Genesis of the Hondsrug A Saalian Megaflute, Drenthe, The Netherlands - aspiring Geopark

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Colophon

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Preface

UNESCO Geopark

This report is written as the scientific supplement to the application of the Hondsrug region (Drenthe, the Netherlands) to become an UNESCO Geopark. The genesis of the Hondsrug's peculiar glacial linear ridges is the core topic. That the ice-age produced geology and geomorphology controls ecohydrology of the modern landscape, and what relation deeper hydrological and geological elements have with the Hondsrug landscape in past and present are, other topics that are addressed. Any contemporary landscape is, of course, the result of a long series of various landscape forming processes, following up each other over time, and interacting through inheritance of substrate and morphology. Imprints of some phases, however, are more dramatic and last to dominate a landscape longer than others. In the case of the northern Netherlands, the penultimate glaciation was the event to last the majorly reorganise the landscape and the landscape of the Hondsrug is exemplary for that. The document serves to answer the question: Why do we need to protect this unique landscape for future generations, besides for its beauty? Labelling the Hondsrug area a UNESCO Geopark status will increase societal awareness for this unique landscape, and aid its protection. In the end, the level at which we understand the properties and history of our landscape determines how many functions society can give to the Hondsrug landscape without depleting it. Hereto, a brief description is given of how contemporary functions of the Hondsrug landscape are affected by the Hondsrug's genesis, particularly for integrated groundwater management in part agricultural, part nature conservational areas.

The Hondsrug Area

The Hondsrug area is located in the northeast part of the Netherlands, in the province of Drenthe [Figure P.1]. This lowland area contains marked linear geological-geomorphological features – NNW-SSE orientated and many tens of kilometres long – which were formed by fast flowing ice over the area, by a so called an ice stream (e.g. Van den Berg & Beets, 1987; Bennet and Glasser, 2009), during a particular phase of the penultimate glaciation (Saalian, Drenthe Substage; within MIS-6, Gibbard and Cohen, 2008), when the Scandinavian ice sheet had expanded to cover the North of the Netherlands. The linear features have a complex build up of till and megafluting-reworked glacial and preglacial substrate, produced by the Hondsrug ice stream, towards the end of the glaciation, ca. 150,000 years ago. During the last glacial (Weichselian), the ice sheet didn't reach as far south as in the Saalian before. The Hondsrug glacial morphostructure has been affected by erosion in the youngest 150,000 years (notably in brook valleys), but in the lowland

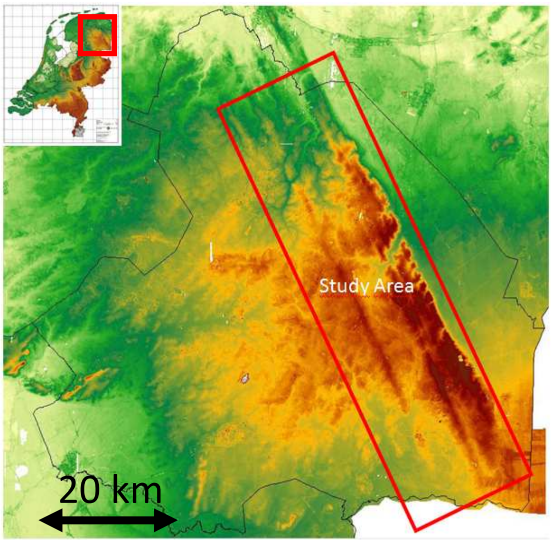

Figure P.1 DEM map showing location of the Hondsrug. *Source*: Dutch Ministry of Infrastructure situation in the vicinity of the North Seam this was localized alteration only, pronouncing rather than destroying the structure, and leaving the Hondsrug glacial landscape relative intact. This allows to study almost pristine sediments of a former ice stream and trace these over substantial distance, unlike in other parts of the European Ice Marginal Landscape (IML), where very similar processes are reasoned to have operated, but where glaciological information has since been lost, because these areas are further inland and closer to the Scaninavian ice sheets and therefore more erosion prone. Because ice streaming has been a common process in the former glaciated landscapes, geologically important (reshaping landscapes) and glaciologically-climatologically important (rapid collapse of margins of ice sheets), they have received attention in many studies.

The Hondsrug former ice stream is considered of great importance for such studies. By studying the contact zone between pre-glacial sediments and glacial sediments, insight in the formation conditions of the complex of till ridges can be deduced, such as the basal glacial regime and basal water pressure (i.e. subglacial hydrology). The Hondsrug linear ridges marks the western side of their forming ice stream. The source area for the streamed ice is sought in to the NNW, in the present North Sea and the terminal zone to the SSW, towards the Münster Basin. The study is not limited to the Hondsrug area itself, but includes source and termination region, and the full width of the ice stream affected area in between: partly in the Netherlands, partly in adjacent Germany. We want to answer questions regarding ice stream initiation, the factors that controlled its position, and the factors that control its behaviour. Building on earlier studies, we present a new genetic model for the Hondsrug Ice stream. We reason the ice stream to have been sourced from ice nearby over the North Sea and from over the Hondsrug area itself, while the Münster Basin to the south is seen as the main depositional area. We propose that the ice stream is triggered by subglacial overpressure of basal meltwater in the source area due to a higher heat flow density (HFD). A (co-triggering) mechanism is found in reorganised ice-marginal drainage in areas adjacent to the Münster basin terminal area, notably the breaching of Lake Weser (c.f. Winsemann *et al.* 2011).

This study could not have been done without cooperation of others and financial support of the Province of Drenthe and the Geopark Hondsrug organization. Grateful thanks are to dr. K.M. Cohen (Utrecht University/Deltares) for discussions and editorial comments; contributions of dr. M. Bakker (Deltares; GPR data); dr. I. Lüse (Latvian University; clay mineral analyses); and H. Huisman for his photographs, interpretation and description of till types on the Hondsrug-complex and a pleasant communication.

Specific thanks are to prof. dr. J. Winsemann (University of Hannover) for discussion about the impact of the breach of Lake Weser; prof. dr. J.A. Piotrowski (University of Aarhus) for discussion about the glacial model and impact of reversed groundwater flows; dr. J. Ehlers for discussion about tills; dr F. Magri for contribution of geophysical and hydrological data data and students (F.W.H. Smit; H-J. Pierik; A. van Hoesel; M. Jansen; A. Klootwijk; M. van Kammen; R. Kleefstra) for data collection and discussions during fieldwork.

At the time of writing, the overview of knowledge on the unique landscape of the Hondsrug expressed in this report, is being shared with the ice age museum of the area (Hunebed Center Borger). This is exactly in the spirit of EUROPEAN GEOPARKS: to share knowledge of geoheritage to a broader public, to local inhabitants, to tourists and other visitors, young and old, from the Netherlands and from abroad. I hope this study will further contribute to that aim.

Drs E.P.H. Bregman
Assen, 22 august 2012

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1. Introduction

1.1 Framework of the research

This report is based on a study of the glacial geological and glaciological history of the Hondsrug area [Figure 1.1], which is formed by a Late Saalian ice stream (MIS 6) (e.g. Van den Berg & Beets, 1987). Ice streams are corridors of fast ice flow within an icesheet (ca. 0.8 km/yr; Bennett, 2002) or at the margin of icesheets, which are well studied and known from Antarctica.

