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GLACIOTECTONIC STRUCTURES IN CENTRAL SWEDEN AND THEIR SIGNIFICANCE FOR GLACIAL THEORY

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ABSTRACT Various glaciotectonic structures and landforms created by ice pushing are common in drift and interstadial sediments in a narrow belt of central Sweden. Described examples from the Lake Storsjön vicinity demonstrate that glaciotectonic deformation took place while the area was deeply covered by the last Fennoscandian Ice Sheet. Deformation was controlled by pressure gradients related to position of the ice divide and ice movement away from the divide. As the position of the divide shifted during the last glaciation, so did the orientation of glaciotectonic structures. The regional distribution of glaciotectonic features in Fennoscandia falls into three zones: (1) inner zone of widespread, small- to moderate-sized features in older drift, (2) intermediate zone of small, isolated features in drift of the last glaciation, and (3) outer zone with all manner of large and small features in drift and soft bedrock. These zones are the cumulative results of multiple glaciations and reflect the overall distribution of deformable sediment and bedrock within the continental substratum.

RÉSUMÉ *Les structures glaciotectoniques du centre de la Suède et leur portée sur la théorie glaciaire.* Diverses structures glaciotectoniques et formes engendrées par la poussée des glaces sont courantes dans les dépôts glaciaires et les sédiments interstadiaires d'une étroite zone du centre de la Suède. La description de certains exemples observés dans les environs du lac Storsjön démontre que des déformations glaciotectoniques se sont produites pendant que la région était profondément enfouie sous le dernier inlandsis finnoscandien. Les déformations étaient commandées par le gradient de pression en relation avec la position de la ligne de partage glaciaire et le mouvement des glaces en direction opposée de cette ligne. Au cours de la dernière glaciation, l'orientation des structures glaciotectoniques s'est déplacée en même temps que la ligne de partage des glaces. En Finnoscandinavie, les structures glaciotectoniques se répartissent en trois zones: 1) une zone interne où les éléments de petite à moyenne tailles abondent dans des dépôts anciens; 2) une zone intermédiaire où de petits éléments sont isolés dans les dépôts de la dernière glaciation; et 3) une zone externe où des éléments de toutes tailles se trouvent dans les dépôts et le substratum sédimentaire. Ces zones sont le résultat du cumul des multiples glaciations et reflètent la répartition totale des sédiments et du substratum non résistant à l'intérieur du socle continental.

SAMMANFATTNING *Glacialtektoniska strukturer i Mellan-Sverige och deras betydelse för glaciationsteorin.* Glacialtektoniska strukturer och landformer uppkomna genom istryck är vanliga i glaciala och interstadiala sediment i ett smalt stråk genom mellersta Sverige. De beskrivna exemplen från Storsjötrakten visar att glacialtektonisk deformation skedde medan området ännu var täckt av mäktig inlandsis. Deformationen uppkom genom ett tryck, vars riktning bestämdes av läget i förhållande till isdelaren och isytans lutning från deanna. Då isdelarens läge ändrades under loppet av den senaste glaciationen, ändrades också orienteringen av de glacialtektoniska strukturerna. De glacialtektoniska fenomenen i Fennoskandia fördelar sig regionalt på tre zoner: (1) en inre zon med vitt utbredda små till medelstora strukturer i äldre glaciala bildningar, (2) en mellanzon med små, isolerade strukturer i glaciala bildningar från den senaste glaciationen, och (3) en yttre zon med alla typer av stora och små former och strukturer i de glaciala bildningarna och deras berggrundsunderlag. Dessa zoner utgör det samlade resultatet av inverkan från upprepade glaciationer och återspeglar utvecklingen under lång tid av de stora inlandsisarnas underlag.

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INTRODUCTION

The possibility that glaciers could deform sedimentary strata was apparently first discussed by Lyell (1863). However, it was not until the last half century that the widespread occurrence of glaciotectonic structures and landforms was generally recognized (Gry, 1940; Maarleveld, 1953; Kupsch, 1962; Moran, 1971; Sauer, 1978). A great variety of glaciotectonic features has now been described from primarily the outer regions of ice-sheet glaciations (Moran *et al.*, 1980; Bluemle and Clayton, 1984; Ruszczyńska-Szenajch, 1985; van den Berg and Beets, 1987).

Glaciotectonic features have not received much attention within the central regions of ice-sheet glaciations. A general impression exists in North America that the major volume of all drift (= deformable strata) is located within the outer third of glaciated regions and that this drift becomes thin to nonexistent toward the central zones of glaciation (Goldthwait, 1971). Thus, the potential for glaciotectonic features in the central regions of ice sheets is considered negligible. However, moderately thick and continuous drift and sedimentary bedrock are present in the regions of ice-sheet divides of central Canada and Scandinavia.

The abundance of till-covered stratified sediments, in places fossil-bearing, in the Storsjön vicinity, Jämtland, central Sweden (Fig. 1) has been known since geological mapping began about a hundred years ago. These deposits were originally interpreted as interglacial (Högbom, 1893). The interglacial interpretation prevailed until recently (G. Lundqvist, 1964), although alternative ideas were sometimes put forward in discussions about similar deposits in adjacent areas (Frödin, 1954; Magnusson, 1962). On the basis of systematic mapping and application of new investigative methods, these deposits were reinterpreted as interstadial and assigned to the Jämtland Interstade (J. Lundqvist, 1967).

