High heat flow in southern Tibet

Jean Francheteau*, Claude Jaupart*, Shen Xian Jie†, Kang Wen-Hua‡, Lee De-Lu‡, Bai Jia-Chi‡, Wei Hung-Pin‡ & Deng Hsia-Yeu§

* Institut de Physique du Globe, Université Paris 6, 4 place Jussieu, 75230 Paris Cedex 05, France
† Institute of Geology, Academia Sinica, Beijing, China
‡ Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing, China
§ Institute of Geophysics, Academia Sinica, Beijing, China

Heat flow measurements have been attempted in two freshwater lakes at altitudes of 4.5 and 5.0 km, south of the Yarlung–Zangbo suture zone in southern Tibet. Probe penetration in the lake sediments was deep enough in the case of eight measurements (5.5–7.2 m) to give reliable temperature gradients. Corrections for seasonal temperature variations, topographic and refraction effects have been applied to the data. In a north–south profile trending perpendicular to the Yarlung–Zangbo suture zone, heat flow is approximately constant at 146 mW m^{-2} over a distance of 30 km and drops to a value of 91 mW m^{-2} in <25 km. The high heat flow and the sharp spatial variation both suggest the existence of a heat anomaly located at relatively shallow depths (no greater than 25 km) in the Tibetan crust, probably due to the recent emplacement of plutonic bodies.

TIBET is a massive plateau with a vast areal extent (2.5×10^6 km^2) at an unusually high elevation (5 km above sea level). It holds a privileged geodynamic position north of the India–Asia collision zone between the Himalaya and Kun Lun mountain ranges. The origin of this remarkable broad regional uplift is still unresolved. Somehow, it must be related to the overly thick (70-km) crust determined by different seismic studies[1,22]. Any model for the plateau uplift must use as a constraint the thermal regime at depth. So far, educated guesses have only been made about a representative geotherm when trying to model the tectonics of Tibet[2] or when trying to recover the uplift rate from fission track analyses in Himalayan rocks[3]. The Tibetan plateau is characterized by strong geothermal activity with numerous boiling springs, hot springs and even geysers scattered over most of its area[4]. Because the rheology of rocks depends strongly on temperature, the thermal structure of Tibet is a most important parameter for understanding the processes active in a continent–continent collision zone. Some predictions have been made. Wang and others[2] assumed a heat flow value of 84 mW m^{-2} on the basis of poorly constrained correlations between heat flow and age in geological provinces[5]. The existence of a thick crust enriched in radioactive elements would also yield a high heat flow. The lack of conductive heat flow measurements leaves the question unsettled. During the last field programme of the French–Chinese cooperation for the study of Tibet and the northern Himalayas which was started in 1980, it was decided to carry out heat flow measurements using oceanographic techniques in the numerous lakes which dot Tibet. The measurements reported here are the first known conductive heat flow measurements in Tibet.

Measurements

Many heat flow measurements have been made in lakes using the oceanic probe technique[6]. They have the obvious advantage that the cost and time required are much less than those needed for boreholes, tunnels or mines. Unfortunately, they are associated with many difficulties. For example, the recent and fast erosion of a lake depression leads to an artificial increase of temperature gradients[7]. These difficulties have been encountered in the Alps where deep lake heat flow data appear systematically higher than tunnel or borehole data[7,8]. There are fewer problems in small and shallow lakes which have been shown to yield results comparable to those from deep boreholes[9]. The ideal lake is probably not too deep, so that the transient erosion effects mentioned above are small, and not too shallow, so that thermal conditions in the lake are rather stable. In Tibet, our main problem has been to find such lakes as well as a suitable vessel from which to conduct the measurements.

We used a pontoon, which could be assembled and disassembled in a few hours, 10×12 m, about 1 m high on the water and powered by three outboard motors. A derrick had been erected in the middle and a gasoline-powered winch permitted the instruments to be lowered on a standard steel cable.

We used seven equally spaced (60 cm) thermistors mounted on outriggers tied either to the 4.5-m long barrel of a standard Kullenberg piston corer or to a thin (48-mm diameter) 6-m long metal rod used in quarry drilling operations. Both the corer barrel or the metal rod were clamped to a Kullenberg coring head with ~250 kg weight. A trigger weight enabled the barrel

