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Original Investigations

Heat-Flow Measurements in Swiss Lakes*

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Abstract. Measurements of geothermal heat flow utilizing the oceanographic probe technique were made in three Swiss lakes in June 1970. Effects of temporal variations of water temperature over the preceeding 3 years are observed in vertical temperature gradients measured to depths of 7 m in bottom sediments of Lakes Zurich and Lucern. Corrections have also been estimated for the effects of (1) inferred temperature changes associated with glaciation, (2) sedimentation rates and (3) the steady-state topography and temperature anomalies of the lakes. Corrections are less than 20% for most measurements except in Lake Lucern, where the inferred high sedimentation rate results in a large (+60%) correction. The corrected geothermal flux is estimated at about 1.6 μcal cm^{-2}sec^{-1} (HFU) (67 mWm^{-2}) in Lake Lucern, and about 2.6 HFU (109 mWm^{-2}) in Lakes Zurich and Zug. The values are comparable to other nearby continental values in South-central Europe.

Key words: Heat Flow — Geothermal — Switzerland — Lakes.

Introduction

The association of high heat flow with active mid-ocean ridges and island arcs (*e.g.*, Langseth and Von Herzen, 1971) suggests that tectonic activity of the sea floor is closely related to dissipation of thermal energy in the earth's interior. Moreover, the time scale of the thermal decay associated with the formation of mid-ocean ridges leads to a specific tectonic model of that feature (McKenzie, 1967; Sclater and Francheteau, 1970).

Mountain ranges are one of the principal results of tectonic activity on continents, and heat-flow measurements could help provide additional constraints on tectonic models. Roy *et al.* (1968) have shown that heat flow from the mantle and/or deep crust in the North American continent also appears to correlate with tectonic provinces, after the measurements have been corrected for upper crustal radioactive heat sources. The Alpine

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* Contribution No. 3263 of the Woods Hole Oceanographic Institution.

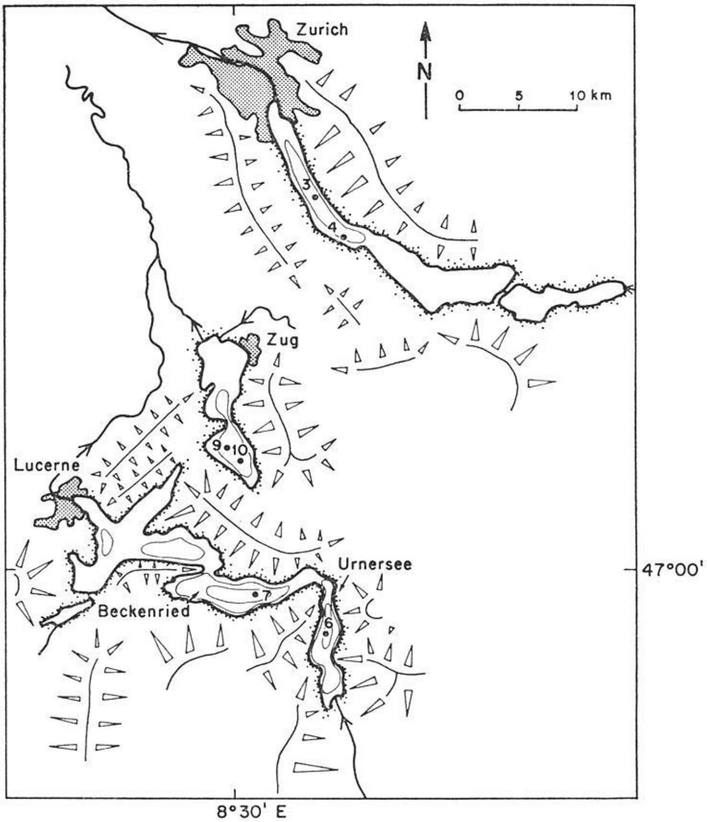


Fig. 1. Location map of Swiss Lakes. Heat-flow coring stations shown as numbered dots. Lines with arrow patterns give locations of elevations and slope directions. Irregular lines with arrows are major rivers and direction of flow. Approximate contours of lake depths at 100 m intervals below lake levels, from Landeskarte der Schweiz, and Hsü and Kelts (1970)

mountain chain is the most visible expression of the most recent (early Tertiary) major orogeny in Europe. Much of the tectonic development of the Alps has been worked out from detailed geologic mapping in Switzerland because of its central location. For the same reasons, heat-flow measurements in Switzerland would be useful to correlate with this major tectonism.

Clark and Niblett (1956) and Clark (1961) made measurements of heat flow in five Swiss and Austrian mountain tunnels. Later, Clark and Jäger (1970) showed that the values require a large but uncertain correction to remove the effects of erosion. Hänel (1970) has utilized oceanographic techniques for heat-flow measurements in lakes of southern Germany. This method has been shown elsewhere to be a relatively inexpensive way to obtain continental heat-flow data (Hart and Steinhart, 1965; Von Herzen and Vacquier, 1967). The availability of numerous lakes makes this method useful for Switzerland. This paper presents results from measurements in June 1970 on three Swiss lakes: Zurich, Lucern, and Zug (Fig. 1).

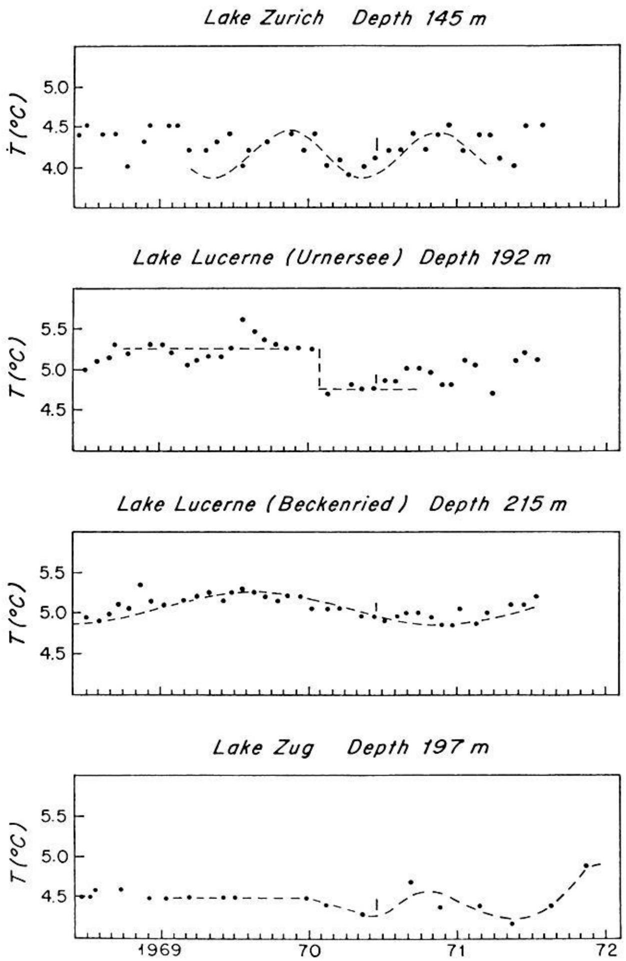
Thermal Stability of Lakes

The oceanographic method for heat-flow measurements requires that the deep lake waters have a stable temperature, or that any variations be of the same order or less than the measured temperature differences in the bottom sediments and be well known. Variations with periods of a few months to a few years may significantly affect vertical temperature gradients measured in the uppermost few meters of bottom sediments. Longer period variations (10 to 10^4 yrs.) may also require corrections as discussed below. In this section, we consider the shorter period variations which lead to first order corrections of the gradients we have measured.

Deep-water temperature data are not available for all of the Swiss lakes, and in some (*e.g.* Walenstadt) the temperature variations appear to be so large that the method is not feasible. Logistical considerations and relatively small deep-water temperature variations led us to concentrate our initial program on Lakes Zurich, Zug and Lucern. Time series of temperature measurements of the deepest bottom water, mostly at monthly intervals, were available for all three lakes over periods of several years. They were made by the district chemist of Zug for Lake Zug, by the Office for Water Supply of the City of Zurich for Lake Zurich, and for the District of Lucern under contract to EAWAG (Eidgenössische Anstalt für Wasserversorgung, Abwasserreinigung und Gewässerschutz). Two different methods were interchangeably used: sometimes the measurements were made with an "Oxitester", sometimes with a reversal thermometer. Both methods provided an accuracy of about ±.1 °C, according to the sources of data.

The data are plotted for the period from July 1968 through 1971 (Fig. 2), therefore including the period of our heat-flow investigations. The data from Lake Zug are intermittent, although it appears that the Lake Zug temperatures were more stable than the other lakes during the period before our measurements.

