CONSOLIDATION OF FINNISH SEDIMENTS BY LOADING ICE SHEETS

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AARIO, RISTO 1971: Consolidation of Finnish sediments by loading ice sheets. *Bull. Geol. Soc. Finland 43*, 55—65.

In the following the consolidation properties of clays are studied in Kimola and Ylikiiminki, Finland and, the general possibilities of the overconsolidation in the Finnish sediments created by the former overriding ice sheets are discussed. In general the conditions have favoured the sediments becoming consolidated by the glacier load and also for the consolidation properties to be preserved in the later history. In some environments the consolidation could, however, have been prevented or been partially or wholly lost. Because of this the non-existence of overconsolidation is not always significant as a negative evidence of a readvance of the ice sheet but greater confidence can be placed on the existence of overconsolidation.

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Introduction

Sediments are consolidated by mechanical loading to an equilibrium state corresponding to the load. If the sediments are later more or less unloaded, *e.g.* by a disappearance of overlying deposits, a slight rebound takes place and the volume of the consolidated sediments will increase accordingly, but a major part of the previous degree of compaction will remain. The sediments are now overconsolidated in respect to the new load. An overconsolidation, however, may also be resulted from reasons other than mechanical load (p. 57).

The degree of consolidation with the excess overburden pressure (kg/cm²) of possibly over-consolidated sediments may be measured by various well established laboratory procedures and can be used as a tool in deciphering the geological history of the sediments *(e.g.* Kögler and

Fig. 1. Studied sites. 1: Kimola, 2: Juminkangas, Ylikiiminki.

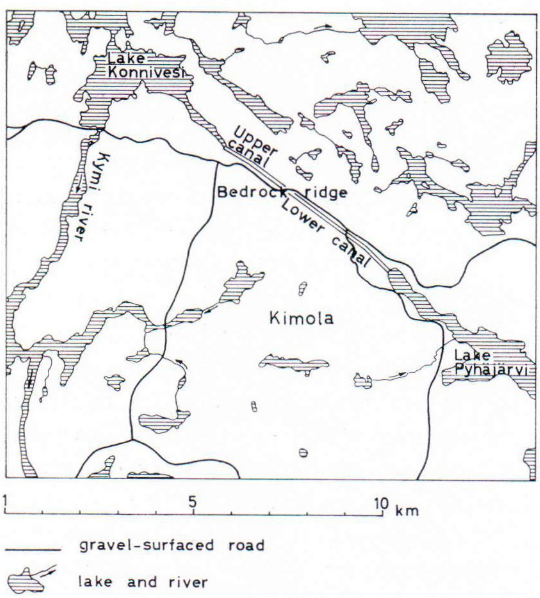

Fig. 2. The Kimola canal area.

Scheidig 1948; Dücker 1951; Keller 1954; Harrison 1957, 1958; Terzaghi and Peck 1962, p. 71; Gardemeister 1967, 1968; Korpela 1969, p. 80). In this paper the consolidation properties of sediments are studied at two sites, Kimola and Ylikiiminki, Finland (Fig. 1) and the general possibilities of the overconsolidation in the Finnish sediments by the former overriding ice sheets are discussed.

Consolidation of clays in Kimola canal

The Kimola canal dissects a thick sequence of glacial and postglacial clays in a valley crossing the belt of the Second Salpausselkä system. It runs from Konnivesi, Iitti, in the northwest to Pyhäjärvi, Jaala, in the southeast (Fig. 1 and 2). The canal is divided by a bedrock ridge, about 1.6 km from Konnivesi, into the upper canal and the lower canal. In the lower canal the clay beds are continuous down to Pyhäjärvi, but in the upper canal the continuity is broken by a till ridge near the northwestern end.

