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Resedimented facies of 1875 Horgen slumps in Lake Zurich and a process model of longitudinal transport of turbidity currents[1])

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ABSTRACT

The weight of landfill materials caused a series of subaqueous slumps on the shore of Lake Zurich near Horgen in 1875. Seismic-reflection-profiling and piston-core studies identified the resedimented deposits of the Horgen events. The catastrophic slump deposits include pebbly mud with chaotic bedding, mud-pebble "conglomerate", mud-pebble mud, and homogeneous mud, and were laid down in a subaqueous fan environment. Turbidity currents were generated by the mass flows. Proximal turbidites include layers of coarse sand and were deposited on the fringe of the lobe. Distal turbidites are mainly silts and clays forming elongate deposits in the flat bottom of the narrow lake basin.

The facies distribution of Lake Zurich turbidites forms the basis of a process model for turbidity-current transport. Turbidity currents flowing down the steep side of a narrow, deep-water basin are commonly deflected by the opposite slope and turned into longitudinal transport along the axis of the trough. Although the coarsest debris are laid down at the foot of the slope to form fans, much of the suspended materials were transported to the bâsin-plain environment to form elongate bodies of turbidite deposits.

ZUSAMMENFASSUNG

Das Aufschüttungsmaterial für den Landgewinn zum Bau des Bahnhofs Horgen ist im Jahr 1875 in mehreren Schüben in den Zürichsee abgefahren. In Seebodenproben (Kolbenlot) sowie in seismischen Profilen konnte dieses resedimentierte Material identifiziert werden. Der Grossteil dieser abgerutschten Masse liegt heute als geröllführender Schlamm mit wilder Schichtung vor, als Tongallen-«Konglomerat», als Tongallen-Schlamm und als homogener Schlamm, abgelagert in einer Art Unterwasser-Schuttfächer. Bei diesem katastrophalen Ereignis wurden auch Trübeströme ausgelöst, deren proximale Sedimente als Sandlagen am Fächerrand liegen, während die distalen Sedimente als Silte und Tone weitverteilt auf dem flachen Boden des engen Seebeckens vorkommen.

Die Faziesverteilung dieser See-Turbidite dient als Grundlage für ein Bewegungsmodell von Trübeströmen. Wenn solche Trübeströme den steilen Abhang von schmalen, tiefen Becken hinuntergleiten, werden sie vom gegenüberliegenden Hang zurückgeworfen und drehen dann in Richtung Beckenachse ab. Die groben Anteile werden am Hangfuss fächerförmig abgelagert, das länger suspendierte Material wird aber in die Beckenebene transportiert, wo es als langgestreckte Turbidit-Ablagerungen deponiert wird.

Introduction

The lower Lake Zurich is underlain by a flat-bottom trough with steep sides some 20 km long, 3 km wide and 135 m deep. The Lake Zurich project was initiated

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in 1967 to investigate the aftermath of events in 1875 when unconsolidated sediments on the shore near Horgen repeatedly slumped away and were resedimented on the bottom of the lake. The project was undertaken to resolve the question if an ancient turbidite bed laid down on a basin plain setting represents the deposits of coalescent submarine fans, as suggested by advocates of the fan model (e.g. WALKER 1978), or if it was deposited by an individual current along the path of its longitudinal transport (HSÜ 1977).

Historical records were examined, seismic-reflection profiling was carried out, piston cores were taken to study the resedimentation. Our efforts have led us to formulate a process model for turbidity currents generated by catastrophic slumping and to emphasize the importance of longitudinal transport.

The Horgen slumps and resedimentation

The slumping of shore near Horgen resulted directly from the loading of sand and gravel landfill on a weak foundation of lacustrine marls. The first slide occurred in February 1875, but this slump mass was apparently only slightly displaced and did not flow into the deepest part of the lake until later. The main events took place in five phases during 22-24 September after heavy rain on 21 September (Table). Almost 100,000 m³ of gravels, sands, clays, marls and chalks were removed by slumping from nearshore areas (HEIM 1933).

Table: *Approximate volume of the Horgen slumps (1875).*

Phase			m^3
I	9 February		30,000
II	22 September	10.30	25,000
III	22 September	11.30	9,000
IV	22 September	13.30	14,000
V	23 September	early	12,000
VI	24 September	9.00/12.00	3,000

53 piston cores from the Lake Zurich were taken, of which 31 gave a record of the Horgen events. A pycnocline came into existence first in 1890, and the anoxic sediments deposited below this level are easily recognizable laminated varves (KELTS & HSÜ 1979). Therefore, it is very easy to recognize the slump events which happened 15 years earlier. Correlation of the resedimented layers posed no difficulty (KELTS 1978). The slump mass is thick enough in the area of the subaqueous fan to leave an identifiable record on seismograms of high-resolution reflection surveys with a 3.5 kHz profiler. Based upon a reconstruction from the seismic results and from study of cores, the total volume of the resedimented deposit is about 1.5 million m³, or 15 times that of the slumps observed from the shore near Horgen. This fact confirms HEIM's interpretation of depth soundings after the slumps, when he concluded that most of the post-glacial muds on the steep slope in the path of slumping has been eroded by the downslope movement of the slumps.