The extreme temperatures in Lake Zurich (Fig. 3), in which the most extensive measurements have been made, show an amplitude of temperature variation which decreases rapidly with water depth to about 1.0°C below 100 m. These fluctuations have a strong yearly component, as expected, but there are significant deviations from a simple periodicity (Fig. 2). The yearly fluctuation of bottom water temperature appears to lag several months behind that of air temperature.


Lake Zurich Depth 145 m

Lake Lucerne (Urnersee) Depth 192 m

Lake Lucerne (Beckenried) Depth 215 m

Lake Zug Depth 197 m

Fig. 2. Temperature variation of bottom water in the deepest parts of Swiss lakes. Dots are the recorded data. Year numbers for horizontal scale centered over January. Dashed curves are fits of simple functions to the data (see text). Vertical bar above each curve indicates time of gradient measurements

Although the temperature fluctuations are irregular near the bottoms of all the lakes, the principal variations may be approximated by simple analytical functions. In the discussion below we consider the quantitative effects on the sediment temperature gradients of these first order approximations to the observed bottom water temperature fluctuations. The data at present do not justify a more exact treatment.

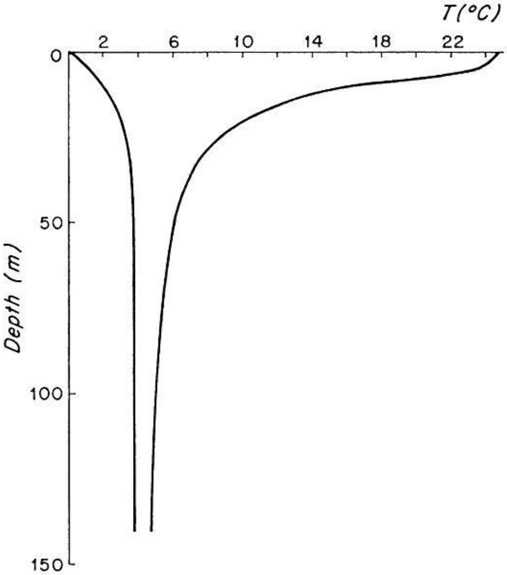


Fig. 3. Maximum temperature variation vs. depth in Lake Zurich, between January 1960 and July 1971. Curves enclose all data at monthly sampling intervals during this period

Geothermal Gradients

1. Apparatus

Two types of apparatus were used to measure temperature and vertical temperature gradients in the bottom sediments of the lakes. Thermistor probes were attached externally to a piston core barrel which penetrated the bottom to a maximum depth of 7.5 m (*e.g.* Gerard *et al.*, 1962). The other apparatus consisted of 3 thermistor probes rigidly attached to a 1.9 cm diameter probe which penetrated the bottom a maximum depth of 3 m. With this apparatus, described by Von Herzen and Anderson (1972), no sediment core is retrieved. Absolute temperatures are determined within ±.02°C, and relative temperatures to about ±.002°C, for both types of apparatus. The thermistor probes (0.3 cm diameter) attain thermal equilibrium with the sediment to the precision of measurement within about 5 minutes after bottom penetration. A tiltmeter which indicates the tilt of either type of apparatus within the ranges of 0 to 15°, 15 to 30°, or greater than 30°, was used on all measurements.

2. Core Measurements

Geothermal gradients were determined at 12 localities in the lake bottoms. Six of these determinations were made with piston-coring apparatus, two in each of Lakes Zurich, Zug, and Lucern (Fig. 1). This relatively deep-penetrating apparatus with up to 5 temperature-sensing points allowed determination of gradient changes with depth in the sediments. *Relative* distances between thermistor probes are known to within ±1 cm. *Absolute* depths below bottom are estimated from the mud smear on the core barrel and/or the extrapolation of sediment temperature gradient to the bottom water temperature determined from an additional thermistor probe; they have an estimated accuracy of about ±0.3 m. The multiprobe measurements proved important for deducing the equilibrium geothermal flux, because the vertical temperature gradients were disturbed by bottom water temperature changes before the measurements in Lakes Zurich and Lucern.

a) *Lake Zurich*

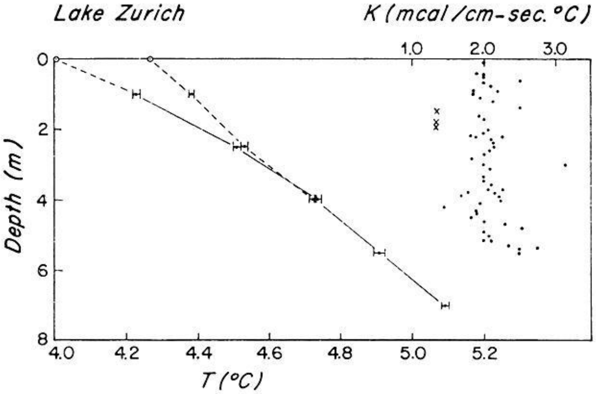
Two piston-core measurements (Fig. 4), obtained in the deep central part of Lake Zurich, clearly indicate a decrease of temperature gradient with depth. The maximum curvature of the temperature vs depth relationship is between 4 and 5 m depth. A trend of increasing thermal conductivity with depth in some of the cores from the Swiss lakes may account for some part of the gradient changes. Also, we must allow for uncertainties in the coring procedures, and the exsolution of gases in cores which created some problems for thermal conductivity measurements (see discussion below). However, the variation of thermal conductivity with depth appears quite insufficient to account for the observed downward decrease of gradient in Zurich by a factor of 1.5 to 2.0.

Temporal variations in the bottom water temperature seem the most likely cause of this depth variation of temperature gradient in Zurich. To first order, this variation (Fig. 2) can be approximated by a sinusoidal function $T = T_0 \sin\omega t$, for which the effect on temperatures at depth z below the bottom is given by (Carslaw and Jaeger, 1959, p. 81)

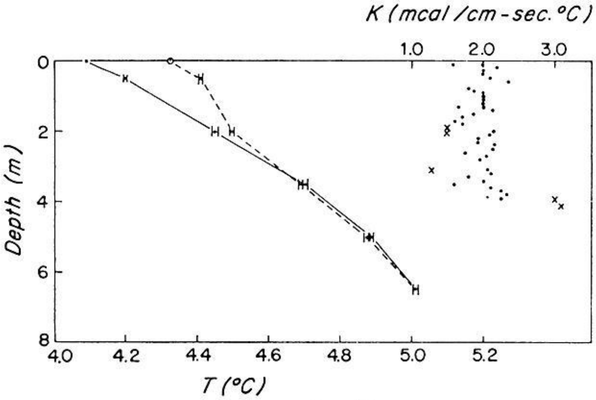
$$T = T_0\, e^{-zk} \sin(\omega t - zk) \tag{1}$$

$$\text{where } k = \sqrt{\omega/2\alpha},\ \omega = 2\pi f$$

f is the frequency of oscillation, and α the thermal diffusivity. In models discussed for all the Swiss lakes, α is taken to be 2×10^{-3} cm^2/sec as deduced from thermal conductivity values (Table 2; Von Herzen and Maxwell, 1959). Although thermal conductivities, and presumably diffusivities, vary between stations, this approximation produces relatively small uncertainties



Station #3



Station #4

Fig. 4. Temperature and thermal conductivity measurements in Lake Zurich. Measured temperature points with estimated error bars connected by solid lines; dashed lines connect points corrected for bottom water temperature variations (See text). Thermal conductivity values (uncorrected) shown as dots, unreliable values as X

for corrected temperatures. The uncertainty of corer penetration (≈ 0.5 m) is more serious for these corrections, especially for the uppermost temperatures; for this reason, the deepest temperature-depth points are given greater weight in bounding the temperature corrections.

Lake Zurich temperatures have been approximated by a sine function of 1 year period which has an origin ($t = 0$) at mid-August, and an amplitude $T_0 = 0.3$°C. The temperature influence on the sediments at the time of our measurements (June 1970), as calculated from Eq. (1), is shown in

Table 1. Temperature gradient summary

Station number	Depth interval	BT	N	Temperature gradient[a] (°C/m)	Correction[b]				Bottom temperature correction[c]
					G	S	T	Total	
3	4.0–7.0	4.00	3	.118 ± 5%					
	1.0–7.0		5	.118 ± 2%	+7.5	+7	0	+14.5	Sine ($T_0 = 0.3$, $P = 1$ yr., $\Delta P = 10$ mo.)
4	5.0–6.5	4.08	2	.086 ± 12%					
	2.0–6.5		4	.115 ± 4%	+7.5	+7	0	+14.5	Sine ($T_0 = 0.3$, $P = 1$ yr., $\Delta P = 10$ mo.)
6	4.0–7.0	4.72	3	.054 ± 4%					
	1.0–7.0		5	.047 ± 2%	+19	+35	+8	+62	Step ($T_0 = -0.25$, $\Delta P = 5.5$ mo.)
7	3.5–5.0	4.83	2	.034 ± 17%					
	2.0–5.0		3	.033 ± 14%					Sine ($T_0 = 0.2$, $P = 2.5$ yr., $\Delta P = 17$ mo.)
	2.0–5.0		3	.054 ± 8%	+16.5	+35	+8	+59.5	Sine ($T_0 = 0.2$, $P = 1.0$ yr., $\Delta P = 8$ mo.)
	2.0–5.0		3	.033 ± 6%					Step ($T_0 = -0.2$, $\Delta P = 1$ yr.)
	2.0–5.0		3	.020 ± 11%					Step ($T_0 = -0.25$, $\Delta P = 5.5$ mo.)