A description of the geological history of the valley area has been given by Risto Aario (1965). After the first retreat of the continental ice sheet the valley experienced a readvance from the northwest. It was, however, only of short duration as evidenced by varved clays. The date for the final retreat of the ice from this area is about 10 400 B.P. (see also Hyyppä 1963; E. Nilsson 1964). After the withdrawal of the ice the area remained submerged until it emerged by land uplift from the Yoldia sea before the end of the birch period in pollen chronology. The C^{14}-age for the birch/pine boundary is here about 9 400 B.P. (corrected by the coefficient 1.03). The cryoturbation features found in the strata were probably formed at that time. The lower part of the valley was later submerged by a Baltic transgression, probably Ancylus, and a new emergence occurred in succession.

A thorough study of the clays and their geotechnical properties was carried out during

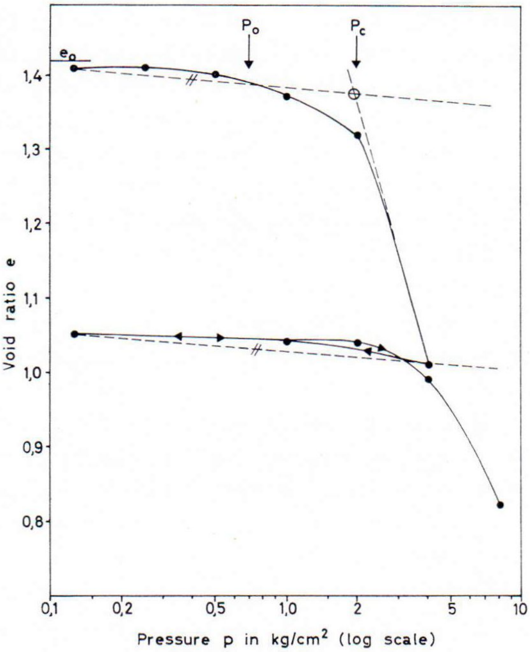

Fig. 3. A typical consolidation-test curve of the overconsolidated clays from the station 43+00 in the upper canal, Kimola. Original ground surface 91.1 m, sampling level 83.5 m a.s.l. Courtesy, Dr. E. Kankare.
Symbols: e void ratio
e_0 void ratio at natural state
p_c consolidation pressure obtained by means of the Ohde method
p_0 effective overburden pressure of the sample in the field

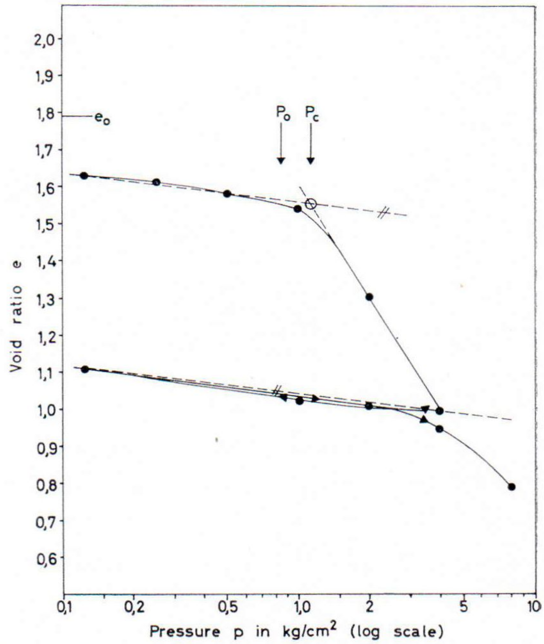

Fig. 4. A typical consolidation-test curve of a slightly (or not at all) overconsolidated sample of clay from the state 52+70 in the upper part of the lower canal, Kimola. Original ground surface 73.3 m, sampling level 62. 9 m a.s.l. Courtesy, Dr. E. Kankare.
Symbols: See fig. 3.

the planning and construction of the canal (Kankare 1967, 1969). Both in the upper end of the lower canal and in the upper canal the clays were found to be overconsolidated. In the former the overconsolidation is slight, corresponding approximately to 0.5 kg/cm² and in the latter it is distinct, corresponding to about 1.3 kg/cm² mechanical load (Kankare 1969, p. 35 and 102). A typical example of the consolidation-test curves from the station 43+00 in the upper canal showing overconsolidation is given in fig. 3. The clays of the example test curve in fig. 4 from the station 52+70 in the upper part of the lower canal can be considered to be slightly overconsolidated or normally consolidated.

