

TILL BASE DEFORMATION AND FABRIC VARIATION IN LOWER ROGOWIEC (WARTANIAN, YOUNGER SAALIAN) TILL, BĘLCHATÓW OUTCROP, CENTRAL POLAND

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Abstract: We documented that the Wartanian (younger Saalian) Lower Rogowiec Till exposed at Bělchatów, central Poland, is not sedimentologically or structurally homogeneous, and suggested that the till macrofabric patterns and deformation structures may be related to stress conditions in the glacier at the time of deposition. The distribution of deformation structures below and within the till forms a pattern, most probably associated with compressive flow and/or with stronger stress reaction, creating stronger fabrics, above clay beds due to high pore water pressure. The intervening areas, lacking deformation structures, occur between the zones of compression, where pressure would have been less. These patterns occur in a repeated sequence along the sections, which suggests that there may be a control, such as basal glacier stress conditions. The sites showing deformation occur about every 10–20 m. This could imply that the zones of shearing at the ice front have a similar spacing. There are no features in the pattern of the till macrofabrics and deformation structures to suggest that the local Kleszczów Graben or a pre-existing valley had any effect on the mode of till deposition.

Key words: till, Rogowiec Till, Wartanian, sand/clay/till body, base deformation, fabric variation, Bělchatów open-cast mine, Poland.

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INTRODUCTION

The Bělchatów outcrop provides an excellent opportunity to study tills, which are exposed in 1–4 km long sections within a brown coal open-cast mine (Figs 1, 2). The mine is located within a tectonic setting, the Kleszczów Graben, central Poland, which was active up to the Saalian (Krzyzkowski, 1989). Generally, the Pleistocene deposits up to Older Saalian (Odranian = Drenthe) are tectonically deformed, whereas the younger deposits show little or no tectonic deformation (Fig. 1). Detailed stratigraphies of the Pleistocene sequence at Bělchatów quarry have been presented in Krzyzkowski (1991, 1995).

Previous results of till investigation in the Bělchatów mine have been presented elsewhere (Krzyzkowski, 1988; Czerwonka & Krzyzkowski, 1992; Krzyzkowski, 1995). The last work concluded that the undeformed, younger tills of the Bělchatów mine preserve features which are indicative of lodgement and melt-out tills, and both occur in the same profiles. Detailed sedimentological investigations, however, have not been presented. The Lower Rogowiec

Till (Fig. 1) is the lowermost till with the minor deformation in its basal zone. It forms a 1–3 m thick, sub-horizontal till body with a lateral extent, at single sections, of *ca.* 1–2 km long, covered by at least 20–30-m-thick cover of younger deposits. The latter preclude the possibility of any influence from the recent ground surface. Such influence is inferred for a part of the Middle and Upper Rogowiec Tills (Krzyzkowski, 1988, 1991) (Fig. 1).

The advantages of the site made it suitable to analyse the deformation structures and the macrofabric structure of the till body in order to investigate its genesis and the influence of neotectonics and the pre-existing topography on the mechanisms of deposition.

1. The genesis of the till. Former investigations (Krzyzkowski, 1995) indicated features of both lodgement and melt-out till deposition. Macrofabric, particle size, as well as petrographic and mineralogical investigations indicate that incorporation of material from below is vertically limited, usually to the first 20–50 cm from the till base and is

Tectonic division	Lithostratigraphy				Chronostratigraphy						
"UPPER" NOT DEFORMED STAGE	WIDAWKA FORMATION	SZEROKIE FORMATION					HOLOCENE				
					a	14 500 BP	WEICH - SELIAN	UPPER			
					b	21 000 BP		MIDDLE			
					c	27 000 BP					
					d	33 000 BP					
					e	> 43 000 BP					
	ALEKSANDRÓW FORMATION				Eemian Interglacial palaeosoil ?			EEMIAN			
	ROGOWIEC FORMATION (glacial)				A	TILL 7	SAALIAN	WARTANIAN 2			
								B	TILL 6	interstadial ?	
								C	TILL 5	WARTANIAN 1	
CHOJNY FORMATION				Pilica Interglacial				PILICIAN			
											?
STAWEK FORMATION (glacial)								?			
ŁAWKI FORMATION (glacial)				TILL 4				ODRANIAN			
ROKITY FORMATION (glacial)				TILL 3				?			
BELCHATÓW STAGE	CZYŻÓW FORMATION				A			Podlesie Interstadial			
					C			Czyżów Interstadial			
					F		Ferdynandovian Interglacial				
					D		Mazovian Interglacial-Holsteinian palaeosoil ?				
					E						
	KUCÓW FORMATION (glacial)				TILL 2			ELSTERIAN	SANIAN		
					TILL 2A						
					palaeosoil ?						
	FOLWARK FORMATION (glacial)				TILL 1			NIDANIAN			
	ŁĘKIŃSKO FORMATION				PRE - TIGLIAN			LOWER PLEISTOCENE			
PLIOCENE											

Fig. 1. General stratigraphy of the Pleistocene sequence in the Kleszczów Graben (these investigations were carried out in 1998 year)

very selective, restricted to medium and coarse sand and/or clay.

2. The influence of neotectonics and pre-existing topography on the deposition of the till.

The Lower Rogowiec Till occurs only within the Kleszczów Graben, not beyond it (Fig. 2), which suggests a tectonic influence on its preservation. So, a tectonic influence on deposition, when the ice sheet advanced into the subsiding zone, cannot be excluded. A palaeovalley, infilled with the Chojny Formation (Figs 1, 2), occurs just below the till. The occurrence of infilled valley in the substratum during the ice-sheet advance could have influenced the mode of till deposition.

METHODS

The methods outlined below were used to investigate the till body.

1. The position of the till body was mapped from sections, supplemented to a small degree by information from boreholes, to determine its relationship to both the graben boundaries and the sub-till topography of the palaeovalley. As the section was worked back, it was measured twice, a year apart, allowing the outcrop to be mapped in three-dimensions.

2. During investigation for this paper the till outcrop was continuous over ca. 1 km. The position and nature of

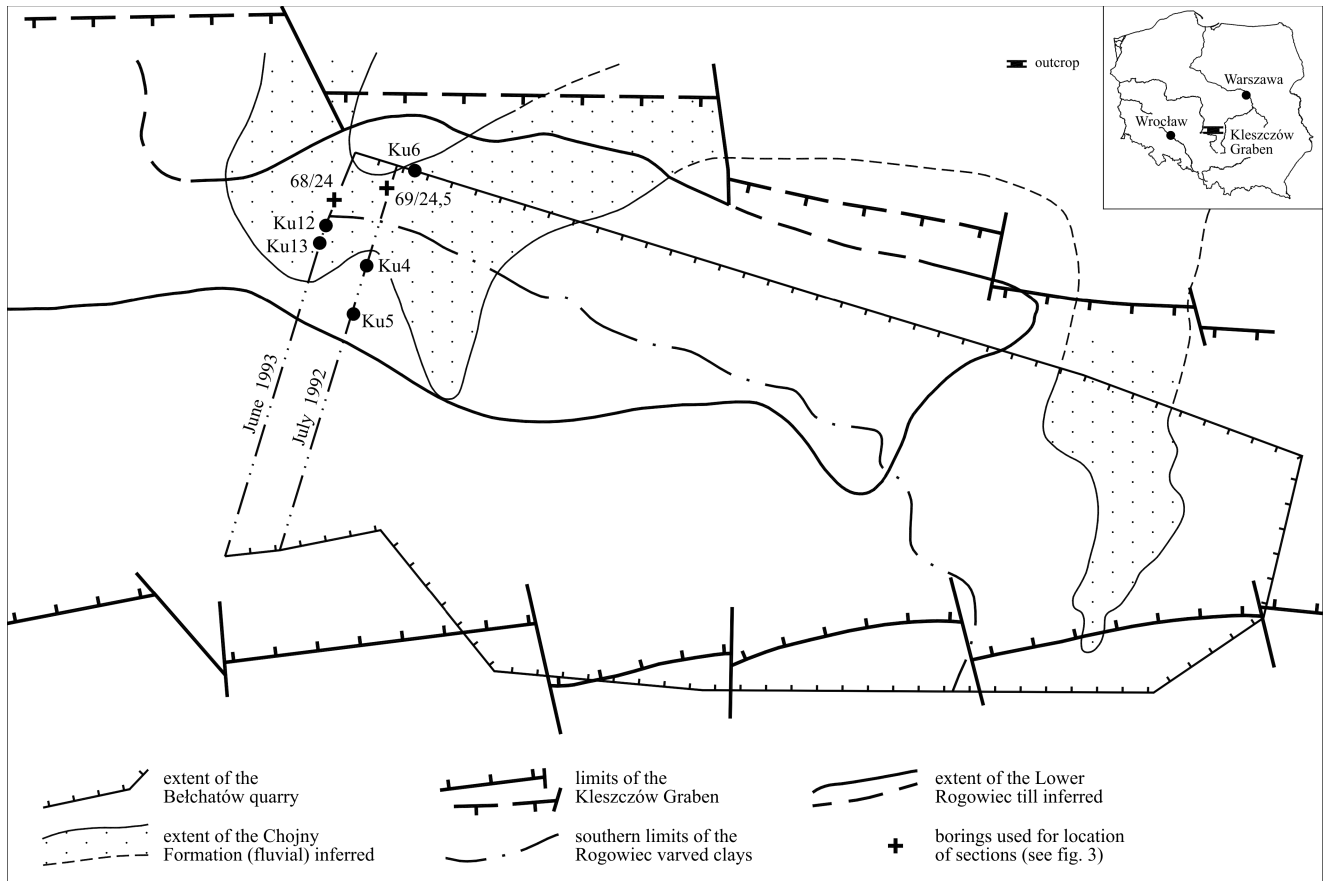


Fig. 2. Extent of the Lower Rogowiec Till and sub-till fluvial deposits and location of the sites investigated

structures within the main till body and at its base, including the top of the underlying sand, were recorded along it. Particular attention was paid to the nature of the till-sand interface.

