 11) is similar to the variation which would result from conductive thermal refraction assuming a two-dimensional structure, although the amplitude of the observed heat flow variation is considerably larger than that predicted by the conductive model.

Discussion

Absolute Heat Flow Values

It was mentioned earlier that one indication that hydrothermal circulation plays an important role in the transfer of

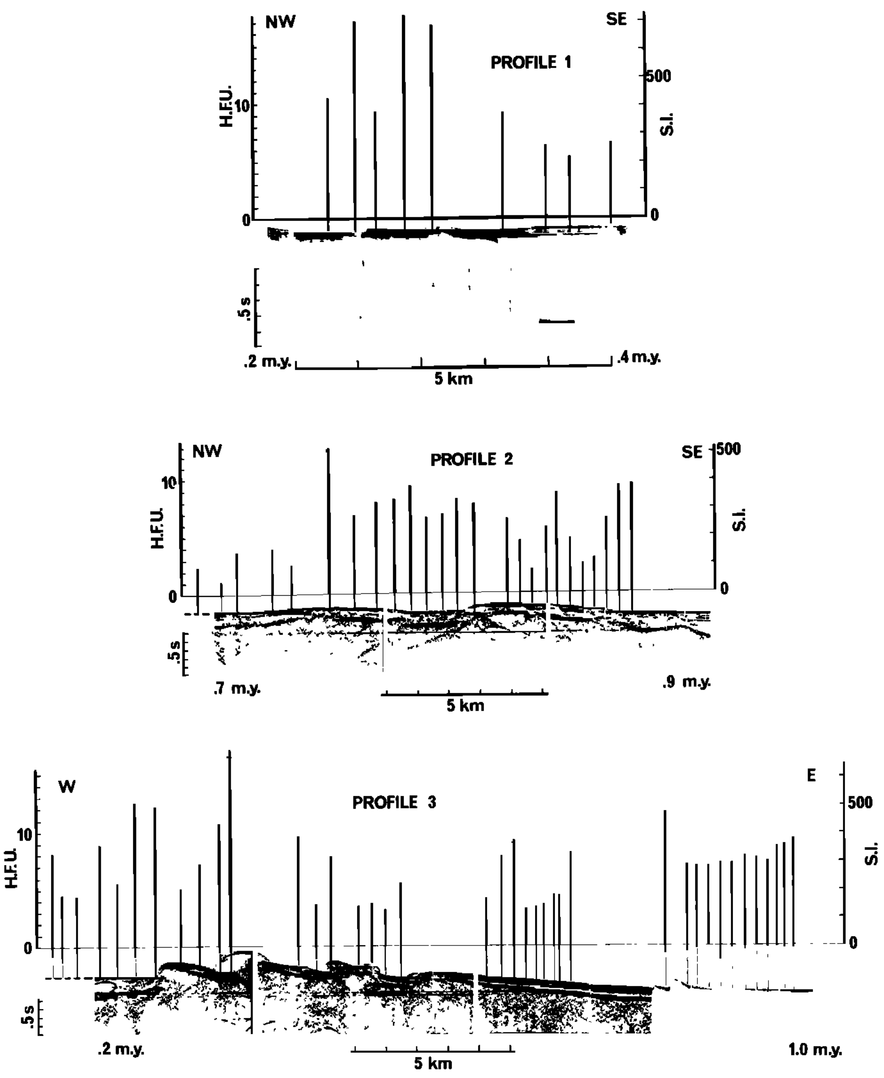

Fig. 5. Heat flow values and basement ages shown superimposed on seismic reflection or 3.5-kHz records taken while drifting along the heat flow lines. The results of a two-dimensional thermal refraction model are shown dashed along profile 11.

heat in the oceanic crust is that the absolute levels of heat flow measured are consistently well below those expected for the ages of lithosphere they represent. This is certainly the case for all the measurements reported here. Ages for the crust at all stations were estimated either directly from the magnetic anomaly pattern as interpreted by *Riddihough* [1977] or from the distance to known spreading axis, and the values are plotted as a function of their age in Figure 6. The estimate of the age dependence of total lithospheric heat flow given by *Lister* [1975], which is based on reliable heat flow values in older lithosphere [*Sclater et al.,* 1976] and on a model of the observed thermal subsidence with age of ocean floor [*Davis and Lister,* 1974], is also shown in the figure for comparison. The large discrepancy between the estimate and the measurements is characteristic of nearly every young region, and the missing heat is attributed to direct heat loss to the sea by open hydrothermal circulation.

