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Initial ice movement directions from the East and South South East during a late Weichselian readvance in NE Germany

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Abstract: Two gravel pits (Kavelpaß and Wusseken), in the hinterland of the Pomeranian ice margin in NE Germany, have been investigated. Both sites possess glacifluvial sediments in the lower part of the available exposures, and a till in the upper part. Sedimentological studies and studies concerning ice movement directions have been carried out. There is a clear evidence that the initial ice movement direction was from E and SSE, which contrasts with the expected regional movement direction from NE through NNE. An explanation by the marginal dome concept is proposed in this paper.

Kurzfassung: Im Hinterland der Pommerschen Endmoräne in Nordostdeutschland sind zwei Kiesgruben (Kavelpaß und Wusseken) untersucht worden. Beide weisen glazifluviale Sedimente im unteren, sowie Geschiebemergel im oberen Teil der Lagerfolge auf. Sedimentologische Studien und Studien zur Eisbewegungsrichtung sind durchgeführt worden. Es ist deutlich, daß das Eis zu Beginn des Vorstoßes von Ost nach West, bzw. von Südsüdost nach Nordnordwest geflossen ist, und somit die Eisfließrichtung als abweichend von der erwarteten regionalen nordost-südwestlichen Bewegungsrichtung betrachtet werden muß. Eine Erklärung dieses Phänomens unter Zuhilfenahme des Marginaldomkonzeptes wird in dieser Arbeit vorgeschlagen.

Introduction

During the last glaciation, the Weichselian ice sheet reached its maximum extension during the Brandenburg Phase (Fig. 1). Thereafter it retreated to the Frankfurt marginal line, where it stagnated. After this Frankfurt Phase the ice margin retreated at least 200 kilometres into the Baltic Sea basin and readvanced during the Pomeranian Phase to the Pomeranian marginal zone. This course resulted in two different till beds, the Brandenburg till and the Pomeranian till, which can be distinguished from each other by the lithological composition of their clast contents (CEPEK, 1967). The Brandenburg till is characterised by a high amount of Silurian shale, whereas the Pomeranian till contains additional cretaceous chalk and flintstone (CEPEK, 1972; TGL 25232). After the Pomeranian Phase the ice sheet retreated successively with only short periods of standstill or possibly minor oscillations, which resulted in the formation of small recessional moraines. In recent years an additional third Weichselian till has been distinguished, the so-called Mecklenburg till (e.g. RÜHBERG & KRIENKE, 1977; EIERMANN, 1984; RÜHBERG, 1987). It is characterised by its low thickness, a high sand/silt ratio and low clay content, and poor consolidation. Another characteristic is its remarkably high $CaCO_3$-percentage.

The expected directions of ice movement during these Phases are from the north-west through north, i.e. perpendicular to the ice margin. However, PETERSS (e.g. 1989, 1990) observed a number of till fabrics and stress joints, which deviate from the expected regional direction, but they were not discussed in detail.

General description

The localities described in this paper are situated in the eastern part of Mecklenburg/Vorpommern, approximately 50 to 60 km north of the Pomeranian ice margin. According to the Geological Map of Mecklenburg/Vorpommern 1:500 000 (1995), an ice margin of the Mecklenburg Sub-Stage (Rosenthal ice margin - W3R (REINHARD 1965; KLIEWE, 1965; SCHULZ, 1965; RÜHBERG, 1987) runs a few kilometres south of the area in question. This margin corresponds roughly with the transition between flat moraine terrain to the north and hummocky moraine terrain to the south. The glaciolimnic basin of the „Haffstausee“ (KLIEWE, 1965) is situated to the east of the actual area. To the north and to the west flat cover moraine areas (AARIO, 1977; ANDERSSON, 1998) dominate.

The surrounding landscape is rather flat, only slightly irregularly undulating. However, river valleys cut deep into the ground, up to 20 metres below the plain. Holocene sediments (sand and peat) are commonly occupy the valley floor. Tills are the dominating surficial sediment type in the

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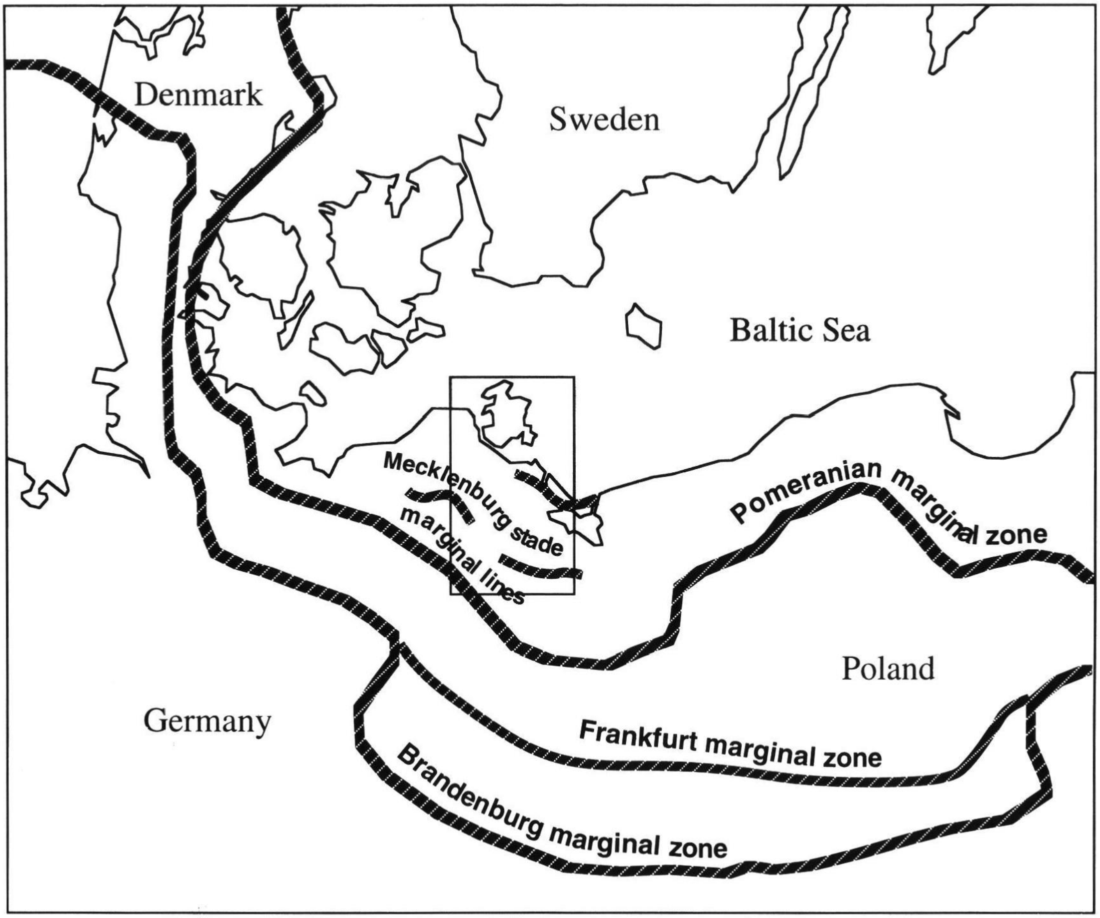

Fig. 1: Geological overview. The Weichselian ice margins are shown. The framed area is shown in Fig. 2.

Abb. 1: Geologische Übersicht. Die Randlagen der Weichsel-Vereisung sind dargestellt. Das eingerahmte Gebiet wird in Abb. 2 gezeigt.

area. Some hollows are scattered throughout the landscape; although it is unknown if they were formed by dead ice or if they simply are marl pits.

Methods

Field work

Field work was carried out during several periods in 1995 and 1996, and an additional complementary field season in 1997.

The thoroughly cleaned sections were photographically documented and described. Overview sketches were drawn in addition to the photographs.

One or several representative places were chosen for sediment logging. At these places the sedimentary units, their structures and their internal contacts were documented layer by layer. Representative sediment samples were taken from each unit, both for gravel analysis and grain-size analysis. The diamicton samples were preferably taken where fabric analysis had been carried out.