3. Within the till body, sampling and measuring points were chosen after the general disposition of the till had been determined in order to provide information about the till body as a whole. The points ranged over the full extent of the outcrop and were chosen on the basis of relation to the graben sides, to the sub-till topography, and to zones where deformation structures had been noted.

4. Till macrofabric analyses were carried out at sampling points through six vertical profiles extending from the base to the top of the till, at positions chosen as described in (3) above. Fifty clasts with an a:b ratio of at least 3:2 were measured at each point. Both authors carried out analyses within the same profiles to eliminate problems of operator bias. Both operators found similar patterns within every profile, though each profile differed in its characteristics.

Five samples were collected from the profile at Kuców 4 for laboratory analyses to determine particle size, petrography (4–256 mm, at 1m intervals), quartz roundness (0.5–1.0 mm), and heavy minerals (0.01–0.25 mm). The particle size analyses covered the range from the largest clast present to +4 phi by sieve analysis and +4 to +9 phi by pipette analysis. The quartz roundness was determined by randomly choosing 300 grains under a binocular microscope and photographically enlarging the image before allocating

them to three classes: well rounded, partially rounded and angular. The quartz roundness and heavy mineral analyses were undertaken in order to determine the degree of incorporation of the underlying sand, which has different roundness and heavy mineral characteristics than the till.

The analyses were carried out using samples from one profile only, because previous analyses had shown the till body to be extremely laterally homogeneous (Czerwonka & Krzyszkowski, 1992).

GENERAL CHARACTERISTICS OF THE LOWER ROGOWIEC TILL: STRATIGRAPHIC POSITION AND EXTENT

The investigated till (T5 in Figs 1 and 3) belongs to the Lower Member of the Rogowiec Formation. This member contains a varved clay, from a few centimetres up to 2 m thick, with the Lower Rogowiec Till lying above. The upper boundary of the member is erosional, with a distinct gravel pavement and scours (Fig. 3). The till is usually 1–3 m thick, but often it is reduced to 0.5 m or less due to erosional processes (Krzyszkowski, 1988, 1991). In some exceptionally thick profiles (ca. 5 m), a palaeosol was documented, with rubification and decalcification in the topmost part of the till (Krzyszkowski, 1988).

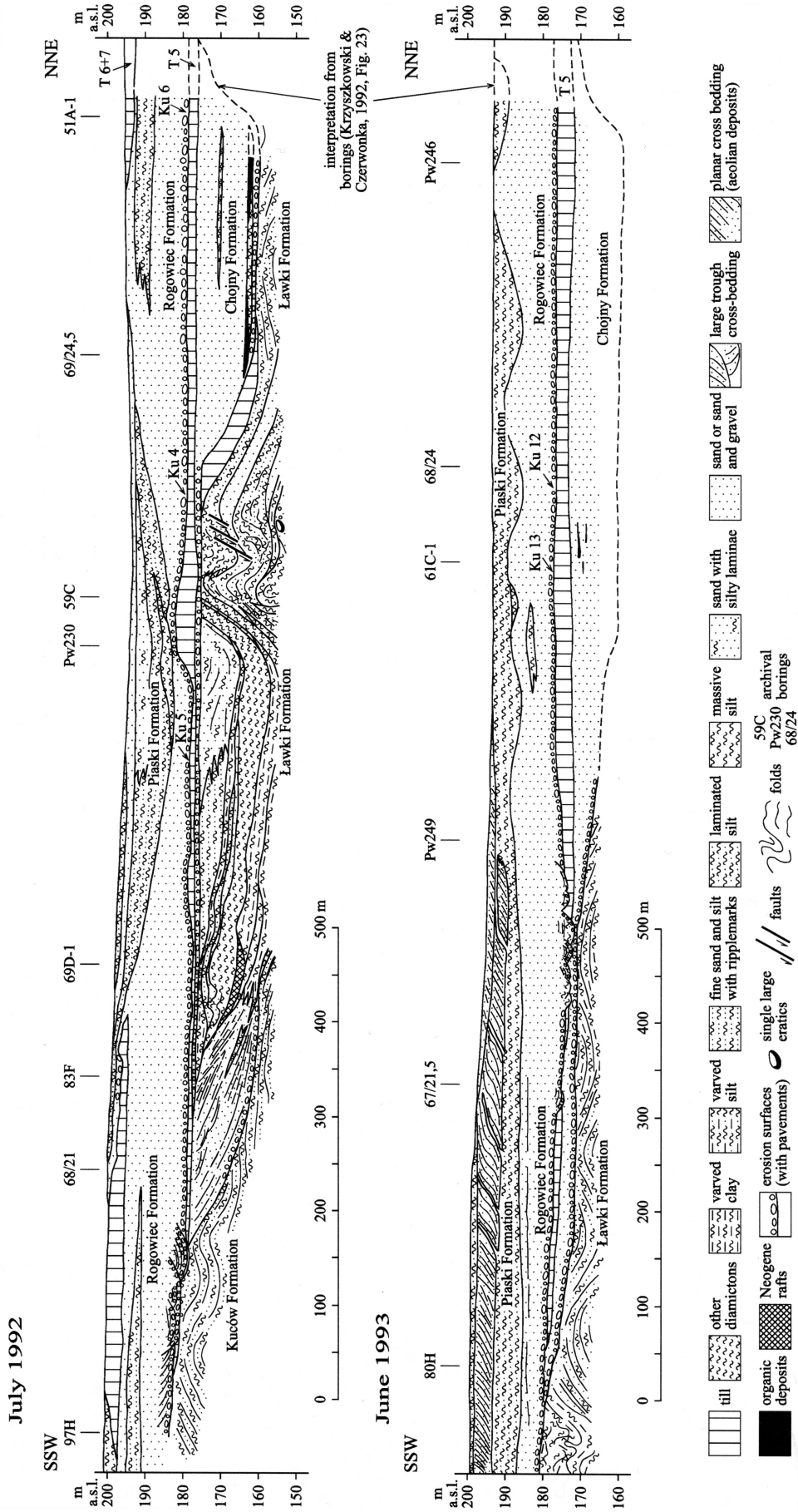


Fig. 3. Geological cross-sections and site locations. Note: the Lower Rogowiec varved clay is too thin to be shown

The Lower Rogowiec Till occurs only in the northern part of the quarry and hence only in the northern part of the Kleszczów Graben (Fig. 2). This till has no equivalent beyond the graben (Rzechowski, 1971; Baraniecka & Sarnacka, 1971; Klatkova, 1972; Nalewajko, 1982). The varved clays have their major outcrop in the eastern part of the quarry, where they are up to 2 m thick (Hałuszczak, 1982), but also occur to a lesser extent in the north-western part of the quarry. In the latter zone, the varved clays become very thin and discontinuous (Fig. 2).

The Rogowiec Formation is considered to represent the Wartanian (Warthe) stage (Krzyszowski, 1988, 1991, 1994, 1995). Below the lower till/varved clay, there usually occurs the fluvial Chojny Formation (Fig. 2) (Krzyszowski, 1990) and, in places, older glacial deposits from the older Saalian Ławki and Stawek formations and the Elsterian Kuców Formation (Figs 1, 3). Above the till, the glacio-fluvial sands of the middle member of Rogowiec Formation are always present, overlain by the middle and upper tills (T6, T7) of the Rogowiec Formation and younger deposits (Figs 1, 3).

TEXTURE

Grain size of the till was investigated at site Kuców 4, with an additional analysis from a flow till at site Kuców 5 (Figs 4 and 5). The mean size of the till matrix varies from very fine sand to coarse silt (4.0–5.4 phi), with an average clay fraction content of 8–16% (maximum *ca.* 20%). Sorting is extremely poor; the till matrix is at least bimodal, often polymodal (Fig. 4). The clay layer below the till has almost the same mean size (4.3 m), but the clay content is up to 40%. The sands below the till comprise moderately well sorted medium sand.

The vertical sequence of grain size distribution of the till shows some interesting trends (Fig. 4). First, the till can be subdivided into sandy till (4.0–4.5 phi) in the lower part, and silty-clay till (4.9–5.4 phi) at the top of the sequence. The increase in the fines content in the latter is possibly due to post-depositional soil processes; this till is reddish-brown and colour-stratified, indicating increases upwards of the fines and CaCO₃ contents.

The modal fraction of the unmodified till is medium sand, which is associated with fine sand to coarse silt. The content of medium sand decreases upwards systematically, from 22% at the till base to 14% below the reddish-brown zone. Medium and fine silt is infrequent throughout the profile, but the clay fraction forms significant peaks (Fig. 4). Within the sandy till, samples 2671 and 2677 both have a higher clay content, *ca.* 16%, than the average 8–12%. Sample 2671 is derived from directly above the sub-till clay, and 2677 was sampled from a lens of ‘clayey’ till, recognised in the field by its higher moisture content and darker colour (Fig. 5). The relatively homogeneous texture of the till suggests that it was formed by mixing, prior to the lodgement process. The high proportion of medium sand and its upward decrease suggest strong incorporation of the underlying sand into the till during the lodgement process. In places, also the clay was incorporated, where the sub-till