Heat Flow Variations

High levels of local heat flow variability have been observed commonly since the first sea floor measurements were made [*Bullard and Day,* 1961; *von Herzen and Uyeda,* 1963; *Lee and Uyeda,* 1965; *Langseth et al.,* 1966; *Le Pichon and Langseth,* 1969]. The estimated conductive effects of sedimentation, thermal refraction, etc., are in some cases significant but are rarely large enough and are often of incorrect sense to account for the local heat flow variations observed. This is certainly the case for the observations made here; only in one suite of measurements can the distribution of values with respect to basement and sediment topography be explained reasonably by the effects of thermal refraction (see profile 11). All other profiles possess large levels of scatter which are often uncorrelated with local topography and sediment distribution, and we conclude that in most of the areas studied here, the thermal distribution in the crust is dominated by hydrothermal circulation.

Tectonic Control of Circulation

With the close spacing of stations and the precise control of the local sea floor structure, the measurements reported here provide some new insight regarding the question, Is the circulation limited to major tectonic fractures or is it widespread in a generally permeable crust? There is good evidence that the presence of faults does influence circulation along profile 3. High values occur near the base of every fault scarp; in one extreme example the heat flow increases from 210 mW m^{-2} in

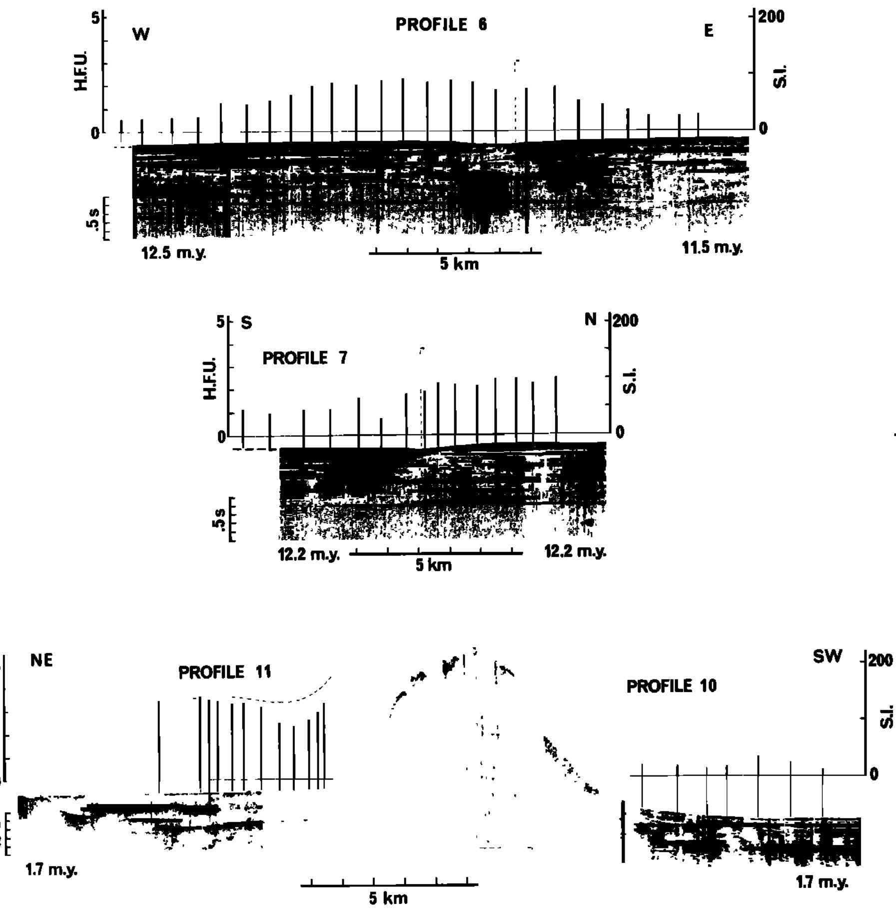

Fig. 5. (continued)