Glacial striae and other forms of glacial erosion on cobbles and boulders were measured.

Fabric analysis

Closely spread pebble fabric analyses were carried out every half meter and in cases even closer in the diamict units. For each analysis, the trend and plunge (TWISS & MOORES, 1992) of the a-axes (i.e. the longest axis) of 25 elongated particles were measured. 25 particles is a sufficient amount for statistical certainty (KRÜGER, 1994). The criteria for a measurable particle, as described by KJÆR & KRÜGER (1998) were: 1. The a-axis should be at least 1.5 times longer than the b-axis, and 2. The particle should be matrix-supprted. Horizontal shelves were dug into the section wall and the

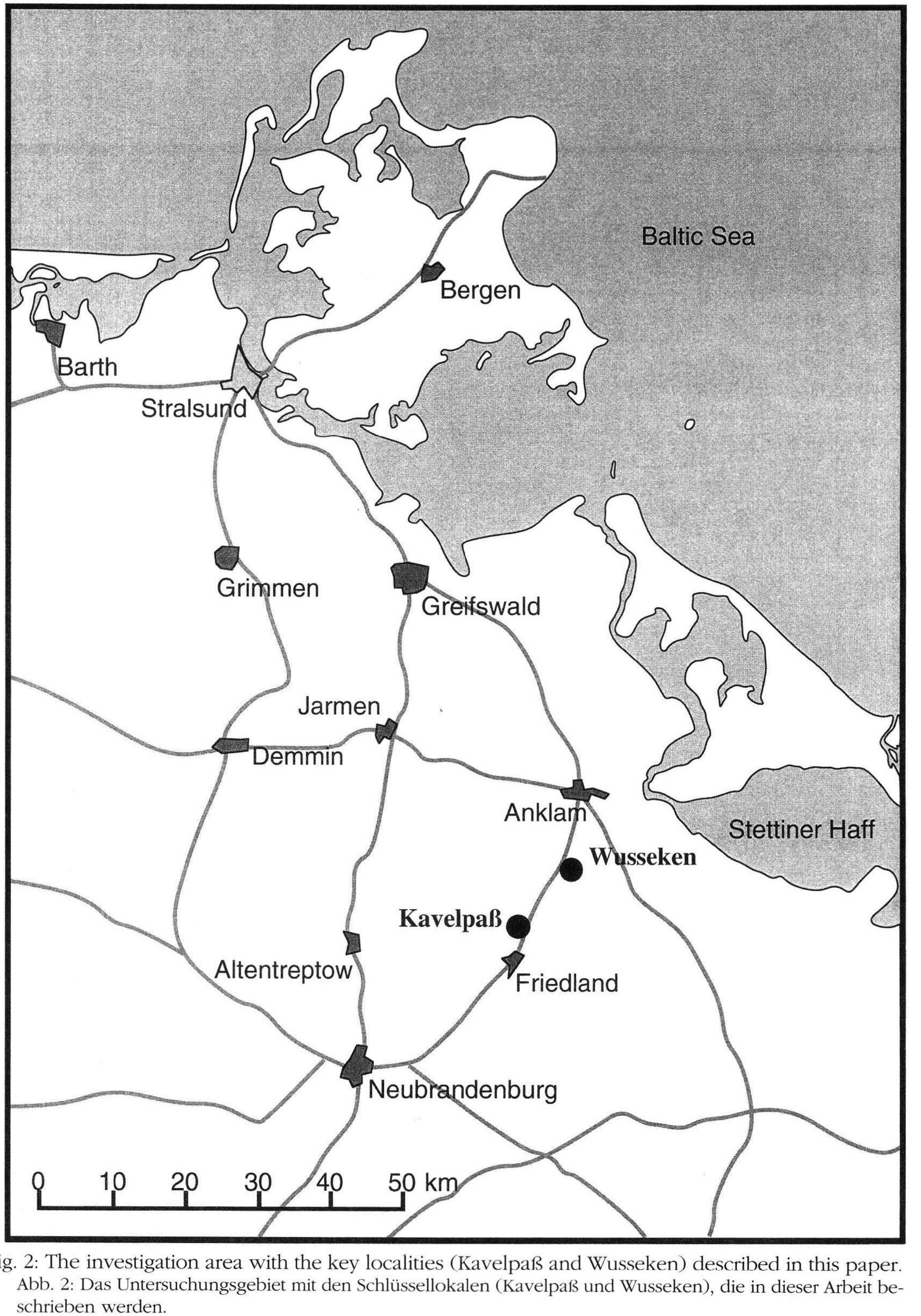

Fig. 2: The investigation area with the key localities (Kavelpaß and Wusseken) described in this paper.
Abb. 2: Das Untersuchungsgebiet mit den Schlüssellokalen (Kavelpaß und Wusseken), die in dieser Arbeit beschrieben werden.

measurable particles carefully uncovered with a knife. An important criterion was that the vertical distribution of the paricles does not exceed a few centimetres.

The data were plotted into a equal angle stereo net and the S1- and V1-values were calculated according to MARK (1973, 1974). Each analysis has its own designation, where K means Kavelpaß and W Wusseken. The number corresponds to the depth in cm above the contact to the underlying sediments.

If possible, even glacitectonical elements, such as fold data (dip and dip direction of fold axes and fold planes) and thrust planes were measured to reconstruct the direction of movement of the ice sheet.

Paleo-current directions were determined in the glaciofluvial units.

Lithological composition

The fraction between 2,8 an 10 mm was used to determine the lithological composition of the diamicton and gravel samples. This fraction was subdivided into subfractions (2,8-4 mm, 4-5,6 mm, 5,6-8 mm and 8-10 mm). For the examination of the clast a binocular microscope with a 6-50 x magnification was used. Each subfraction was counted separately. Every single particle was determined as detailed as possible in means of its rock type. The number of analyzed clasts in each sample varied between 400 and 900.

The determination of the different rock types and the division into groups and subgroups was based upon a modified German standard on lithological analysis (TGL 25232). According to CEPEK (1969) special weight has been attached to the dolomites.

The recognized rock types (subgroups within brackets) are:

Crystalline rocks (acid granites and gneisses, gabbros, diabases and dolerites, amfibolites); *Paleozoic limestones* (grey, red, glauconitic, sandy); *Dolomites; Paleozoic shales and alumshales; Sandstones* (red, purple, glauconitic, quartzitic, calcareous, siltstones, other) and quartzites; *Flintstones; Cretaceous limestone* (white, sandy, glauconitic); *Other* (eg coal, charcoal, limonite, iron clay stone, recent $CaCO_3$ precipitations).

The results of the analysis of the lithological composition are presented in horizontal bar diagrams. The different samples are plotted in their sedimentological order.

In some sections certain samples did not contain any calcareous matter, whereas other samples contained a lot of recent calcium carbonate precipitations. In those cases the recent precipitations were not taken into account.

Information about rock sources are taken from geological maps, e.g. Geologisk kort over den danske undergrund (1992) and FLODÉN (1977).

The magmatic and metamorphic rock types originate from the Baltic Shield and the Caledonides, whereas the paleozoic limestones and shales have their source in the central Baltic Sea. Cretaceous limestones and flintstones are components of the local bedrock. Sandstones and quartzites can be both long- and short-transported. The amount of their individual subgroups is often non-significant though.

Grain-size analysis

The grain size of both the diamictic and the sorted sediments were analyzed. For the coarse fractions (sand and gravel) sieving analysis was applied. The fractions correspond to the international Phi-scale. The finer fractions were analyzed with the hydrometer method (GANDAHL, 1952). The recieved values were recalculated and correlated to the Phi-scale. Results are presented as cumulative curves.

Site descriptions and local interpretations

Kavelpaß

The gravel pit at Kavelpaß is situated four kilometres north of Friedland (Fig. 2). The pit is cut into the southern edge of a relatively flat drumlinoid landform (1,5 x 1 km). The exposed section is about 80 m in length.

