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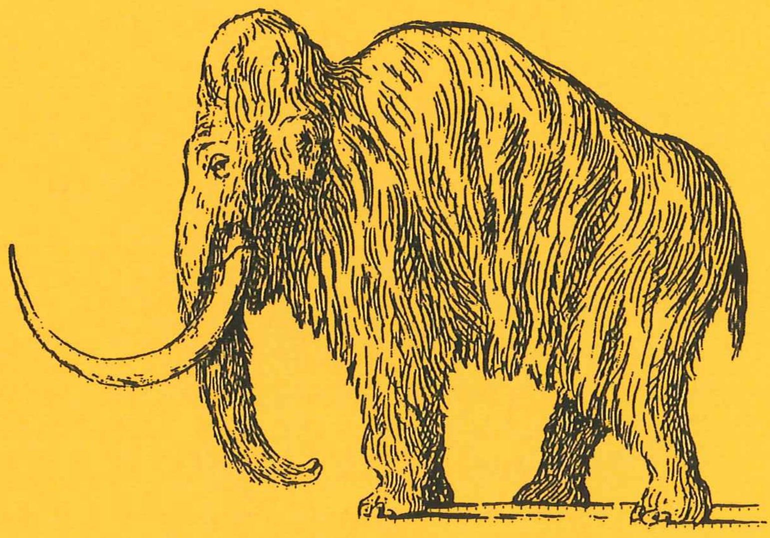

Proglacial deformation of glaciofluvial sediments during the Pomeranian deglaciation in the Neubrandenburg area, NE Germany

Mattias Lindén

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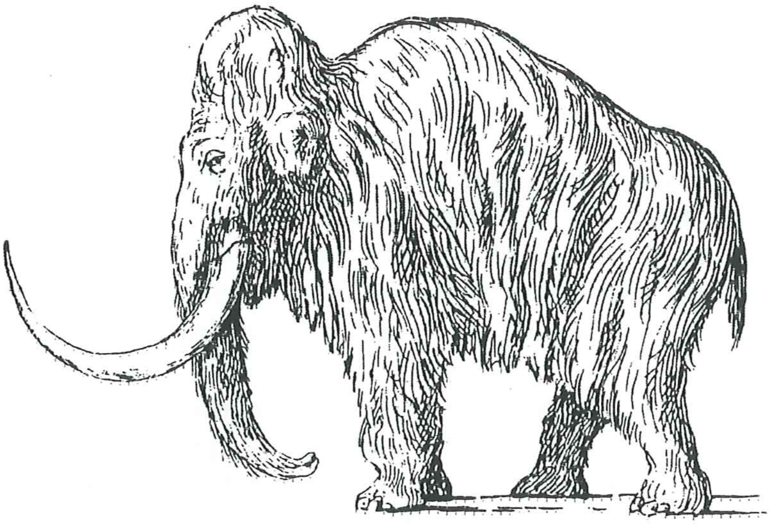

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Abstract

Three gravel pits near Neubrandenburg, NE Germany, were investigated - Kreuzbruchhof, Spargelberg and Fritscheshof. The investigated gravel pits are situated in an undulating kame landscape 150 km south of the Baltic Sea. The aim of this study was to reconstruct the Late Weichselian history (e.g. deglaciation of the Pomeranian ice sheet) of the area. Reconstruction was based mainly on sedimentological and structural investigations.

Two of the gravel pits, Kreuzbruchhof and Spargelberg consist mainly of glaciofluvial sediments. The glaciofluvial sediments are represented mainly by laminated and trough-cross bedded sand and gravel indicating intermediate to proximal braided river facies. In Kreuzbruchhof the glaciofluvial sediments are close to the top interbedded with thin silt and diamict beds. Spargelberg show only ductile deformation while both ductile and brittle deformation (folds and reverse faults) is present in Kreuzbruchhof, as well as normal faults in the uppermost part. The sediments of Kreuzbruchhof were deposited during two periods before and after deformation while all sediments in Spargelberg were deposited before deformation. The diamict units in Kreuzbruchhof are interpreted as flow till. The orientation of the deformation structures in Spargelberg and Kreuzbruchhof indicate an opposite direction of stress, NNE and SW respectively. The third gravel pit, Fritscheshof, consists mainly of a raft of Tertiary quartz sand. Parts of the gravel pit show folded glaciofluvial sediments. A restricted part of the raft is covered by flow till. Clear evidence for specific stress directions could not be found.

To reconstruct the environment (resulting in opposite directions of deformation) a model consisting of an oscillating ice sheet, referring to Spargelberg and Fritscheshof, and a local ice dome, referring to Kreuzbruchhof, is suggested. The deforming process is suggested to be proglacial deformation since no subglacial till was found.

Proglacial deformation, glacial tectonics, local ice dome, Pomeranian deglaciation, NE Germany

Proglacial deformation i glacifluviala sediment under Pommerska deglaciationen i Neubrandenburg området, NÖ Tyskland

Sammanfattning
Tre grustag undersöktes i nordöstra Tyskland, Kreuzbruchhof, Fritscheshof och Spargelberg. Syftet var att rekonstruera den senaste glaciala aktiviteten i området. Tolkningarna och således rekonstruktionen grundar sig till största delen på sedimentologiska och strukturella undersökningar.

Kreuzbruchhof består mestadels av glacifluviala sediment med undantag för några mindre diamikta enheter tolkade som flytmorän. Strukturellt kan sedimenten delas in i två enheter. Den undre (dominerande) har utsatts för kompressiv deformation vilket resulterat i veckning och reversa förkastningar, och den övre som avsatts efter den kompressiva deformationen. Uppmätta deformationsriktningar tyder på en deformation från SV.

Spargelberg ligger norr om Kreuzbruchhof och består enbart av glacifluviala sediment, som är duktilt deformerade från NÖ.

Fritscheshof är något mer komplicerad då hela basen utgörs av en skolla bestående av tertiär kvartssand och ett kol-lager. Eventuellt ingår även två diamikta enheterna samt veckade fluviala sediment. De diamikta enheterna är tolkade som flytmorän. De veckade sedimenten är troligtvis glacifluviala och deformerade från en östlig sektor. Några helt säkra deformationsriktningar har inte kunnat dokumenteras varför tolkningen är influerad av närliggande Spargelberg.

De motsatta deformationsriktningarna har tolkats som deformation av två glaciala element. De två norra grustagen, Spargelberg och Fritscheshof, har deformerats av en oscillerande Pommersk is medan Kreuzbruchhof har deformerats av en expanderande lokal isdom.

Eftersom någon subglacial morän inte har dokumenterats och inte heller några indikatorer på att det varit permafrost tolkas deformationen ha ägt rum proglacialt.

CONTENTS

1 Introduction

This paper is a part of the project "Lithostratigraphycal and deglaciation dynamics during and after the Pomeranian stage in NE Germany" (PhD student: J. Albrecht), which is connected to the "Anomalous Late Weichselian ice movement directions in NW Poland, NE Germany and S Sweden indicating local ice domes" (co-ordinator: E. Lagerlund). The aim of the project is to correlate the Quaternary stratigraphies in the countries in the Baltic Sea region. In recent years investigations have been carried out in Poland, Germany and Sweden. The aim of this paper was to investigate the local deglaciation history as a case study in three gravel pits situated in the area south to southeast of Neubrandeburg.

Pre-Quaternary history

The area of investigation is located on the young and tectonic unstable West-European peninsula south of the Tornquist-line. During Triassic-Cretaceous, Mesozoic, 1600-1800 m of sediments were deposited. The Buntsandstein alone contributes with 750 m thick sediments. Middle and upper Jurassic as well as lower Cretaceous sediments are missing in the sequence. Pleistocene sediments are often found directly on top of the Cretaceous bedrock, indicating a sedimentary gap, a hiatus. The Tertiary sediments were eroded by the Weichselian glaciations. Locally Tertiary clay and quartz sand are present in situ or as rafts.

Quaternary history

During the last three major ice ages, the Elsterian, Saalian and Weichselian the county of Mecklenburg-Vorpommern was covered by several ice sheets (Fig. 1). Every advance caused large-scale erosion and redeposition. The thickness and distribution of the glacial sediments are known by a large number of drill sites in the area (Rühberg & Bremer, 1995). The lithological composition of the tills is mainly known from petrographical investi-gations introduced by Cepek (1972), TGL 25232 (1980).

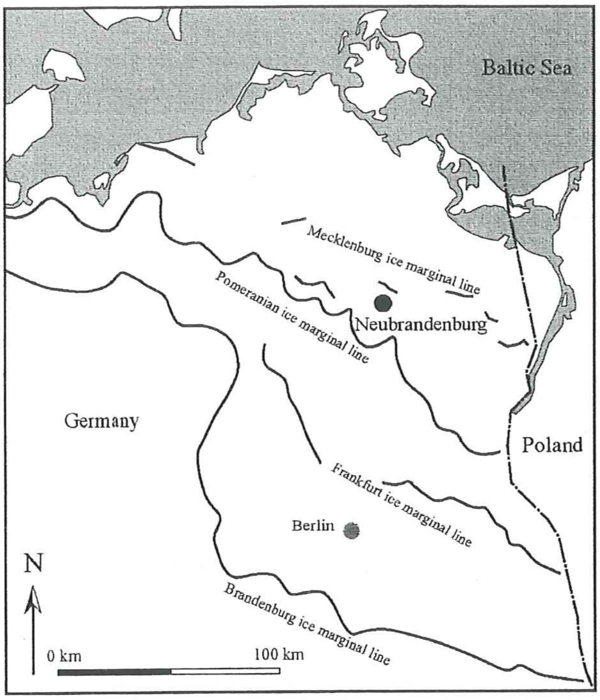

Fig. 1. Overview of the Weichselian ice marginal lines in NE Germany. The investigated sites are situated in the area of Neubrandenburg approximately 100 km south of the Baltic Sea.

The oldest glacial sediments in Mecklenburg-Vorpommern are of Elsterian age, dominated by partly brownish till with high concentration of flintstones (Müller *et al.* 1995). The till is interbedded with glaciofluvial and glaciolacustrine sediments. These sediments are conserved in deep tectonic zones.