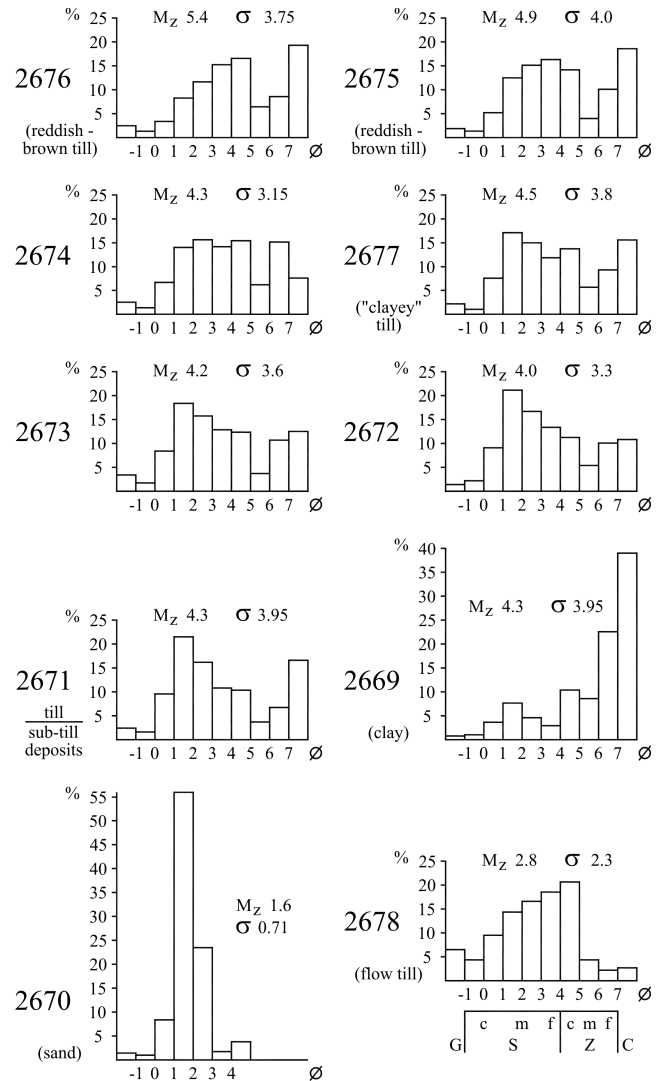


Fig. 4. Histograms of grain size distribution in the Lower Rogowiec Till and sub-till deposits at sites Kuców 4 and 5; g,s, c – gravel, sand, silt, clay; c, m, f – coarse, medium, fine

clay layer was present. Sample no. 2671 has a large proportion of medium sand and clay (Figs 4 and 5). This was most probably due to selective incorporation from the sub-till deposits: from the clay layer (clay fraction 40%) and from the sand layer (medium sand fraction 56%). The lenses of ‘clayey’ till in the middle and upper parts of till profile may represent the “rafts” of clay-enriched material moved upwards from the sub-till position.

The lower till from site Kuców 5 (Fig. 5) has a contrasting texture. It is coarser (mean size 2.8 phi) and better sorted (2.3 phi). Although the modal fraction is coarse silt, the fine silt and clay content is very low, with simultaneous high contents of sand and fine pebbles up to 6.3% (in ‘normal’ till, below 3%). These features are in keeping with a flow till, in which the fines would have been removed selectively, making a coarser, better sorted unit.

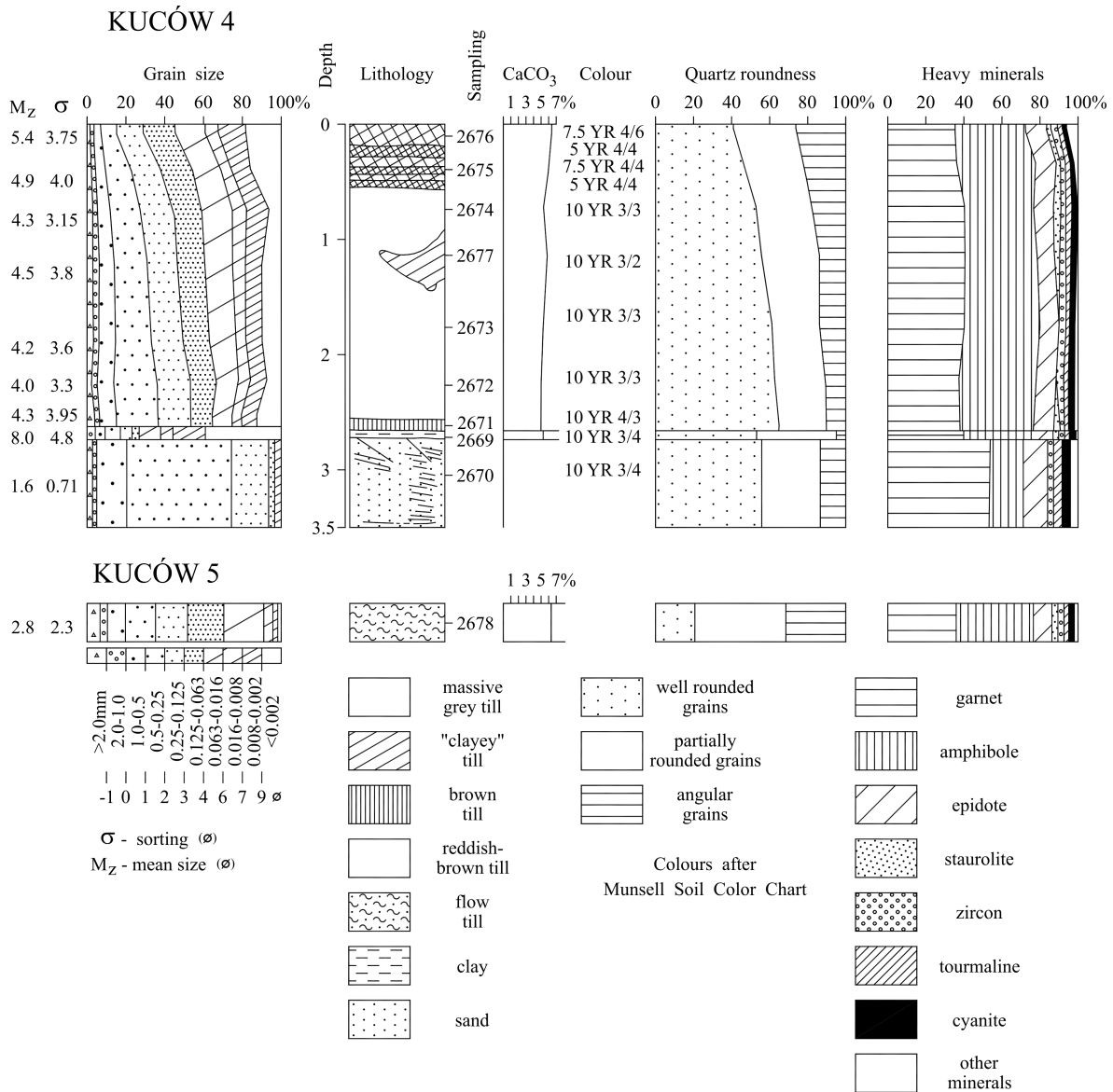


Fig. 5. Properties of the Lower Rogowiec Till

STRUCTURE

The Lower Rogowiec Till is usually massive, matrix-supported and normally consolidated. It has a 'porphyritic' structure, with rare, floating gravels within the matrix. Preferred orientation of the stones is commonly observed, indicating flow in a NW-SE direction. A common feature in the massive till is the occurrence of joints, which are most probably dilation joints (Krzyszowski, 1994).

Sandy laminae/lenses are rare, except at the till base, and they are thin, from a few millimetres up to 1-2 centimetres. They occur in groups, parallel one with another, and are separated by layers of massive till up to several centimetres thick. The sandy layers disappear laterally after a few metres or less. The sand within the laminae is massive, but this observation may be due to the very limited thickness. Sometimes the sand lenses are draped over stones as described by Shaw (1979, 1982, 1983).

PETROGRAPHY

Gravel petrography was analysed within various size ranges (Fig. 6). Generally, a greater number of resistant rocks (crystalline, quartzites) are observed in the larger sizes with a corresponding decrease of other rocks, especially limestones. The petrographic content stabilises at -6 to -5 phi, and is almost the same down to -2 phi (Fig. 6). The till is dominated by northern rocks (80-85%): Scandinavian crystalline rocks, Jotnian quartzites, East Baltic limestones and dolomites. Local rocks from the Polish Lowland and Southern Baltic are represented by Mesozoic limestones and sandstones, flint, Neogene mudstones, and milk quartz. Some crystalline rocks are highly weathered, although the structure of the rock is preserved until the till is disturbed.

T5 (Lower Rogowiec Till)

