Zeitschrift: Eclogae Geologicae Helvetiae

Herausgeber: Schweizerische Geologische Gesellschaft

Band: 80 (1987)

Heft: 1

Artikel: Earthquake and seiche deposits in Lake Lucerne, Switzerland

Autor: Siegenthaler, Christoph / Finger, Willi / Kelts, Kerry

DOI: https://doi.org/10.5169/seals-165993

Nutzungsbedingungen

Die ETH-Bibliothek ist die Anbieterin der digitalisierten Zeitschriften auf E-Periodica. Sie besitzt keine Urheberrechte an den Zeitschriften und ist nicht verantwortlich für deren Inhalte. Die Rechte liegen in der Regel bei den Herausgebern beziehungsweise den externen Rechteinhabern. Das Veröffentlichen von Bildern in Print- und Online-Publikationen sowie auf Social Media-Kanälen oder Webseiten ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Mehr erfahren

Conditions d'utilisation

L'ETH Library est le fournisseur des revues numérisées. Elle ne détient aucun droit d'auteur sur les revues et n'est pas responsable de leur contenu. En règle générale, les droits sont détenus par les éditeurs ou les détenteurs de droits externes. La reproduction d'images dans des publications imprimées ou en ligne ainsi que sur des canaux de médias sociaux ou des sites web n'est autorisée qu'avec l'accord préalable des détenteurs des droits. En savoir plus

Terms of use

The ETH Library is the provider of the digitised journals. It does not own any copyrights to the journals and is not responsible for their content. The rights usually lie with the publishers or the external rights holders. Publishing images in print and online publications, as well as on social media channels or websites, is only permitted with the prior consent of the rights holders. Find out more

Download PDF: 27.04.2026

ETH-Bibliothek Zürich, E-Periodica, https://www.e-periodica.ch

Eclogae geol. Helv.	Vol. 80	Nr. 1	Pages 241–260	Basle, April 1987

Earthquake and seiche deposits in Lake Lucerne, Switzerland

By CHRISTOPH SIEGENTHALER[1]), WILLI FINGER[2]), KERRY KELTS[1]), and SUMIN WANG[3])

ABSTRACT

Large slump deposits occur within well-layered Late Quaternary sediments from separate basins of Lake Lucerne. These comprise wedges of contorted and deformed lake sediments and their upper surface is generally smooth. Slump deposits found in the central basin plain areas are often overlain by massive, muddy homogenites, commonly with a few thin sand laminae at their base. 3.5 kHz seismic and piston coring investigation of these deposits and a correlation with historical chronicles of the region suggests that at least the two most prominent ones which could be sampled by piston coring have resulted from strong, local earthquakes and that the large slumps caused seiches with possibly large amplitude: during the 1601 events, these reached 1–2 m. The slumps flowed rapidly down steep slopes in a liquified state, and were accompanied by slower-moving suspension clouds which were augmented by the slump and possibly resuspension of bottom sediments by the concomitant seiche movements. The dimensions of the large slump deposits and their overlying homogenite beds, as mapped using the 3.5 kHz records, seem to reflect the magnitude of the causal earthquakes.

ZUSAMMENFASSUNG

In den Becken des Vierwaldstättersees sind grosse Rutschmassen in die gut geschichteten postglazialen Seesedimente eingeschaltet. Diese Rutschmassen bestehen aus gefalteten und zerscherten Seesedimenten, die Oberfläche ist glatt und eben. In den tieferen Beckenteilen wurden zudem homogene massige Schichten aus siltigem Ton oder tonigem Silt abgesetzt, oft mit einzelnen Sandlaminae an der Basis. Diese Homogenite überlagern dabei an scharfer Grenze diejenigen Rutschungen, welche bis ins Beckeninnere vorgestossen sind. Mit Sedimentkern-Entnahmen und mit seismischen Aufnahmen (3,5 kHz) konnten einige Rutschkörper in einzelnen Teilbecken des Vierwaldstättersees miteinander korreliert und zudem mit lokalen Erdbeben in Verbindung gebracht werden. Auf Grund der genauen historischen Aufzeichnungen über das Erdbeben von 1601 postulieren und belegen wir die folgende erdbebenbedingte Ereignisabfolge im Vierwaldstättersee: Durch das Beben wird in einem Becken eine subaquatische Rutschung ausgelöst, die mit grosser Geschwindigkeit abfliesst und sowohl eine Seiche wie eine feinkörnige Trübewolke verursacht, welche als bodenberührender Trübestrom sich relativ langsam gegen die Beckenmitte zu bewegt; die Seiche schiebt dann die Trübewolke im Seebecken hin und her, sodass die Basis des sonst homogenen Turbidits (= Homogenit) sandig laminiert ist. Die Amplituden historischer Seiches können 1–2 m gross werden; 1601 beispielsweise wurden durch Seiches die Ebene von Buochs unter Wasser gesetzt und das Reussbett bei Luzern periodisch trocken gelegt. Es wird vermutet, dass auch die älteren, nur in den seismischen Aufnahmen erkennbaren Rutschmassen und Homogenite in den Sedimenten des Vierwaldstättersees in ähnlicher Weise durch lokale Beben ausgelöst wurden und so die Intensität prähistorischer Erdbeben dokumentieren.