After the succeeding Holsteinian interglacial, the area was covered by the Saalian ice sheet, which moved from north to south terminating in the Sachsen-Thüringen area in southern Germany.

The Saalian glacial is subdivided into two different glacial phases, Drenthe and Warthe. They differ in transportation direction, from north and east respectively, which is reflected in the colour of the sediments and their lithological composition. Drenthe represented by a green to blue-green coloured till with high amounts of Tertiary clay and a lithological composition of Nordic igneous and metamorphic rocks, chalk, flintstones and Paleozoic shale. Warthe represented by a grey-brown to red-brown coloured till with a lithological composition of high amounts of Paleozoic carbonate, dolomite and low amounts of sandstone (Müller *et al.*, 1995), the sandstone indicating an ice movement from the east.

Interglacial marine sediments of Eemian age are only found in the coastal areas of today. In the rest of the region, limnic and organic sediments represent this warm period.

The youngest ice age, the Weichselian, is geomorphologically divided into three cold phases, stadials. However, no interstadial sediments have been found between the Weich-selian tills in the area (Müller *et al.* 1995). Weichselian tills differ from Elsterian and Saalian tills in their lithological composition. Weichselian tills can be distinguished by their high concentration of Paleozoic shale. Little is known about early and middle Weichselian in NE Germany. According to Rühberg (1998), drillings provide evidences for a glaciation during early or middle Weichselian, which is represented by the so-called W0-till. The first Late Weichselian stadial (W1) was the most extensive, reaching as far south as to the county of Brandenburg, therefore called the Brandenburg stage. W1 is represented by a large continuous terminal moraine system (Fig. 1). The Frankfurt terminal moraine (Fig. 1) was deposited when the recession, after W1, came to a halt. The Frankfurt sub-stage is not re-presented by a separate till bed. After this stagnation phase the ice sheet retreated to the Baltic Sea before the next advance, W2 (Cepek 1972). A new advance (W2) deposited the Pome-ranian terminal moraine system (Fig. 1). This (terminal moraine) system is the best developed in the area and consists of the thickest till of Weichselian age. In the central and northwe-stern parts of Mecklenburg the moraine systems have been subdivided into one older (W2u) and one younger (W2o) system. According to Cepek (1972) and Rühberg & Bremer (1995) the two major Weichselian ice-advances, Brandenburg advance and the Pomeranian advance, are represented by separate till beds characterised by typical lithological compositions. The W1-till is distinguished by a high amount of Palaeozoic shale, whereas the W2-till contains remarkably high amounts of Cretaceous chalk. The history of the last cold-phase (W3), the Mecklenburg stage, in northern Germany is not fully known. The absence of a distinct and continuous terminal moraine system, in contrast to the W1 and W2, is one of the reasons. North of the Pomeranian terminal moraine system a number of minor end-moraines are found. However, no clear correlation has yet been done. A possible explanation for the features might be a series of minor oscillations during deglaciation. Rühberg & Bremer (1995) have distinguished a separate till bed representing the Mecklenburg stadial.
The area was finally deglaciated around 14000 BP (e.g. Lundqvist & Saarnisto, 1995).

Local geology

The investigated area is situated in northeastern Germany, nearby Neubrandenburg, approximately 150 km south of the Baltic Sea (Fig. 1). Three gravel pits were investigated, Kreuzbruchhof, Fritscheshof and Spargelberg (Fig. 2). There is no information on the pre-glacial landscape. The topography of today is a product of the erosion and redeposition of the Weichselian glaciation, especially the Pomeranian

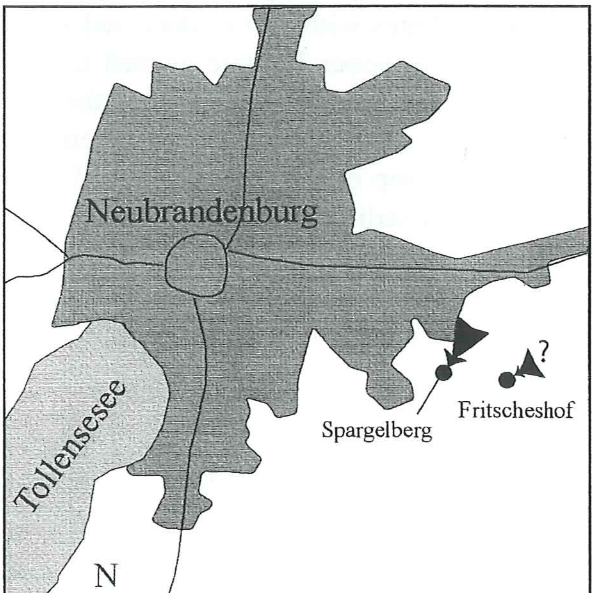

Fig. 2. An overview of the investigated gravel-pits in the Neubrandenburg area. Arrows represent interpreted directions of deformation, discussed in chapter 3-5.

stadial. The topography of the landscape is undulating with smooth hills and depressions. The relief in the landscape is relatively low; usually less than 30 m with exception of larger melt water channels parallel to the former ice front, some of them occupied by water today. The Weichselian glacial landscape in northern Germany is characterised by a large variety of sedimentary environments. Sedimentation patterns have changed over short distances in time and space (Bremer & Schulz 1994). The relief in the county of Mecklenburg-Vorpommern is dominated by the Pomeranian terminal moraine system reaching up to 179 m.a.s.l. The lateral orientation of this system is seen in fig. 1. Between the moraine systems well-developed fluvial systems are present.

2 Methods

To get a picture of the landscape and the features, the documentation started with a two-day excursion. It was an introduction to the local Quaternary history in the area but also necessary background for (the procedure of) finding suitable sites for more detailed studies. The three chosen sites are located in gravel pits in the Neubrandenburg area. The selection of the sites was based on a couple of factors, such as: access from Neubrandenburg, frequency of relatively clean headwalls, sediment content and structures in the sediments. The profiles were photographed, mapped and samples were taken for grain-size and petro-graphical analysis. Geometrical orientation was measured on dipping sediments, faults, folds and clasts (fabric-analyses). Lithofacies coding was done according to Benn & Evans (1998). To make the documentation easier pinpoints were put out with nails and string. Some help to remove huge amounts of sediments were given by the employees of the pit. In some of the larger sections detailed drawings were made on more complex structures.

Fabric analysis

In the only suitable diamict sediment, located in one of the sites, Fritscheshof, particle orientation was measured. In each fabric level a minimum of 25 A-axes or 15 B-axes were measured. This was done to find indications concerning orientation, imbrication and/or rolling of clasts (Ehlers, 1996; Reading, 1996). A certain orientation pattern may provide important information about genesis and pressure implications in the sediment. This is a quantitative tool used to identify the genesis of the diamicton (Bennett & Glasser, 1996; Lowe & Walker, 1997). Fabric analyses were carried out in the diamictons on medium gravel-sized particles with a longitudinal (a-) axis at least $1^1/_2$ times longer than the intermediate (b-) axis. To assure the individuality of the particles the fabric analyses should only be carried out in matrix-supported sediments (Dowdeswell & Sharp, 1986). The results were plotted in a stereonet-diagram.

Measuring of faults and folds

The purpose of measuring folds and faults is to distinguish an applied force. By measuring the faults and folds in detail it is possible to make a statistical interpretation of the pressure applied by the moving ice in the affected area, and thereby determine the dynamics of the ice (Berthelsen, 1978; Ehlers, 1996; Reading, 1996). Small-scale synsedimentary faults caused by melting of buried ice can also be identified. Reverse faults represent pressure applied by moving ice while normal faults represent collapse in the sediments when buried or supporting stagnant ice melts. The measurements where plotted in stereonet-diagram.

Grain-size analysis

Laboratory analysis of grain-size distribution was made by sieving of the coarse fraction (>0.063 mm) and by sedimentation analysis of the finer fraction. The results are illustrated by plots of grain-size (in mm) vs. mass-percentage and grain-size vs. cumulative mass-percentage (Talme & Almén 1975). Grain-size analyses were carried out to determine the genesis and facies of the sediments.

Petrographical analysis

Petrographical analysis was carried out on the gravel grades 2.8-4 mm, 4-5.6 mm and 5.6-8 mm. For identification of the rock-types a microscope was used. The aim was to determine the provenance of the sediments. Correlation to petrographical analyses introduced by Cepek (1972) was made when possible. The identified rock-types were di-vided as follows:

- *Crystalline*
- *Paleozoic limestone*
- *Dolomite*
- *Cretaceous limestone and flint*
- *Sandstone/Siltstone/Shale*
- *Quartzitic sandstone*
- *Others*

3 Localities

Kreuzbruchhof

Kreuzbruchhof is a gravel pit situated south of Neubrandenburg (Fig. 2). It is located in an undulating cultivated landscape with a relatively low relief, consisting of smooth hills and depressions. The hills consist mostly of glaciofluvial sediments. No continuous diamicton has been found in the extent of the gravel pit. There might have been a thin diamicton at the top of the sequence, which has been removed. A number of deformation structures are present in the profiles, represented by faults, folds and tilted sediments. The uppermost sediments seem to be, more or less, conform to the topography. Kreuzbruchhof is dominated by different sets of sandy glaciofluvial beds (App. 1: Log. 1). Thin horizons of silt occur. In the uppermost part of the pit fine-grained sediments dominate and the facies vary to a greater degree. In general the deformation structures increase in frequency and decrease in size upward, with exception of a large fold cut by a number of faults at the base of the pit. The structures change upwards, from folds and reverse faults at the bottom via reverse faults in the middle, back to folds a couple of meters below the top to normal faults at the top. The depth of the pit is limited by the ground-water surface. Five profiles, KB1-KB5 are described and interpreted below (Fig. 3).

