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Geophysical Investigations into the Nature of Pre-Holocene Sediments of Lake Zurich

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ZUSAMMENFASSUNG

Im Sommer 1975 wurden an vier Orten im Zürichsee mittels Refraktionsseismik erstmals die Schallgeschwindigkeiten der Sedimentfüllung gemessen. Es wurden 6 Schichten mit Schallgeschwindigkeiten zwischen 1,45 km/sec und 5,2 km/sec unterschieden. Diese Angaben erlaubten die Berechnung der wahren Schichtmächtigkeiten sowie der echten Übertiefung von ca. 395 m des Zürichsees auf etwa 10 m ü. Meer. Drei Modelle für die eiszeitliche Geschichte des Sees werden diskutiert. Deren Einfluss auf die Geothermik sowie pollenanalytische Altersbestimmungen führen zur Folgerung, dass die Sedimentschichten wahrscheinlich verschiedene Vorstoss- und Rückzugstadien der Würmeiszeit darstellen. Tiefere Lagen sind vielleicht sogar älter, und das Ausschleifen des Zürichsee-Troges dürfte eher in der Risseiszeit als im Würm stattgefunden haben.

Introduction

During the establishment of the glacial erosion theory the Quaternary history of the lake Zurich Basin was frequently at the focus of heated controversy. For recent historical reviews see HSÜ & KELTS (1970) or SCHINDLER (1968). In spite of the attention, no direct access to the sediments was available to the early workers and the many fundamental questions remained unanswered. These include the absolute depth of the basin, the amount of overdeepening, the amount and characteristics of post-Molasse sedimentary fill and the timing of the presumed glacial erosive stages. In the past few years investigations moved from the surrounding terrain into the subaqueous realm with studies by SCHINDLER (1968, 1974) encompassing the results of hundreds of geotechnical soundings in near shore areas. LÜDI (1957), and THOMPSON & KELTS (1974) examined piston cores from the top 8 meters of lacustrine sediments. They demonstrated that these cores contain a 13,000 year old sedimentary record covering most of the Late Glacial and Post-glacial period.

Our present knowledge of the nature of more deeply buried sediments relies mostly on indirect geophysical methods. VON HERZEN and others (1974) recorded

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elevated heatflow values through the lake basin sediments. HSÜ & KELTS (1970) and HINZ and others (1970) first showed from the results of an air-gun seismic reflection survey, that over 150 meters of glacial drift and possibly interglacial sediments are present in a deeply scoured basin. Their estimates were based on minimum values necessary for seismic layer velocities and the geological nature of the internal reflectors.

Problem statement

The following models have been postulated for the sedimentary fill:

I. All the sediments in the lake basin were deposited during or after the last retreat of the glacier front from Zurich. HANTKE (1968, 1970) has estimated this event around 17,000 years B.P.

II. The basin contains older drift and sedimentary remnants from early and late Würm advance and retreat stages.

III. The basin contains material from the Riss/Würm interglacial or older glacial stages.

The possibilities of interstadial or even interglacial sediments in the lake basin is an intriguing question. It would imply a limited erosive capability of the Würm glaciers and an initial overdeepening of the basin by Riss and/or earlier glacial activity. Most recent interpretations of the acoustic structure of perialpine lakes favor the model such as given in Case I or have left the question open (e.g. MÜLLER & GEES 1968; VERNET et al. 1974; MATTER et al. 1973; SCHINDLER 1974).

This short communication proposes to test these models in the light of new information from sonobuoy seismic refraction results, improved seismic reflection profiles and heat flow studies. Our contribution will show some of the limitations applicable to these models and demonstrate some of the internal complexities of the sedimentary fill.

Seismic methods

Our refraction program, in summer 1975, utilized sonobuoys launched from the ETH research vessel *Tethys*. A Bolt Air Gun system served as a sound source. Theory and method are described in LE PICHON et al. (1968). A supplementary air-gun reflection profile was run along the longitudinal axis from Rapperswil to Zurich (see Fig. 1) using a modified technique similar to that described in HINZ et al. (1970). In particular, an 80 ccm chamber provided greater penetration and more detail. Instantaneous topographical positioning was recorded every 5 min. (see Fig. 1) by photographing the screen of the ship's radar and then later projecting the image onto a base map. The accuracy, during this program, was better than ± 30 meters. It was also possible to follow a predetermined course by monitoring the radar screen.