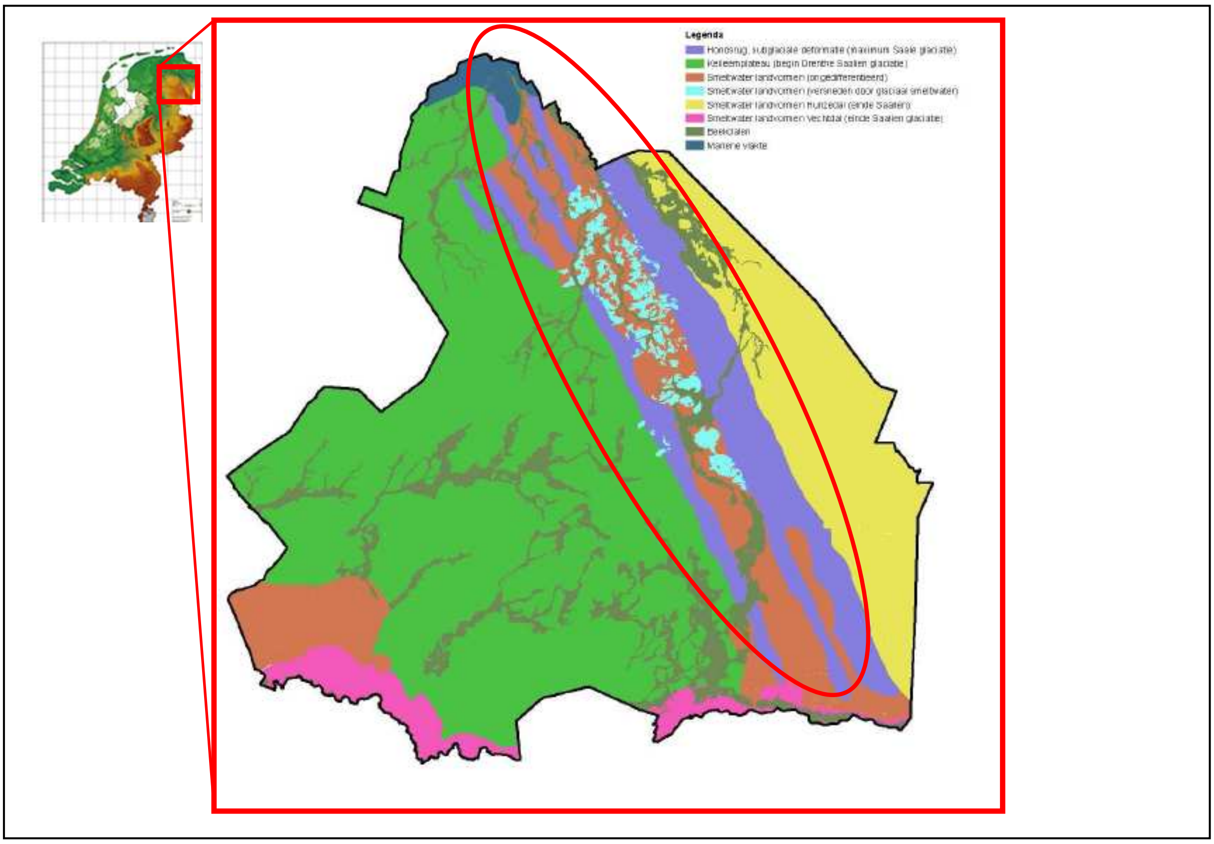


Figure 1.1. *Geomorphological Map of Drenthe (2010): main landscapes.. The till ridges of the Hondsrug area are well pronounced in the eastern part of the Province of Drenthe (pink color) because of NNW-SSE direction that forms the Hondsrug complex. Near surface presence of Elsterian deposits (blue color): infillings of buried glacial valleys. Lower laying areas(brown color): rather peaty areas due to occurrence of impermeable boulder clay. (Source: Alterra, New Geomorphological map of Drenthe, Assen, 2010).*

The occurrence of ice streams in the margins of ice sheets is an expression of the imbalance between accumulation and ablation in ice sheets and are highly variable and dynamic in space and time. Numerous contemporary ice streams have been studied, and show behavior that can be characterized by episodic activity; acceleration; deceleration; migration and changes in ice-flow direction (Winsborow, 2010). In ice sheet margins, they control the mass balance because they set the rate of melting (bringing more ice beneath the equilibrium line) and provide more ice to calve off from the margins of ice sheets into ice lakes, seas and oceans. Knowledge about controlling factors and (thermodynamic) feedback mechanisms (Stokes and Clark, 2003) of actual ice streams is growing, but on the contrary, less process-related studies of palaeo-ice streams onshore exist and most of them are in North Western Europe and Weichelian in age.

The focus of this report is the investigation of the mega-scale lineations of the Hondsrug area, but is extended to the glaciological context of the area and therefore the ice marginal Saalian (MIS 6; ≈150 kyr BP) Hondsrug – Hümmling Ice stream as a whole is investigated too. Undisturbed glacial landforms left by Saalian ice streams are very rare in northwestern Europe, because of overprinting by Weichselian ice streams, except in the Netherlands and Northwestern Germany. The best expression is the 60 km long and 4 km broad lineation of the Hondsrug. In concern to the ridges itself, the focus point is a glaciological/sedimentological description of the contact surfaces between pre-glacial sediments and glacial sediments.
Because of the unique genesis, the Hondsrug area is nominated by the Province of Drenthe as a UNESCO-Geopark (figure 1.2).

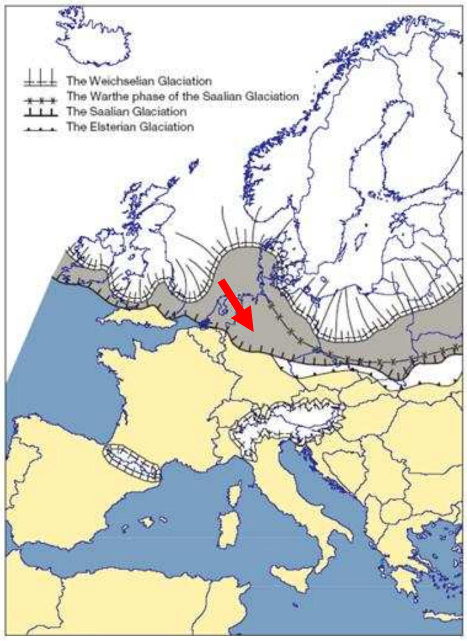


Figure 1.2 The glacial limits from the Pleistocene glaciations. Red arrow shows Hondsrug Ice stream position. From Plant *et al.* (2005).

1.2 Geological setting

1.2.1 Large-scale geological context

The Hondsrug area is situated at the edge of the North Sea Basin which is characterized by a large variety in substrates and morphology, mainly due to differences in tectonical settings. Because of this, the relief of the Province of Drenthe, with highest points at the Hondsrug, generally reaches a larger height in the eastern part and is lower and more gentle dipping in the northwest and southeast.

Ongoing subsidence caused deposition of thick sets of Tertiary marine and Pleistocene fluvial unconsolidated deposits (Westerhoff *et al.*, 2003). Most of these tectonical structures were reactivated during the Tertiary (Van Balen *et al.*, 2005). The central Dutch basin (including the Zuiderzee Basin), the Lauwerszee Trough and the Lower Saxony Basin became the locus of subsidence. The Texel-IJsselmeer High, the Groningen High and the Peel Block are stable highs. A very tectonically active region occurs around the SE-NW trending Peel faults (Geluk *et al.*, 1994). Tertiairy and (Neo) tectonic activities are not recorded in the Northern part of the Netherlands (Van Balen, *et al.*, 2005), whereas Frikken (1999) states that this complex interplay of dominantly NW-SE oriented wrench tectonics has been active from Carboniferous times to the present. Main deep geological faults connected to the Hondsrug direction are the Hangtum graben system related to the Louwerszee Trough and the Holsloot fault zone. Rotational displacement caused antithetic Riedels ("open wrench faults") with significant strike-slip components (up to 750 m) besides significant dip slip components (up to 400 m; Frikken, 1999). The relevance of these tectonic structures is that – in our study area during the Pleistocene (as do now) – relative high amounts of open faults existed which could have been activated due to the large shear stresses induced by vicinity of the Hondsrug area with respect to the forebulge [Figure 1.3]. The extensional forces that occur at the top of the forebulge due to an advancing glacier or due to unloading after the retreat of the ice mass, will lead to a decrease in friction in the existing faults and might lead to displacement of block structures and other faults or create new faults (e.g. Lund, 2005). Several authors have shown that this is a common feature in the ice marginal landscape. Szeder and Sirocko (2005) and Lehné and Sirocko (2004) demonstrated the impact of glacio-isostacy on morphology in the Hunte valley, west of Bremen and Sliaupa, 2007 for example showed how river patterns in Lithuania are related to differential uplift. Cohen, 2003, 2010 has shown the impact of glaciations on the Rhine - Meuse delta at the distal part of the (Weichselian) forebulge, whereas our studies focusses on the proximal part. So far no studies are done at the distal part of the forbulge in the Netherlands.