The excess stress to which the overconsolidated clays have been subjected may have been set up by a mechanical load, though this is not necessary (see Kankare 1967, 1969, p. 34). Cementing with the development of chemical bonds between particles, hardening due to secondary consolidation and mineralogical changes involved in the initial diagenesis can also be responsible for an overconsolidation (see *e.g.* Grim 1953, pp. 348—366; Harrison 1958; Terzaghi and Peck 1962; Keinonen 1963, p. 78; Bjerrum 1967, p. 96 and 108; Kenney, Moum and Berre 1968; Gillot 1968, pp. 42—50; Kankare 1969, p. 34). A thorough drying of the sediment could also produce capillary forces of several thousands of atmospheres and give dried

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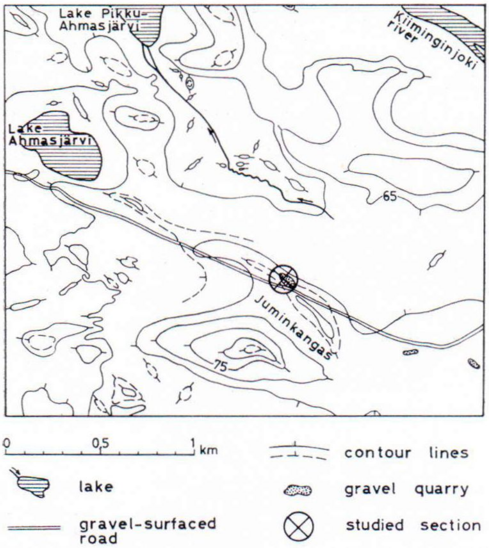

Fig. 5. The Juminkangas site in Ylikiiminki.

up clays similar properties to the clays preconsolidated under load (see *e.g.* Gillot 1968, p. 45; Kankare 1969, p. 34).

The geological studies show no disappearance of former deposits in the areas of overconsolidation, which could have formed the mechanical loading responsible for the preconsolidation. In addition it seems to be difficult to find a reliable explanation from the other phenomena mentioned above. According to Kankare (1969, p. 35 and 102) the causes for the overconsolidation are not clear either in the lower or in the upper canal.

If we study the areal distribution of the overconsolidated clays, we can see that the overconsolidation is higher in the upper canal in the northwest, slight in the upper part of the lower canal and does not exist any longer towards the southeast. The area thus coincides with the area once covered by the readvance of ice coming from the northwest (p. 56 and R. Aario 1965). The magnitude of overconsolidation also corresponds to the probable relative differences in thickness and the loading time of the lobe. The greatest values are from the upper part of the valley, in the direction of the oncoming glacier lobe. These data thus suggest that the preconsolidation was derived from the glacier loading; this possibility cannot be proved conclusively though. The idea could, however, be further supported by the thorough earlier studies of Kögler and Scheidig (1948), Dücker (1951), and Harrison (1957, 1958) who recognized and measured similar compaction of sediments brought about by glacier load. They also estimated the thicknesses of the former glaciers from the measured consolidation values. In Finland overconsolidation due to the loading of overriding ice has been demonstrated by Korpela (1969, p. 80) from Finnish Lapland and by Gardemeister (1968, p. 34) from Somero, South Finland.