---

[1]) Geology Division, EAWAG, CH–8600, Dübendorf, Switzerland

[2]) Geological Institute ETHZ, CH–8092 Zürich, Switzerland

[3]) Dept. Geography, Academia Sinica, Nanjing, China

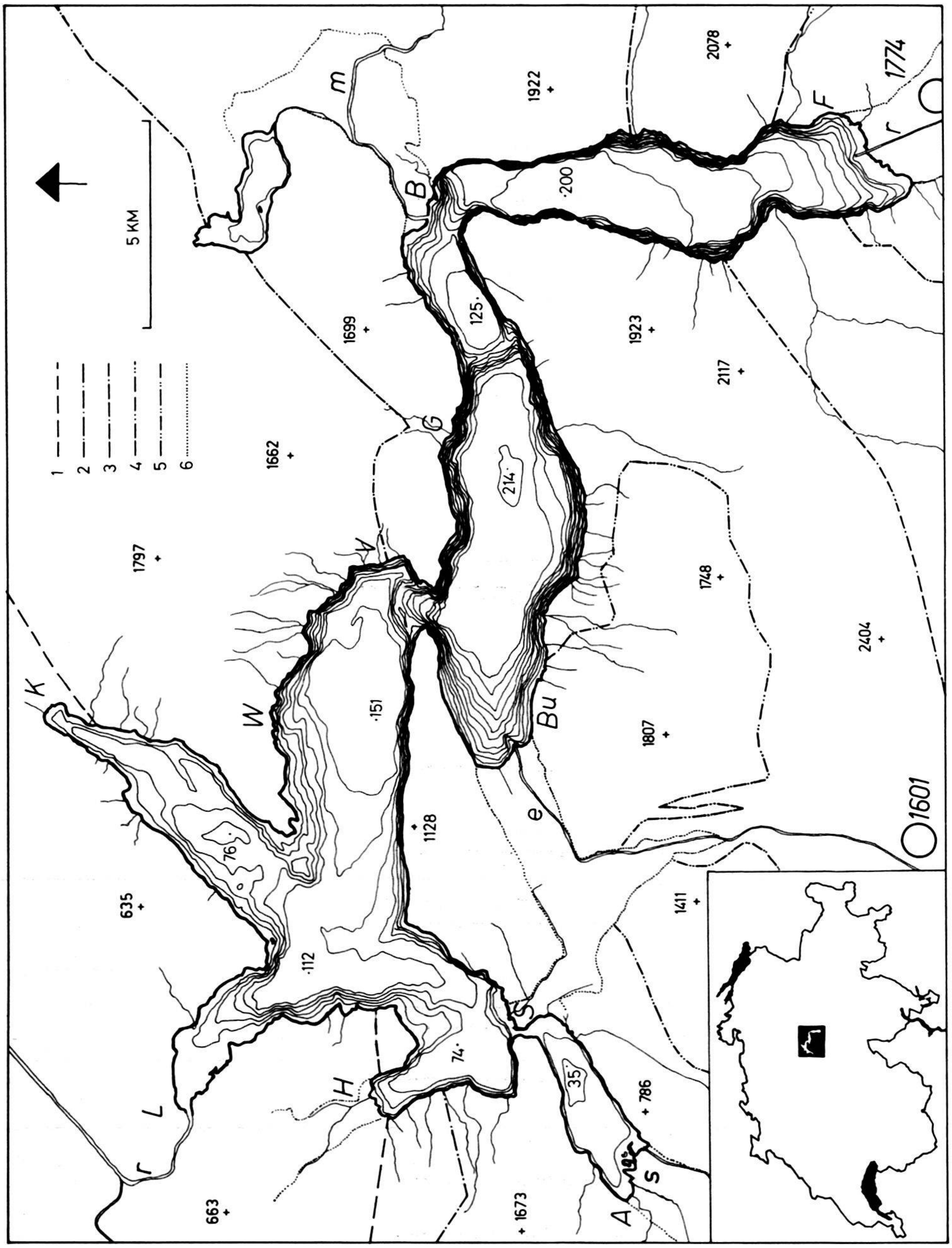


Fig. 1. Topography with 20 m contour lines of Lake Lucerne. Inset: Switzerland with Lake Lucerne. The maximum depth of the individual basins are given in meters: Lake Uri (200), Treib- (125) and Gersau basin (214); Lucerne basins: Weggis- (151), Küssnacht- (76), Horwbasin (74) and Chrüztrichter (112); Alpnachbasin (35). Also, the altitudes of the main peaks around the lake are in meters.

Tributaries: Reuss (r), Muota (m), Engelberger Aa (e), Sarner Aa/Chli Schliere (s).

Towns and villages: Lucerne (L), Horw (H), Alpnachstad (A), Stansstad (S), Küssnacht (K), Weggis (W), Vitznau (V), Buochs (Bu), Gersau (G), Brunnen (B), Flüelen (F).

The lines 1 to 5 are tectonic boundaries in the lake area and the line 6 represents the maximum extension of the Lake Lucerne at approx. 10.000 years BP. Circles: Epicenters of the 1601 and 1774 earthquakes.

Table 1: *The basins of Lake Lucerne with the largest tributaries. The Reuss at the outflow of the lake at Lucerne is indicated by a star*.*

	Max. depth m	Tributaries	Mean runoff m^3/s	Max. runoff m^3/s
Lake Uri, with	200	Reuss	44.9	550
Treib basin	125	Muota	19	330
Gersau basin	214	Engelberger Aa	12.5	130
Lucerne basins:		*Reuss	*138	*390
Horw basin	74			
Chrueztrichter	112			
Kuessnacht basin	76			
Weggis basin	151			
Alpnach basin	35	Sarner Aa/ Chli Schliere	11	115

Introduction

Lake Lucerne comprises a series of linked, deep basins nestled within the northern border of the Swiss Alps (Fig. 1 and Table 1). The total surface is 144 km^2. The most prominent subaqueous sills are at only 2–3 m water depth between the Alpnach and the Lucerne basins, and at 30 m water depth between the Weggis and Gersau basins. The mean surface elevation of Lake Lucerne is 433.58 m above mean sea level, and the extremes this century have ranged from 433.05 m in 1917 to 435.25 m in 1910. Four large tributaries account for $^2/_3$ of the total mean inflow (Table 1). Lake levels were probably higher after the retreat of the Late Würm glaciers about 13000 years ago; the surface area was larger and the Bürgenstock (1128 m, see Fig. 1) was an island. This was followed by low stands in the Holocene, and, subsequently, a steady rise due to progradation of small deltas on the north and south sides of the outflowing Reuss river and due to anthropogenic influences such as various city water works projects at Lucerne. In all, since Paleolithic or Mesolithic periods, the lake surface has risen at least 9 m (Kopp 1938).

Previous limnogeologic studies in Swiss lakes revealed the occurrence of various types of mass flow deposits such as slumps and slump generated turbidity currents (Lambert 1976, Kelts 1978, Sturm & Matter 1978, Kelts & Hsü 1980). The purpose of this paper is to provide evidence of a link between thick mass flow units in lake Lucerne and a possible initial trigger mechanism by earthquake shocks.

The paper is based mainly on 3.5 kHz high-resolution profiling and piston-coring carried out in the Summer of 1982 (Fig. 2) with the Limnogeology-ETH System Corer (Kelts et al. 1986), and supplemented by earlier seismic and coring reconnaissance. In addition we utilized data from short (1 m) gravity cores in the Uri basin and the Lucerne basins. No data is available from the shallow Alpnach basin.

Sedimentation in Lake Lucerne

Most detritus enters Lake Lucerne via the largest tributaries: Reuss, Muota, Engelberger Aa and Sarner Aa/Chli Schliere rivers (Fig. 1 and Table 1). These rivers have constructed major deltas in Uri and Gersau basins or almost filled up the Alpnach basin.