Investigations and assumptions

We recorded sonobuoy profiles in each of the four geomorphic provinces of lake Zurich (see SCHINDLER 1974; HSÜ & KELTS 1970), (Fig. 1). These encompass: the shallow area behind the Hurden-Rapperswil dam (LZHSB 3); the shallow sediment-filled mid-basin behind the Männedorf-Stäfa submerged rock barrier (LZHSB 2); the deepest section of the lower lake basin (LZHSB 1) and the shallow area near the city of Zurich (LZHSB 4).

The sonobuoy method enables an accurate determination of the sound velocities for both the layered sedimentary fill and the bedrock. With this information we calculated the thicknesses of the sedimentary layers as well as the true depth to bedrock. Good estimates were also possible for the thicknesses between major reflecting horizons. Layer thicknesses, corresponding to the acoustic velocities were calculated either on the basis of reflectors visible in the reflection profiles of that area (Fig. 2A) or with the aid of the zero time intercept of the refracted signal. We assumed a vertical wave velocity of 1.45 km/sec for the water layer which is consistent with the temperature distribution common in the lake (BARK et al. 1964).

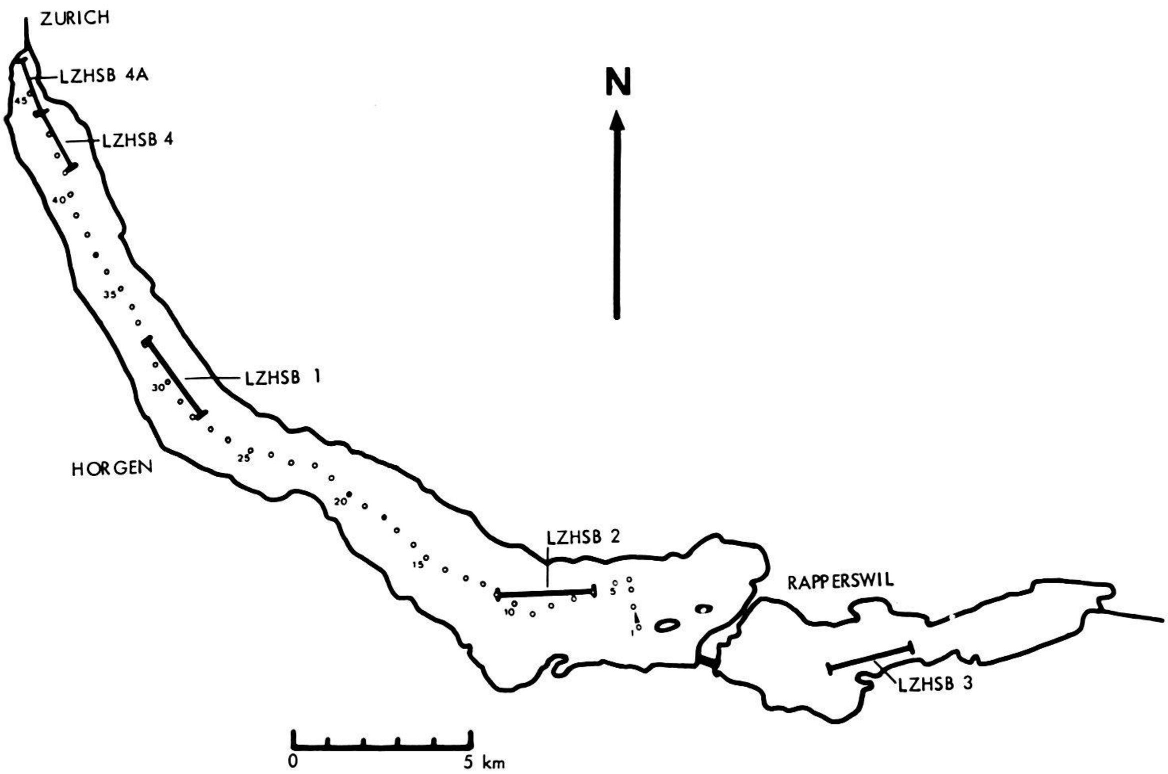

Fig. 1. Index map Lake Zurich: Locations of the 1975 sonobuoy refraction profiles are shown by the heavy bars. Open circles denote the 5-minute interval positioning of a longitudinal reflection profile with numbered locations referred to in Figure 2 and in the text.