the middle of a 3-km wide fault block to 1250 mW m^{-2} near the base of the bounding scarp. Somewhat less spectacular but nevertheless significant, similar behavior occurs at at least four other faults along the profile. It is uncertain how the faults affect the circulation. If groundwater flow occurs only in the near-vertical fault zones, both elevated and depressed heat flow should be seen near the faults relative to the heat flow within the blocks, since both rising and sinking limbs of convective circulation would be encountered. From the nature of heat flow variations over the apparently unfaulted areas, it is seen that circulation is not limited to normal faults. It is more probable that the general permeability of the crust is merely enhanced by normal faulting and that this has some influence on the regional pattern of convective circulation. For example, in the region of profile 3, porous media convection in the crust driven by heat sources at depth (conductive cooling of the young lithosphere) is bounded by a layer of sediments at the surface which is both impermeable and insulating. A localized zone of higher permeability would tend to force the position of rising limbs of convection, and this could be the source of elevated heat flow at the surface near the normal fault scarps.

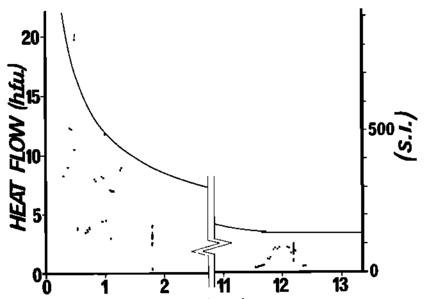

Fig. 6. Heat flow versus age shown for all measurements reported here. For comparison, a theoretical cooling curve for conductively cooled lithosphere is also shown (see text).

In addition to possibly enhancing the permeability, the normal faults along profile 3 probably provide locations for hydrothermal discharge. The crust along the profile is continuously covered by 50–100 m of sediments, except at normal fault scarps where basement is exposed. In this situation, convection could be forced in a manner demonstrated by *Elder* [1965], who observed that rising limbs of convection were strongly forced by the location of discharge points. Thus higher relative permeability and surface crustal exposure at normal faults may serve together to provide efficient chimneys for rising limbs of convection, and consequent elevated water temperatures in the crust near the bases of fault scarps may provide the small-scale heat flow pattern observed.

Large variability is not associated with fault scarps only; heat flow varies within fault blocks on profiles 2 and 3 and in crust with little tectonic disturbance visible at all (profiles 1, 6, and 7). Much of the variability occurs on a very small scale, and it is reasonable to conclude that convective circulation patterns occur in the crust at a scale down to at least a few hundred meters. At the same time, some profiles display smooth station to station variation on a much larger scale (up to 20 km in profiles 6 and 7), and we conclude that the crust