The area of abundant interstadial deposits lies in a narrow belt east of the Caledonian mountain range from southern Jämtland northward to Lapland. The study area covers a small portion of this belt in the vicinity around the eastern part of Lake Storsjön (Fig. 1). The lake occupies two large valleys in gently undulating terrain developed on Cambrian-Silurian sedimentary rocks with the boundary between these rocks and the Precambrian basement located to the southeast close to Brunflo.

The Weichselian history of central Jämtland was outlined by J. Lundqvist (1967, 1973; see also Ljungner, 1949). In the Early Weichselian, an ice sheet developed and at its maximum completely covered the study area. A basal till with local or western-derived lithological composition was deposited by

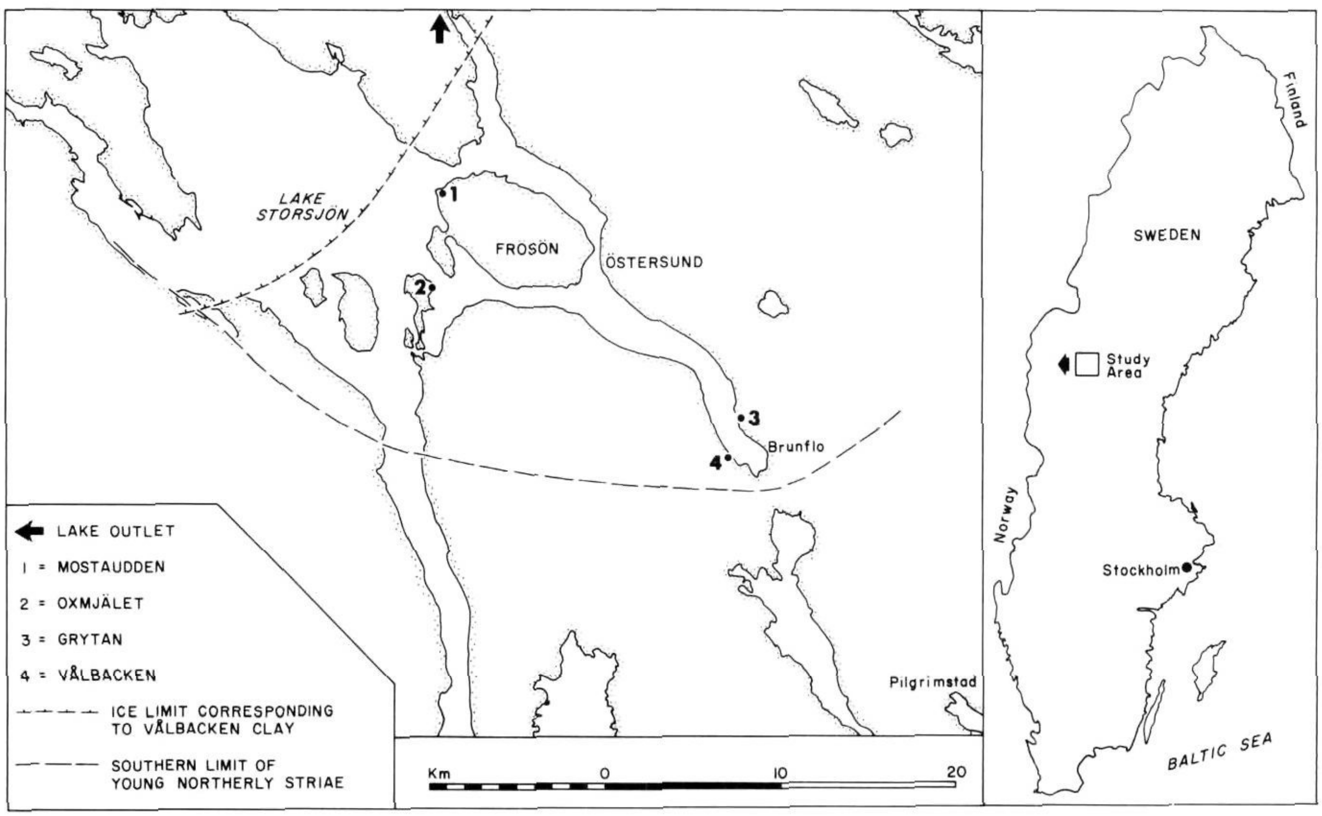

FIGURE 1. Sweden location map (right), and map of study area showing locations of described sites (1-4) around Lake Storsjön (left). Position of ice limit corresponding to beginning of deposition of Vålbacken clay from J. Lundqvist (1967, Fig. 52); position of young northerly striae limit from J. Lundqvist (1969, Fig. 80).