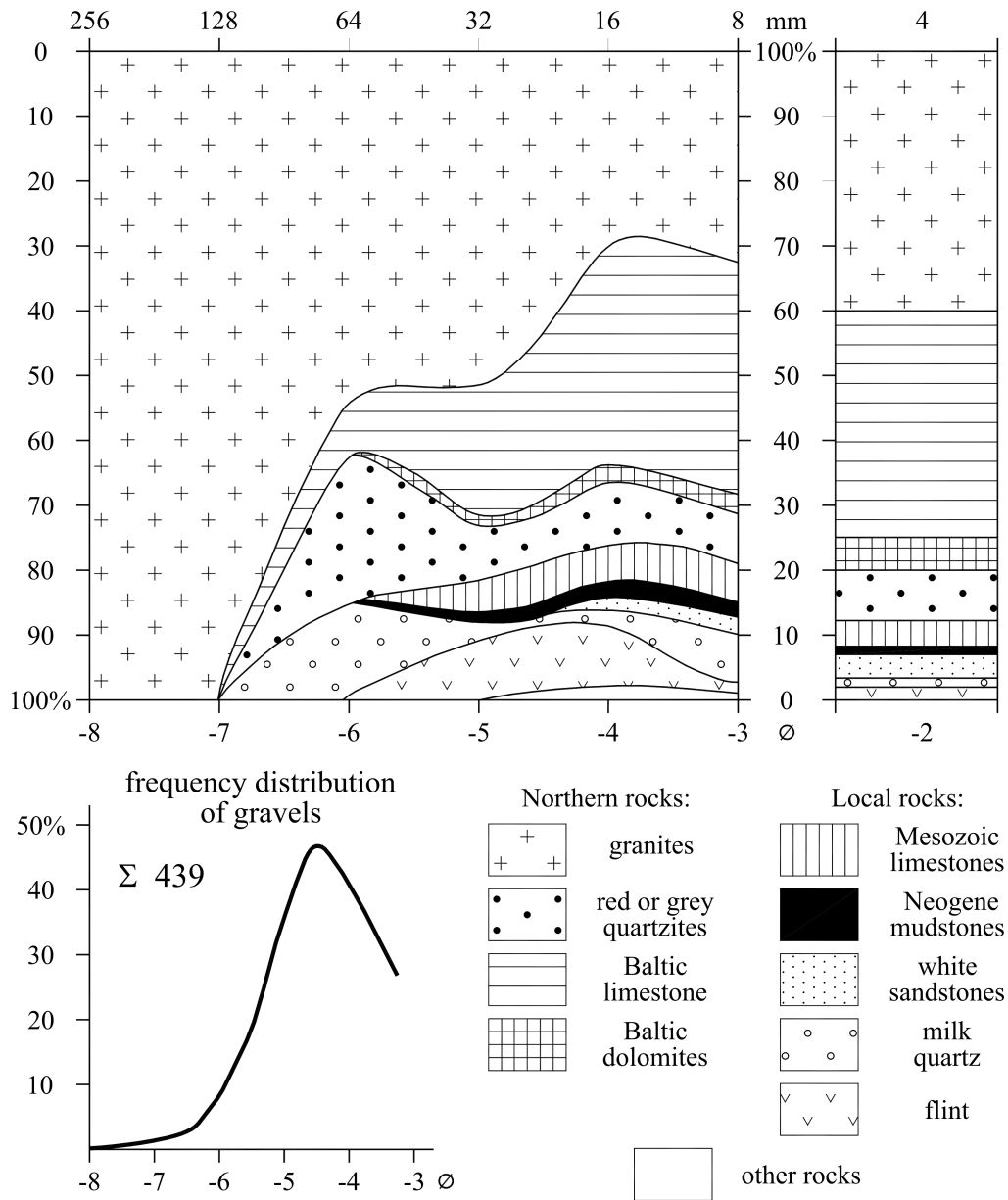


Fig. 6. Gravel petrography of the Lower Rogowiec Till

QUARTZ ROUNDNESS AND HEAVY MINERALS

Quartz roundness in the lowermost part of the till is almost the same as in the fluvial deposits below – well rounded grains predominate. These grains systematically decrease in number upwards (Fig. 5).

The flow till (Kuców 5; Fig. 10) has quite different characteristics, with angular grains common, partially rounded dominant and well rounded relatively rare (Fig. 5). This pattern is characteristic of tills in Bełchatów quarry (Czerwonka & Krzyszkowski, 1992). Thus, it is clear that the well rounded particles were incorporated into the till from the deposits below. The well rounded grains (Goździk,

1980) come from ‘aeolianised’ fluvial and aeolian deposits of the uppermost part of the Chojny Formation (Goździk, 1980, 1992; Krzyszkowski, 1990).

The Lower Rogowiec Till has a heavy mineral assemblage, dominated by garnet, amphibole and epidote (Fig. 5), typical of all the tills in the Bełchatów quarry (Czerwonka & Krzyszkowski, 1992). There is no change of mineral assemblages, either in stratigraphic order or in the different till facies, and the varved clay at the till base has similar heavy minerals. The sandy deposits lying below have quite different characteristics, with garnet predominating (Fig. 5). The latter assemblage is characteristic of the upper member of the Chojny Formation (Krzyszkowski, 1990).

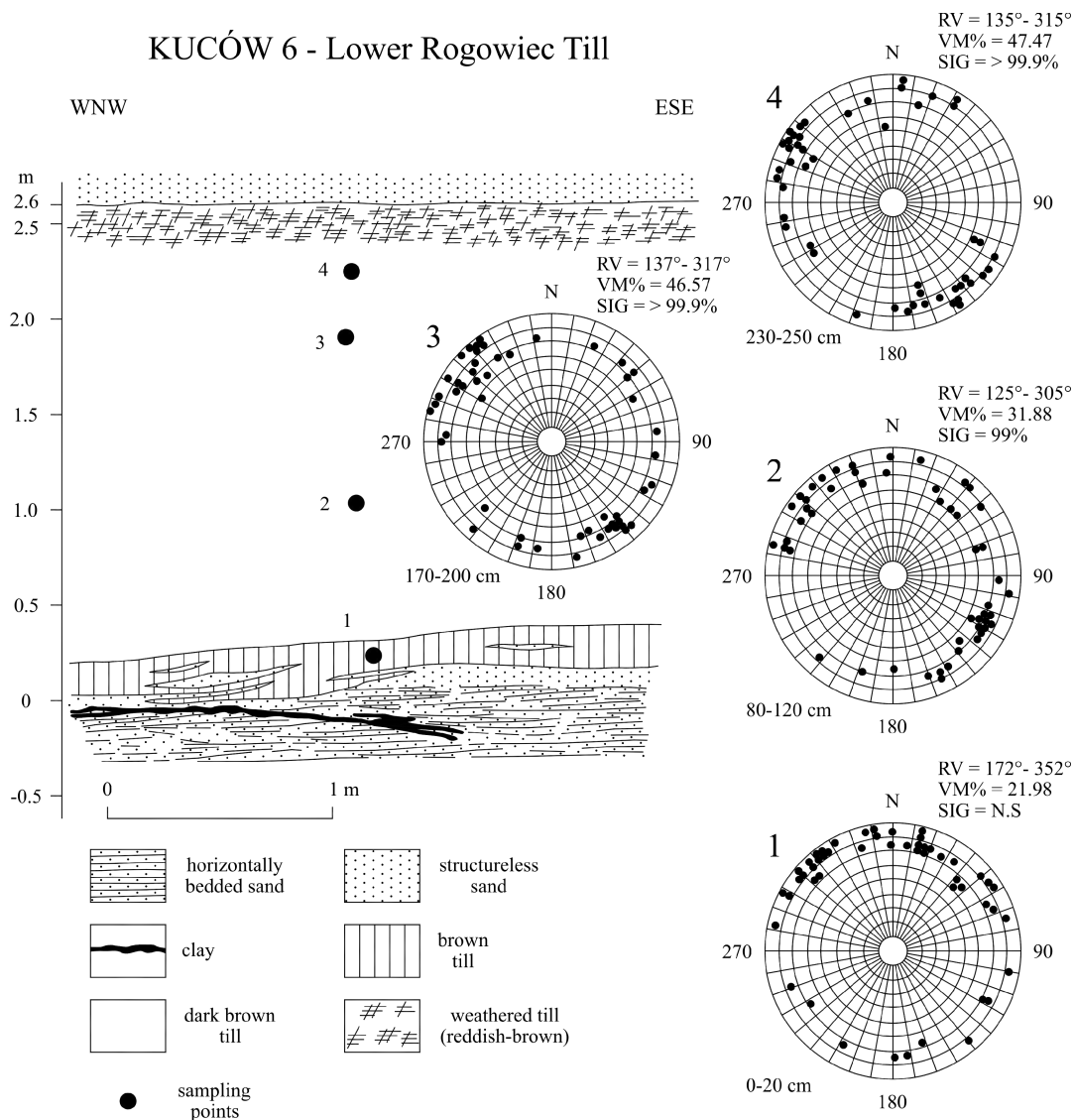


Fig. 7. Characteristics of the till and sub-till deposits at Kuców 6

DEFORMATION STRUCTURES AND TILL MACROFABRIC ANALYSES

The relationship of the till sites, at which detailed structural description and macrofabric analyses were undertaken, to the underlying formations can be seen in Figure 3. The till was deposited on a nearly planar surface which cuts across the fluvial sands of the Chojny Formation. These sands vary in thickness, from 10 to 15 m in the palaeovalley, to 0.5–2.0 m beyond; they overlie strongly folded silts, sandy silts, varved clays and diamictons of the Ławki Formation. The 1–10 cm thick varved clay at the base of the Rogowiec Formation is present intermittently between the older formations and the till.

Site Kuców 6

This site lies immediately above 15 m of sands of the Chojny Formation. These sands are horizontally bedded, but their uppermost part, just below the till, is structureless

(massive) and in part interbedded with the basal till. A 1–2 cm thick clay layer is present within the sand, but it has no contact with the till.

The till has three distinct layers which differ in colour and structure (Fig. 7). The basal 10–20 cm of the till is brown (10YR4/3) and contains many sand lenses. Moreover, some sub-horizontal till wedges (Westgate, 1968; Ehlers & Stephan, 1979; Rappol, 1987), 1–5 cm thick and several centimetres long, are interstratified with the underlying sand (Fig. 8A). Above, there occurs the main, dark brown (10YR3/3), till body, ca. 2.5 m thick. It is massive, with no inclusions. There is a gradual transition upwards into the topmost 10–20 cm thick, reddish-brown (5YR4/4) till, which may be the lowermost part of a weathering/palaeosoil horizon.

The macrofabric pattern (Fig. 7) of the basal till, although not demonstrating a statistically significant clustering, does show a strong concentration of readings forming a girdle between 295° and 075°, with dips generally below 20°. In the main body of the till, the macrofabric patterns