9	0.5–6.5	4.33	5	.104±3%	+8.5	+7	−3	+12.5	
			4	.088±3%					Linear (T_0 = −0.25, ΔP = 6 mo.)
10	1.0–5.5	4.39	4	.098±2%	+9	+7	0	+16	—
11	0.5–2.5	4.37	3	.133±1%	+6.5	+7	−7	+ 6.5	—
12	1.0–3.0	4.33	3	.116±2%	+7.5	+7	−3	+11.5	—
13	1.0–3.0	4.31	3	.096±3%	+9.5	+7	0	+16.5	—
14	1.0–3.0	4.33	3	.132±1%	+6.5	+7	−7	+6.5	—

BT = Bottom water temperature, °C.

N = Number of temp. vs. depth values used for computation of temperature gradient.

[a] = Uncertainty (±) in measured temperature gradient computed from uncertainties in temp.-depth points and least-squares fit to uniform gradient (Von Herzen and Anderson, 1972). Underlined value is preferred fit, corrected for bottom water temperature variations (See text).

[b] = Correction: G = glacial; S = sedimentation rate; T = steady-state topography and temperature anomaly (See text).

[c] = Sine: $T = T_0 \sin \omega t$, P = period, ΔP = phase after $t = 0$ at time of measurement.
Step: T_0 = step function amplitude, at time ΔP before measurement.
Linear: T_0 = total linear change, initiated at time ΔP before measurement.

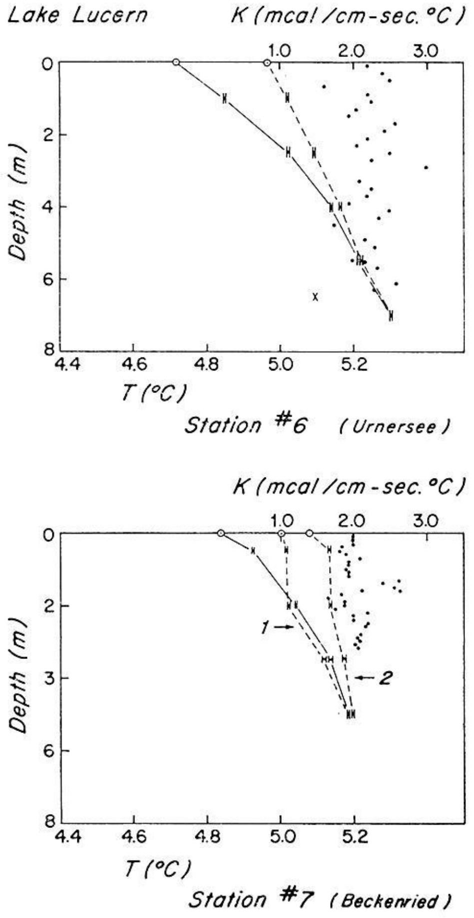


Fig. 5. Temperature and thermal conductivity measurements in Lake Lucern. Symbols same as Fig. 4. Corrected temperatures for sta. 7 given for: Curve 1 — Sinusoidal, period 1 yr., phase 8 mo., amplitude 0.2°C; Curve 2 — Step function 0.25 °C at 5.5 mo. ago (also sta. 6)

Fig. 7a. The corrected temperatures (Fig. 4) are much more nearly linear with depth than the uncorrected ones, suggesting that the correction is in the right direction, even if this simple model does not fit the water temperature data in detail. The bottom water temperature at station 3 is close to the minimum recorded at this depth for Zurich (Fig. 3); the difference between stations 3 and 4 is probably due principally to a horizontally layered structure of water temperature.

At sta. 3, the gradient based on 5 corrected temperature vs. depth data points is the same as that computed from the uncorrected data of the 3 lowermost points (Table 1). The corrected value of the shallowest data point at Sta. 4 is not consistent with the others, and has therefore been omitted from the gradient computation.

b) *Lake Lucern*

The piston-core measurements in Lucern (stations 6 and 7, Fig. 5) show a decrease of gradient with depth similar to Zurich, with maximum curvature in the temperature vs. depth curve at similar depths. The gradients are generally lower in Lucern than in Zurich by perhaps a factor of 2. Bottom water temperatures are higher in Lucern, and at Station 7 the water temperature increases with depth in the deepest several tens of meters. The minimum water temperature at Station 7 is the same as that measured at Station 6, within the accuracy of the measurements. Stations 6 and 7 are in different arms of Lucern (Urnersee and Beckenried, Fig. 1) which are separated by a topographic ridge with a sill depth at or less than the depth of minimum water temperature. The difference in bottom water temperature between the two stations probably is associated with density stratification of the deepest waters.

The two arms of Lucern show rather different fluctuations of bottom water temperature (Fig. 2). In Urnersee, a drop of about 0.5°C in January 1970 is superimposed on irregular fluctuations of smaller amplitude. Hence, to a first approximation we assume a model of a step change in temperature of $T_0 = 0.5$°C. The subsequent temperature distribution is given by (Carslaw and Jaeger, 1959, p. 63)

$$T = T_0 \operatorname{erfc} \frac{z}{2\sqrt{at}} \tag{2}$$

$$\text{where } \operatorname{erfc} y = \frac{2}{\sqrt{\pi}} \int_y^\infty e^{-\eta^2}\, d\eta$$

the complementary error function, and the symbols are the same as for Eq. (1).

The temperature drop in Urnersee occurred in January 1970, approximately 5-$^1/_2$ months before our gradient measurements. The calculated effect of a step change of 0.5°C at this time on the sub-bottom temperatures at the time of our gradient measurements (Fig. 7b), as determined from Eq. (2), is about twice as large as required to produce a nearly constant gradient with depth (Fig. 5). The corrected gradient of Station 6 has been computed as the effect of a step change of only 0.25°C. Part of this discrepancy may be due to the errors inherent in the measurement of bottom water temperature. Alternatively, the simplified analytical model may not be adequate to fit the detailed water temperature data.

In the Beckenried arm of Lake Lucern, the bottom water temperature variation appears, to first order, as a sine wave of period about 2.5 yrs. and amplitude 0.2°C, with an origin time near the beginning of January, 1969. The temperature disturbance with depth at the time of the gradient measurement (June 1970), calculated from Eq. (1), is given in Fig. 7c. Application of this correction to the observed data does not correct for the nonlinearity of the temperature gradient, and also results in an overall low gradient (Table 1). The linearity of the gradient determined by the lowest 3 temperature measurements is improved by assuming a step function variation, as in Urnersee, but the computed gradient is even lower. Indeed, the correction for any step decrease in water temperature will decrease the already low gradient determined from the deepest temperature measurements of this station. A correction due to a sine variation of about 1 yr. period also improves the fit to the lowermost 3 points (Fig. 5) and in addition gives a higher gradient (Table 1). For these reasons, we prefer this latter correction to obtain a heat-flow value. An even better fit might be obtained with a sine variation of somewhat longer period. However, we do not feel that our limited data justify a more exact treatment, especially since the temperature points used for gradient determination have depth uncertainties of perhaps $^1/_2$ m, and the corrections due to bottom water temperature changes are sensitive to depth.