Carte de localisation de la Suède (droite) et carte de la région à l'étude montrant la localisation des sites décrits (1-4) autour du lac Storsjön (gauche). Limite de la glace correspondant au début de la mise en place de l'argile de Vålbacken de J. Lundqvist (1967, fig. 52); limite des jeunes stries de direction nord de J. Lundqvist (1969, fig. 80).

this glaciation. The area was then deglaciated in Early or Middle Weichselian time during the Jämtland Interstade, which has been radiocarbon dated in the range 40,000 to 60,000 years BP (J. Lundqvist and Mook, 1981).

At the end of the interstade, ice advanced southeastward from the mountain range in western Jämtland. When the advancing ice margin reached and blocked the outlet of Lake Storsjön (Fig. 1), lakes were ponded in the southeastern bays of the basin. As the ice margin approached individual sites, a coarsening-upward sequence was deposited, beginning with thinly varved clay and passing upward through thicker, silty varves, sand, and finally gravel. The gravel was deposited as eskers or kame terraces along valley sides. These sediments were eventually overridden by ice coming from a divide located to the northwest.

As the ice sheet grew to its maximum, the center of outflow shifted from the mountains to somewhere east of the study area, and ice movement from the southeast took place. During deglaciation the ice divide gradually migrated westward reaching a position across the Storsjön area. At this point, the ice divide split, which caused ice flow from the north over most of the area (Fig. 1). The till deposited during this glaciation consequently shows lithologic compositions and fabrics corresponding to ice movements from first the northwest, then the southeast, and lastly the north.

The interstadial sediments commonly show well-developed glaciotectonic structures (J. Lundqvist, 1967, 1985). These were mentioned in many earlier reports, but special study of them was not previously undertaken. This paper aims to describe this aspect of some of the more important sites. These sites were previously described (in Swedish) by J. Lundqvist (1967), who also reviewed earlier studies. Field investigation was carried out by the two authors in 1987, with additional observations made by one of us (JL) during the period 1967-86.

STUDY SITES

Mostaudden

This site was earlier described under the name "Frösöns NV-udde" (J. Lundqvist, 1967). It consists of a terrace of interbedded sand and gravel exposed in a pit (Fig. 1, site 1). The stratified sediments are partly covered by diamicton, up to about 1 m thick, which is interpreted as a till of local lithologies, possibly transported from the north. Below the stratified sediments, a till of local or western lithology has been found in borings.

Various glaciotectonic structures have been observed over the years in this gravel pit (Fig. 2). J. Lundqvist (1967) described disturbances indicating ice pushing from the north as well as from the east (or west). Later, several folds were seen with axes trending 25°, indicating ice pressure from the northwest. A fissure, filled with silt originating from a thin silt bed in the sand, showed pushing from the southeast.

Older parts of the pit are now smoothed over and covered, but one good section still remains at the pit's southern end. Up to 10 m of glaciofluvial silt, sand and gravel are exposed in a section 30 m long and 5 m high that strikes 70°. No till is visible in the present section.

A series of east-dipping thrust faults cuts through the western one-third of the section. These thrusts are accompanied by drag folds, and one thrust passes upward into an S-shaped fold. Actual displacement on individual faults could not be measured, but appears to be no more than a few meters. Thrusts and drag folds display consistent orientations (Fig. 3), corresponding to structural shortening in an east-west direction amounting to as much as 10 m total.

The central portion of the section includes some small kink folds and attenuated folds that plunge slightly toward the south-southeast. Small normal faults with only 10-20 cm of visible displacement are also present. These faults dip toward the southwest. Overall disturbance of this portion is much less than to the west.

In the eastern portion of the section, fine sand and silt have intruded up into a gravel layer and form a series of small diapiric folds. These folds are mostly overturned to recumbent, although a few have irregular to box forms. Fold axes are near horizontal, trending north-south, with the exception of one box-fold axis that plunges more steeply toward the southeast. The trends of these diapiric folds are essentially identical to strikes of the thrust faults in the western portion, so they were presumably all created at the same time in response to the same stress.

Trends of fold axes and strikes of fault planes are quite consistent; more than 80% of measurements fall in the range from 340° to 20° (Fig. 3). In fact, only the small normal faults

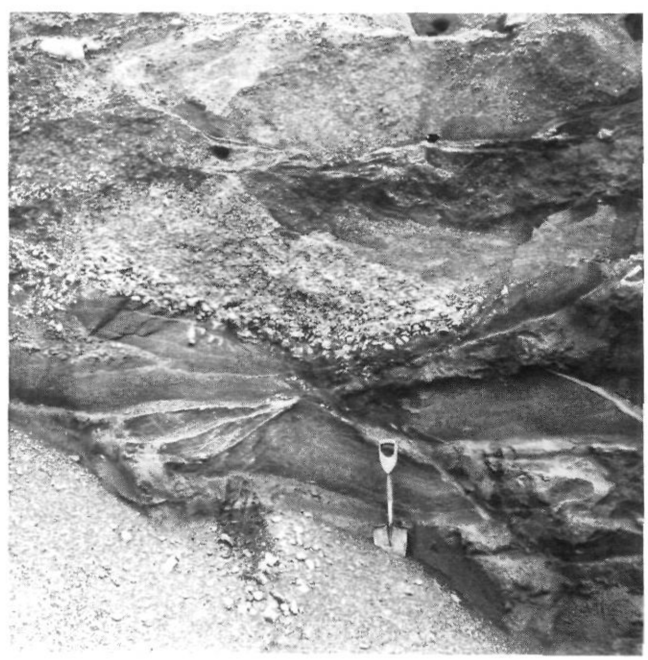

FIGURE 2. Photograph of complexly faulted and folded stratified drift at Mostaudden (Fig. 1, site 1). Photo by J. Lundqvist (1959).

