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Weichselian red tills in the Gardno Phase End Moraine (De• bina Cliff) – criteriadr distinction, origin and stratigraphic position, and implications for the origin and course of the Baltic Ice Stream

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Abstract: The paper presents the results of investigations of red tills from the South Baltic Middle Sea-Coast recorded in cliff exposures of Gardno Phase End Moraine. Distinctive features of these tills are: high percentage of Aland granitoids and porphyries identified in the 16-32 mm fraction, and large amounts of non-carbonate rocks, mostly red feldspars in relation to quartz, in the sandy fractions of 0,5-0,8 mm and 2-4 mm. Based on structural-textural features, the red till has been classified as flow till of local origin. The ice dynamism during Gardno Phase can be correlated with the Young Baltic Advance and most probably with the Belt Sea advance. On the basis of the petrographic properties of the Gardno red till and the results of radiocarbon dating, a new hypothesis regarding the origin, chronology and rate of flow of the Baltic Ice Stream is developed.

Keywords: Red till, Baltic Ice Stream, Petrography, Stratigraphy, Poland

1 Introduction

Red tills are a well-known phenomenon in northern Germany, and a significant criterion for establishing changes in the dynamics of ice sheets during individual glaciations. Their common feature is the dominance of rock derived from the eastern and mid Baltic regions. In the majority of cases, the tills are grey, but red tills are also found in northern Germany. According to Kabel (1982) and Ehlers (1992), four till types are recognisable, based on dominant pebble composition as follows:

- tills containing abundant Devonian dolomites and intensively crushed Devonian siltstones, with a high percentage of Paleozoic limestone. Such tills are widespread in north-western Germany, directly on the older Saale glaciation tills. Similar tills of Elsterian age have been found in Lower Saxony (Niedersachsen);
- tills with abundant Eocambrian sandstones;
- tills with concentrations of red crystalline rocks, mainly large red feldspars; and
- tills with a high percentage of Rotliegend siltstones and carbonate rocks.

The available information on Weichselian red tills in northern Germany has been summarised by Stephan (1985), with further information given subsequent publications (Stephan 1987, 1998, 2001). Kabel (1982) has also published the results of fine gravel analyses of Weichselian red tills from northern Germany and Denmark. Jasiewicz (1999, 2001a, b 2005) was the first to report red till in the middle part of the south Baltic coast, in a cliff exposure at Dębina (Fig. 1a). The main aims of this paper are to describe the lithological properties of the red tills found at Dębina, indicate the criteria used in distinguishing them as a separate lithostratigraphic

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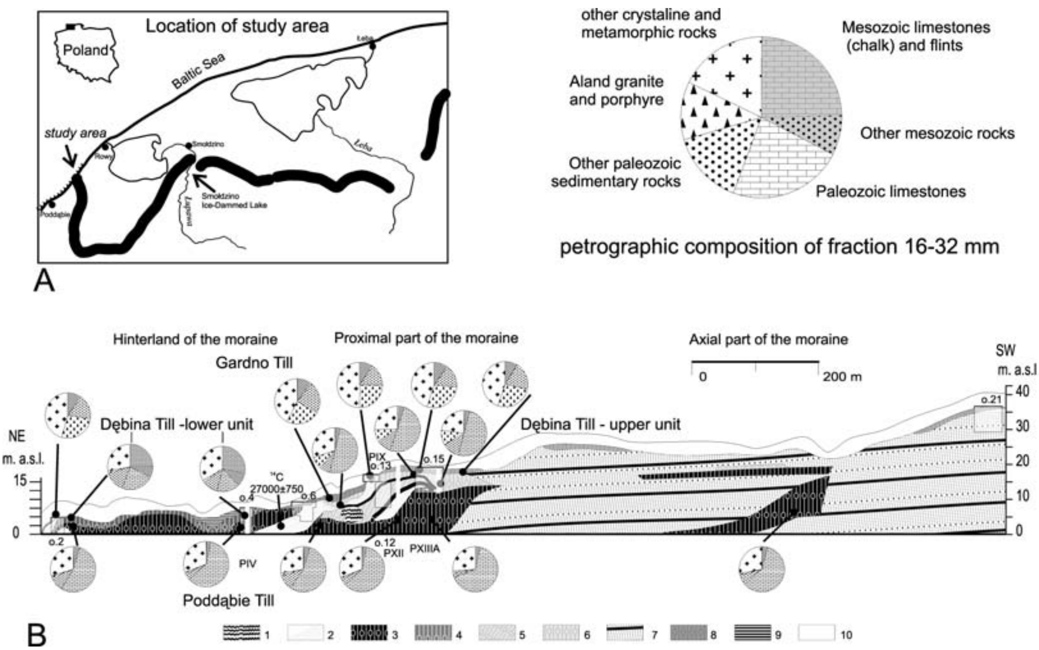


Fig. 1: Geological structure of the Gardno Phase end moraine in the cross-section of the Dębina cliff indicating the sampling points presented in the paper:
(1) Inter-Pleni-Weichselian: silts with organic matter, (2) sands; Weichselian, Leszno-Pomeranian Phase: (3) Poddąbie till, (4) brownish till (Dębina till, lower unit), (5) deformed Weichselian deposits: mostly sands and tills, (6) light brown till (Dębina till, upper unit), (7) Wytowno Formation (glacio-lacustrine deposits - sands, silts, clays); Weichselian, Gardno Phase: (8) red till (Gardno formation); Holocene: (10) Holocene cover (aeolian sands).

unit, and establish their lithostratigraphic position. Furthermore, the work seeks to explain the origin of the Weichselian red tills in the light of new insights into ice sheet movement at the edge of the Weichselian glaciation.

The stratigraphy of morainic tills exposed in the cliff cross-section of the Gardno Phase end moraine has been a subject of research for a long time. The first mention of tills in the Dębina cliff occurs in the work by BORN (1857). Later, JENTZSCH (1916) distinguished two levels of till, while HARTNACK (1926) and BÜLOW (1925, 1930) indicated three levels. GIEDROJĆ-JURAHA (1949) identified one more till level under the lacustrine deposits that he interpreted as a deposit from an older glaciation.

Results of the initial investigations into the stratigraphy of the Gardno end moraine were presented by PETELSKI (1976). He examined a 770-m long segment of the cliff and distinguished three levels of till, which he referred to as g1, g2 and g3. The youngest, g3, is a light-brown till that may be associated with one of the phases of deglaciation of the Gardno Phase ice sheet. Level g2, a brown moraine till, was deposited during the maximum extent of the Gardno Phase, whereas the brownish till of level g1 is associated with an older glaciation according to PETELSKI (1976). The first petrographic study of the deposits of the cliff between Rowy and Orzechowo was carried out by RACINOWSKI et al. (1993).