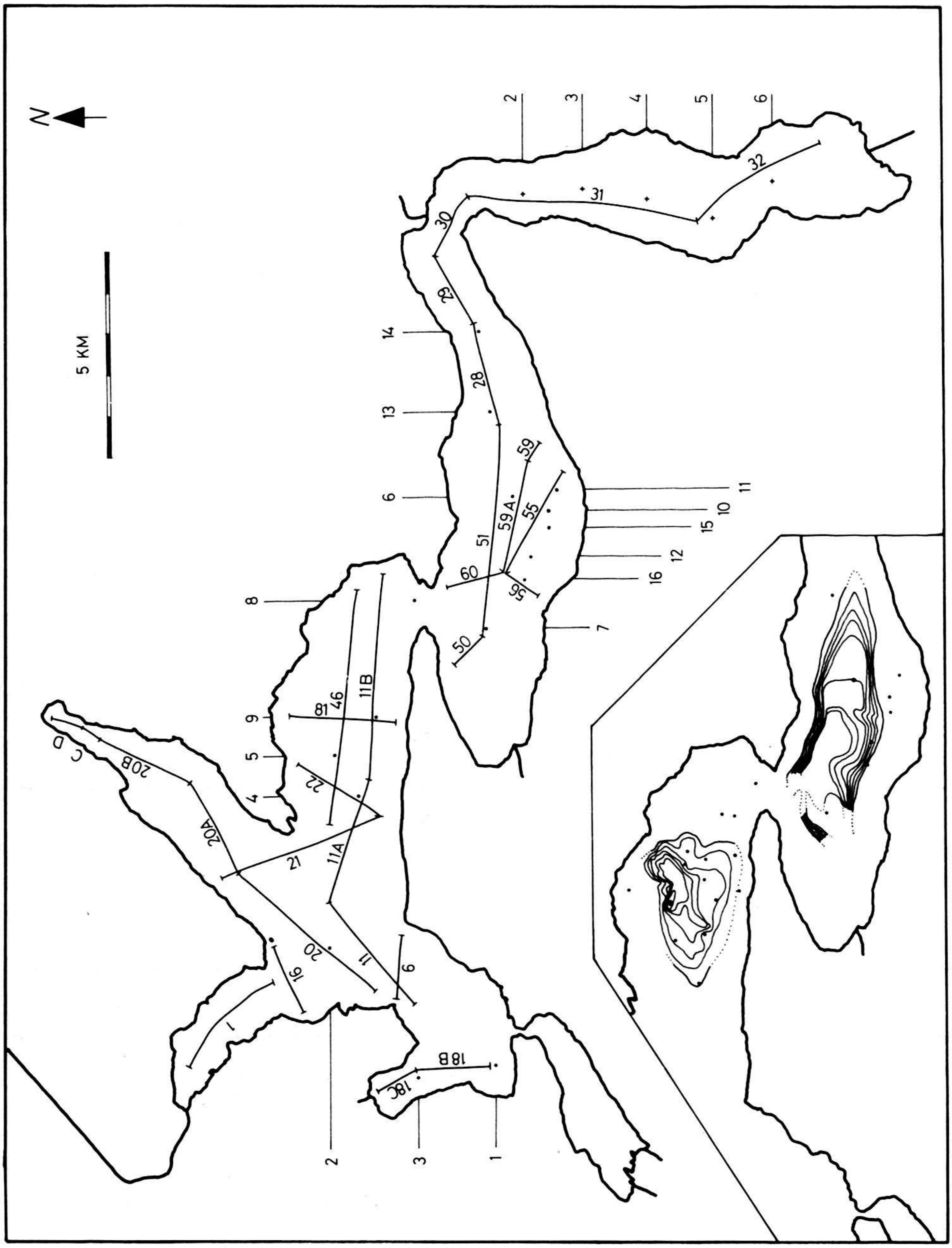


Fig. 2. Traces of the 3.5 kHz soundings and the position of the piston cores (dots 1 to 16) and of the gravity cores (crosses 2 to 6). Inset: the totality of all cores and the 1 m isopachs of the 1601 slumps in the Weggis and Gersau basin.

The Horw basin also has a large delta from times when the Engelberger Aa inlet shifted to the northwest at Stanstad. Coarse clastic input would be expected to dominate the sediments in the Uri and Alpnach basins, and to be important in the Horw and Gersau basins. The coarse clastics are deposited as turbidite beds, commonly a few cm-thick outside delta areas, which form excellent marker horizons for intra-basinal correlation of cores. Such a correlation, see Figure 6, illustrates the two important depot centers which exist in Lake Uri: the Muota in the north and the Reuss in the south. The material brought into the lake by these rivers, but also by some minor tributaries, is slightly different in composition and color. It is, thus, occasionally possible to document interfingering of turbidites from different sources. This not only implies that the turbidity currents derived directly from synchronous river underflow during rain fall flood stages, but also that locally the turbidity current from one source can temporally push aside the current from another source. The host sediments for these turbidites comprises laminated mud in various gray hues.

With the exception of Horw basin, the Lucerne basins (Chrüztrichter, Küssnacht and Weggis basins) are characterized by faintly laminated gray mud, and only sporadic redeposits which mostly differ little from the host muds. We did not find evidence for annual rhythmic bedding (varves). One index horizon occurs as a several cm-thick earthen brown, fine-grained, graded silt layer which can be traced throughout Lucerne basins (layer A in Fig. 3) into the Gersau basin (layer A′ in Fig. 3). This turbidite is considered to be the result of an extraordinary rain-fall, river-bed flushing event. Within the Weggis basin there is another distinctive reddish-orange silty clay bed (layer *a* in Fig. 3) which was attributed by STAUB (1981) to a slowly-moving, subaerial debris flow which partially destroyed the village of Weggis in 1795. A subaqueous continuation of this debris flow into the lake as a sediment gravity flow, as postulated by HSÜ & KELTS (1985), was not observed.

As background to the later interpretations, we note a few pertinent observations from the basins. A few of the thin, gray mud layers contain up to 50% land-plant debris; these layers occur only very locally and cannot be traced from core to core. Just 3.5 km to the east of Point 112 (Fig. 1), a submerged platform at 12 m depth has thin beds of shell hash. Seismics and coring indicate bare rock or moraine outcrops within the narrow straits separating Gersau and Vitznau basins. The most spectacular deposits within sediments from Lake Lucerne, comprise thick mass flows redeposits in basinal areas and on gentle slopes in the Gersau and Lucerne basins. Their thicknesses may exceed 10 m, and cores display structures ranging from contorted and sheared bedding (indicated by a broken line in Fig. 3) to homogeneous muds (dotted line in Fig. 3). On seismic profiles (see Figs. 4, 5), mass flow deposits appear as transparent bodies in contrast with the uniform reflector layering of the host sediments. The upper contact of these beds is commonly smooth and even, whereas the lower contact may display irregularities interpreted as erosion gouging. These deposits derive from subaqueous slumps which have redeposited both slope and basinal sediments. This is shown clearly by the presence of a characteristic orange index layer which can be recognized in slump deposits as well as in the undisturbed host sequence (layer g in Fig. 3). In core sections from the basin plain areas, the slump deposits are directly overlain by up to 3-meter thick homogeneous gray mud layers which may be distinguished by a few thin sand/mud laminations at the base (indicated by a dotted line in Fig. 3). We call these deposits *homogenites*, after KASTENS & CITA (1981), to denote