Table 1 Heat flow data

Station no.	Lat.	Long.	Water depth (m)	Penetration depth (m)	G_1 (°C km^{-1})	T_1 (°C)	G_2 (°C km^{-1})	Steady-state correction			Heat flow (mW m^{-2})
								Topography (%)	Refraction (%)	Warm rim (%)	
6	29°10′15″	90°37′00″	40	3.9	/	5.07	185	−13.3	+2.6	−7.2	127
10	29°08′00″	90°41′30″	40	3.9	/	5.08	218	−7.1	+0.8	−3.0	166
14	28°58′45″	90°45′00″	44	6.7	192	5.11	176	−4.3	+1.6	−3.2	138
15	28°51′30″	90°37′30″	33	6.3	294	5.10	299	−1.6	+0.3	−1.3	242
16	28°50′45″	90°36′45″	31	7.0	206	5.11	188	−2.0	+0.4	−1.4	152
17	28°34′00″	90°26′45″	53	7.0	99	4.78	101	/	/	/	88
18	28°33′30″	90°24′45″	57	7.2	101	4.74	103	−1.8	+1.8	−0.3	90
19	28°33′45″	90°28′30″	60	6.9	116	4.88	101	−0.3	+1.0	−0.2	88
20	28°34′00″	90°28′45″	65	7.2	118	4.80	114	−0.2	+1.1	−0.2	100
21	28°34′45″	90°28′15″	60	7.2	131	4.85	101	−0.3	+0.8	−0.4	88

The average heat flow for Yang-Zho-Yung lake (stations 6, 10, 14–16) = 146 ± 17 mW m^{-2} (excluding station 15). Average heat flow for Pu-Mu-Yung lake (stations 17–21) = 91 ± 5 mW m^{-2}. G_1 is the uncorrected temperature gradient which can be estimated from the deepest data points. G_2 is the temperature gradient after correcting for seasonal bottom-lake temperature fluctuations. T_1 is the average bottom-lake temperature, obtained after extrapolating the corrected temperatures.

0028–0836/84/010032—05$01.00

or rod to free fall through the last 2 m of the water column before penetrating the sediments.

The temperature recorder for the seven sediments and one water temperatures was housed in a basket fastened to the coring head. We used an AANDERAA recorder modified for oceanic heat flow work at the Centre Oceanologique de Bretagne, France. Temperatures were recorded internally on magnetic tape which could be read later in our base camp Lang-Ka-Zhe (Fig. 1).

Water depth was monitored by a Furuno FE-400C echo-sounder operating at 50 kHz and good to 480 m. We lacked a 3.5-kHz seismic system so that the sediment thickness was assumed from previous drilling by a Chinese party in one of the lakes (Yang-Zho-Yung lake). Navigation was by means of triangulation on key-features of the shore using large-scale topographic maps (1 : 100,000) and a hydrographic circle good to 1°.

Conductivity measurements were made on cores using the standard needle-probe method[11].

The two lakes where heat flow work was feasible during our field trip are located south of the Yarlung-Zangbo suture zone (Fig. 1). The northern lake, Yang-Zho-Yung, lies 4,400 m south of a prominent range. It is very tortuous in plan view (Fig. 1) and clearly represents a blocked river valley which used to drain into the Zangbo river and which probably got cut off through tilting in the active extensional tectonic zone striking roughly north–south between Yadong and Gulu[12] (Fig. 1). On the basis of a preliminary description of one core from the deepest part of the lake (core K1), the sediments consist mainly of light-grey, carbonate-rich muds including many layers with grassy mats and seem to have sedimented quietly (K. Kelts, personal communication).

The southern lake, Pu-Mu-Yung, lies at 5,000 m altitude just to the north of the Himalayan mountain range (Fig. 1). Some glaciers feed into the lake. One core (core K4) shows that the sediments are siltier with less admixture of carbonate and fewer diatoms. The core material is being studied for mineralogy, ^{14}C dating, palynology, organic content and ^{210}Pb.

The temperature measurements were conducted by selecting a site away from the shore, lowering the probe 10 or 5 m off the bottom for a few minutes, free-falling the probe into the sediments and waiting for 17 and up to 70 min in the sediments. The thermistors were off scale in the bottom water so that possible instrumental bias between the probes could not be removed.

Results

Four cores about 5 m long were taken before or during the temperature measurements. To check on possible conductivity changes between stations, outrigger sampling was undertaken at 12 stations. A total of 124 conductivity measurements including 24 repeated runs were made within 12 h after samples were retrieved from the lake bottoms.

The results show that thermal conductivity is rather uniform both horizontally and vertically (Fig. 2). There is good agreement between measurements on core and outrigger samples, although a subtle tendency can be detected showing a slight underestimation of conductivity in the outrigger samples, which can be attributed to a slightly different water content. There is no systematic variation of thermal conductivity with depth, except for the lowermost part of the cores (40 cm) where a dramatic increase of k values occurs, presumably due to compaction at the end of penetration (Fig. 2). These high values were omitted from the data set. We therefore used simple average values of 2.00 ± 0.16 (8%) and 2.09 ± 0.20 (9%), in units of 10^{-3} cal cm^{-1} s^{-1} °C^{-1}, for Yang-Zho-Yung and Pu-Mu-Yung lakes respectively.