The stratigraphy consists of two main units (Fig. 3), glacifluvial sediments (unit 1) and a diamicton (unit 2). The section starts with 5-6 metres of glacifluvial sediments, mainly sand and gravel, but also some silt and some cobbles and boulders. These sediments are heavily deformed. Folds are common, mainly recumbent isoclinal and tight folds, boxfolds, etc. Faults are almost absent.

The transition to the next unit is represented by a very distinct and sharp erosive horizontal contact. A remarkable amount of boulders are situated at the contact. All of them show glacial striae on their upper side (Fig. 4). Grooves have been found in connection to these boulders (Fig. 5). Additional striated boulders have been found not in situ in the pit.

Above this contact follows a 3 to 4 metre thick diamicton (unit 2). This diamicton is homogeneous, massive, matrix-supported and contains only a very few gravel- or boulder-sized clasts. Its colour

Fig. 3: The section at Kavelpaß. Note the boulder assemblage at the distinct contact between the two sedimentary units.

Abb. 3: Der Aufschluß in Kavelpaß. Bemerkenswert ist die Ansammlung von Blöcken im Bereich der deutlichen Grenze zwischen den beiden sedimentären Einheiten.

Fig. 4: A boulder from the contact. The glacial striae are well-developed. Note the distinct stoss- and lee side.

Abb. 4: Ein Stein von der Grenze zwischen Einheit 1 und 2 mit deutlich entwickelten Gletscherschrammen. Stoß- und Leeseite sind deutlich zu sehen.

is brown. The matrix consists of sand and silt. In its lower part some deformed sand lenses exist. There is a poorly developed fissility visible in the lowermost 1-2 m. At the level of 2-2,5 m above the contact streaks of sand and silt occur. The uppermost meter of the diamicton is weathered. Calcareous components have been leached out. $CaCO_3$ has precipitated at the level 0,75 to 1,8 metres be-

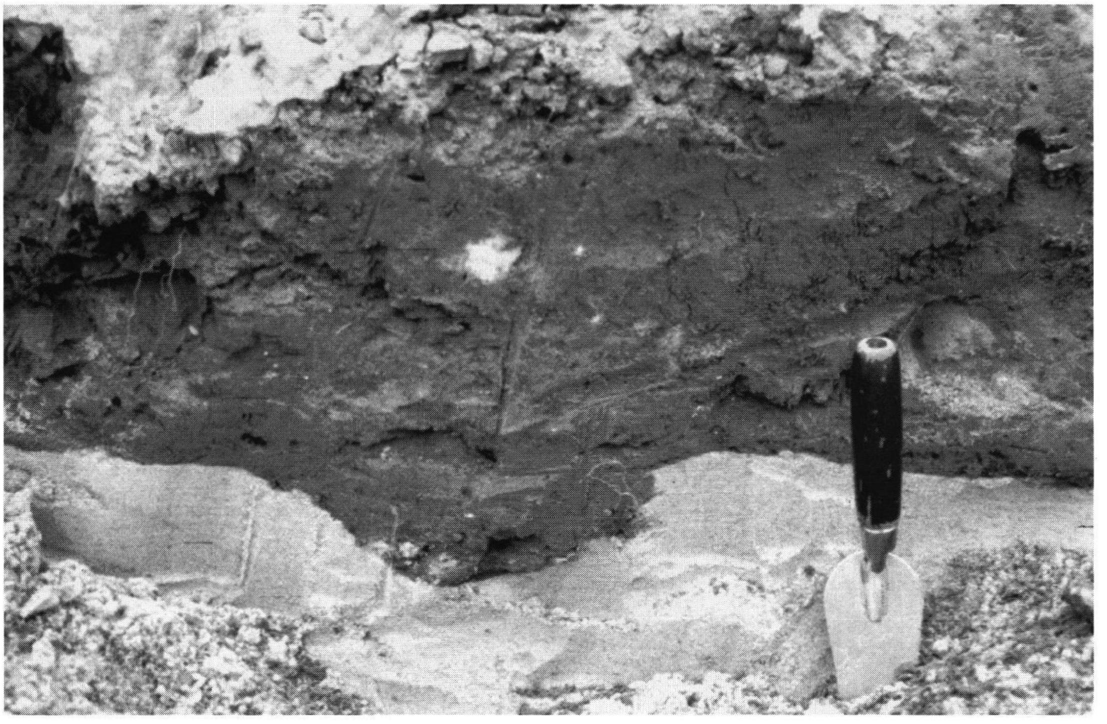

Fig. 5: In connection with a vast majority of the boulders found at the contact grooves have been observed.

Abb. 5: In Verbindung mit der großen Mehrheit der Steine und Blöcke sind Grooves beobachtet worden.

low the surface at the sand and silt streaks mentioned above.

Signs of wind erosion have been observed on several boulders at the surface, eg on the so-called "Blücherstein", a huge erratic, which is situated just outside the pit. Such erosion can also be seen on numerous boulders in the pit, which are not in situ.

Results

The results of fabric analysis and lithological analysis are illustrated together with a simplified log through the section at Kavelpaß (Fig. 6).

Flow indicators: Stress indicators were measured in both the glacifluvial sediments (glaciotectonical elements) and in the diamicton (glacial striae and clast fabric).

The directions of the glacial striae were measured on 25 boulders and stoss and lee-side were determined in many cases. All the striae extend in a nearly exact east-west direction, with only a few degrees deviation. The stoss sides imply a movement direction from the east. Additional striated boulders and cobbles, which show the same direction of ice movement, have been observed at several other occasions. The grooves which are connected to the boulders indicate the same ice movement direction from the east.

In the diamicton very tight fabric analyses were carried out, 50 cm apart in a vertical profile. In the critical zone close to unit 1, the analyses have been done even tighter, 4 analyses within a space of 25 cm.

The first analysis (K 5) shows a hardly preferred orientation pattern. A certain east-west directed stress can be seen, but some measurements lie perpendicular to this east-west distribution, which lower the S1-value.

The next analysis (K 10) shows a similar but more preferred orientation pattern. The east-west stress direction is more marked and there are fewer perpendicularly situated particles.

20 cm above the contact (K 20) the orientation pattern has strengthened. The measurements are clustered around 80 degrees ± 60 degrees with a dip of around 10 to 30 degrees.

At K 25 a remarkable change in the stress direction occurs. The direction of V1 has switched towards north-north east. S1 is fairly strong. This pattern continues more or less through the next

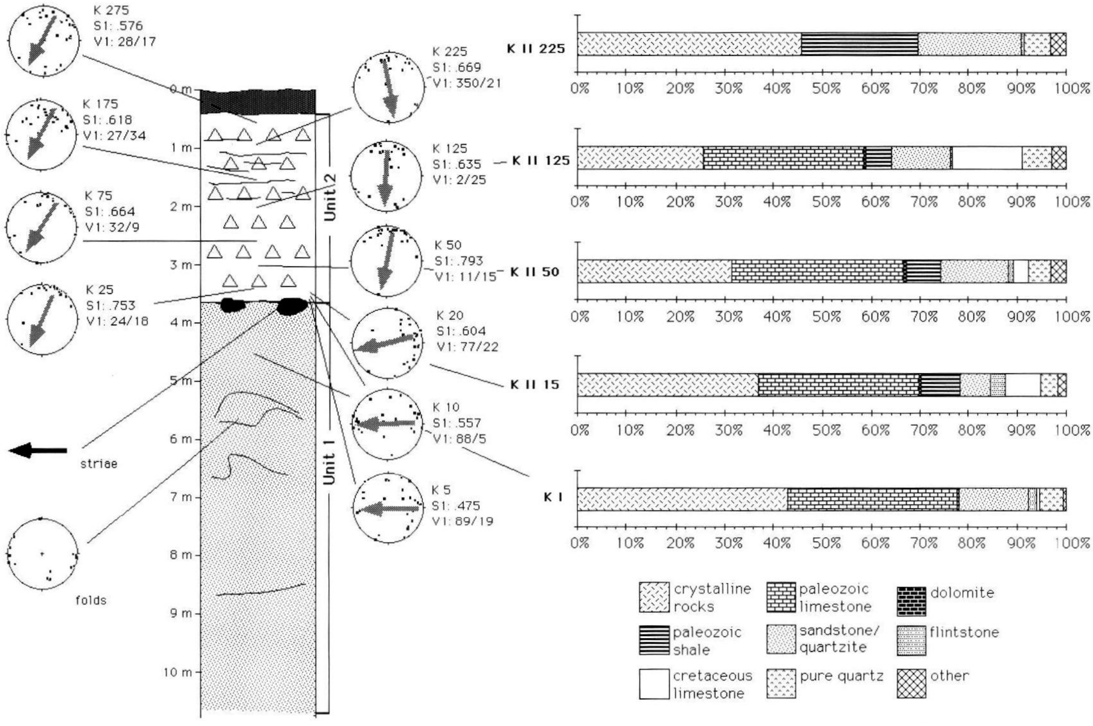

Fig. 6: A simplified log through the section at Kavelpaß. The results of both fabric analysis and lithological analysis are plotted in relation to their stratigraphical level.