The rate of consolidation has been mainly controlled by the drainage conditions of the sediments during the loading (see Terzaghi and Peck 1962, pp. 71—76 and 233—242; Gillot 1968, p. 264), which are difficult to estimate with sufficient accuracy. A possibility exists therefore that the final equilibrium state of consolidation corresponding to the full load did not result at every point owing to the short duration of the glacier advance. This could be indicated by the somewhat smaller overconsolidation at greater depths (see Kankare 1969, p. 102) closer to the less permeable igneous bedrock. As the ice lobe, suggested to be possibly responsible for the overconsolidation, was also supported by deep water that decreased the effective pressure of the ice masses, it is not necessary or even probable that the measured overconsolidation values in this case could directly reflect the thicknesses of the overriding ice.

Consolidation of clays in Juminkangas ridge, Ylikiiminki

In Ylikiiminki, a gravel quarry in Juminkangas esker, about 25 km east of the Oulu city, was

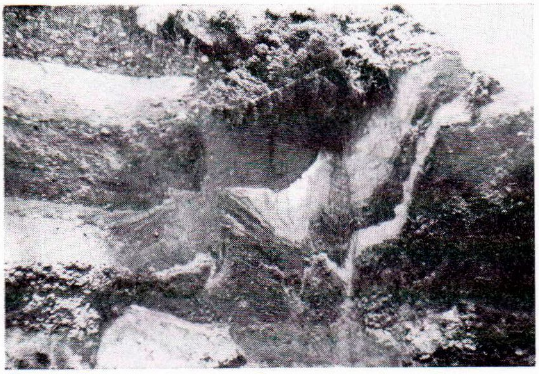

Fig. 6. Faulted bodies of gravel and sand in the southwestern part of the studied section in the Juminkangas ridge, Ylikiiminki.

Fig. 7. A deformed body of silt and clay under gravel in the ice contact northeastern part of the studied section in the Juminkangas ridge, Ylikiiminki.

chosen for the study (Fig. 5). The esker runs from the northwest to the southeast (Hyyppä and Penttilä 1961) thus coinciding with the general trend of the ice movements observed in this area (Okko 1960). The following stratigraphy was established by frequent visits to the site as new sedimentary faces were opened by quarrying.

The section is composed of nonstratified to stratified drift with all gradations. The southwestern part is mainly stratified with only some occasional interbedded bodies of poorly sorted material in it. The sorted material shows ripple-lamination of the ripple-drift type to the sinusoidal type of Jopling and Walker (1968) and implies a dominant current direction from the northwest, parallel to the long axis of the ridge. The strata are disturbed by several faults but other postdepositional deformation is not commonly present (Fig. 6).

In the northeastern part of the section the material is not on the whole as well sorted and it includes coarser grades. However, all gradations exist between nonsorted and well sorted material, till and stratified drift respectively. They change horizontally and vertically into each other with boundaries both gradational and abrupt. Collapses, contortion, folds and faults are common (Fig. 7). The northeastern part of the esker is further characterized by well preserved to badly deformed units of clay and silt incorporated in the poorly or nonsorted material. Some of the units are blocks with sharp edges and were most likely frozen during sedimentation and deformation. The strata also show load casts due to an uneven loading of sediments (Sullwold 1959, p. 1247; Potter and Pettijohn 1963, p. 147).

The esker ridge is capped in many places by a horizontal layer of washed but poorly sorted material, which generally sits discordantly on the underlying deposits. The faults and other kinds of deformation do not continue into this horizon, a littoral accumulation of the Baltic sea.

The stratigraphy reveals an ice contact origin for the esker. It was built by a stream running through the ice sheet from the northwest to the southeast parallel to the general ice movements. When being formed the northeastern part of the studied section bordered against the ice that was still active. The ice overrode at least part of the ridge leaving units of till between stratified drift, and disturbing and compacting the underlying deposits. Some of the material was frozen during the overrun and deformation. The freezing of the sediments may have taken place during the overrun or already prior to it by a cessation of water flow in the esker building channel. Other characteristics of the ice contact environments (see *e.g.* Hoppe 1963; Flint 1967, p. 146) were further responsible for many irregularities and disturbances in the strata.

