Zeitschrift: Eclogae Geologicae Helvetiae
Herausgeber: Schweizerische Geologische Gesellschaft
Band: 63 (1970)
Heft: 2

Artikel: Seismic investigation of Lake Zurich. Part II, Geology
Autor: Hsü, K. Jinghwa / Kelts, Kerry R.
DOI: https://doi.org/10.5169/seals-163858

Eclogae geol. Helv.	Vol. 63/2	Pages 525–538	With 2 figures in the text and 1 plate (I)	Basle, July 1970

Seismic Investigation of Lake Zurich: Part. II Geology

By K. JINGHWA HSÜ and KERRY R. KELTS

Geological Institute, Swiss Federal Institute of Technology, Zurich

ABSTRACT

A seismic investigation of the Lake Zurich has been carried out. The seismic data permitted us to estimate:

1. the thickness of the Lake sediments,
2. their nature and probable origins,
3. the depth of the Molasse "basement" and
4. its tectonic and geomorphic history.

An interpretation of these data in the framework of existent geological knowledge helps clarify some of the questions concerning the origin of Lake Zurich.

ZUSAMMENFASSUNG

Die bei der Untersuchung des Zürichsees gewonnenen Daten geben Aufschluss über:

1. die Mächtigkeit der Sedimente,
2. ihre Beschaffenheit und ihre wahrscheinliche Herkunft,
3. die Tiefe der anstehenden Molasse unter dem Seeboden,
4. ihre tektonische und geomorphologische Geschichte.

Eine Interpretation der seismischen Daten im Rahmen der vorhandenen geologischen Kenntnisse trägt dazu bei, einige der Fragen betreffend den Ursprung des Zürichsees abzuklären.

Introduction

The origin of Lake Zurich has been a subject of much interest during the last hundred years. HEIM (1894) and students (AEPPLI, 1894; GOGARTEN, 1910) interpreted Alpine-border lakes such as Lake Zurich as drowned valleys within a zone of subsidence along the Alpine front. Their arguments were based largely upon geomorphic evidence that has been discredited in recent years (e.g., PAVONI, 1957; RINGGER, 1964). Meanwhile, the idea first advanced by RAMSAY (1862), and further developed by PENCK and BRÜCKNER (1908), of a Lake Zurich basin eroded by glaciers has received general acceptance. The role of tectonics in shaping the alpine lake basins remain uncertain. STAUB (1951), PAVONI (1957) and HANTKE (1967) all postulated faulting on both sides of the Lake Zurich. The idea of relating alpine valleys and lake basins to graben-tectonics has been popular (e.g., ROTHPLETZ, 1884; SCHMIDLE, 1911; 1931). Yet the recent seismic investigation of Lake Constance led MÜLLER and GEES (1968) to a contrary conclusion.

A further question was raised by STAUB (1938) why the alpine lake basins were not filled by post-glacial debris. AEPPLI (1894, p. 111) postulated the presence of a moraine under Lake Zurich between Wädenswil and Männedorf. Such a moraine, if existent, should serve to trap the sediments behind the barrier, thereby leaving the lower lake basin unfilled. STAUB (1938), related the origin of alpine lakes to the presence of dead-ice bodies long after the retreat of glaciers. This very ingenious idea is appealing (see SUTER and HANTKE, 1962; RINGGER, 1964), yet supporting evidence is lacking (HANTKE, 1959b; SCHINDLER, 1968, p. 430).

Closely related to the question of the origin of Lake Zurich are the many problems of Quarternary and Molasse geology. Notable contributions to the geology of Zurich have been made through the classic work of HEER and ESCHER (1862), WETTSTEIN (1885), AEPPLI (1894), PENCK and BRÜCKNER (1909), HUG (1907; 1917), and more recently by SUTER (1944), HANTKE (1959a; 1967), VON MOOS (1943), JÄCKLI (1962), PAVONI (1957), SCHINDLER (1968) and others. Yet a considerable part of Canton Zurich lies under water, and some questions remain controversial because of the lack of clear-cut critical evidence.

The purpose of the present investigation has been mainly methodological. We attempted to test the applicability of the air-gun seismic method to Swiss geology. The Lake Zurich investigation has been chosen as a pilot project. We have chosen, for logistical reasons, an apparatus with a small air chamber of 1 cm^3. The conditions in the Lake Zurich proper were sufficiently favorable. A "basement" reflector has been readily identified as the top of the Molasse formation underlying Quaternary lake sediments, and the internal structures of the Molasse could be locally discerned. An interpretation of the seismic data, within the framework of existent geological knowledge, has contributed to the clarification of some controversial problems. An investigation of the Obersee (Upper Lake) was also carried out. Unfortunatly the apparatus did not send signals of sufficient energy to penetrate beyond the lake bottom, and we were not able to obtain useful geological data there.

This study is a part of the limnogeology project supported by the Geological Institute, ETH, and by the Swiss Nationalfonds. We are indebted to Professor Augusto Gansser for his continued interests and his unfailing support. Dr. J. Kläy and Mr. N. Sieber assisted us in the field. Dr. N. Pavoni kindly provided us with a structural contour map of a Molasse horizon along the shores of Lake Zurich, revised from his 1957 publication. Prof. Dr. R. Hantke read a draft of the manuscript and his suggestions are appreciated.

Tectonics

The Lake Zurich basin is underlain by Molasse and partly filled with Quaternary sediments. The task of unravelling the structures of the flat-lying Molasse beds on the side of the Lake Zurich has not been a simple task. HEIM (1894; 1919, p. 190) postulated a flexure zone south of Horgen-Meilen line, because he assumed the presence of a warped terrace-system along both shores of Lake Zurich. This interpretation, which was shared by his students (e.g., WETTSTEIN, 1885; AEPPLI, 1894; GOGARTEN, 1910), has been proven incorrect by recent detailed investigations (e.g., PAVONI, 1953; RINGGER, 1964).

AEPPLI did recognize the northerly dip of the Käpfnach Brown Coal within the Molasse south of Horgen. He postulated an anticlinal bend along the Au-Männedorf axis and a synclinal trough Wädenswil-Stäfa. The presence of such ENE-trending structures within the Molasse were also recognized by HERBORDT (1907), and by ZINGG (1934), and were finally confirmed, on the basis of drilling through the Brown Coal by VON MOOS (1946). The last author suggested the names Käpfnach-Roten anticline and Wädenswil-Schnebelhorn syncline. He further postulated a more northerly Üetliberg-Schauenberg syncline, with its axis passing through the northern end of the Lake Zurich.