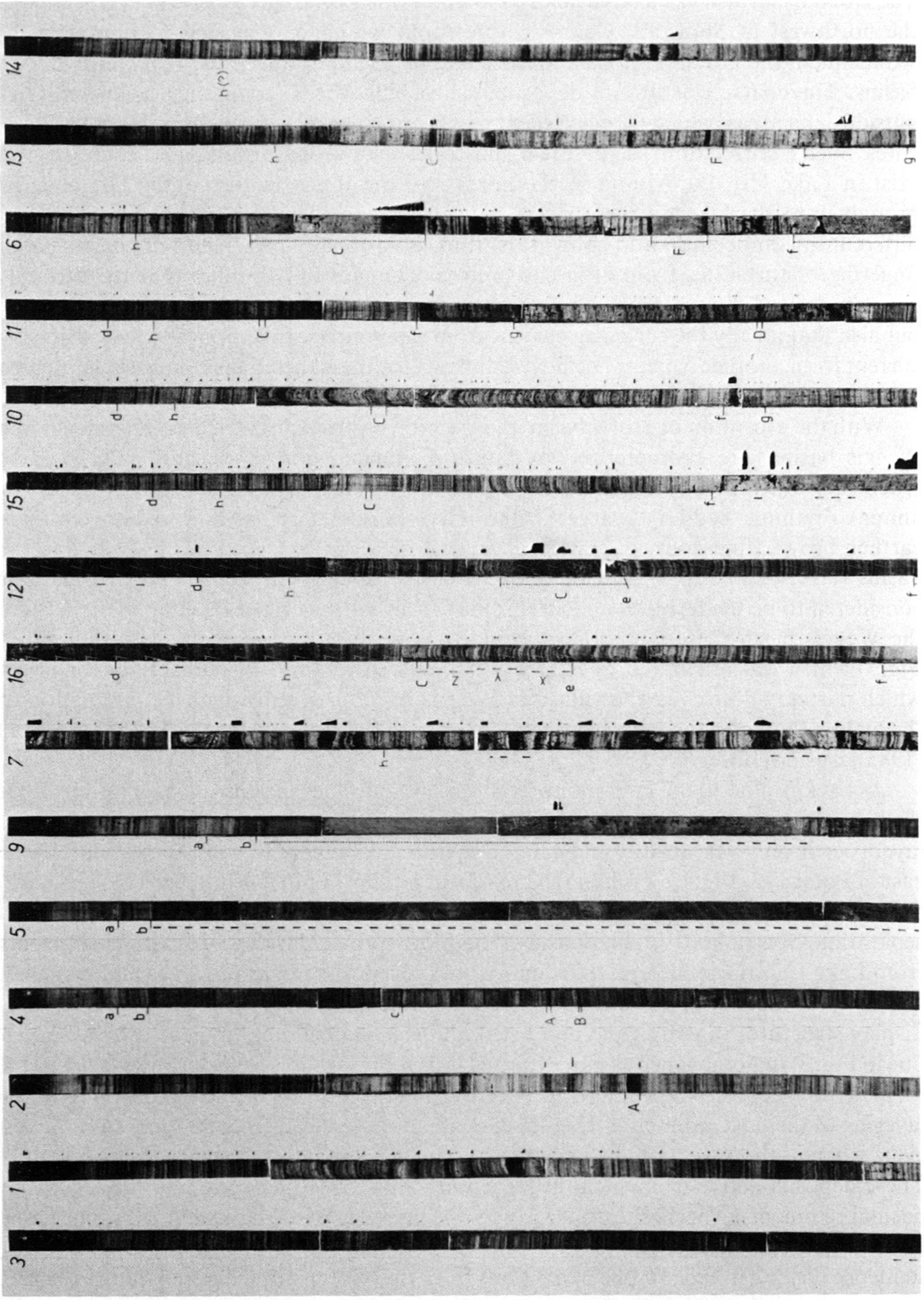
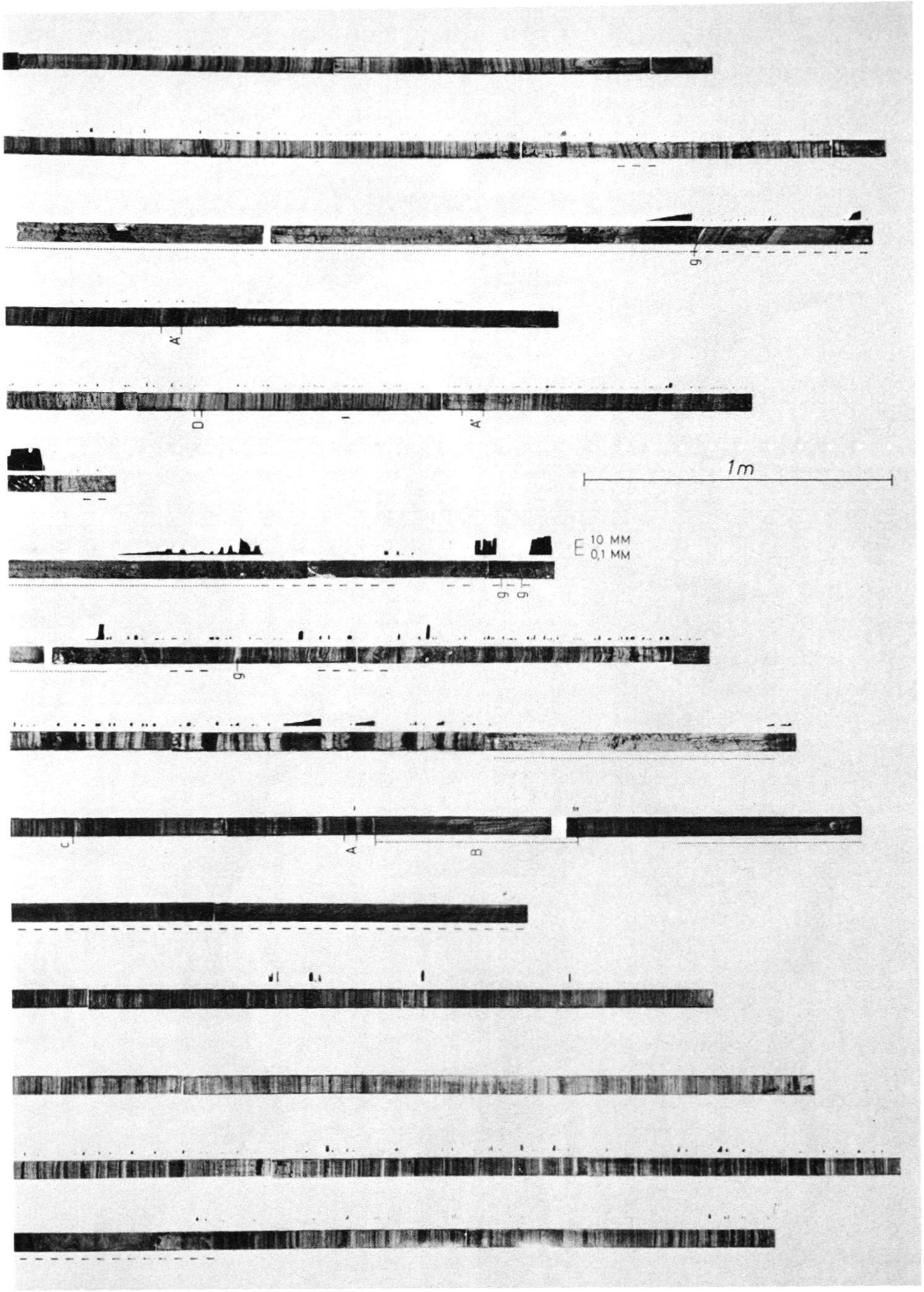


Fig. 3. Piston cores. Broken line: contorted and distorted bedding (slumps), dotted line: fine grained and homogeneous turbidite with sandy base (homogenite). The diameters of the largest grains are indicated in black to the right of the profile (according to the scale given in core 12). Individual marker beds are indicated by upper and lower case



characters (for explanation see text; the intervals x, y and z in core 16 are identical, repeated, sections due to slumping). b and f is considered to be the top of the slump/homogenite generated by the 1601 earthquake, layer C is attributed to the 1774 earthquake.

Fig. 4a, 4b, 4c and 4d. Seismic sections in Lake Lucerne, for position see Figure 2. Hatched areas: slumps, black areas: associated homogenites, deposited in 1601. Horizontal bar: 1 km, vertical bar: 15 m.