2 Study area

The Gardno Phase end moraine is a thrust moraine that form a series of hills enclosing the Gardno-Łeba Coastal Plain (ROTNICKI & BORÓWKA 1995). In its southern and eastern part, from the Łeba River to the Łupawa Valley, the moraine consists of a row of isolated hummocks that reach maximum heights of 30-50 m a.s.l. and are cut through by streams. Rowokół hill (115 m) is the culmination of the moraine. In the western part, the moraine rampart turns into a characteristic lobate form oriented north-east to south-west. The western arm of the lobe, near the village of Dębina, stretches to the seashore where it is undercut by the sea. This undercut constitutes the study area chosen for detailed investigations (Fig. 1a).

Pleistocene deposits appear about 4.5 km south-west of Rowy, in the base of the dune cliff, and are displayed along a 1,5 km segment of a sand-till cliff that extends to the culmination of the moraine (43 m a.s.l.). The height of the cliff ranges from 8 m where the Pleistocene deposits begin and reach 43 m at the end. In addition, a forested, poorly exposed fragment of the cliff stretches to the mouth of the Orzechówka stream at Poddąbie. The stratigraphic study only focused on the segment that embraces the exposures of Pleistocene deposits along the cliff near the village of Dębina (Ustka commune, Pomeranian province), where the hinterland of the moraine and its proximal (close to the ice front) and axial parts are situated (Fig. 1b).

3 Methods

Field research was carried out at the exposures after identifying the geological structure of the entire cross-section. The material for this petrographic study was collected from selected exposures. The pebble material was extracted from the samples using sieves with mesh sizes of 16 and 5 mm. Sieving continued until 500 and 300 pebbles, respectively, were obtained in this way from a total of 34 samples and the pebbles in both classes were identified. The material for the study of fine fractions was obtained in the course of grain-size analyses. Altogether over 200 samples from 12 profiles were studied. The location of the sampling sites and the profiles is shown in Fig. 1b.

The petrographic composition of the tills was investigated in order to determine the mutual stratigraphic position of the deformed glaciotectonic deposits present in the Gardno Phase end moraine. This involved mainly analysis of the 5-10 mm fraction (Trembaczowski 1967, Rzechowski 1971, 1974, 1976), which is standard procedure in the Polish Geological Institute and commonly applied in geological cartography in Poland. However, due to the absence of carbonate rocks in the uppermost till, which lies discordantly on deformed Weichselian deposits, the following additional fractions were also used: 16-32 mm (Rutkowski 1995), 2-4 mm (Krygowski 1967, Houmark-Nielsen 1993) and 0,5-0,8 mm. The results from those fractions provided enough data to define the uppermost till as a separate lithostratigraphic unit.

Fraction 5-10 mm: The investigations carried out on this fraction followed the methodology used in the Polish Geological Institute (Trembaczowski 1967, Rzechowski 1971, 1974, 1976). In the sample, selected types were distinguished and then placed into petrographic groups (Tab. 1). Additionally, due to the characteristic pebble composition of the uppermost till, alkaline granites were distinguished as a separate category of crystalline rocks.

Table 1: Petrographic types and groups used in the 5-10 mm fraction.

Indicators:	O/K	K/W	A/B
Crystalline - K	Crystalline - K	Crystalline - K	Resistant - B
Quartzite - Qz	Sedimentary rocks - O	Not included	
Paleozoic shales - Sh		Not included	Non-resistant – A
Paleozoic sandstones - Ps		Not included	
Dolomites - Dp		Carbonates - W	
Paleozoic limestones – Wp			
Local rocks: chalk+flints, siderites, phosphoranes, Mesozoic shales, mesozioic sandstones, Quartz			

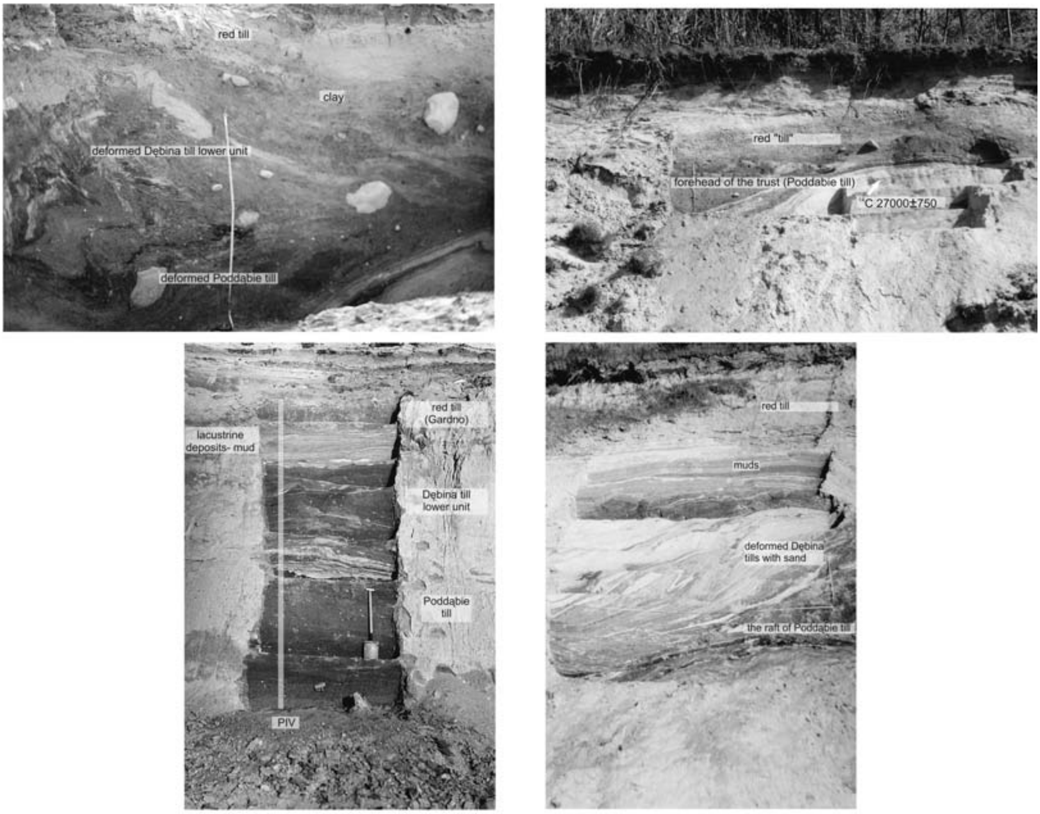


Fig. 2: a) Red till lying discordantly over deformed Weichselian deposits. Under the till, a fine asymmetric fold in the Dębina till, lower unit. The scale used in this Figure is 2 m long.
b) Red till over deformed Poddąbie till (black). Below the sands a piece of wood was dated to 27000 BP.
c) Red till over mud deposits. Below Dębina till (brownish) and Poddąbie till (black)
d) Dębina till – lower unit (light-brown) mixed with sands in a duplex structure. Red till over muds, over a deformation structure.