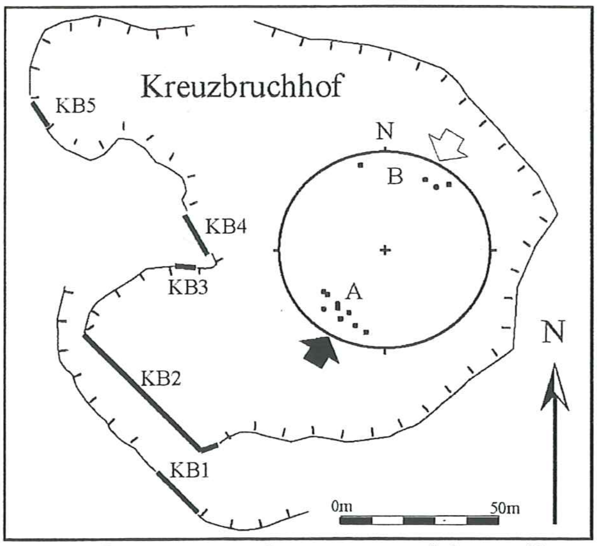

Fig. 3. The position and orientation of the profiles in Kreuzbruchhof. Stereonet-diagram representing dip and dip-direction of (A) reverse faults and (B) relaxation faults. The black arrow represents orientation of the exerted deforming force and white arrow represent orientation of stress release, relaxation faults.

Notable is a rather chaotic section (App. 2:1) just below the KB1 section but above the KB2 section. Unfortunately lack of time and huge amounts of scree material prevented documentation of this part. However the lowermost part of the KB1-profile show some vertically standing folds reflecting the chaos below.

Sections

KB1-Description

This section consists of sorted and laminated sediments with exception of a diamicton present in the left side of the profile just below the scree material. The overall grain-size is fining upward. Silt and sand dominate the top of the profile while sand and sandy-gravel constitute the lower part (Fig. 4). Some internal structures are visible and most of them are plane-parallel but the deformation overprints the primary structures. The top sediments seem to be draping the more deformed underlying sediments. A large number of normal faults and some minor folding are present in the upper part of the profile. The lower part of the profile is deformed to a much larger extent and in a compressive pattern with folded and reverse

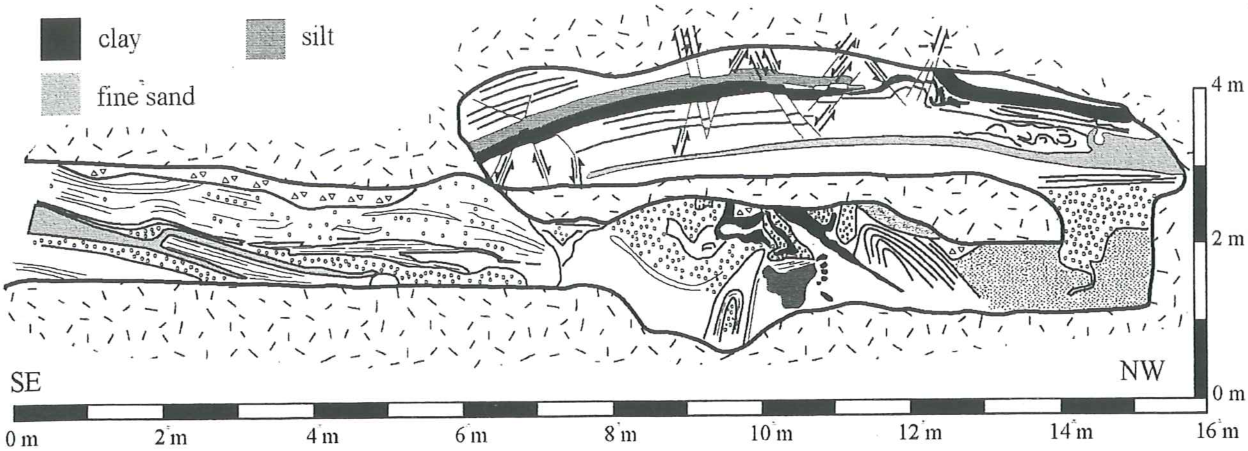

Fig. 4. The KB1-profile located in the uppermost part of the gravel pit. The position of KB1 is the highest of the six profiles in Kreuzbruchhof. The upper part consisting of sand and silt sediments show only normal faults while the lower part consisting of sand and sandy-gravel represent a more complex and chaotic pattern dominated by folding. Notable is the thin diamict sediment partly exposed under the scree material. The only exposed contact between the upper and lower part is in the right side of the section.

faulted sediments. Unfortunately, the contact between the upper and lower part was not found throughout the profile due to a huge amount of scree material.

Notable is that the normal faults are only present in the uppermost (1-2 m) part of the profile.

KB1-Interpretation

The folded sediments in the bottom of the profile are interpreted as glaciofluvial material deposited in a dead-ice landscape. This applies to the uppermost sediments as well. An exception is the diamict layer inbetween, which probably was deposited as a flow till. The difference between the upper and lower part is the deformation history. The uncompressed top sediments were not deposited until after deformation of the lower part, hence lacking compressive deformation structures. Deposition is interpreted to have occurred twice, before (lower part) and after (upper part) compressive deformation. An ice advance in the area, resulting in folding and reverse faulting, deformed the lower part. The folding and reverse faulting in the lower part is a product of both ductile and brittle deformation. Brittle deformation absorbs the shear stress when the limit of ductile deformation is reached. The top of the profile is faulted (normal faults) as a result of melting stagnant ice. The minor folding is probably a result of faulting. There might be some faults in the lower part as well but the sediments are coarser. Since coarser sediment gives rise to a less defined slip-plane, the grain-size might explain their absence (in the documentation). In fact there is a possibility that the exerted tension created movement grain by grain in the coarser sediment where cohesion is absent. This might be the case in the coarse-grained sediment on the right side of the profile. However, it seems as if the normal faults dis-appear at a distinct depth, possibly reflecting the depth of a periglacial active layer. An active layer in permafrost may have caused the top sediments to move as a rigid plug, possibly as a response to failure further down-slope, due to melting of stagnant ice. When the permafrost was degrading the active layer became thicker and penetrated further down. This could have saturated the sediments below, except that the coarser sediments in the lower part of KB1 which have a higher permeability and would not have got saturated, thus preventing failure. A third more probable possibility is that the sediments in the upper part have been subject to settling as a result of melting stagnant ice.

KB2-Description

The head wall (Fig. 5) of the pit is dominated by glaciofluvial sand and sandy-gravel beds interbedded with a couple of thin silt layers. Some plane-parallel bedding is present but most of the sediments are trough-cross bedded with minor lags (App 1: Log. 1). This part of the pit is following the same com-pressive pattern as

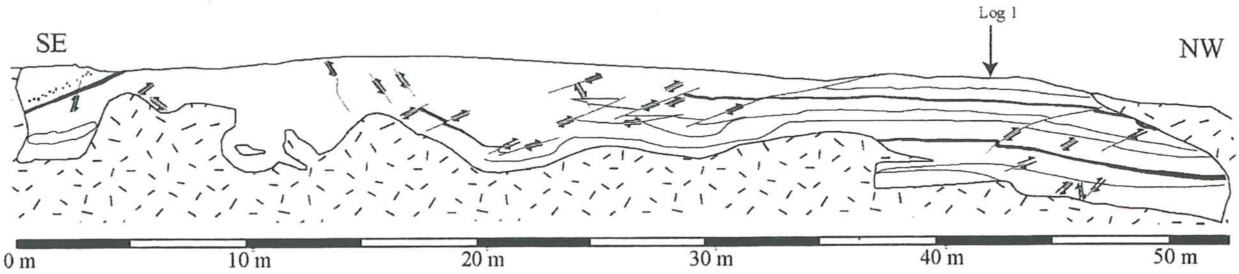

Fig. 5. The KB2-profile is located 2-3 m below the KB1-profile and the undocumented distance is represented by a large amount of scree material. Some exposed patches reveal strongly folded or tilted sediments. The section consists mainly of sand and sandy-gravel sediment, trough-cross bedded and laminated. A couple of thin silt horizons are observed through the section. Mainly reverse faults and a few relaxation faults represent the deformation structures corresponding to a compressive regime with brittle deformation.

the lower part of the KB1 section, with the difference of reverse faulting (App. 2:2) instead of folding. The displacement of the faults is not larger than a few decimetres. The instability of this wall and the fact that it was an active part of the gravel pit made documentation difficult as well as limited. The profile was therefore not documented in detail and the log is to some extent a compilation in this part of the pit.

The average dip-direction and dip of the reverse faults was measured to approximately 215°/26° (S_1=0.95).

KB2-Interpretation

The sediments in this profile are interpreted as glaciofluvial material deposited in an ice-decay landscape. The facies represent a rather distal braided-river system with fluctuations in distribution and thereby water energy. The trough-cross bedded sediments represent deposition in channels while the plane-parallel sediments represent higher water level and sedimentation on bars and banks. Reverse faulting instead of folding is probably due to different response to the exerted shear stress. The criteria for ductile deformation might not have been reached. The high permeability in the coarser sediments in KB2 prevented them from being water-saturated, causing the deformation to be brittle. The absence of normal faults indicates that melting of stagnant ice did not affected this part. The force producing the reverse faults was exerted from approximately 215° (SSW). The direction of the exerted force was not the expected from deformation by a Scandinavian ice sheet extending into northern Germany but surprisingly opposite.

KB3-Description

This profile (Fig. 6, App. 2:3) consists of an upright fold, consisting of glaciofluvial sand and silt. The sediments are relatively fine-grained and plane-parallel lamination is dominating. Most internal structures are preserved even though the sediments have been strongly folded. The fold is cut by a number of almost horizontal faults and a series of reverse faults in the right side of the profile.

The dip-direction of the sub-horizontal faults and the orientation of the fold plane were measured to approximately, NNE (26°/17°, S_1=0.87) and SSE (172°/33°, S_1=0.90) respectively.