It is somewhat puzzling why the bottom water temperature fluctuations in the different arms of Lucern should appear so different. The greater amplitude of variation in Urnersee vs. Beckenried may be related to the distribution of water sources and sinks in this morphologically complex lake. The principal source is at the south end of Urnersee and the principal outflow at Lucern. Any flow of deep water between Urnersee and Beckenried is probably inhibited by the topographic sill near the bend between the two arms of the lake.

c) *Lake Zug*

The two piston core measurements in Zug (Sta. 9 and 10, Fig. 6) show relatively uniform gradients at each site. At Sta. 9, the gradient measured between 3.5 and 6.5 m depth is somewhat smaller than that measured above 3.5 m. Although the bottom water temperature record for Lake Zug is not as complete or as accurate as for the other lakes, it suggests a linear decrease from January 1970 until our measurements (June 1970). The resultant temperature distribution in the sediments is given by (Carslaw and Jaeger, 1959, p. 63)

$$T = T_0 \cdot 4\, i^2 \mathrm{erfc} \frac{z}{2\sqrt{at}} \tag{3}$$

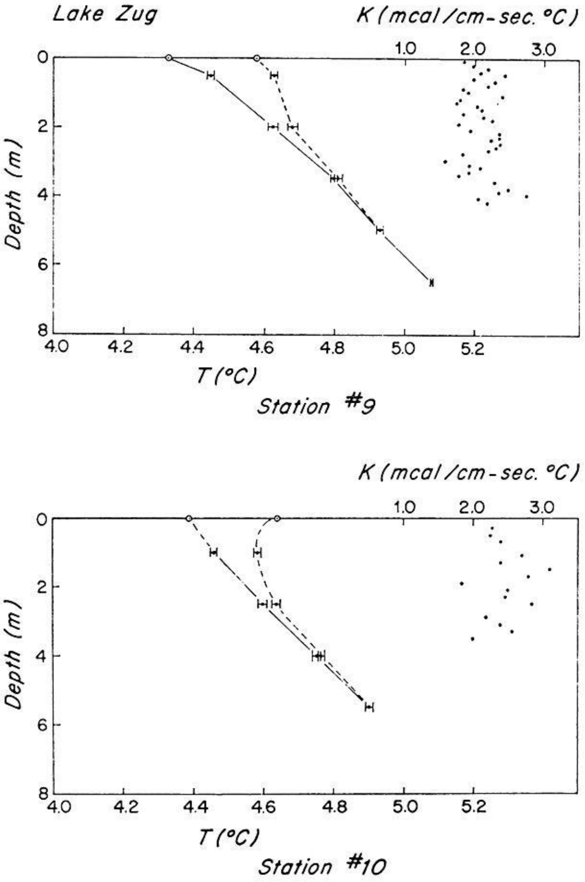


Fig. 6. Temperature and thermal conductivity measurements in Lake Zug. Symbols same as Fig. 4. "Corrected" temperatures given by Eq. 3 (Fig. 7d)

where i^2erfc is the second integral of the complementary error function (*e.g.* Carslaw and Jaeger, 1959, Appendix II). T_0 is here the total change of temperature (—0.25 °C) from $t = 0$ until the date of measurement. With $t =$ 6 months (January to June, 1970), Fig. 7d represents the temperature distribution calculated from Eq. (3).

The temperature distribution in the bottom sediments of Lake Zug, corrected for such a linear bottom water temperature change, should show the marked curvature with depth indicated by the dashed lines of Fig. 6. In fact, the calculated curvature and reversed gradient near the surface are not observed on any of the Zug measurements. We note that the suggested linear decrease of water temperature is based on only two measurements of

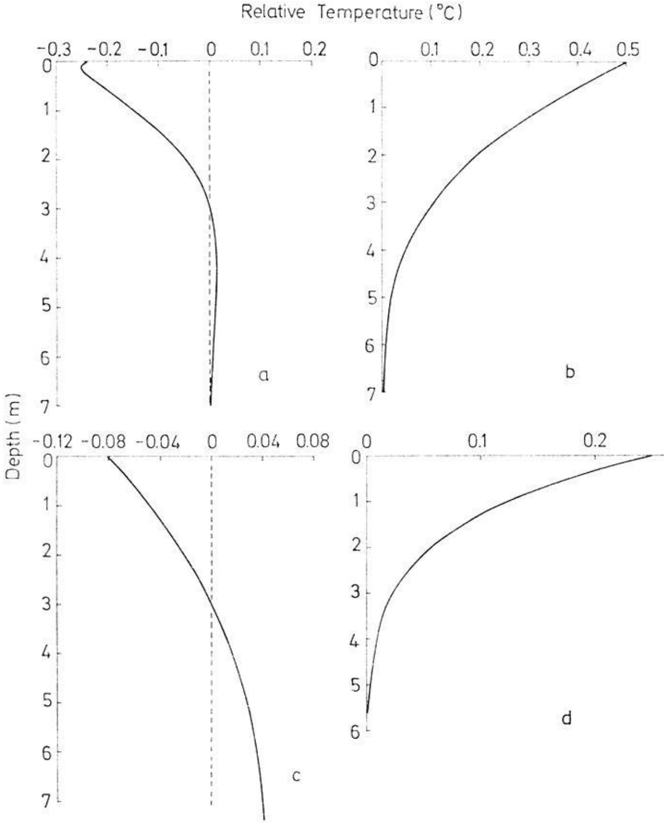


Fig. 7. Theoretical temperature disturbances below lake bottom caused by fluctuations in bottom water temperatures, T_0. Thermal diffusivity, α, assumed .002 cm^2/sec. (a) Sinusoidal variation of amplitude $T_0 = 0.3$°C, period = 1 yr., phase = 10 mo. (from Eq. 1); (b) 5.5 mo. after step change of $T = 0.5$°C (from Eq. 2); (c) Sinusoidal variation of amplitude $T_0 = 0.2$°C, period = 2.5 yr., phase = 17 mo. (from Eq. 1); (d) 6 mo. after beginning of a linear change of T_0 with time at a rate of 0.5°C/yr. (from Eq. 3)

questionable quality from January to June 1970. As thermal conductivity also appears to be relatively constant with depth, except for perhaps increased values at the bottom of the Sta. 9 core, we have made no corrections to the measured gradients at stations 9 and 10 to obtain heat-flow values.

3. Short (3-m.) Probe Measurements

Short probe measurements were carried out in Lakes Zurich and Zug. In Zurich, two successive penetrations of the probe at the same station (# 2) resulted in the same gradient, within the uncertainty of measurements. This station is located close to Sta. 3 (Fig. 1). In both measurements at Sta. 2

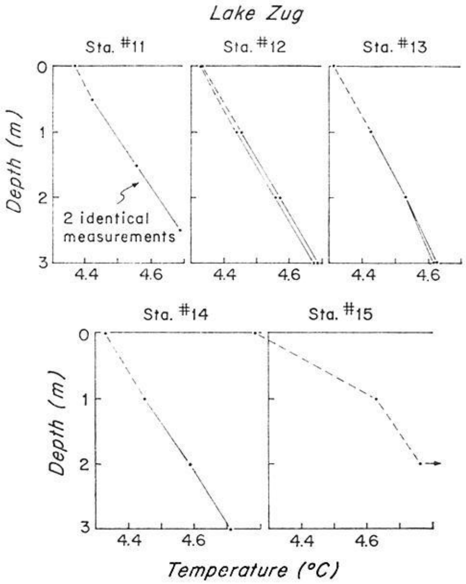


Fig. 8. Temperature vs. depth for short probe measurements in Lake Zug. Two measurements made for each of stations 11, 12, and 13

the gradient decreases with depth and is of the same magnitude (within 10%) as the results obtained at piston core stations 3 and 4. The gradient changes with depth confirm those found at the piston coring stations, but are only of limited value for independent determinations of the geotheral flux; they are not discussed further here.

In Zug, measurements at 4 locations in profile across the deepest portion of the lake (Fig. 8) show relatively constant gradients with depth at each station where 3 probes penetrated the bottom (Table 1). At Sta. 15, only the upper thermistor probe recorded on scale, indicating a significantly higher gradient compared to the other stations of the profiles. The shallower depth and different bottom water temperature at this station suggest that this gradient may be affected by fluctuations in bottom water temperature.

The gradients at the other 4 stations are quite comparable to those measured with the piston coring technique and are constant with depth at each station over two intervals, confirming the assumption that bottom water temperature changes within the several months preceding the measurements did not significantly affect the gradient. The gradients vary systematically across the profile (Fig. 9) such that values measured at the edges of the central basin (Sta. 11 and 14) are about 50% larger than those measured in the center (Sta. 13). This geographic variation of gradient is probably best understood by the steady-state refraction of heat through the sedimented basin of Lake Zug, as discussed below.