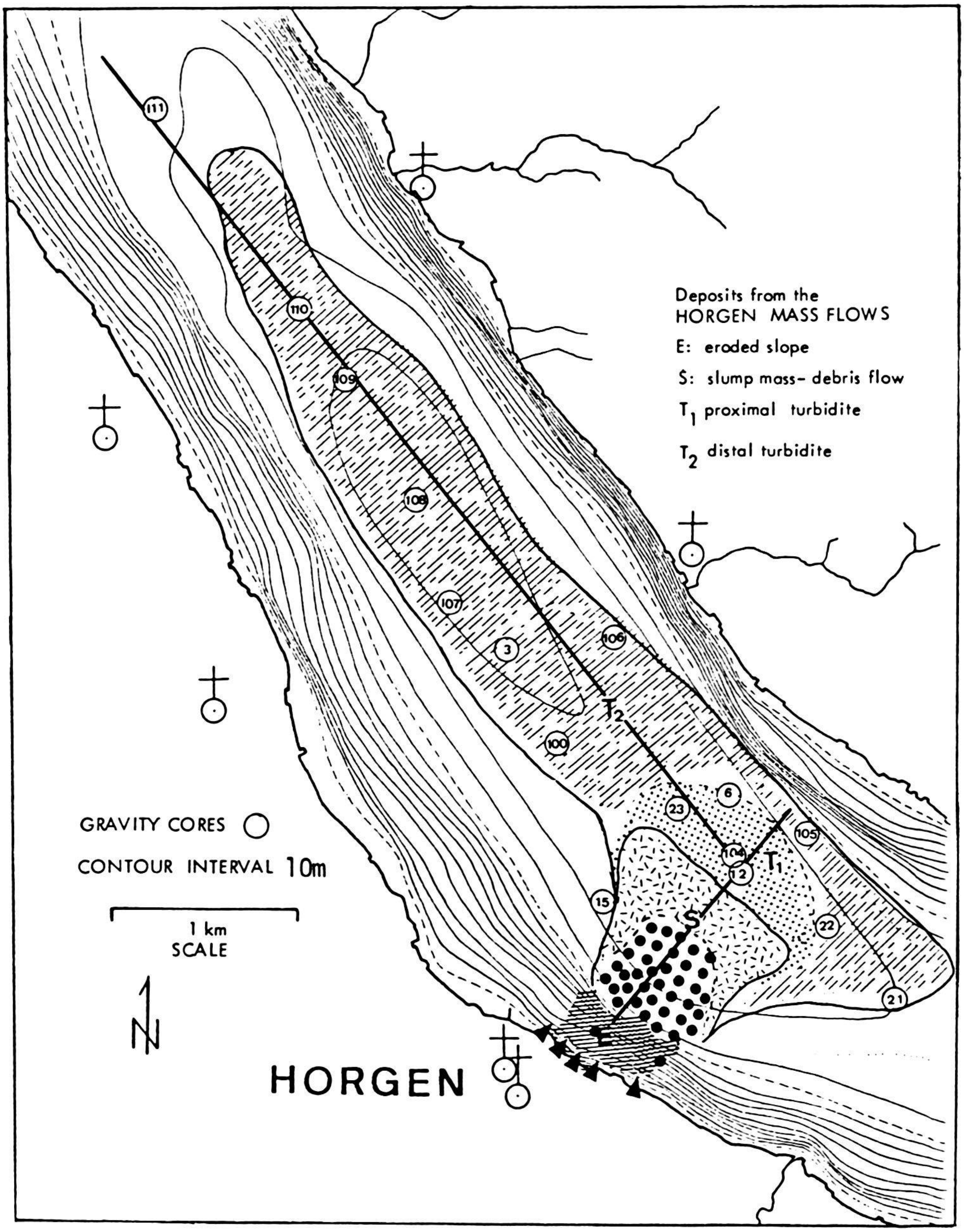

Fig. 1. Distribution of resedimented facies of the Horgen events, 1875, in Lake Zürich. Shows positioning of a piston-core cross profile (Fig. 2 & 3) and gravity cores used to compile a longitudinal profile (Fig. 4). Note the longitudinal orientation of the turbidite facies. Dotted contour lines for 100 m interval.

The Lake Zurich near Horgen is steep-sided and flat-bottomed. The steep side is about 18–20° down to 110 m depth and changes suddenly at the foot of the slope to an apron with 1–2° inclination; the latter is comparable to continental rise or to submarine fan in a deep-sea environment. The flat bottom is characterized by a very gentle longitudinal gradient; it averages about $4/_{1000}$ for several kilometers northwestward before it reaches the deepest spot of the lake at 135 m depth.