Fraction 16-32 mm (Fig. 1): In this fraction a detailed study was conducted taking into consideration crystalline rocks and selected carbonate rocks. For this purpose, the sample was not divided into local and Baltic rocks, but considered as a whole. This fraction was analysed to study the lithological differences within the crystalline rocks and carbonates, with a view to making comparisons with the uppermost till, which lacks carbonates.

Fine fraction: Within the 2-4 mm fraction the following petrographic groups were identified: quartz; carbonate rocks; alkaline granites; crystallines; and sedimentary rocks (Fig. 3). The basis for classification as alkaline granites was the presence of alkaline (red) feldspars. In this fraction the Ga/K indicator (alkaline granites/other crystallines) was calculated. This factor does not include carbonates, which mostly depends on post-depositional processes. The 0,5-0,8 mm fraction consists of quartz, carbonates, and fragments of non-carbonate rocks. The determination was made using a binocular microscope. In this fraction, the Ok/Q indicator (clasts of non-carbonates/quartz) does not take carbonates into account, too.

Analysis of the elevation of the Baltic Ice Stream was made using the GRASS GIS program, which is open source software. A digital elevation model Etopo2 was imported, the size

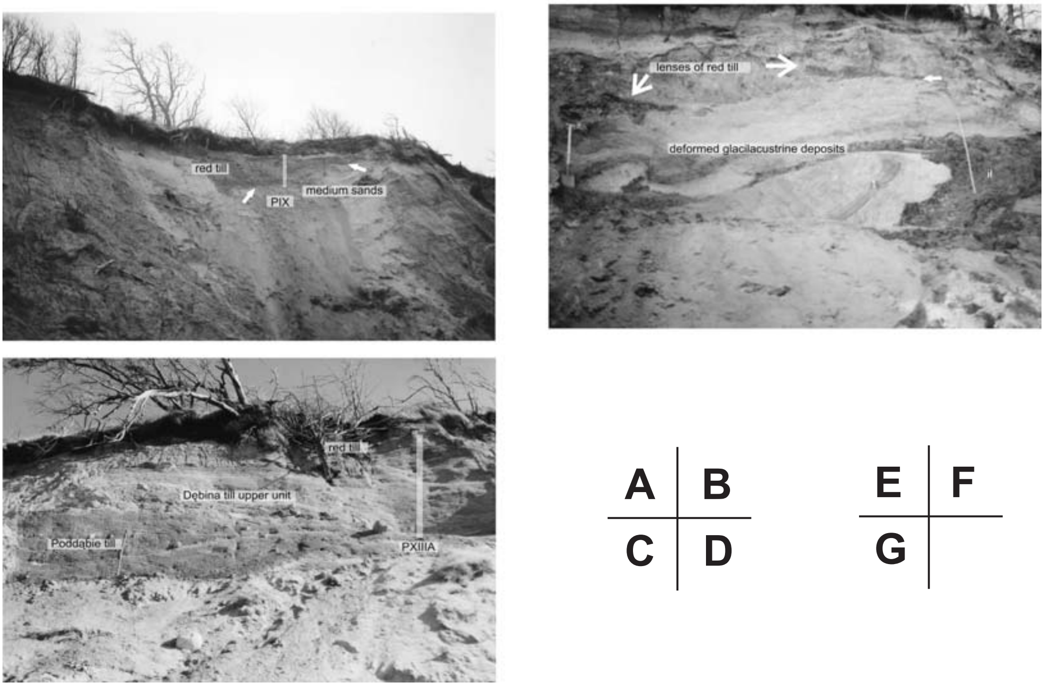


Fig. 2: e) A red till lens, probably a remnant of dead ice
f) Lenses of red till over deformed Wytowno formation (glacio-lacustrine deposits) in the culmination (highest point) of the moraine rampart.
g) Red tills lying concordantly on the Dębina till, upper unit (light brown till). The difference between the tills was established on the basis of a petrographic analysis of the fine fractions (see Fig. 3a).