STAUB (1934) rejuvenated the classic idea, once championed by ROTHPLETZ (1884), that the Linth and Lake Zurich Valleys were related to faulting. He postulated faults on both sides of Lake Zurich (STAUB, 1951; 1954). This idea was further developed by BÜCHI (1957) who envisioned the Lake Zurich basin as a down-faulted structural graben. HANTKE (1967) adopted this interpretation for the new geological map of Canton Zurich.

A detailed study of the Molasse geology of Lake Zurich region was carried out by PAVONI (1957). He used mainly two index horizons to construct structural-contour maps, namely

1. Lacustrine Horizon of Zurich Molasse (*limnisches Leitniveau der Zürcher Molasse*), which is locally coaly and lies 210 m above the previously mentioned Käpfnach Coal (PAVONI, 1957, p. 169).

2. "Appenzell granite", which is a quarryman's term for a resistant, dark gray conglomerate horizon (*Hüllisteiner Nagelfluh*) in the Upper Freshwater Molasse, and which has been traced from eastern Switzerland to the right shore of Lake Zurich before the first geological map of Canton Zurich was made (see HEER and ESCHER, 1862, p. 15). The Appenzell granite lies some 150 m under the Lacustrine Horizon.

Pavoni noted that the Käpfnach-Roten anticline, which was renamed Käpfnach-Grüningen anticline, and the Wädenswil-Stäfa syncline have a structural relief of 180 m on the right shore of the Lake Zurich, but only 140 m on the left shore. He postulated a vertically dipping Lake Zurich fault, which leads from Meilen toward Richterswil. The vertical displacement was estimated to range from 30–40 m, and the horizontal offset some 1/2 km.

The structural interpretation of the seismic results are presented in Plate I, Figure A. We assumed that the Molasse beds under the Lake Zurich strike ENE-WSW, as they do on both shores. The dip directions are thus either NNW or SSE, and a choice could be made by examining whether a Molasse reflexion is dipping in, or away from the direction of the ship movement. Plotted on a map, the subaqeous continuations of the Grüningen anticline and of the Stäfa syncline could be seen to extend almost to the left bank of the Lake, where the fold was cut off by the Lake Zurich fault. Incidentally the Grüningen anticline is present approximately at the position where HEIM (1894) postulated a downwarp, which does not exist.

The structural relief north of the Horgen-Meilen line is flat and we were not able to recognize distinct dip-variations within the Molasse. We found no evidence of an anticlinal nose, – the socalled Erlenbach flexure of PAVONI (1957), – under the lake west of Erlenbach. Pavoni himself recognized the uncertainty of that interpretation and has communicated to us personally that an alternative is possible. BÜCHI (1958, p. 22) suggested another graben in the lower Lake basin. We re-interpreted PAVONI's data on the elevation of the Lacustrine Horizon and postulated an ENE-trending synclinal flexure, with a structural relief of some 10 m, in the Kilchberg area on the left shore and the Küsnacht area on the right shore (Pl. I, Fig. A). Farther down near the lower end of Lake Zurich, the Molasse structure is even more uncertain. The Üetliberg syncline on the right shore is indicated by PAVONI's outcrop data, but the relief of this structure is too small to be registered on the seismic record.

Faults and fracture zones, which have been postulated by STAUB, by PAVONI, by BÜCHI and by HANTKE, do exist under the Lake Zurich and their locations could be delineated on the basis of the seismic data. These faults are, however, not normal-, or graben-faults. Instead, the predominant movement has taken place along a strike-slip fault, which will be called the Lake Zurich fault. This fault has been located on the left side in the middle lake basin just off shore from Au, Wädenswil and Richterswil, having brought the distinctly south-dipping beds of the Stäfa syncline in contact with the north-dipping beds of the Wädenswil syncline. Fracture zones are associated with this fault, and additional fractures are present near the center of the middle lake basin. In the lower lake basin, a fault on the right shore just off Meilen has been recognized. We agree with PAVONI that this fault represents the northwest extension of the Lake Zurich fault. We disagree, however, to his postulate that the fault terminated near Meilen. The extension of this fault farther northwest is indicated by the seismic record (see HINZ et al., 1970) and by the offset of the Kilchberg-Küsnacht syncline which has been displaced by about the same amount as the fold in the middle lake basin. The Lake Zurich fault may extend even farther to the northwest and may have offset the Üetliberg syncline near the City of Zurich. Unfortunately the flat dips of the Molasse in the Lower Lake Zurich render a positive identification difficult.

The Lake Zurich fault played a prominent role in determining the present course of the lake. Yet the Lake Zurich basin is not a structural graben, nor is it bounded on both shores by normal faults. More likely, the fault and associated fractures produced zones less resistant to erosion, and thereby localized the present course of the lake basin.

The displacement along the Lake Zurich fault is mainly strike slip, although the offset of fold axes results in apparent vertical displacement. The sense of movement is right-lateral and the amount is approximately one and half kilometers. This Lake Zurich fault has not been identified in the flat-lying Molasse of the Limmat Valley. Nor could the fault be traced to the Subalpine Molasse south of the Lake, where the exposures are poor and geology is complex. However, strike-slip faults with comparable displacement are not uncommon in nearby areas, having been described by TRÜMPY (1969) in the Linth Valley, and suggested by HANTKE and by H. P. MÜLLER (personal communication) in the Biber, the Alp and Sihl Valleys.

The question if the Lake Zurich fault is still active cannot be ascertained. Evidence to be presented later suggests that the Grüningen anticline may have been active during the Quarternary. Since the fault is related to the folding (see PAVONI, 1967, p. 283), it seems probable that the Lake Zurich fault has been active till today and that such movement is responsible for the earthquakes of the Zurich region. Preliminary heat-flow measurements carried out by us in co-operation with the German Geological

Survey yielded unexpectedly high values of 2.2–2.4 $\times 10^{-6}$ cal/cm^2 s (HSÜ, unpublished), and may be explained in terms of heat-flow anomaly along an active fault (see BRUNE et al., 1969). A systematic heat-flow study is being undertaken and may provide further clues.

Topography of Molasse Surface

The topography of the Molasse surface under the Lake Zurich is typically that of a glacially eroded U-valley. The seismic result reveals the presence of a subaqueous Molasse barrier across Wädenswil-Männedorf which divides a simple trough to the north from a valley system to the southeast where the topography on Molasse surface is complex. We suggest the terms lower Lake Zurich and middle Lake Zurich basins for the sake of convenience in this discussion, reserving the term "Upper Lake" for the Obersee above the Pfäffikon-Rapperswil barrier.

That a subsurface barrier exists across Wädenswil–Männedorf has long been surmised: The Middle Lake is relatively shallow, having a water depth ranging from about 20 m at the upper end to about 30 m some 8 km down stream at Wädenswil-Stäfa line. Then the gradient increases sharply, and the Lake deepens by more than 80 m within $2^1/_2$ km. Farther down in the lower lake the water depth increases very gradually to about a maximum of about 143 m at Oberrieden-Herrliberg area, before shoaling toward the City of Zurich. This fact did not escape AEPPLI (1894, p. 111).