We also assumed an acoustic velocity of 1.50 km/sec for the uppermost, approximately 20 m-thick, sediment layer. Although no refracted signals were discernible for this layer, piston-core analysis indicates that the top few meters are unconsolidated sediments with a water content ranging from 80–45% by weight. This assumption does not greatly affect the overall depth figures but provides the necessary acoustical contrast for a reflection at the water-sediments interface.

Seismic results

Up to 6 distinct acoustic layers have been recognized in the refraction records. Their seismic velocities and corresponding thicknesses are tabulated in Table 1. The original seismic reflection profile recording which traverses the sonobuoy sites along the axis of lake Zurich is shown in Figure 2A. A comparison with HINZ et al. (1970) shows a significant improvement in penetration and clarity of internal reflections over the earlier recordings.

We have combined the refraction and reflection results into a schematic reconstruction of the lake's longitudinal geophysical structure as shown in Figure 2B. Two observations have been made which modified the previous conclusions of the earlier air-gun survey (HINZ et al. 1970; HSÜ & KELTS 1970):

1. What was interpreted as a significantly oversteepened Molasse floor is shown to be the top of the 4.0 km/sec layer in central lake-basin and the top of the layers 3 and 4 farther down towards Zurich.
2. The Molasse rock floor has a very minor oversteepening. Its maximum depth is about 395 m below the lake water-level (or about 10 above sea level).

The thickest sedimentary package but not the deepest rockfloor, was found in the upper-lake Zurich (LZHSB 3) where earlier reflection profiles showed no penetration. Over 290 meters of unconsolidated sediments completely fill a deeply scoured basin. In the area near Zurich (LZHSB 4, pos. 45) where reflection profiles revealed a mass of strong but chaotic reflectors the bedrock also has a depth over 250 meters; this new finding is consistent with the drilling results presented by SCHINDLER (1974). The mid-basin (LZHSB 2) is filled to the brim of its submerged rockbarrier by 180 meters of sediment.

Geophysical and geological characteristics of acoustic layering

Our improved seismic reflection profile (Fig. 2A, cf. HINZ et al. 1970; SCHINDLER 1974) shows a complex section of irregular surfaces and unconformities. Some of the features and their possible interpretations are summarized below:

Seismic layer 1 presents the water layer. It reaches a maximum of 142 meters in the deepest lake region which forms the basis of the following discussion.

Seismic layer 2 shows a set of parallel reflectors, partly masked by the air-gun bubble-pulse. They drap uniformly over subsurface irregularities, varying in thickness from 14 m in the deep basin to nearly 40 m near Zurich and 70 m behind the Hurden dam. Based on drillings (SCHINDLER 1974) and core analysis (THOMPSON & KELTS 1974; LÜDI 1957) the 1.50 km/sec layer 2 encompasses post-glacial and Holocene lacustrine muds, silts and chalks, and may include some tills. A disturbance near position 30 on the reflection profile (Fig. 2A) marks in addition to surficial slumps deposits, a hummocky set of reflections at the base of the layer. This, approximately 20 m thick, chaotic zone could correlate with an end moraine mapped on the shore by SCHINDLER (1974), who interpreted it as evidence of a pause in the final retreat of the glaciers from Lake Zurich.

Table 1: *Summary of sonobuoy survey showing velocities (V_p) in km/sec and corresponding layer thickness (D) in meters.*

Station nr.	LZHSB 1		LZHSB 2		LZHSB 3		LZHSB 4		Comments
	V_p	D	V_p	D	V_p	D	V_p	D	
Layer 1	1.45	140	1.45	35	1.45	20	1.45	20	Water layer
Layer 2	1.50	14	1.50	10	1.50	70	1.50	40	Topmost sediment
Layer 3	1.74	55	1.75	64	1.75	224	1.90	110	
Layer 4	2.05	70					2.05	73	
Layer 5	4.00	120	3.85	90			4.00	═	
Layer 6	4.60	═	5.22	═	5.57	═			
Total sediment thickness		259		174		294		223	