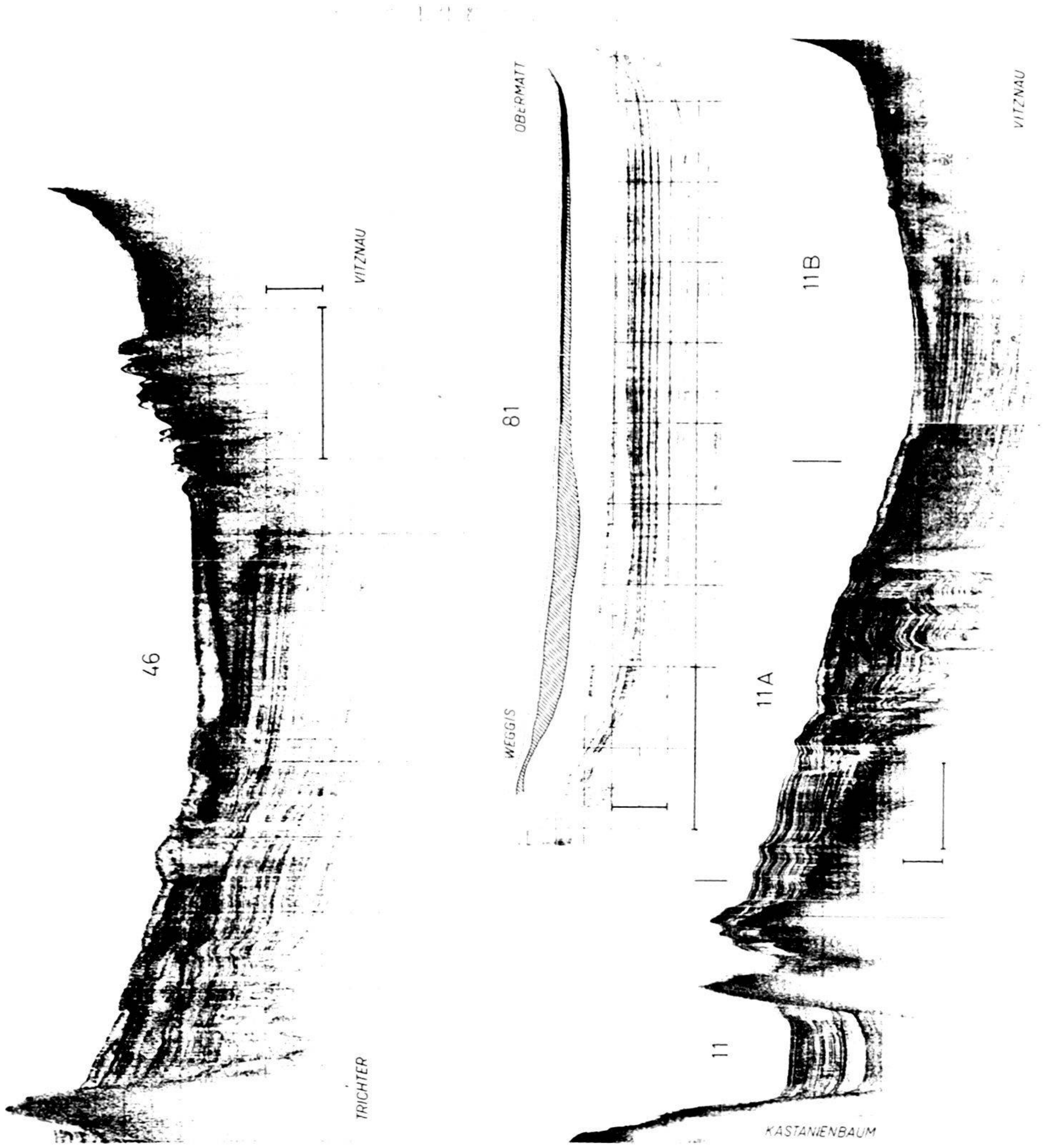

46
VITZNAU
TRICHTER
81
OBERMATT
WEGGIS
11B
11A
11
VITZNAU
KASTANIENBAUM

Fig. 4b

Fig. 4c


CHINDLI
28
51
50
NAS
FLUELEN
32
BRUNNEN
29
28
CHINDLI
31
30
BRUNNEN

Fig. 4d

relatively large turbidity current deposits ponded in a small basin. Kastens & Cita (1981) described similar accoustically transparent layers found in deep, isolated basins of the Mediterranean ridge. There, they were attributed to tsunami-induced intrabasinal and ponded turbidity currents.

Many seismic descriptions of subaqueous slumps have emphasized a hummocky surface (Almagor & Wiseman 1977, Carlson & Molnia 1977, Embley & Jacobi 1977, Hampton & Bouma 1977, McGregor & Bennet 1977, Woodbury 1977, Prior & Coleman 1978, Choung, Jeong & Honza 1985) which is in contrast with the smoothed surfaces of the Lake Lucerne deposits. We assume that the slump deposits in Lake Lucerne derive from highly liquified mud flows that rapidly moved across the gentle

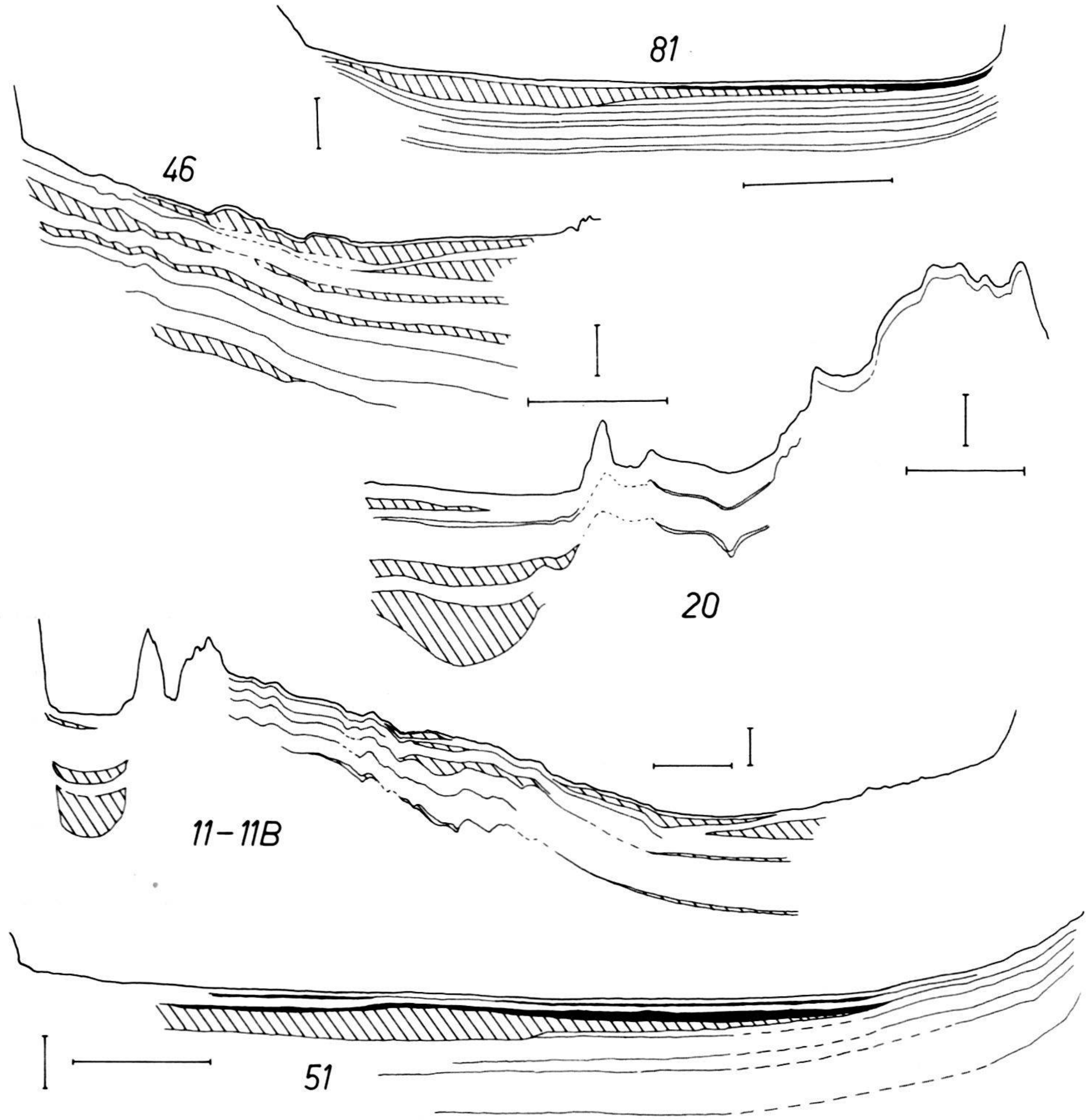


Fig. 5. Slumps (hatched areas) and associated homogenites (black areas), as interpreted from the seismic sections, for position see Figure 2. The youngest slump in each profile is due to the 1601 earthquake. In profile 51 the rather thin homogenite above the slump/homogenite couplet of 1601 is attributed to the 1774 earthquake. Horizontal bar: 1 km, vertical bar: 15 m.