Abb. 6: Ein vereinfachtes Profil durch den Aufschluß bei Kavelpaß. Die Ergebnisse von sowohl der Richtungsanalyse als auch der lithologischen Analyse (Kleingeschiebezählung) sind im Verhältnis zu ihrer stratigraphischen Position dargestellt.

two levels (K 75 and K 125), but thereafter S1 decreases, even if it is still preferred. The V1-values remain more or less the same between north through north-northeast throughout the remaining part of unit 2.

The dip and the dip direction of 15 fold axes and the vergence of the folds were analyzed in the glacifluvial sediments. The fold planes of four major folds have a vergence towards the west, i.e. the stress direction was from the east. The other folds are minor folds that verge towards the south.

Lithological composition: Four samples were taken in the diamicton and one in the underlying glacifluvial sediments. The most remarkable feature is the complete lack of calcareous material in the uppermost sample, whereas the sample beneath contains a lot of calcium-carbonate precipitations, which in some cases are difficult to distinguish from chalk.

The content of Precambrian crystalline rocks remains more or less the same throughout the succession, only somewhat higher values in the lowest diamicton sample and the sorted sediments. They amount to 30 to 50 % in all samples. The second largest group are paleozoic limestones, with around 30 % in each sample except the uppermost one, which does not contain any calcareous matter.

The other rock groups occur in minor amounts. It may be worth mentioning that Paleozoic shales are relatively abundant in the uppermost sample, whereas sandstones are relatively rare in the lowermost diamicton sample. The group "others“ consists nearly solely of iron clay stone.

The gravel fraction consists therefore of both long-transported material and more local material (above all chalk and flintstone), but the impact of weathering makes it hard to draw any conclusions about the original composition.

Grain-size analysis: There are no significant differences between the samples taken in unit 2.

Interpretations

Unit 1

The glacifluvial sediments of unit 1 may have been deposited as an outwash plain or another type of glacifluvial supra-aquatic landform. They

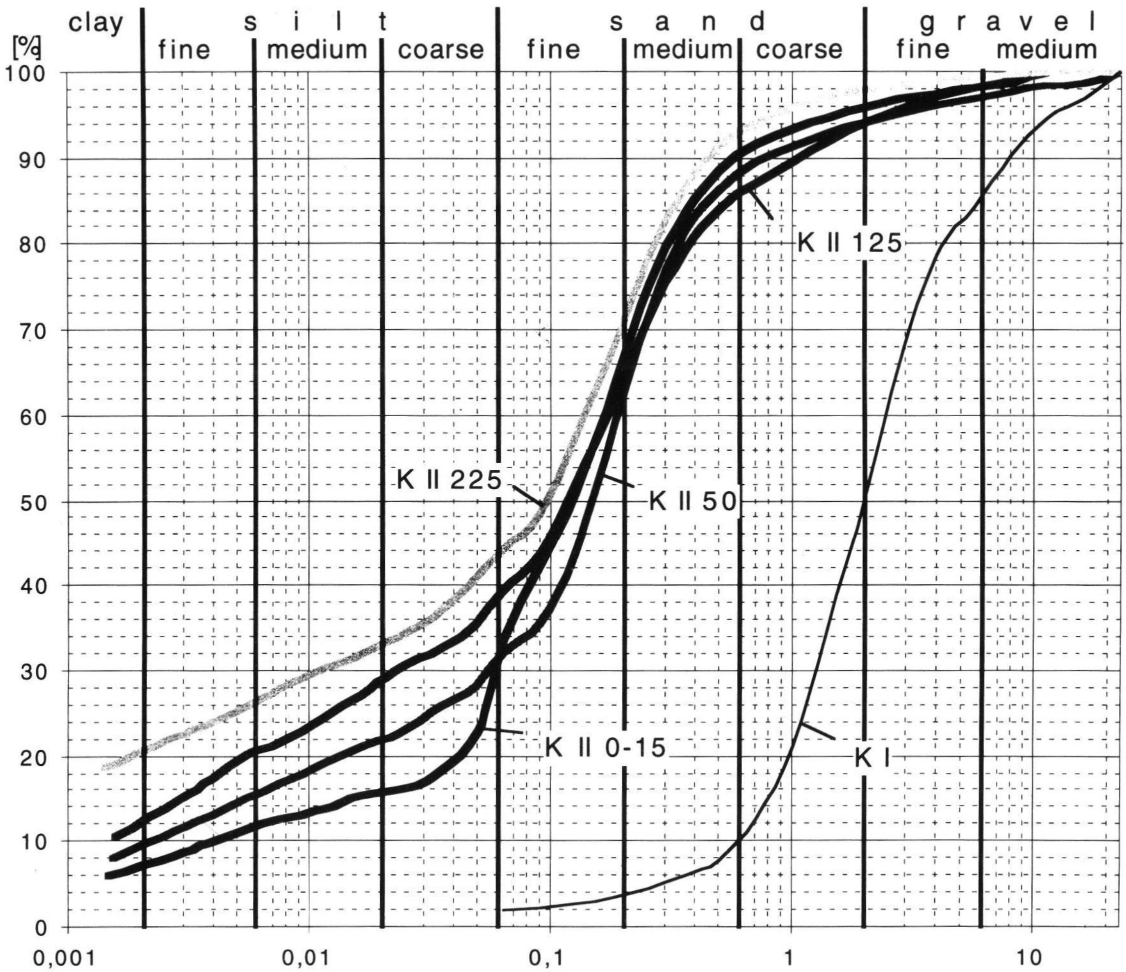

Fig. 7: Cumulative grain size of the samples taken in Kavelpaß

Abb. 7: Korngrößenkurven der Proben von Kavelpaß

have been glacitectonized by an ice advancing from the east. The glacier has eroded the upper part of the unit. With increasing ice thickness erosion ceased and deposition started (BOULTON, 1974; SUDGEN & JOHN, 1976). Cobbles and boulders were lodged and striated. Finally sedimentation of till (unit 2) started.

Unit 2

Very important are the differences in stress direction measured in the clast fabric analyses and indicated by the glacial striae. The glacial striae (along with the fold data) leave no doubt that the initial ice movement direction was from the east, which the fabric measurement results confirm. In the critical zone between the contact and 25 cm above the switch from eastern directions to the expected north-eastern directions takes place. The three lowermost measurements (K 5, K 10 and K 20) imply a stress direction from the east. K 20 possibly indicates a transition to a more northeastward direction.

At K 25 the movement direction has changed completely to the expected regional ice movement direction from the north north east. The orientation is preferred. This north north east direction continues throughout the remaining part of the till.

The uppermost analysis (K 275) is less preferred and may represent a flow till succession.

The lower part of the diamicton (up to approximately two meters from the contact) is regarded as a lodgement till. This interpretation is based upon its compactness, fissility, the erosive contact, deformed sand lenses, and the strong S1-values of the fabric measurements. The upper part of the diamicton possibly consists of basal melt out till and flow till. The lower degree of consolidation of the till, the sand streaks, which are cemented with precipitated lime and the somewhat lower S1-values support this interpretation.