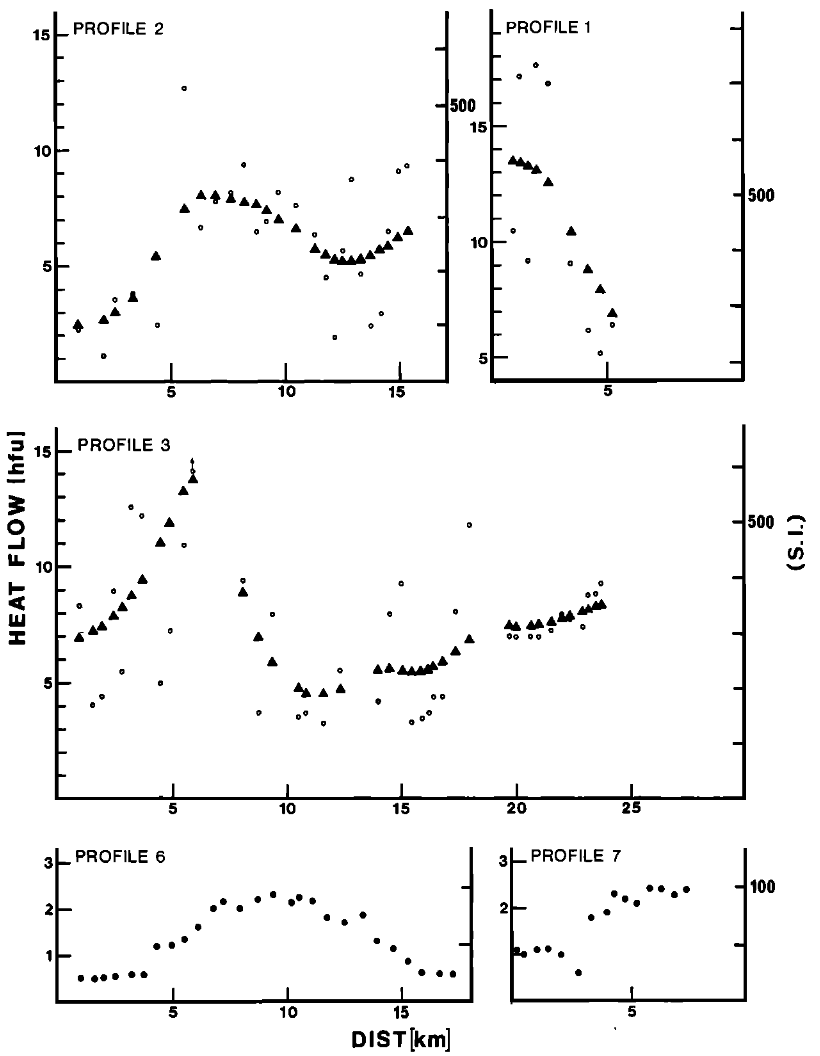

Fig. 7. Heat flow profiles 6 and 7 compared to profiles 1, 2, and 3 which have been smoothed with a Gaussian filter of 1-km width.

must be effectively permeable in a bulk sense well below this scale.

Scale of Circulation

Heat flow variability occurs at a wide variety of scales in the profiles presented here. Small-scale variations (subkilometer to about 2–3 km) are dominant over young crust with thin sediment cover (profiles 1–3, Figure 5), whereas long wavelength variations are most clearly visible over older and more heavily sedimented crust (profiles 4–7, appendix (on microfiche) and Figure 5). There is some indication that large-scale variations (10- to 20-km wavelength) are present, but masked by small-scale variations, on the younger profiles. This observation is made clear by smoothing the heat flow values along the profiles. A somewhat arbitrary Gaussian filter of 1-km width is used for Figure 7. The smoothed young profiles appear very similar to the older unsmoothed profiles 6 and 7, and it seems that large-scale variations occur at all ages and that small-scale variations which are superimposed merely decrease in amplitude with increasing age or sediment cover.

Such a change in the dominant scale of heat flow variability may reflect a change in the nature of hydrothermal circulation, or it may be purely an artifact of the increasing sediment thickness. A few possible causes of the change in dominant scale are as follows.

1. The horizontal scale of circulation is in part dependent on the depth to which hydrothermal convection penetrates [*Elder*, 1965; *Williams et al.*, 1974; *Hartline and Lister*, 1977]. If the depth were to increase with time, an increase in the horizontal scale of convection and heat flow variability would result, although the presence of long wavelength variations in the young profiles discounts this suggestion.

2. Local variations of permeability could strongly influence small-scale fluid flow in the crust and, in turn, the heat flow at the surface. If the permeability were to become more homogeneous with time, a decrease in the magnitude of small-scale heat flow variability would result. This could occur by either an increase in permeability of low permeability zones (e.g., thermal cracking of massive rock units) or vice versa (e.g., hydrothermal mineral deposition in highly permeable zones).

3. Hydrothermal convection in basement rocks is undoubtedly forced by local heat sources (e.g., residual hot rock reservoirs, local plutons, or simply zones of lower permeability). These heat sources will become weaker and more diffuse with time, and this will be reflected in the nature of the hydrothermal circulation and surface heat flow.