1.2.2 Salt diapirs

Salt diapirs are present in the Hondsrug area as well, which were formed mainly during the Late Jurassic and Early Cretaceous from Late-Permian Zechstein salt (Baldschuhn *et al.*, 2001; Sirocko *et al.*, 2002). These salt structures are present in large parts of northern Holland and NW Germany at shallow depths (up to 100 m below the surface). The presence of salt domes may have influenced forbulging in front of the advancing glaciers due to their relative rigidity compared to the surrounding unconsolidated sediments. In addition, they probably created some undulating relief in the pre-glacial landscape due to updoming. It was in the areas where salt diapirs were located close to the surface, that large-scale glacial erosion occurred to the pre-glacial sediments. Increased glacial erosion above the saltdomes of Anloo and Schoonlo could be the reason why Elsterian sediments are thinner (*et al.* de Gans, 2010; Kips and van Olm, 1978; Bregman, in prep).

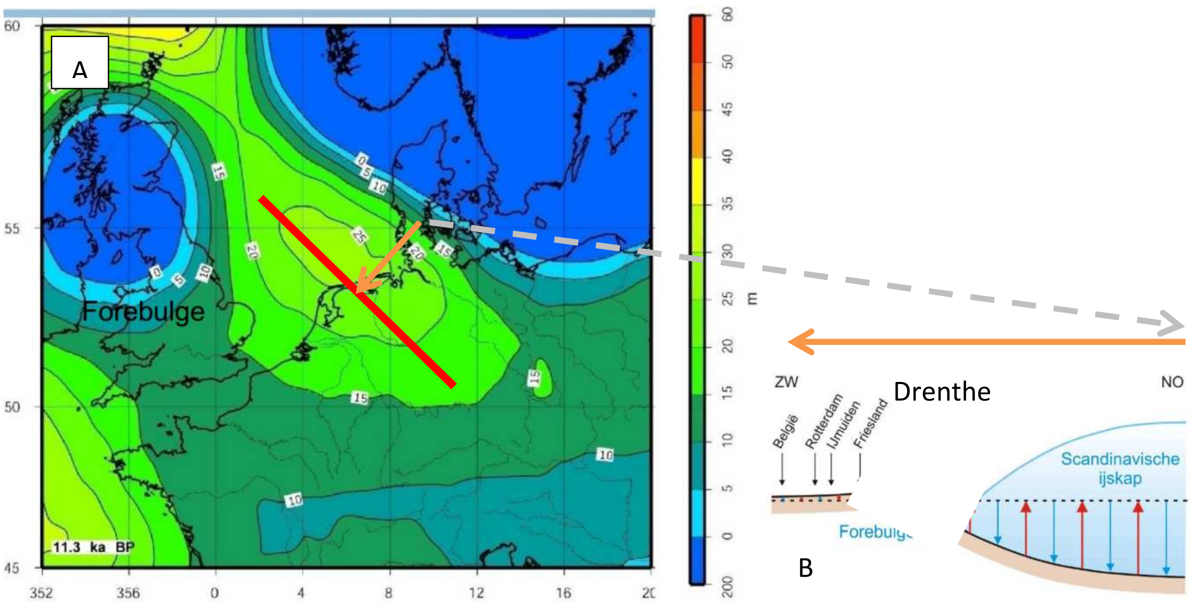


Figure 1.3. *(A,B) Positioning of Drenthe on the forebulge 21 kyr ago (Steffen, 2006). The situation presented, concerns the change of earth surface by ice pressure (B) with uplift and top near the northern of the Netherlands. However in Weichselian land-ice did not reach the Netherlands. In Saalian maximum extension was in the middle of the Netherlands. Forbulge lay somemore to the south. We suppose for that reason that the top of the of the forebulge was positioned in the middle of south of Drenthe.*

1.2.3 Shallow substratum

In the northern part of Germany, the eastern part of the Netherlands and the adjacent areas north of the Variscan heights, Tertiary (Miocene) marine clays and fine sands are present which were deposited in actively subsiding parts of the North Sea Basin. They form a continuous hydrogeological base (Van den Berg & Beets, 1987). The total thickness of these sediments varies from over 1000 m near Hamburg to ±400 m in the area of Drenthe. The major part (75 %) of the infill of the North Sea basin consists of deposits from Late-Tertiary, Early and Middle Pleistocene river deposits. The largest part originates from the 'Baltic' or 'Eridanos' river system (Bijlsma, 1981; Overeem *et al.*, 2001). They consist of coarse white sands (90% quartz) and typically have a very high permeability (Van den Berg & Beets, 1987). These 'Eridanos' deposits are in Drenthe covered by sediments from a minor ice-marginal river system, which deposited coarse and very coarse highly permeable sands (Westerhoff *et al.*, 2003).

In the northern part of the Netherlands and in adjacent northern Germany deep glacial tunnel valleys are present. They were formed during the Elsterian (MIS 12; 475-410 ka), which is the oldest extensive glaciation in NW Europe and land-ice reached the Hondsrug area as well. They originate from immense episodic subglacial melt water discharges, which scoured deep into the substratum. These generally overdeepened (the depth is lower than lowest base level drop) features may reach down to 400 m below MSL in the area around Hamburg (Ehlers, 1990). After the scouring event, sedimentation occurred and most tunnel valleys are mainly filled in with varved silts and clays known as '*Lauenburger Ton*' (Lauenburger Clay) in Germany (Kuster & Meyer, 1979) and '*Potklei*' - Peelo Formation in the northern Netherlands (Ter Wee; 1979; Bosch, 1990; Westerhoff *et al.*, 2003; Figure 1.4). The upper part of these deposits consists of fine sands with mica (Ter Wee, 1979; Bosch, 1990). They form a hydrological barrier of very low permeable sediments in the pre-Saalian subsoil in the northern part of the Netherlands (Van den Berg & Beets, 1987).

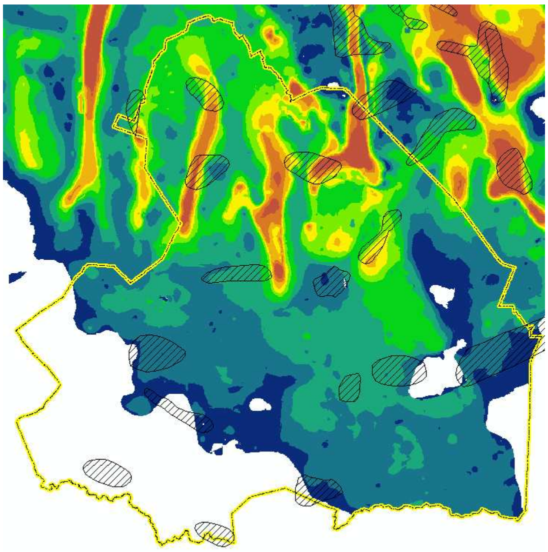


Figure 1.4. *Overview of Elsterian deposits in the northern part of the Netherlands with Buried Glacial Valleys, BGV's (brown color) The shaded areas indicate saltdomes. BGV's are sometimes superimposed on saltdomes, as in Drouwen and Anloo at the Hondsrug area. (Source: DINO, TNO)*

At the time the Saalian ice reached the area where Elsterian depressions occurred, they had most likely already been filled up to a large extent to the regional ground water level by lacustrine and fluvial deposits. This implies that the relief, at least in Northern Netherlands and so part of the Hondrug area near Borger and Anloo must have been relatively smooth (cf. Van der Wateren, 1985; Van den Berg & Beets, 1987). This is supported by the absence of Elsterian ice-pushed ridges, but as is shown in Figure 1.5, in some parts of the province of Drenthe Saalian ice streams eroded the surface (e.g. at the location of the Odoornerveen, southwest of Borger.