According to the diffusivity–conductivity relation reported by Von Herzen and Maxwell[11], the thermal diffusivity of these sediments should be $\sim 2.5 \times 10^{-3}$ cm^2 s^{-1}. This value will be used throughout this study.

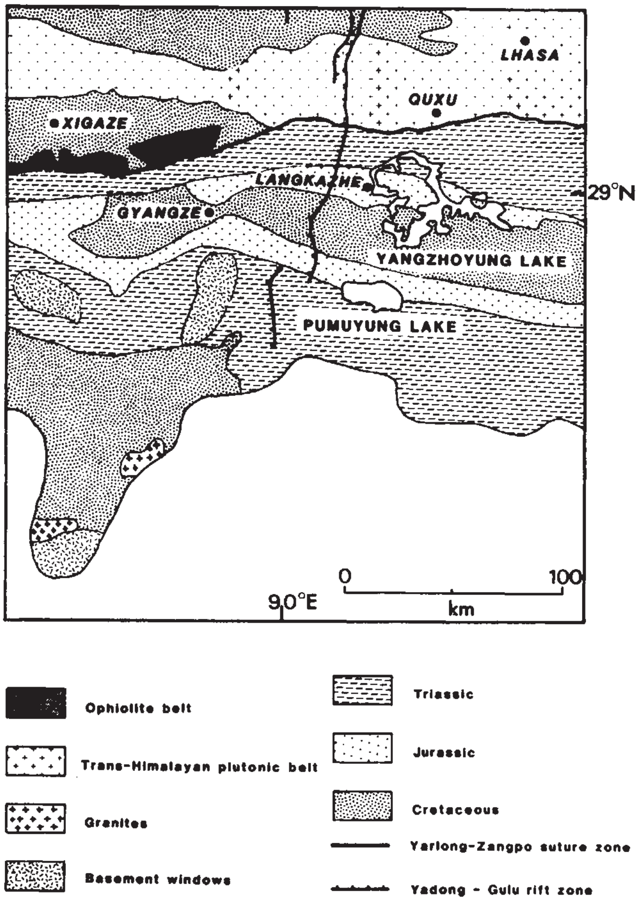

Fig. 1 Schematic geological map of Tibet in the vicinity of Lhasa showing the location of the two lakes where heat flow measurements have been made (modified from ref. 12).

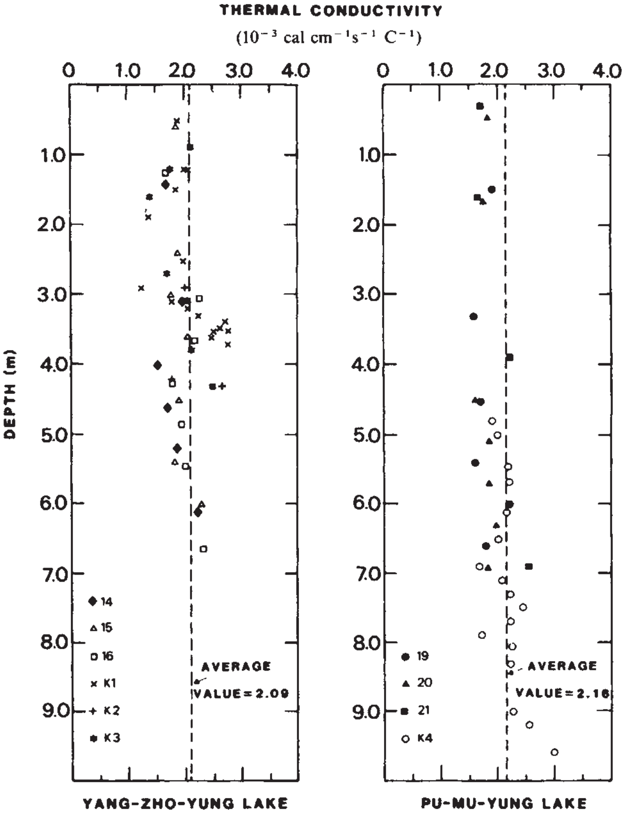

Fig. 2 Thermal conductivity of sediments from the two Tibetan lakes. The average value is that for all measurements.