4. Thickening sediment cover may reduce the amplitude of small-scale heat flow variations measured at the surface. Simple upward continuation of short wavelength variations

through thick sediments will reduce their amplitudes. Local lateral basement temperature variations, which could result from sources mentioned in causes 2 and 3 above or from simple cellular convection, also would have a decreasing effect on heat flow variations with increasing sediment thickness. For example, if regional heat flow averaged 100 mW m^{-2}, a 5 K basement temperature variation would produce a 100% variation in heat flow if sediments were 50 m thick, but only a 5% variation if sediments were 1 km thick.

Horizontal Heat Transport and the Effects of Seamount Ventilation

Previous measurements on the Juan de Fuca ridge [*Davis and Lister,* 1977*a*] indicated that ventilated hydrothermal circulation was effective in cooling young oceanic crust even when sediment cover was thick and basement outcrops were as far away as 10–15 km. The crust beneath the measurements reported here is found to transport heat equally readily, even at the 12-m.y. age beneath profiles 6 and 7. Total heat flow expected from lithosphere of this age is about 145 mW m^{-2}, whereas measured values peak at about 100 mW m^{-2}. For the missing heat flux (more than half) to be ventilated to the sea, horizontal heat transport must be efficient over at least the distance to the nearest basement outcrop, which appears to be a seamount 15 km away. Much lower than expected values were similarly found on the Juan de Fuca ridge by *Lister* [1970*b*], where a cluster of measurements made over young crust but near a group of small seamounts averaged only 25 mW m^{-2}. Remarkably low values near seamounts are also found at profiles 8, 9, and 10. In all cases, the ocean floor near the base of the seamounts is well sedimented and apparently sealed to open hydrothermal circulation, so that the missing heat flow must be lost by horizontal advective heat transport and ventilation to the sea through the outcropping seamounts themselves. This means that hot water must escape and cold ocean water must enter the crust at these seamounts, either at points close together on a single seamount or at widely separated outcrops.

In either case, large-scale lateral variation of the observed heat flow must result, irrespective of whether local convective cells coexist with the large-scale circulation. General flow between widely separated recharge and discharge points is the easiest to visualize. Near the recharge point, the groundwater is close to ocean temperature and near-zero heat flow should be observed. However, the groundwater will absorb the mantle heat flow through the base of the permeable layer, and the thermal gradient will eventually become large enough to promote convection. The local convective breakdown should be on a normal lateral scale, as predicted by *Prats* [1966], but the cells will move along with the general flow as observed in a Hele-Shaw cell by *Hartline* [1978]. The base of the sedimentary thermal blanket should thus see a fluctuating water temperature, but one that increases steadily at the distance to the recharge point increases. If the discharge point is far enough away from the recharge, the average observed heat flow will approach that expected from the mantle for the region, but in all cases the heat flow will be highest near the discharge outcrop.

Where the recharge and discharge points are close together on the same outcrop, the thermal regime is more complex. The large-scale flow is straightforward: cold water sinks to the lower boundary of the permeable region and spreads out laterally, absorbing mantle heat as it flows. In some distant region there is a generalized upwelling, and the water then flows back toward the discharge spring along the underside of the sediment blanket. If only the large-scale circulation occurred, the observed surface heat flow would come only from this upper return flow and would decrease toward the outlet from a maximum in the upwelling region. The decrease in heat flow through a uniform sediment blanket should be exponential away from a linear zone of upwelling, and even more peaked from a point, or plume, upwelling. The actual data from a region of uniform sediment cover (profiles 6 and 7, Figure 5) show a very broad peak of heat flow, with steepening gradients at the sides, but the peak is nevertheless well below the expected absolute level for lithosphere of the known age. Some form of very diffuse, distributed upwelling is needed to explain the observed anomaly shape, and this means that the temperature gradient in the permeable layer is supercritical over the large peak area. Thus breakdown into normal local convection cells would be expected.