KB3-Interpretation

The deposited glaciofluvial sediments represent an environment with relatively low water energy. The low energy might be due to low

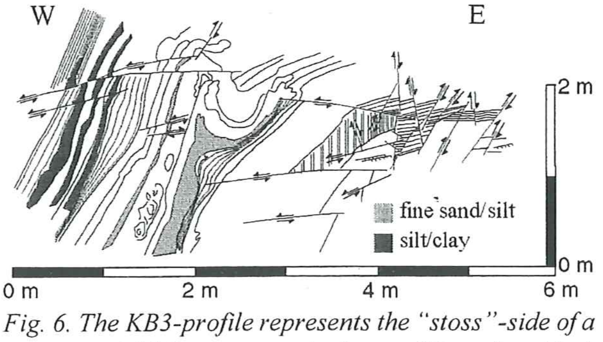

Fig. 6. The KB3-profile represents the "stoss"-side of a overturned fold present at the base of Kreuzbruchhof. Sediments consist of sand to silty-clay with preserved internal structures, which are laminated or ripples. Reverse faults in the eastern part and sub-horizontal relaxation faults cutting both reverse faults and the overturned fold represent brittle deformation. The fold-plane was measured to approximately 172°/33°. The fold continues in the KB4-profile (Fig. 7).

melting rate of stagnant ice, increased distance to the retreating ice sheet or due to a sheltered position in the glaciofluvial distribution system. The deformation structures indicate that a strong shear stress has been exerted on the sediments. The fold is cut by the faults indicating that the fold is older than the faults. The sub-horizontal faults have probably developed as relaxation faults when the stress applied by the ice sheet was released and are interpreted in the same way as the backward extension faults described in Poland by Björklund *et al.* (2000). For the reverse faults in the right part of the profile a possibility is that the faults developed synchronously with the folding when folding was reaching the accommodation space limit and could not absorb more stress. The change of deformation pattern from folding to faulting is thus related to the change from ductile to brittle deformation. The upright fold indicate an exerted force from approximately SW, however compressive folds tend to deform into non-cylindrical shapes instead of cylindrical. In this case the dip-directions of the relaxation faults are more reliable indicators than the fold-axis. This is because the faults were measured throughout the profile and the fold-axis more or less at one point.

KB4-Description

This profile (Fig. 7, App. 2:4) is found close to KB3 and consists of strongly folded sediments cut by a few sub-horizontal faults in the right part and a few more inclined in the left part. The sediments are in general coarser than in KB3. The beds are plane-parallel as well as the observed internal structures. The glaciofluvial sediments in this profile are more proximal than the sediments of KB3. The orientation of the profile is close to the orientation of the fold axis. This gives the structures in the profile a more complex appearance. Projection of the glaciofluvial sediments forming an anticline in KB3 and KB4 gives the internal relationship of KB4 deposited on top of KB3, hence indicating an upward coarsening trend.

The fold-axis was measured to approximately 170°/0°.

KB4-Interpretation

The small distance and resembling structures to the KB3 section, indicate the same history, hence the same interpretation. The upward coarsening trend between KB3 and KB4 indicate that water energy at some time increased. The sub-horizontal faults in KB4 are due to failure during deformation while these in KB3 are backward extension faults, or relaxation faults. The more inclined reverse faults in the left part of the profile also represent relaxation faults. The fold is interpreted as an overturned fold and correlation to KB3 gives the same direction of the applied force.

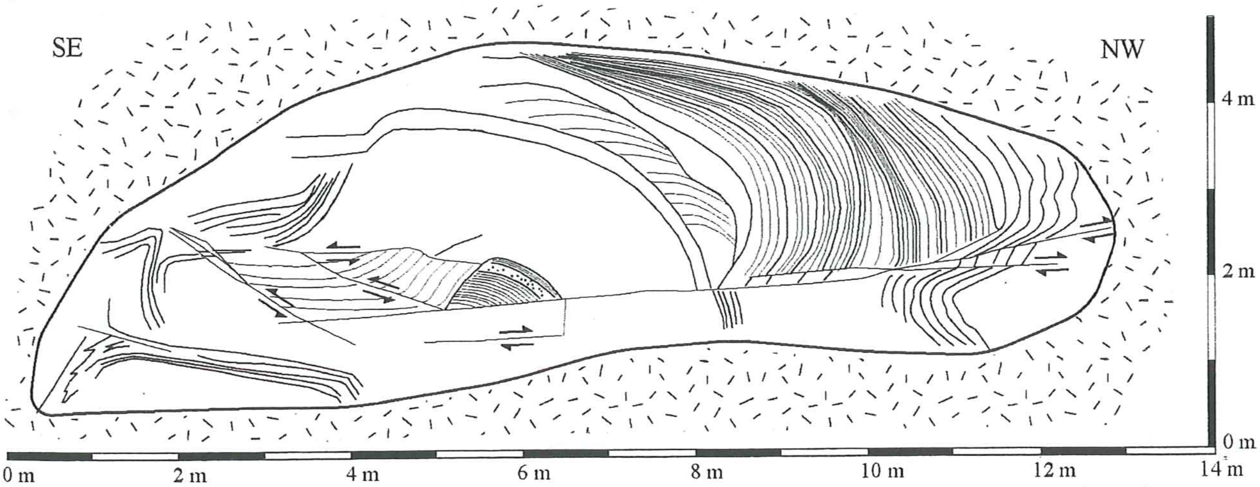

Fig. 7. The KB4-profile represents the overturned part of the fold found in the KB3-profile (Fig. 6). The sediments are slightly coarser, sand and gravel. Sub-horizontal faults represent the brittle deformation when the limit for ductile was reached and the reverse faults in the left part of the profile represent relaxation faults. The fold-axis was measured to approximately 170°/0°.

KB5-Description

KB5 is a profile (Fig. 8) situated closer to the depression north of the gravel pit than the other profiles. It consists mainly of glaciofluvial (App. 1: Log. 2) sandy sediments from the base up to approximately 1 meter below the top. The sand beds are trough-cross bedded, plane-parallel bedded or massive. Normal faults are present in the plane-parallel bedded lower part. The sediments seem to be disturbed and a large intraclast consisting of trough-cross bedded sand was found in the massive sand. The top bed is built up by an intercalation of diamict material and sandy-silty layers. In the middle of the profile there is a complex of two normal faults cutting each other and thereby creating a bulge in the beds above (Fig. 8). It is difficult to see if the sediments are cut by the fault or if they have adjusted plastically. The normal faults in the laminated sand (App. 2:5), in the lower part of the profile, are more distinct even though they are smaller. The section continues below the profile and consists of a thin package of sheared fine-grained sediments close to the base.

KB5-Interpretation

The diamict top sediments are interpreted as generations of debris flows, a result of sediments saturated with water moving down-slope from the stagnant ice. Water-saturated sediments are unstable and prominent to failure. When the debris flows come to a halt due to loss of water while moving, most of the residual water leaves the sediment, bringing out the finer particles, which represent the silt layers in-between the diamict beds. The intraclast has probably been frozen when deposited in its present position in the massive sand. The massive sand may have been deposited in two ways: either through rapid glaciofluvial deposition with the intraclast falling in from the adjacent dead ice or through deposition by a debris flow plucking up the frozen interclast nearby. The small-scale synsedimentary faults in the laminated sand are only minor and do not correspond to the topography of today. The fine-grained sediments in the bottom of the KB6-profile have probably acted as a water-saturated slip plane, when a barrier of stagnant ice melted in the depression.

Local interpretation

The dominating deformation structures in the pit are folding and reverse faulting and not normal faulting as was expected in an ice-decay landscape.

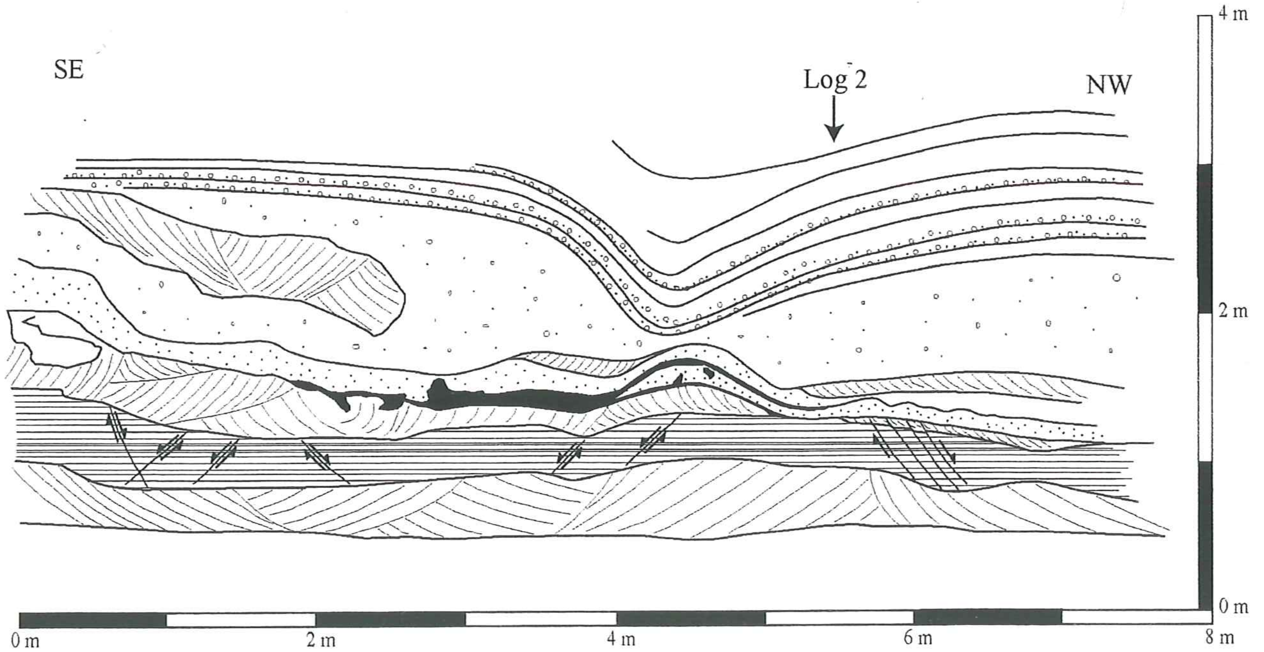

Fig. 8. The KB5-profile is situated further to the north and closer to the depression than the other profiles. Generations of flow tills are present in the upper part of the profile as an intercalation of diamict units and sandy-silt. An intraclast of through-cross bedded sand in massive sand was found in the left part of the profile. The bulge in the middle of the profile is created by two normal faults cutting each other.