The ice advanced from the east, rode over preexisting glacifluvial sediments, deformed and eroded them. Boulders were striated at the erosion level. The lowermost 20 cm of the till bed were deposited from the east. Later the ice changed its movement direction. The new direction was from the north north east. This direction remained the same throughout the rest of the sequence. Lodgement till was deposited, which was possibly followed by a basal melt out till and a flow till during the final deglaciation. Despite the two different directions the continous sedimentation of the till bed implies a single ice advance.

The advance from the north north east caused a second generation of deformation structures in the glacifluvial sediments. Because of the increasing thickness of till the pore water pressure increased in the underlying sediments, which caused a lowering of the effective normal strain and thus caused deformation.

The diamicton looks the same throughout the whole section, except for some differences in color, which can be explained by the leaching and re-precipitation of lime. There are differences in the lithological compostion of the sediment, e.g. the lack of calcareous matter in the upper part. This lack is likely a result of weathering. The leached lime has then been precipitated at the light-streaked level within the diamicton. Both cretaceous limestone and sandstone/quartzite are unevenly distributed, whereas the other components are present in roughly the same percentage throughout the section.

According to the TGL 25232 the lithological composition of the till suggests a Weichselian age. This is in agreement with the present interpretation that the till represents the latest glaciation in the area. Its relatively high content in cretaceous chalk and flint may suggest a Pomeranian age. On the other hand, if the Mecklenburg Sub-Stage is represented by an own till, this Mecklenburg till should be the youngest and consequently unit 2 should be the Mecklenburg till, which is additionally indicated by the high lime content. This is in agreement with RÜHBERG (1987).

The lithological relationship between unit 1 and unit 2 is unclear. The differences in their lithological composition may imply different events. However, such differences may also be explained by different physical conditions of transport and sedimentation in running water and ice.

Wusseken

The large gravel pit Wusseken is situated 9 kilometres NNW of Kavelpaß, ca. 10 kilometres SSW of Anklam (Fig. 2). The quarried glacifluvial sediments extend over a large area.

The stratigraphy, subdivided into two main units, looks similar to that of Kavelpaß: glacifluvial sediments at the bottom (unit 1) and a diamicton on the top (unit 2). The contact is erosive. Boulders with glacial striae are common at the contact. The lower part of the section is shown in fig. 8.

The glacifluvial sediments (unit 1) consist mainly of sand and fine gravel, and the outcropped part of them reaches an approximate thickness of 5 metres. Average grain sizes appears larger in the lower part than in the upper part. Dominating bedforms are tilted beds (tilt angle around 20°), which transist laterally into ripples. Folds are rare and sets of normal faults occur.

The upper part consists of the same type of sediment as the lower part, but on average the grain size appears smaller than below. Planar parallel laminated sands and fine gravel are dominating, but ripples and trough cross bedding are also common. The degree of deformation increases towards the top. Folds are common, often they are non-cylindrical. Some minor normal faults also occur.

The contact between unit 1 and unit 2 is distinct and clearly erosive, but not as horizontal as in Kavelpaß. It is slightly undulating. In general, the boulders at the transition between the two units are larger than in Kavelpaß, up to 1 metre in diameter (Fig. 9), but there are a lot of cobbles as well. They show glacial striation, but also other features of glacial erosion, such as crescentic fractures. In some cases there are two generations of striae or crescentic fractures from different directions exposed. Additional two-generation-marks are found on several boulders not in situ in the pit.

The diamicton (unit 2) is homogeneous, massive and matrix supported. The thickness varies between 1 metre and 4 metres, with an approximate medium size of 2 metres. The clasts are rounded. The upper meter of the sequence is weathered.

In places there is a distinct facies difference between the lower and the upper part of unit 2. The lower part is massive, over-consolidated and shows a distinct fissilitiy, whereas the upper part is stratified, not consolidated and lacks fissility.

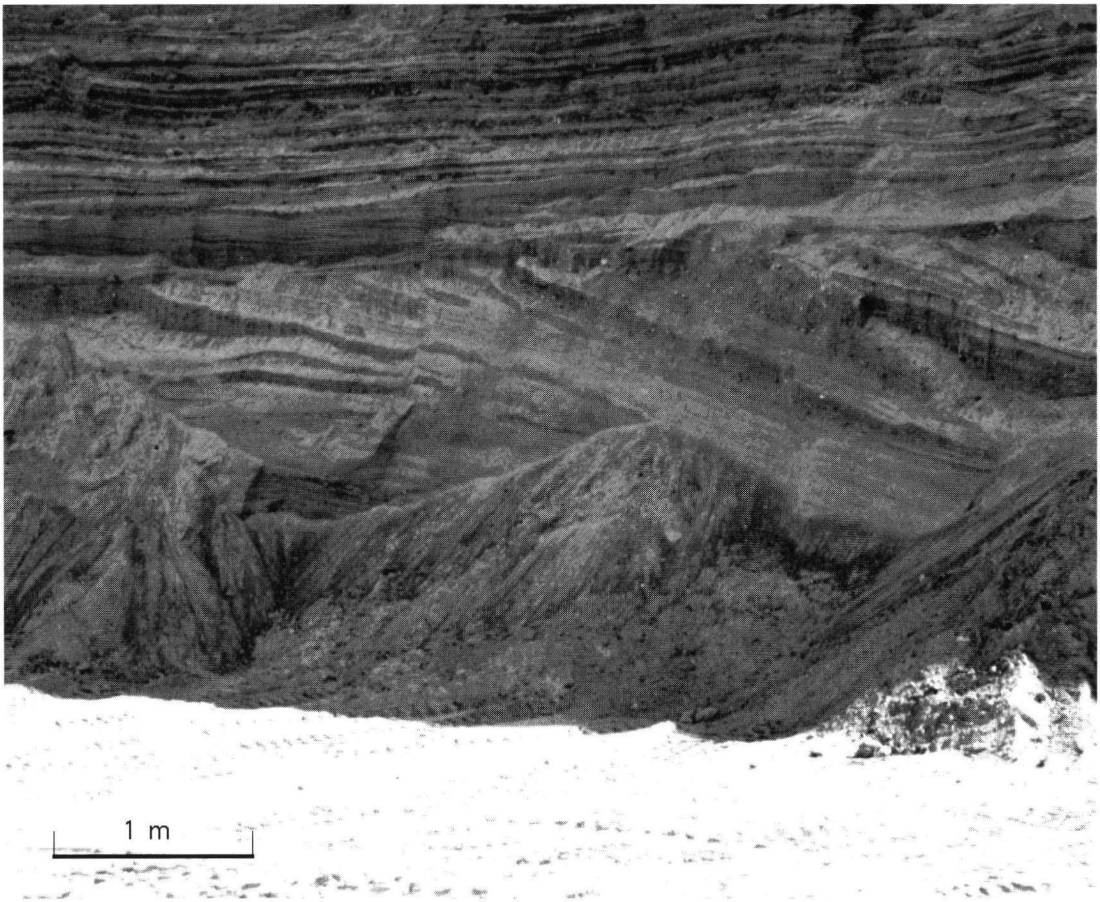

Fig. 8: Section through the sorted sediments (unit 1) in Wusseken. The diamicton (unit 2) has been removed by the excavator.

Abb. 8: Schnitt durch die sortierten Sedimente (Einheit 1) in Wusseken. Das Diamikton (Einheit 2) ist abgeschoben worden und deshalb nicht zu sehen.

Results

At the contact between unit 1 and unit 2, the numerous boulders show glacial striae and crescentic fractures. They indicate two different directions, one from the north east and another from the south-south east, which is implied by both stoss and lee sides and the orientation of the crescentic fractures. Two boulders show glacial striae (from both directions) and crescentic fractures (from the south south east). Stoss and lee side are well-developed. The north east striae are younger than the south south east striae. Additonally, c. ten more boulders have been found not in situ with two directions of striae with the same angle inbetween the two sets of striae.

The areal distribution of the boulders is depicted in Fig. 10.

The results of fabric analysis and lithological analysis are illustrated together with a simplified log through the section at Wusseken (Fig. 11).

Flow indicators: A number of analyses were carried out to determine the paleostress conditions, both in the glacifluvial sediments (unit 1) and the diamicton (unit 2).