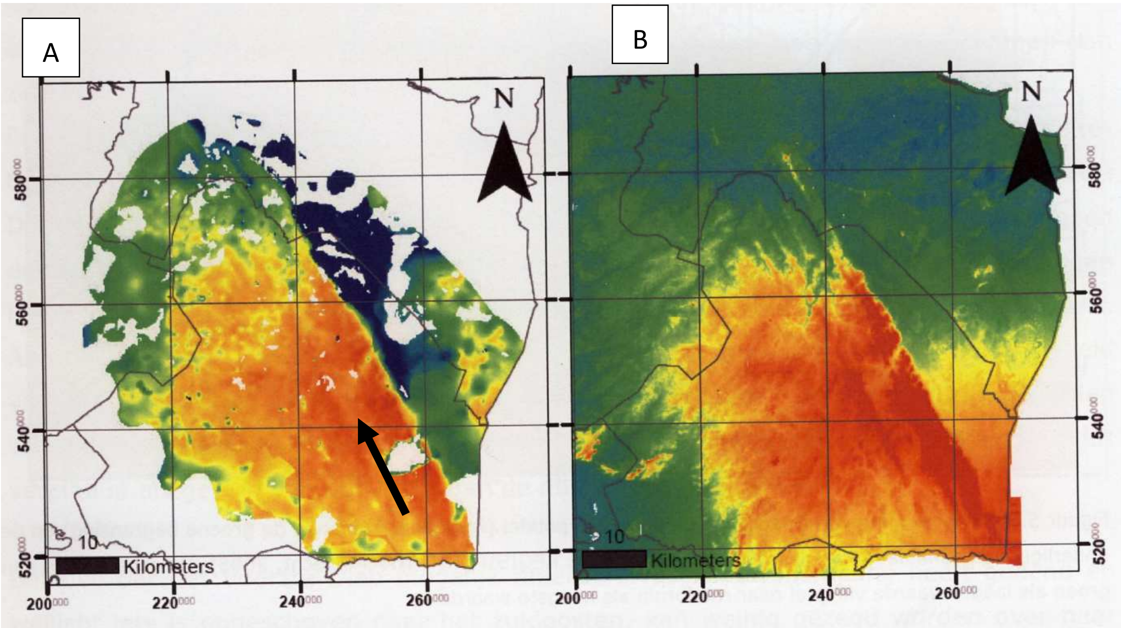


Figure 1.5. *A indicates the top of the Peelo formation in Drenthe (REGIS II). Fig. 1.5B represents the relative altitude in Drenthe (RWS-AGI, Delft, 2005). Comparison of the two maps indicate in the north and most eastern part of Drenthe a lower top of the Peelo formation, caused by respectively Saalian subglacial erosion and erosion discharge of meltwater. In the Hondsrug area Peelo formation is surfacing (Figure 1.1). The top of the Peelo formation is also subglacial eroded in the Hondsrug area, east of the Rolder/ Sleenerrug (most western ridge in fig. 1.5B).*

The Rhine river formed river terraces during the Early and Middle Saalian, but these were subsequently filled up by proglacial Rhine sediments that have a widespread occurrence in the Netherlands (Busschers *et al.*, 2008). On the southern edge of the maximum Saalian land-ice extent, deeper geological obstacles are present: Pierik, Bregman & Cohen (in prep.) supposed that the Peel horst, with a NNW-SSE orientation, formed an obstacle to reversed groundwater flow (cf. Maarleveld *et al.*, 1958) in front of the advancing Saalian ice streams in the central parts of the Netherlands (this report; e.g. Piotrowski, 2008), which also formed the most southern Dutch push moraines. In the northern part of the Netherlands, we suppose that main obstacles for Saalian ice streams are more or less similar to the southern part of the Netherlands and also related to the positioning of geological structures, e.g. the positioning of the Texel IJsselmeer High, salt-ridges and salt-domes.

In the last part of the Saalian, parts of NW-Europe were covered by ice-sheets from Scandinavia. The ice extended further southwest into the Netherlands than ever before or after. It left high push moraines and deep glacial basins in central Netherlands and in the north, in Drenthe, it left a till sheet of complex build and morphology. These ridges are the result of an ice stream event at the end of the Saalian-Drenthe substage. During this phase there was an active ice stream flowing from the North Sea towards the southeast and the Hondsrug area was only a small part of the area covered by an ice stream: the Hondsrug – Hümmling Ice stream.

1.2.4 Hondsrug area

Although the influence of the ice stream continues towards the area of Münster, the main area of interest in this report is the Hondsrug-area (Figure 1.6). It has a SW dipping gentle topography with ridges in the Hondsrug area that are most pronounced towards the NNW – SSE with a length of 60 km (Groningen to Nieuw Schoonebeek) and climbing height from 2 - 24 m in the SE part, with the highest point near Weerdinge. The higher elevation of the ridges in comparison to its surroundings is the result of a sandy subsurface geology and glacial deposition of tills, whereas lower parts in between the ridges seem to be eroded. This is the conclusion of a study of the topography of Elsterian deposits, which upper boundary is located significant lower in the Odoornerveen area between the Hondsrug and the Sleener- or Rolderrug.

In contrast to the central part of the Netherlands, the late-Saalian glaciation has not left pronounced push moraines in Drenthe. The smooth topography of the till plateau is thought to be the result of a continuous overrun by a glacier, without a significant standstill (Van den Berg & Beets, 1987). Meltwater production was insufficient to create channels in front of the advancing glacier, and subglacial meltwater was discharged by groundwater flow.

The Drenthe till plateau is restricted to the area where it is not covered by marine clays (Rappol, 1987). The till thickness varies between 1 – 5 m and in (former) river valleys it may be absent, but is evident from boulder accumulations and stone pavements. Only in the southwestern part of the till plateau, till thickness is much larger, partly due to pushing. The push moraine Havelterberg (19 m above m.s.l.) has been formed by an ice stream from an older advance of the ice-sheet than the Hondsrug-Hümmling ice stream with a NE – SW direction.

As a result of different directions of ice flows, two main orientations can be identified and seen on the topographic map: NE-SW orientated forms in the SW of Drenthe and NNW-SSE orientated ridges of the Hondsrug complex. These orientations reflect the different directions of ice-movement across the Drenthe Plateau (see also paragraph 1.5 for further explanation). The different directions of till ridges determine the drainage patterns of the rivers. The (former) rivers have further increased relief by eroding the valleys, a process which is influenced too by differential postglacial rebound resulting in the central part of Drenthe a radial drainage pattern which influences too the drainage pattern in general, leads to a shift of the Drentsche Aa brook valley system to the north and formed terraces in the same area (e.g. de Gans, 2010; Bregman, b, in prep.).

Four major SSE-NNW trending ridges are observed and named subsequently from NE to SW (Figure 1.4):

1. The Hondsrug
2. The Tynaarlo ridge
3. The Rolder Ridge or Sleener Ridge in south of Drenthe
4. The Zeijen ridge

Although the Hondsrug (1) may occur as one ridge as seen from the topographic map, it actually consists of two ridges: an Eastern ridge and a Western Ridge. Till sequences are very different between these two ridges and this will be highlighted in the Gieten outcrops. Striking to the eye ridges seem to disappear in the northern part of Drenthe, although very thick sequences of till can still be found here which are much thicker than generally observed on the Hondsrug. This is explained by different phases of the Hondsrug- Hümmling Ice stream flow around the region of Groningen and Haren. Re-activation of the ice-movement and fast flow led to large scale erosion of deposits whereas in other parts tills are less eroded. As a result till is locally thicker or absent with great variations (3-4m on Hondsrug-complex vs. >7m at Haren). SE of Nieuw Schoonebeek till dips in the former valley of the Vecht and the Itterbeck Basin and is also > 7 m thick.