The correlation between KB1 (except the upper part), KB2, KB3 and KB4 is good, represented by reverse faults and folds in a compressive flow pattern. Proglacial deformation generated folds and reverse faults. Reverse faulting is the result when the limit for ductile deformation is reached. Folding also creates tension (secondary) in the sediments but mainly compression due to the nature of the exerted force. The absence of compressive deformation in the top sediments in KB1 and the generations of flow till in KB5 indicates that these glaciofluvial sediments were not affected by the last glacial advance but were more likely deposited after the proglacial deformation. The normal faults at a greater depth in KB5 are probably due to its position closer to the depression, thus more exposed to failure when the stagnant ice melted.

Deformation could also have occurred subglacially if the ice was cold-based. A cold-based ice would not leave a large amount of material, possibly responding to the thin diamict sediment in the KB1 section.

The history of the pit can be divided into four phases:

- Glaciofluvial deposition in a recently deglaciated area containing relatively large amounts of stagnant ice.
- Deformation by an advancing glacier from approximately SW resulting in folding and thrusting (reverse faults).
- A second period of glaciofluvial deposition in an area with relatively large amounts of stagnant ice present.
- Deposition of flow till (KB5) synchronous with melting of remnant stagnant ice resulting in faulting (normal faults).

Fritscheshof

Fritscheshof is situated southeast of Neubrandenburg (Fig. 2), located in the same undulating landscape as Kreuzbruchhof. Most of the pit consists of a Tertiary raft of quartz sand (Rühberg, 1998). The quartz sand underlies all the other exposed sediments in the pit and on top of it a continuous coal horizon is found (Fig. 9). The thickness of the coal layer varies laterally but the general trend is thinning out towards the south. According to Rühberg (1998) the quartz sand constitutes the ground surface in the nearby area. In the northern part of the profile, just above the coal, a thin glaciofluvial bed consisting mainly of quartz sand is found. A couple of very complex structures are seen in this part and they cut both beds. Further south the glaciofluvial sediment vanishes and is replaced by two diamict units. The diamict sediments, referred to as diamicton 1 and diamicton 2, are interbedded with a large number of thin sand lenses (App. 1: Log. 3, App. 2:6, 7). In diamicton 1 the sand lenses seem to be deformed to some extent while in diamicton 2 the orientation of the sand lenses follows the orientation of the contact. Diamicton 2 is slightly darker than diamicton 1, the grain-size is coarser and carbonate is absent. The boundary between diamicton 1 and 2 is an unconformity. Typical shear-stress features like reverse faults and thrusting are common in the different sets of beds, especially in the contact between quartz sand/coal and diamicton. The contact (unconformity) is sharp with displaced quartz sand lenses in the in diamicton 1 close to the contact. Above the quartz sand, in diamicton 1, deformation seems to be less distinct but is still present. Indications for compressive deformation are mainly found in small scale folding of the sand lenses. In the 62-meter long profile five detailed studies, three fabric analyses (Table 1, App. 1: Log. 3) and sampling have been carried out. The details are presented in the figure text (Fig. 9).

An overturned fold was found in the nearby area of the profile, just above the coal horizon (App. 2:11). At this position the coal horizon is thicker (0.5 m). The 2-3 m large fold is cut

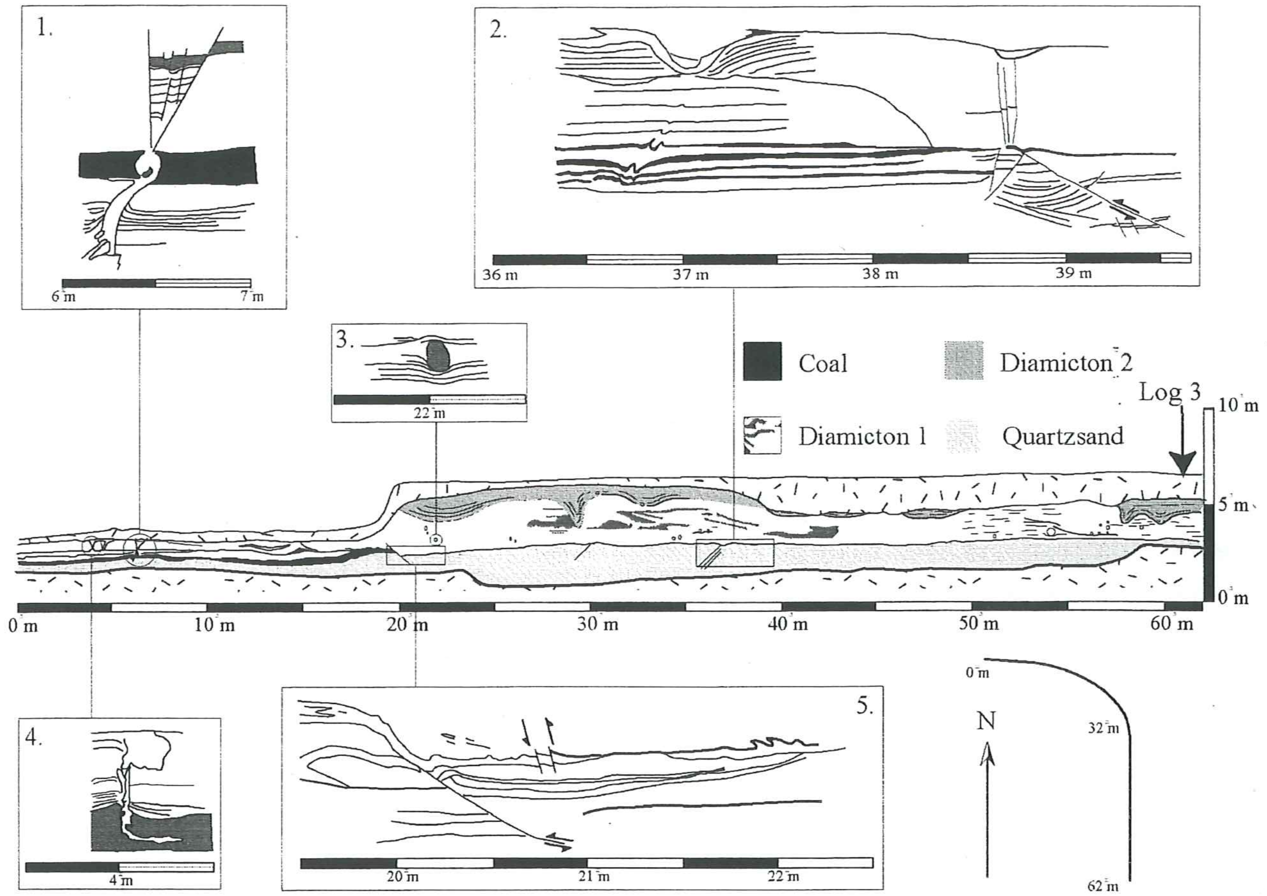

Fig. 9. 1. A complex structure consisting of normal faults in the upper part and grain flow in the lower part. Interpreted as a melting product of pre-proglacial deformation age, probably through adjusting to its position after transportation and deposition. Joints opening up, due to stress release allowing debris-rich melt water to percolate down, rendering in normal faulting in the upper part.
2. This section shows clear evidence of normal faults, some which later have been reactivated, as reverse faults or have allowed movement in these weak zones. Normal faults, settings, derived from when the raft adjusted to its position before proglacial deformation or from applied stresses during transportation. Reactivation of normal faults as reverse faults due to an unequal melting of the buried ice, hence tilting the sediments. Some of these weaker zones have also been absorbing the stress exerted by the proglacial deformation. In the left part of the section an upward declining movement along the weak zone is responding to this phenomenon.
Trusting is present in the contact quartz sand-diamicton indicating shear stress applied by the debris flow deposits, flow tills.
3. Small scale deformation and thrusting around a 10-15 cm large stone. The shear stress exerted by the debris flow has made the stone rotate, deforming the sediments due to its non-spherical form.
4. A very complex structure, interpreted to be of pre-proglacial deformation age. The deformation is probably related to the transportation and adjustment to its position.
5. This section shows the same features as detail 2, except no weak zone absorption of stress.

by a reverse fault. The fold-axis was mea-sured to approximately 320° in the horizontal plane while the dip-direction and dip of the reverse fault was measured to approximately 228°/40°. A second complex fault was also found indicating more or less an opposite orientation.

Deformation is present in most of the pit. In the profile faulted sediments are most common while in the rest of the pit the sediments are tilted and folded to a much greater extent. Some of these sections further north were tilted 90° or more. At this position the coal layer was atleast 1 meter thick and situated with quartz sand both above and beneath (App. 1: Log. 4). Unfortunately the exposed sections are very limited.

Table 1. Results of fabric analyses concerning orientation of V_1 and its significance are displayed below.

Fabric	V_1	S_1
1	284°/1.7°	0.62
2	218°/3.5°	0.59
3	229°/0.2°	0.69

Interpretation

The Tertiary quartz sand has been transported by a glacier to the area as a frozen raft, a process described by Moran (1971). The coal has probably been transported attached to the Tertiary quartz sand, hence representing the same raft. The diamictons might also have been transported attached to the quartz sand but more probably they were deposited after the raft had settled in its present position. The diamictons are interpreted as flow tills due to the nature of the observed structures (App. 2:7-10) and interpreted fabric results (Table 1, App. 1: Log. 3). The three fabric analyses give a preferred orientation of shear stress from the western sector.

The unconformity between diamicton 1 and 2 is interpreted as the result of a short period with glaciofluvial activity/erosion, before deposition of the second unit. Another possibility is that the diamict units were deposited as one. Water-saturation re-activated the upper part as a fluidisation flow along the undulating surface separating the units today. This would mean that the undulating surface is a product of weak zones. The absence of carbonate in diamicton 2 is probably due to depletion by percolating surface water. The depletion seems to be limited to diamicton 2, accounting for its darker appearance. The small scale thrusting in the contact between quartz sand and diamicton is a result of the shear stress applied by the debris flows. Normal faults are dominating in the quartz sand but some of them seem to have been reactivated as reverse faults. The normal faults are probably from when the raft and adjacent buried ice melted and adjusted its position to the underlying topography. Unequal melting of buried ice caused the raft or parts of the raft to tilt, hence the reactivation of normal faults as reverse faults.