Whereas the slump eroded as it moved down the steep slope, the subaqueous apron and the flat trough bottom were the sites of resedimentation of deposits of the slump debris and the turbidite facies respectively. Their distribution within the Lake Zurich basin is shown by Figure 1. Deposition on subaqueous fan is characterized by transversed or oblique current transport, and that on basin plain by longitudinal current transport parallel to trough axis. In the outermost fringe of the fan toward the basin plain, the facies is transitional, where one finds thin proximal turbidite beds associated with slump debris. The zone of erosion has been traced by unsuccessful coring trials and by seismic profiling from the shore of Horgen to the foot of the slope where slump debris is deposited (Fig. 1). This broad erosional feature is comparable to submarine canyons in a deep-sea environment.

Slump-debris facies

Sediments from this facies include deposits of chaotically bedded pebbly or cobbly mud, mud-pebble "conglomerates", mud-pebble mud with syngenetic folds, and homogeneous mud (Fig. 2 and 3).

The chaotic deposit consists mainly of pebbly mud, which is similar to that of the slump facies of the upper-fan environment described by WALKER (1978, Fig. 12). Pebbles of stones are scattered in a fine-grained sediment with chaotic bedding. The largest pebbles were in cores near the slope break and have a diameter up to 6 cm, which is the diameter of the core barrel. In some cases, lacustrine chalk occurs as large blocks, not yet dispersed, so that sediment layering is still visible within the blocks. Pockets of coarse sand and of shale fragments are part of the detritus from the landfill that has been incorporated into the sediment-gravity flow.

We have not been able to penetrate to the bottom of this chaotic deposit. Seismic surveys have shown a fan-shaped wedge, 500 m in radius, extending from the slope break where it is about 10 m thick, to the basin plain halfway across the lake (Fig. 2). The bulk of the wedge consists of the pebbly dispersed mud layers. Several discordant erosional surfaces have been identified within the slump facies, they may mark the arrival of successive pulses of the Horgen events.

The mud-pebble "conglomerate" is found on the toe and locally (e.g. core 9) on the top, of the slump mass. A very similar sediment incidentally, has been found in the Holocene deposits near the slope break of the Hellenic Trench in eastern Mediterranean (RYAN, HSÜ et al. 1973, p. 262). In contrast to normal conglomerates with rounded clasts of lithified rocks, this type of "conglomerate" is composed of soft mud pebbles. The mud pebbles of Horgen slumps deposits include rounded "chunks" of lacustrine chalk, tillitic clay, and of semi-cohesive silty and sandy sediments. Like the pebbles in pebbly mud, the "conglomerate" clasts are also