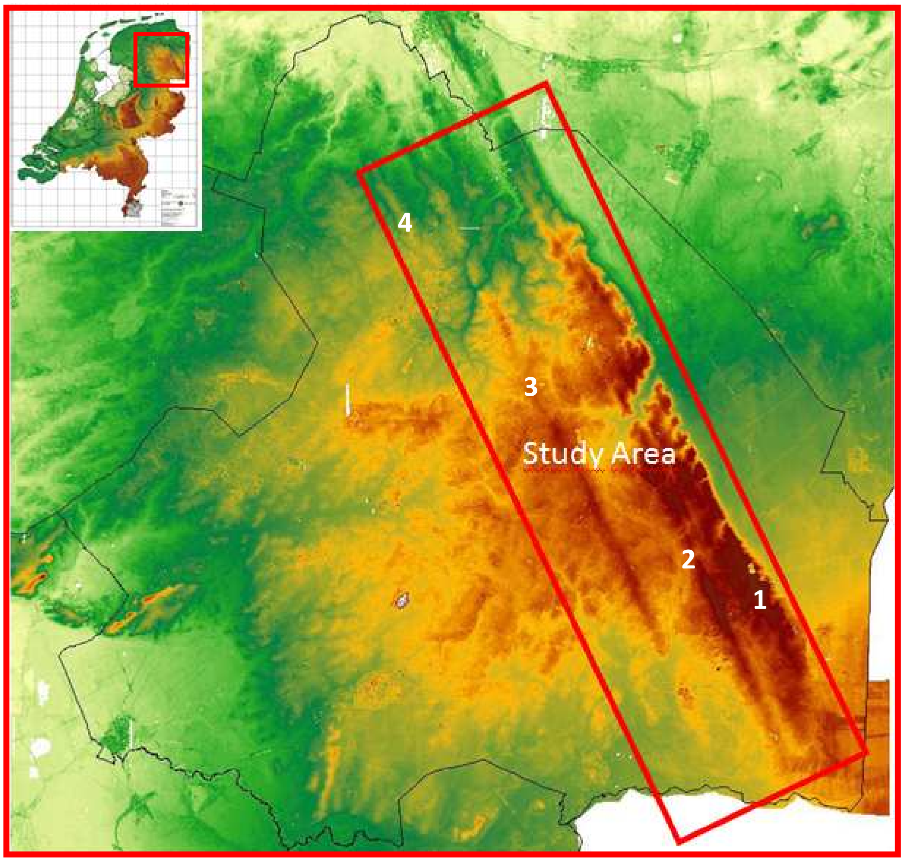


Figure 1.6. *Area of interest during this study (Source: DEM of the Netherlands, Rijkswaterstaat 2005). Shown ridges are: 1) The Hondsrug, 2) Tynaarlo Ridge, 3) Rolder Ridge, 4) Zeijen Ridge*

The largest obstacles for the advancing Hondsrug – Hümmling Ice stream were high ridges of the Weserbergland (Teutoburgerwald and the Wiehengebirge in Germany) composed of Jurrasic limestones and mudstones which had impact on the flow direction of Saalian ice streams in the Hondsrug area. South of the Weserbergland the ice-front reached in the area of the Münsterland and Ruhrgebied its maximum extent.

1.3 Aim of research

The Hondsrug is formed by a NNW-SSE oriented ice stream. Our main aim is to reconstruct the genesis of the linear ridges by a detailed glacial geological and glaciological study of the area. A second step is extrapolation of our insight, to predict how the ice stream could have been initated. The last step is to reconstruct the behavior of an onshore ice stream, which is a function of ice-marginal processes (glaciological processes sensu stricto), climate (externally triggered glaciological responses of the ice-margin), substratum, and deeper geological structures. We do this on the basis of the Hondsrug-Hümmling Ice stream, within the context of the northwest European history of glacial landscapes.

We focus on the Hondsrug till complex as a collection of genetically related sediments and subsequently zoom into outcrops which show contact surfaces between glacial and pre-glacial sediments, in order to get insight in the basal contact pressure at the time the sediment was deposited. If the sediment is intensely deformed, the effective pressure was very high (and basal water pressure low), whereas no deformation indicates a lower effective pressure (high basal water pressure) and basal sliding may have occurred. No deformation could also be the result of a frozen subsurface (permafrost) below the ice stream. In this fashion some relationships between glacial geology and glacier behavior laterally across the Hondsrug complex may be described. This will give a more detailed insight in the overall behavior of the ice stream.

The glacial geological concepts are based on modern glaciological observations on Antarctica and Svalbard and from late-Weichselian (≈25 ka) sediments from former glaciated areas such as eastern part of Denmark. These studies describe sub-glacial processes that determine sedimentation, deformation and erosion and the impact of the glacier on morphology. Following the chapter of observations, descriptions and interpretation of the outcrops, we use this information to try to find patterns along the longitudinal direction of the Hondsrug-complex. By doing so, we can deduce laterally varying ice stream behavior. Next we zoom out to the Hondsrug-Hümmling Ice stream to get an overview of behaviour of the ice stream as a whole.

1.4 The Hondsrug-Hümmling-ice stream in general

In the last part of the Saalian, parts of NW-Europe were covered by ice-sheets from Scandinavia. The ice extended further southwest into the Netherlands than ever before or after. It left high push moraines and deep glacial basins in central Netherlands and in the north, in Drenthe, it left a till sheet of complex build and morphology. These ridges are seen as the result of an ice stream event at the end of the Saalian-Drenthe substage. During this phase there was an active ice stream flowing from the North Sea towards the southeast and the Hondsrug area was only a small part of the area covered by this stream.

Several authors, whose work will be described in paragraph 1.7, have made glaciation models which tend to describe how the ice stream behaved and how deposition occurred. We compare the newly acquired data with these glaciation models and propose a new glaciation model of the Hondsrug area. Modern glaciological studies on ice streams in Antarctica and Svalbard have shed light on the characteristics of ice streams and the mechanisms that control the flow (e.g. Winsborrow *et al.*, 2010) and will be discussed in Chapter 6 in relation to our conclusions.

The knowledge of contemporary glacial processes occurring under ice streams and ice-sheets is the key to the past to reconstruct Pleistocene glacial impact on the landscape and to understand postglacial processes. With the use of SRTM (Space Radar Topographic Mission) DEMs, regional scale palaeo-glaciological reconstructions can be made (e.g. Boulton, 2002; Kleman *et al.*, 2006; Clark and Stokes, 2003; Bennett and Glasser, 2009; Pierik, Bregman & Cohen, in prep.). In addition, the glacial sedimentary record provides extra information on basal regime and forms an extra control point in these reconstructions. Techniques like Ground Penetrator Radar (GPR; e.g. Bakker, 2004), XRPD analyses of clay minerals and the study of sedimentological structures - as used in this study - provides additional small-scale data to more classical data (e.g. clasts; stress analyses). They provide information about deeper structures (deformation- or erosion) and the direction of flow of ice streams. Offshore palaeo-reconstructions are mainly based on mega-scale geomorphological mapping based on remotely sensed data, 2D and 3D seismic records, multi-beam bathymetric- and log-data (e.g. Andreassen *et al.*, 2009; Winsborrow *et al.*, 2010b)

Contemporary studies of basal sediment deformation, provide a toolbox to translate glacial sediments back into palaeo-glaciological processes (inversion). With the effort of these modern glaciological studies, several characteristics of ice streams (Boulton *et al.,* 2001) have been deduced. Ice streams are for example fast-flowing ice-bodies, are typical 10-100 km in width and several hundred kilometres in length, and are separated by low-velocity zones. They leave behind highly convergent and divergent flow patterns on the sub-surface. Ice streams can fan out in 2 settings: 1) calve out into sea, thereby releasing large amounts of glacial debris: high calving rates increases the ice stream velocity by a drag force and 2) fan out in a terminal zone of a coastal plain which creates strong divergent patterns.

The behaviour of ice streams is studied extensively on Antarctica and Svalbard. This has led to the insight that ice streams can be initiated and terminated in several hundreds of years and merging or capturing of ice streams can happen readily over short periods of time (<100 yrs). Even though upstream of an ice stream may be relatively stable, termini may shift laterally in an unstable fashion over several hundreds of years. This illustrates the highly dynamic character of these fast-flowing ice bodies.

One has made a distinction between ice-surges and ice streams based on the temporal scale of their lifetime. An ice-surge is a relatively short lived feature (<10 yrs) that happens several times during an ice-age. In contrast, ice streams in ice-sheets tend to be more stable over an ice-age and surge over longer periods. Because of the positioning at the margin of the Scandinavian ice-sheet, the Hondsrug-Hümmling Ice stream can be classified as a marginal ice stream. Marginal ice streams do have relative high velocities, and have dynamic character and can even cross older ice streams as has been shown by a many glacial geological studies (Winsborrow *et al.*, 2010, 2010a; Kleman, *et al.*, 2007; Stokes *et al.*, 2005) .