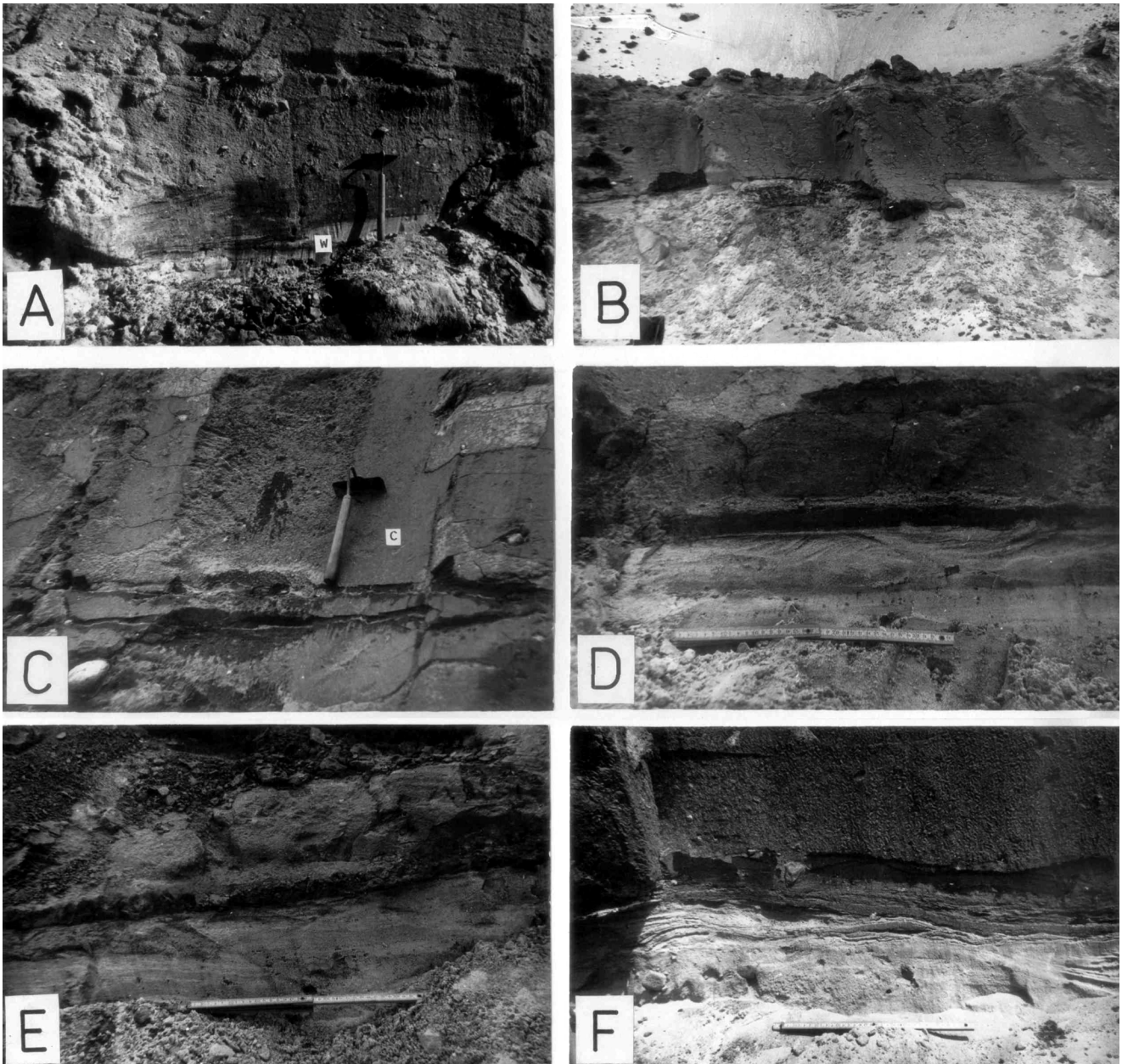


Fig. 8. Base of till at sites Kuców 4 and 6: **A** – till wedge (w) at Kuców 6; **B** – general view, Kuców 4, load cast structure; **C** – sandy laminae within the massive, sandy (s) and ‘clayey’ (c) tills; **D** – undeformed small-scale cross-bedding beneath the till base; **E** – small faults beneath the till, dark layer at the base of till is varved clay (v); **F** – interbedded sand and till laminae at the base of till between Kuców 4 and 5

show a strong (<99%) bipolar NW–SE distribution. The bipolar macrofabrics from the main till body are in accord with the inferred direction of regional ice movement.

Site Kuców 4

Kuców 4 lies in the south bank area of the palaeovalley (Figs 2, 3). The substratum is composed of 0.5–1.0 m of fluvial, mostly horizontally bedded, sands (10YR3/4) of the Chojny Formation, and 1–5 cm of varved clay (10YR3/4) (Fig. 9), below which are deformed silty sands. The till has three main facies. The basal, 3–12 cm thick, layer comprises

a brown till (10YR4/3) with many sandy inclusions. The main till body is a dark brown (10YR3/3), sandy till containing numerous, irregular but distinct lenses of more clayey till (10YR3/2) (Fig. 8B and C). Transitions between them are, however, gradual. Two parallel, 1–3 cm thick, sandy laminae occur within the main till. They cross both sandy and clayey tills with no change in character (Fig. 8C and 9). Individual clasts with underlying scours have been observed within the sandy laminae (Fig. 9). The uppermost part of the till is represented by alternating strong brown (7.5YR4/4) to reddish brown (5YR4/4) layers, most probably representing the lower part of the weathering/palaeosoil horizon.

KUCÓW 4 - Lower Rogowiec Till

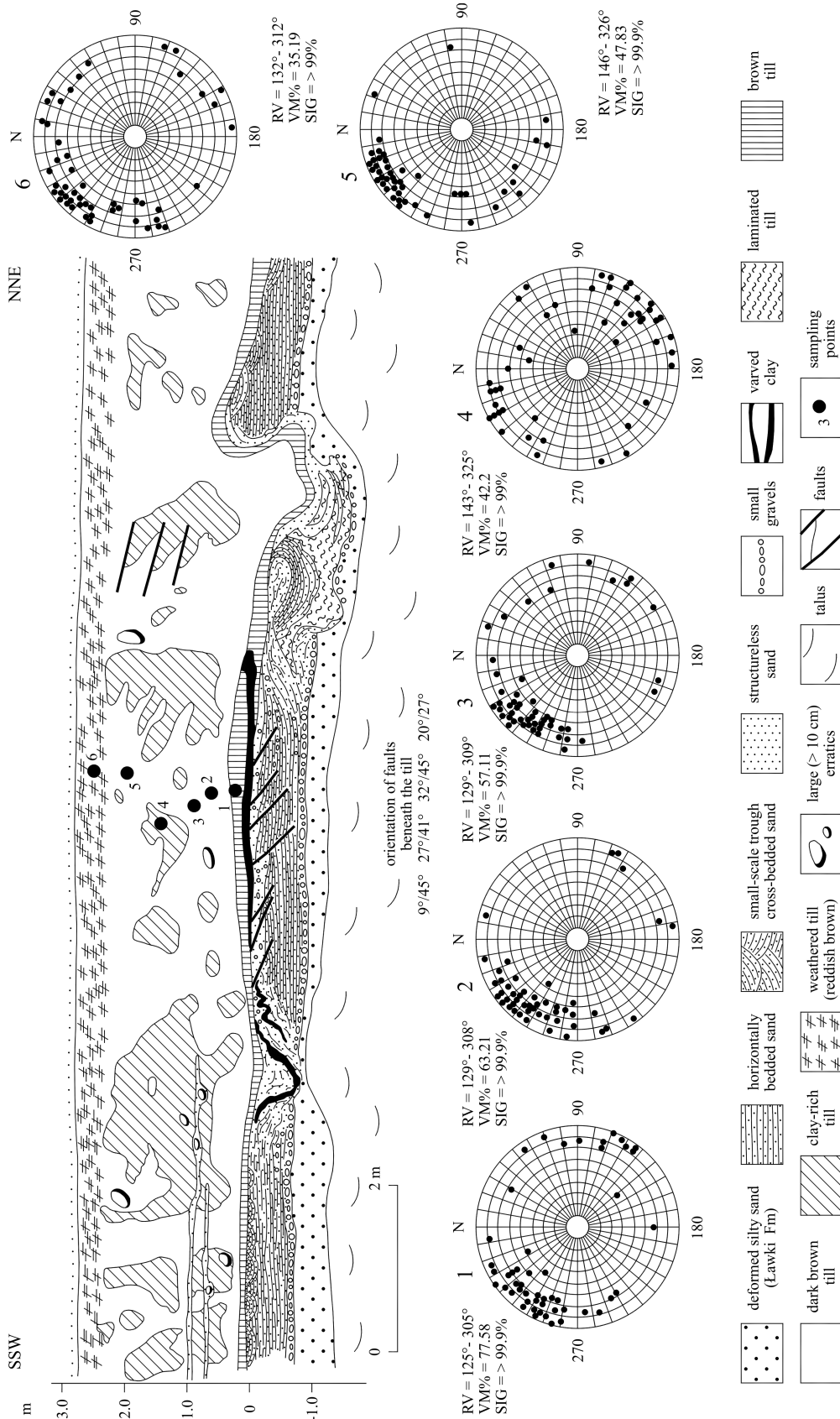


Fig. 9. Characteristics of the till and sub-till deposits at Kuców 4

The till/sub-till transition is very complex. Three zones can be recognized. In the southern and northern parts of the section (Fig. 9), the till/sand boundaries are sharp with no deformation of the underlying sand. Ripplemarks (small-

scale trough cross-bedding) are observed immediately below the basal till (Fig. 8D). The central part of the section is strongly deformed. There are two load casts, involving the lowermost part of the till, sand and varved clay (Figs 8B and