He postulated the presence of a subqueous moraine between Wädenswil and Männedorf, which supposedly trapped the sediments transported by density underflows. STAUB (1938) also noticed the abrupt bathemetrical change. He assumed that a dead ice mass existed: the part above the barrier near Stäfa melted much earlier, leaving the middle lake silted by outwash sediments. RINGGER (1964, p. 103) questioned AEPPLI's endmoraine interpretation, because there are no corresponding side-moraines on either shore at this place. He suggested, as proven correct by the seismic record, that the barrier owes its presence to resistant Molasse beds.

A contour map of subsurface molasse topography has been made and is shown by Plate I, Figure B[1]). This topography is a manifestation of the varying depth of glacial erosion. From the correlation of the profiles, we discovered that the middle lake basin consists of a number of parallel troughs separated by narrow ridges (Pl. I, Fig. B). Four systems have been distinguished, representing four generations of glacial erosion. In several profiles, for example, Wädenswil–Ramenstein (18–19), the successive erosional surface could be easily recognized. In a few, namely Mülenen–Stäfa (20–21), some uncertainty exists. The interpretated profiles of the middle lake basin are shown by Figure 1.

We have named the trough systems, Z-1, Z-2, Z-3 and Z-4 respectively. The two earlier troughs occupied more northeasterly position than the two later ones. All the four systems converge in the "sill area" at Wädenswil–Männedorf, so that the profile 16–17 shows only one trough, but apparently four levels of erosion (Fig. 1). The „sill area" coincides almost exactly with the axis of the Grüningen anticline. Farther down in the lower lake basin a simple U-shaped trough underlies the Quaternary

[1]) The depth-contours of the Molasse floor at the lower end of the Lake north of Rüschlikon-Küsnacht should be deeper than that shown on Plate I B, now that HINZ et al. (1970) recognized a 0.3″-reflector as the Molasse Valey floor there.

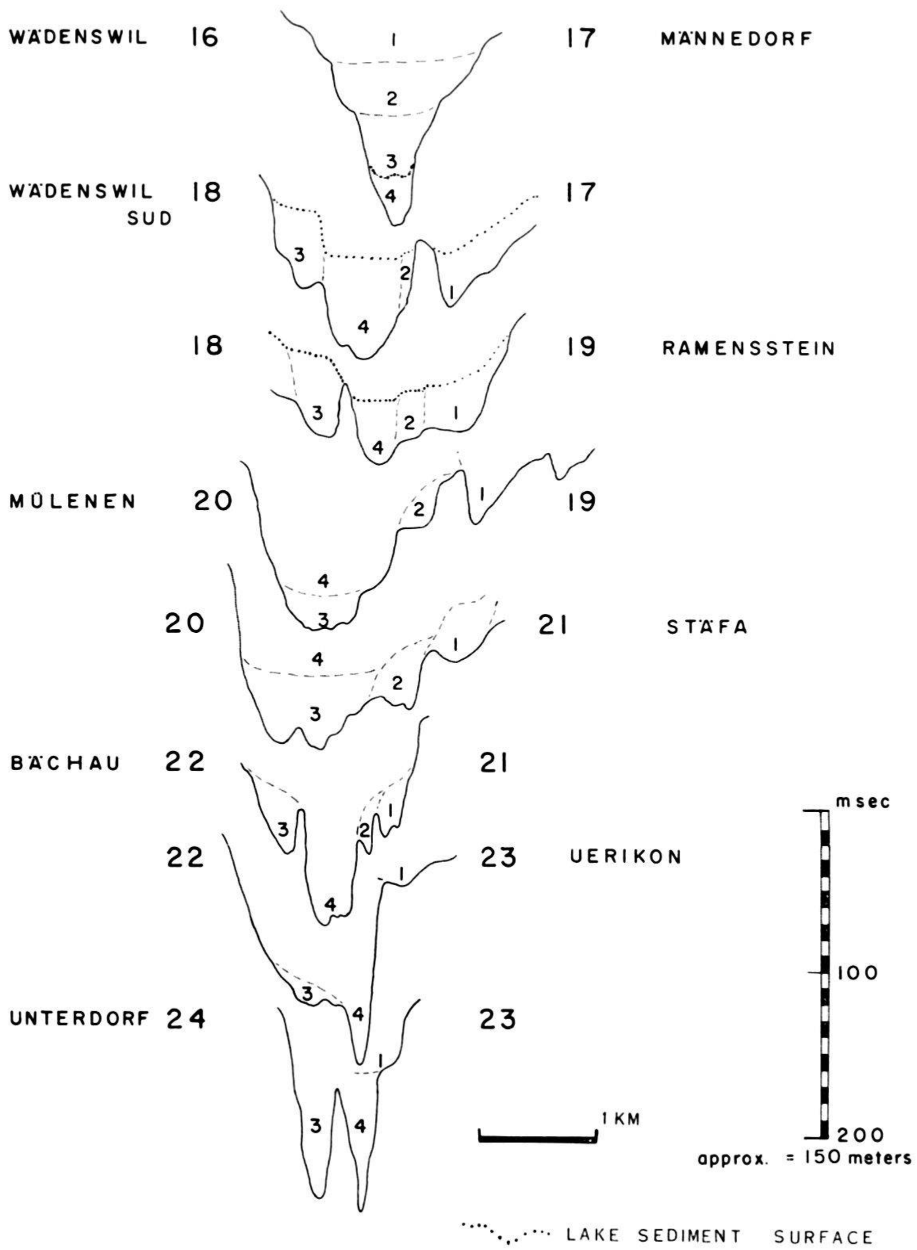


Fig. 1. Seismic cross sections in the Middle Lake Zurich area. The numbers 1, 2, 3, 4 represent the glacial valley systems Z-1, Z-2, Z-3, Z-4. The vertical exaggeration is about 1:10. Dashed lines are reflectors which may represent partially eroded, earlier deposits.

sediments, although both the Au-Uetikon (14–15) and the Horgen–Meilen (12–13) profiles indicate the presence of a higher trough on the right side (Fig. 2).

The erosional depth of the various troughs was probably influenced by two factors: 1. the growth of structures, 2. the weakening of resistance to erosion along fracture zones.