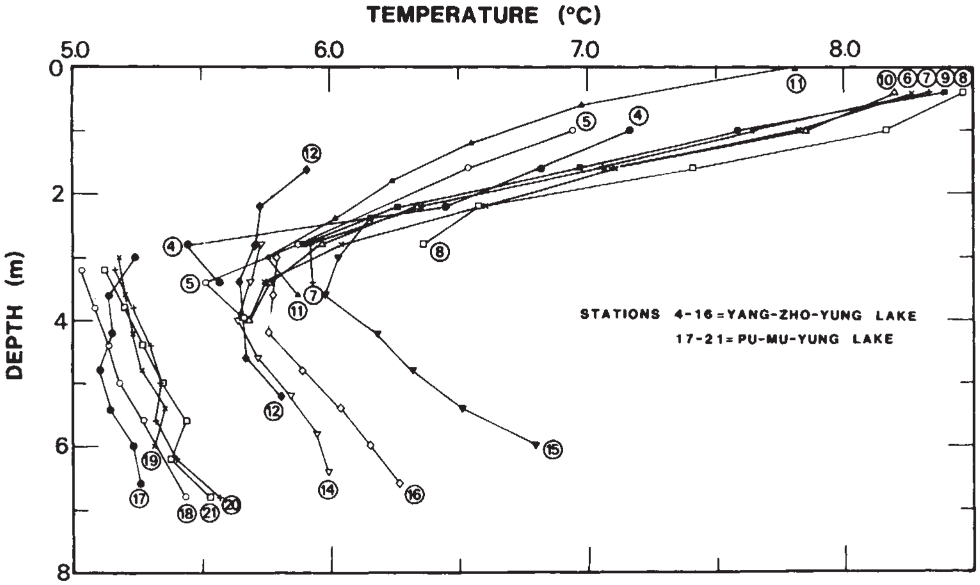

Fig. 3 Temperature versus depth plots for all the heat flow stations of this study.

Seventeen temperature stations were achieved with penetration depths ranging from 2.7 to 7.2 m (Table 1). For most of the stations, the duration of stationing was sufficiently long (>20 min) for equilibrium temperatures to be obtained. All the available measurements can be seen in Fig. 3. Note the good consistency of the data within each lake, and the marked difference between the two lakes. The data are believed to be reliable except for stations 4 and 5 where the measurement duration was too short to yield equilibrium conditions. In stations 11 and 17, the estimates of penetration depths seem to be wrong. Above a depth of 4–5 m, temperatures are obviously affected dramatically by seasonal climatic variations.

We now turn to the various corrections which must be applied to these raw data.

The correction for lake-bottom water temperature fluctuations requires the knowledge of the sediment–water interface temperature variations. In the remote highlands of the Tibetan plateau, none of these data are available or easy to obtain. However, climatic records are available over a 20-yr period from the Lang-Ka-Zhe meteorological station close to our lakes (Fig. 1). Figure 4 shows the evolution of the yearly mean temperature over this length of time, as well as the monthly mean air and ground temperatures. The data can be fitted by a simple cosine function with a period of 1 yr (Fig. 4). The lakes do not freeze in the winter season. The external forcing due to weather conditions is regular and it is likely that the lake water temperature varies with the same 1 yr period. In any case, the 1 yr cycle with 8 °C amplitude must be the dominant component of temperature fluctuations.

Fluctuations with shorter periods are possible due to transient water transport phenomena in the lakes, but would be of smaller magnitude and of much smaller depth penetration. For an amplitude T_0 and a pulsation ω, the resulting amplitude of fluctuations at depth z is (ref. 13, p. 63)

$$T_0 \exp\{-(\omega/2\kappa)^{1/2} z\} \qquad (1)$$

Considering the high gradients observed, such fluctuations must be smaller than 0.02 °C in amplitude to be considered as negligible. For the main 1 yr cycle, we found that a good estimate for T_0 was 4 °C. From equation (1), this perturbation has no measurable effect at depths >8.4 m. Shorter period fluctuations must be of smaller amplitudes. Taking for example, a 1 °C amplitude and a 6-month period, we find that the effects are significant down to depths of 4 m only.

As a consequence, we assumed that the major correction to be applied is for a 1 yr cycle, with an amplitude smaller than that of the air temperature (T_0) and a time-delay (ϕ) due to the lake response. The formula used for the temperature fluctuations at depth z is:

$$T_0 \exp\{-\alpha . z\} \cos\{(\Pi/6)t - (7.5/6)\Pi - \phi - \alpha z\} \qquad (2)$$