KUCÓW 5 - Lower Rogowiec Till

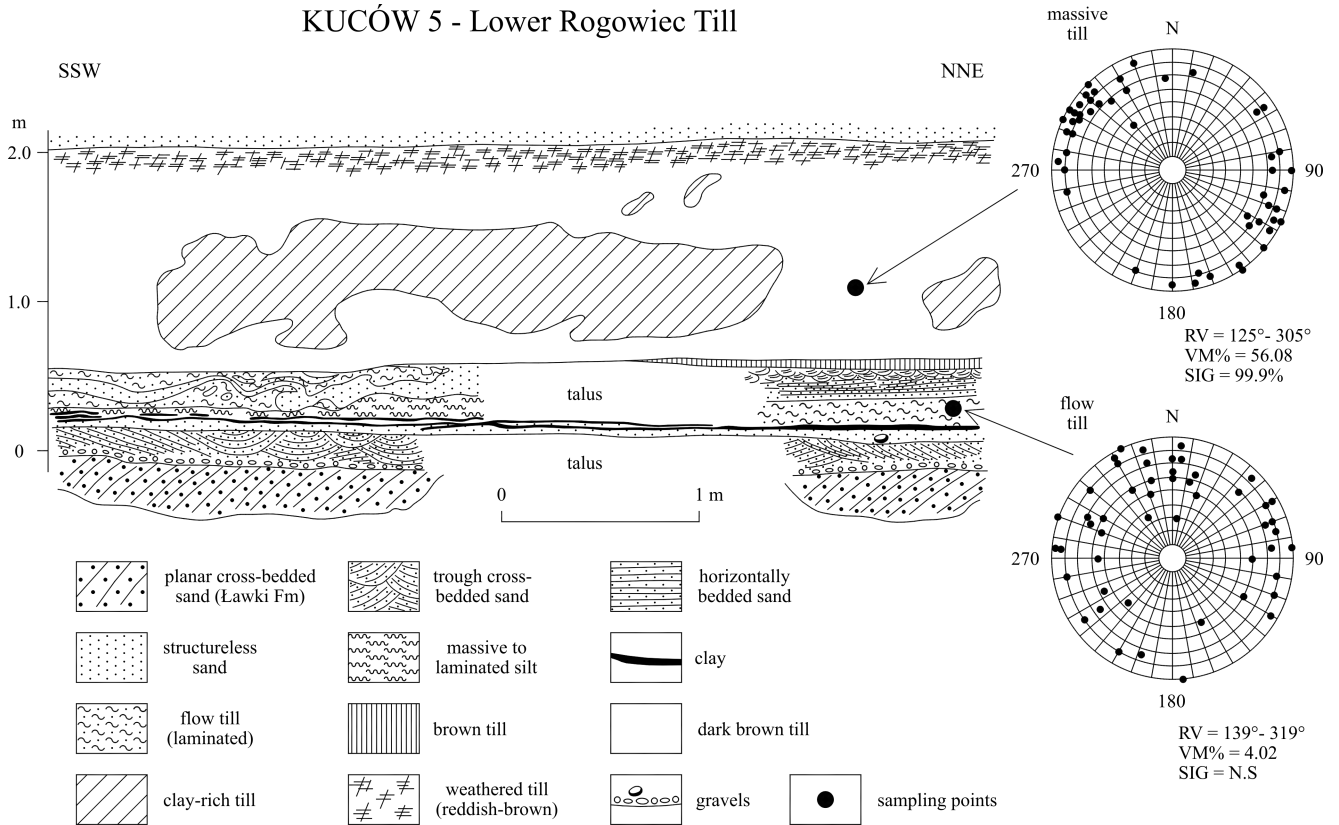


Fig. 10. Characteristics of the till and sub-till deposits at Kuców 5

9). The section between the load casts contains undeformed varved clay, in part incorporated into the basal till. Immediately below is faulted, but otherwise structureless, sand which becomes horizontally bedded in lower positions. The fault orientation is not consistent with the fabric orientation. The fault plane orientation varies from 009° to 032°, i.e. north-northeast direction; dips are from 027° to 045°.

The macrofabrics all trend NW–SE. Three of the six fabrics are unimodal with statistically strong (>99.9%) clustering to the NW. The other three fabrics are bipolar, but still have strong (99% or better) clustering. All these trends are in accord with the inferred direction of regional ice movement.

Site Kuców 5

This site lies ca. 300 m south of Kuców 4 (Figs 2, 3, 10). It comprises a lower massive to laminated till lying above a clay/silt layer. The laminated till is separated from the main till body by 15–20 cm of horizontally and trough cross-bedded sands. Both the laminated till and clay/silt layer are deformed in the southern part of the section, although the main till/sub-till boundary is sharp throughout the section. The main till body is represented mainly by dark brown sandy till with clay-rich till inclusions, like in Kuców 4. The basal, brown till is 3–6 cm thick and thins out southwards. The topmost, reddish-brown till is similar also to that of Kuców 4.

The macrofabric pattern of the lower, laminated, till is very dispersed and there is no clustering. The pattern from

the main till is a strongly bipolar, significant at the >99.9% level.

The till/sand boundary between sites Kuców 4 and 5

A ca. 300 m long exposure of the till base, with only two, 30–40 m long sections covered by talus, was examined between sites Kuców 4 and 5. Six types of till/sand contact were recorded:

1. straight boundary with undeformed ripplemarks (small-scale cross bedding) or horizontally bedded sands immediately below the till (e.g. Fig. 8D),
2. slightly undulating till base, but with no deformation of the deposits below,
3. till wedges/sand inclusions within the basal till and a thin layer of structureless sand below (e.g. Fig. 8A),
4. interbedded till and massive sand layers with thickness commonly up to several centimetres (Fig. 8F),
5. faulted sands, similar to those of Kuców 4 (Fig. 8E),
6. folded sand and silt.

The 300 m of till base demonstrated a pattern of alternating sections, with and without sub-till deformations (Fig. 11). The latter are usually longer (5–20 m), but sections with deformations are more variable in length, from 1 m to several metres. The pattern repeats about every 10–20 metres (Fig. 11). Moreover, the basal brown till with sandy inclusions occurred both over the non-deformed and deformed sands. Sub-till deformations were observed also when the basal brown till was not present.

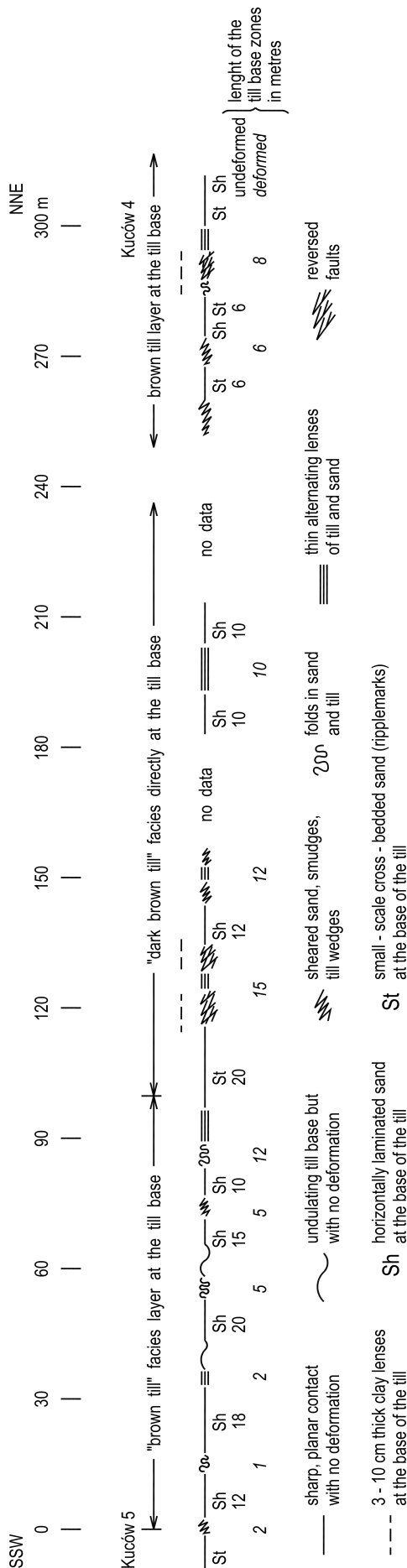


Fig. 11. Schematic representation of the till base between Kuców 5 and 4

Site Kuców 12

Two till sections were described, one 14 m long (A) and the other 10 m (B) (Fig. 12). Both lie above 10–15 m of sand of the Chojny Formation.

Kuców 12A contains a massive dark brown till lying above horizontally or cross-bedded sands and in one place above 5–10 cm of varved clay. The uppermost part of the sands is usually structureless. Here, the basal brown till or the uppermost reddish-brown till are absent. The till base is characterized by frequent till wedges in various stages of development and by various degrees of mixing, from massive sand to silty sand, sandy till, and finally to till (Figs 12 and 13A–C). Sand lenses pass up into the base of the till, forming a layer which becomes discontinuous the further the penetration extends into the till. The clay layer becomes incorporated into the till in the same way (Fig. 12A). At the base of the till, the clast macrofabric shows a unimodal pattern significant at the 99% level, with a spread of readings from 225° to 090°. In the upper part of the till, a strong (>99.9%) bipolar pattern occurs, trending NW–SE, consistent with the inferred direction of regional ice movement.

Kuców 12B shows similar sediments and structures to Kuców 12A. Additionally, two parallel layers of sands occur in the dark brown till and the clay-rich till (Fig. 12). Macrofabrics were measured throughout the profile. Two are significant at the 95% level with NW–SE trends. Two other fabrics, from the lowermost (basal) and uppermost parts of the till bed, show very dispersed patterns, lacking any significant preferred orientation. A fabric from a nearby clay-rich inclusion within the till showed a significant (99%) NW–SE trend.

Site Kuców 13

This site lies ca. 50 m south of Kuców 12. It consists only of dark brown, massive till (Fig. 14). The till base has two different characteristics. In the southern part of the section, beneath the till, structureless sand occurs, within which there are till wedges. The basal part of the till has sand inclusions/layers. In contrast, the northern part of the section has a very sharp contact between the till and the sand, with no deformation of the cross-bedded sand (Figs 13D and 14). These two zones are separated by a fault (Fig. 14). The dip of the plane of the fault (340/20°) is consistent with the direction of regional ice movement. The site was sampled only in the basal 10 cm of the till in the undeformed zone and macrofabric showed a very strong (>99.9%) unimodal clustering to the NW.