The very uneven Molasse topography under the middle Lake basin could well be related to the folding of the area: The profiles near the anticlinal axis (16–17, 17–18, 18–19) indicate that the Z-4 trough cut considerably deeper into the older troughs, while those near the synclinal axis (19–20, 20–21) show that the Z-4 trough widened itself and did not cut as deep as the Z-3 valley. Furthermore, it is noteworthy that the profiles across the lower lake basin, which is a structural depression, show little evidence of progressively deeper erosion. On the contrary, as the Horgen–Meilen profile (12–13) shows, younger valleys of the lower lake basin probably did not cut as deeply as the older ones, so that the older sediments were partly preserved below erosional unconformities (Fig. 2). This pattern is consistent with the postulate of antecedent erosion across an actively growing fold. We believe therefore, that the Grüningen anticline underwent an episode of active growth while the Lake Zurich basin was being eroded, especially between the erosional stages Z-3 and Z-4. That tectonic activities took place during the Pleistocene has been established by HANTKE (1959a, p. 18) based upon his studies of terrace deposits around and near Lake Zurich.

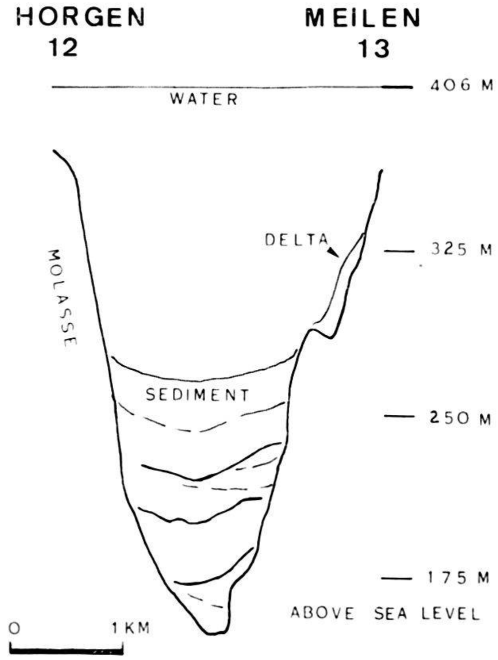


Fig. 2. Seismic profile traced directly from record. Vertical exaggeration is about 1:10. Solid lines may represent erosional disconformities.

Unfortunately a glacially eroded valley does not necessarily have a gradient sloping downstream everywhere; over-steepening is more a rule than an exception. The longitudinal profile of an ancient glacial valley cannot be used to unravel structural growth. Although the trough systems Z-3 and Z-4 reach their maximum depth at the synclinal area, the older troughs have been apparently over-steepened farther down. We did note, however, that all the troughs cut deepest into the Molasse where their axis coincides with the Lake Zurich fault, or with a fracture zone. We believe that the reduced erosional resistance there played an important role in causing over-steepening.

The troughs, issuing from the Rapperswil-Hurden gap, took first a ENE–WSW course, approximately parallel to the strike of the Molasse beds, and along some less resistant intervals. Parallel hogback ridges, with exhumed dip-slopes, are clearly shown by the longitudinal seismic profile, separating three trough systems (HINZ et al., 1970). All the troughs turn sharply to the northwest just before they reach the Stäfa syncline.

The cause of the sharp bend of Lake Zurich has been a matter of speculation. AEPPLI (1894, p. 102) postulated that the ancestral Sihl Valley occupied the present course of Lake Zurich, when the Linth was flowing down the Glatt Valley. Later the Sihl found the present course to the left, and the Lake Zurich basin was captured by the Linth system. HANTKE (1961) further developed this interesting idea, which however cannot be confirmed by our seismic investigation. All the troughs that can now be recognized, including the earliest Z-1, have apparently been a part of the Linth system.

The age of the four trough systems cannot be ascertained. They could hardly be construed to represent the four classical glacial stages postulated by PENCK and BRÜCKNER (1908). Vestiges of earliest glaciation are rare and questionable in the vicinity of Zurich, where the moraines and associated sediments are mainly the product of the last glaciation (SUTER and HANTKE, 1962, p. 80). These moraines were already recognized and mapped by ESCHER (see KELLER, 1843, map). Later HUG (1917) distinguished three glacial stands during the Würm glaciation in the lower Lake Zurich and Limmat Valley region: Killwangen Stadium, Schlieren Stadium, and Zurich Stadium. These stands, with additional minor readvances, are now well established (e.g., JÄCKLI, 1956, 1959; HANTKE, 1959, 1963; SCHINDLER, 1968), although some dissenters still disputed the relative chronology (e.g., KNAUER, 1938; ANNAHEIM et al., 1958). The trough system in the middle lake basin may eventually be correlated – at least in part – to these Würm stages.

The presence of Riss/Würm interglacial lacustrine deposits in the Limmat Valley indicates that the Lake Zurich basin originated before the Würm glaciation (HANTKE, 1959; SCHINDLER, 1968). The age of the lower lake basin, as computed from sedimentation rate (see p. 534) supports this conclusion. It is indeed probable that the deepest incision there took place during the Riss glaciation. The Würm glaciers did not erode sufficiently deep to clean out the lacustrine clays which were accumulated in the lower lake basin during the Riss/Würm interglacial time. Only in the uplifted parts of the middle lake basin were the interglacial deposits partly or completely removed by the Würm glaciers. The possibility is thus not excluded that the earliest trough or troughs there (Z-1, or Z-1 plus Z-2) outline the course of the Riss glacier.

A correlation of erosional stages in the middle lake basin to the depositional stages on the shores of Lake Zurich is not impossible. The sequence of interlayered sands and clays identified by the seismic record offshore from Wädenswil (see HINZ et al., 1970) is probably the subaqueous extension of the "Reidbach delta-deposits" described by AEPPLI (1894, p. 71). This subaqueous delta bottom-set deposit filled part of the trough Z-3 and has been eroded by the trough Z-4. Unfortunately the chronology of the terrace deposits of the Lake Zurich is uncertain. The Reidbach deposits were mapped by HANTKE (1961) as a part of "Frühwürmschotter", although recent C^{14}-dates prove that the age of the terrace gravels has been locally overestimated. For example, the "Mitterrterassenschotter" at Buechburg near Wangen was once thought pre-Würm (JEANNET, 1923; BECK, 1933), but has been dated to be around 30000 to 40000 years old by C^{14}-method (KLÄY, 1969). My colleague, R. HANTKE, is working on the problem of the chronology of those terrace gravels. He may come up with a scheme to correlate the erosional stages within the middle lake basin with the depositional stages on the shores of Lake Zurich.

Sediments of Lake Zurich

The sediments of Lake Zurich are presumably all Quaternary. The contrasting acoustical behaviors between the sediments of the middle and of the lower lake basins manifest their different origins.

The lower lake basin sediments are mainly acoustically transparent, which is a behaviour typical of unconsolidated clays or marls. It reaches a maximum thickness of some 120 m just about where the lake is deepest in the Oberrieden-Herrliberg area.