Photo de dépôts stratifiés faillés et pliés de façon complexe à Mostaudden (fig. 1, site 1). Photo de J. Lundqvist (1959).

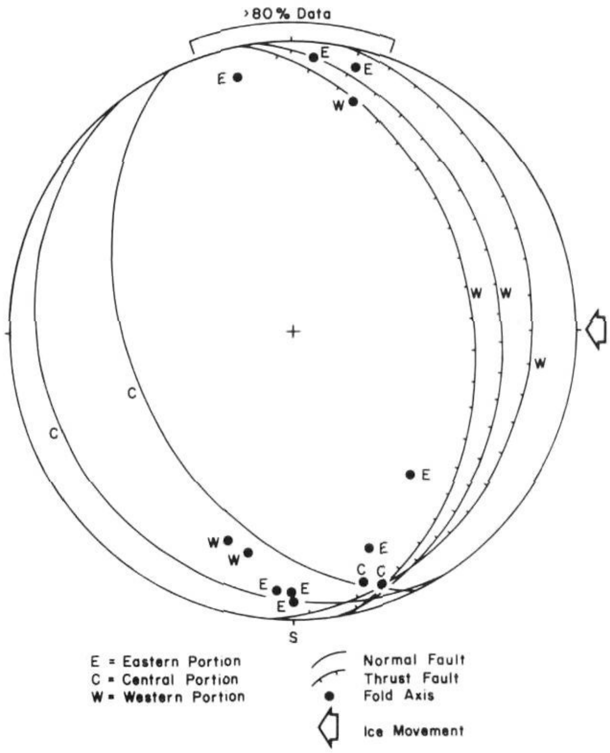

FIGURE 3. Equal-area stereonet plot of structural measurements from Mostaudden (Fig. 1, site 1). A single phase of ice pushing from the east is indicated.

Stéréogramme à projection équivalente des mesures structurales faites à Mostaudden (fig. 1, site 1). On n'indique qu'une seule phase de poussée glaciaire venant de l'est.

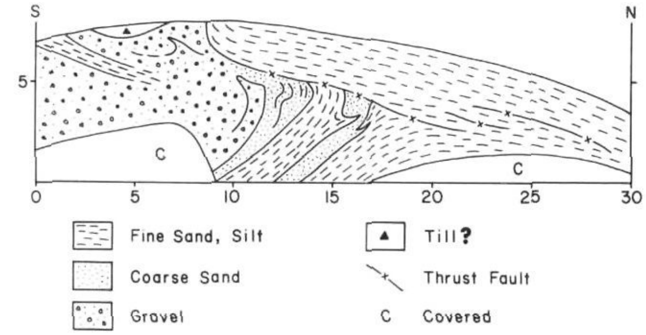

FIGURE 4. Field sketch of Oxmjälet section (Fig. 1, site 2), as it appeared in 1987. Base of section is approximately 10 m above lake level. High point of section is also high point of ridge, approximately 18 m above lake level.

Schéma de la coupe d'Oxmjälet (fig. 1, site 2), telle qu'elle apparaissait en 1987. La base de la coupe est à environ 10 m au-dessus du niveau du lac. Le plus haut point de la coupe est aussi le plus haut point de la crête, à environ 18 m au-dessus du niveau du lac.

and the box-shaped fold lie slightly outside this range. The deformations now exposed at Mostaudden are, therefore, interpreted as the result of a single phase of ice movement from the east. This presumably took place when the site was covered by thick ice and the ice divide was located to the east.

Oxmjälet

Oxmjälet is a cliff exposure on the eastern side of a small ridge located at the northeastern point of Andersön Island (Fig. 1, site 2). The ridge is about 120 m long, 60 m wide, and stands up to 18 m above lake level. Its long axis trends 10°. J. Lundqvist (1967, fig. 21) measured more than 5 m of glaciofluvial gravel capped with a thin diamicton, up to 1 m thick, which is interpreted as a till formed of reworked sediments. Boulders of granite from the east are found on the surface.

Below the gravel lie 3.5 m of interbedded fine sand, silt and clay that were deposited in an interstadial lake. The fine-grained strata rest on a basal gravelly till of local lithology, of which 0.5 m could be seen. J. Lundqvist (1967) interpreted strong folding of sand and gravel as the result of ice movement from the northeast.

A large overturned fold is revealed in the present section (Fig. 4). The steep lower limb of the fold consists of coarse and fine sand layers with an average strike/dip of about 315/65° SW (Fig. 5). The core of the fold is disrupted by smaller irregular folds and numerous faults. The upper limb of the fold is overturned beneath a thrust fault and dips gently toward the north-northeast. This results in a constructed fold axis that trends/plunges 315/02° NW (Fig. 6).