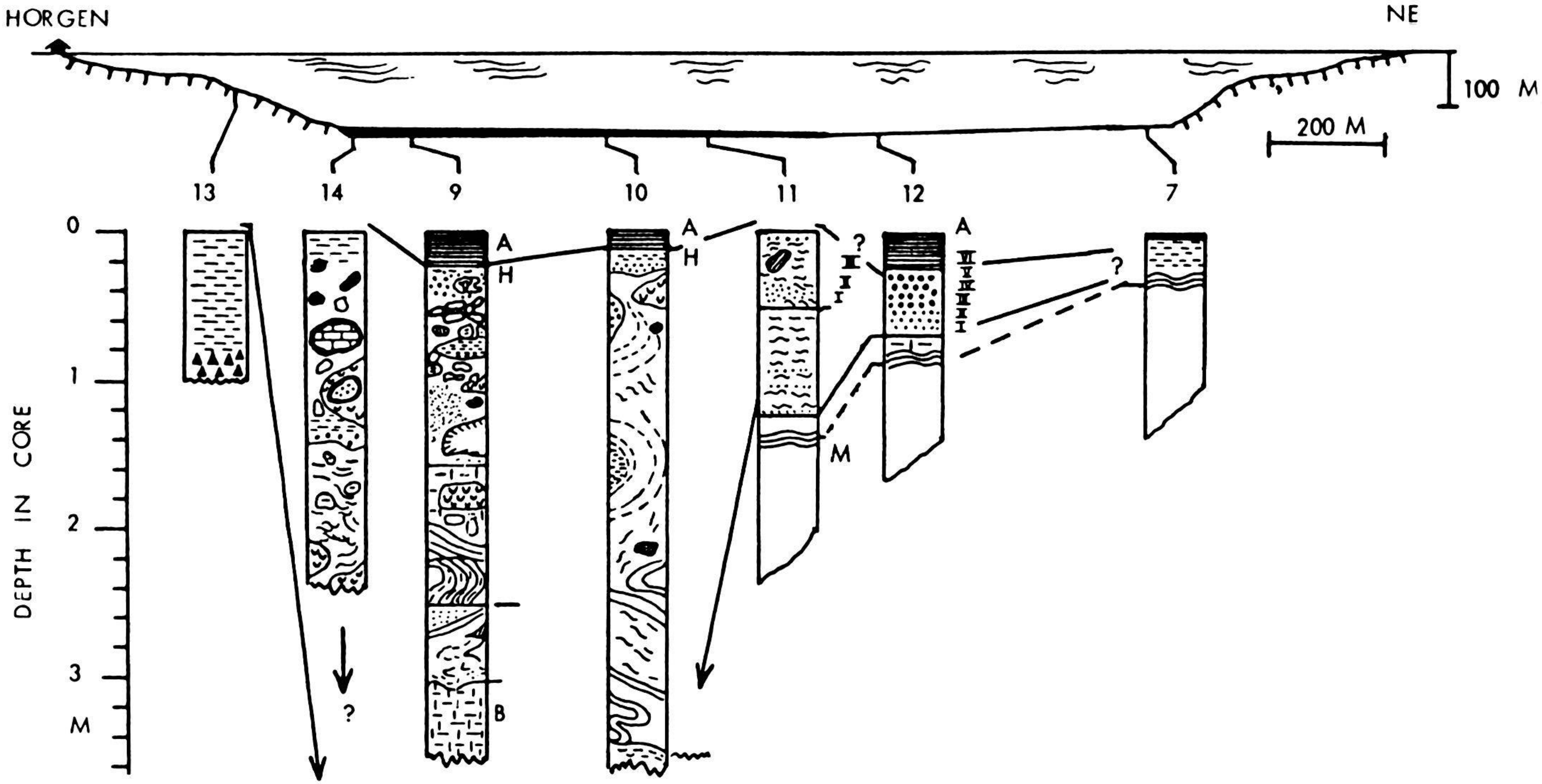

Fig. 2. Slump debris cross-section from piston cores. Upper part shows location of cores and lake bottom bathymetry without vertical exaggeration. Lower part illustrates core results with depth in meters. *A*: indicates black, organic-rich, varved muds overlying the Horgen deposits. *H* marks the top of the resedimented facies. Location 13 is on the eroded slope and contains only thin relicts of glacial mud. Thick (3–10 m) slump debris present at locations 14, 9 and 10. A transitional facies occurs above homogenized slump muds at location 11. Thin, coarse proximal sands were recovered from location 12 whilst fine-grained distal beds occur upslope at location 7.

