Annually Laminated Late-Glacial Sediments in the Eastern Baltic Countries and the Evolution of Ice-Dammed Lakes

The Eastern Baltic area (Estonia, Latvia, Lithuania and neighbouring regions) was freed from the continental ice in Daniglacial and Gotiglacial times, about 18,000 to 11,000 years ago. Against a background of a gradual climatic warming, a number of major cooling periods probably occurred, causing halts or even readvances in the ice cover and leaving markers in the form of distinct ice marginal formations. On account of the flat topography of the area, with small relative and absolute altitudes, and the inclination of the land towards the retreating ice in many places, the land in front of the edge of the glacier was covered with huge ice-dammed lakes, providing favourable conditions for the accumulation of varved clays and other types of laminated sediment.

It is not clear when the Eastern Baltic area was first inhabited, but the early hunters evidently moved northwards immediately behind the retreating ice. Thus the dating of the ice marginal formations and corresponding icedammed lakes is a matter of some consequence for resolving problems related to the oldest sediments and to human impact.

The dating of ice marginal formations is a complex problem, due to the lack of autochthonous organogenous material in glacial sediments. Interstadial sediments as a rule contain older, allochthonous material, mainly from Eemian deposits, and layers used for radiocarbon dating often contain intrusive elements such as roots etc. and are highly susceptible to the « hard water » effect which arises in connection with calcareous bedrock or limy till. Thus no entirely reliable ^{14}C dates have yet been obtained for this area.

The physical principles of another promising method, thermoluminescence dating, are still poorly understood, and the instrumental error is too great to permit its use for solving the problems discussed above. Meanwhile the palynological method cannot give us ages in calendar years, and in any case all Late-glacial sediments, which are mainly represented by clays, silts and sands, contain a great deal of redeposited pollen, hampering examination of the autochthonous pollen derived from the periglacial vegetation which may have existed in the area under ice-free conditions, and restricting the possibilities for arriving at reliable stratigraphical and palaeogeographical conclusions.

The investigation of laminated sediments therefore seems to be the most promising dating method by which to estimate with reasonable precision the speed of the glacial retreat, the points of arrest of the ice margin and the existence of ice lakes.

The evolution of ice-dammed lakes in the Eastern Baltic area has been reasonably well studied and summarized in a number of publications (see Aboltinš *et al.*, 1972; Aboltinš *et al.*, 1974; Kvasov, 1979). Three main stadials are distinguished in the history of the deglaciation in Lithuania and neighbouring countries (i.e. Poland and Germany): the Brandenburgian, Frankfurtian and Pomeranian. Conditions at the time of the maximum distribution of the ice (Brandenburgian zone) and during the following Frankfurtian period did not favour the formation of ice lakes, and the free outflow to the south and west allowed a well-developed river system to form, with the accumulation of large outwash plains, or sandurs.

Three phases are distinguished in the Pomeranian stadial: the maximum, the South Lithuanian and the Central Lithuanian. At the maximum the ice lakes and outwash plains were absent and the system of ice marginal formations was cut across everywhere by glacial meltwater rills which flowed into the major pra-Neris – pra-Merkis drainage artery to form the largest valley sandur in the Eastern Baltic. The development of sandurs continued in the South Lithuanian phase, with outwash material accumulating mainly in the glacial ice lobe depressions. Individual ice lakes were also formed, in which the thickness of the deposits amounted to as much as seven metres, e.g. near the settlement of Balberishkis in Lithuania (Mikaila, 1957).

The Central Lithuanian phase involved a large-scale development of ice lakes, particularly in the basins of the Rivers Jura and Syashupe. These lakes remained in existence for about 300 years and acquired some 13 metres of glaciolacustrine clays and silts, e.g. between Kaunas and Kaishyadoris (Mikaila, 1957).

The further retreat of the ice sheet across Latvia and Estonia was inseparably linked with the evolution of glaciolacustrine basins. The vast Nitzgale and Liubane basins, for instance, were formed in front of the Pampalo-Ranka ice marginal formations in eastern Latvia and the Saldius-Amuli basin developed on the East Kurzeme Upland in western Latvia. The glaciolacustrine clays and silts laid down in these bodies of water amounted to some ten metres.