A very prominent set of reflectors at 55–56 m interval below the lake bottom is present in the Meilen area (between position 39 and 40 on the longitudinal profile; HINZ et al., 1970). An overlying reflector is identified at 25 m subbottom. Sedimentological investigations revealed that the area offshore from Meilen has been a site for recurrent turbidity-current deposition. Numerous thin-bedded sands with graded bedding have been recovered by coring, which penetrates 6 meters deep below the surface (KELTS, 1969). We believe, therefore, that the multiple reflectors of the Meilen area are turbidite-sands, which represent the bottom-set deposits of ancestral Meilen deltas. Less prominent but correlative reflectors offshore from Küsnacht are presumably similar turbidites at the foot of ancestral Küsnacht and Erlenbach deltas.

The stratigraphy of the middle lake basin sediments is complex, as indicated by the history of multiple erosion there. Taking the Wädenswil-Rämenstein profile (18–19) for example, we noted that the sediments filling the troughs Z-1, Z-2 and Z-4 are mainly transparent, which are probably lacustrine marls. Yet the sediments filling the trough Z-3 are multiple reflectors and are probably a subaqueous extension of the Reitbach terrace-gravels. The possibility that there have been three of four generations of lacustiine clays in the middle lake basin implies that the Linth glacier may have retreated and *readvanced* a number of times through the Lake Zurich during the last glaciation, and interstadial clays were deposited between stages of readvances. That such interstadial lakes existed is suggested by KLÄY (1969), based on his interpretation of the subsurface data from a Linth-Plain well near Tuggen (BRAUN, 1925), where two generations of lacustrine marls are separated by a latest Würm moraine.

The bulk of the sediments of the middle lake basin fills the trough Z-4. These youngest sediments include the multiple reflectors of the longitudinal seismic profile (HINZ et al., 1970). The sequence, which has a maximum thickness of about 120 m in the Wädenswil syncline area, presumably consists of sand and gravel layers, with interstratified clays. These coarse deposits in front of the Hurden-Rapperswil moraine were probably laid down during the last glacial stand (Hurden Stadium) in the Lake Zurich region; they occupy a similar position as the fluvio-glacial deposits of the Limmat Valley in front of the Killwangen, Schlieren and Zurich moraines (see SCHINDLER, 1968). Coarse gravels and sands were encountered in the boreholes of the Hurden-Rapperswil area and have been considered bottom-set deposits of a fluvioglacial delta (VON MOOS, 1943, Fig. 2). The farther transport of coarse debris several kilometers down the middle lake basin probably took place in the form of turbidity underflows. These consideration led us to postulate that the multiple-reflectors of the middle lake basin are largely turbidity-current deposits, genetically similar to those in Lake Geneva (see HOUBOULT and JONKER, 1968). The Wädenswil-Männedorf rock-bar has served as a barrier to obstruct turbidity underflows. Consequently the longitudinally transported turbidites were limited mainly to the middle lake basin, whereas the lower lake basin sediments are largely pelagic except for some turbidites derived from the right and left shores.

The thickness of the late Pleistocene and Holocene sediments under the lake bottom is shown by Plate I, Figure C. Two centers of maximum deposition are 1. the middle part of the lower lake basin and 2. the synclinal part of the middle lake basin. The area of minimum sediment-accumulation is in the anticlinal area. Such a pattern of sediment-distribution is consistent with our postulate of syntectonic sedimentation.

The sediment-thickness permit us to make a rough estimate of the age of the Lake Zurich basins. Of the 120 m thick sequence in the deepest part of the lower lake basin, 8 meters of sediments have been penetrated by coring (ZÜLLIG, 1956). The cored sediments are mainly marls and marly chalk (*Seekreide*, with 40% or more $CaCO_3$). Only a few thin sandy layers were intercalated. The oldest sediment at 8 m depth has been dated by LÜDI (1957) as early Dryas time before the Alleröd Stadium, and some 7.6 m of sediments have been deposited since the beginning of Alleröd at about 12000 years before present. This gives an average sedimentation rate of 0.63 mm/yr. At this rate, some 200000 years would be required to accumulate the 120 m thick sequence. Furthermore, those years should represent accumulative span of some interglacial and interstadial intervals, because lacustrine sedimentation could only have taken place between glacial advances. The duration of the last major glaciation (Würm) was about 150000 years, with interstadial intervals of the order of a few tens of thousand years (ERICSON and WOLLIN, 1968). The bulk of the sediments in the lower lake basin must, therefore, be deposited during the last major interglacial stage (Riss-Würm), which had a duration of approximately 200000 years (ERICSON and WOLLIN, 1968). This would date the last erosion of the lower lake basin floor as the work of Riss glaciers. This conclusion coincides with the interpretation of Quaternary geologists that the alpine valleys were over-steepened and earlier deposits were cleaned out during the Riss glaciation (SUTER and HANTKE, 1962), for which HANTKE has additional arguments. The sedimentary record, combined with ERICSON and WOLLIN's chronology for the duration of Würm, thus dates the lower lake basin as 350000 years B.P. at the beginning of the Riss-Würm interval. Incidentally, the results of dating deep-sea cores in the Pacific and Atlantic by Th^{230}-method also gave a 300000 to 350000 years B.P. age as the beginning of the last major (presumably Riss-Würm) interglacial interval (KU and BROECKER, 1966; GEITZENAUER, 1969).

The maximum sediment thickness of the middle lake basin is more than 100 m, or just slightly less than that of the lower lake basin. However, these sediments are in part transparent and in part multiple-reflectors, filling the various trough systems. Since this sequence must include considerable coarse clastics, deposited at a much greater rate than lacustrine marls, we cannot apply the 0.63 mm/yr rate to calculate the age of the valleys. We have as yet not dated any long core from the middle-lake basin, and the age of this last stage of glacial erosion can only be speculated upon. We have postulated that sediments began to accumulate in this youngest valley system after the Zurich Stadium. SCHINDLER (1968) placed the timing as somewhere between 17000 years B.P., when the ice still stood by Zurich, and 8000 years B.P. when inner alpine valleys became free of ice. In fact, NEHER and HANTKE (pers. comm.) suggested that the valleys became icefree much earlier, probably at 10000 B.P. when the Rhine glacier left definitionely the Schams Valley.

Suppose we assume that the 100 m plus sediments in the Z-4 valley were deposited during the 12000 years since the Alleröd time, the sedimentation rate would be almost 1 cm/yr, or more than 10 times greater than the rate of lacustrine marl accumulation in the lower lake basin. This fast rate is not surprising, as the sand layers of the middle lake basin were probably deposited by turbidity underflows when the glaciers stood nearby. In fact, deposition of turbidite sands in Lake Constance at the mouth of the Rhine proceeded at an even greater rate of several centimeters per year (FÖRSTNER et al., 1968).