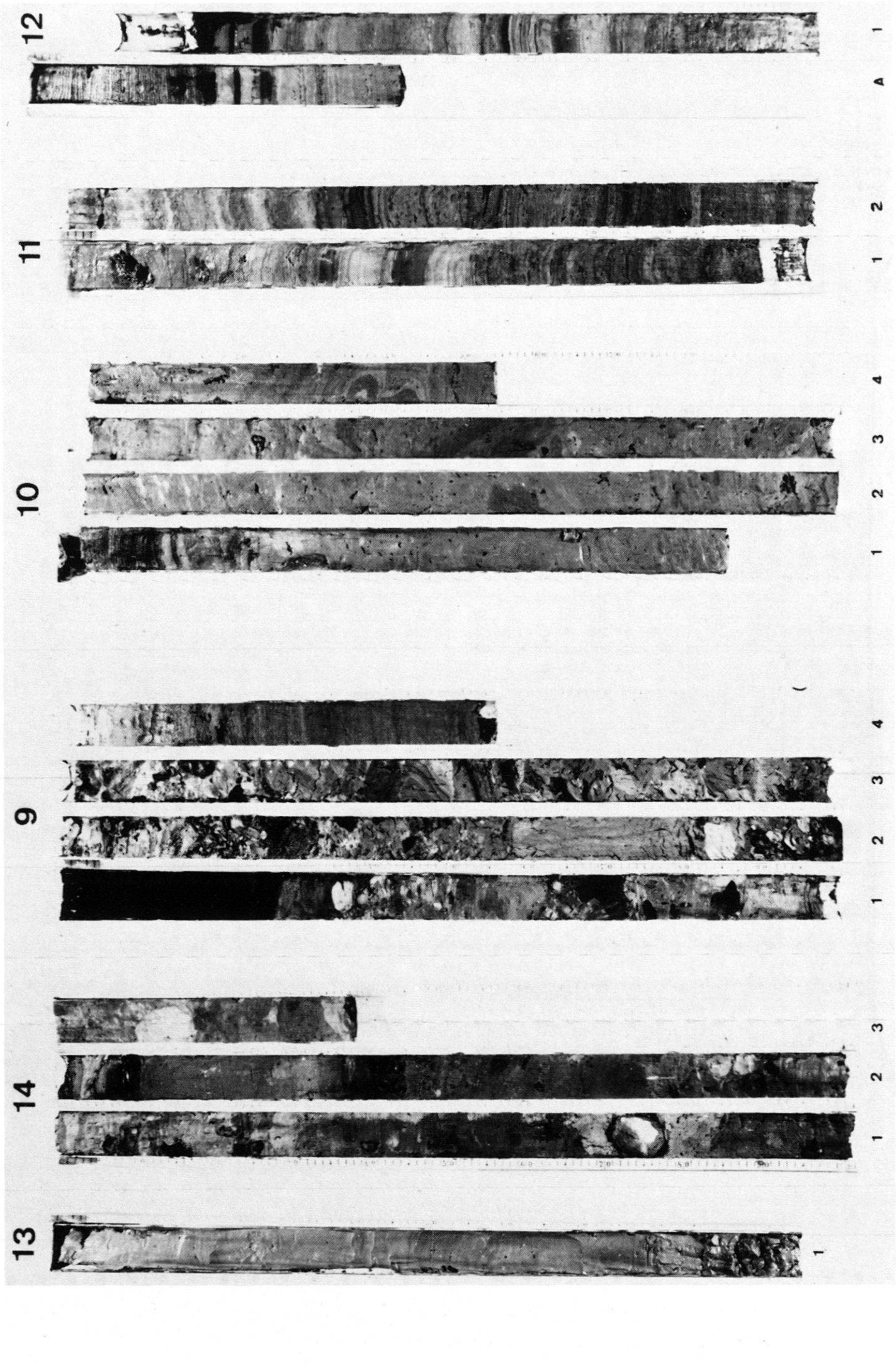

Fig. 3. Photographs of cores of slump debris for cross profile (Fig. 2). One meter long sections are numbered from top down. *A*: indicates a gravity core which shows the top 50 cm of Core 12 without disturbance.

supported by their muddy matrix. In most places, the "conglomerate" is overlain by a sand of the transitional facies.

The mud-pebble mud also occurs near the toe of the slump mass, where the layering within the slump mass has been thrown into folds of decimeters or meters in scale. A large part of the slump has, however, dispersed and homogenized to form a mudstone. Only a few undigested mud pebbles remain, but they are small and their outline is commonly rather diffuse. The pebble mud is at places overlain by sand without graded bedding, which belongs to the transitional facies.

Homogeneous mud is present only on the outer trim of the slump mass. This sediment is a fine-grained, brownish silty mud, containing some dispersed grains of coarse sand and pieces of wood. The homogeneous mud represents the final product of disaggregation during the slumping and was deposited after the catastrophic slide has been changed to a mud flow (= debris flow), which could spread farther out than the main slide mass.

Transitional facies

A coarse, ungraded, sand layer occurs along the outer fringe of the slump mass, and as mentioned previously, partly overlies the main slump deposit. The sand is grain-supported, with or without a mud matrix. The sand is present in the area beyond the slope break, where the catastrophic slide is believed to have been transformed into a turbidity current. The ungraded sand apparently was deposited by the turbidity current shortly after it underwent a hydraulic jump at the slope break (see KOMAR 1971). The sudden loss of transporting power led to the settling of coarse debris, while the finer debris, which normally forms the upper portion of a graded bed, was carried away by the current. Interpreting on the basis of our experiences with flume studies, we envision that the settling coarse sand, carried for some distance forward by the momentum, goes through a "grain-flow" stage before its final deposition.

Turbidite facies

Six turbidite beds have been identified in each of the cores which penetrated the turbidite facies. They are sands, silts and muds, showing distinct graded bedding and overlie with a distinct bottom contact, on the sulphide-pigmented lacustrine marls. In thin section, the turbidite sediments consist of various proportions of terrigeneous silt grains scattered in a mud matrix; they are thus petrographically easily distinguishable from the carbonate-rich (30–40%) light gray, structureless marls, which are the normal hemipelagic sediments of the lake.

The distribution of the turbidite facies in the basin plain environment clearly indicates that turbidity currents were generated by the slump events, and that the currents have been deflected from a northeastward transverse transport to a northwestward longitudinal transport (Fig. 1). The farthest transport distance is 7 km from the source.

The proximal turbidites include the coarse sediments deposited by the turbidity currents before their deflection (cores 12, 104, 23, see Fig. 4). They include two layers of coarse sand (beds III and VI), which have a maximum grain size of 1.5 mm. Those layers are more than 1 cm thick, and they show graded bedding. One coarse