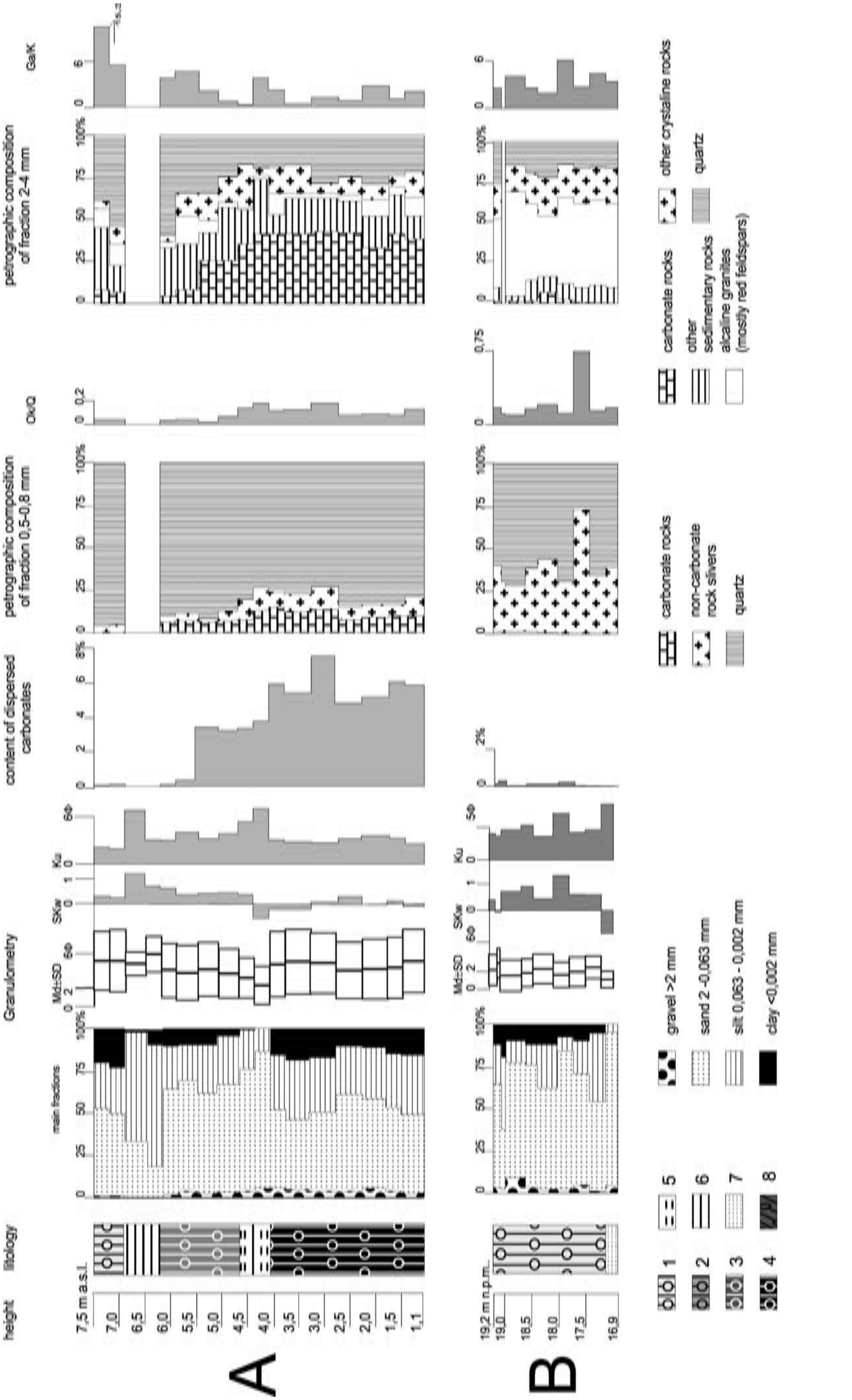
of the isostatic depression (Mörner 1980) was subsequently digitalised and subtracted from the original elevation model. Finally hypsometric cross-sections were made.

4 Geological structure of the glaciotectonite: lithostratigraphic units

In the section of the cliff near Dębina three series of deposits are exposed: (1) glaciotectonically deformed Weichselian deposits; (2) Weichselian red tills lying on deformed deposits; and (3) Late-glacial and Holocene aeolian cover sands, which cover Pleistocene deposits. These geological and glaciotectonic structures are shown in Fig. 1b. Jasiewicz (2005) distinguishes the following lithostratigraphic units: Poddąbie formation, Dębina formation, and Wytowno formation. The Poddąbie formation includes till that relate to the advance of the main stadial of the Weichselian glaciation. The Dębina formation embraces tills that represent sub- and end-glacial facies of the late Pomeranian Phase. Finally, the Wytowno formation is a glacio-lacustrine series over 20 m thickness, exposed in the highest part of the cross-section. The origin and stratigraphic position of the last series is the subject of a separate research project. As it is of marginal significance to the matters under consideration in this paper, the results are not presented in detail. The red till covering the deformed Weichselian deposits is treated as a unit of a different formation, namely, the Gardno formation.

4.1 Podd• abie till (black or dark gray till)

The Poddąbie till appears along the entire cross-section (Fig. 1). In the hinterland of the moraine and in its proximal part, the till forms a 1,5 m


A
B
height
litology
Granulometry
main fractions
Md±SD
SKw
Ku
content of dispersed carbonates
petrographic composition of fraction 0,5-0,8 mm
petrographic composition of fraction 2-4 mm
7,5 m a.s.l.
19,2 m n.p.m.
gravel >2 mm
sand 2 -0,063 mm
silt 0,063 - 0,002 mm
clay <0,002 mm
carbonate rocks
non-carbonate rock slivers
quartz
other sedimentary rocks
alcaline granites (mostly red feldspars)
other crystaline rocks