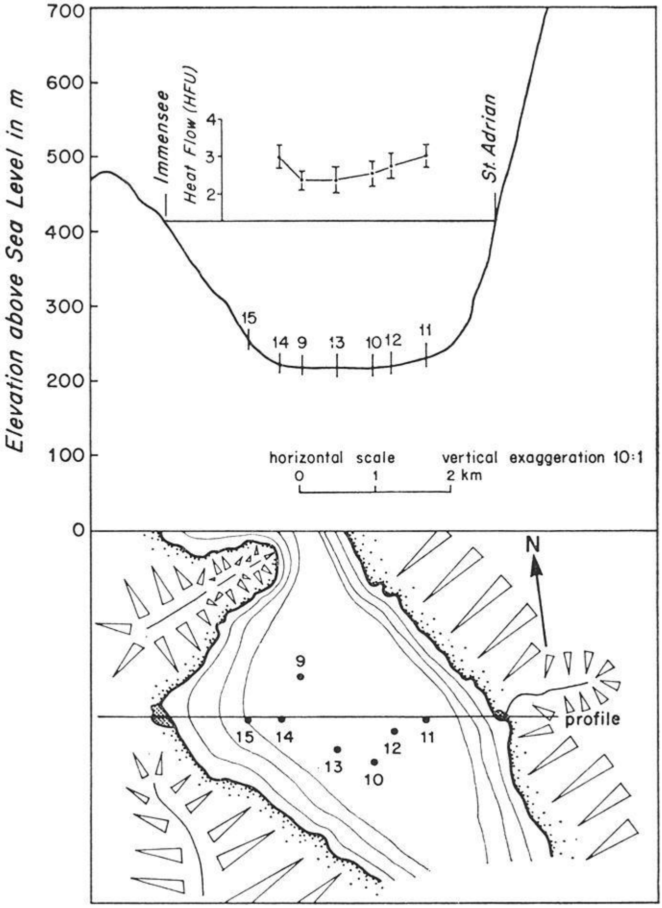


Fig. 9. Plan view and profile of stations (numbered) in Lake Zug. Symbols for map same as Figure 1. Contours of lake depth in 50 m intervals below lake level, from Landeskarte der Schweiz, Blatt 32 (Beromünster). Stations projected perpendicular to profile line. Heat-flow values (from Table 3) plotted above profile of stations

4. Other Corrections to the Measured Gradients

a) *Climatic Variations*

1) *Glacial Effect.* The alternation of glacial and interglacial stages over the past 10^6 years (Quaternary) must have been associated with changes in surface temperature in temperate latitudes. Except for the end of the last glaciation about 10^4 years ago, these variations are sufficiently far in the past to have had only a negligible effect on the present temperature gradients.

Since the ice cover of the last glaciation in the northern part of Switzerland originated locally in the Alps (Brinkmann, 1960), the ground surface under the ice was probably about 0°C or perhaps somewhat lower. The subsequent climatic warming must have brought the water of the lakes to higher temperatures so that the highest density water (4°C) would remain just above the bottom, thereby relatively well insulated from temperature or climatic changes. Thus we make the simple assumption of a step change of about 4°C which occurred about 10^4 years ago at the end of the last glaciation. By applying Eq. (2) for these conditions, the temperature gradient would be decreased by 0.0089°C/m. The gradient disturbance caused by this effect decreases with depth, but is constant within 2% in the upper 10 m due to the long time period involved. The relative correction for each measurement is tabulated in Table 2.

2) *Intermediate Period (10 to 10^3 yr) Variations.* We also need to assess the possibility that climatic variations associated with temperature changes in the period range of 10 to several thousand years may have affected the measurements. The larger gradients in Lakes Zurich and Zug, for example, might possibly be caused by a drop in water temperature during that period range before the measurements. The magnitude of the temperature drop required to produce that part of the gradient in excess of normal for these lakes, about .07°C/m, is computed from Eq. (2), summarized as follows:

Temperature drop ΔT at time t before present required to produce temperature gradient of .07°C/m

t	ΔT
10 yrs.	1.0 °C
100 yrs.	3.2 °C
1000 yrs.	10 °C

We have obtained monthly data on bottom water temperatures of Lakes Zurich and Zug which extend back to about the year 1950. Other than annual or shorter period fluctuations, there appear to be no systematic changes in bottom water temperature over this period for either lake, within the accuracy of the measurements (about 0.1°C). Hence, we conclude that no more than perhaps 10% of the excess gradient above normal in the lakes can be explained by water temperature changes in the period range of a few years to a few tens of years.

Although quantitative measurements are lacking, we are not aware of any recorded significant changes in climate over the past several hundred years which might have affected the lakes. To have a similar effect on the temperature gradient, fluctuations 200 years ago would have to be several times greater than those at 20 years; we believe this is unlikely, but a reliable method to assess temperature variations for this period range is needed. The largest uncertainty may be for the period of several hundred to several thousand years ago for which we have no recorded climatic history. Nevertheless, the changes required to account for the excess gradient would have to be of the order of 10°C or more, which would have implied a very warm lake indeed for the latitude of Switzerland. It seems more probable that the melting of ice, either within the lakes or from their influxes, has always had a continuous stabilizing effect on the deep lake temperatures since they were formed.

b) *Sedimentation Rate*

Sediments deposited on the lake bottoms will reduce the heat flux measured because part of the heat from below will be used to warm the sediments as they are buried. The sedimentation history of the Swiss lakes is uncertain principally because the origin of the lakes themselves is uncertain. In Lake Zurich, the most extensively investigated of the Swiss lakes, the sediments have a maximum thickness over molasse basement rocks somewhat more than 100 m., from seismic evidence (Hinz *et al.*, 1970). The average sedimentation rate over the past 10^4 years or so, determined from dating of sediment cores (Lüdi, 1957), is about 0.6 mm/yr. Hsü and Kelts (1970) have advanced arguments to conclude that total thickness of sediments has been deposited over the last 350.000 yrs. at a similar rate, principally during the last interglacial stage. There is a possibility, although less probable, that all the sediments were deposited since the end of the last glacial stage, about 10^4 years ago.

The cases of constant sedimentation rate and sudden deposition have been considered by Von Herzen and Uyeda (1963) (after Carslaw and Jaeger, 1959, p. 388) and by Birch *et al.* (1968). The formulas are somewhat different, but give similar results near the surface of the accreting layer.

Although the cores from the Swiss Lakes show evidence of suddenly deposited turbidity flows several cm thick, the model of constant sedimentation rate over time scales of several hundred years or longer seems more correct. Calculations with the formula of Von Herzen and Uyeda (1963, Eq. 2) show that if the time, t, since initiation of sedimentation is less than about 10^6 years, and the sedimentation rate, U, is smaller than 1 cm/yr, the temperature gradient does not sensibly depend on depth within the uppermost few m (Hänel, 1968). Neglecting heat generation within the sediments, the formula given by Von Herzen and Uyeda can thus be simplified as

$$\frac{1}{g}\left(\frac{\partial T}{\partial z}\right)_{z=0} = (1+2\,\tau^2)\operatorname{erfc}\tau - \frac{2}{\sqrt{\pi}}\,\tau e^{-\tau^2} = 4\,i^2\operatorname{erfc}\tau \tag{4}$$

where $\tau = \frac{U}{2}\left(\frac{t}{\alpha}\right)^{1/2}$, a dimensionless parameter, g = undisturbed gradient before sedimentation, α = thermal diffusivity.

If the 100 m or more of sediments in Lake Zurich began to be deposited 350,000 years ago, the average sedimentation rate to the present would be $U = 0.35$ mm/yr. Assuming an average α for sediment and underlying rock of .004 cm^2/sec (both are involved in the transient thermal process), and ignoring the changes in sedimentation rate which probably occurred between glacial and interglacial stages, Eq. 4 gives a relative thermal gradient (compared to the undisturbed value), of 0.94. If we assume that the presently observed sedimentation rate, 0,6 mm/yr, commenced about 10,000 yrs ago, the gradient at that time would now be reduced by the factor 0.96. Therefore, depending on the sedimentation history in Lake Zurich, it appears that the measured heat flow should be increased by 5 to 10% to account for this effect.

More extreme assumptions may be made about the sedimentation history, such as all the sediment being deposited over the last 10,000 yrs, either at a constant rate (1 cm/yr) or suddenly at the end of the last glacial stage (moraine?). In these cases, the reduction in heat flow would be by factors of 0.62 and 0.75, respectively. Thus the measured values would need to be increased by $^1/_3$ to $^1/_2$ to correct to steady-state conditions. Because the measured heat flow in Lake Zurich is already about twice normal, it seems unlikely that these more extreme sedimentation models should be considered.