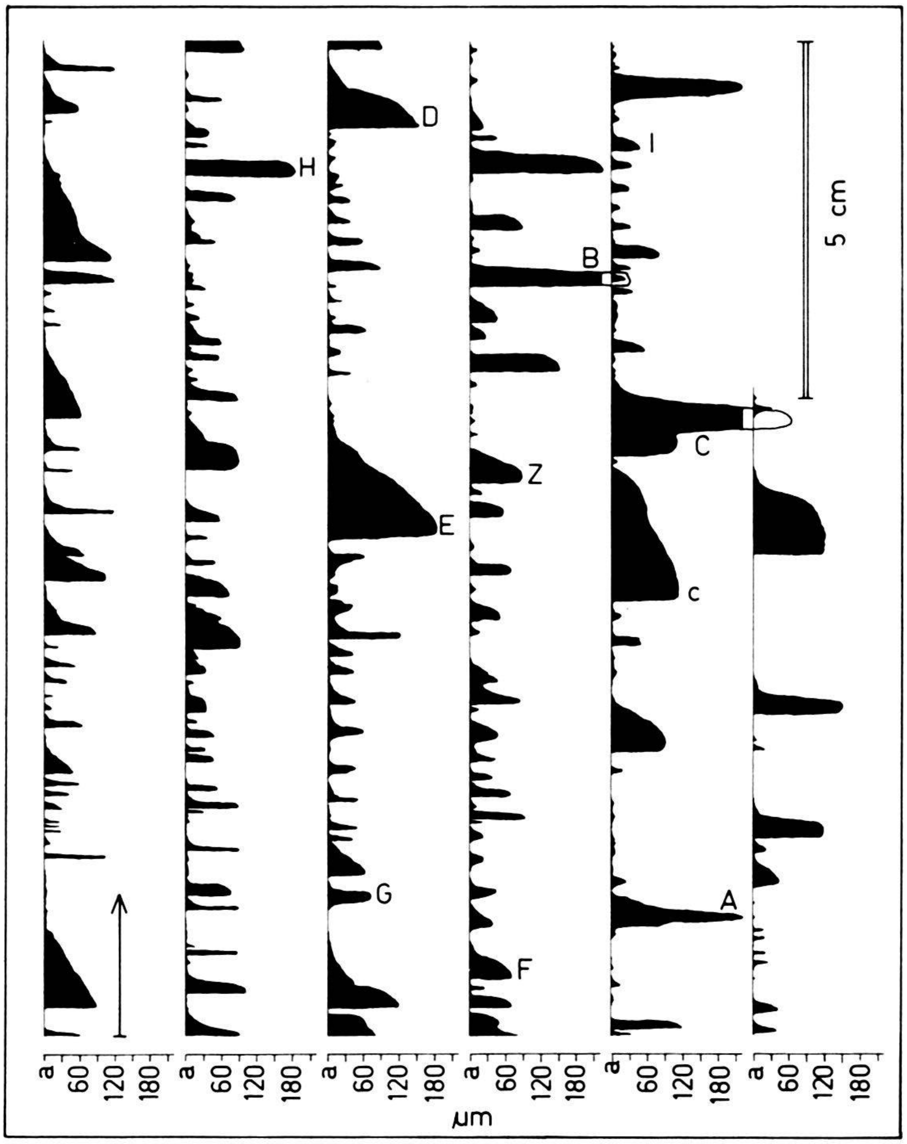


Fig. 6. Grain size logs from the Lake Uri gravity cores. The logs give the diameter of the maximum grain size, *a* stands for grain size less than fine silt. Figure 6a: core 5, the base of the core is in the lower left corner (arrow) and the top in the upper right corner. Figure 6b (next page): representation of individual marker beds, correlated from core 2 (left) to core 6 (right); inset: stratigraphic position and lateral continuation of some marker beds in core 2 to 6.

slopes. A tendency toward liquefaction would be enhanced by the high silt content of these muds, and possible sandier or gaseous zones within a slope sequence (SANGREY 1977). Seismic sections (eg. Fig. 4b) show that redeposits flowed along discrete horizons and that these tend to ramp upwards in more distal regions. Slump and overlying homogenite deposits – which are accustically slightly different, the latter being somewhat more transparent than the former, see eg. section 51 of Figure 4d – are distinctly separate, with sharp and even contacts and without evidence of intermingling. The emplacement of a slump, thus, finished before the mud suspension arrived to settle. This signals rapid transport velocities for slumps as a probable consequence of sudden liquefaction. The question arises as to what mechanism might produce these sparse, liquefaction events?

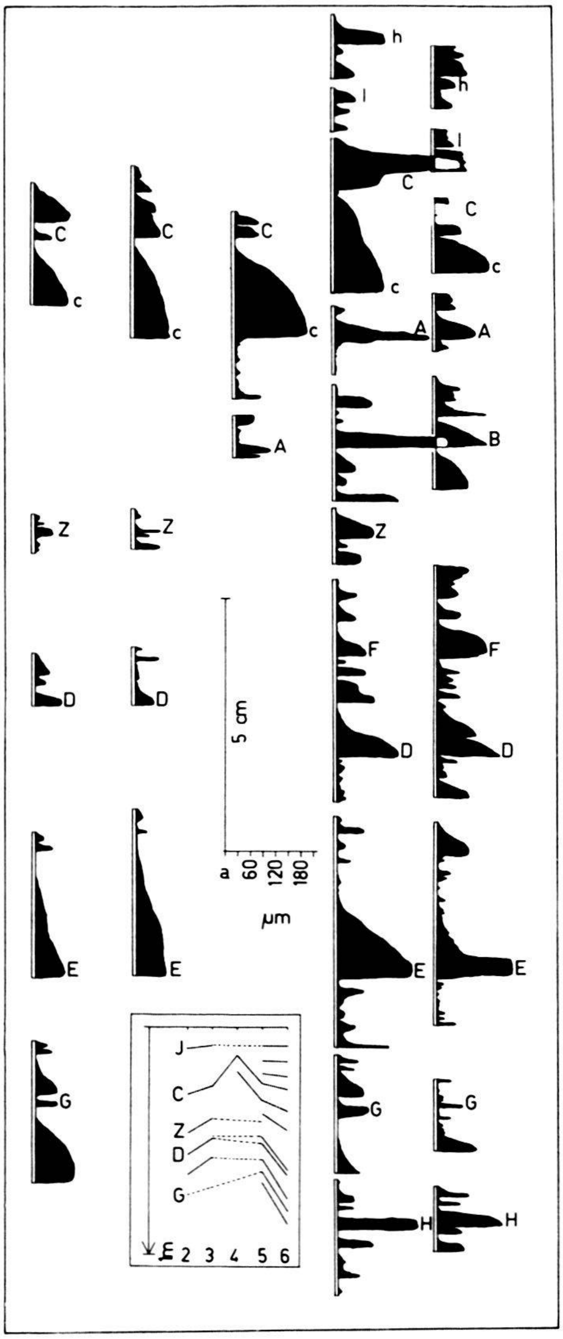


Fig. 6b.

Strong earthquakes in the Lake Lucerne area

The epicenters of some of the strongest (> VIII MSK) historical earthquakes in Switzerland were located in the regions near Lake Lucerne (Pavoni 1977). The most important occurred in 1601 and 1774, and possibly also in 1674 (Montandon 1953).

The earthquake of 1601, which occurred during a fair weather period in autumn, is particularly well-documented by an eye-witness account from the scribe of the city of Lucerne at that time, Renward Cysat (Cysat, manuscript):

Many churches were damaged, and several houses collapsed. A large rockfall occurred along the northern flank of the Bürgenstock (Pt. 1128 in Fig. 1), which produced a surge in the Weggis basin. Several landslides are reported along the edges of Lake Lucerne with a total of 9 human lives lost. Large parts of the land adjacent to the lake was innundated, in Buochs over 1 km inland, and ships were thrown onto dry ground. At regular intervals of six times per hour, the rise and fall of the lake surface caused the river Reuss outlet of the lake at the city of Lucerne to run almost dry. Several people could thus ford the river bed on foot. In the Chrüztrichter (Pt. 112 in Fig. 1), the agitated waters built up "mountains of water to frightful proportions" (CYSAT, manuscript) and several small islands on the shoals (east of Pt. 112) dissappeared completely. The periodic rise and fall of the lake level could be observed for 8 days in the Uri basin. The shoaling of the Reuss was so spectacular that several inhabitants fled Lucerne, suspecting that the earth itself will swallow up the river and the whole town.

Little is known of the earthquake of 1674 except that it was probably felt in all of Switzerland and produced severe damage in the town of Schwyz, located 5 km northeast of Brunnen (MONTANDON 1953). The earthquake of 1774 damaged all houses constructed of stone in Altdorf (a town 3 km south of Flüelen) and two collapsed entirely. Several rockfalls and two landslides were reported along the shores of the Uri basin. In the town of Lucerne, chimneys dropped, but here the lake remained calm with the exception of large bubbles observed surfacing in the water. A total of three persons were reported to have been killed by the events (MONTANDON 1953).