The exposed patches of tilted and folded sediments are interpreted as segments of overturned folds (Fig. 10). The position of this ductile deformation is on the same level as the diamict units, above the coal/quartz sand. Furthermore the folded sediments are forming an unconformity with the ground surface, probably developed through erosion. A probable explanation is that these sediment structures represent an overturned fold corresponding to an applied stress from the eastern sector. The direction above correlates well to the nearby overturned fold (App. 2:11) where shearing is interpreted to have been exerted from 50°-60° (NE), then the reverse fault could be a relaxation fault. However the structure of the overturned fold is very complex and could be a result of shearing into or out from the profile. The raft and possibly the diamictons probably acted as a competent layer transferring the applied stress instead of deforming. Furthermore there is a possibility that the folded sediments have been a part of the raft, too.

Deformation structures are present but the absence of a preferred sense of shear is a weak factor in this investigation. The interpretation of Fritscheshof will therefore be influenced by the interpretation of the nearby gravel pit - Spargelberg (below).

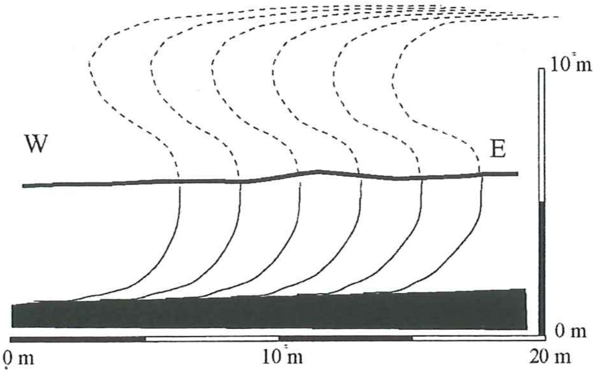

Fig. 10. A principal drawing of the interpreted folded sediments in Fritscheshof.

Spargelberg

Spargelberg is the third investigated gravel pit situated southeast of Neubrandenburg (Fig. 2). A complementary study was done and gravel samples taken in the gravel pit. The high and instable walls limited detail study of the pit. Glaciofluvial sediments dominate in Spargelberg and the topsoil has been removed in the extent of the gravel pit. No proof that the removed sediments included a diamicton was found.

In the lower part of the pit no deformation structures were observed. The height (8 m) of this unstable wall prevented all detail studies. The sediment consists mainly of plane-parallel coarse sand to gravel with minor trough-cross bedded units.

Some large deformation structures (folds) are present in the pit, especially in the headwall (Fig. 11, App. 2:12). The instability of the exposed sediments limited the investigation and documentation in the gravel pit of Spargelberg to visual examination. The exceptions are two detailed studies (Fig. 12, 13) and a few measurements of fold-axis and gravel samples.

Measurements on fold-axes yielded approximately NW-SE (120°/0°).

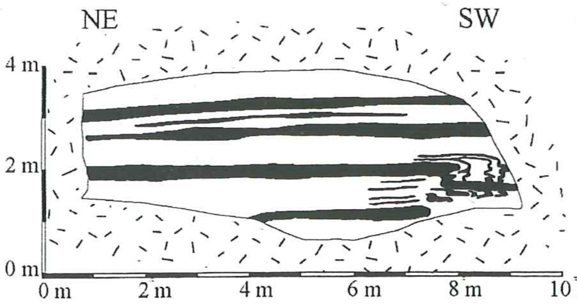

Fig. 12. Ductile deformation located north of the headwall of Spargelberg. The fold-axis was measured to approximately 120°/0°, responding to an applied stress from 30° (NE).

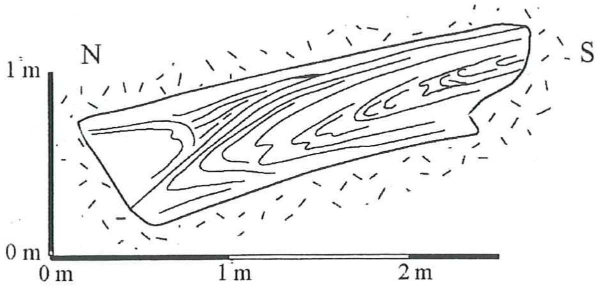

Fig. 13. An exposed part just north of the headwall (Fig. 11) with ductile deformation. The fold-axis was measured to approximately 120°/0°. The force corresponding to the deformation is interpreted to have been exerted from 30° (NE).

Interpretation

In general the grain-size of these glaciofluvial sediments are larger than in the other investigated sites. This means that the water energy must have been greater in this area of the ice-decay landscape. The topography is less undulating and could be responding to an outwash plain. The coarser sediments are interpreted to respond to intermediate braided-river facies. The deformation structures are interpreted as overturned folds produced by a force from approximately 30°, indicating a compressive regime opposite to the one documented in Kreuzbruchhof.

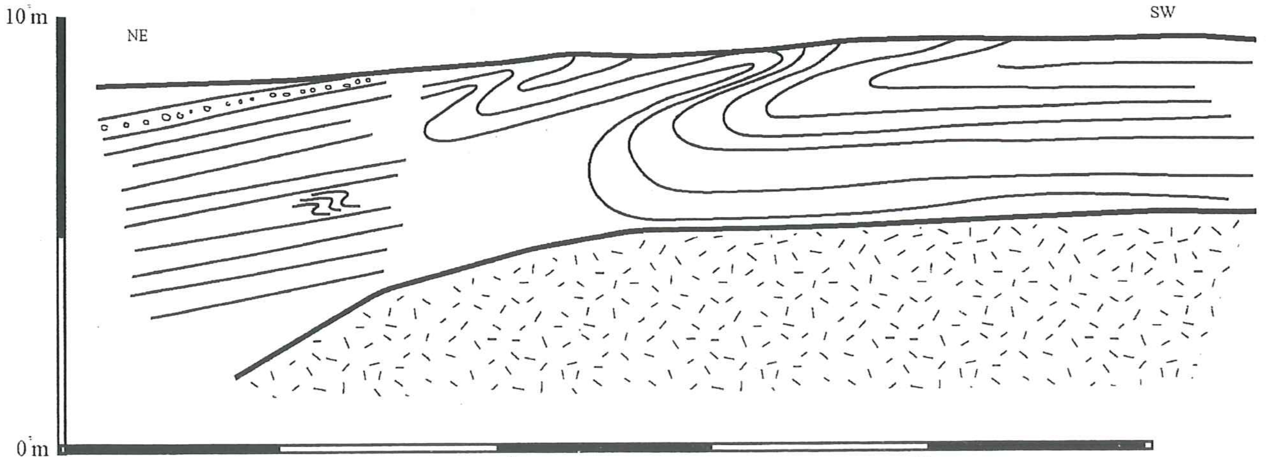

Fig. 11. Large-scale ductile deformation, represented by a large overturned fold located in the headwall of Spargelberg. The sediments consist mainly of laminated sandy-gravel and gravel deposited plane-parallel. The fold-axis was estimated to approximately 120°/0°, responding to an applied stress from 30° (NE).

4 Discussion

The topography and the glaciofluvial sediments as well as the flow tills in Kreuzbruchhof, and possibly in Fritscheshof, indicate an ice-decay landscape (Boulton, 1972; Ehlers, 1996; Gray, 1991). After deposition of the sediments in Spargelberg, Fritscheshof and parts of Kreuzbruchhof the landscape was affected by glacitectonic deformation, however from different directions. The directions documented in Kreuzbruchhof indicate deformation from SW. This does not correlate with the two northern sites (e.g. Spargelberg), which were deformed from NE, as was expected with a Scandinavian ice sheet expanding into northern Germany. The different directions of deformation and the absence of a lodgement till suggest more than one possible explanation, proglacial deformation or subglacial deformation. Since no lodgement till was found subglacial deformation must have occurred beneath a cold-based glacier (van der Wateren, 1995), e.g. a cold-based margin.Two scenarios of proglacial deformation are possible. Therefore the discussion is divided into three hypotheses concerning the two northern gravel pits, especially Spargelberg. The gravel pit of Kreuzbruchhof is correlated to the other two when possible. The first hypothesis concerns the Mecklenburg stage and permafrost, the second refers to an oscillating Pomeranian deglaciation and frozen ground (e.g. cold-based ice margin) while the third refers to an oscillating Pomeranian deglaciation and unfrozen ground.

The distance between the Mecklenburg terminal moraine system (Fig. 1) and the investigated gravel pits is relatively large. Proglacial deformation in the sense of folds and reverse faults at these distances require very favourable conditions. Compressive deformation up to 9 km outside the ice margin has been documented on Iceland (Hart 1994). According to Boulton et al. (1999) long distance deformation is favoured in frozen (permafrost) sand-rich sediments. The respons to an aplied force would be rather plastical (Hart 1994). In Fritscheshof small-scale reverse faulting and some minor thrusting are present in the profile. The reverse faults are a result of an unequal melting of buried ice (tilting) while the thrusting corresponds to the shear stress applied by the flow tills. The gravel pit sediments as a whole seem to be deformed by folding corresponding to an applied force from the eastern sector, but with only a few exposed patches the observation is rather restricted. Spargelberg on the other hand represents large-scale ductile deformation, represented by overturned folds corresponding to an applied force from northeast. All above is compatible to the criteria for proglacial deformation in permafrost by the Mecklenburg readvance. However, no evidence of permafrost, e.g. ice-wedge casts, has been documented in this region. The absence of ice-wedge casts and other permafrost features reveal an uncertainty in the permafrost theory. Hence, without permafrost the distance is too large for deformation by the Mecklenburg readvance.

There is a possibility that the deformation occurred subglacially by a cold-based Pomeranian ice margin in Spargelberg and Fritscheshof since no basal till was documented. A problem is that permafrost conditions are required to produce the cold-based ice margin. However permafrost conditions could have been present only a short time, hence not producing any permafrost features.

An oscillating retreat of the Pomeranian ice sheet seems more likely to have deformed the sediments. The distance to the deforming ice is unknown, however, in this case the ice has been present in the area. Permafrost conditions are not necessary to preserve the stagnant ice during the short time span dealt with here.