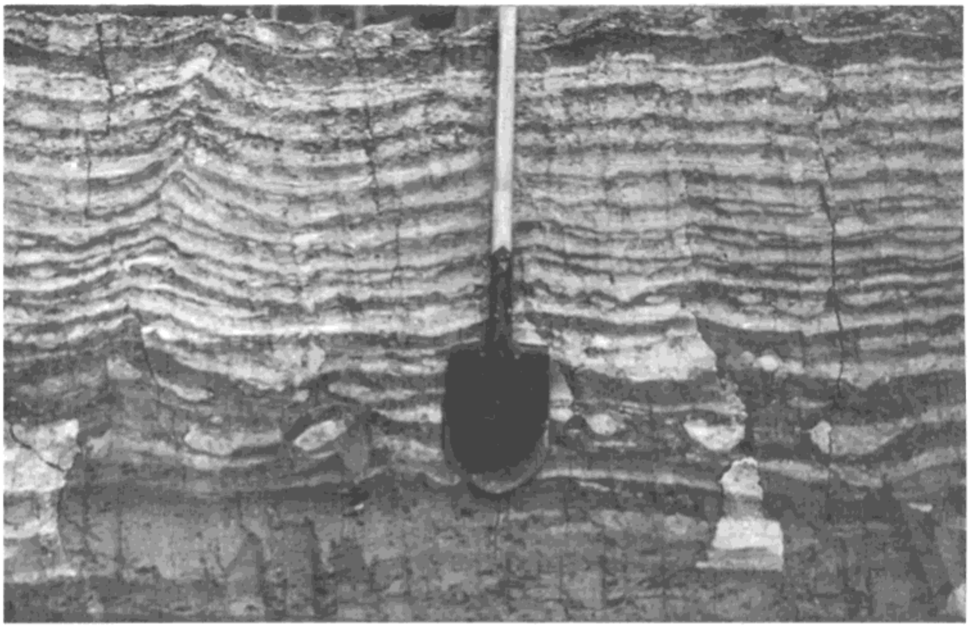

Plate 1. Varved clays in the Tsirgulinna clay pit (South Estonia), slightly deformed by freezing and tree roots. Photographed by E. Pirrus.

In eastern Latvia, the Gauja, Daudze and Venta-Usma ice lakes (Aboltinš *et al.*, 1974) were formed in the marginal zone of the Luga (Linkuva, Haanja) stage, which marks the transition from the Daniglacial to the Gotiglacial (Serebryanny and Raukas, 1966). According to Kvasov (1975), these basins belonged to the Baltic system of ice lakes. Large bodies of water formed in western Estonia and the Peipsi depression (Raukas *et al.*, 1971) in front of the ice margin in the Otepää-Pliena, Sakala-Valdemarpils and Pandivere zones. In consequence of the tilt in the earth's surface towards the glacier, large glaciolacustrine basins came into being in the Palivere zone in northern Estonia, where the thickness of the varved clays attains 26 metres in places, e.g. near Loksa in the Lahemaa National Park. The data presented above show that the compilation of a reliable varvometric scale for the northern and central Baltic area is indeed a feasible task.

The technique used for counting the annual layers in varved clays (Plate 1) is a simple one, and has been widely discussed in many papers. It is based on the assumption that the formation of varves on the bottoms of the ice lakes began immediately after the ice receded from a given point. The further the ice had receded, the greater the area of annual laminated sediments became (Fig. 1). Things are much more complicated in practice, however. Sometimes one cannot dig through the thick mantle of varved clays, while it is difficult to detect secondary disturbances in bedding

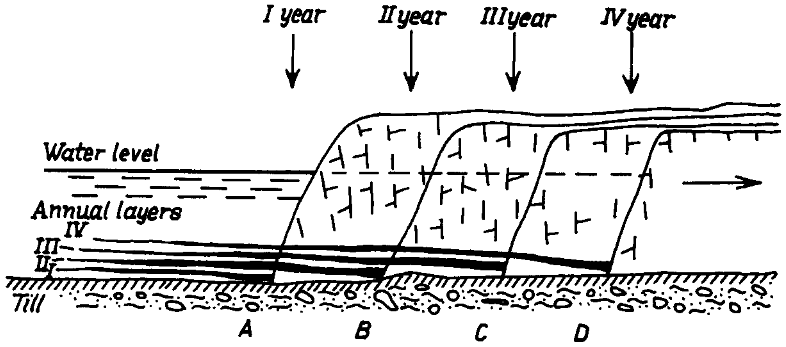

Fig. 1. Basic scheme for the formation of varved clays, according to Krasnov (1955).