FIGURE 5. Photograph of large fold displayed in Oxmjälet section. View of photo approximately in line with northwestern trend of fold axis; scale pole is 2 m long. Photo by J. Aber (1987).

Photo d'un pli de grande dimension observé dans la coupe d'Oxmjälet. La photo est à peu près en ligne avec la direction nord-ouest de l'axe du pli; la perche mesure 2 m de long. Photo de J. Aber (1987).

North of the large fold, a series of imbricated thrust faults cuts through fine sand and silt, and the sand and silt are thrust southward over the fold for a distance of at least 10 m. Most thrusts have consistent orientations dipping at shallow angles to the north, but one thrust dips slightly more steeply

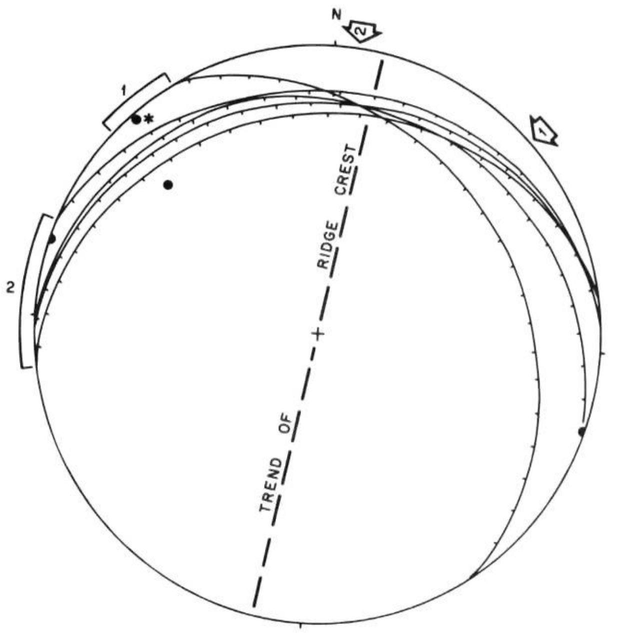

FIGURE 6. Equal-area stereonet plot of structural measurements from Oxmjälet. See Figure 3 for symbols; constructed axis of large fold shown by asterisk. Two phases of deformation are indicated by numbers.

Stéréogramme à projection équivalente des mesures structurales faites à Oxmjälet (voir la fig. 3 pour la signification des symboles) L'astérisque montre l'axe du grand pli. Les chiffres indiquent deux phases de déformation.

to the northeast. South of the large fold, smaller overturned folded sand layers are present within the gravel, and a small lens of diamicton is visible at the top of the section.

Sand and silt thrust over the ridge top at Oxmjälet were derived from below the base of the section (Fig. 4). Thus, at least half of the present topographic height of the ridge is the result of structural uplift. The total amount of lateral shortening is probably several tens of meters. Oxmjälet ridge has the overall form of a small cupola-hill, an ice-shoved hill that was streamlined by an overriding glacier (Aber, 1988).

Structural data are clustered in two groups (Fig. 6): (1) 310° to 325° and (2) 260° to 290°, with no measurements in between. The first group is generally from the lower part of the section, including the large fold; the second group is toward the top, including most of the thrust faults. It thus appears that group 1 structures were formed first by ice pushing from about 45°. Group 2 structures were created by later ice movement from slightly east of north, which also streamlined the ridge.

There is no indication of a hiatus in glaciation between the two phases of deformation, and therefore the site was probably ice covered continuously during and between both phases. The shifting direction of ice movement corresponds to the post-maximum westward migration of the ice divide. Ice pushing from the north relates to the final regional phase of ice movement in which young northerly striations were created over a broad area extending several kilometers south of Andersön (Fig. 1). Thus, it seems as if the deformations at Oxmjälet and creation of the cupola-hill took place well behind the ice margin.

FIGURE 7. Photograph of block consisting of sand (above) and clay (below) thrust over bedded pebbly sand at Grytan (Fig. 1, site 3). Note smearing of clay along fault toward left. Photo by J. Lundqvist (1976).

Photo d'un bloc composé de sable (au-dessus) et d'argile (au-dessous) chevauchant du sable caillouteux stratifié, à Grytan (fig. 1, site 3). À noter l'étalement d'argile le long de la faille vers la gauche. Photo de J. Lundqvist (1976).

Grytan

Three large pits have exposed gravel and sand with thin silt beds having a total thickness of >20 m (Fig. 1, site 3). These beds are covered with till ranging from 0 m to about 3 m in thickness. The till is partly clayey, partly reworked gravel and sand. In some places in the northern pit, the till was observed to wedge down into the sediments in connection with folding and thrusting. Blocks of clay occur in the sediments, and it was possible to follow the transition from undisturbed clay to clayey till (J. Lundqvist, 1985). Clay probably lies below the gravel and sand. This can be inferred from the existence of dislocated clay blocks and comparison with the nearby site, Vålbacken. Till was not observed underneath these sediments.