Origin of Lake Zurich

The seismic data do not lend support to the specific hypothesis advanced by HEIM (1894) that Lake Zurich was a fluviatile valley drowned by subsidence along Wädenswil-Männedorf axis. Neither the structure of the Molasse nor that the Quaternary lake sediments is synclinal in the area of postulated downwarp. On the contrary, we find there the prolongation of the Grüningen anticline, which may have been recurrently uplifted during the Quaternary.

The generally accepted theory by PENCK and BRÜCKNER receives further confirmation: The morphology of the basement under the lake is typically that of a glacially eroded valley. The Molasse under the middle lake basin has a considerable relief, reaching to more than 120 m below the lake level along some deeply eroded channels. Oversteepening of a few tens of meters has been observed within a course of less than 10 km. The basement of the lower lake basin has been shaped into single trough, with U-shaped profiles. The trough bottom is relatively flat, except for two rock-bars across the valley near Oberrieden (see HINZ et al., 1970). Much of the trough bottom lies some 200 m below the lake level. The maximum of depth of the lake basin is 260 m in the Oberrieden-Herrliberg area (between pos. 41 and 42) at about 145 m above sea-level.

The apparent over-steepening of the lower lake basin is impressive. From the nadir of 145 m near Oberrieden, the Molasse basement rises rapidly to 245 m elevation 5 km downstream. The negative gradient is thus 2% and the radius of curvature only 1500 m. The Molasse basement near Schlachthof Zurich has been reached by drill at 278 m elevation (SCHINDLER, 1968). Farther down the Limmat near Baden, the Molasse basement rises to 330 m above sea level (SUTER, 1944). This represents a total apparent over-steepening of 185 m.

Glacially over-steepened valleys are not uncommon. Seismic investigations showed that the Gorner Glacier under Monte Rosa, for example, has been over-steepened at its juncture with two tributaries (BEARTH, 1953). The over-steepening has been enhanced by abrupt gradient changes. Yet the total over-steepening was not more than 100 m within a course of some 5 km. The remarkable over-steepening of the lower Lake Zurich basin is, in fact, of about the same magnitude, where the condition was far less favorable.

NYE and MARTIN (1968) treated the problem theoretically and came to the conclusion that there is a limit to the longitudinal concavity of a glacially eroded bed. Assuming a perfectly plastic glacier moving over an irregular bed in a nearly horizontal direction, they believe that the curvature represents the envelope of slip lines (α-lines). Solving for the radius of curvature quantitatively as a two dimensional problem, they found that the minimum radius of curvature under a thick ice should not be smaller than four times the thickness of the ice cover. The Riss glacier must have been more than 750 m thick, as the Riss moraine is present on the Albis Ridge west of Lake Zurich at about 900 m, (namely about 750 m above the rock floor of Lake Zurich, see HANTKE, 1967). Accepting the theory of NYE, the radius of curvature of an over-steepened Lake Zurich basin should not be smaller than 3000 m, four times the ice thickness. Yet the minimum radius of curvature between position 41 and 42 (near Oberrieden) is only 1500 m, and that just below the Wädenswil-Männedorf rock-bar is 2000 m. In other words, the estimated minimum radius of curvature, of the Lake Zurich rock floor is about half, or the maximum concavity is about twice, as large as that one expects from over-steepening by glacial erosion. It is possible that the lower basin might have been warped tectonically after it was carved out by the Riss glaciers, and that the apparent oversteepening is caused only in part by glacial erosion. On the other hand, the theoretical computations were based upon several simplifying assumptions, and the discrepancy between the computed and observed values is not sufficiently large to warrant a definitive conclusion.

Finally the question if the origin of Lake Zurich is related in anyway to a dead ice mass cannot be resolved. We would like to point out, that the Wädenswil-Männedorf transverse rock-bar served as a sediment-trap, and may have effectively prevented the silting of the lower lake basin. This fact, in addition to the possibility of tectonic deepening, renders the dead-ice postulate by STAUB superfluous.

Summary

The seismic investigation of the Lake Zurich basin led us to the following conclusions:

1) The lake basin has been sculptured by glacial erosion.

2) The course of the lake is apparently related to weakened resistance along the Lake Zurich fault, which is a right-lateral strike slip fault, with some $1^1/_2$ km displacement, although this fault cannot be traced to the land areas.

3) The middle lake basin has been traversed by several trough systems, resulting from several generations of glacial advances. This basin is separated from the lower basin by the Wädenswil-Männedorf transverse rock-bar.

4) The lower lake basin is a simple trough with U-shaped profiles. The concavity of the longitudinal profile is an expression of oversteepening by glacial erosion. The

possibility that the curvature has been accentuated by late Quarternary subsidence cannot be excluded.

5. The thickest section observed of the lower lake basin is 120 m. These sediments may have been accumulated mainly during a 200000 year Riss/Würm interglacial interval.

6. The Wädenswil-Männedorf rock-bar is an efficient sediment-trap to prevent the silting of the lower lake basin by fluvioglacial sediments; it is not necessary to postulate that the origin of alpine lakes is related to dead ice bodies.

REFERENCES

AEPPLI, A. (1894): *Erosionsterrassen und Glacialschotter in ihrer Beziehung zur Entstehung des Zürichsees.* Beitr. geol. Karte Schweiz, N.F. *4*, 117 pp.

ANNAHEIM, H., BÖGLI, A., and MOSER, S. (1958): *Die Phasengliederung der Eisrandlagen des würmeiszeitlichen Reussgletschers im zentralen schweizerischen Mittelland.* Geogr. Helv. *13*/3, 217–231.

BECK, P. (1933): *Über das schweizerische und europäische Pliozän und Pleistozän.* Eclogae geol. Helv. *26*, 335–437.

BRAUN, L. (1925): *Erster–sechster geologischer Bericht über die Tiefbohrung in Tuggen (Kt. Schwyz), 17.–28. August 1925.* Manuskr. dep. Schweiz. Geotechn. Komm. Zürich.

BRUNE, J., HENYEY, T., and ROY, R. (1969): *Heat Flow, Stress and Rate of Slip Along the San Andreas Fault, California.* Jour. Geoph. Res. *74*, 3821–3827.

BÜCHI, U. P. (1958): *Geologie der oberen Süsswassermolasse (OSM) zwischen Reuss und Glatt.* Bull. Ver. schweiz. Petrol. Geol. und Ing. *25*, 5–24.

ERICSON, D., and WOLLIN, G. (1968): *Pleistocene Climates and Deep-sea Core Chronology.* Science *162*, 1227.