Observations of porous medium convection in the presence of large-scale bilateral flows have not been made, but there is some interesting evidence that such flows can exist spontaneously during normal convection between impermeable boundaries. Figure 8 reproduces photographs of a dye line distorted from an initial horizontal configuration by convective motions in a Hele-Shaw cell [*Hartline,* 1978]. Flows have been estimated by determining the area enclosed between the dye line and the originating wire on an enlarged photograph of an earlier exposure than the one shown. The numerical values, in arbitrary units, are inscribed in their respective plumes. The interesting features are the substantial variation from plume to plume and the existence of large regions of upwelling/downwelling imbalance. The latter require substantial bilateral flows between regions along the upper and lower boundaries. The drive for the variations in the Hele-Shaw experiment is probably a variation in permeability caused by warping of the cell boundary wall plates; the variation is unlikely to be suf-

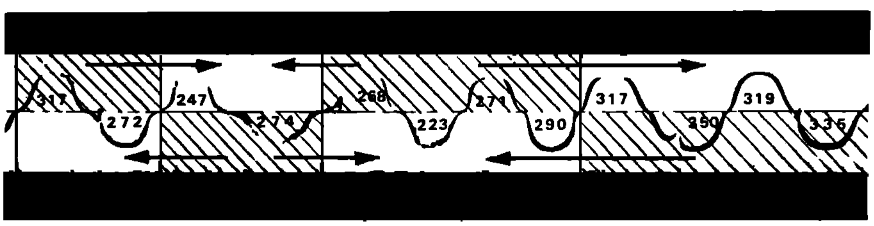

Fig. 8. Photograph of convection in a Hele-Shaw cell with thin, and therefore slightly warped, walls. The dye line is displaced from the central generating electrode by the fluid motion, and the relative areas of the plumes (arbitrary units) were measured on an enlargement of an earlier photograph of the same dye line. Upwelling and downwelling areas were compared to the average of adjacent half cells; regions of excess flow are shown shaded. Exchange of fluid is required between the shaded and unshaded regions as shown by the arrows.

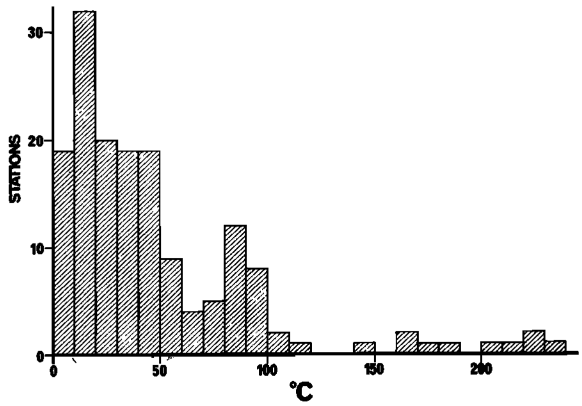

Fig. 9. Basement temperatures (above bottom water ≈2°C) for all stations, estimated from surface heat flow measurements, sediment thicknesses, and an assumed conductivity of 2.5 mcal cm^{-1} s^{-1} $°C^{-1}$ (1.05 W m^{-1} K^{-1}).

ficient to invalidate the flux estimates, since the changes are gross and visually obvious on the photographs.

The compatibility of regional bilateral flows with otherwise normal cellular convection in a porous medium removes a serious constraint from the explanation of the large-scale lateral heat flow variation. It is not necessary to choose between laterally elongated vent-driven convection on the one hand and isolated cellular convection with the regionally expected heat flow on the other. The two modes of convection can coexist, and the large-scale bilateral flow can transport heat from generally warmer to generally cooler regions in the presence of vigorous local convection, and even of local venting. Herein may lie the explanation of the large-scale variation observed on very young oceanic crust after the local scatter has been removed by a spatial filter (Figure 7). Local variations are probably present in profiles 6 and 7, but they may be diminished at the surface by the thick sediment cover for the reasons given earlier. If significant unilateral groundwater flow causes time-varying local convective patterns, thick sediment cover will have an additional smoothing effect in time on surface heat flow.

The consequences of ocean/groundwater exchange at permeable outcrops can be summarized simply. Regional heat flow is reduced below that expected from lithosphere of a given age, and the effects of an outcrop can be felt at a considerable distance, especially if the sediment thermal blanket is thick. Chemical exchange between seawater and crustal rocks can continue beneath substantial thicknesses of sediment, and may even be enhanced by the elevated temperatures that occur under thick insulating layers. Finally, due to the pressure head needed to drive the regional flow back toward the outcrop, the groundwater beneath a sediment blanket should have some artesian pressurization. This may explain the breakthrough of hot spring flow in the middle of sedimented areas, forming sediment mounds [e.g., *Williams et al.,* 1974], and the anomalous upward migration of the interstitial water in sediments, observed by some studies of chemical diffusion (J. W. Murray, personal communication, 1979), and suggested by the nonlinear temperature profiles in a few regions of high sediment permeability [e.g., *von Herzen et al.,* 1977, 1979; *Abbott et al.,* 1979; *Herman et al.,* 1979; *Hobart et al.,* 1979].