In the diamicton, fabric analyses were carried out in a vertical profile, 50 cm apart from each other. Close to the contact between the two sedimentary units, additional 4 analyses were made within 25 cm.

The lowermost analysis, at the level between 2 and 4 cm above the contact (W 2-4), shows a strongly preferred orientation from the south south east, which is roughly the same value as the glacial striae on the boulders.

At the next level, W 5, all directions except the sector between 180 to 270 degrees are present. Particles lie more or less horizontally.

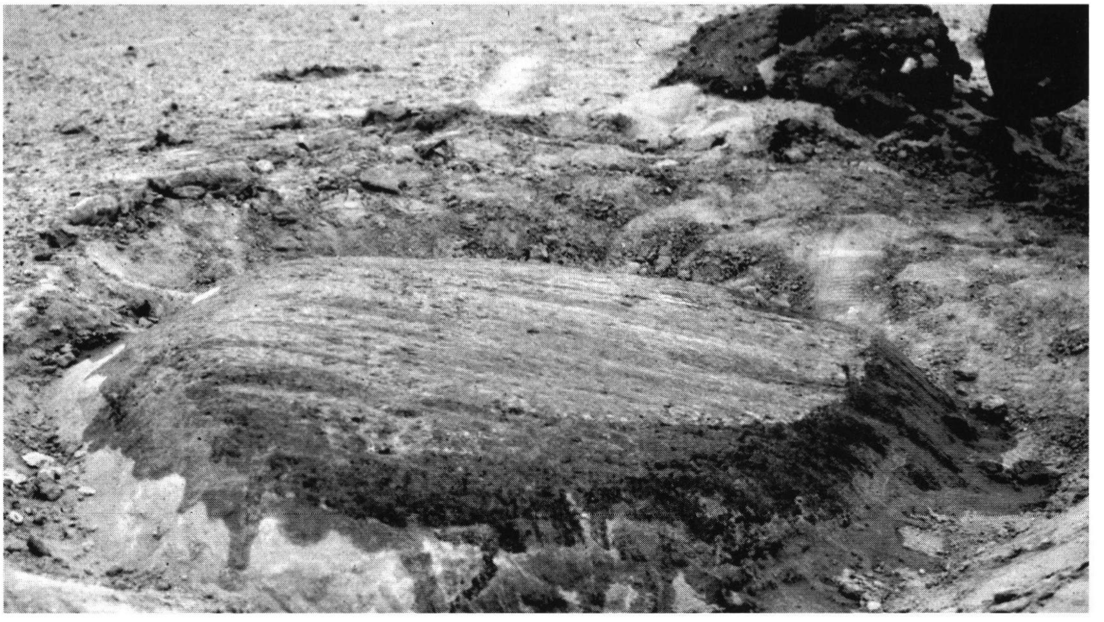

Fig. 9: A large striated boulder found at the contact between unit 1 and unit 2. Stoss and lee side are very well-developed. Scale: around 1 m in diameter.

Abb. 9: Ein großer geritzter Block, gefunden an der Grenze zwischen Einheit 1 und Einheit 2. Stoß- und Leeseite sind gut ausgebildet. Maßstab: ca. 1 m im Durchmesser.

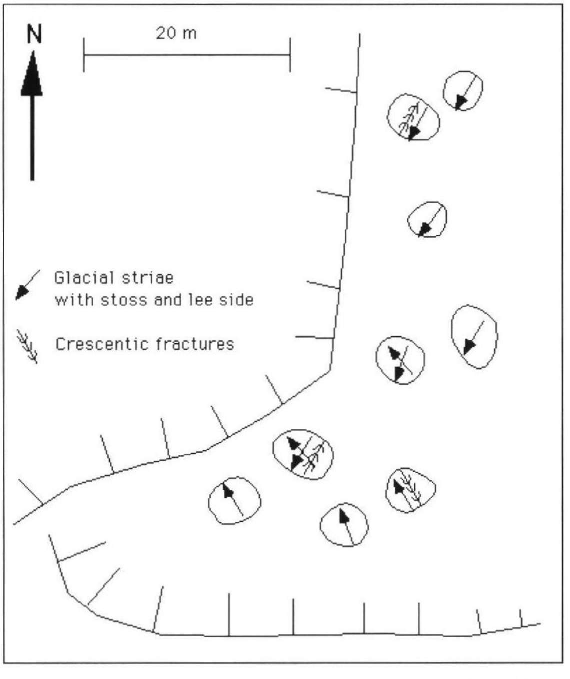

Fig. 10: The areal distribution of the striated boulders from the interface between unit 1 and unit 2. The boulders are not in scale.

Abb. 10: Die Verteilung der geritzten Blöcke zwischen Einheit 1 und Einheit 2. Die Blöcke sind nicht maßstäblich dargestellt.

At W 10, the south south east - north north west component becomes weaker and the north east component becomes dominant. At W 25, the measurements are clustered around north north east with a dip between 0 and 30 degrees. This pattern continues with very small variations up to the W 200. The analyses in the uppermost part of the diamicton (W 250 and W 300) show a less preferred pattern.

In both the lower and the upper part of unit 1, the direction of sediment transport has been determined. Sedimentary structures indicate a mean flow direction from the north east.

In unit 1, the vergence of a couple of folds and the dip and dip direction of the fold axes were measured. The fold axes extend roughly in north south direction. They dip in both directions, but their dip angel is normally quite low. The folds verge normally to the west.

Lithological analysis: Two samples were taken in the glacifluvial sediments (unit 1). In the diamicton, four samples were taken in a vertical profile, one directly above the contact between unit 1 and unit 2, the next 50 cm above and the remaining two one meter apart, respectively.

The lithological composition does not vary very much throughout the section. The amount of crystalline rocks (gneisses, granites, amphibolites etc.) exceeds mostly 40 %, but does not reach

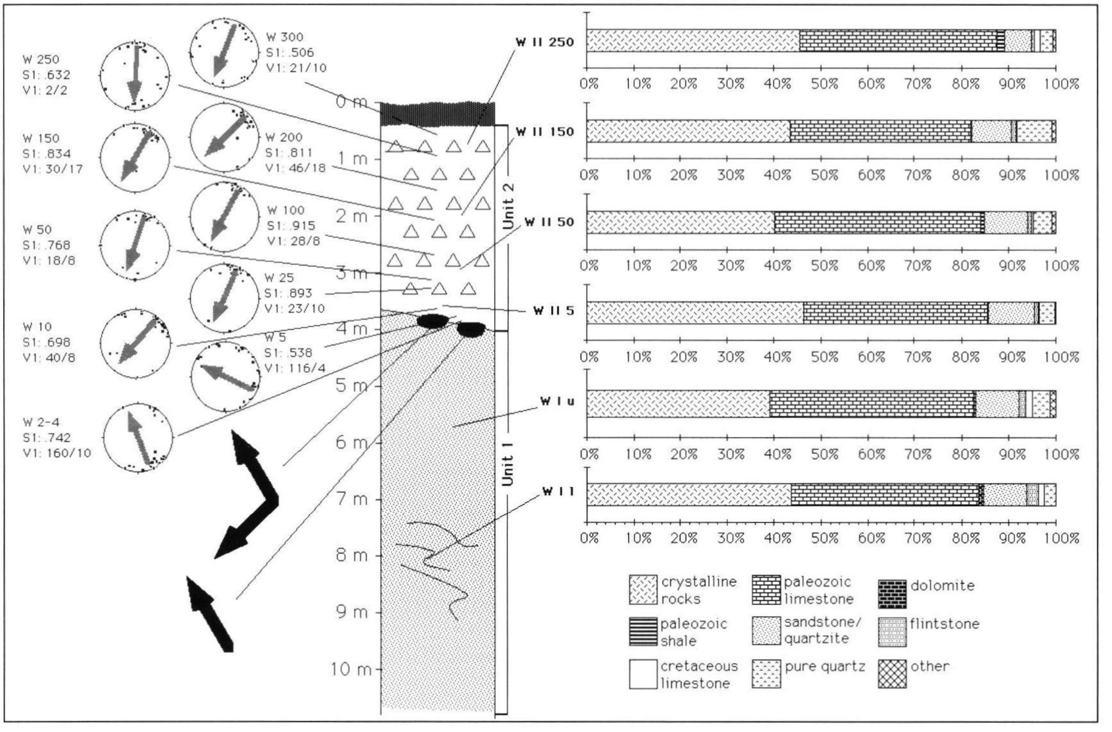

Fig. 11: Simplified log through the section at Wusseken. The results of both fabric analysis and lithological analysis are plotted in relation to their stratigraphical level.