In Kreuzbruchhof where the direction of deformation had opposite orientation the simplest explaination is deformation by a local ice-dome. The local ice dome developed through accumulation on the stagnant ice remnants of the retreating Pomeranian ice sheet. Local ice domes or marginal domes developed through accumulation on stagnant ice has earlier been used to explain anomalous ice movement directions by Lagerlund (1987), Lagerlund *et al.* (1995), Albrecht (1999) and Björklund *et* *al.* (2000). The sub-horizontal faults (in section KB3) interpreted as relaxation faults do not relate to permafrost. The short distance between Kreuzbruchhof and the two northern gravel pits would mean exposure to approximately the same air temperatures, and thus the same ground conditions. If applied to a theory that they were deformed synchronously it means unfrozen ground also in the two northern gravel pits, thus indicating that deformation during the oscillating Pomeranian deglaciation is more likely. Furthermore the preference of reverse faults instead of folds in the sand-rich sediments means brittle deformation, which can be used as an indication of unfrozen ground (Hart 1994). The reverse faults are relatively small and do not account for any large displacement. On the other hand normal faults in the upper part of KB1 may represent an active layer, in a position prominent to slope-failure. However normal faults are common in ice-decay landscapes due to melting of stagnant ice. The absence of compressive deformation the uppermost sediments (1-2 m) means that they probably not were deposited until after proglacial deformation.

If Kreuzbruchhof was deformed by an expanding local ice-dome there is a possibility that the same happened in the two northern sites as well. This would mean deformation by two separated local ice domes. However, the simplest explaination is in Fritscheshof and Spargelberg deformation by a retreating oscillating Pomeranian ice while the simplest explanation for Kreuzbruchhof is a local ice-dome. Furthermore no deformation is documented in Hinterste Mühle (Albecht in prep.), a gravel pit situated between Spargelberg/Fritscheshof and Kreuzbruchhof. This means that the two ice masses never were in contact, at least not in this area, and that the zone of deformation was rather restricted, which also could indicate unfrozen ground.

According to Lagerlund (1987) a high-pressure over the ice sheet would include the dead-ice area, due to the similar albedo. This would force the weather systems (low pressures, cyclones) to follow the extension of the high-pressure (Wallace & Hobbs, 1977) and the precipitation to fall in the marginal area, possibly resulting in accumulation both at the ice margin and in the dead-ice area. Hence, both readvancing of ice margins and expanding of local ice-domes would be favoured if precipitation increased.

This further support that proglacial deformation under unfrozen conditions is the most probable explanation for the deformation from NNE (in Spargelberg and Fritscheshof) by an oscillating Pomeranian ice sheet and from SW (in Kreuzbruchhof) by a local ice-dome. This hypothesis is relying on a synchronous reaction to a specific climatic signal.

Notable: The petrographical analyses resulted, when displayed in a Ternary-plot, in Saalian ages, with exception of the "Tertiary raft" derived sediments. The Saalian age does not correlate to the stratigraphic position they represent. Other investigations in this area with sediments of stratigraphically Weichselian age reveal the same Saalian age problem (Albrecht, 1993).
Grain-size analyses did only confirm the interpretations done during fieldwork, hence not displayed in this paper.

5 Conclusion

With reference to the descriptions, interpretations and the discussion above the following can be concluded concerning the sedimentation and deformation during the Late Weichselian in the investigate area (Fig. 1, 2):

- The glaciofluvial sediments, the small-scale synsedimentary faults and the topography of the landscape indicate development as an ice-decay landscape.
- The stratigraphical position of the sediments suggests deposition during the Pomeranian deglaciation (Fig. 1).
- During deposition the glaciofluvial sediments have been affected by glaciotectonic deformation from opposite directions (Fig. 2). Furthermore temperature indicators reveal unfrozen ground (absence of ice-wedge casts, presence of relaxation faults and the restricted zone of deformation), hence indirectly indicating a relatively short distance to the deforming ice.
- The opposite directions of deformation suggest a model consisting of two deforming elements. Deformation in the two northern gravel pits, Fritscheshof and Spargelberg, from NE-E is simplest explained by the retreat of an oscillating Pomeranian ice sheet. In the southern gravel pit, Kreuzbruchhof, a local ice dome would explain the direction of deformation (from SW).
- Since neither a subglacial till nor evidence of permafrost conditions have been found the deformation is suggested to have occurred proglacial.

6 Acknowledgements

Above all I wish to thank my supervisors Erik Lagerlund and Joachim Albrecht for all help provided in fieldwork and at the department especially the constructive discussions. Many others not mentioned by name have supported me during this work and to all of them I offer my sincere thanks.

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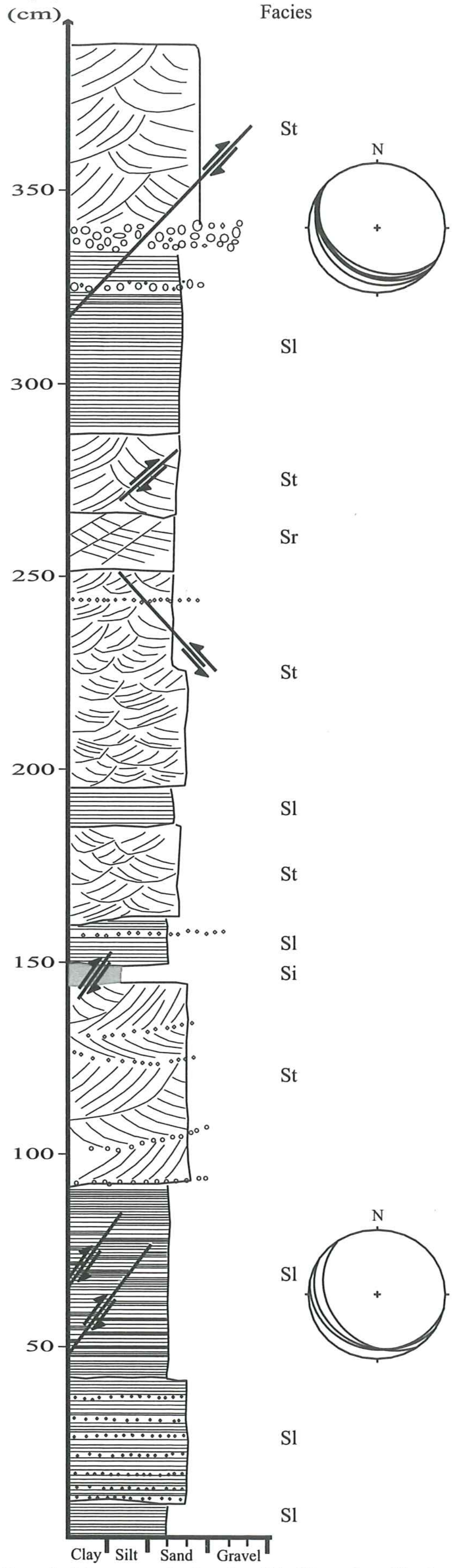
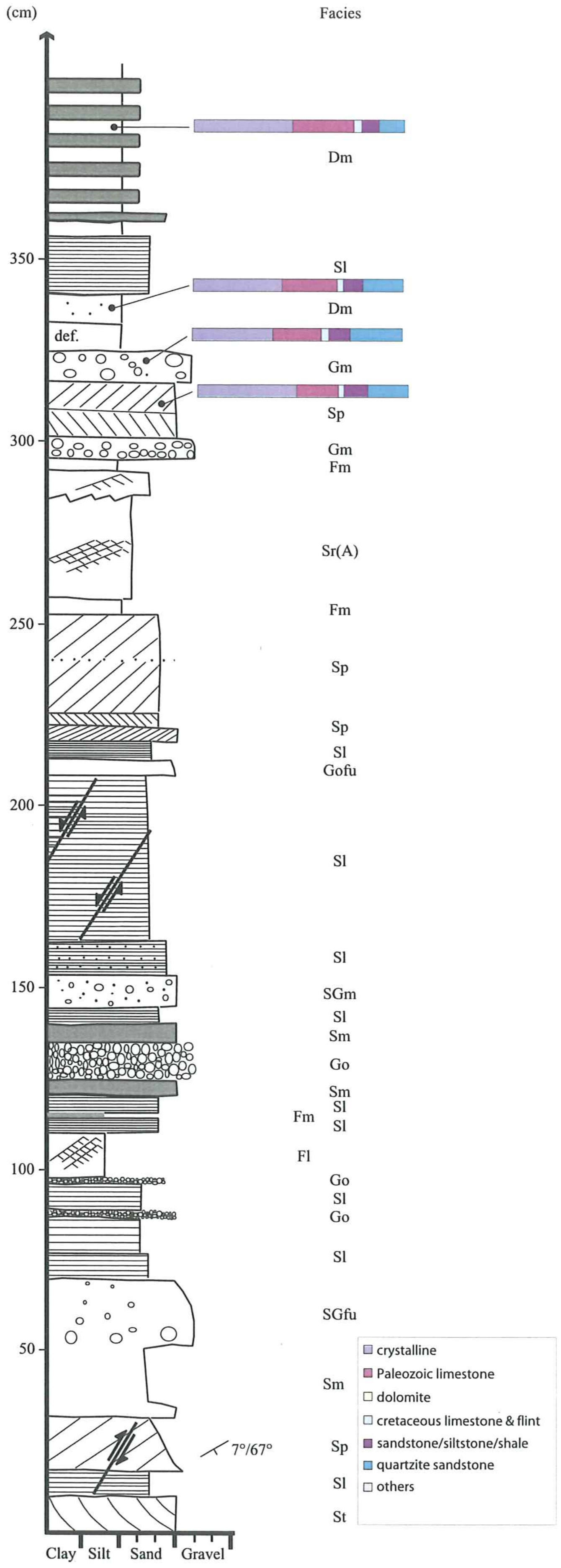
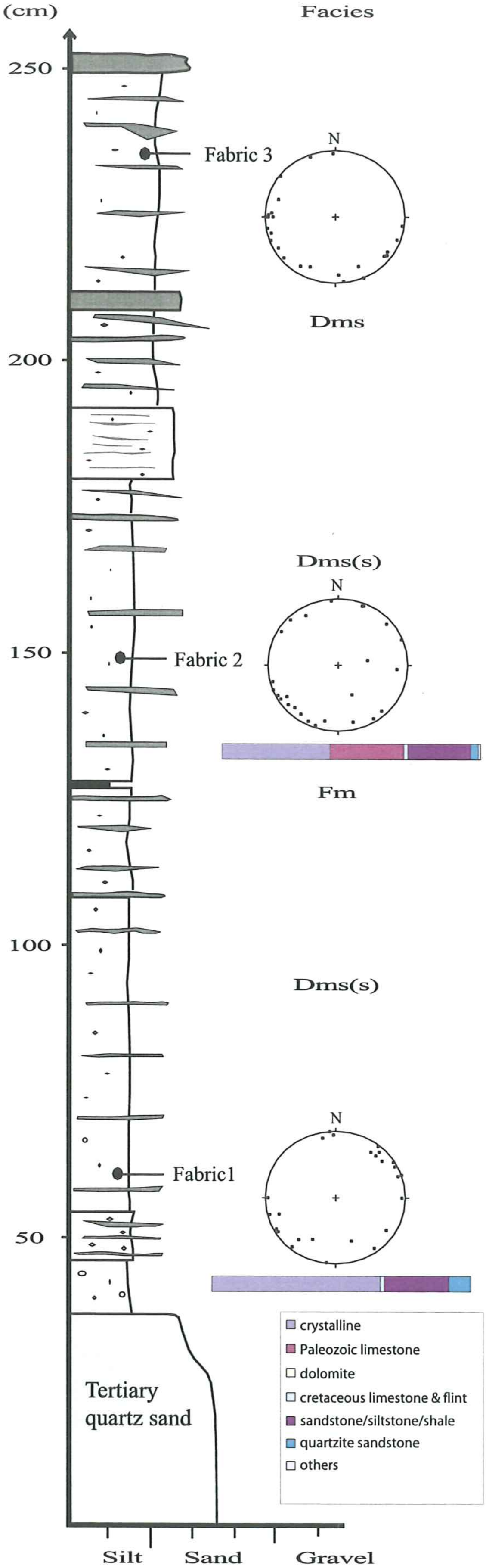
Appendix 1