where α is equal to $\{\omega/2\kappa\}^{1/2}$, ω is the pulsation ($\Pi/6$) and t is time (in months). The correction was applied to all stations on a trial basis, varying both the amplitude and the delay, until optimum linear profiles were obtained. Parameters used in establishing the best correction were: amplitudes of 3.2–4.0 °C for both lakes, and small delays of 1.3–1.7 months which are not unexpected since the lakes are rather shallow. The extrapolated sediment–water interface temperatures were checked to be uniform in all cases (Table 1). In each lake, a single type of correction was found to correct most of the stations. The corrected gradients are in good agreement with each other, except for station 15 which yields a very high value. We attribute this anomaly to local refraction and topographic effects because this station is close to a small island in Yang-Zho-Yung lake (Fig. 5). No correction could be applied with reasonable success to several stations with shallow penetrations in Yang-Zho-Yung lake. This is probably due to temperature fluctuations with periods smaller than 1 yr, over which we have no control but which have negligible effects on the deeper data points. These stations do not constitute a heavy loss because they are clustered near stations 6 and 10 where reasonable corrections could be applied. A more detailed discussion of these corrections will be reported elsewhere.

Steady-state corrections are made up of corrections for local topography, thermal refraction at the sediment–basement boundary, and the warm-rim effect of the lake.

These effects were estimated numerically using a finite-element computer program. Calculations were done mostly at the Institute of Geology, Academia Sinica, Beijing and some on a different program in Paris. We took seven profiles between 14 and 30 km long, roughly perpendicular to local topographic features, which covered all heat flow stations. Most of these corrections are of small magnitude (<10%) (Table 1).

Transient corrections involve long-term climatic changes, sedimentation rates and uplift and erosion. Using available climatic models for Tibet[14] and the preliminary observation that the lakes have sedimented quietly, the first two corrections are found to be small (~1.7–3.5% and 1.0–2.6% for climatic and sedimentation effects respectively). The correction for uplift and erosion is more difficult to evaluate because we have no good estimates for erosion and uplift rates. We now discuss the implications of these measurements, with due consideration for the remaining uncertainties.

Discussion

Figure 5 summarizes the heat flow values obtained in this study after all corrections excluding those for uplift and erosion. Note the good consistency of the values within each lake. Given the magnitude of measurement errors which is certainly larger than

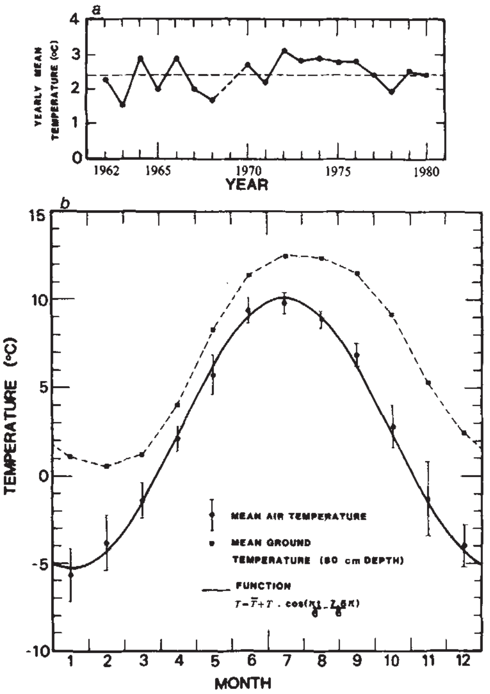

Fig. 4 *a*, Evolution of the yearly mean temperature at the Lang-Ka-Zhe meteorological station. *b*, Evolution of the air and ground temperature (at 80 cm depth) over a period of 1 yr. The air temperature data is made of average monthly values over 20 yr (bars represent ±1 s.d.). Also shown is the simplest cosine function which fits these data.

10% (a representative value for the conventional oceanographic technique), the data do not provide any evidence for a significant variation of heat flow within Yang-Zho-Yung Lake. Our measurements show that heat flow rises sharply from 91 to 146 mW m^{-2} in ≤25 km, and remains approximately constant over a distance of 30 km towards the Yarlung–Zangbo suture zone (Fig. 6). There are *a priori* three possible explanations for such high heat flow values: high heat production, an anomalous heat source (magma), or an anomalous mantle heat flow. A detailed interpretation of the data requires a proper understanding of: (1) uplift and erosion; (2) the regional thermal structure and its evolution with time; and (3) the age of the hypothetical intrusion or melting event. More extensive thermal modelling will be reported elsewhere.