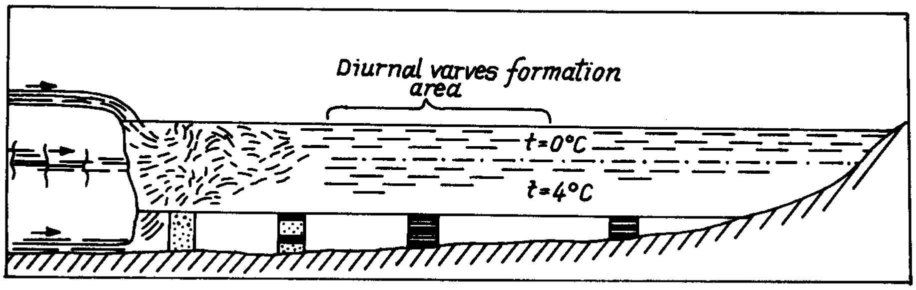

Fig. 2. Model for the sedimentation of diurnal varves, after E. Pirrus (1968).

in boreholes (Plate 2). Annual layers are far from always identifiable, and in any case the seasonal lamination is frequently accompanied by the arrangement of material in layers within one annual cycle. The most favourable conditions for the formation of what we call diurnal varves seem to have existed about 500-1000 metres away from the ice margin (Fig. 2), i.e. in parts of the basin with clearly differentiable layers of water of varying density and temperature, which promoted calm sedimentation. According to E. Pirrus (1968), the area in which diurnal varves are usually formed extends for up to 5-6 kilometres from the ice margin.

Although the investigation of « diurnal » laminations may provide valuable information on the details of the formation of deposits in sedimentary basins, particularly with regard to the climate under which the clayey deposits accumulated, they constitute an obstacle to geochronological investigations because it is sometimes difficult to distinguish diurnal rhythms from annual ones.

In order to achieve reliable correlations, additional criteria should be found. The first of these are reference layers, which are different from ordinary varves and may be formed in the course of unusually warm or cold years (being markedly thick or thin respectively) or as a result of rapid

Plate 2. Annually laminated sediments, highly deformed under ice pressure, at Kuzmolovo, St. Petersburg District. Photographed by O. Znamenskaya.

changes in water level in the basin. The thickness of the « drainage » varves, created when waters of one of the ice-dammed lakes broke through into another, can be as much as 50-80 cm in this area (Rähni, 1963).

The correlation of the NE Estonian varve series with those of the Luga basin in the St. Petersburg district, for example (Rähni, 1963) is based mainly on a drainage varve series showing that the Luga and Neva basins were joined about 12,000 years B.P., when the ice margin receded from the klint edge near the village of Koporje (Markov, 1931). This event, which occurred twice, in the 79th and 111st years of the existence of the Luga basin, was used as a fixed point for dating the ice retreat from the Pandivere Upland and from the Pärnu line (Raukas *et al.*, 1969).

In practice, however, the correlation of ice marginal zones on the basis of varve chronology is much more complicated, because the retreat of the ice altered many times, with intervening new advances.