The till left by the active ice and much of the other evidence suggesting the overrun are incorporated in the internal part of the esker ridge, and consequently the esker and the overrun are contemporaneous. The overrun, possibly only short-lived and very local, most likely dates from the latest deglaciation phase of the area.

After the final retreat of the ice sheet the area was left submerged by the Baltic until the uplift later raised it out of the sea. The littoral accumulation, which caps the ridge dates from that time. The altitude of Juminkangas in this area ranges from about 65 m to 70 m and the highest Littorina shoreline is above it at an altitude of about 100 m above the present sea level (see Hyyppä 1963). The accumulation was thus formed by the Littorina sea. The climate was rather mild at that time and later on and no disturbances due to frost action occurred.

The stratigraphical characteristics of the studied section are not restricted to this site only. It is possible to run across similar features in the sections cut into some neighbouring ridges and accordingly a similar kind of origin can be suggested.

A horizontal layer of bedded clay under till and disturbed strata in the northeastern part of the section was chosen for the consolidation tests. The clay lay just above the present ground water table and under the present frost activity at the depth of about 5.5 m. The layer was deduced not to have been dried up after sedimentation and no disturbances were found in it. The tests were run by the author assisted by P. Viitanen in the Road and Geotechnical Laboratory of Oulu, Finland.

The sediments were found to be normally consolidated, *i.e.* the degree of consolidation corresponded to the present load at the sampling depth. The load of the overrunning ice either did not compact the studied clay in spite of the till and compaction features left in the strata above, or its effect was later eliminated. As parts of the sequence were frozen during the ice advance, the tested layer may also have been, and as there are numerous disturbances in the adjacent strata, both explanations could be valid (see Harrison 1958). The concept of the frozen state of the tested layer during the advance could be supported by the lack of disturbances in it, though the subjacent strata are badly deformed.

As described earlier (p. 57) the clays in Kimola are overconsolidated in the northwestern part of the canal area once overrun and loaded by an ice lobe but the clays in Ylikiiminki are normally consolidated though also overridden by ice. In both cases the glacial advance was only a minor one. A comparison of the situations can be summarized as follows.

In Kimola the ice flowed unobstructed into a bay in the canal valley. It did not cause remarkable disturbances in the underlying sediments. The heat content of the surrounding water may have helped the sediments remain unfrozen during the ephemeral oscillation of the ice lobe resulting in a measurable overconsolidation in the sediments.

In Ylikiiminki the advance was obstructed by the ridge of Juminkangas and the strata were badly deformed. The ice contact ridge was within the ice sheet and no greater water bodies existed there to prevent rapid freezing. Some parts of the sequence were found to have been frozen ringdu the advance (p. 59). It istherefore possible that no significant consolidation occurred from the load of ice, and if any consolidation was brought about, the subsequent melting of the strata and the buried blocks of ice could have possibly changed the consolidation properties later.

Discussion

In the following, general factors responsible for the consolidation properties of Finnish sediments are discussed with special consideration to the overconsolidation owing to the loading by an ice sheet.

Sediments may be compacted by drying as if they were compacted by a mechanical load (p. 57). Once dried up sediments should therefore be avoided when studying the consolidation due to the mechanical loading of ice only. The sediments tested should have been saturated with water throughout their existence until tested in a laboratory. Samples *e.g.* from the dried crusts are thus of little or no value.

During the deglaciation most of Finland, except parts in the north and east, lay under sea level and the ice advances which occurred met favourably waterlogged sediments that could be compressed (Fig. 8). In the further geological development, however, wide areas emerged out of the water by land uplift due to isostatic rebound and the surficial parts of the ground could dry up. Since that time, conditions under ground water table or close to prevented the drying and helped the overconsolidation to be preserved.