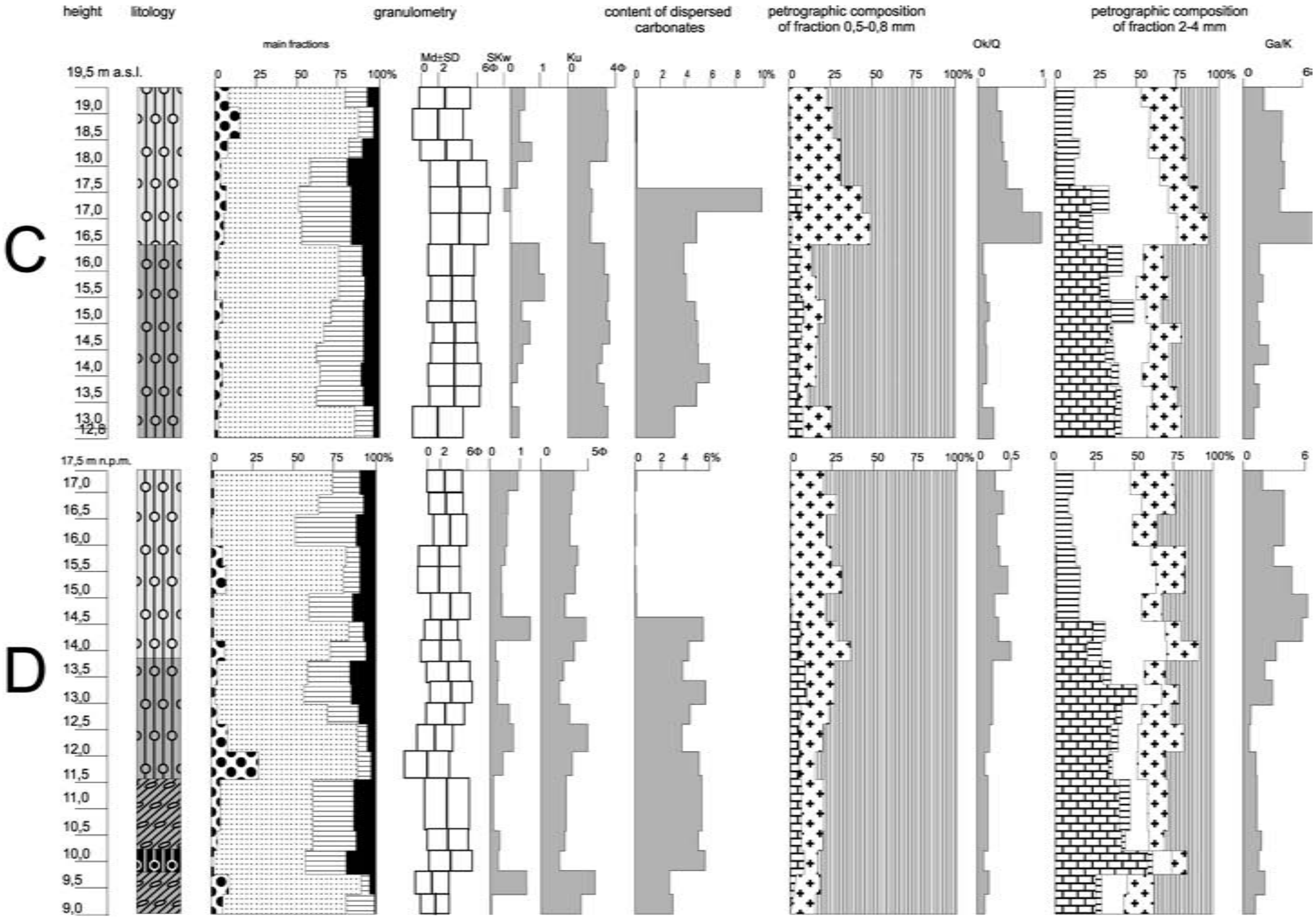


Fig. 3: Lithological characteristics of tills in the Dębina cliff: (1) red till (Gardno formation), (2) light-brown till (Dębina formation, upper unit); (3) brownish till (Dębina formation, lower unit); (4) black till (Poddąbie formation)
a) Profile PXIIIA, exposure 15; b) Profile PXII; c) Profile PIV, exposure 4; d) Profile PIX, exposure 13.

thick layer at the base of the cliff. Due to a glaciotectonic thrust, at the boundary between the proximal and the axial part, the ostensible thickness of this till increases to about 12 m. A similar till is exposed 600 m and 1200 m further in the south-westerly direction, at the base and on top of the glacio-lacustrine series. The thickness of this till fluctuates between 3 and 5 m.

The gravel content of the 16-32 mm fraction is dominated by Palaeozoic limestones, mainly grey in colour, with visible Palaeozoic fauna such as *Rugosa* corals and *Spirifer* brachiopods. Light limestones, without a macroscopically visible fauna, are limited to the upper third of the deposit. The K/W indicator for the 5-10 mm fraction ranges between 0,6 to 0,9 (Table 1).

The Poddąbie formation also includes fine and medium sands overlying the till. Fragments of redeposited wood in these deposits have been dated to 27000±750 BP (Figs. 1b, 2b).

4.2 De• bina till – the lower unit (brownish and green till)

This till – maximum thickness of 1,5 m – was observed only in the south-western part of the section, in the hinterland of the moraine. It is separated from the underlying Poddąbie tills (Fig. 2b) by a 20-cm thick sand-clay layer with an admixture of organic matter. In the proximal and axial parts of the moraine, deposits of this unit were not observed. Some thin lenses of this till were found within lacustrine deposits only in the cliff at Poddąbie, i.e. beyond the main study area (Krzyszkowski et al. 1998, Jasiewicz 2005).

The till discussed here is either layered (and brownish) or massive (and green). In the layered till, the thickness of the sandy layers ranges from several millimetres to a few centimetres. The green till is not laminated, but it does show traces of folded lenses of sands and organic matter (Fig. 2a).

The fining-upward, grain-size distribution within the sandy laminae in the brownish till and the chaotic arrangement of the long axes of pebbles allows this till to be classified as a subaquatic till facies (Hart & Roberts 1994), or waterlain till (Dremanis 1980, 1989). In both the 5-10 mm and 16-32 mm fractions, the two variants of till are dominated by Mesozoic limestones, mostly chalk, which constitutes up to 40% of the whole fraction. The characteristic feature of the till is that both fractions are poor in Paleozoic limestones.

4.3 De• bina till – the upper unit (light-brown till)

This till appears predominantly in the proximal part of the moraine, in the middle and top parts of the glaciotectonite, and within deformation structures. In some areas, contact between the Dębina till and the overlying Gardno till was observed (Fig. 3g). This lithostratigraphic unit is dominated by light-brown sandy till (diamicton). In these deposits, lenses and layers of varigrained sands and gravels are frequently found. Not much can be said about the sedimentary structures noted in these deposits, because in most cases the original sedimentary structure has been overprinted by a new fabric resulting from deformation processes.

The characteristic quality of this till in the 5-10 mm fraction is a balance between crystalline rocks and Baltic carbonates (K/W 0,9-1,1). The till has been classified as a separate type on the basis of lithological differences and the results of study of the 16-32 mm fraction. Apart from crystallines, light limestones are another dominating component. Grey limestones constitute about a quarter of the carbonates, whereas dolomites (in the 5-10 mm and 16-32 mm fractions) constitute less than 0,5% or do not appear at all.

5 Lithological-petrographic characteristics of the red till

The red till is exposed along the whole section of the Gardno end moraine and lies discordantly on deformed older deposits. It does not have continuous cover, but appears as isolated beds with thickness of several centimetres up to two metres. The boundary between the Gardno till and the overlying series of Holocene cover sands is erosive. The original thickness of the till is impossible to establish. In the north-eastern part of the section, at the hinterland of the moraine (Fig. 1b), the till has a massive structure. It covers discordantly older deformed tills, that are separated in places by a series of silt deposits (Figs. 2a, b, c). The thickness of that layer is up to 50 cm, and border between till and underlying deposits is distinct. In the proximal (middle) part of the moraine, Gardno deposits are formed as alternate layers of till, clay and sand that dip in various directions at gradients of 20°-22° and lying discordantly on older deposits, or laminated till lying directly on older Dębina till (Fig. 2g), with no discordance. In the axial part, the till appears in a few places as patches with massive structure, lying discordantly over the deformed lacustrine deposits (Fig. 2f). In some parts, the only traces of the red till are lag sediments of gravel. The course fraction in these gravels is very small. The structural-textural features of the red till enable it to be classified as a flow till of local origin.