It would be very difficult or even impossible to estimate how many years it took for the ice margin to retreat from a chronologically dated line to the north and to readvance back to a new line. What is more, we do

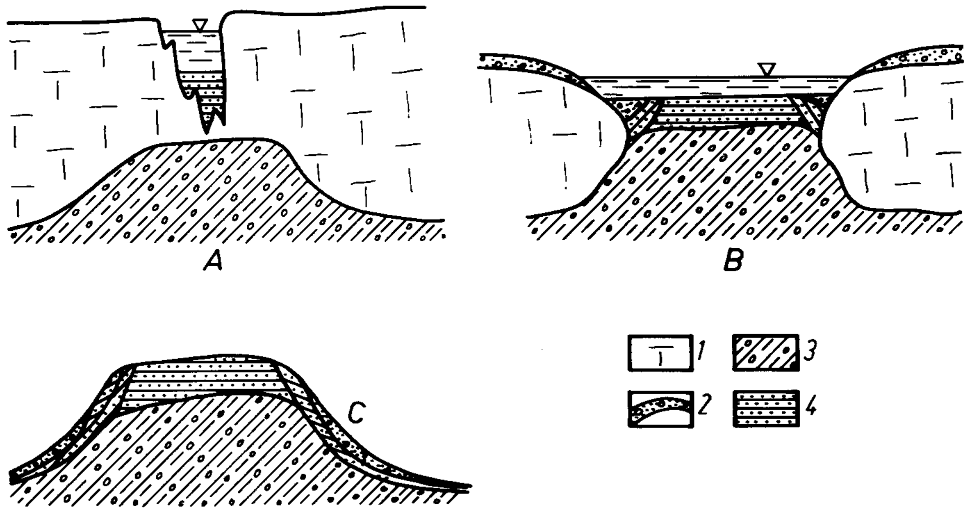

Fig. 3. Stages of formation of superposed limnoglacial kames (« zvontsy ») on a morainic base : A : formation of cracks in the ice under the influence of the underlying topography ; B : ice-walled lake ; C : complex hillock after melting of the ice. 1 : ice ; 2 : surficial till on top of the ice ; 3 : basal till ; 4 : glaciolacustrine sediments. Compiled by R. Karukäpp.

not know how far the ice margin retreated before it was subjected to a new advance.

Growing support is being found nowadays for the notion of a relatively conservative character for the Fennoscandian ice sheet during the Pleistocene, when it displayed a limited scale of stadial movements and a considerable spread of stagnant ice fields.

This idea is also reflected in the structure of the Estonian varved clays (Pirrus, 1968), since the thickness of the varves in glaciolacustrine sediments decreases regularly towards the upper horizons and the varves formed in the proximal parts of the ice-dammed lakes are usually overlain by layers deposited in the central parts of the lakes, which are in turn covered by those of the distal zones, all of which is indicative of a more or less gradual retreat of the ice margin.

Varve counting for correlation purposes is possible only in large ice lakes, although the configurations of the lake undoubtedly changed rapidly due to the retreats and readvances of the ice, with the connections between lakes closing and opening again and many of the lakes drying up. In the case of distant correlations, it should be borne in mind that single ice flows could have existed and developed independently, depending on the subglacial topography, feeding type, regional climatic peculiarities and other factors, which also complicates the correlation of varves. In view of this, qualitatively new methods of correlation are needed.