FORSTNER, U., MÜLLER, G., and REINECK, H. E. (1968): *Sedimente und Sedimentgefüge des Rheindeltas im Bodensee.* N. Jb. Miner. Abh. *109*, 33–62.

GEITZNAUER, K. R. (1969): *Coccoliths as Late Quaternary Palaeoclimatic Indicators in the Subantarctic Pacific Ocean.* Nature *223*, 170–172.

GOGARTEN, E. (1910): *Über alpine Randseen und Erosionsterrassen im besondern des Linthtales.* Dr. A. Petermanns Geographische Mitteilungen, Heft 1965, 77 pp.

HANTKE, R. (1959a): *Zur Altersfrage der Mittelterrassenschotter.* Vjschr. Naturf. Ges. Zürich *104*/1.

– (1959b): *Zur Phasenfolge der Hochwürmeiszeit des Linth- und des Reuss-Systems.* Vjschr. Naturf. Ges. Zürich *104*/Schluss.

– (1961): *Zur Quartärgeologie im Grenzbereich zwischen Muota/Reuss- und Linth/Rheinsystem.* Geographica Helv. *26*/4, 212–222.

– (1963): *Chronologische Probleme im schweizerischen Quartär.* Jber. u. Mitt. oberrh. geol. Ver. N.F. *45*, 45–60.

HEIM, A. (1894): *Die Geologie der Umgebung von Zürich.* Internat. Geol. Congress, 181–197.

– (1919): *Geologie der Schweiz.* Bd. I (Leipzig, Tauchnitz), 704 pp.

HEER, O., and ESCHER, A.: *Übersicht der Geologie des Kt. Zürich.* Neujahrsbt. an die zürcherische Jugend auf das Jahr 1862. Naturf. Ges. Zürich *64*, 33 pp.

HINZ, K., RICHTER, I., and SIEBER, N. (1970): *Reflexionsseismische Untersuchungen im Zürichsee.* Eclogae geol. Helv. *63*/2.

HERBORDT, O. (1907): *Geologische Aufnahme der Umgebung von Rapperswil und Pfäffikon am Zürichsee.* Diss. Univ. Zürich, 38 pp.

HOUBOLT, J., and JONKER, J. (1968): *Recent Sediments in the Eastern Part of the Lake of Geneva (Lac Léman).* Geologie en Mijnbouw *47*/2, 131–148.

HUG, J. (1907): *Die letzte Eiszeit im nördlichen Teil des Kantons Zürich.* Diss. Univ. Zürich, 97 pp.

– (1917): *Die letzte Eiszeit der Umgebung von Zürich.* Vjschr. Naturf. Ges. Zürich *62*, 125–142.

JÄCKLI, H. (1956): *Talgeschichtliche Probleme im aargauischen Reusstal.* Geogr. Helv. *11*/I.

– (1959): *Wurde das Schlieren-Stadium überfahren?* Geogr. Helv. *14*/2.

– (1962): *Die Vergletscherung der Schweiz im Würmmaximum.* Eclogae geol. Helv. *55*/2.

Jeannet, A. (1922): *Schieferkohlen zwischen Walensee und Zürichsee*. Nachtr. zu Heim, Alb.: Geologie der Schweiz 2/2, Leipzig, Tauchnitz: 897–901.

Kelts, K. (1969): *Recent Sediments in Lake Zurich between Horgen and Meilen*. Dipl. Arb. ETH Zürich, Manuskr. 82 pp.

Kläy, R. (1969): *Quartärgeologische Untersuchungen in der Linth-Ebene*. Diss. Geol. Inst., ETH Zürich (Zimmermann, P., Uster), 87 pp.

Knauer, J. (1938): *Über das Alter der Moränen der Zürich-Phase im Linthgletscher-Gebiet*, Abh. geol. Landes. Bayer. Oberbergamt *33*, 1–25.

Ku, T. L., and Broecker, W. S. (1966): *Atlantic Deep-sea Stratigraphy Extension of Absolute Chronology to 320000 Years*. Science *151*, 448.

Ludi, W. (1957): *Ein Pollen-Diagramm aus dem Untergrund des Zürichsees*. Schweiz. Zeitschr. Hydrolog. *19*, 523–565.

Von Moos, A. (1943): *Zur Quartärgeologie von Hurden-Rapperswil (Zürichsee)*. Eclogae geol. Helv. *36*/1, 125–137.

– (1946): *Die Kohlebohrungen von Sihlbrugg (Kt. Zürich) und die Molassestrukturen um Zürich*. Eclogae geol. Helv. *39*/2, 244–254.

Müller, G., and Gees, R. (1968): *Erste Ergebnisse reflexionsseismischer Untersuchungen des Bodensee-Untergrundes*. N. Jb. Geol. Paläont. Mh. *6*, 364–369.

Nye, J. F., and Martin, P. C. S. (1968): *Glacial Erosion*. Int. Union of Geod. and Geoph. (IUGG), Commission of Snow and Ice, Publ. *79*, 78–86.

Pavoni, N. (1953): *Die Rückläufigen Terrassen am Zürichsee und ihre Beziehungen zur Geologie der Molasse*. Geographica Helv. *3*, 217–226.

– (1957): *Geologie der Zürcher Molasse zwischen Albiskamm und Pfannenstiel*. Vjschr. Naturf. Ges. Zürich *105*/5, 315 pp.

Penck, A., and Brückner, E. (1909): *Die Alpen im Eiszeitalter*, Bd. *2* (Tauchnitz, Leipzig), 716 pp.

Ramsay, A. C. (1862): *On the Glacial Origin of Certain Lakes in Switzerland, the Black Forest, Great Britain, Sweden, N. America and Elsewhere*. Quart. Jour. Geol. Soc. London *18*, 185–204.

Ringger, H. (1964): *Die Terrassen im Zürichseetal und ihre morphologische Deutung*. Diss. Univ. Zürich, Geographie (Jäggli, Winterthur), 130 pp.

Rothpletz, A. (1883): *Zum Gebirgsbau der Alpen beiderseits des Rheins*. Zeitschr. deutsch. Geol. Ges. *176*, 134–189.

Schindler, C. (1968): *Zur Quartärgeologie zwischen dem untersten Zürichsee und Baden*. Eclogae Geol. Helv. *61*/2, 395–433.

Schmidle, W. (1911): *Zur Kenntnis der Molasse und der Tektonik am nordwestlichen Bodensee*. Deutsch. geol. Ges. *63*/4, 523–551.

– (1931): *Die Geschichte der geologischen Erforschung des Bodensees*. Badisch. geol. Abhand. *3*/2, 1–95.

Staub, R. (1938): *Prinzipielles zur Entstehung der alpinen Randseen*. Eclogae geol. Helv. *31*/2, 239–258.