The critical seismic evidence is not available for Lake Lucern, although the steep sides of the lake suggest that the sediment thickness may reach 600 m or more (see Appendix 2, Fig. 11). The increased rate of sedimentation could be provided by erosion of steep slopes locally, and by the relatively large Reuss River which drains the central part of the high Swiss Alps (Gotthard) where erosion is undoubtedly severe. The deposition of such a sediment thickness over the last 350,000 years gives an average sedimentation rate of 1.7 mm/yr, about 3 times the rate for Lake Zurich. For these parameter values, Eq. (4) gives a reduction in heat flow by a factor of 0.75. If the sediment should have a thickness of 1 km, the factor would be 0.55. Again, the heat-flow reduction would be severe if the sediment were all deposited in the last 10^4 years, which we consider unlikely. To

Table 2. Thermal conductivity. Mean values for each 1-m interval, corrected for depth and temperature (Ratcliffe, 1960), followed by the standard error (units: mcal/cm sec °C). Brackets indicate values included from next lower incomplete 1-m interval

Depth (m)	Sta. 3	Sta. 4	Sta. 6	Sta. 7	Sta. 9	Sta. 10
0–1	1.93 ± 0.99	1.89 ± 0.11	2.03 ± 0.24	1.85 ± 0.05	1.98 ± 0.10	2.18 ± 0.08
1–2	1.93 ± 0.13	1.80 ± 0.09	2.07 ± 0.17	1.98 ± 0.17	1.89 ± 0.11	2.37 ± 0.31
2–3	2.00 ± 0.15	1.93 ± 0.05	2.19 ± 0.21	1.93 ± 0.06]	2.09 ± 0.11	2.07 ± 0.13]
3–4	1.96 ± 0.08	2.04 ± 0.09	2.01 ± 0.09		2.05 ± 0.15]	
4–5	1.96 ± 0.13		2.06 ± 0.23			
5–6	2.20 ± 0.15		2.15 ± 0.12			
6–7						

be conservative, we have chosen a correction for the Lucern measurements (Table 2) which is closer to the model with 600 m of sediments. Even so, it is the largest part of the correction to the measured gradients.

Neither do we have seismic data for Lake Zug, although the topography and setting seem more similar to Zurich than to Lucern. By inference, the sedimentation rates in Zug are also probably more similar to Zurich, and the same sedimentation rate correction has been assumed (Table 2).

c) *Lake Basin Geometry and Regional Temperature Anomaly*

As a result of their location in a topographically anomalous setting (valley), and average bottom temperature which may differ from that of the

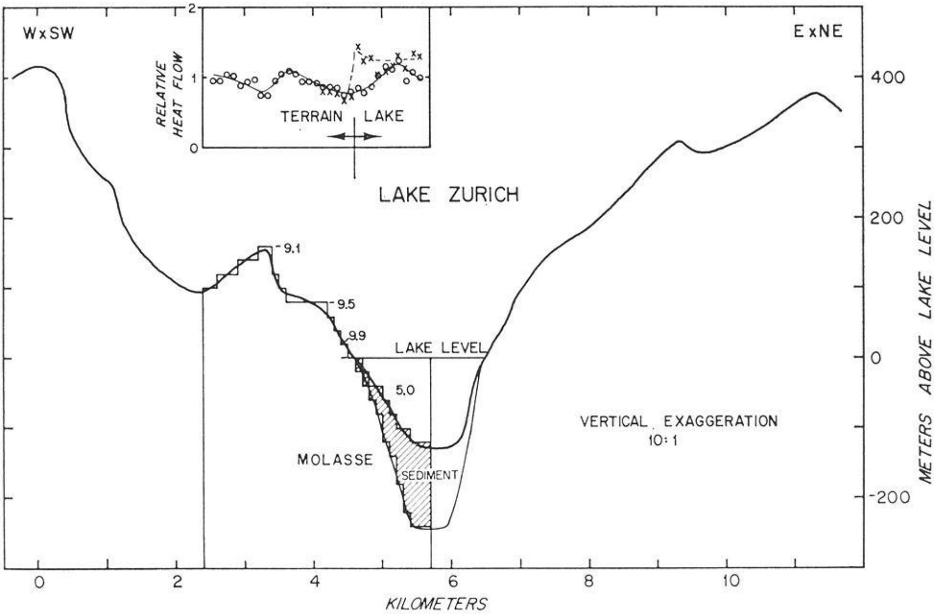


Fig. 10. Cross-section of 2-dimensional model of Lake Zurich, along a profile through Thalwil – Erlenbach (strike 070°). Topography above lake level from Landeskarte der Schweiz, Blatt 32 (Beromünster); lake bottom and sediment thickness from Hsü and Kelts (1970). Sediment thermal conductivity assumed 2.0 m cal/°C cm sec, uniform; thermal conductivity of rock basement (molasse) assumed 5.0 m cal/°C cm sec. Stepwise approximation to topography and sediment layers (cross-latched) used for numerical calculations of heat flow (Appendix 2); vertical grid = 20 m., horizontal grid = 100 m. Numbers are examples of mean terrain temperatures (°C) used in calculations. Relative heat flow through upper grid surface resulting from numerical calculations given by circled points continued by solid line (assuming sediment as shown), or by x symbols, smoothed as the dashed line (no sediment assumed)

surrounding terrain, the steady geothermal flux through the lake bottoms may differ systematically from the regional average. The magnitude of this difference depends on the elevation differences and topographic slopes of the valley, and the magnitude of the temperature anomaly. Hänel (1970) used numerical techniques on radially symmetrical models of several German lakes to show that apparent heat fluxes are greater than the regional values by factors ranging from 1.15 to 2.7. The highest factors were obtained from extremely steep valley slopes, up to 45°. However, the compensating effects of bottom sediments of relatively low thermal conductivity were not considered. We have carried out numerical studies for 2-dimensional models of two of the Swiss lakes (Zurich and Lucern), taking into account the variation of temperature, topography, and sediment distribution (Appendix 2).

The results for Lake Zurich (Fig. 10) show that the heat flow at the center is approximately the same as the regional value, and that the surface heat-flow transition across the lake margin is rather smooth. Computed variations within the lake range over approximately ±20% of the regional

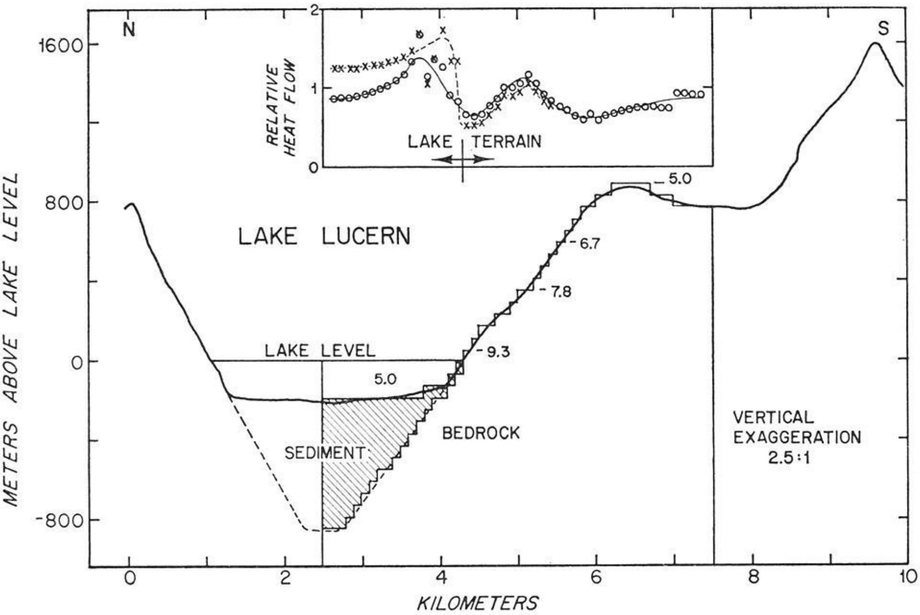


Fig. 11. Cross-section of 2-dimensional model of Lake Lucern (Beckenried), along a profile through Gersau – Emetten (strike 175°). Topography from Landeskarte der Schweiz, Blatt 37 (Brünigpass); sediment: basement interface extrapolated from topographic slopes near lake shore. Vertical grid step = 60 m., horizontal grid step = 100 m. Other parameters and symbols same as for Fig. 10

value, depending on location, and are smoothly varying. The neglect of sediment in the lake leads to a computed value at the center (x symbols) which is about 25% higher than the regional value (Hänel, 1970). There is also a sharp heat-flow contrast at the lake shore, due to the temperature contrast between lake and terrain. Apparently the sediment cover nearly cancels these effects for Lake Zurich.

The heat-flow pattern is similar for a comparable model of Lake Lucern (Beckenried) (Fig. 11). The steeper topographic slopes and probable thicker sediments give larger heat-flow anomalies than in Lake Zurich. Although without sediment the topographic and temperature effects would give a 25% enhancement of the regional flux at the lake center, similar to Lake Zurich, the inclusion of sediment decreases this to about 15% *below* the regional value. The profile for Zurich (Fig. 10) shows that bedrock (molasse) slopes beneath the lake are greater than the adjacent topographic slopes above lake level. Extending this observation to Lake Lucern, we have also made computations for models in which the sediment thickness there is about 1 km; the heat flow at the lake center is decreased about 20% from the regional value.