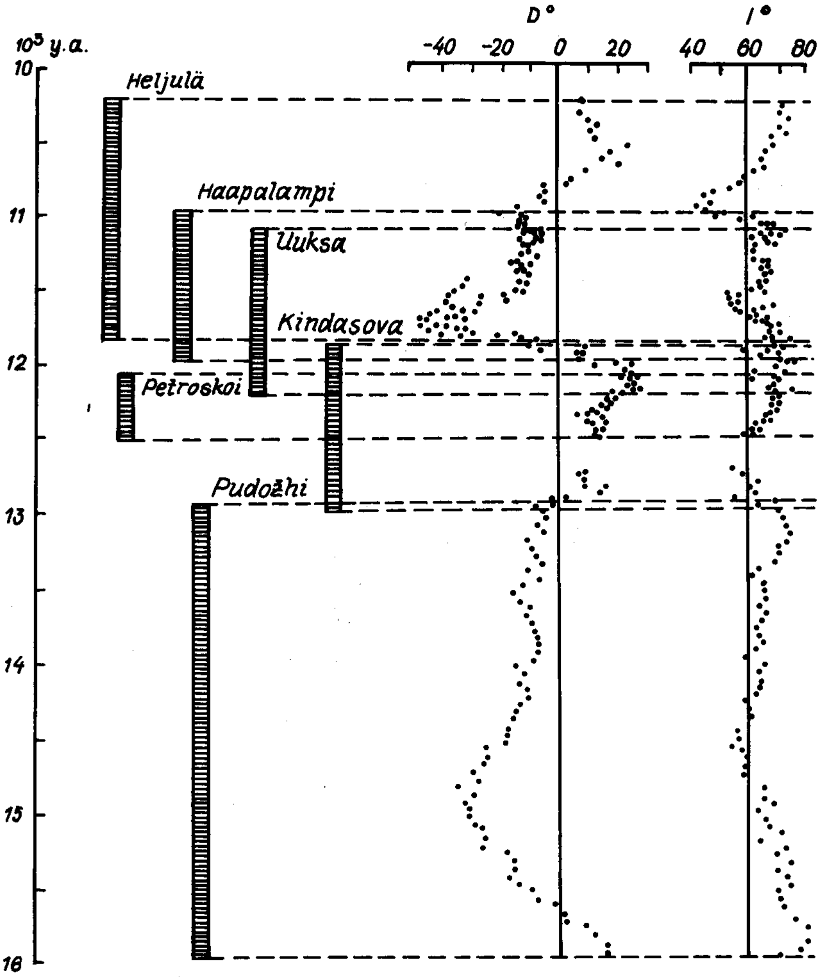

Fig. 4. Correlation of Karelian varved clay sections based on palaeomagnetic data, after Ekman et al., *(1987). D° : declination, I° : inclination.*

The palaeomagnetic method shows great promise, since it enables one to correlate varved clays in different glacial lakes over a vast area. Records of variations in inclination and declination can then be correlated both with each other and with reference curves from other countries. The Late-Glacial palaeomagnetic chronology compiled for the St. Petersburg area and Karelia (Ekman *et al.*, 1987) covers about 6000 years (Fig. 3), and detailed curves of declination and inclination changes in the geomagnetic field have been compiled for the time span 16,000-10,000 years B.P. But we would like to point out that the magnetic method used for the correlation of ice lake sediments contributes to the adjustment of the existing chronological scales and to the determination of the time succession of events in different

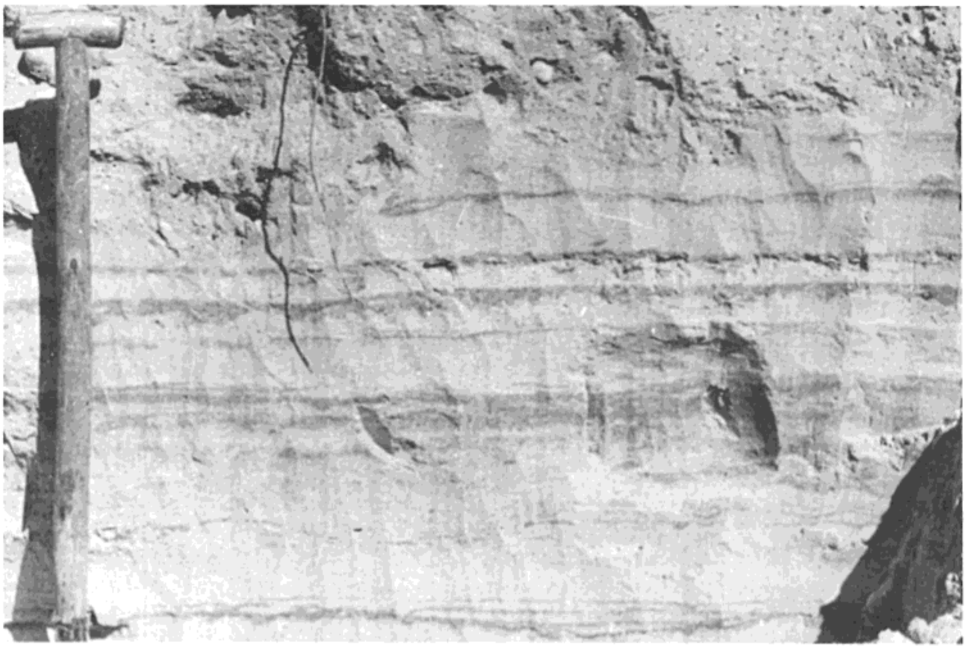

Plate 3. Horizontal annual (?) lamination in a limnoglacial kame near Palivere, Estonia. Photographed by A. Raukas.