The uplift problem is probably the most crucial one. Several authors have argued on palaeontological evidence and fission track studies[3] that the uplift is recent (2 Myr) and fast (0.2 cm yr^{-1}). Such fast uplift rates could increase the heat flow values by as much as 60%. However, some of these estimates depend on an assumed thermal regime and the reality of such a dramatic pulse remains questionable. The India–Asia collision has been occurring for ~45 Myr (ref. 15) and there is no obvious reason why a major change in tectonic regime occurred 2 Myr ago. Typical epeirogenic uplift rates in active regions are of the order of 0.2 mm yr^{-1} (ref. 16), which would spread out in time the plateau uplifting, making it more compatible with the overall evolution of the region. In such a case, the uplift effect would be much smaller, around 20%. However, these corrections were estimated in the usual fashion (ref. 13, p. 338) and, in the very transient thermal state of Tibet, are of little interpretative value.

Erosion effects must also be taken into consideration. In the absence of any information concerning the shaping of the present terraine morphology, it is impossible to estimate the effects of local and recent erosion, such as those discussed by England[7]. In the plateau environment, they are probably small because local topography is very subdued, as witnessed by the small magnitude of the topographic correction (Table 1). Relief is more pronounced near sites 6 and 10 in Yang-Zho-Yung Lake. However, these stations yield values which are comparable to those from stations 14 and 16, 20 km away to the South where local topography is negligible (<70 m). We believe that the difference between the heat flow values for the two lakes is real. As will be stated later, electromagnetic measurements yield evidence for a discontinuity at the same location. The regional erosion of the Tibetan highlands is more of a problem. It represents an additional increase of heat flow, as it corresponds to a vertical advection of hot material (see, for example, ref. 17).

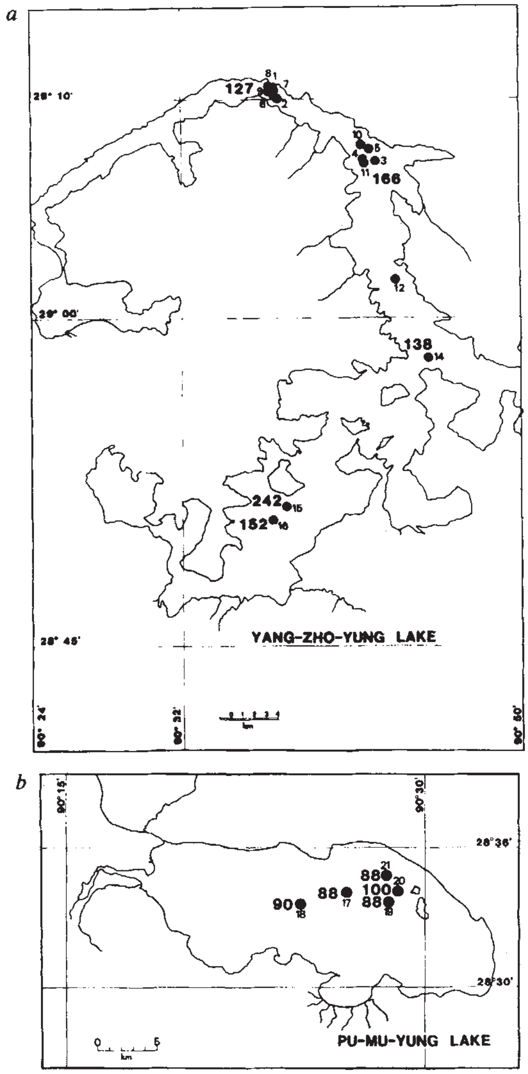

Fig. 5 *a*, Heat flow stations (small numbers) and values (large numbers) in Yang-Zho-Yung lake. Heat flow values are in mW m^{-2} (not corrected for uplift and erosion, see text). *b*, As *a* for Pu-Mu-Yung lake.

Note that in the extreme conditions prevailing here, the usual procedure for 'correction' is not valid. It is designed to account for transient effects which are significant at shallow depths only in otherwise steady-state conditions and to allow the calculation of representative geotherms. In the case of Tibet, we must take into account the full transient thermal evolution of the region, including crustal shortening and the resulting stretching of geotherms[18] as well as regional cooling due to the underthrusting of cold continental lithosphere.

At any rate, such regional phenomena must affect all heat flow values and cannot account for the sharp spatial variation which is observed. Even if the maximum correction of 60% is applied, the Yang-Zho-Yung values would still be high by continental standards: at 58 mW m^{-2} they would clearly stand above 'equilibrium' regions where the mean heat flow is 46 mW m^{-2} (ref. 19). This difference is not due to anomalously high heat production. There are few radioactivity determinations on Tibetan rocks. The available data from basement material