We have not made detailed studies for the Urnersee arm of Lake Lucern, nor for Lake Zug. In Urnersee, the adjacent topography appears quite similar to that of Beckenried, so that similar results are expected. The profile of the section across Lake Zug (Fig. 9) is somewhat asymmetrical, and extrapolation of the adjacent slopes down into the lake basin implies a sediment thickness of 100 to 200 m. The topographic plan of the southern Zug basin (Fig. 1) tends to be more 3-dimensional than the other lakes studied, although there is still an obvious N—S lineation. Nevertheless, the general physical configuration, and hence presumably the heat-flow correction, of Zug appears more similar to that of Zurich than of Lucern. The corrections for the Zug measurements (Table 2) are estimated by comparing the station locations (Fig. 9) with the computed relative heat-flow variation in Zurich (Fig. 10).

We emphasize that these lake models are assumed to be in steady-state, whereas both the temperature anomaly and the sediment distribution are transient. We have discussed a temperature change in the lakes of about 4°C, accompanied by a similar change on the surrounding terrain perhaps twice as large, associated with the end of the last glaciation about 10^4 years ago. The bottom sediments of least Lake Zurich have been filled in over the past 350,000 years. The transient effect of the temperature anomaly, which because of its more recent origin is probably more important, can be estimated from Eq. (2). One-half of the temperature change T_0 at the surface will be seen at a depth z given by $\sqrt{\alpha t}$; this may be considered the "skin depth" for a temperature change at the surface. For $\alpha = .01$ cm^2/sec (basement rock) and $t = 10^4$ years, we obtain $z \simeq 500$ m. This is comparable to some of the Swiss lake basin depths, and since the half-widths of the lakes range between 0.5 to 1.5 km (Fig. 1. 10, 11), the full effect of the present temperature anomaly would not be seen in gradient measurements in the lake bottom.

The time interval represented by the previous glacial stage (1 to 1.5 × 10^5 yrs) has a "skin depth" of nearly 2 km, as do the previous interglacial stages of comparable duration. Without a more elaborate model, it is difficult to predict the exact effect on lake temperature gradients of the present surface temperature regime superimposed on the complete previous temperature history. Somewhat arbitrarily, we assume that one-half of the anomalous effect computed from steady-state numerical models based on present surface temperatures is seen on the lake bottoms (Table 1).

d) *Combined Correction*

In Table 1, we have simply added the calculated effect of each correction discussed above to obtain a total correction at each station. Although the origins of the various corrections are quite distinct, it should be recognized that there will be, in general, mutual non-linear interactions between the different sources of the corrections through the heat equation. An exact total correction is probably attainable only through a numerical solution of the complete boundary conditions. We have generally attempted to be conservative in assignment of corrections; except for the measurements in Lake Lucern, the total corrections are less than 20% of the measured value at each station (Table 1).

Thermal Conductivity

Thermal conductivity was measured with the needle probe method (Von Herzen and Maxwell, 1959) in the laboratory on sediment cores recovered within plastic liners. All measurements were made within two weeks after core recovery at intervals of 10 or 20 cm. The results are presented in Figs. 4, 5, and 9 as conductivity profiles, and in Table 2 as mean values over depth intervals.

The measurements and visual inspection on core sections showed that cavities created by exsolution of gases from interstitial waters were numerous in some sections. These cavities were likely caused by the decrease in hydrostatic pressure and the increase of ambient temperature after core recovery. The cavities were generally of elliptical shape, with the major axes parallel to the direction of stratification of the sediment, but occasionally appearing as irregular fissures.

Such cavities may affect the conductivity measurements when the needle probe measurement is nearby because of the contrast in molecular conductivity of gases (about $5 \cdot 10^{-5}$ cal/cm sec °C for air) compared to sediments (about $2 \cdot 10^{-3}$ cal/cm sec °C).

All measurements which showed a non-linear relationship of temperature vs. logarithm of time, or a wide scatter of data points, were eliminated from figures and further calculations. Some measurements plot linearly but the calculated value for the conductivity is less than that of water, which is most likely also caused by included gas. These values, and some others rejected for various reasons such as obvious dehydration of the core, are indicated in the figures with an x symbol, but are omitted in further calculations. It is difficult to estimate quantitatively the effect of cavities, but their presence suggests that the higher values are more reliable.

The mean conductivity values in Table 2 were calculated as the reciprocal of the mean thermal resistivity of the measurements over one meter intervals of the core length. The number of values on which the mean and the standard errors were calculated varies between 4 and 11 but is usually 8 ± 1. The coring technique has probably caused some loss of core material, and the top 30—50 cm were frequently lost on recovery due to the high water content and soupy texture. Figs. 4, 5, and 6 suggest that an uncertainty of as much as 2 m may exist in the depth correlation of gradients and conductivity measurements.

Discussion of Heat-Flow Values

The corrected heat-flow values are given in Table 3. Station values are grouped closely for each lake. In Lake Zug, which has the most extensive measurements, the values form a systematic pattern with the lowest values towards the center (Fig. 9). The pattern appears significant even though most of the values fall within the range of the estimated uncertainty, because most of the uncertainty is the same for all values due to regional effects. The systematic variation may suggest that the correction assumed for the steady-state topography and temperature anomaly (Column T, Table 1) is not large enough, in which case the equilibrium heat flow for Zug may be closer to the values at stations 9 and 13, about 2.4 μcal/cm^2 sec (HFU).

The Lucern value is within the range of the continental averages, but has a larger uncertainty because of the larger corrections, principally due to a high sedimentation rate, inferred for that lake. Geographically, the measurements in Lucern are located only 10—15 km south of those in Zug (Fig. 1). Except for geothermal regions (*e.g.* Blackwell and Baag, 1973), it seems surprising that such large differences in heat flux would occur over such short distances on continents. Possibilities to reconcile the values are: (1) The influence of sediments in reducing the steady-state correction has been over-estimated in Zurich and Zug; instead, the steady-state correction should be much more negative, similar to models developed by Hänel

Table 3. Summary of Heat-Flow Measurements

Sta. No.	Position Lat (N)	Long (E)	Water[a] depth (m)	Temp. grad.[b]	Therm cond.[c]	Heat flow[d]
3 (Zurich)	47°16.8′	8°36.0′	130	.135	2.01 ± 7% (0.84)	2.71 ± .31 (113 ± 13)
4 (Zurich)	47°15.7′	8°38.0′	120	.132	1.98 ± 6% (0.83)	2.61 ± .70 (109 ± 29)
6 (Lucern)	46°57.7′	8°36.2′	200	.076	2.09 ± 5% (0.88)	1.59 ± .64 (67 ± 27)
7 (Lucern)	46°58.8′	8°31.0′	214	.086	1.96 ± 4% (0.82)	1.69 ± 1.03 (71 ± 43)
9 (Zug)	47°5.8′	8°29.2′	187	.117	2.00 ± 6% (0.84)	2.34 ± .26 (98 ± 11)
10 (Zug)	47°5.2′	8°30.3′	197	.114	2.20 ± 9% (0.92)	2.51 ± .34 (105 ± 14)
11 (Zug)	47°5.5′	8°30.5′	178	.142	(2.1) ± 10% ((0.88))	2.98 ± .32 (125 ± 13)
12 (Zug)	47°5.4′	8°30.2′	194	.129	(2.1) ± 10% ((0.88))	2.71 ± .34 (113 ± 14)
13 (Zug)	47°5.3′	8°29.6′	199	.112	(2.1) ± 10% ((0.88))	2.35 ± .35 (98 ± 15)
14 (Zug)	47°5.5′	8°29.0′	195	.141	(2.1) ± 10% ((0.88))	2.96 ± .32 (124 ± 13)

[a] Water depth from metering sheave at sta. 11, 12, 13, and 14; deduced from contoured maps or other measurements for other stations.

[b] Units of °C/m, corrected for glacial, sedimentation rate, and heat-flow refraction effects, from Table 1.

[c] Units of mcal/°C cm sec or $Wm^{-1}K^{-1}$ (parentheses). Error given as ± standard deviation of appropriate depth interval values of Table 2, with additional ±2% possible systematic error. Values for stations 11 through 14 assumed from nearby stations.

[d] Units of 10^{-6} cal/cm^2 sec or mWm^{-2} (parentheses). Uncertainty (±) from Appendix 1.

(1970). (2) Different water temperature fluctuations of intermediate period (10 to 10^3 years) have produced different apparent gradients between the lakes. (3) The influence of sedimentation rate and the steady-state effects of sediment fill in Lucern has been over-estimated. The possibilities that sedimentation rate and sediment thickness effects have not been properly evaluated may be resolved by seismic reflection studies planned in the near future.