Seismic layer 3 has a bulk seismic velocity of 1.74 km/sec which corresponds best to values for unconsolidated, watersaturated alluvium or till (PRESS 1966). The surface boundary varies from slightly undulating to highly irregular suggesting modification by ice or water (see Fig. 2, pos. 30–35). Reflections within the layer have a regular layered acoustic character. This layer is about 55 m thick in the deeper regions but reaches 224 m in the basin behind the Hurden dam (LZHSB 3). A mound of chaotic reflections up to 50 meters thick within layer 3 is visible near position 32 indicating a possible end moraine. The seismic character of the layer 3 is consistent with a sequence of glacio-lacustrine deposits or outwash alluvium.

Seismic layer 4 (2.05 km/sec) appears to reach a maximum of 100 meters near position Nr. 26. Within this layer reflections are poorly defined, fuzzy to almost transparent. An irregular but strong reflecting surface and higher velocities than layer 3 suggest a possible hiatus with more consolidated alluvial or outwash sediments. The seismic characteristics suggest that the layer could be in parts gravels, such as the overridden, compacted early Würm gravels found below the lignite horizon in the Buchberg region of upper Lake Zurich (KLÄY 1969). This is confirmed by drillings in the lower lake at position 45 where glacial tills and gravels were found (C. Schindler, pers. comm.).

Seismic layer 5 begins with sharp, irregular reflector, which shows a strong acoustic contrast to layer 4. This is consistent with the high seismic velocities (3.85–4.0 km/sec) which indicate a hard, well-cemented sedimentary sequence, 100–150 m thick. Such velocities are possible for Molasse sandstones but reflections within this layer indicate beds dipping unconformably to the underlying layer 6. The reflection profile shows a two part separation for layer 5. The upper part varies rapidly in thickness from about 50 to 5 meters and has highly irregular, hummocky internal reflections. It forms pods and fills and smooths out irregularities in the surface of the lower part as if smeared as a paste. The lower part exhibits a more regular set of hard, discontinuous reflectors which dip gently northward (see position 27). The seismic characteristics might suggest that the sediments be the hard, cemented