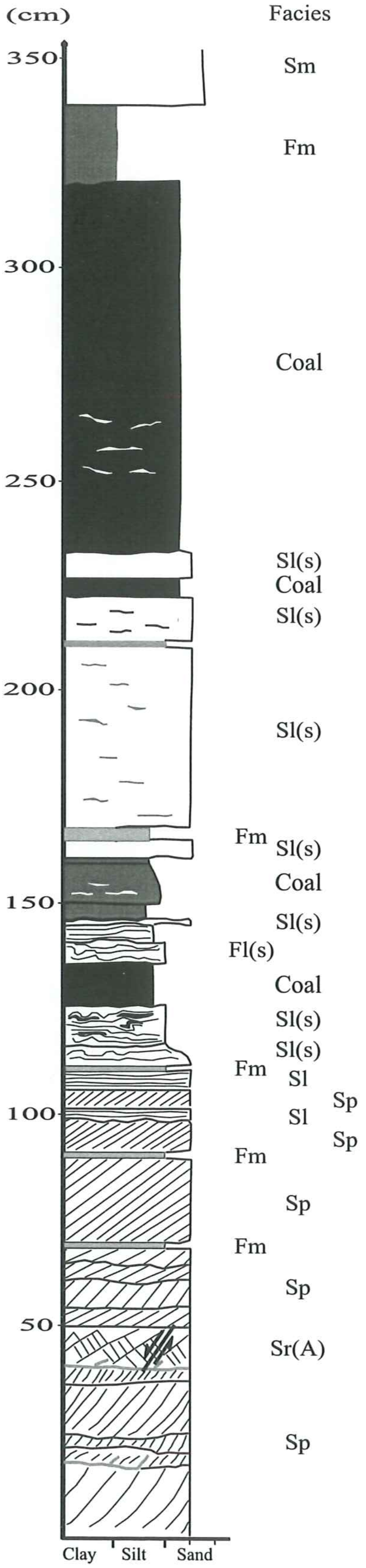
Log. 1. A log over the headwall in Kreuzbruchhof – KB2.



Log. 2. A log over the KB5-profile in Kreuzbruchhof.



Log. 3. A log over the sediments in Fritscheshof (at 62 m), where sampling and fabric analyses were carried out

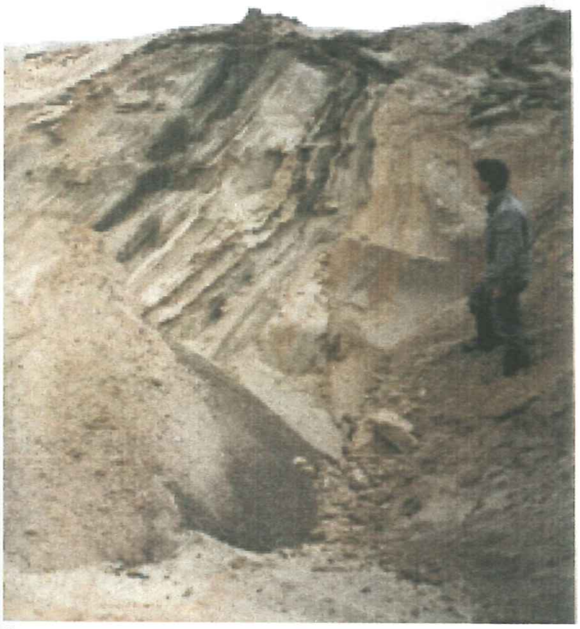


Log. 4. An average log of the coal-quartz sand contact below the folded sediments.

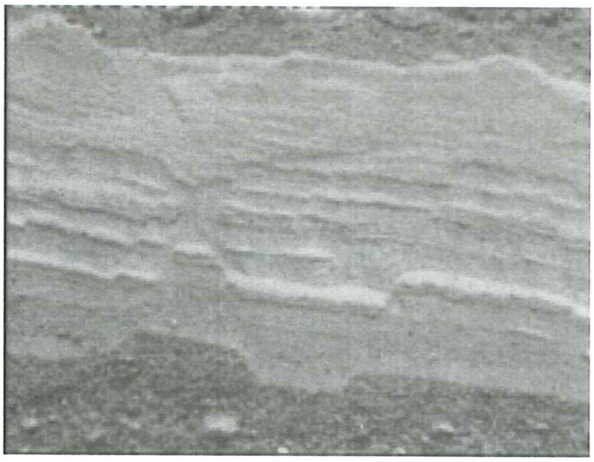
Appendix 2

1. Vertically standing sediments inbetween KB1 and KB2.

2. Reverse faults in KB2.



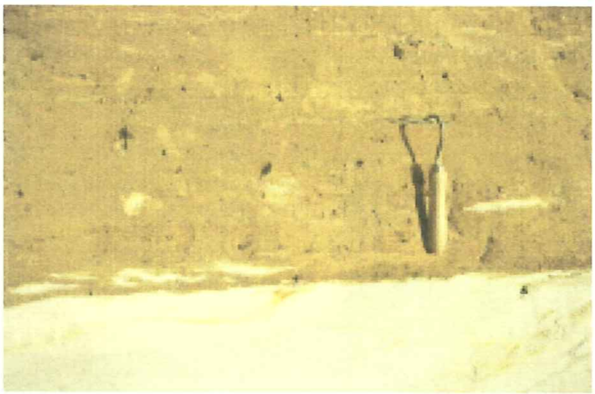
3. The overturned fold in Kreuzbruchhof – KB3.



5. Normal faults in KB5.

4. The overturned fold in Kreuzbruchhof – KB4.

6. The contact between the diamict units and the Tertiary quartz sand in Fritscheshof.

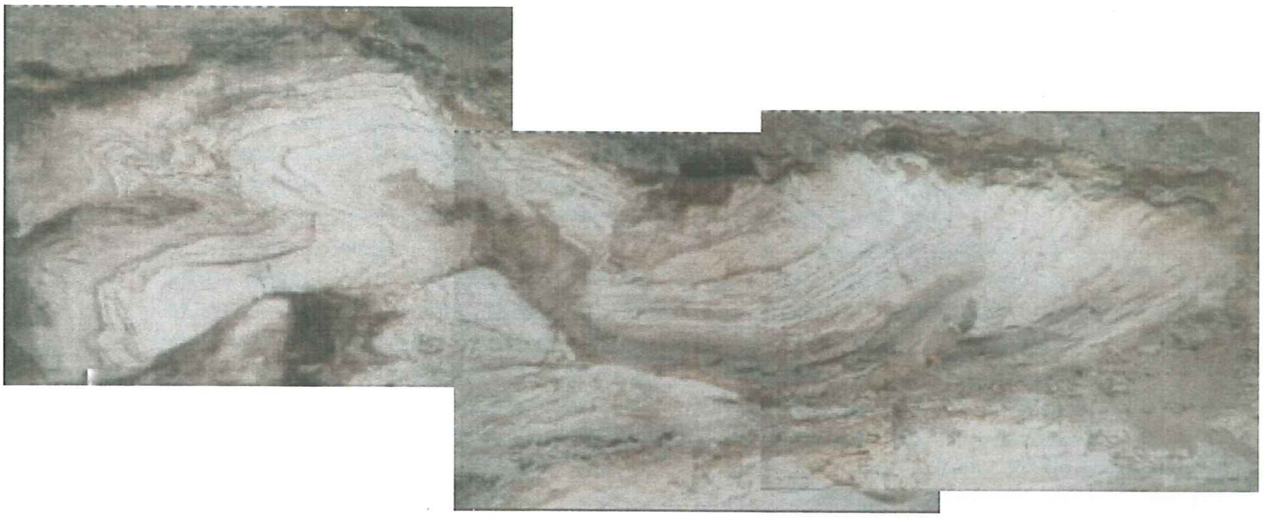


7. The erosive contact between diamicton 1 and the Tertiary quartz sand in Fritscheshof. The colour is not correct.

8. Internal structures in the flow tills in Fritscheshof.

9. Internal structures in the flow tills, diamicton 1 – Fritscheshof. The colour is not correct.

10. The deformation structures around the rotating clast in Fritscheshof. The colour is not correct.



11. The complex fold/reverse fault-structure close to the profile in Fritscheshof.

12. The folded headwall in Spargelberg.

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