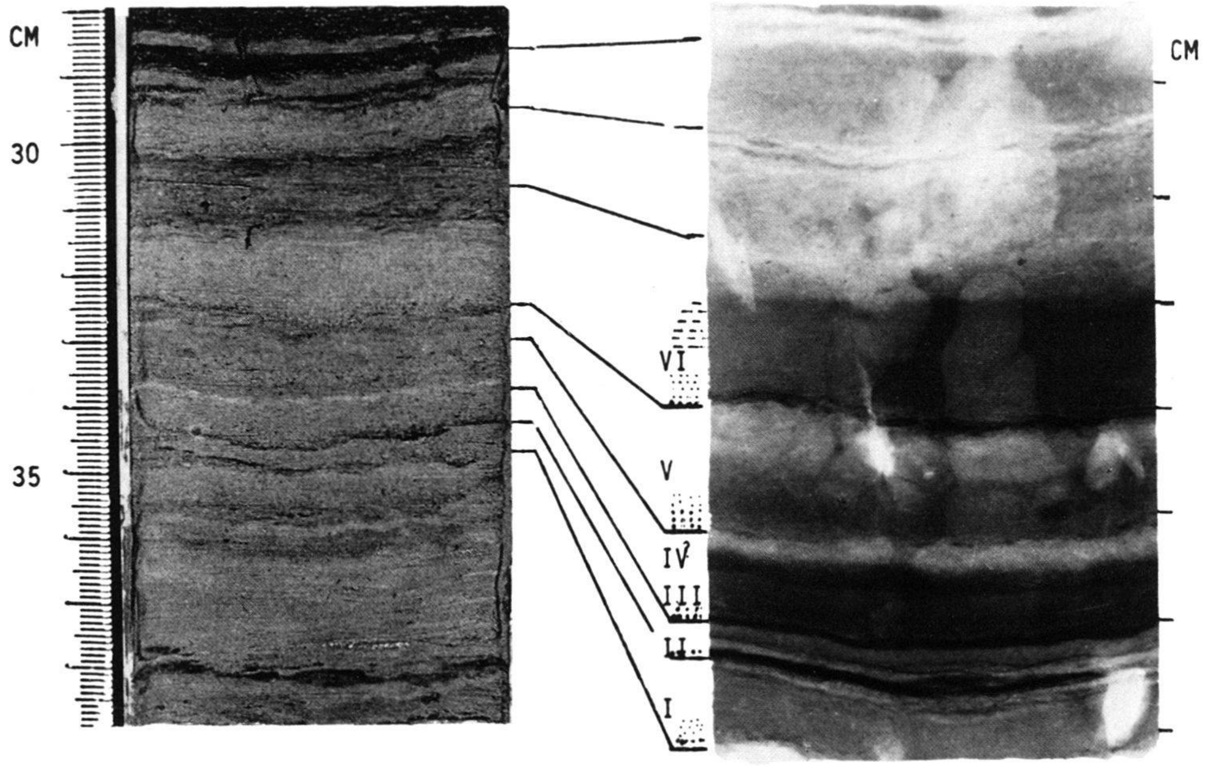

Fig. 4. Detail photograph and radiograph from thin graded beds from the Horgen events. Core is from 132 m water depth located at the base of the opposite slope, 2 km away from the source. Radiograph shows six thin layers with thin basal sands (dark) and distinct grading of the lutite fraction.

layer (in core 12) shows scouring and some faint cross lamination. The basal contact is invariably sharp, but the upper contact can either be gradational to lutite, or sharp.

The proximal facies has been traced from the outer fringe of the subaqueous fan at basin middle all the way to the opposite slope, where the sediments are much finer and are lithologically indistinguishable from distal turbidites (Fig. 4), except for the presence of coarse sand as laminae at the base of some layers. The deposition of those turbidites indicates upslope current transport, giving credence to an eyewitness account that faintly turbid water turned up as far as the shore opposite from Horgen (Heim 1908).

The main body of the turbidity currents generated by the Horgen slumps was deflected and turned into longitudinal transport. The distal turbidites on the basin plain are mainly silts and clays. Graded bedding is common, but no current laminations of any kind has been observed. This fact seems to contradict the common assumption that distal turbidites are characteristically cross-laminated. Paradoxically, finer distal turbidites are thicker than the proximal beds. Some distal layers are more than 20 cm thick, as a result of ponding in the deepest part of the lake (Fig. 5). The thickness of layers diminishes rapidly where the basin plain has a gentle ($<4‰$) counter slope. None of the currents were more than 10 m thick, because we did not find any turbidites on the basin flanks at depths 10 m shallower than the basin axis; this deduction is in agreement with the theoretical analysis by Kersey & Hsü (1976).