Abb. 11: Ein vereinfachtes Profil durch den Aufschluß bei Wusseken. Die Ergebnisse von sowohl der Richtungsanalyse als auch der lithologischen Analyse (Kleingeschiebezählung) sind im Verhältnis zu ihrer stratigraphischen Position dargestellt.

50 %. The percentage of paleozoic limestone is nearly of the same figure, maybe somewhat lower than crystalline. The remaining 15 to 20 % consist mainly of sandstone and quartz. Chalk and flintstone do not exceed 2 % (except in unit 1 with 3-4 %) and neither do palezoic shales. Dolomites and cretaceous limestones are very rare, almost absent in all of the samples.

The lithological composition of all samples is thus dominated by long-transported material. The local bedrock (cretaceous and tertiary rocks) is represented in very low amounts.

Grain-size analysis: The samples taken in unit 2 appear to be without significant differences. They contain a large amount of sand and are poorly sorted (Fig. 12).

Interpretation

Unit 1

The sediments in unit 1 are deposited in a glacifluvial environment, maybe as a proglacial outwash plain. Deformation structures are rare in the lower part of unit 1, but there are some normal faults indicating melting of buried dead ice somewhere in the ground.

As unit 1 is deposited from the north east, it should be connected to the main ice sheet and not to the advance from the south south east.

The boulders at the contact can be the remains of an eroded coarse-grained bed. They show crescentic fractures and glacial striae with two different directions. Boulders with two different directions gave the opportunity to determine the relative age between the two sets of striae and crescentic fractures. On those boulders the striae from the south south-east are the older ones. The boulders with striae from the south south east may have been covered by till at an early stage, which prevented the erosion of the striae. Maybe even the other boulders were striaed from the south south-east, but those striae have been eroded by the new ice movement direction from the north-east.

Unit 2

Despite different ice movement directions the till represents a single ice advance. It is a complete till succession with a compact and overconso-

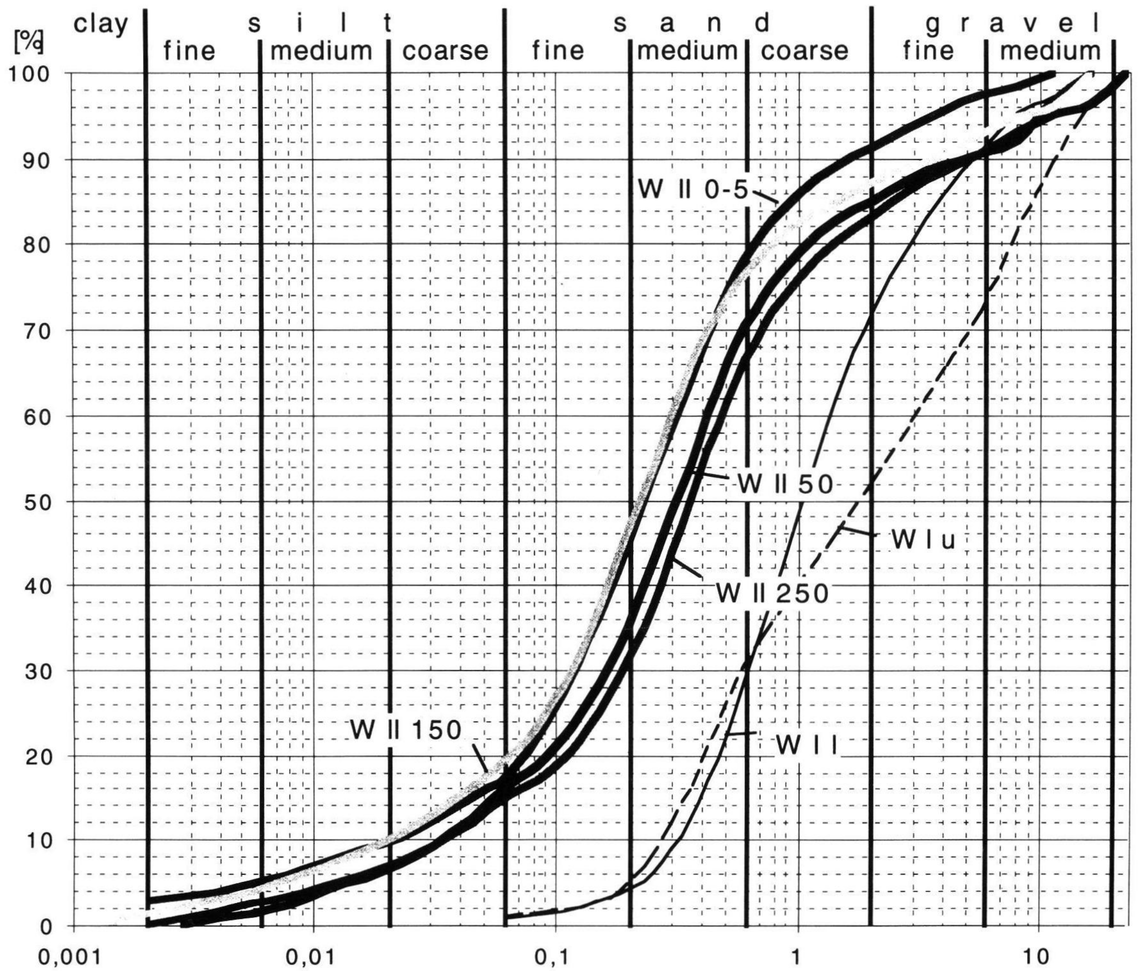

Fig. 12: Cumulative grain size of the samples taken in Wusseken

Abb. 12: Korngrößenkurven der Proben von Wusseken

In the following six fabric levels (W 10, W 25, W 50, W 100, W 150, W 200) a clear north-east stress direction prevails. As this part of the till succession can be interpreted as a lodgement till and

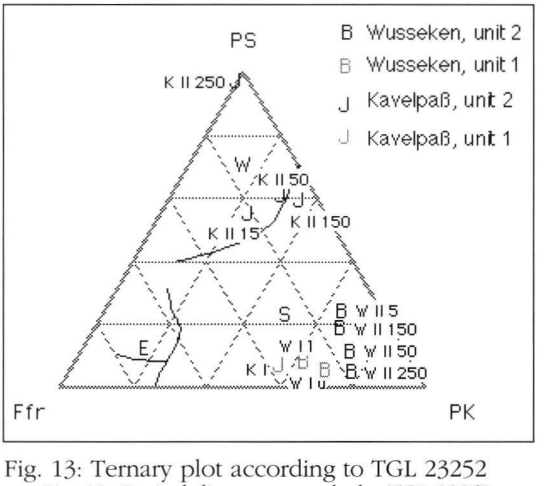

Fig. 13: Ternary plot according to TGL 23252

Fig. 13: Dreieckdiagramm nach der TGL 23252

lidated lodgement till with fissility at the bottom, followed by a less consolidated, stratified melt out till and finally a flow till on top.

As already explained, the till may first have been deposited in small depressions in the landscape, and preserved the signs of initial ice movement directions in those depressions. In such a depression the series of clast fabric analyses was carried out, which show an initial ice movement direction from the south south-east and a transition towards the normal north-east direction occurs within a vertical space of 10 cm. The lowermost fabric analysis shows the same stress direction from the south south-east as the striae on the boulders. The following analysis (W 5) represents the transition between the south south eastern and the north eastern direction of ice flow.