In many places, especially in the southern pit, clay blocks were observed, most usually within the sand beds (Fig. 7). The sand at these places does not show any bedding. It looks completely uniform and is probably totally reworked as a result of glaciotectonic disturbance. In such sand, the clay blocks indicate strong folding; they usually represent the noses of folds, the limbs of which extend southeastward. The limbs are broken and pass into trains of clay fragments of decreasing sizes.

Large folds with wave lengths of several 10s of meters and faults, often striking parallel to the valley side, were described by J. Lundqvist (1967). New observations between 1974 to 1985 were made, and fold axes trending NNE-SSW were measured. Drag folds clearly indicated ice pushing from the southeast. Other folds and faults showed just as clearly pressure from the northwest. Symmetric, small folds in a different part of the deposit could be interpreted as caused by ice pushing from either direction. Fold axes trending both parallel and transverse to the valley indicate that glaciotectonic deformation has been complicated.

Vålbacken

The site consisted of a large clay pit (Fig. 1, site 4), in which 13 m of thick silty, varved, extremely hard, glacial clay was revealed. The clay is covered with 0.5 to 1.0 m of clayey till, in which fabrics and lithology indicate various transport directions from the northwest as well as southeast and north. The uppermost clay varves are about 1 m thick; the lowermost are only about 1 mm thick and contain thin layers of pure organic detritus. A thin sand layer separates the clay from underlying basal till. This till contains lithologies of only local or western origin.

The clay pit is situated in the lower part of a terrace forming the valley side. The clay extends horizontally beneath the terrace, where a gradually thicker bed of sand and gravel occurs between it and covering till. This sand and gravel corresponds stratigraphically to the sediments at Grytan, which were deposited as kame terraces.

The upper part of the clay is strongly folded (Fig. 8). Fold axes indicate ice pressure from the northeast (J. Lundqvist, 1967). Fold axes trending about east-west were also measured later. Below some of these folds, the clay is completely brecciated and reworked into clayey till.

As of 1987, the clay and gravel pits were smoothed over and no new measurements were possible. Based on the older observations, the following conclusions may be drawn. The upper till was apparently influenced by all ice movements that took place after the clay was overridden by the ice sheet. The tectonic dislocations were caused by outflow from the ice divide, as it shifted from east to west, north of the Storsjön basin. This corresponds to the later part of the deglaciation, but to a somewhat earlier flow stage than that of the young northerly striations (Fig. 1). Considering the general pattern of deglaciation in the area (J. Lundqvist, 1973), this means that deformation took place subglacially under thick ice some distance behind the ice margin.

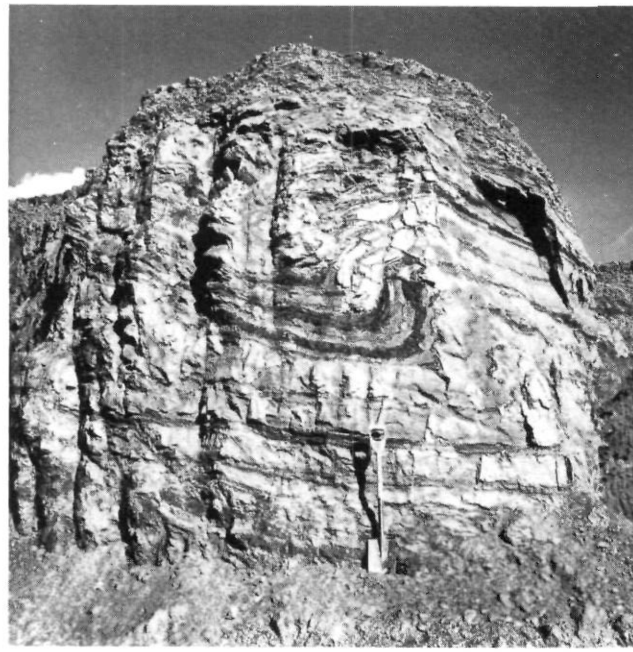

FIGURE 8. Photograph of overturned and thrust-faulted fold in thick, silty-clay varves at Vålbacken (Fig. 1, site 4). Taken from J. Lundqvist (1967, Fig. 35).

Photographie d'un pli-faille déversé dans des varves limono-argileuses épaisses à Välbacken (fig. 1, site 4). Photo de J. Lundqvist (1967, fig. 35).

MECHANISM OF DEFORMATION

The described sites contain various glaciotectonic structures that were created in drift beneath the thick center of the Fennoscandian Ice Sheet. J. Lundqvist (1967) offered three possible reasons for preservation of interstadial strata in this situation: (1) position in the ice divide region, (2) frozen substratum, and (3) lubricant effect of clay strata beneath ice. The notion that basal ice in the divide region was inactive or nearly motionless must be rejected. Glaciotectonic features, well-developed striations, and distribution of erratics prove that ice was dynamically active during all phases of glaciation.

The condition of the substratum as regards permafrost is uncertain. The Fennoscandian and Laurentide Ice Sheets presumably developed from perennial snowfields on permafrost. As the ice masses grew, however, geothermal and frictional heat may have raised the basal-ice temperature in the central region to the pressure-melting point (Hughes, 1981). Whether this actually happened in central Sweden, however, is unknown. The deformed strata, likewise, provide little evidence concerning permafrost. Similar unconsolidated sediments have been deformed in both frozen (Mackay, 1959; Klassen, 1982) and unfrozen (Humlum, 1983; van der Wateren, 1985) situations during Pleistocene and Holocene glacier advances.