On the other hand, the differences in heat flux between lakes may be real. We note that Zug and Zurich are located in the molasse formation, whereas Lucern is in the northern front of the Alps proper (Commission de la Carte Geologique du Monde, 1962). It may be that these formations or their underlying crystalline basements contain different amounts of radioactive elements. Birch and others (1968) found a close correlation between heat flow and radioactive heat production in rocks at closely spaced measurements in New Hampshire, USA. It would be important to establish if a similar correlation exists in Switzerland and Europe between crustal radioactivity and heat flow, as has been found in North America (Lachenbruch, 1968; Roy *et al.* 1968). Carefully located borehole measurements are probably the best means to establish this; if located sufficiently close to the Swiss lakes in which we have measured, they would also serve to calibrate these measurements.

The 10 new heat-flow values of this study (Table 3) represent a significant addition to the data for Switzerland. Previous measurements have been made in five railroad tunnels of the Swiss and Austrian Alps (Clark and Niblett, 1956; Clark, 1961). Subsequently, Clark and Jaeger (1969) have corrected the equilibrium heat flux in three of the tunnels for erosion rates in the Alps. The corrections amounted to 30 to 50% reductions in the measured values for erosion rates up to 1 mm/yr (1 km/m. y.), which have a large uncertainty.

We have not corrected the heat-flow values in the Swiss lakes for erosion, partly because we do not have data for quantitative estimates. Nevertheless, it seems improbable that erosion rates over the past several tens of m. y. could be nearly a large as those for the high Alps. The lake valleys have obviously been eroded (and probably created) by glaciers over the past 10^6 years, but the effect of such erosion on the surface heat flux is probably more than compensated by subsequent infilling by sediments.

Perhaps the most notable feature of the heat-flow values presented in Table 3 is the relatively high average. The averages for each of Lakes Zurich, Lucern, and Zug are 2.66, 1.64, and 2.64 μcal/cm^{2}sec (HFU), respectively. The average of these values is 2.31 HFU, compared to a continental average of 1.5 HFU; we consider this difference to be significant.

The values for Lakes Zurich and Zug are comparable with values in other lakes of South-central Europe (Hänel, 1970), especially if the corrections for sedimentation rate and sediment thickness in these other lakes are similar to those we have calculated for the Swiss lakes. Similarly high values have been measured in boreholes in southern Germany (Fig. 12). The higher values in South-central Europe may be related to the relatively recent Alpine orogeny, although the problem remains as to why the values in the central Alps are not similarly high.

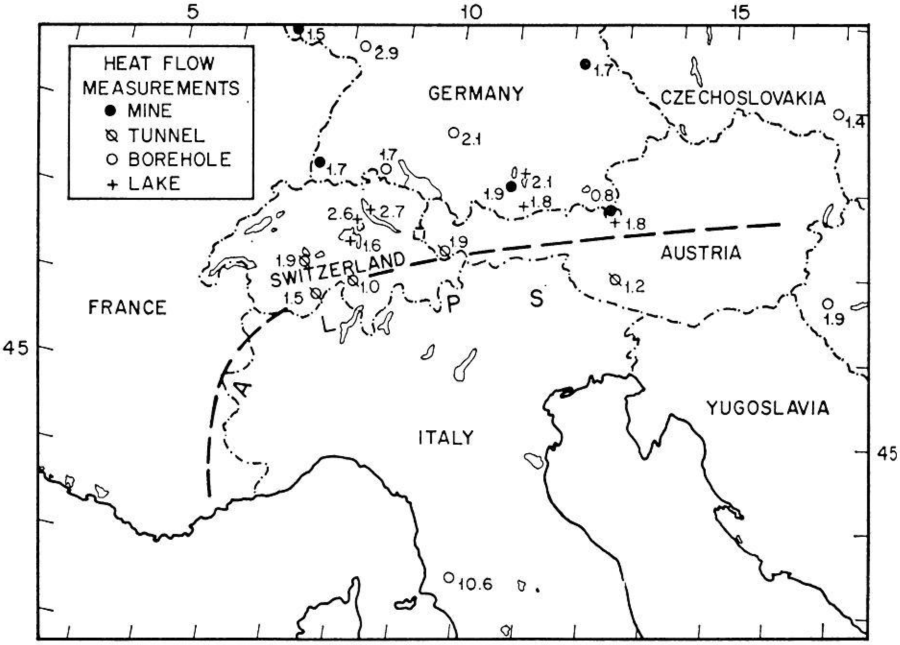


Fig. 12. Heat-flow values (in 10^{-6} cal/cm^2 sec.) of south-central Europe (after Hänel, 1970, Fig. 8). Approximate axis of Alps shown as heavy dashed line; larger lakes of Alpine Region also outlined

As yet, the heat-flow data of South-central Europe are insufficient to deduce significant geographical variations, if any. High values, up to several times normal, have been obtained by oceanographic methods in the Tyrrhenian Sea to the south (Erickson, 1970); these may be related to the high value and geothermal area at Ladarello, Italy (Fig. 12). Other deep lakes in the northern Italian Alps may be useful to deduce the distribution of geothermal flux across the Alps, which are central to the tectonic development of this region.

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Appendix 1: Computation of Heat-Flow Uncertainty

The computation of heat flow is the product of the independently measured temperature gradient and thermal conductivity at each station. The uncertainty in gradient (E_G) is computed as the sum of the following (Table 3):

(1) Uncertainty in the measured temperature gradient, as listed in Table 1 (%).

(2) One half the difference between the measured temperature gradient and that corrected for bottom water temperature changes, if any, as a percentage of the average of these.

(3) One half the total correction (Table 1, column 9) for glacial (G), sedimentation rate (S), and topography and temperature anomaly (T) effects.

The uncertainty in thermal conductivity (E_K) is that listed in Table 2. The heat-flow uncertainty is computed as

$$E_H = \sqrt{(E_G)^2 + (E_K)^2}$$

Appendix 2: Corrections to the Heat Flow from Numerical Models

Lakes are usually thermal and topographic anomalies in the regional terrain, which causes the heat flow through their bottoms to vary regionally and locally as a function of their anomalous characteristics. Hänel (1970) developed a numerical solution for lakes with approximate radial symmetry and with a mean temperature difference between the lake and regional terrain. However, he did not include a contrast in thermal conductivity between bottom sediments and underlying rock which seems to be a significant factor in corrections for heat flow in these Swiss lakes.

Because the Swiss lakes, particularly Zurich and Lucern, have relatively large length: width ratios, we have modified a 2-dimensional model developed for sea floor values (Sclater and others, 1970) to include a mean temperature difference between the lake and regional terrain, and also a variation of temperature corresponding to elevation changes of the terrain.

The mean lake temperatures were estimated from the temperature vs. time data available for lake bottom waters (Fig. 2), and from temperature vs. depth data in the lakes (Fig. 3). In all of the lakes in this study, the mean temperatures below 50 m depth ranged between about 4.5 to 5.5°C. From meteorological station data and climate maps (Imhof, 1962), we have derived a mean temperature difference of 5.0 °C between the lakes and the surrounding terrain at lake level, which is comparable to the 4.5 °C difference assumed by Hänel (1970) for lakes in southern Germany. The rate of change of temperature with terrain elevation has been assumed as —4.7 °C/km, a value derived from a study of heat flow in a nearby region of the Swiss Alps (Clark and Niblett, 1956).

The model used for computation and its results for Lake Zurich are given in Fig. 10. Some scatter in the computed heat flow is caused by the numerical grid steps in topography and bedrock boundaries. A sediment mantle appears over most all of the lake bottom, generally increasing in thickness with depth (Hsü and Kelts, 1970). Bedrock (molasse) is assumed to outcrop on the terrain, although the overall heat-flow pattern would not be changed significantly by a uniform, thin cover of lower conducting soil. Because of approximate profile symmetry to either side of the lake axis, only the southwest side (Thalwil) of the topography has been modeled. The numerical results show that the inclusion of terrain topography beyond (southwest of) that shown in the grid model has a negligible effect on the magnitude or pattern of heat flow in the lake.

A similar model has also been used for computations for Lake Lucern (Beckenried), illustrated in Fig. 11. In Lucern, we have seen only unpublished seismic reflection data for the Urnersee arm which does not show any clear basement reflections. The basement surface in our model has been estimated by downward extrapolation of topographic slopes above lake level, resulting in a total sediment thickness of about 600 m. The increased thickness compared to that of Zurich is consistent with the greater width, steeper side slopes, and the greater sedimentation rate of Lucern (K. Kelts personal communication). Note that this extrapolation places the deepest part of the bedrock surface below present sea level, a feature also found in Lake Thun from seismic evidence (Matter *et al.*, 1971).

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