In all fractions, there was a complete lack of carbonate rocks and hence the use of the K/W, O/K and A/B indicators (Table 1) for the purpose of comparing the tills with other deposits was impossible. In order to test how it differs from the underlying deposits, indicators that disregard carbonates were employed. In the 16-32 mm fraction, the proportion of Aland rocks (Aland granitoids and porphyries) to other crystallines was estimated. This indicator varied between 0,91 and 0,45 with a mean of 0,62±0,18 (this contrasts with 0,34±0,18 in the upper unit of the Dębina till and 0,03 in the remaining tills). These data clearly demonstrate the uniqueness of the Gardno till, which was confirmed by analysis of variance. The uniqueness of the petrographic composition of the till is readily visible especially in the 0,5-0,8 mm fraction (Fig. 3). The value of the Ok/Q indicator (clasts of non-carbonates/quartz) is usually 0,59, which is three times higher than that found in other tills. Similar differences were observed in the 2-4 mm fraction, where the Ga/K indicator was also significantly bigger than in the other petrographic types (Fig. 3), and again they were confirmed by the analysis of variance. The lack of carbonates in the till is probably due to post-depositional weathering, which explains the high content of precipitated carbonate at the boundary between the Gardno and Dębina tills (Fig. 3). However, a low percentage of quartz in the 2-4 mm fraction and high of non-carbonate clasts in the finest fraction show that the untypical petrographic composition of this till is not only the effect of the post-depositional weathering of carbonates (Woźniak 2004).

In the proximal part of the moraine a structure formed by Gardno till with an underlying series of sandy deposits was noted (Fig. 2e). The north-eastern part of the structure consists of a thin series of till with laminae of sand and gravel that dip in a south-westerly direction at a 40° angle. The south-western part of the structure is built of similar deposits, but they dip in the opposite, north-easterly, direction at an angle of 20°-30°. Between them lies a block of massive till, with maximum thickness of 2,2 m.

6 Criteria for distinguishing red tills

The Gardno formation was established as a separate lithostratigraphic unit on the basis of the deposits lying discordantly on deformed Weichselian deposits that build the glaciotectonite of the Gardno Phase end moraine. The evidence for this is as follows. The red till is sometimes found lying on the light brown till (Fig. 2g), but also on silt deposits (Figs. 2a, d, f). It is formed either as a flow till with frequent interbeddings of clay and sand, or as a massive till. In some places, a discordance between the red and the light brown till was noted. The upper unit of the Dębina till (light brown) is always found within the glaciotectonic structure, and its original fabric is often destroyed and overprinted by one of glaciotectonic origin (Fig. 2d), often in the form of a mixture of till and sand beds.

The lithological criteria of the red tills include a high concentration of Aland rocks in compari-

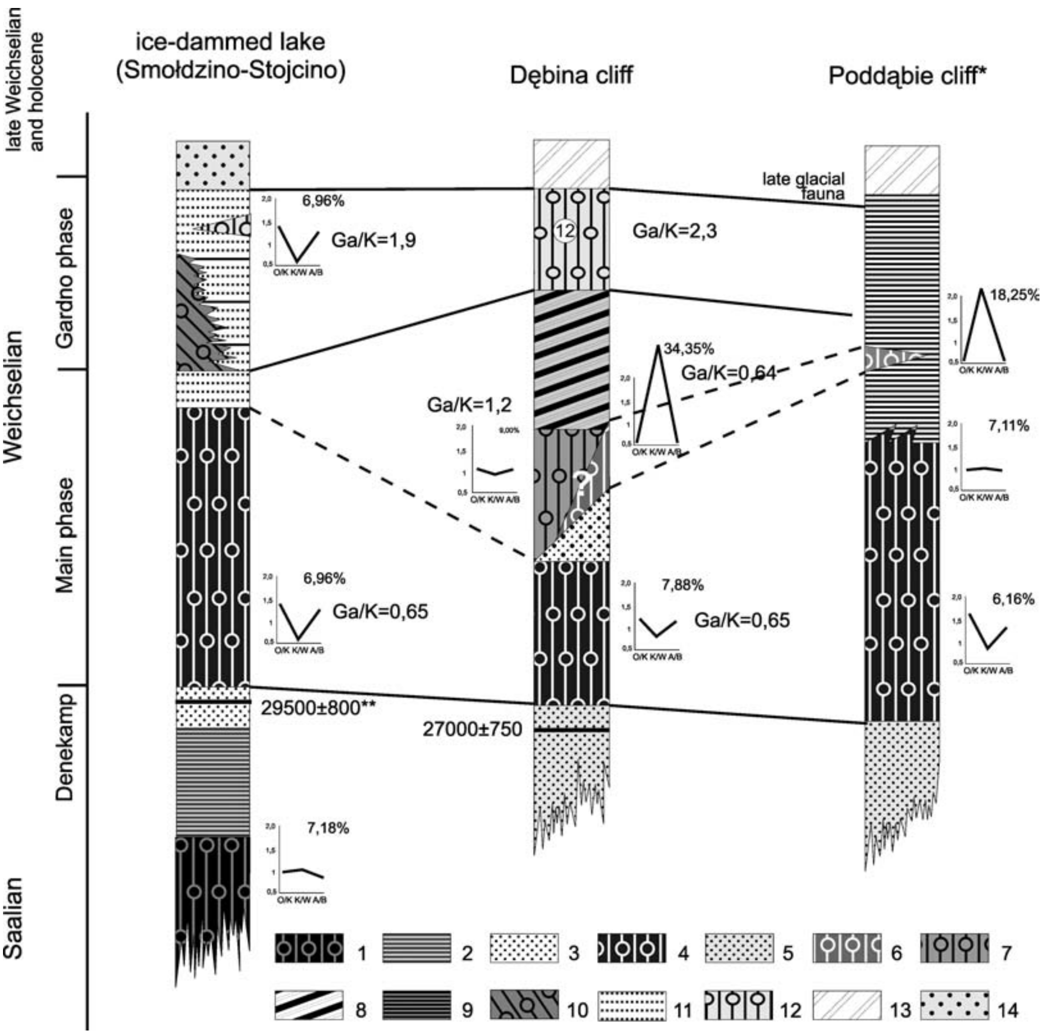


Fig. 4: Lithostratigraphic correlation of the glacial deposits of the marginal zone of the Gardno Phase end moraine: *Saale Glaciation*: (1) till, (2) glacio-lacustrine deposits; *Inter-Pleni-Weichselian*: (Denekamp) (3) medium sands with organic matter; *Weichselian, Leszno-Pomeranian Phase*: (4) Poddąbie till, (5) fine sands of fluvioglacial origin, (6) brownish till (Dębina till, lower unit), (7) light brown till (Dębina till, upper unit), (8) Wytowno formation (glacio-lacustrine deposits), *Weichselian, Gardno Phase*: (9) glacio-lacustrine deposits in Poddąbie (Wytowno formation: sands, silts, clays), (10) Poddąbie till redeposited in ice-dammed lake, (11) glacio-lacustrine deposits (sands, silts, clays), (12) red till (Gardno formation); *Holocene*: (13) Holocene aeolian cover sands, (14) fluvial deposits of Łupawa river valley.

son with other crystalline rocks components. This is confirmed by a high concentration of red feldspars in the fine gravel fraction. A large amount of non-carbonate clasts in comparison with quartz in the sandy fraction is the most distinctive feature of the red till that helps to differentiate it from other tills (Fig. 4). This feature is helpful in two cases: when the Gardno till lies discordantly on deformed non-till deposits or on light brown till. Thus the lack of carbonates, caused by the post-depositional weathering, is not a serious impediment to certain identification of the red till.