Various dynamic factors are generally thought to enhance the likelihood for glaciotectonic deformation (Mathews and Mackay, 1960; Moran, 1971; Clayton and Moran, 1974; Banham, 1975; Berthelsen, 1979; Moran *et al.*, 1980; Aber, 1982): compressional ice flow, topographic obstacles, ice moving upslope, downice transition from thawed to frozen bed, and high groundwater pressure. The locations of confined aquifers below glaciotectonic disturbances seem to be particularly important (Bluemle and Clayton, 1984).

Drainage from aquifers in central Sweden was restricted during glaciation by long distance to the ice margin and possibly by permafrost. Excess hydrostatic pressure may have built up in confined aquifers, thus reducing sediment shear strength and facilitating glaciotectonic deformation. The direction of ice pushing was probably dictated by the lateral pressure gradient caused by unequal loading beneath the ice (Rotnicki, 1976; van der Wateren, 1985). The direction of glaciotectonic deformation was, therefore, controlled by location of the ice divide and ice movement away from the divide.

Most glaciotectonic landforms are associated with known margins representing either advance or stillstand positions of active ice. Several geologists have, therefore, concluded that glaciotectonic deformations take place at or within a few kilometers of active margins under thin ice or even proglacially (Kupsch, 1962; Clayton and Moran, 1974; Rotnicki, 1976; Berthelsen, 1979; Moran *et al.*, 1980; Aber, 1982; van der Wateren, 1985). This conclusion is strengthened by the fact that ice-pushed ridges are observed forming today at the margins of some glaciers (Klassen, 1982; Eybergen, 1987).

The examples from Lake Storsjön vicinity demonstrate that significant glaciotectonic structures can also form beneath the thick central portion of an ice sheet with no relationship to the ice margin. We conclude that glaciotectonic structures and landforms may be created, either in marginal or central positions, wherever appropriate sedimentary strata are overrun by a glacier.

REGIONAL DISTRIBUTION OF FENNOSCANDIAN GLACIOTECTONIC FEATURES

Of all glaciotectonic features, most are found in the outer zone of Fennoscandian glaciation, where soft sedimentary bedrock and thick drift make up the substratum. Glaciotectonic landforms and structures are widespread in the southern Baltic region, including the southern tip of Sweden (Skåne), Danish and German islands, and across northern continental Europe. Many of these glaciotectonic features are large in size; vertical dimensions of several tens of meters to >100 m and horizontal areas of a few square kilometers to several tens of square kilometers are known in many places. Glaciotectonic structures are also present on continental shelves of the western Baltic Sea (Nielsen and Jensen, 1984), the North Sea (Konradi, 1988), the Norwegian Sea and Barents Sea (Vorren and Lebesbye, 1988).

The northern limit of the outer glacial zone is sharply marked in southern Sweden by the Tornquist Line (Fig. 9), a major structural lineament. Immediately to its north, a mosaic of Precambrian crystalline and younger sedimentary bedrock is found in the Fennoscandian Border Zone (Fig. 9), which includes the Danish island of Bornholm. The Swedish islands of Öland and Gotland are underlain by Paleozoic strata. These places form a transitional belt between the outer and intermediate glacial zones. Small (<10 m vertical) glaciotectonic structures are present in drift on Öland (Königsson and Linde, 1977) and in weakly consolidated Jurassic sandstone on Bornholm.

Moving northward, occurrences and sizes of glaciotectonic structures diminish rapidly as sedimentary bedrock disappears and drift becomes thin and patchy on the Fennoscandian Shield of southern Sweden and Finland and in the Caledonian Mountains of Norway and western Sweden. Within this intermediate zone of glaciation, locally thick accumulations of drift, such as the Younger Dryas moraines (Fig. 9), were left during deglaciation, and deposits predating the last glaciation are rarely preserved in scattered pockets. Such strata do contain various small (<10 m vertical) and isolated glaciotectonic structures (Sønstegaard, 1979; Mangerud *et al.*, 1981; Aber and Aarseth, 1988).

Some of the small end moraines along the western coast of Sweden at Halland were reinterpreted by Fernlund (1988) as glaciotectonic ridges. For the most part, these ice-pushed structures were produced quite locally by the final readvance during the last deglaciation and involve only sediments of Late Weichselian age. Such glaciotectonic features are absent, however, throughout most of the intermediate zone of glaciation.