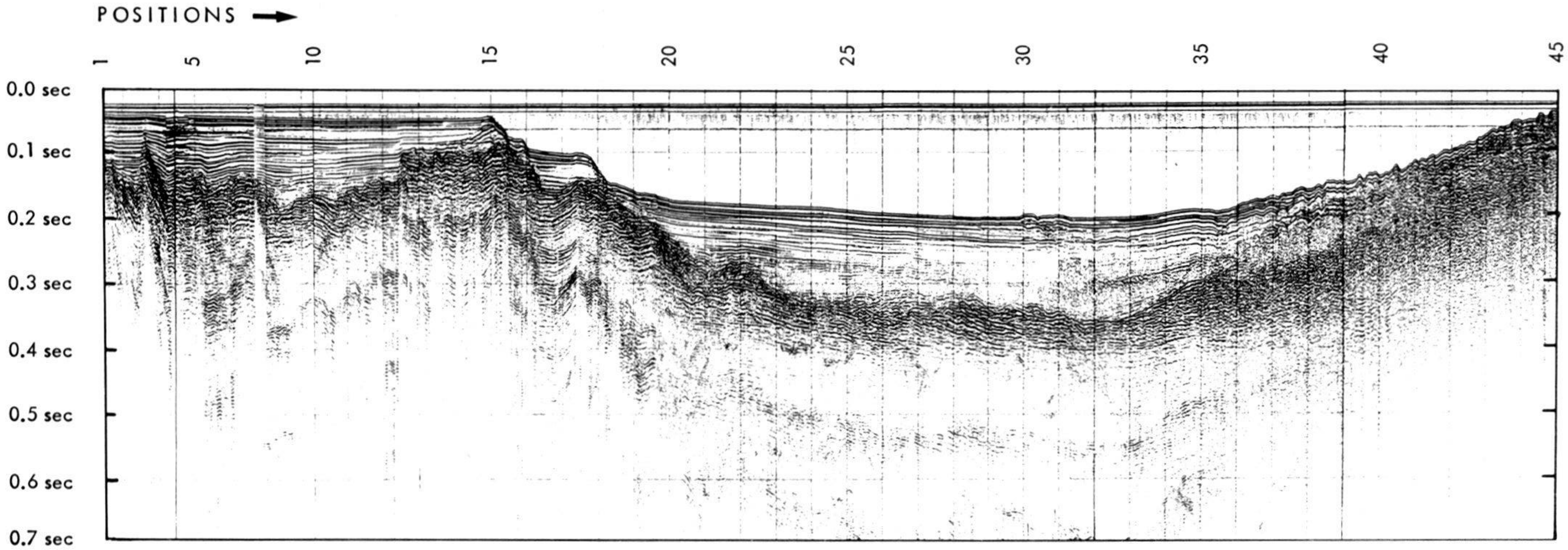

Fig. 2A. Reflection profile along the middle of Lake Zurich. Equidistant vertical marks are the 5-minute intervals corresponding to the positions, in Figure 1.

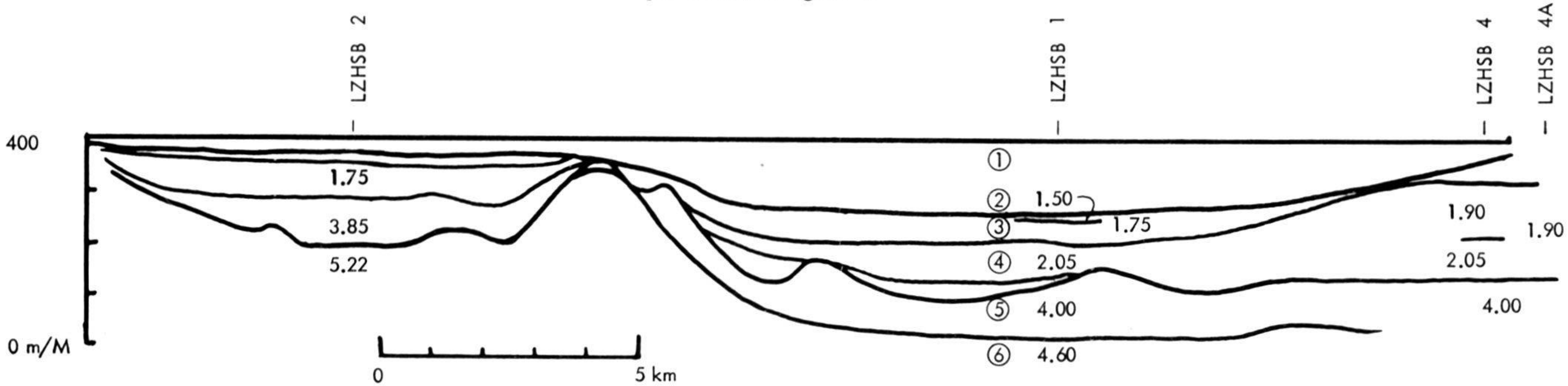

Fig. 2B. Schematic reconstruction of the interpreted geophysical structure of Lake Zurich. Seismic layer velocities are given in km/sec, the elevations are given by the scale on the left as meters above sea level. Circled numbers indicate the layer numbers used in the text. Note that the horizontal, true km-scale does not correlate exactly with the length of the reflection profile above.

interstadial (or interglacial) gravels and conglomerates such as those presently found as outcropping on the Au peninsula (near position 22). The top of this layer is marked by at least 3 elevations (at pos. 18, 22, and 28); they may represent end moraines of earlier Würm or pre-Würm glaciers. In part, the isopach maps for the lake infill prepared by HSÜ & KELTS (1970), refer to the layers above layer 5.

Seismic layer 6 begins with a flat-lying, uniform reflector, partially masked by layer 5. The uniform character and seismic velocity of 4.6 km/sec strongly suggest that this is the Molasse basement of Lake Zurich. The surface dips down (position 33) to an elevation of only a few meters above sea level rising near Zurich to almost 100 meters above sea level. Behind the rock barrier in the middle basin, the sonobuoy station (LZHSB 2) recorded an extremely high layer 6 seismic velocity (5.2 km/sec) suggesting that the refracted signal passed through the highly-indurated layers of the Obere Meeresmolasse Formation. The geological character of the rock barrier remains an enigma but it appears to have a Molasse foundation at about 50 meters subsurface capped by a mound of hard, compacted sediments (position 15).