The large seiches which occurred in Lucerne following the earthquake of 1601 are of special interest, and it is worthy to note that, in the Lucerne basins, similar features were not linked with the other earthquakes. The inundation of shorelines during a fair weather period in 1601 and the periodical withdrawal of water from the outflow in intervals of 10 minutes is reminiscent of tsunamis caused by earthquake-induced slumps in the Pacific ocean (SHEPARD 1948, p. 47). Cysat's observations allow a reasonable estimate of the amplitude of the seiche at Lucerne. Today, the bay of Lucerne is quite shallow, with water depths not greater than 3.5 m along a southwest to northeast cross-section located about 1–1.5 km SE of the town. In the 13th century, mean water levels were even lower, and large ships had to be unloaded in a special harbor several kilometers further away (CYSAT, manuscript). By the 16th century, mean water levels had risen due to constructions along and in the Reuss river, but in the winter season, large ships could still barely serve the town (CYSAT, manuscript). A comparison of the water level at that time, as revealed by a very accurate copperplate engraving from 1597 (Fig. 7), with the present water level suggests a rise of up to two meters since the 16th century. From this information we conclude that a seiche with an amplitude of about 1 to 2 m in the Lucerne embayment would be enough to periodically shut off the outflow of the lake in 1601.

Uninodal seiche movement may be described by:

$$T = A\frac{2l}{\sqrt{(gh)}} \qquad (1)$$

where: T is the period of a seiche, g is acceleration due to gravity, l is the basin length, h is water depth, and A is a shape factor which ranges from 1 for a rectangular up to 1.6 for a triangular basin (WILSON 1972). Taking Cysat's observation of T = 10 min, the oscil-

Fig. 7. Downstream view of the outflow of the lake at Lucerne, section of a copperplate engraving from Martin Martini, 1597. The three long buildings in the Reuss (middle of the left edge) are mills; their wheels stood periodically in the air when the 1601 seiche occurred, and a few brave folk walked then across the river bed. The bridge in the foreground is still in use today and a comparison of the copperplate with the situation today indicates a rise of the water level of 1 to 2 m since that time.

lating basin was 6–10 km long, if the mean water depth was 100 m, and a uninodal seiche is assumed. This is the order of magnitude of the lengths of the Lucerne basins. Independent large seiches would have occurred in the Gersau basin – as indicated by the reported large innundations in Buochs – and also in the Uri basin. The large gradients, which must have had occurred between independently oscillating basins, probably produced strong bottom currents able to erode sediments in the narrow, shallow straits such as between the Gersau and Weggis basin. Seismics and coring indicate that these are floored only by bare rock or moraine. Also, strong bottom currents must have flowed over other sills and shallow shoals. The maximum velocity for bottom currents produced by a standing wave in shallow water, and below a node, may be estimated from the linear wave theory:

$$u_{max} = a\sqrt{(g/h)} \tag{2}$$

where: a is the amplitude and h is water depth (WIEGEL 1964, Eq. 2.26). Assuming an amplitude of 1.5 m and a depth of 100 m, a maximum bottom current of 0.5 m/s may be expected which is quite adequate to transport fine to medium sand.

Although some seiches in lakes have been linked to surface waves from remote earthquakes (see WILSON 1972), it seems improbable that a direct jolt near the epicenter would be adequate to stimulate a seiche. The high frequencies of the shocks in the range of a few Hertz are quite different than the seiche frequencies (D. Mayer-Rosa, pers. comm. 1985). We conclude that the seiche movements associated with the earthquake of 1601 were rather produced by large and rapidly flowing subaquatic slumps that were triggered by the earthquakes. We do not discuss the possible mechanisms of seiche generation by slumping, but just show by a rough balance that such a generation is a least compatible with conservation of energy: The energy of a standing wave in water with density ρ is

$$E = \rho \, g \, a^2 \, L/4 \tag{3}$$

per unit width (WIEGEL 1964, Eq. 2.28). Assuming a width of 2 km, a wavelength L of 20 km and an amplitude a of 1.5 m, then the energy of the seiche was 100 GJ. This is equivalent to about 5% of the energy expended by a slump with a volume of 10^7 m^3, flowing down a vertical distance of 20 m.

A series of large slump deposits, sometimes associated with homogenites, were identified in the uppermost 30 m of soft sediments in Lake Lucerne basins (see Fig. 5). Two deposits which could be sampled by piston coring occur at a similar stratigraphic position – as compared with the marker layer A (= A′, see Fig. 3) – near the sediment surface in the Weggis and in the Gersau basins (indicated in Fig. 3 by their top b and f respectively). From their burial depths these slumps/homogenites must have occurred in historical times. The basal part of the homogenite layer is characterized by laminated sand/mud couplets as would be expected from strong seiches (or tsunamis, see KASTENS & CITA 1981). The town of Lucerne was founded in the 13th century. Since we were unable to locate any other historical accounts of strong seiche activity affecting the town than the ones referring to the earthquake of 1601, we argue that the large slump/homogenite deposits found near the sediment surface in Gersau and Weggis basins are indeed initiated by the 1601 event. Two other minor slump/homogenite deposits in the Gersau basin then occur stratigraphically at levels which could correlate with the more recent 1774, and possibly the 1674, earthquake (layers C and F respectively in Fig. 3). In fact, neglecting the thicknesses of the deposits C and F, the mean ratio of the thickness intervals: "f (presumed top of 1601 event) – C (presumed 1774 event) – lake bottom (1982)" from the cores 16, 12, 10, 11, 6 and 13 in the Gersau basin is identical with the ratio of the corresponding time intervals. No deposits analogous to C (or F) were recovered in the Lucerne basin cores. This corresponds well with eye witness accounts of the 1774 event which explicitly note that no seiche activity was observed following the earthquake (MONTANDON 1953). As a result we attribute the youngest large slump/homogenite in the Lucerne and Weggis basin (indicated by the top layer b or f in Fig. 3) to the 1601 earthquake and the homogenite C in the Gersau basin to the 1774 earthquake. Slumps and slump generated turbidites are described from other Swiss lakes (HSÜ & KELTS 1985), but these are linked to anthropogenetic activity rather than earthquakes. We think that the larger number of large subaquatic slumps in the - seismically active – area of Lake Lucerne suggests that earthquakes are also responsible for the generation of at least part of the older slumps in lake Lucerne. Obviously, a conclusive proof would have to show that individual slumps in separate basins have exactly the same age.

We imagine the following sequence of events during and after a strong earthquake in the Lake Lucerne area:

1. Sediment layers from slope and basin plain are liquified by an earthquake shock and a several meter-thick sediment sheet flows rapidly downslope, deforming rafted internal bedding, but producing a smooth upper surface on the slump deposit. Flow separation releases sediment into suspension, and a density suspension cloud is produced which lags somewhat but also moves towards basin center.
2. A seiche generated by the slump produces currents that move the suspension cloud back and forth. This motion enables erosion and incorporation of further sediment within the cloud. During the moments of maximum bottom current flow velocities, the lake bottom is reworked and eventually planed off whilst sand is transported and deposited. During slack water moments, fine-grained muds settle out resulting in alternations of sand and mud laminae.
3. As a seiche movement wanes, a suspension cloud flows towards the basin plain center, and ponds; the suspended matter settles. This produces a massive, macroscopically structureless, fine-grained deposit that sediments onto the slump mass if the latter reached the basin plain. This type of massive bed has variously been called a "homogenite" (KASTENS & CITA 1981), "unifite" (FELDHAUSEN et al. 1981) or "mud turbidite" (EINSELE & KELTS 1982).

The above model resembles in some repects the model elaborated by PICKERING & HISCOTT (1985) for the Ordovician "contained turbidites" from Quebec, which in their upper part are similar to the homogeneites. According to Pickering & Hiscott the turbidity current had been deflected and reflected several times from the side slopes of the relatively small basin, generating a deposit with bimodal cross-stratification. These flow reversals gave way to an internal seiche which produced silty laminations at the base of the thick and homogeneous mudstone cap of the contained turbidite (PICKERING & HISCOTT 1985).