Drift cover once again increases in the inner zone of Weichselian ice-sheet divides (Fig. 9). A belt of moderately thick and continuous drift extends from south-central Norway, across central and northern Sweden, into northern Finland,

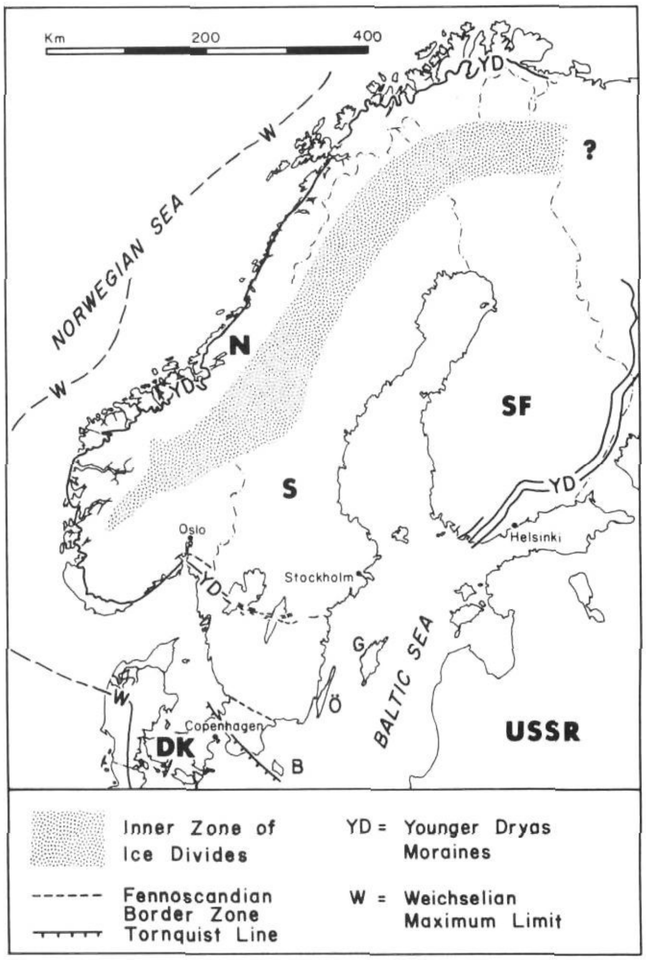

FIGURE 9. Map of Fennoscandia showing some Weichselian glacial features. Moderately thick and continuous drift containing many glaciotectonic structures and small landforms is found in the inner zone. The Tornquist Line in southern Sweden marks the boundary between the intermediate and outer zones of glaciation. Position of inner zone based on J. Lundqvist (1969), Vorren (1977), Punkari (1982), and Haldorsen and Sørensen (1987); position of Younger Dryas moraines from Mangerud (1987). Baltic islands are: B = Bornholm, Ö = Öland, and G = Gotland.

Carte de la Finnoscandinavie montrant certaines marques glaciaires du Weichsélien. Les dépôts glaciaires moyennement épais et continus de la zone intérieure renferment de nombreuses structures et petites formes glaciotectoniques. La ligne de Tornquist dans le sud de la Suède indique la limite entre les zones intermédiaire et externe de glaciation. La position de la zone interne est fondée sur les travaux de J. Lundqvist (1969), Vorren (1977), Punkari (1982) et Haldorsen et Sørensen (1987); la position des moraines du Dryas inférieur sont de Mangerud (1987). Les îles de la mer Baltique: B = Bornholm, Ö = Öland, and G = Gotland.

and possibly into the Soviet Union. Interstadial and interglacial deposits are commonly preserved beneath till of the last glaciation, and multiple Weichselian till sequences are present (J. Lundqvist, 1967; Vorren 1979; Hirvas *et al.*, 1981; Haldorsen and Sørensen, 1987). Drift covers most of the surface, and bedrock exposures constitute only about 10% of the surface in central Swedish counties of Jämtlands Län (J. Lundqvist, 1969) and Västernorrlands Län (J. Lundqvist, 1987) between the Caledonian Mountains and Bothnia coastal zone.

Glaciotectonic structures are widespread within overridden drift throughout the inner zone, as described for the Storsjön vicinity. Such structures normally involve drift that predates the last glaciation. The ice-pushed structures may achieve moderate size (>10 m, but <30 m vertical) and give rise to noticeable landforms.

On the basis of the overall distribution of ice-pushed landforms and structures in Fennoscandia, we propose a continent-scale zonal model for glaciotectonic phenomena:

(1) *Inner zone* in which widespread, small- and moderate-sized glaciotectonic features are developed in older drift.
(2) *Intermediate zone* where small, isolated glaciotectonic features are found in locally thick drift of late glacial age.
(3) *Outer zone* in which all manner of large and small glaciotectonic features is present in drift and soft bedrock both onshore and offshore.

The model is, of course, generalized. The zonal pattern is actually the cumulative result of multiple glaciations. The widths of each zone vary considerably depending on local geologic circumstances. Transitional belts may exist between the major zones.

The distribution and sizes of glaciotectonic features are related in a general way to availability of deformable substrata (= thick drift or soft sedimentary bedrock). The three-zone model, thus, reflects long-term modification of the substratum during repeated ice-sheet glaciation. Within each zone, the local presence or absence of glaciotectonic phenomena may reflect variations in glacier dynamics, groundwater conditions, permafrost, lithologic boundaries, etc. Similar geomorphic zonation of glacial features related to the Laurentide Ice Sheet is developed in North America (Dyke and Prest, 1987), although the inner zones of glaciation in northern Québec and the District of Keewatin are not so well known as in Scandinavia.

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