The rate of consolidation depends upon the rate water is squeezed outof the sediments (p. 58). To reach the equilibrium state of consolidation corresponding to the full load imposed, the loading time must therefore be sufficient in respect to the prevailing permeability. According to Harrison (1958, p. 77) medium silts and inorganic clays of low plasticity are consolidated fast enough to generally satisfy these permeability and time rate of consolidation requirements so as to reach the equilibrium rapidly within the loading time. The drainage conditions depend also greatly on locality and the stratification there. In Ylikiiminki the studied clays were surrounded by well conducting gravel and sand which seemingly fill well the drainage requirements. In Kimola the drainage conditions were not equally good and it is possible that the full degree of consolidation was not reached during the short loading time (p. 58). Though the drainage conditions of today might be estimated with sufficient accuracy, the conditions during the loading by ice may, however, differ significantly from them *e.g.* owing to a possible frozen state of some parts of the sequence. Estimations of the former permeability are therefore often uncertain.

The diagenetic changes (p. 57) in the sediments are also difficult to estimate, but in general the glacial and postglacial clays in Finland are not significantly changed in this way; the seemingly oxidized sediments should, however, be avoided (see Kenney, Moum and Berre 1968).

Freezing of the sediments tends to prevent the consolidation and especially if repeated freezing and thawing occurs, the waterlogged material swells and becomes loose thus changing its previous consolidation properties. The thermal conditions in the glacial environment are therefore of great importance for consolidation taking place and its preservation. It is important that there has been no frost action in the later history of the sediments to be tested (see also Terzaghi and Peck 1962, p. 132). The samples

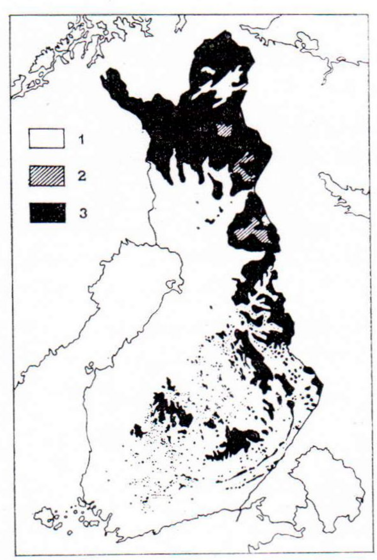

Fig. 8. Supra-aquatic and sub-aquatic areas in Finland. 1: Sub-aquatic areas, 2: Large ice-dammed lakes, 3: Supra-aquatic areas. (Hyyppä 1960).

should be taken from below the deepest level of possible frost activity.

The subglacial conditions vary in different parts of the ice sheets. Taking into account *e.g.* the effect of the geothermal heat, heat produced by any sliding and the dependance of the freezing point on pressure,*) the possibilities that temperature will rise to the melting point and free water be formed under an ice sheet grow with increasing thickness of the ice (see Robin 1955, 1962; Baranov 1959, pp. 23—25; Weertman 1961, 1964, 1966; Wilson 1964; Lliboutry 1968 b). Data also suggest that the basal part of the Greenland ice sheet below a certain horizon is at the pressure melting point and its bed is unfrozen *(e.g.* Charlesworth 1957, p. 108; Baranov 1959, p. 23). In a deep core drilling of January 1968 at Byrd Station, Antarctica, through 2 164 m of ice, temperature increased to pressure melting point at the ice-till interface, and within a day after reaching bottom, fresh water rose in the drill hole to a height of 60 m (Hoinkes 1970, pp. 138—139). How widely the bottoms of the Greenland and Antarctica ice sheets are at the melting point is not, however, known at the present time. The general conditions in the thicker parts of the glaciers at least seem to favour water being squeezed out and sediments becoming consolidated by the loading ice. A part of the load of the ice is, however, carried by the basal melt water layer which is in a hydrostatic pressure and flows down a pressure gradient (Weertman 1961, p. 970, 1966, p. 207, 1967, pp. 492—493; Lliboutry 1968 a). This hydrostatic pressure where it exists is ineffective and does not cause consolidation.