Summary

The deformation structures are restricted to the basal 0.25 m of the till and the uppermost 0.5 m of the sub-till sediments, and the sites showing deformation occur every 10–20 m. The deformations divide into two groups which never occur in the same situation. One group comprises small, centimetre-scale reversed faults. The second comprises a continuum from structureless sand, through irregularly folded sand and till, till wedges, interpenetrating sand

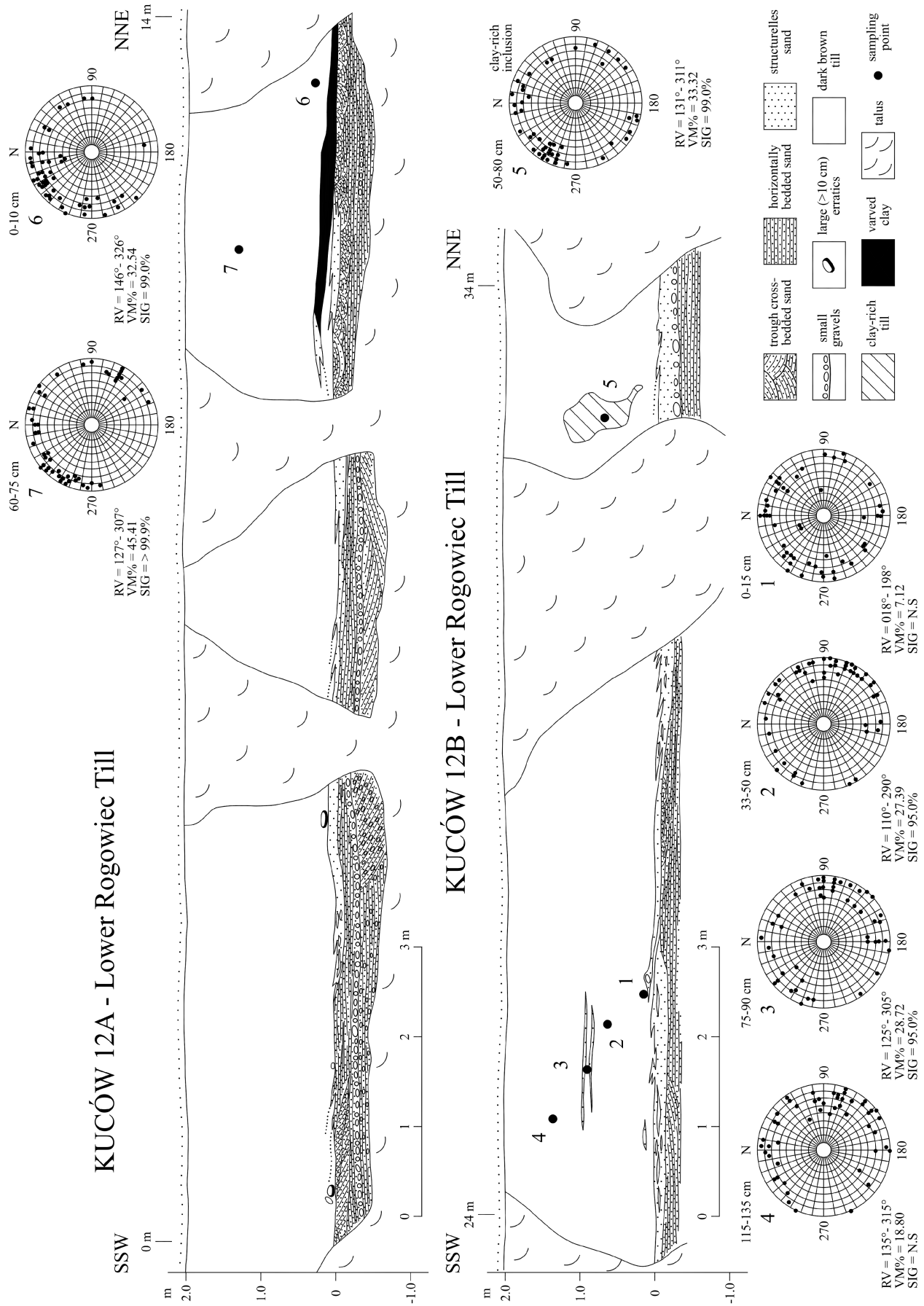


Fig. 12. Characteristics of the till and sub-till deposits at Kuców 12

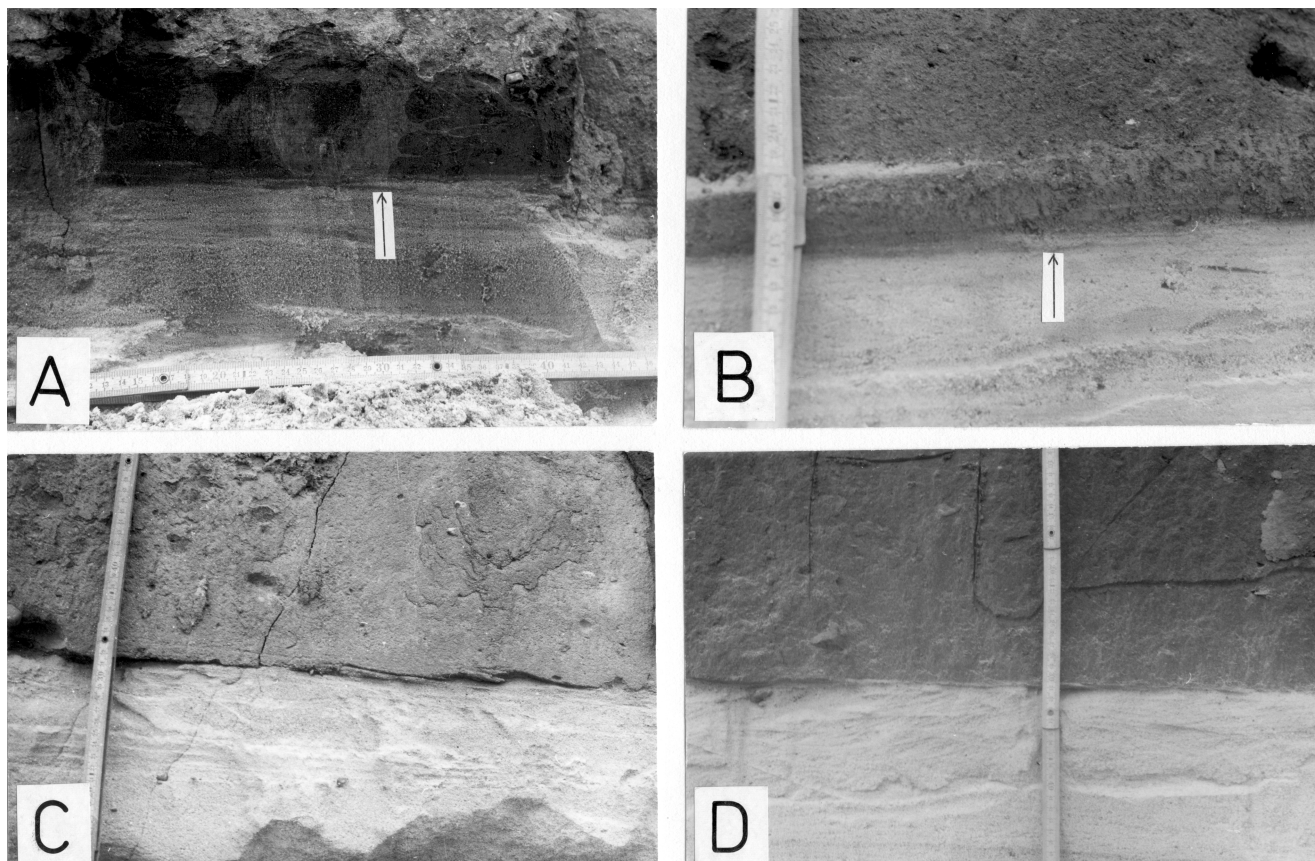


Fig. 13. Base of the till at Kuców 12 and 13: **A** – small till wedges (arrowed) at the base of till at Kuców 12; **B** – small till wedge at Kuców 12 with gradual transition from sand to till (arrowed); **C** – series of till wedges and sandy laminae in the basal till at Kuców 12 showing the incorporation process; **D** – undeformed small-scale cross-bedded sand at the till base at Kuców 13