7 The stratigraphic rank and position of the red till

The stratigraphic position of the red till, which lies discordantly on glaciotectonically disturbed Weichselian deposits, is easy to establish: it is as old as, or younger than, the disturbance zone (Jaroszewski 1963, Rotnicki 1983). Therefore, it can only be connected with the Gardno Phase, the youngest advance on the middle-south coast of the Baltic Sea. Additionally, the chronostratigraphic position of the Gardno advance is well-documented by radiometric methods. According to Rotnicki & Borówka (1995), the oldest post-glacial deposits from the Gardno-Łeba lowland has been ^{14}C dated to 14300±150 BP. On this basis, Rotnicki (2001) estimated the time of the Gardno advance to be 15000 BP.

Correlation of till cover with the regional and trans-regional glaciology remains problematic. In the hinterland of the Gardno Phase end moraine Rotnicki (1995) and Rotnicki & Borówka (1995) suggested the existence of lags connected with Gardno Phase till. Recently, Jasiewicz (2005) suggest the possible presence of Gardno till flows in the lower Łupawa ice-dammed area, in the foreland of the Gardno Phase. However, no Gardno till, was found on land yet, having originated as basal till, due to connected with the limited extent of this phase south of the contemporary coast of the Baltic Sea. The correlation of marginal zone deposits of the Gardno Phase end moraine is shown in Fig. 4.

In turn, the correlation at a trans-regional scale based on the numerical values of the indicators is not possible because of the lack of carbonates makes the calculation of the O/K, K/W and A/B indicators impossible, and the rest of the indicators calculated for this till cannot be compared with other indices used in Polish geological cartography. Furthermore, a trans-regional correlation based solely on boulder indicators often fails because tills belonging to the same lithostratigraphic unit may have various petrographic compositions in different regions (Lüttig 1999). In this situation it is necessary to compare the lithological features of till, that are not directly dependent on the numerical values of the indicators. Crystalline rocks, dominated by material transported from a distant, relatively restricted area, and in the finest gravel fraction a high concentration of non-limestone rock clasts (mainly orthoclases) in proportion to quartz suggest that there was restricted interaction with the substratum during transport of the material.

Both the chronostratigraphy (ca. 15000 BP (Rotnicki & Borówka 1995) and the lithological features of the Gardno till suggest a correlation of the Gardno with the Young Baltic Advance (Kjaer et al. 2003, cf. Fig. 1b) is appropriate. The Gardno advance is the last advance in the Middle-South-Baltic area that left the Baltic basin and it is probably with this advance that all glaciotectonic disturbances described from the islands of Rügen (Panzig 1995) and Wolin (Ruszczyńska-Szenajch 1996) are connected. Pebble composition of the Young Baltic advances till also formed under conditions of limited interaction with the substratum (Stephan 2001, Kjaer et al. 2003). The extent and direction of the advancing lobes were strictly controlled by substratum relief. A higher than usual concentration of Aland rocks in tills that relate to the Young Baltic Belt Sea Advance (Warleberg Advance in Germany) was also stressed by Stephan (2001) The Gardno Phase may well be connected with this advance. Similarly, the Gardno ice sheet probably took advantage of the natural depression of the Gardno-Łeba Coastal Plain. Thus, features that allow correlation of the Belt Sea and Gardno advances are the dynamics of the ice sheet, petrographic composition and the chronostratigraphic position.

All deposits in the region of Gardno-Łeba Lowland connected with this advance belong to the same formation, i.e. the Gardno formation, whatever their degree of preservation or weathering. The red till, which originated mostly in the flow facies, is regarded as one of the units in this formation.

8 Origin of the red till

The presence of rock from a restricted geographical provenance and a high percentage of rock fragments in the sandy fraction indicate that the red till retains features of material that derives from the Aland Islands, 600 km distant. The genesis of its petrographic composition may be explained in two ways, i.e. the original material did not scatter during glacial transport (Donner 1995, Stephan 2001) or the red till has gained the above mentioned features due to a disintegration of a large granite raft.

Since the second variant seems unlikely, it is useful to consider the conditions during the erosion–transport–accumulation cycle that might have resulted in till with such a composition. These include limited interaction between the basal ice and the substratum, and transport of the material high above the ice foot (Ehlers 1981, Stephan 2001). A possible scenario is that presented by Kabel (1982), where a depression filled by dead ice is postulated.

Such a model, however, is hard to accept on glaciological grounds, especially taking into account the pace of the ice sheets. The fundamental assumption states that material transport is at most as fast as ice sheet movement. Unfortunately, there are no geological remnants which allow an indirect determination of the pace of the ice masses. Attempts at a computer reconstruction (Holmlund & Fastook 1995, Arnold & Sharp 2001, Siegert et al. 2001, Näslund et al. 2003) cannot be an unambiguous indicator due to divergences in the results and some unfounded premises, and the authors cited are fully aware of these caveats (Arnold & Sharp 2001). Contemporary studies based on the results of measurements from the area of the Siple Coast (Antarctica) should be treated with caution (Bentley 1987, Bennet 2003) because they refer to a specific glaciological situation, i.e. a marginal zone that flows directly to the ocean. A more appropriate analogy may be the data from East Antarctica (Young 1979).

Reliable information on the rate of advance of the Weichselian ice sheet may be provided by the results of radiocarbon dating of the youngest organic sediments deposited before the last ice advance, i.e. 22300±700 BP which relates to the Gardno-Łeba Coastal Plain (Rotnicki & Borówka 1995) and 20500±500 BP from Macew on the Prosna (Rotnicki & Borówka 1989). On this basis, Rotnicki (2001) estimated the rate of the ice sheet advance into the territory of present-day Poland, from the Baltic coast to the line of glacial maximum (LGM) at 150-160 m/year. The dates 21480±440 and 22780±660 BP from Ławica Odrzańska (Kramarska 1998) and 21600±1060 BP from Niechorze (Krzyszowski et al. 1999) support these estimates and agree with the rate of advance the Antarctica ice sheet published by Young (1979), i.e. 127-150 m/year in the area where ice sheet thickness was 800-1000 m. Similar results were achieved in investigations that measured the movement of the ice mass in the Ice Stream B (Alley & Willians 1991) where a rate of 800 m/year was noted, with an average for the stream as a whole of 400 m/year.