Under the thinner marginal belts of the ice sheets the ground tends to be frozen (Baranov *op. cit.;* Weertman *op. cit.)* and the general conditions thus prevent consolidation. Local differences, however, occur and fluctuations across freezing point are common in the temperature regime at the bottom (see *e.g.* Okko 1955, pp. 108—112; Weertman 1961). In the unfrozen layers consolidation is possible, provided adequate drainage is supplied. Local consolidation may also be caused by pressure melting. The repeated freezing and thawing and the other processes of deformation common in this belt *(e.g.* Hoppe 1948, pp. 7—41, 1963; Okko 1955, pp. 108—112), however, contributes to the destruction of the consolidation properties produced in this environment or previously in the thicker central parts of the ice sheet. Especially the layers close to surface are most suspect of having been affected in this manner. In the esker building environments conditions comparable to those in the marginal belt exist.

As the retreating ice sheet bordered against the Baltic water masses in most of Finland the heat content of that water could somewhat reduce the freezing trend of the marginal zone (see also Hoppe 1948). This effect was restricted to the outer edge only and numerous data show, that freezing occurred generally in ice margin environments.

Periglacial environment outside the glaciers is characterized *e.g.* by permafrost and frequent fluctuations of temperature across freezing point. This environment thus contributes to a change of the state of consolidation, especially if the sediments are saturated as the sediments used for consolidation tests must have been. In coarse and dry sediments the effect is only slight. Also in this case the destruction is most vigorous in the surface layers. Though this environment is suspected of causing the loss of overconsolidation, it is not necessary, or only a part of the overconsolidation may be lost. Harrison studied an area most probably under the effect of the periglacial phenomena after deglaciation but the overconsolidation due to the former loading

* Where the pressure exerted on the ice, which fills the pore spaces in the frozen sediment, becomes great enough to cause pressure melting, the excess water may be driven out of the voids and a compaction takes place. This process continues till the excess pressure which is able to cause the melting is transferred to the sedimentary structure. As only part of the load set up by the ice sheet may thus produce compaction through the phenomenon of pressure melting, the state of consolidation brought about this way does not directly reveal the thickness of the ice masses which build up the load.

ice was still accurately measurable in the sediments (Harrison 1957, 1958).

In Finland the areas covered by the marginal sea were preserved by the water from the subaerial effect of the harsh periglacial climate. In Kimola some cryoturbation features exist but the frost activity has been only surficial and of minor significance. The supra-aquatic areas of Finland were in a less favourable position.

In the foregoing reference has been primarily to the overconsolidation of sediments set up by rather small scale ice advances during the last deglaciation of Finland. The history experienced by the sediments of interglacial or interstadial age still remains to be discussed.

The period before the last marked ice advance is represented in Finland and in Sweden by submorainic peat layers and submorainic sediments of both fresh and salt water origin (*e.g.* Brander 1937; Hyyppä 1937; Aurola 1949; Mölder 1949; G. Lundqvist 1964; R. Aario 1966; J. Lundqvist 1967; Korpela 1969). They also occur at rather low altitudes. In Ossauskoski, North Finland, the fresh water sediments of the »Peräpohjola interstadial» (45 400±2 000 yrs B.P.; not corrected by the coefficient 1.03: Korpela 1969, p. 65) were found at an altitude of 23 m, in Härnö, Sweden at an altitude of 5 m and in Ale, Sweden also only a few meters above the present sea level (Fromm 1960, p. 5; Korpela 1969, p. 43; G. Lundqvist 1964, p. 20). The contemporaneous sea level was clearly below those sites; according to Fromm (*ibid* p. 9) it was not higher than the present Baltic sea level. The highest Baltic shore line that formed after deglaciation is for instance in the areas adjacent to Ossauskoski at an altitude of over 200 m (Yoldia) above the present sea level (Hyyppä 1936, p. 413, 1963). The position of the sea level relative to the land was thus much lower prior to than after the last conspicuous advance of the Fennoscandian ice sheet.*)