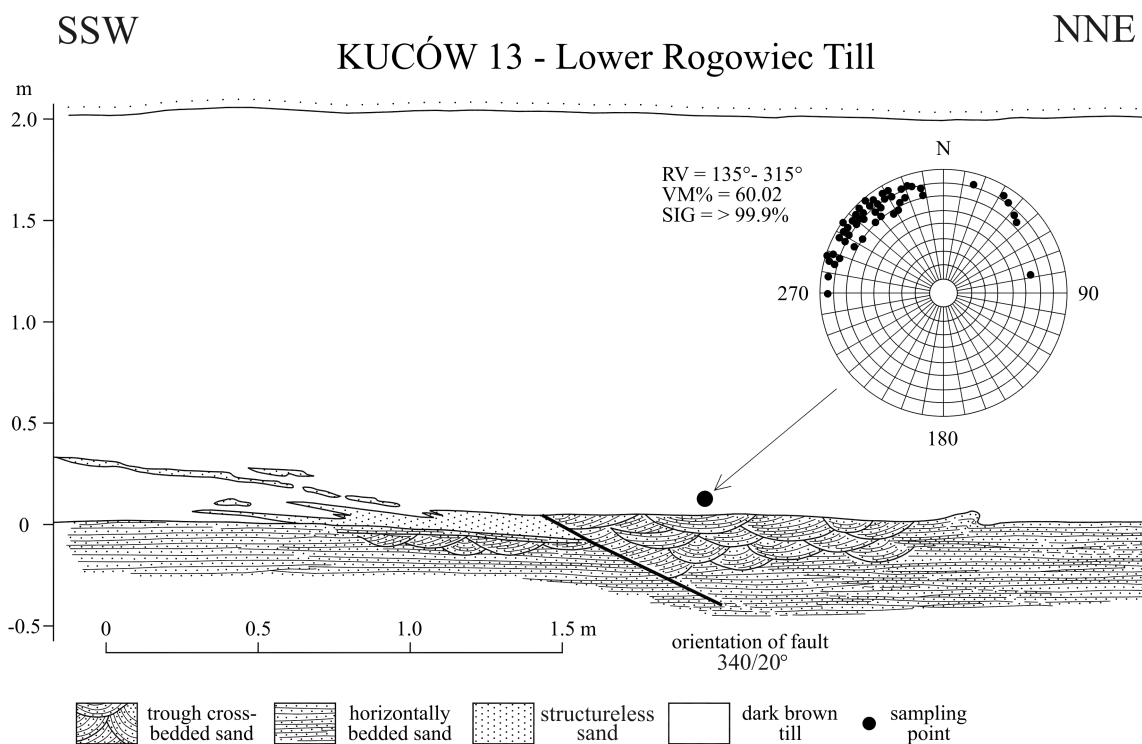


Fig. 14. Characteristics of the till and sub-till deposits at Kuców 13

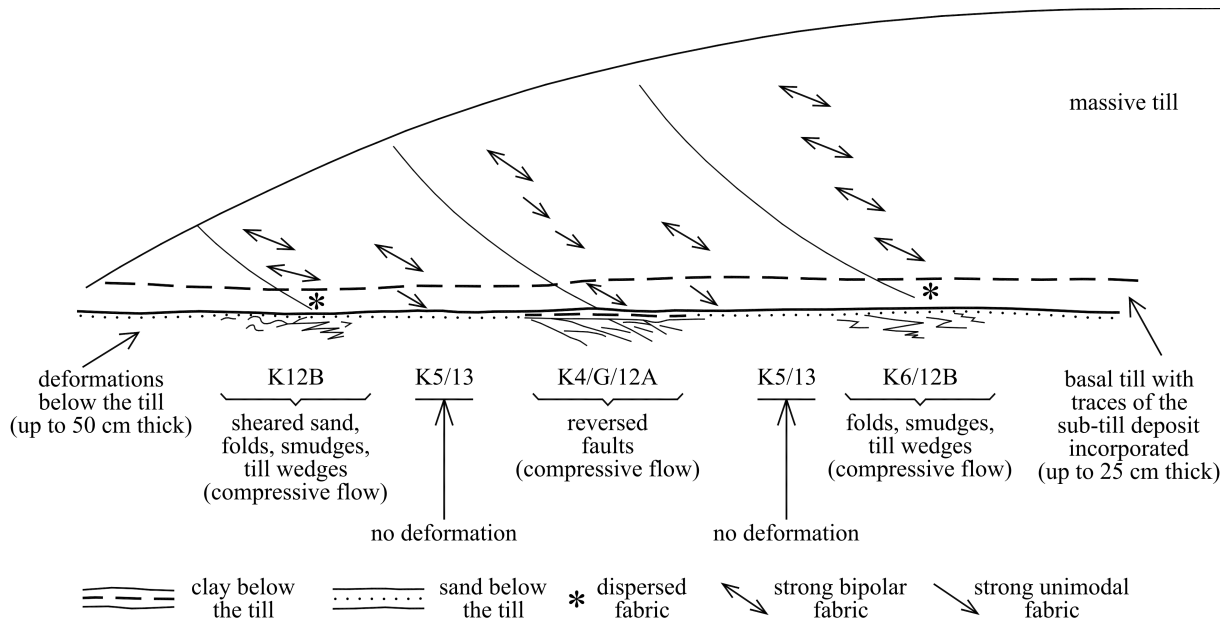


Fig. 15. Possible relationships between till fabrics and sub-till deformation

and till, to till with sand inclusions. This second group of structures affect only the basal 0.25 m of the till. The till above is usually massive.

When the till macrofabric patterns are considered with the deformation structures, three types of relationship occur between the till and the underlying strata.

1. Sub-till deformations occur, with weakly developed macrofabric clustering in the basal part of the till, becoming stronger upwards, e.g. Kuców 12B.

2. Sub-till deformation and a clay layer occur, with strongly developed macrofabric patterns throughout the till above, e.g. Kuców 4, Kuców 6, and Kuców 12A. Macrofabrics often show strong clustering on the up-glacier side, either confined to the basal zone (Kuców 6, Kuców 12A) or throughout (Kuców 4).

3. No basal deformation, but with strong macrofabric patterns throughout the till. Clast dips are confined to the up-glacier side in the basal zone, e.g. Kuców 13 and Kuców 5.

Within the above scheme further relationships can be determined. The basal till and the main till body have different relationships to the sub-till deformation.

The main till body (M) has two types:

M-A. where the clay layer is present and faulting occurs in the sand below, the fabric is strong and unimodal (Kuców 4, Kuców 6) and,

M-B. where there are no clay or faulting, but only incorporation of sand, the fabric is strong and bimodal (Kuców 12B).

The basal till (B):

B-A. has a strong fabric pattern only where there is clay below (Kuców 4, Kuców 6, Kuców 12A).

B-B. in other cases the fabric is very weak (Kuców 12B).

The above patterns can be seen to occur in a repeated sequence along the sections (Fig. 11).

It is notable that the till macrofabric patterns at any one site are similar. At Kuców 4, all six macrofabrics were unimodal and very strongly clustered, with significance levels of 99% or higher. At Kuców 6, the four macrofabric patterns were bipolar and the vector strengths consistently decreased upwards. The four analyses at Kuców 12B all showed much poorer clustering, with only two reaching the minimum significance level of 95%. Only Kuców 12A does show variation, with one analysis showing a unimodal pattern and the other a bipolar one. At Kuców 5 and 13 only one macrofabric was undertaken.

INTERPRETATION

The heavy minerals (0.01–0.25 mm) and gravel petrography (>4.0 mm) are uniform throughout the till body and provide no evidence for incorporation of material from beneath the ice. However, the grain size distribution does indicate incorporation from beneath the ice of medium sand (0.25–0.5 mm) and clay (<0.002 mm), the latter only in places where sub-till clay occurs. This incorporation is clearly visible in the basal 20–50 cm of the till, systematically disappearing upwards. Well rounded quartz grains (0.5–1.0 mm) occur in their highest numbers in the basal part of the till and reduce upwards, again indicating that they were derived from the fluvial sediment below. Thus, incorporation of material from below was very selective and was restricted to the medium and coarse sand and/or clay fractions.

The pattern of deformation and the variation in the macrofabric patterns indicate that the till is not structurally homogeneous. As the sites showing deformation occur about every 10–20 m (Fig. 11), it is suggested that there may be a control such as basal glacier stress conditions associated with the zones of shearing at the ice front. This

would imply that the shear zones have a similar spacing and that the compression at these points develops sufficiently strongly that shearing affects both the till and the substrate beneath the ice. At these points, the basal till and the main till body will have strong fabrics if there is a sub-till clay present (Kuców 4, 6, 12A). The macrofabrics with strong up-glacier clustering particularly indicate shearing and compressive flow. Thus, the clay is associated with stronger stress reactions, most probably due to high pore water pressures (Boulton *et al.*, 1974). This stress appears to transmit to the sand below also, as small reverse faults are found there. This is best developed in Kuców 4, where compression and shearing affect not only the underlying sands, where there are reversed faults, but also the main till body, where the adjacent clay-rich till inclusions show shears and down-glacier attenuation, and the till base, which is folded. The fabric in the basal till is weak where there is no clay (Kuców 12B), but there will be a strong bimodal pattern in the main till body (Fig. 15). In this case, the fabric in the basal till is weak because the deformation stresses created as the sand and till are mixed are absorbed by the till and the fabric strength is reduced (Hart, 1994). Both cases represent compressive flow (Fig. 15).

The intervening areas, lacking deformation structures, occur between the zones of compressive flow, where pressures would have been less. In these areas, the main till body has some features, such as sand layers and scours beneath clasts, which in the past have been described as indicators of melt-out (Shaw, 1979, 1982, 1983). Such an interpretation is not consistent with the conclusions reached here. Hence, the interpretation by Rappol (1987) that these structures were formed due to shearing is more probable.

Varying degrees of stress are also indicated by the macrofabric patterns. The unimodal patterns with high vector strengths at Kuców 4, 5 and 13 suggest a significant degree of compression, while the poor clustering at Kuców 12B implies a far lower stress level. Kuców 6 and 12A are intermediate.

DISCUSSION AND CONCLUSIONS

Two opposite views on basal till origin exist recently in the literature. The traditional concept explained basal till as a result of melting of debris-rich basal ice and lodgement of material below the moving ice (Boulton, 1970, 1972, 1980; Marcussen, 1975; Krüger, 1979; Rappol, 1987; Dreimanis, 1989). This process is accompanied by subglacial deformation and incorporation of underlying deposits into the basal till (Elson, 1961, 1989; Rappol, 1987; Dreimanis, 1989; Stephan, 1989). The latter process occurs discretely and tills with predominance of local material are usually interpreted as a "special case", involving special processes during the sedimentation.

Boulton *et al.* (1974), Boulton and Hindmarsh (1987), Alley (1991), and Hart (1994) have argued that the basal till is formed due to pervasive deformation of debris-rich basal ice and its substratum. Thus, there is no distinct boundary between the ice and its substratum, and the deformed layer is continuous along the moving ice. The final effect of this

deformation is mixing of deposits and formation of homogeneous till, in which local material play a significant role, if not predominate.

The results of our work suggest that the incorporation can be very selective and that homogenisation of material from beneath ice may not occur. The latter occurs more frequently only in the lower, 0.25 m thick, till bed and disappears upwards. On the other hand, an increase of medium sand and rounded quartz grains in the basal till indicate for only selective incorporation of the underlying fluvial sand. The upper and major part of the till contains, however, practically only the far-transported material.

The basal deformation structures, such as wedges and faults, show that the incorporation occurs by shearing of the sand into the till. On the other hand, the regularly spaced deformation sequences at the base of the till and the variations in the macrofabric patterns show that shearing occurred only at certain points. These points occur at 10–20 m intervals, thought to coincide with shears such as occur at an ice margin. Thus, the limited deformation and incorporation of sub-till material into the main till body suggests that the till was formed not by a simple continuous process of homogenisation and pervasive deformation (Alley, 1991; Hart, 1994), but that the process occurs in stages controlled by different factors. This was previously concluded by Clayton *et al.* (1989) from a large-scale deformation pattern in tills, and probably is a result of rheological nonlinearity of the subglacial material (Kamb, 1991). Brown *et al.* (1987) suggested that the occurrence of limited shear strain in the basal till exclude a significant role of pervasive deformation in the ice movement. This movement was limited to the ice-bed interface or along the faults within the substrate, what is probably the case in our profiles.

Our work supports the view of Banham (1977) that stresses at the base of the glacier lead to both exodiamict and endiamict deformation, but indicates that the processes operate discontinuously, being restricted to those areas where, in our opinion, basal stresses were higher. A previous suggestion (Krzyszowski, 1994) that there was melt-out till present can be questioned. The relevant structures found within the till are now shown to be associated with compressive flow.

The zones of deformation affect the basal area of the whole outcrop of the till, irrespective of the nature of the underlying sequences. Hence, differences in the permeability of the strata older than the Rogowiec Formation appear to have had no effect on the pattern of deformation, as it is independent and can be explained in terms of varying shear stress within the zone of compressive flow in the glacier. Where higher pore water pressures may have had an effect, this appears to be connected to the thin clay layer that occurs intermittently beneath the till, rather than the underlying Chojny and Ławki Formations.

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