Temperatures of Circulating Water

If water circulates through the crust as freely as it appears, then an estimate of the temperature of the sediment/basement boundary should provide a reasonable estimate of the water temperature [*Davis and Lister,* 1977*a*]. Exceptions to this conclusion are bound to occur, for it is likely that the permeability of the crust is highly variable and that conductive heat transport occurs in some areas (e.g., see the observations at profile 11). Nevertheless, the basement temperature calculated from the surface gradient and the sediment thickness does provide a minimum estimate for fluid temperatures in the crust. It was found that over the Juan de Fuca ridge, temperatures are commonly 100°–200°C where sedimentation has sealed the crust to local ventilation, but where frequent basement outcrops occur (which is the common situation over mid-ocean ridge crests), values tend to be well below 100°–200°C. Except for profiles 4 and 5 (mean estimated basement temperature of 220° and 90°, respectively), the heat flow stations reported here are relatively near basement outcrops, and the basement temperatures calculated are similarly low (Figure 9, Appendix 1 (on microfiche).

SUMMARY

Heat transport in young oceanic crust is observed to be dominated by hydrothermal circulation in most young regions, and recent measurements over the Juan de Fuca ridge system provide no exceptions. Eleven profiles of closely spaced heat flow stations (0.4–1.0 km apart) have been completed over crust ranging in age from about 0.1 to 12 m.y. Large variability occurs down to a very fine scale, and the absolute levels of heat flow are extremely low compared to the values expected from crust of corresponding age. Both of these observations are common to other measurements over young crust, and they are attributed to the effects of hydrothermal circulation in the crust which is ventilated to the sea.

Because the measurements reported here are closely spaced and accurately positioned with respect to the local sea floor structure, additional insight has been gained into the nature of hydrothermal circulation.

1. Large-scale normal faults have some influence on circulation. There is a tendency for high heat flow values to be located near the base of normal fault scarps; this may be due to an enhancement of permeability in the fault zones and a consequent concentration of rising limbs of convection at these locations, or it may be due to a general concentration of hydrothermal ventilation at hot springs located at the basement exposures along the base of fault scarps.

2. The scale of variability (the distance between significant heat flow maxima or minima) ranges from about 1 km up to about 20 km. Large-scale (10–20 km) variations (up to 4:1) exist along all profiles, but over young crust having thin sediment cover, small-scale (≤2 km) variations of similar magnitude (up to 2:1) exist as well. This difference in the nature of heat flow variability may result from a difference in the nature of convective circulation, although it can be explained equally well by the filtering effects of an increasing sediment cover.

3. Low average heat flow is observed in 12-m.y. old crust which is well sealed to open hydrothermal circulation by a thick cover of turbidite sediments. Basement outcrops occur above the sediment cover at a seamount about 15 km away, and we conclude that hydrothermal circulation is efficient in ventilating heat over at least this horizontal distance.

4. Very low heat flow values are often measured near seamounts, and it is likely that seamounts are extremely effective in ventilating hydrothermal circulation. This may be due solely to their being free of sediment cover. The localized

source of cold water that seamounts (and other crustal outcrops) supply to crustal circulation may provide a strong driving force to large-scale horizontal heat transport. Observations in the field (Figures 5 and 7) and in the lab (Figure 8) suggest that such large-scale flow and smaller-scale cellular convection can coexist. If so, surface heat flow variations cannot be used to estimate the thickness of permeable layer convection.

5. Temperatures predicted for the upper crust by extrapolating surface gradients to the base of the sediments may be representative of a large portion of the crust if hydrothermal circulation is as widespread and efficient as it appears. Extrapolated temperatures beneath most measurements are low (<100°C), even at the very young sites.

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