The ice advanced consequently in most Finland over supra-aquatic areas, most probably under the influence of the periglacial climate and deep permafrost (R. Aario 1966, p. 26). Korpela notes also that the sediments of the »Peräpohjola interstadial» in Permantokoski were most probably frozen during the ice advance and they could therefore stay undamaged in situ (Korpela 1969, p. 28). According to Reinhard (1962, p. 31; see also Poser 1947) permafrost existed in Germany during the time of the maximum spread of the ice to the depth of about 200 m in the areas surrounding the ice sheet. It coincides with the values obtained from present permafrost areas (Baranov 1959) and also it suggests a possible depth for Finland.

The frozen state of the sediments probably prevented consolidation during the initial phases of the advance. As a result of the increasing thickness of the ice, the temperature regime at the bottom of the ice sheet was changed, and when the ice was thick enough to cause the sediments to be unfrozen (see Baranov 1959, p. 23) consolidation could occur.

During the final retreat of the ice margin the sediments were again brought into the thinner marginal belt of the ice sheet, where the consolidation properties could have been possibly changed. The under water position after the ice retreat was conducive to the preservation of the overconsolidat on in the later history. The overconsolidation results now in the sediments

* As the crustal uplift preceding Yoldia adds up to several hundred meters (see *e.g.* Hyyppä 1936, 1963; Flint 1967, p. 244) the difference in the relative sea level positions appears to be very great and cannot be explained by the eustatic changes only (see e.g. Kuenen 1964, pp. 532—550; Flint 1967, pp. 258—271). A crustal subsidence has taken place. If the only available finite C^{14}-date 45 400 ± 2 000 yrs B.P. for the »Peräpohjola interstadial» is correct, it implies that the earth crust responded closely and sensitively also to the glacial fluctuations of this rank. Anyway, the evidence of the subsidence during the advance of the ice sheet and the subsequent uplift after it coincides with the theory of glacial isostacy. The recent criticism against the theory has often ignored this evidence (*cf. e.g.* Seppälä 1969, p. 243). It is true, however, that some arguments have also been raised against this theory and other hypotheses for the uplift in the Baltic sphere have been suggested (*e.g.* Lyustikh 1957), but thus far the glacial origin seems to be very strongly supported by evidence (*e.g.* Flint 1967, pp. 240—241). This does not exclude, though, the possibility that uplift of nonglacial origin may play part in the system (*ibid.*).

of the »Peräpohjola interstadial» (Korpela 1969, p. 80).

To summarize, the conditions have been generally rather good in Finland for consolidation of sediments by glacier load and also for the consolidation to be preserved during the later history. The areas covered by water prior to the ice advances and after deglaciation that prevented the drying up and the periglacial frost activity, were in this respect in an especially favourable position. In the supra-aquatic areas the conditions were not equally good.

The full consolidation could, however, have been prevented or been partially or wholly lost in some environments, especially near the ice margin, and this possibility is difficult to estimate. In Ylikiiminki the sediments were not overconsolidated though overridden by ice. Because of this and the fact that the ice was often supported by water in its marginal zone it is not possible, or at least it is difficult, to calculate the thicknesses of the former ice sheet directly from the measured overconsolidation values in Finnish sediments. The non-existence of overconsolidation is thus also not so significant as a negative evidence of the readvance of the ice sheet. More confidence can be placed on the existence of overconsolidation.

Acknowledgements — I wish to thank Prof. Dr. L. Keinonen for making available the laboratory facilities of the Road and Geotechnical Laboratory of Oulu, and Dr. E. Kankare for making available material of the geotechnical studies carried out during the planning and construction of the Kimola canal. I also wish to thank Prof. Dr. A. Karinen for kindly checking the English of the manuscript and P. Viitanen for helping in the laboratory work.

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Manuscript received, April 22, 1970.

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