As regards the speed within the Baltic Ice Stream (BIS), assuming that the thickness of the ice sheet in this area varied from 1500 to 2400 m (Kleman et al. 2001), a rate of 160 m/year is unlikely due to insufficient supplies of snow and ice masses from the Scandinavian region. According to Patterson (1994), the rate for such ice sheet thicknesses is 10 to 90 m/year. This implies that it would have taken at least 8000, and a maximum of 60000 years, for material to be transported from the Aland Islands to the Baltic coast, a distance of ca. 600 km. Assuming the age of the Gardno Phase to be 15000 BP (Rotnicki 1995), the glacial structure of the Baltic Ice Stream as an area of increased speed would have had to function since at least 23000 BP, because such a large concentration of morainic material from the same source zone largely rules out transport during several glacial cycles. On this interpretation, the Baltic Ice Stream would not have been a Late Glacial phenomenon; rather it would have functioned from the time the eastern Baltic Sea was filled by the ice sheet, that is, 28000-24000 BP (Boulton et al. 2001). This is in accordance with mathematical modelling (Holmlund & Fastook 1993, 1995; Arnold & Sharp 2001).

The Baltic Ice Stream is a unique palaeoglacial structure, which has no equivalent either in the contemporary ice sheets or in the Laurentide ice

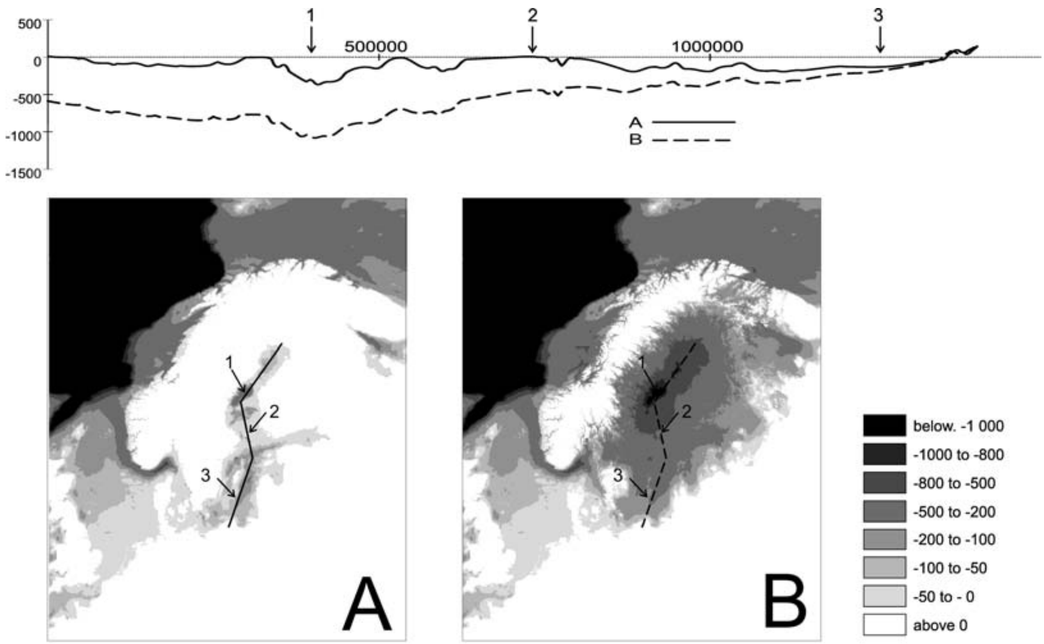


Fig. 5: Substratum relief along the potential route of the Baltic Ice Stream: (A) recent; (B) with isostatic depression, after Mörner (1980).

sheet zone. Its functioning is strictly defined by the relief of its substratum, i.e. the Baltic basin south of the Aland Islands, by the considerable inclination of the basin slope in the west (the Scandinavian mountains), and by the slope in the east. The area of the Aland Islands today is a threshold that separates the thickest portions of the ice sheet and places of maximum isostatic depression (Mörner 1980) from the area of a distinct transport route in the Baltic basin. On the basis of the results of glacial process modelling, Holmlund & Fastook (1993, 1995) suggest that the threshold of the Aland Islands was a great obstacle for the Baltic Ice Stream and was eroded during its functioning much more intensely than for example Gotland, which lies farther to the south (Holmlund & Fastook 1993, 1995). In the Younger Dryas, the Aland Islands could even have risen above the surface of the ice sheet as nunataks. However, a relief analysis that takes isostatic depression into consideration (Fig. 5) shows that at the height, and during the retreat, of the glaciation the Aland Islands had already stopped being an obstacle. This suggests that the incorporation of material into the ice sheet took place at the beginning of the glaciation. If we assume, after Boulton et al. (2001), that the Aland Islands found themselves at the limit of the ice sheet in the Inter-Pleni-Weichselian, they would be an area of intense weathering during periglacial conditions. The presence of poorly scattered material proves that the Baltic Ice Stream began to function immediately after filling up the Baltic basin with ice, but due to time and distance the effects of its functioning are not clearly visible until the deposits of the final stage of the glaciation.

9. Conclusions

Weichselian red tills identified in the cross-section of the cliff of the Gardno Phase end moraine include flow tills that are connected with the advance of the Gardno ice sheet. Hence they constitute a component of the Gardno formation that is regarded as a series of deposits left during the advance and recession of the Gardno ice lobe. The stratigraphic status of the red tills was established on the basis of their discordant position on deformed Weichselian deposits, and confirmed by an analysis of their petrographic composition in the 16-32 mm and 0,5-0,8 mm fractions. Though the red tills lack carbonate rocks and dispersed carbonates (probably due to weathering), this is not an impediment to establishing lithostratigraphic identity or genesis of the red tills if the methods, referred to above, are applied. The unique composition of the red tills is probably the effect of specific erosion conditions, i.e. transport and accumulation in the area of the Baltic Ice Stream. These conditions are not present until the end of every glaciation (Ehlers 1992). Nevertheless, the hypothesis presented here concerning the dynamics of the Baltic Ice Stream still requires further research.

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