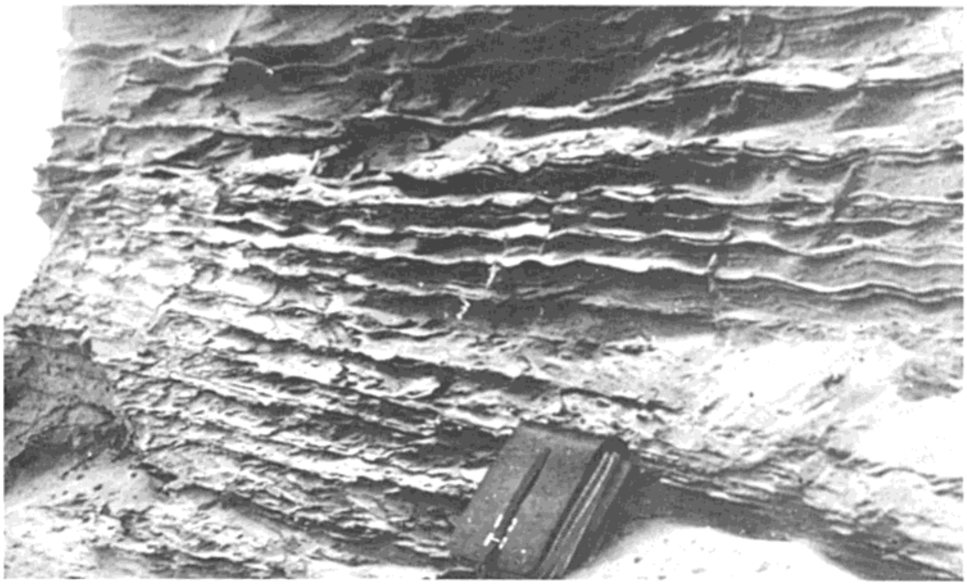

Plate 4. Wave-like annual (?) lamination in a limnoglacial kame at Toksovo, St. Petersburg District. Photographed by O. Znamenskaya.