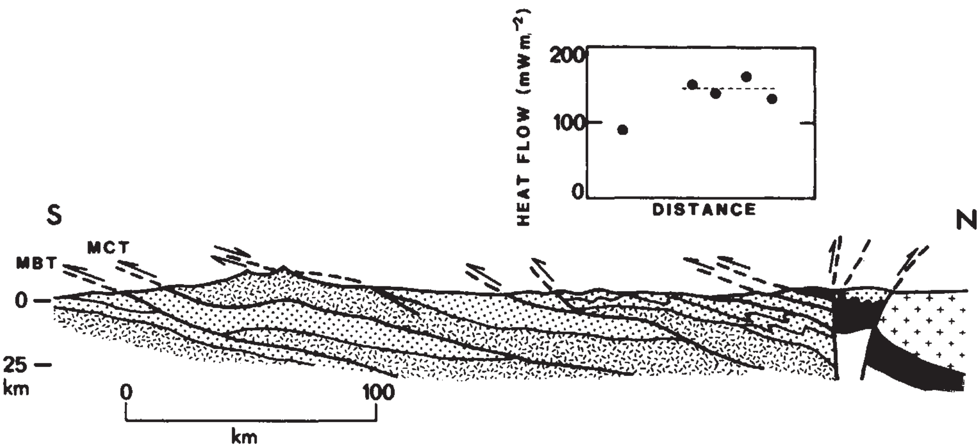

Fig. 6 Schematic cross-section perpendicular to the Yarlung-Zangbo suture zone (from ref. 15). Crosses and dots indicate granitic and sedimentary formations. The stippled and grey patterns are for basement and ophiolite rocks. The heat flow values are shown at their respective locations.

which outcrops to the West of our lakes (Fig. 1) indicate a value of 2.7 μW m^{-3} for the heat production rate[20]. This value is normal for old continental formations, and, according to empirical heat flow/heat production relations, corresponds to heat flow values around 45 mW m^{-2} (see, for example, ref. 19).

One explanation for the high heat flow values would be that because the crust is anomalously thick, there is a larger amount of radioactive elements beneath the plateau. Considering an average heat production of 0.7 μW m^{-3} for continental crust material[21], it would take a thickness of 140 km to yield a radiogenic contribution of 100 mW m^{-2} to the surface heat flow (that is corresponding to an observed average heat flow of 125 mW m^{-2}). Furthermore, we would also have to explain why heat flow increases so rapidly between the two lakes. Similarly, an anomalous mantle heat flow is not a suitable hypothesis because it should have a regional effect. Even if it was localized in a narrow zone below the lithosphere, it could not create a sharp horizontal variation because of the masking effect of the plate.

The most likely explanation is therefore that there is a source of heat in the crust which terminates abruptly somewhere between the two lakes. Such a discontinuity at this particular spot was also found from magneto-telluric soundings carried out in the same area[21]. This anomalous source of heat is most probably a hot intrusive body. To model the associated thermal effects would require some knowledge about the time of emplacement or melting: a recent event must be shallow to be detectable by surface heat flow measurements. The conductive time scale is $\tau = d^2/4\kappa$, where d is the depth to the anomaly and κ thermal diffusivity. Because the intrusive or melting event must somehow be associated with the underthrusting of India beneath Asia, it must be younger than 45 Myr[15,22,23] and must therefore be shallower than ~70 km (using a κ of 10^{-2} cm^2 s^{-1}). The Makalu granite in the Himalayan range has been recently dated at about 21 My[24]. This is evidence that melting conditions have been reached in the Tibetan crust after India collided with Asia.

From the value of 146 mW m^{-2} and the maximum range in corrections, it is possible to give a rough estimate of the depth to the anomalous body. Assuming steady-state conditions and a standard radioactivity model (see ref. 19), and taking the 600 °C isotherm as a reference for crustal solidus temperatures (for hydrated material such as sediments), we find that this depth must be between 10 and 25 km. Allowing for transient effects, these estimates must be considered as upper bounds. A conservative conclusion is therefore that the heat source must be shallower than 25 km. Such small crustal depths would indeed yield a sharp horizontal variation of heat flow in the vicinity of the body edge. The horizontal distribution of heat flow allows some further constraints on the timing and depth of the intrusive or melting event which will be developed in a future paper.

Our data yield no evidence for any significant heat flow variation over a distance of ~30 km (Fig. 6). This suggests that the heat source is of large horizontal dimensions. If this source is also the cause of the widespread geothermal activity of the plateau, it is not surprising that it has large horizontal dimensions. This would agree with geological observations made in old continental collision zones which typically exhibit tabular granitic formations extending over whole provinces[24].

Sharp horizontal heat flow variations are reminiscent of other tectonically active regions such as the southwestern United States[25,26] or geothermal areas[27]. Finally, note that the heat flow increase occurs at a distance of about 230 km from the main locale of underthrusting (Fig. 6). This is typical of subduction environments where high heat flows and volcanic activity show up abruptly at similar distances from trenches[28].