Limitations on sedimentary model

a) Sedimentological arguments

Concerning the age sequence of the thick basinal sediments in the deepest region one parameter is set by pollen analysis of recent 7-10 meter piston cores. Finely laminated sediments of the Bölling stage (13,300 years B.P.; ZOLLER 1968) have been penetrated in several cores (B. Ammann, pers. comm.). These confirm the earlier estimates of LÜDI (1957). We have traced this layer as a seismic reflector at depths less than 20 meters below the sediment/water interface over much of the deep basin. Thus, the bulk of 240 m remaining sediment must be older than about 14,000 years.

b) Geothermal arguments

SCHINDLER (1974) suggested that all the Lake Zurich sediments (layers 2 to 5) could be deposited during and after the last Würm advance to the Zurich glacial stage. A strong counter-argument comes from the results of heat flow measurements which were made in the deepest area of Lake Zurich (VON HERZEN et al. 1974). These showed a heat flow of 2.66 HFU (μcal/cm^{2}sec) which is significantly higher than the continental average of 1.5 HFU (SCLATER et al. 1970). This high regional heat flow is comparable to the results obtained from alpine tunnels (CLARKS & NIBLETT 1956).

When making heat flow determinations some correction factors due to the environment must be applied. In particular measurements in lakes need to be corrected for the rate of sediment deposition. In other words, the regional heat flow is reduced to the measured value by a multiplicative disturbance factor, because of the blanketing effect of rapid sedimentation. Two theoretical cases have been considered for the sediment fill of Lake Zurich trough. Case I treats heat flow through a layer continuously thickening by a constant sedimentation rate. Case II treats heat flow through a thick layer rapidly deposited at the same time in the past