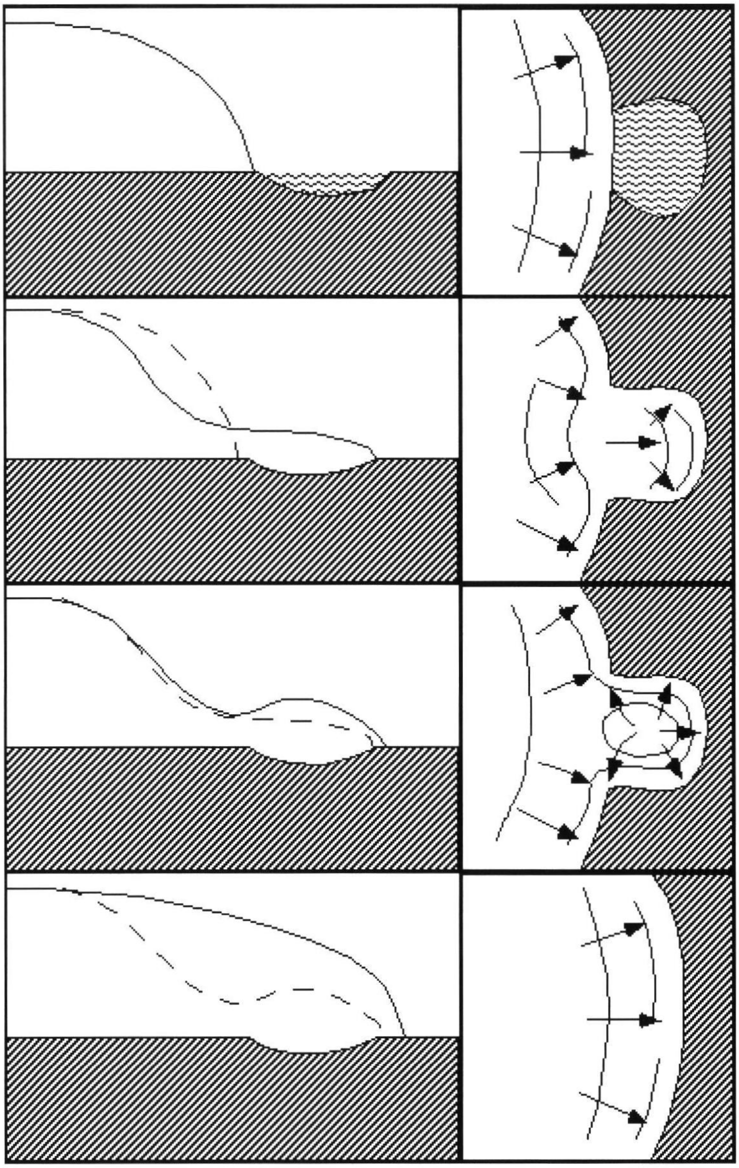

Fig. 14: Possible regional interpretation. The advancing glacier surges into a basin. On top of the flat glacier tongue a marginal dome builds up, which has a movement pattern independent from the main ice sheet. Movement direction can thus become perpendicular (Kavelpaß) or nearly opposite (Wusseken) to the regional movement pattern. When the ice sheet overrides the marginal dome, the ice movement becomes normal again.

Abb. 14: Mögliche regionale Interpretation. Der vorstoßende Gletscher fließt in ein proglaciales Becken aus. Auf der flachen Oberfläche der entstandenen Gletscherzunge wird ein Marginaldom aufgebaut, der ein vom Haupteis abweichendes Bewegungsmuster hat. Die Bewegungsrichtungen können somit rechtwinklig (Kavelpaß) oder sogar entgegengesetzt (Wusseken) zur regionalen Fließrichtung werden. Wenn der Hauptgletscher schließlich den Marginaldom überfährt, normalisiert sich die Eisbewegungsrichtung wieder.

a basal melt-out till, this northeast direction can be regarded as the movement direction of the ice sheet when this succession was deposited.
The uppermost two fabric analyses (W 250 and W 300) show a significantly less preferred distribution pattern, which together with the characteristics mentioned above can be interpreted as a flow till pattern.

The conclusion is that during its advance from the south south east the ice has overridden probably proglacial sediments, eroded them to a certain amount, striated boulders and cobbles and finally deposited till. Then the ice changed its movement direction to a north-eastern direction. The ice eroded the uncovered erosion marks on the boulders and maybe deformed the upper part of the underlying sediments. The boulders were striated once again from this new north-eastern direction and lodgement till was deposited. Only in depressions the older striae and the previously deposited till are preserved. Lodgement till was deposited at first, then the ice stagnated and melt out till formed. Finally a flow till sequence with random clast fabric directions was formed at the top, which filled out the depressions in the landscape, explaining the variations in thickness of the diamicton.

A chronological interpretation of the sequence is difficult to make. According to the TGL 25232 the lithological composition of the till (and the glacifluvial sediments as well) should be of Saalian age, which is very unlikely because of its stratigraphical position. In this case the two or three younger tills would be missing. Instead the till certainly represents the youngest glaciation in the area. The glacier can have picked up material from the underlying glacifluvial sediments. This interpretation is also supported by the presence of the rounded clasts in the till. Thus the lithological composition of the till reflects the lithological composition of the older sediments beneath.

Discussion and conclusions

The tills in Kavelpaß and Wusseken can be correlated with each other. Both represent the youngest glacial event in the area. The two sites are close to each other. There is no end moraine between them. Both tills display an anomalous initial ice movement direction. The ternary diagram of the TGL 25232 (Fig. 13) is contradictory, however. It shows a Saalian age for the till in Wusseken, which is not likely. The ice has probably picked up material from the underlying sediments. The till reflects thus the lithological composition of the underlying sediments. Hence, the standard plot may be used with caution.

Anomalous ice movement directions are not especially uncommon. Similar phenomena have been reported from other parts of central Europe (e.g. MALMBERG-PERSSON & LAGERLUND, 1994; LAGERLUND et al., 1995; PETTERSSON, 1997).

Surges can explain variations in ice movement (Fig. 14). A large ice sheet can surge into a water-filled depression because of various reasons (LAGERLUND, 1987; SHARP, 1988a; SHARP, 1988b; SHARP et al., 1988). The thermal regime of the glacier, the nature of the subglacial hydrological system and the character of the subglacial bed are important parametres (SHARP, 1988a). It is almost impossible to reconstruct both the thermal regime of the glacier and the subglacial hydrological system, but a water- or ice-filled basin in front of an advancing glacier could trigger a surge. The present-day basin of the Stettiner Haff and the lowland around it could have acted as such a basin. The movement direction from the east in Kavelpaß can be explained by such a surge into the Stettiner Haff basin. However, explaining the movement from the south south east in Wusseken remains a problem. An ice movement direction from the south south east is nearly 180° opposite to the expected regional ice movement direction. Even if a surge could possibly explain such a direction, other alternative possibilities must be taken into account. The marginal dome concept proposed by LAGERLUND (1987) is one of those likely interpretations. In Fig. 11 the idea of a glacial surge is developed further more: The surge causes a flat ice surface to form. Because of the high albedo of the ice sheet, a very strong high pressure developes above the ice sheet, which forces the low-pressure systems along a track at the margin of the ice sheet. Precipitation is released predominantly at the margin of the glacier. On the flat surface of the surged ice tongue a lot of that precipitation accumulates, which causes the tongue to increase in thickness. Eventually the pressure melting point is reached at the base and the created local ice dome becomes activ independently from the major ice sheet. Movement directions are thus perpendicular towards the edge of the dome and deviate in this way from the regional direction. Even completely unusual and hard-explained directions may occur. Finally, the advancing glacier overruns the local ice dome, incorporates it and the movement direction changes to the normal direction from the north east.

There are other possibilities to explain anoumalous ice movement directions. Topographic obstacles, like pronounced hills or bedrock, in front of the advancing ice sheet could cause a change of the ice movement direction. In the actual area this possibility seems to be unlikely.

The course described above probably occurs during the main retreat of the Weichselian ice sheet and represents a minor readvance. According to the Geological map (1995) the tills could be Mecklenburg Sub-Stage tills. Thus the glacifluvial deposits should be connected to the Pomeranian deglaciation, even if their lithological composition suggests a Saalian age.

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