The measurements reported here suggest that regional melting conditions are reached at relatively shallow crustal depths in Tibet. This represents a powerful contraint for thermomechanical models of continental collisions.

The field work was funded by CNRS and INAG (France) and the Chinese Academy of Geological Sciences and Academia Sinica (China). It would not have been possible without the loan of heat flow and coring equipment by CNEXO and GENAVIR. We thank C. Allegré, chief scientist of the French expedition, for his encouragements in setting up this project. Professor Shau Shu Chang was the chief scientist of the Chinese party. We thank H. Lossouarn for help in the field, J. P. Foucher, R. Conogan, C. Toularastel and J. Le Pavec for assistance in preparing the Tibetan cruise and K. Kelts for advice. We also thank the Math Geology Research Group at the Institute of Geology, Academia Sinica, Beijing. We acknowledge the important logistical support provided by the People's Liberation Army and all the individuals who helped us in the field.

Received 5 August; accepted 20 September 1983.

1. Chen, W. P. & Molnar, P. *J. geophys. Res.* **86,** 5937–5962 (1981).
2. Wang Chi-Yuen, Shi Yao-Lin & Wen Hu-Zhou *J. geophys. Res.* **87,** 2949–2957 (1982).
3. Zeitler, P. K., Johnson, N. M., Naeser, C. W. & Tahirkheli, R. A. K. *Nature* **298,** 255–257 (1982).
4. Wang Ji-Yang *et al. J. Volcan. geotherm. Res.* **9,** 57–76 (1981).
5. Chapman, D. S. & Pollack, H. N. *Earth planet. Sci. Lett.* **28,** 23–32 (1975).
6. Hart, S. R. & Steinhart, J. S. *Science* **149,** 1499–1501 (1965).
7. England, P. C. *Earth planet. Sci. Lett.* **39,** 427–434 (1978).
8. Finckh, P. *Bull. geol. Soc. Am.* **92,** 452–514 (1981).
9. Allis, R. G. & Garland, C. D. *Can. J. Earth Sci.* **16,** 1951–1964 (1979).
10. *Geological Map of the Tibetan Plateau,* 1/1,500,000 (Chengdu, China, 1981).
11. Von Herzen, R. P. & Maxwell, A. E. *J. geophys. Res.* **64,** 1557–1563 (1959).
12. Tapponnier, P., Mercier, J. L., Armijo, R., Tong Li-Han & Zhou-Ji *Nature* **294,** 410–414 (1981).
13. Carslaw, H. S. & Jaeger, J. C. *Conduction of Heat in Solids* (Oxford University Press, 1959).
14. Guo, S. in *Symposium on Qinghai-Xizang (Tibet) Plateau,* Beijing, 13–14 (Gordon & Breach, New York, 1980).
15. Allègre, C. J. *et al. Nature* **307,** 17–22 (1984).
16. Blatt, H., Middleton, G. & Murray, R. *Origin of Sedimentary Rocks* (Prentice Hall, Englewood Cliffs, 1980).
17. England, P. C. & Richardson, S. W. *Geophys. J. R. astr. Soc.* **62,** 421–437 (1980).
18. Houseman, G., McKenzie, D. & Molnar, P. *J. geophys. Res.* **86,** 6115–6132 (1981).
19. Sclater, J. G., Jaupart, C. & Galson, D. *Rev. Geophys. Space Phys.* **18,** 269–311 (1980).
20. Vidal, P., Cocherie, A. & Lefort, P. *Geochim. cosmochim. Acta* **46,** 2279–2292 (1982).
21. Van Ngoc, P., Boyer, D. & Therme, P. *Terra Cognita* **3,** 270 (1983).
22. Scharer, U. *Earth planet. Sci. Lett.* in the press (1983).
23. Scharer, U., Xu, R.-H. & Allegré, C. J. *Earth planet. Sci. Lett.* in the press (1983).
24. Nielson, D. L., Clark, R. G., Lyons, J. B., England, E. J. & Borns, D. J. *Geol. Soc. Am. Mem.* **146,** 301–318 (1976).
25. Warren, A. E., Sclater, J. G., Vacquier, V. & Roy, R. F. *Geophysics* **34,** 463–478 (1969).
26. Bodell, J. M. & Chapman, D. S. *J. geophys. Res.* **87,** 2869–2884 (1982).
27. Blackwell, D. D. & Baag, C. G. *Geophysics* **38,** 941–956 (1973).
28. Blackwell, D. D., Bowen, R. G., Hull, D. A., Riccio, J. & Steele, J. L. *J. geophys. Res.* **87,** 8735–8754 (1982).