1.5 Scientific revivals on the Hondsrug-complex

1.5.1: 1880 – 1900 Prof. F.J.P. van Calker: The Hondsrug as an end-moraine

During a time span of 20 years, the author published several papers on the origin of the Hondsrug. By means of fieldwork around the village of Groningen, he found large boulder accumulations and glacial deformation in the subsurface. He concluded that the Hondsrug must be a pushed end-moraine formed by a long lasting stagnation of a glacier (van Calker, 1901). This would have created the pattern of lineations.

Lorié (1891) visited the Hondsrug at the locality of Schoonoord, where he studied peat-mosses. After exploration of the sedimentary succession, he concluded that it could not be a terminal moraine. He suggested that the Hondsrug was the border of the Till Plateau, and that the NE – retreating glacier folded back the sediments to form the ridges.

1.5.2: 1902 – 1907 Prof. E. Dubois vs. Dr. H.G. Jonker

1902 – Prof. Eugiène Dubois

The author disagreed with Lorié (1891) regarding the direction from which the ice stream must have flowed. He observed that the nucleus of the 'folds' (the ridges) still contained its stratified layers without intense deformation, as would be expected the folding mechanism Lorié described. Therefore he continued to study the Hondsrug. Data for this research (Dubois, 1902) comes from numerous hand-dug pits around the villages of Exloo, Odoorn and Valthe due to the construction of a railway from Emmen to Stadskanaal (Figure 1.7). The author recognizes some typical sedimentary successions and describes the spatial pattern of these.

- *Succession A* contains: i) boulder-sand(0.2 – 0.8 m) on ii) pre-glacial sediments (Rhine-diluvium),
- *Succession B* contains: i) boulder-sand (0.8 m) on ii) boulder-clay (1-1.5 m thick) iii) on pre-glacial sediments
- *Succession C* contains: i) Peat-moss on ii) light bluish Pottery-clay, 0.4m thick

Succession A and B are found on the Hondsrug, while succession C is found in the valleys (west of Odoorn) in between the ridges. The author made a hypothesis on the origin of this spatial distribution based on contemporary ideas of the structure and motion of Greenland's inland-ice. To his opinion the pattern is the reflection englacial transported strata, where in the eastern part of the inland-ice more coarse debris was concentrated and in the western part more clay.

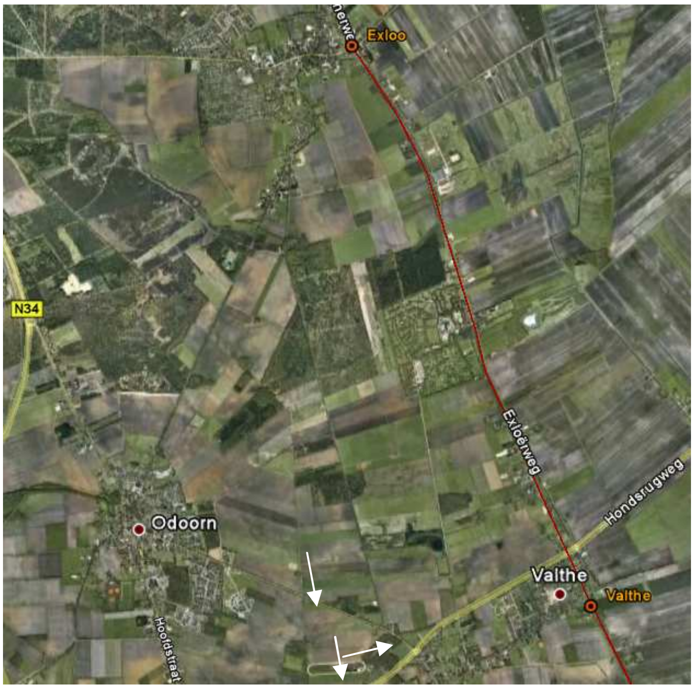


Figure 1.7. Location of the railroad construction (red) from the NOLS (Noord Ooster Locaalspoorwegen) with its train stations Dubois collected his observations on the Hondsrug (ridge), and corresponds to the region of the GPR-location (white). (Source: Google Earth)

Due to melt-out of the glacier, this would create the patterns found in the field. He also thinks that the western part of the inland-ice was more laden with clay and the eastern part was relatively 'clean'.

Stagnation occurred in the west and faster flow in the east, leading to a thickening of the ice-sheet in the west and a higher pressure. The low pressure region in the east would then be lifted 5 m relative to the valley. The general concept Dubois grasps, is that elevation of the surface is inversely related to the pressure applied by the ice and flow rates increase with decreasing pressure.
He is also convinced that the inland-ice movement was orientated SSE-NNW because of the clay layers were parallel deposited along the ridges. Secondly, this flow-direction might has been the result of the confluence of the British ice-cap and Scandinavian ice-cap in the North Sea.

1905 - Dr. H.G. Jonker

The author was a pupil of Prof. van Calker and strongly opposes Dubois' view on the origin of the Hondsrug. He completely disagrees with Dubois' opinion that 1) a SSE-NNW ice stream have formed the ridges and holds on to ice-flow from the NE and that 2) generally boulder-sand occurs at the ridges, while boulder-clay is found along the sides and that 3) boulder-sand and boulder-clay are not related to each other. The tone of Jonker (1905) towards Dubois (1902) is almost insulting, because he is deeply convinced in the established opinions regarding the origin of the Hondsrug and is unpleasantly surprised to hear that Dubois' opinions are about to be taught at schools:

As his opinions seem to me to be wrong and yet have been propagated to an undue extent by their insertion into a little book *For the use of Schools* – I have to thank Dr. J. Lorié for this information – I consider it my duty at once to develop in a somewhat detailed criticism, why I do not agree with him in his opinions."

In this paper, Jonker points out that Dubois' observations - which led him to his hypothesis - between Buinen and Emmen are only the southern part of the Hondsrug. He claims that Dubois made an impermissible generalization, by not testing his hypothesis on other parts of the Hondsrug. He thinks that if the observations of his mentor Prof. van Calker were included, Dubois' should have adjusted his hypothesis (or refuted it completely).

1.5.3: 1950 – 1980 Maarleveld, Ter Wee, Zonneveld, de Gans

Crommelin & Maarleveld (1949) and Maarleveld (1953) distinguished three push moraine lines, interpreted as recession lines of the ice front. Glacial thrusting was observed on the Hondsrug by Ligterink (1954), but Ter Wee (1979) argued that this could not explain the origin of the Hondsrug.

Ter wee (1962) extended this model of Maarleveld (1953) to the northern Netherlands with two stabilized glacier fronts within the general retreat. He concluded that the line of pushed ridges between Hoogeveen and Texel are continuation of the Rehburg phase from Germany. The push moraines in the area around Winschoten must have been formed during a younger phase. He believed that the Vecht valley was the ice-marginal river with a fluvioglacial character during this phase.

1975: Zonneveld

Zonneveld (1975) mentioned the drumlinized ridges and the Hondsrug-complex which were not explained by the glaciation model of Ter Wee (1962). He argued that the retreat of the ice may have been less systematic, with large masses of stagnant ice. The Vecht- and Hunze - valley were formed during this stage of dead ice fields and tectonics might have had an influence on forming.

1981: De Gans

In his dissertation, de Gans (1981) assigns the origin of the Hondsrug to a fluvial origin, where the Drenthsche Aa valley has further deepened intermediate depressions and crossed perpendicular to the relative heights. The pattern of straight river valleys and cross river valleys, are the reflections of the fault systems in the subsurface that determine river courses. He dismisses a salt tectonic origin, since he states that sediments on the ridges have not been altered by this process.

1.5.4: 1980 – 1990 Rappol, Zandstra, Van den Berg & Beets (1987)

Where glacial deposits occur at or near the surface, two distinct orientations can be recognized. An older NW-SE direction expressed in low ridges in the till and fluted shapes of till ridges. This direction is overprinted by SSW-NNE lineations of 'megaflutes' up to 15 km in width and 70 km in length. Data from clasts in the till (Rappol, 1983) show the same orientation as the morphology. Zandstra (1987) and Rappol (1987) came to the conclusion that most of the till in the Netherlands is sub-glacial in origin.