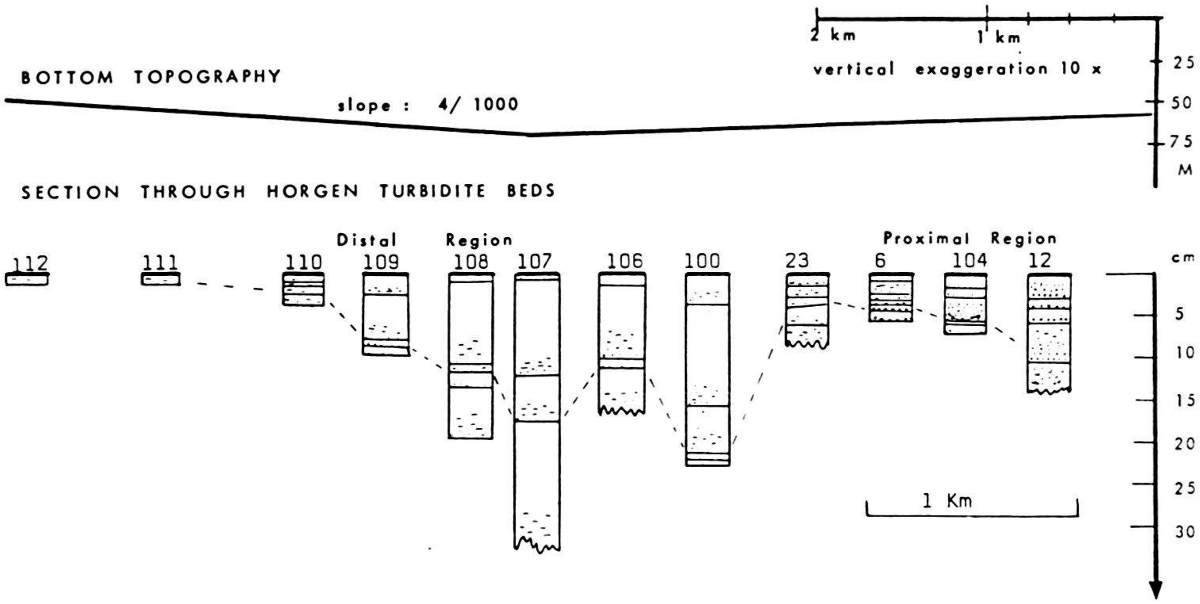

Fig. 5. Longitudinal profile of resedimented facies compiled from gravity cores (Fig. 1). Lithology changes from thinner beds of proximal sandy facies to lutite-rich, thicker distal beds which show ponding effects at mid-lake.

Because the six distinct graded beds identified in both proximal and distal deposits correspond to the number of phases of the Horgen slump, we believe that each phase generated one turbidity current. However, the thickness of the turbidite layers is not directly proportional to the size of the slump mass from near shore. In fact the two thickest layers (III and VI) correspond to two of the smallest masses (see Table). Two explanations could be offered: recalling the fact that the first slump in February was not carried into the deep until a later phase, one might postulate that several other slumps have also gone through similar intermediate stages; only the third and sixth slump did go "all the way". Incorporating previously half-slumped masses, they became the largest catastrophic slides that generated the most powerful turbidity currents. An alternative explanation is to assume that the larger slump masses were only partially disintegrated; they formed mainly the chaotic slump facies. The smaller (the third and sixth) slump masses, on the other hand, were more easily disintegrated and they produced more powerful turbidity currents to deposit the thickest turbidite layers.

Horgen events as a process model of longitudinal transport

The fan model of turbidite sedimentation has dominated our thinking during the past decade (see Walker & Mutti 1973; Normark 1978; Walker 1978); it was assumed that deposition took place on subaqueous fans at the foot of the steep slope of a deep-water basin. The presence of elongate turbidite bodies in a basin-plain setting is assumed to coalescent deposits of "suprafan lobes" (Walker 1978). Current transport in the regions of submarine fans is commonly transverse or oblique to the direction of shoreline, and that of the axis of an elongate basin, as diagrammatically illustrated by the fan model (see WALKER 1978). In fact, numerous paleocurrent studies indicate that the common transport direction of turbidity currents in flysch troughs or in elongate deep-water basins was parallel to the basin axis (see POTTER & PETTIJOHN 1977). Investigations of the Pliocene turbidites of the Ventura Basin have led to the recognition that basin-trough turbidites are commonly not coalescent fan deposits, but "shoe-string sands" deposited by longitudinal transport (HSÜ 1977; HSÜ et al. 1980). Nevertheless, the controversy continues because proponents of the fan model would not accept the apparently equivocal interpretations of ancient deposits. The Horgen events took place in 1875 and were recorded by history. The Horgen turbidites could be clearly identified as having been laid down from currents issued from a single source offshore from the village of Horgen; they are not "supra-fan lobes" sediments deposited by currents fed by a set of parallel subaqueous channels.

The Horgen catastrophic slumps have been induced by the loading of coarse clastics on weak formations in the shallow water of a steep-sided basin. Each slump was accelerated during its slide down the steep slope, became partially dispersed, and a very large volume of unconsolidated sediments (perhaps 10 or 15 times the original volume) was eroded en route and carried along as sediment-gravity flows. The bulk (about 60%) of the resedimented deposits was laid down as a wedge of slump debris to form a subaqueous fan. Meanwhile, a turbidity current was generated by each of the slump masses as it approached the slope break. After the current crossed the deepest part of the lake, it was deflected by the opposite steep side and was forced to turn sharply to flow longitudinally along the axis of the basin plain to deposit a turbidite layer.