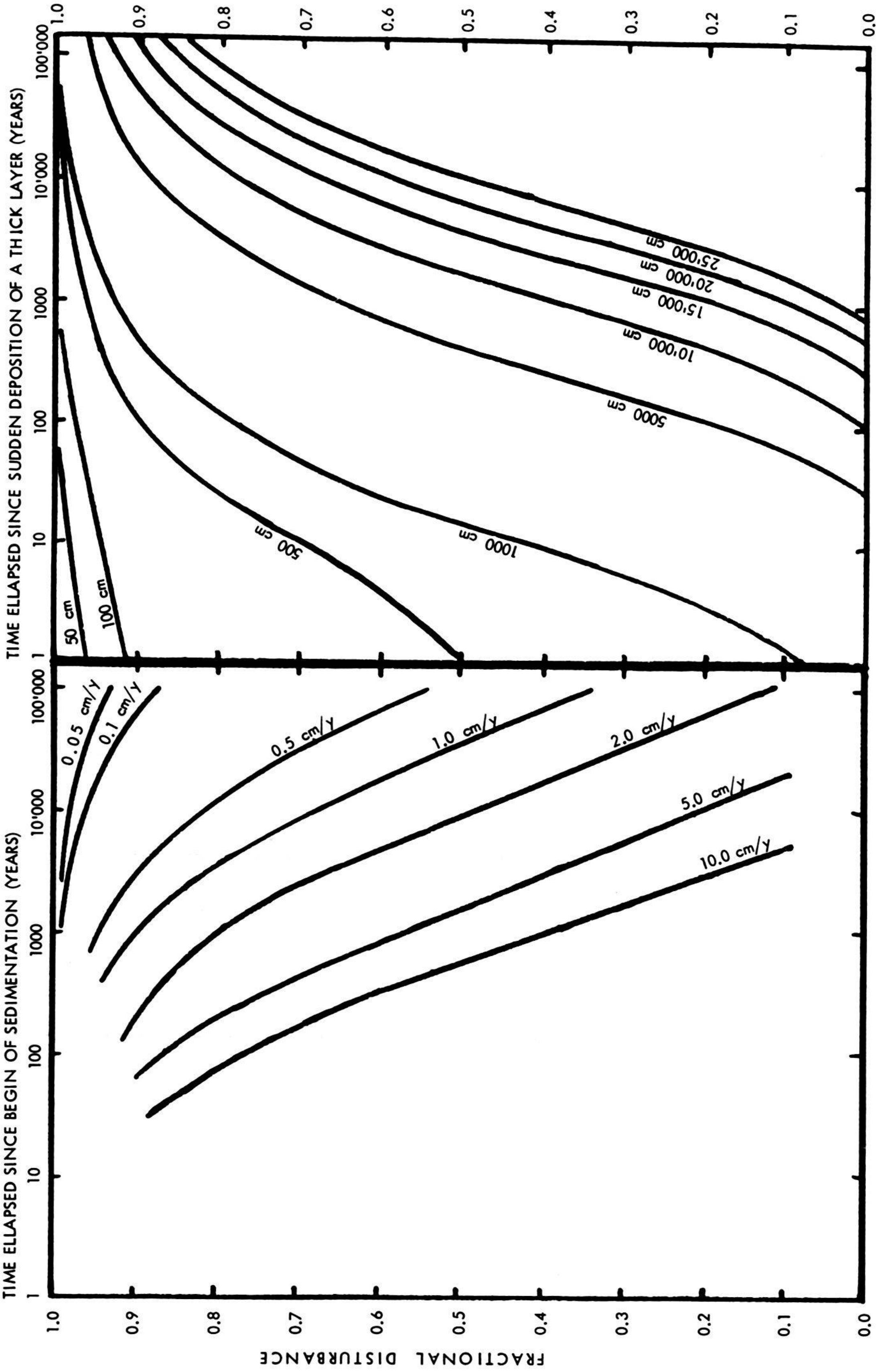

Fig. 3A. Curves necessary for the correction of surface heat flow which is affected by various constant sedimentation rates.

Fig. 3B. Curves necessary for the correction of surface heat flow which is affected by rapid deposition of a sediment layer (after CARSLAW & JAEGER 1959).

and its subsequent equilibration assuming insignificant additional deposition. CARSLAW & JAEGER (1959) derived the equations with which the disturbance from equilibrium heat flow can be calculated. This was carried out for both cases using numerical values which encompass probable ranges for the history of Lake Zurich. The results are shown in Figures 3 A and 3 B.

If we apply these results to Model I, some inconsistencies are readily apparent. Let us assume that layer 5 is a highly compacted ground moraine from the last Würm glacial advance to Zurich. Consequently the overlying 150 to 200 m of sediment would have been deposited within the last 10,000 to 15,000 years or at an average rate of about 1 to 2 cm/yr. We can read off Figure 3A the disturbance factor and according to this computation, the regional heat flow of Lake Zurich in this case should be between 3.19 and 4.07 HFU (see Table 2). Treating Case II we

Table 2: *Corrected regional heat flow values for Lake Zurich based on a numerical solution of a model assuming rapid sedimentary fill from a retreating glacier. Heat flow units in ($\mu cal/cm^2$ sec).*

Thickness of sediment layer in m	elapsed time in years	resulting sedimentation rate in cm/y	fractional disturbance	measured heat flow	corrected heat flow
100	10'000	1.00	0.66	2.66	3.57
100	15'000	0.66	0.80	2.66	3.19
150	10'000	1.50	0.55	2.66	3.86
150	15'000	1.00	0.66	2.66	3.57
200	10'000	2.00	0.47	2.66	4.07
200	15'000	1.33	0.57	2.66	3.72

assume a rapid deposition of a sediment layer with a thickness between 150 and 200 m some 15,000 years ago. It can be seen from Figure 3B that the disturbance would be between 0.63 and 0.72 and the consequent heat flow between 3.4 HFU and 3.64 HFU.

In summary, for both models the heat flow at the boundary Molasse/Lake sediments would be 28% to 53% higher than the measured heat flow. Similar high heat flow values on the continents are only known from areas of active volcanism or rift zones (SCLATER et al. 1970). This comparison as well as the significantly lower heat flow values measured in alpine tunnels lead us to the conclusion that the Lake Zurich sediments could not be deposited at such high rates. Therefore, much of the sedimentary fill must be older than the last Zurich glacial phase.

Conclusions

The accurate determination of seismic velocities in the lake sediments and geothermal considerations add new constraints to the ongoing discussions of the Quaternary geology of Lake Zurich. The results support the tennant of an early scoured basin with sedimentary remnants of several interstadial, advance or glacial retreat stages. However, a more exact sedimentary history of Lake Zurich can only be provided by a future deep lake drilling.

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