Observations regarding the glacial sediments in the Netherlands by Van den Berg & Beets (1987):

- One basal till is found, suggesting that the Saalian ice-sheet only one time covered the Netherlands
- Both NE-SW lineations and the NNW-SSE lineation of the Hondsrug-complex are of glacial origin.
- Pushed ridges are formed during the glacier advance
- With exception of the ridges in central Netherlands, all ridges have been overridden by ice.

3-phase glacial model

During the first phase, the ice-movement in Drenthe was N-S directed and stagnation occurred at the line Texel – Wierdingen – Steenwijk – Almelo. Thick till deposits could be deposited. The boulder configuration suggests that the ice originated from the East-Baltic. Reactivation of the ice-sheet led to rapid thickening of the ice-sheet, leading to the formation of pushed moraines at the stagnation lines. Flow direction was NW-SE directed. The boulder configuration suggests that the ice originated from the West- and South-Baltic.

During this last phase, ice-movement originated from the North Sea Basin and flowed towards the SSE. It flowed in between dead ice bodies (Van den Berg & Beets 1987; Rappol, 1991) from the former glaciation phase and created the Gelderse Vallei and the Hondsrug-complex. The difference in angle is almost 90 degrees and is witnessed in clast orientations. Boulder configurations suggest that the ice originated from the East-Baltic, and may reflect a shift of the ice-divide towards the east (Rappol, 1991).

The ridges of the Hondsrug have been formed during the third Saalian glaciation, and the ice must have invaded an open landscape with permafrost (Zagwijn, 1973). Glacier advance was fast over the fine-grained Drenthe till plateau as result of high basal water pressures. At the transition to the coarser Rhine sediments, movement was impeded by the large drainage capacity of the sediment, leading to deformation of the substratum. Push moraines of central Netherlands formed during the Rehburg phase.

The ice-tongue of the Nordhorn Basin could have overridden its pushed ridge due to the fine-grained tertiary sediments at Oldenzaal. This could have triggered the SSE-NNW ice streaming which created, according to Van den Berg & Beets (1987), the Hondsrug-complex. The Hondsrug – Hümmling Ice flow fed, to their insight, an area reaching to the IJssel basin in the West towards the Rheinische Schiefergebirge in the East and the Münster Basin.

1.5.5: 2008 – 2012 Pierik, Bregman & Cohen

The authors extended the glaciation model [Figure 1.8] with four phases towards maximum ice extend and a deglaciation complex comprising two phases.

Phase 1 and 2: During the onset of the Saalian glaciation, the ice invaded NW – Europe from towards the South at first, but changed later on towards SE. This might have been the result of a shift in the ice-divide region of Scandinavia. Rivers were deflected towards the west, as a result of large meltwater fluxes from the glacier. The Hunze valley may have been active at the first phase. The end-line of Phase 2 corresponds to the Rehburg line.

Phase 3: During phase three, the maximum ice extent was reached in the Netherlands, where large push moraines are formed at its southern border in Central Netherlands. Moraine failure led to formation of sandurs, and the meltwater could be discharged by the Rhine-Meuse river system towards the North Sea Basin, where a pro-glacial lake formed.

Phase 4: Stagnating ice occurred throughout the Netherlands, but due to an ice-mass increase in the North Sea Basin, and probably enhanced or even triggered by the combination of glacial lake formation in the Münsterland Embayment and burst out floods of Glacial Lake Weser in the Weserbergland (Winsemann, *et al.* 2011). The ice stream protruded in between dead ice masses and flowed towards the Münsterland Embayment, creating megaflutings of the Hondsrug-complex.

Phase 5: During deglaciation, large meltwater rivers formed to drain the huge amounts of water from the ice-sheet. Intra-marginal lakes formed in former glacial basins in the Netherlands. The Hunze-river and Vecht-river probably drained part of the meltwater as well, causing erosion of its sediments and deepening of its bed.

Phase 6: As the pro-glacial lake located at the North Sea stopped to exist, sea level dropped significantly, leading to a much lower erosion level for the rivers. This led to deep incision into pre-existing meltwater valleys.

The main phase for the genesis of the present exposed Hondsrug area is phase 4. The name of ice stream (Hondsrug-Hümmling Ice stream) is given because of indications that this ice stream reached from the eastern part of Drenthe to the Hümmling, where the ice stream stagnated and partly deformed the Hümmling (Schröder, 1978). Based on geological evidence the dimensions of the ice stream are min. 20 km wide and 120 km in length. As we will discuss in Chapter 6 we have now strong indications that differences in heat flow densities (HFD) with higher temperatures in the area NW of Schiermonnikoog, positioning of deeper and surficial geological structures influenced subglacial melt with overpressure thereby controlling the positioning and the direction of the Hondsrug-Hümmling Ice- Stream. Overprinting of the Hondsrug megaflute on NE – SW till ridges of connecting areas with different (NE-SW) directions indicates that the Hondsrug-Hümmling Ice stream was the last major active ice flow through the area and was probably produced immediately prior to deglaciation.

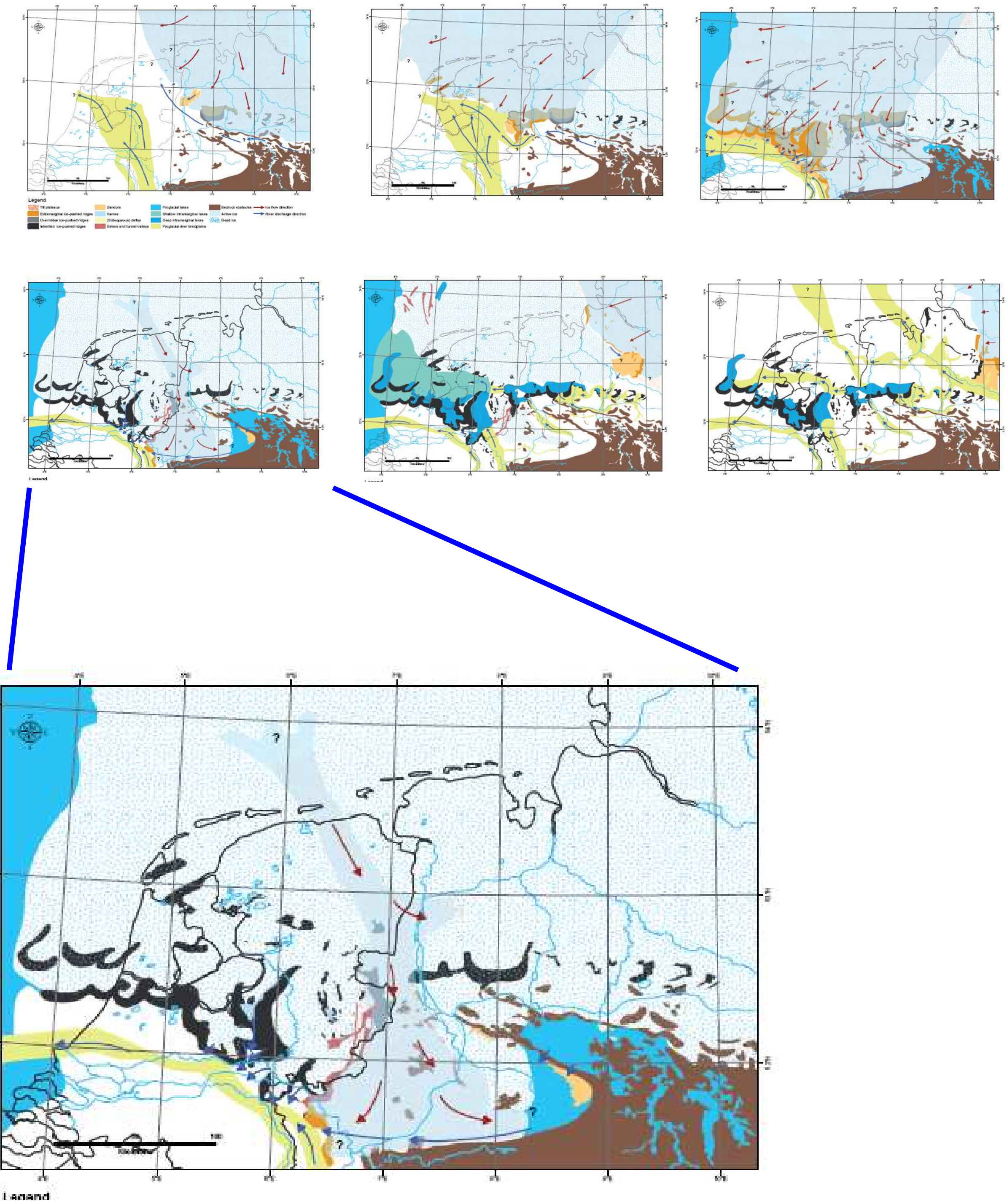


Figure 1.8; *Glaciation model of the Saalian glaciation of the Netherlands. (Pierik, Bregman & Cohen, in prep).Phase IV is the last phase at the stagnation – deglaciation stage of the Saalian (MIS 6) Scandinavian Icesheet. Tthe Hondsrug – Hümmling Ice Stream (light blue)is positioned in between dead or stagnant icefields .Flowdirection is indicated by red arrows.*