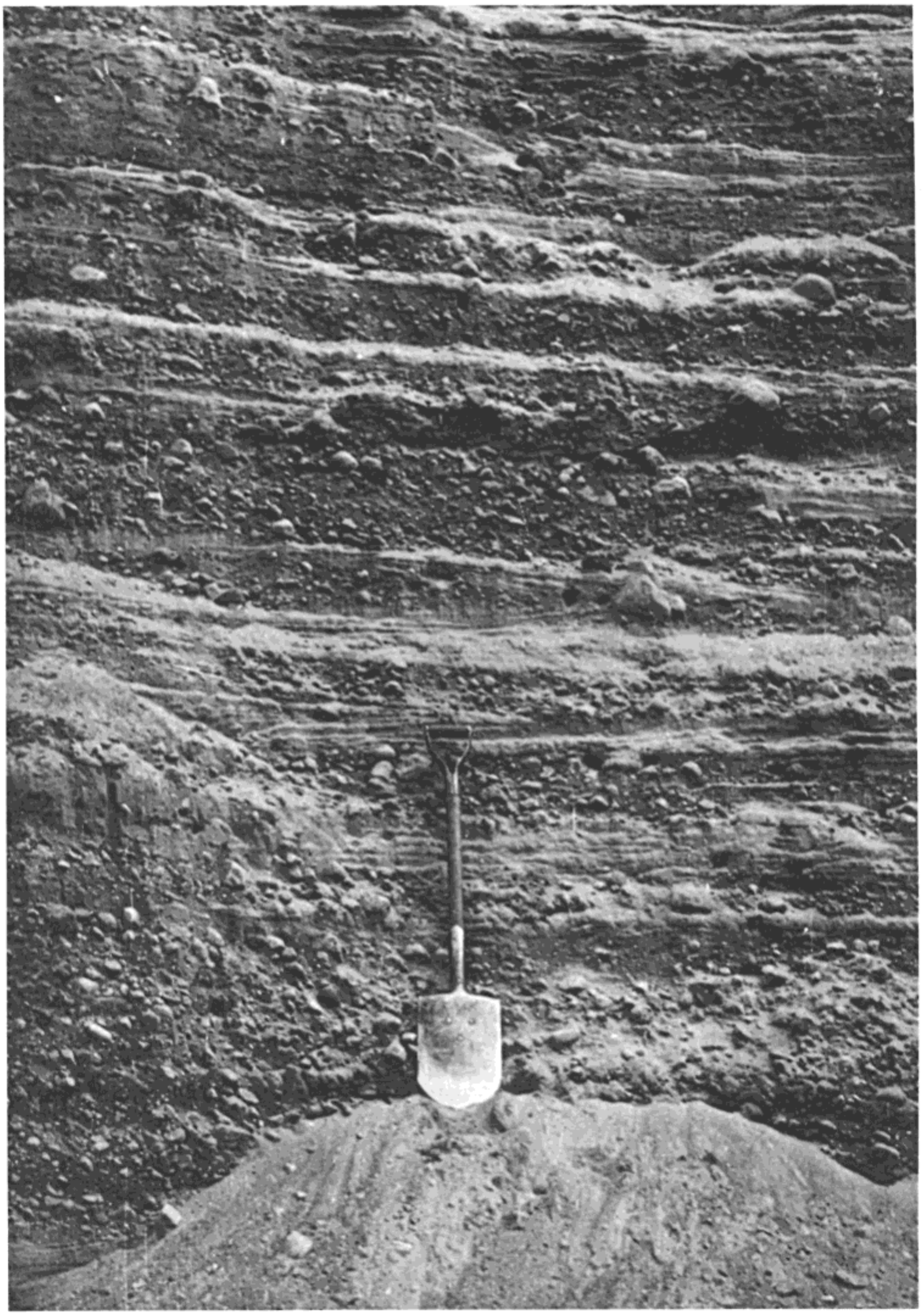

Plate 5. Horizontal bedding in the central part of a glaciofluvial kame in the Bogushishkes gravel pit, commune of Alitus, SE Lithuania. Photographed by A. Jurgaitis.

regions and cannot be considered an absolute dating method (Bakhmutov *et al.*, 1987). Interpretation of the susceptibility variation records shows the great sensitivity and effectiveness of the method, however, supporting the lithostratigraphic correlations. Measurements of the anisotropy of susceptibility can also reveal a disturbed fabric in the sediments.

Glaciolacustrine sediments also accumulated quite often in small ice-walled lakes, so that the clayey bottom deposits were preserved on the tops of morainic hillocks after the ice-walls had melted (Fig. 4) while the beach deposits slid down the slope. These small, isolated outcrops of clay up to ten metres in thickness are for the most part devoid of any distinct annual lamination, because the influence of sedimentary material came from different sides of the basin and the distance was not far enough for proper differentiation of annual layers. Such superimposed kames are widely distributed on the insular heights (Haanja, Otepää etc.)

In many places on the morainic base we cannot find any clays but only silts and sands, which sometimes form huge glaciolacustrine plateaux several square kilometres in area with steep slopes (up to 25°) and level tops up to 50 metres in height. These are termed « zvontsy » in Russian publications. Superimposed complexes of this kind often display a stratification similar to annual layers of varved clays. Horizontal lamination prevails in most cases (Plate 3), but occasionally they have a wave-like lamination (Plate 4). If these are annual layers, then the glaciolacustrine plateaux were formed in the course of 200-400 years (Raukas *et al.*, 1971).

Cyclic lamination is frequent in the bottomset beds of glaciofluvial deltas, glaciofluvial kames (Plate 5) and even eskers, but it is very difficult to say how long the formation of such stratification took.

In conclusion, it may be stated that the annual character of lamination must be established separately in each case, and the importance of varve counting cannot be overemphasized. Sometimes microfossil (pollen, diatom), X-ray and chemical analyses are needed, but only careful revision of the dates and joint use of varve chronology, palaeomagnetic investigations and other methods can give reliable results in the correlations and varve teleconstructions necessary for elaborating a palaeogeographical hypothesis and investigating the impact of humans on their surrounding.

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