– (1951): *Über die Beziehungen zwischen Alpen und Apenninen und die Gestaltung der alpinen Leitlinien Europas*. Eclogae geol. Helv. *44*/1, 29–130.

Suter, H. (1944): *Glazialgeologische Studien im Gebiet zwischen Limmat, Glatt und Rhein*. Eclogae geol. Helv. *37*/1, 83–97.

Suter, H., and Hantke, R. (1962): *Geologie des Kantons Zürich* (Leemann, Zürich), 172 pp.

Wettstein, A. (1885): *Geologie von Zürich und Umgebung* (Wurster Verlag, Zürich), 84 pp.

Zingg, Th. (1934): *Erläuterung zu Blatt 7, Mönchaltorf–Hinwil–Wädenswil–Rapperswil*. Geol. Atlas d. Schweiz.

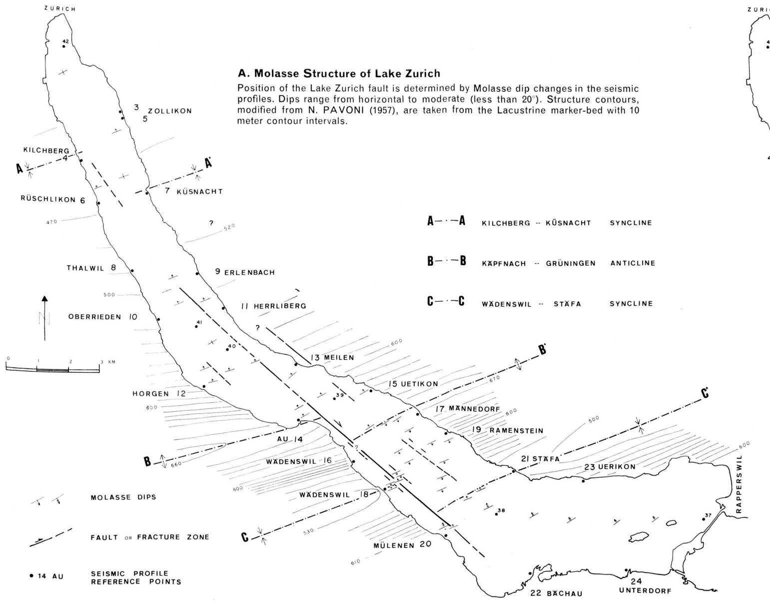
Züllig, H. (1956): *Sedimente als Ausdruck des Zustandes eines Gewässers*. Schweiz. Z. Hydrologie *18*, 487–529.

MAPS

Bearth, P. (1953): *Geologischer Atlas der Schweiz, Sheet 535, Zermatt, 1:25000, with explanation*. Schweiz. Geol. Komm.

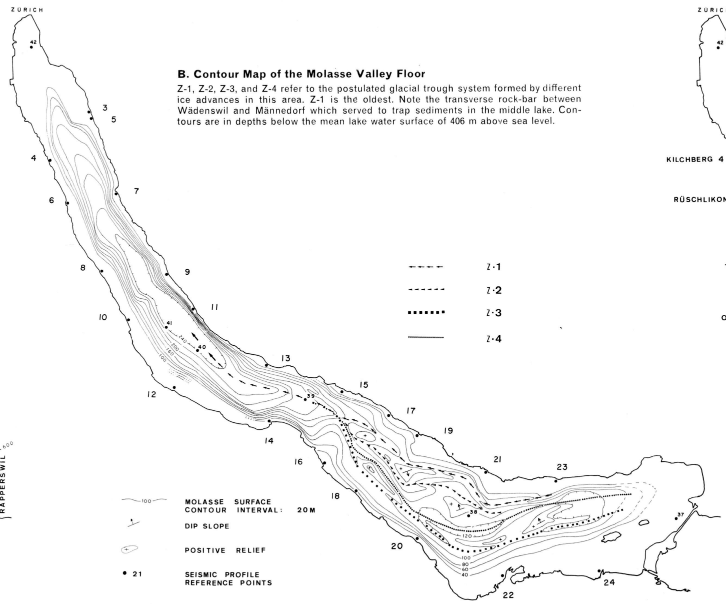
Hantke, R., and Assistants (1967): *Geologische Karte des Kantons Zürich und seiner Nachbargebiete, 1:50000*. Leemann, Zürich.

Keller, H. C. H. (1843): *Geologische Karte des Kantons Zürich, 1:250000*. Gezeichnet und herausgegeben von H. C. H. Keller.



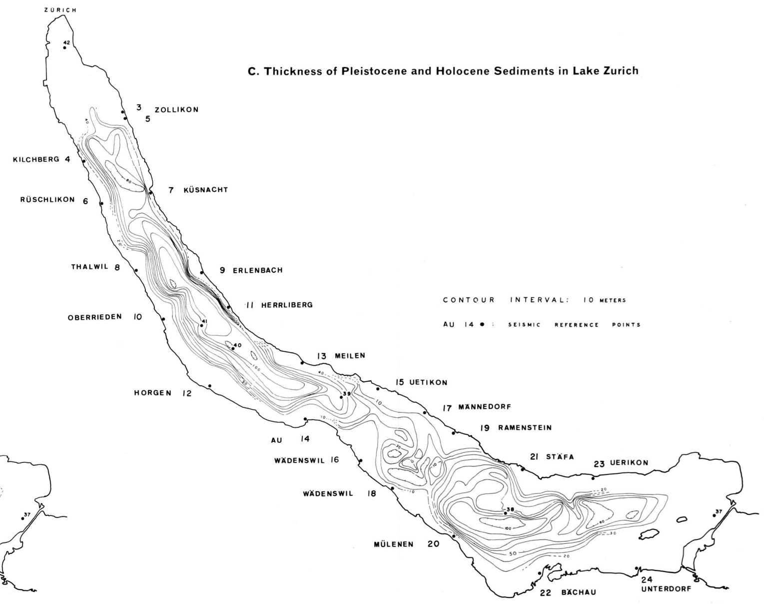
A. Molasse Structure of Lake Zurich

Position of the Lake Zurich fault is determined by Molasse dip changes in the seismic profiles. Dips range from horizontal to moderate (less than 20°). Structure contours, modified from N. PAVONI (1957), are taken from the Lacustrine marker-bed with 10 meter contour intervals.



B. Contour Map of the Molasse Valley Floor

Z-1, Z-2, Z-3, and Z-4 refer to the postulated glacial trough system formed by different ice advances in this area. Z-1 is the oldest. Note the transverse rock-bar between Wädenswil and Männedorf which served to trap sediments in the middle lake. Contours are in depths below the mean lake water surface of 406 m above sea level.



C. Thickness of Pleistocene and Holocene Sediments in Lake Zurich