This process model of longitudinal transport is identical to the one established by us on the basis of our investigations of the Plio-Pleistocene turbidites of the Ventura Basin (HSÜ et al. 1980). However, the sedimentary facies deposited in corresponding environments in Ventura are apparently different from those in Lake Zurich. The difference is easily understood because the Ventura Basin is about 10 times larger than the lake basin. The Plio-Pleistocene slumping masses at Ventura were about thousand times greater than those of Horgen and were thus able to generate larger and denser turbidity currents. Instead of a slump debris consisting of sands, silts and muds as in Lake Zurich, the submarine fan deposits at Ventura include cobble and boulder-size clasts in a muddy matrix. Also the basin-plain turbidites there, are mainly sands, much coarser in grain size than the lutitic turbidites of Lake Zurich. This comparison shows clearly that ancient deep-sea environments cannot be identified on the basis of recognizing sediment facies only: the "proximal facies" deposited by a small current on a subaqueous fan may be identical in its lithologic and sediment association to the "distal facies" deposited by a large current on the basin-floor province. One has to take into consideration the current-transport direction when a distinction between fan and basin-plain deposits is to be made.

Summary

Studies of resedimentation in Lake Zurich triggered by the Horgen slumps of 1875 indicated that turbidity currents can be generated by subaqueous slumping.

The deposits of catastrophic slump can move down very steep slopes and tend to accumulate at the foot of the slope to form a subaqueous fan. On the other hand, turbidity currents generated by the slump acquired so much kinetic energy that all but the coarsest debris were carried in suspension for a distance of 7 km to the deep part of the lake. Since the currents flowing down the steep side were deflected by the opposite slope of the narrow basin, the transport direction of the turbidites was mainly longitudinal in contrast to the transverse direction of the slump debris.

The trough facies of the Lake Zurich turbidites are silts and muds, not suitable as reservoirs of petroleum accumulations. However, the process of longitudinal transport suggests that denser currents in larger lake or marine basins could transport sands to the basin-plain province, as we found in Ventura Basin (Hsü et al. 1980). In places, such as the Tachin Oil Field of China, the trough turbidites seem to be the only suitable reservoirs in sediments of lacustrine facies (see Drake et al. 1977). The process model of turbidite sedimentation proposed by us should thus be of particular relevance to geologists exploring for oil in nonmarine basins.

Acknowledgments

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REFERENCES

Drake, C., Hsü, K.J., & Trümpy, R. (1977): *China revisited.* - Geotimes, p. 112-113.

Heim, Alb. (1933): *Bergsturz und Menschenleben.* - Fretz & Wasmuth, Zürich.

Heim, Arn. (1908): *Über rezente und fossile subaquatische Rutschungen und deren lithologische Bedeutungen.* - N. Jb. Mineral. *100*, 136-157.

Hsü, K.J. (1977): *Studies of Ventura Field, California. I. Facies geometry and genesis of Lower Pliocene Turbidites.* - Bull. amer. Assoc. Petroleum Geol. *61*, 137-168.

Hsü, K.J., Kelts, K., & Valentine, J. (1980): *Resedimented facies in Ventura Basin and a model of longitudinal transport of turbidity currents.* - Bull. amer. Assoc. Petroleum Geol. (in press).

Kelts, K. (1978): *Geological and sedimentary evolution of Lakes Zurich and Zug, Switzerland.* - Diss. ETH Zürich 6146.

Kelts, K., & Hsü, K.J. (1978): *Freshwater carbonate sedimentation.* In: Lerman, A. (Ed.): *Lakes: Chemistry, Geology, Physics* (p. 295-323). - Springer, Heidelberg.

Kersey, D.G., & Hsü, K.J. (1976): *Energy relations of density current flows: an experimental investigation.* - Sedimentology *23*, 761-789.

Komar, P. (1971): *Hydraulic jumps in turbidity currents.* - Bull. geol. Soc. Amer. *82*, 1477-1488.

Normark, W.R. (1978): *Fan valleys, channels, and depositional lobes on modern submarine fans: characters for recognition of sandy turbidite environments.* - Bull. amer. Assoc. Petroleum Geol. *62*, 912-931.

Potter, P.E., & Pettijohn, F.J. (1977): *Paleocurrents and Basin Analysis.* - Springer, Heidelberg.

Ryan, W.B.F., Hsü, K.J., et al. (1973): Init. Rep. Deep Sea Drill. Proj. *13*A.

Walker, R.G. (1978): *Deep water sandstone and ancient submarine fans: Models for exploration for stratigraphic traps.* - Bull. amer. Assoc. Petroleum Geol. *62*, 932-966.

Walker, R.G., & Mutti, E. (1973): *Turbidite facies and facies associations.* In: Middleton, G.V., & Bouma, A.H. (Ed.): *Turbidites and deep water sedimentation, Pacific Section* (p. 119-157). - Soc. Econ. Paleont. Mineral. Short Course Notes.