Conclusions

Recent developments in radiocarbon dating by accelerator mass spectrometry should eventually enable us to test the proposed synchroneity of slump/mass flow events in the multiple basins of Lake Lucerne. We have however found strong evidence that earthquakes in the Lake Lucerne area can simultaneously trigger rapidly flowing, liquified slump masses as well as concomitant suspension clouds in separate sediment basins of Lake of Lucerne. As a secondary effect, the slumps can initiate seiche movements which, by to and fro feedback, modify the sedimentation from the suspension cloud to produce a series of laminated sand/mud couplets at the base of the suspension deposit, the homogenite.

The characteristic features of the slump/homogenite assemblages are:

- Slumps move along bedding planes ramping up to higher stratigraphic intervals as their erosive power fades. Slump masses occur on very gentle slopes and on the basin plain with angles as low as a fraction of a degree.
- The slump mass is intensively folded and sheared, but the upper surface is smoothed. This may be a result of either an overshoot deposit in a liquified state, or by reworking effects of a strong seiche activity.
- Homogenite deposits can only be recognized as entities on the basin plain. They overly slump masses with sharp contacts. The beds are macroscopically structureless, with thinly laminated sand/mud couplets at the contact with the slump deposit. Probably, thicknesses can range up to several meters.
- In proximal positions the slump may not be covered by the homogenite (slump in core 5, Fig. 3). Also, homogenites can be deposited outside the distal slump front (homogenite C in core 6 and probably core 12, Fig. 3).

It seems that the volumes of slumped material and homogenites are roughly correlated with the magnitude of an earthquake and the distance from the epicenter. Slumps, especially very large one's and beyond the reach of the corer, are encountered in almost every seismic section with good penetration, see Figure 5. We presume that they represent large prehistoric earthquakes in the region.

There is strong evidence to attribute specific slumps/homogenites in the Weggis- and Gersau basin to the 1601 and 1774 earthquakes. The mean sedimentation rates are then 0.9 to 1.8 mm/y in the Weggis basin and up to 8 or even 12 mm/y in the Gersau basin. The latter figure results from core 7 at the foot of the Buochs delta, correlating the large homogenite in that core with the 1601 event. These calculated mean sedimentation rates do no take into account the very high water contents in the deposits near the sediment surface, and the actual sedimentation rates in the Weggis basin are probably less by a factor of approximately 2.

Acknowledgments

We acknowledge with appreciation the support of K.J. Hsü. We also thank K. Ghilardi for his technical assistance, R. Hofmann, H.-J. Schäppi and G. Schmid for field help and U. Gerber for photographs. Our collegues P. Finckh and F. Niessen kindly commented on our results, and St. Lüthi and M. Sturm carefully reviewed and discussed the submitted manuscript. This is a contribution to the NF project 2.403.0.84, and Nr. 311 of the Lab. Exp. Geol. ETH-Zürich.

REFERENCES

ALMAGOR, G. & WISEMAN, G. (1977): Analysis of submarine slumping in the continental slope off the southern coast of Israel. - Marine Geotechnol. *2*, 349–388.

CARLSON, P. R. & MONIA, B. F. (1977): Submarine faults and slides on the continental shelf, northeastern Gulf of Alaska. - Marine Geotechnol. *2*, 275–290.

CHOUNG, S. K., JEOUNG, K. S. & HONZA, E. (1985): Zoned facies of mass-flow deposits in the Ulleung (Tsushima) basin, East Sea (Sea of Japan). - Marine Geol. *65*, 113–135.

CYSAT, R. (manuscript) In: J. SCHMID, 1969, Quellen und Forschungen zur Kulturgeschichte von Luzern und Innerschweiz. Luzern, Erste Abt., Erster Band, Zweiter Teil, p. 882–888.

EINSELE, G. & KELTS, K. (1982): Pliocene and Quaternary mud turbidites in the Gulf of California: Sedimentology, mass physical properties and significance. Init. Rep. DSD project (Blakeslee, Platt & Stout, eds.) *64*/2, 511–528.

EMBLEY, R.W. & JACOBI, R.D. (1977): Distribution and morphology of large submarine sediment slides and slumps on Atlantic continental margins. – Marine Geotechnol. *2*, 205–228.

FELDHAUSEN, D.H., STANLEY, D.J., KNIGHT, R.J. & MALDONADO, A. (1981): Homogenization of gravity emplaced muds and unifites: models from the Hellenic Trench. In: F.C. WEZEL (ED.) Sedimentary Basins of the Mediterranian Margins, Technoprint, Bologna, p.285–298.

HAMPTON, M.A. & BOUMA, A.H. (1977): Slope instability near the shelf break, western Gulf of Alaska. – Marine Geotechnol. *2*, 309–331.

HSÜ, K.J. & KELTS, K. (1985): Swiss lakes as a geological laboratory. Part I: Turbidity currents. Naturwissenschaften *72*, 315–321.

KASTENS, K.A. & CITA, M.B. (1981); Tsunami induced sediment transport in the abyssal Mediterranian Sea. – Geol. Soc. Amer. Bull. *92*, 845–857.

KELTS, K. (1978) Geological and sedimentary evolution of lakes Zurich and Zug, Switzerland. – Diss. ETH Zurich Nr.6146.

KELTS, K. & HSÜ, K.J. (1980): Resedimented facies of 1875 Horgen slump in lake Zurich and a process model of longitudinal transport of turbidity currents. – Eclogae geol. Helv. *73*/1, 271–281.

KELTS, K., BRIEGEL, U., GHILARDI, K. & HSÜ, K. (1986): The limnogeology-ETH coring system. Schweiz. Z. Hydrol., *48*/1, 103–115.

KOPP, J. (1938): Der Einfluss des Krienbaches auf die Gestaltung des Luzernersees und die Hebung des Vierwaldstättersees. – Eclogae geol. Helv. *31*, 376–378.

LAMBERT, A. (1976): Über die klastische Sedimentation im Walensee. – Diss. ETH Zürich, Nr.5717.

MCGREGOR, B.A. & BENNET, R.H. (1977): Continental slope sediment instability northeast of Wilmington Canyon. – AAPG Bull. *61*, 918–928.

MONTANDON, F. (1953): Les tremblements de terre destructeurs en Europe. – Genève, Union Internationale de Secours.

PAVONI, N. (1977): Erdbeben in der Schweiz. – Eclogae geol. Helv. *70*, 351–370.

PICKERING, K.T. & HISCOTT, R.N. (1985): Contained (reflected) turbidity currents from the Middle Ordovician Cloridorme Formation, Quebec, Canada: an alternative to the antidune hypothesis. – Sedimentology *32*, 373–394.

PRIOR, D.B. & COLEMAN, J.M. (1978) Submarine landslides on the Mississippi delta-front slope. – Geoscience and Man *19*, 41–53.

SANGREY, D.A. (1977): Marine geotechnology – state of the art. – Marine Geotechnol. *2*, 45–80.

SHEPARD, F.A. (1948): Submarine Geology. – Harpers, N.Y.

STAUB, E.A. (1981):Diagenese im rezenten Sediment des Vierwaldstättersees und ihre Veränderung durch die Eutrophierung; Tiefenprofile biologisch-chemischer Parameter im Sediment und Porenwasser. – Diss. ETH, Nr.6841.

STURM, M. & MATTER, A. (1978): Turbidites and varves in lake Brienz (Switzerland). Deposition of clastic detritus by density currents. – Modern and Ancient Lake Sediments (Matter & Tucker, eds.) Spec. Publ. Int. Assoc. Sedim., *2*, 147–168.

WIEGEL, R.L. (1964): Oceanographical Engineering. – Prentice Hall, Englewood & Cliffs, N.J.

WILSON, B.W. (1972): Seiches. In: VEN TE CHOW (Ed.): Advances in Hydroscience. – Academic Press, New York, London, *8*, 1–94.

WOODBURY, P.R. (1977): Movement of sediment on the Gulf Mexico, continental slope and upper continental shelf. – Marine Geotechnol. *2*, 263–273.

Manuscript received 16 October 1986
Revision accepted 25 December 1986