2. Methods and materials

2.1 Methods of data collection

The fundamental data for our research of the Hondsrug area consist of:

1. A database of GPS-pinpointed photographs and lithological descriptions of outcrops. Outcrops became available during the construction of a road in spring 2010, which was sunk 6 meter underground, at Borger (roadcut N34) and in 2011 at Gieten (roadcut N33; Figure 2.1). The pictures were shot digitally and can therefore be processed digitally as well (e.g. for inserting formation boundaries, lithofacies codes etc.)
2. Ground Penetrating Radar (GPR) cross-sections in addition to outcrop photographs. GPR survey is obtained with a 100 MHZ Sense and Software® pulseEKKO PRO Full Bistatic Configuration, and partly with 400 MHZ Sense. Raw data has been processed by M.A.J. Bakker (TNO/Geological Survey Netherlands), to provide interpretable seismic cross-sections.
3. Hand core drillings obtained lithological insight in the reflected stratigraphy. Drilling is performed with a standard Edelman-corer. The classification of the sediment follows the system of Verbraeck (1984) who made an adjustment to the classification system of De Bakker & Schelling (1966) (e.g. Berendsen & Stouthamer, 2002).
4. DINO borehole-database (source of the Geological Survey Netherlands). In the whole study area, borehole descriptions are available, but are generally less detailed described than our borings. The DINO database provides the general sequence of the subsurface, such as occurrence of till and its thickness. Visual interpretation was aimed with ArcGIS software applications. In addition, interpreted data (maps, e.g. from the Geological Atlas of the Netherlands) were used to give detailed information of deeper geological structures.

2.2 Methods of data interpretation

The structure of this research is graphically represented by Figure 2.1. Furthermore, we utilize concepts from glaciology and glacial geology to build up our reasoning. These include:

1. Outcrop observations at the locations in Donderen, Gieten, Gasselte, Borger and Klazienaveen (see Figure 4.1) are described by a glacial geological classification system c.f. Kjær & Krüger (1999).
2. The glacial geological toolbox (e.g. Benn and Evans, 2001) we used to deduce glacial history from sediments – in our case the basal surface between preglacial and glacial sediments – relies on many concepts from glacial geology (the science of glacial sediments) and glaciology (the science of ice-flow). Since end users of this report are most likely not too familiar with these concepts, we included relevant theory in Chapter 3, so that understanding of our reasoning will be more easy in subsequent chapters. The importance of the theory for the Hondsrug-complex will be highlighted in each paragraph.

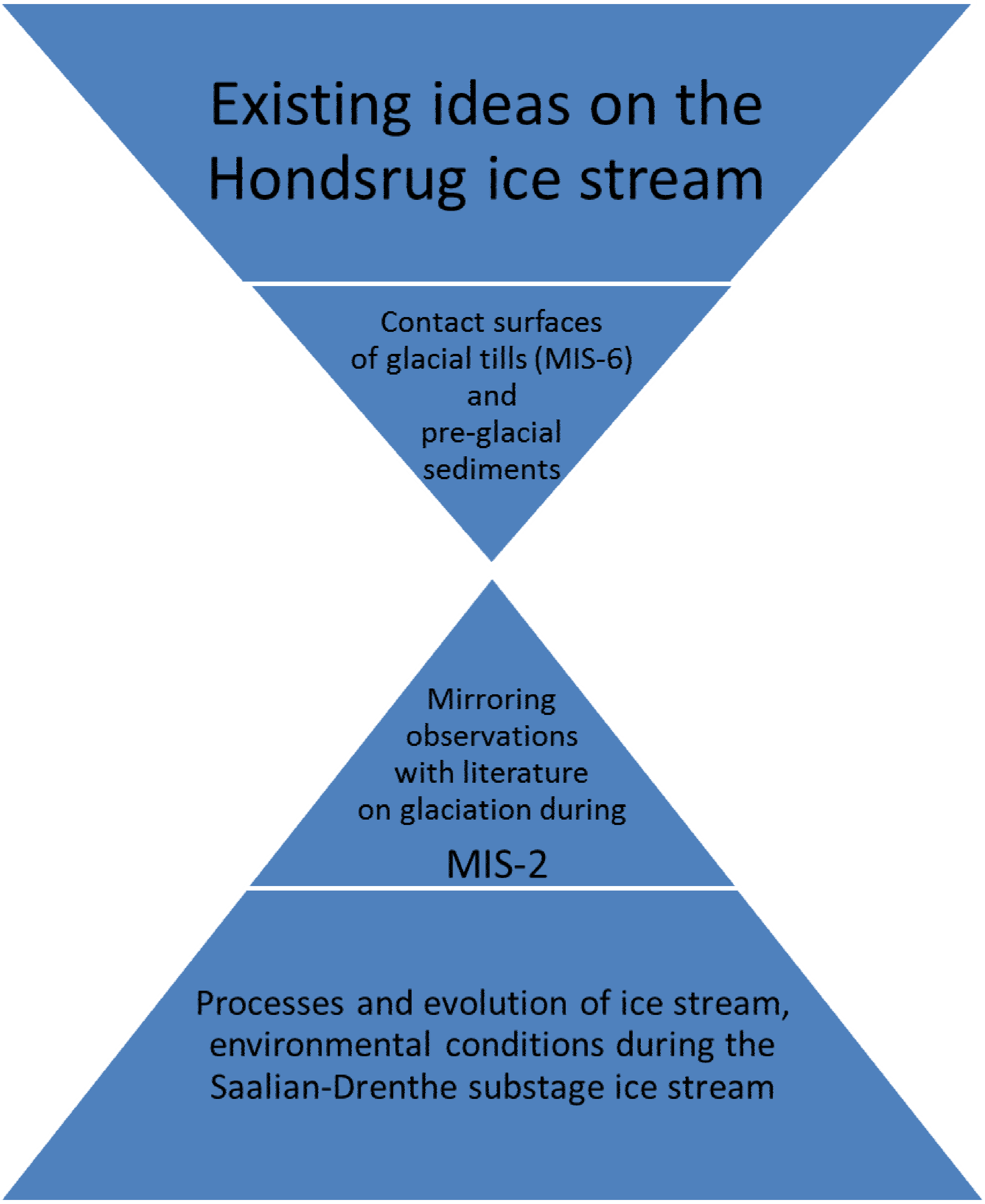


Figure 2.1 General concept of this research. Observations from the Saalian will be compared to similar sediments described in studies from the last glacial (Weichselian, MIS-2).

3. The interpretation of the outcrop photographs will follow a distinct scaling path, from an outcrop scale towards bed/lamination scale. In this way, large scale structures such as subglacial meltwater channels, pipes and convoluted beds can be distinguished and therefore basic information about the subglacial conditions can be extracted. By zooming in on the scale of a lamination or bed, the type of deformation (e.g. brittle/ductile or a combination) tells us something about the pore-water pressure in the sediment during deformation and therefore the basal water pressure.

4. The GPR cross-sections provide spatial information of subsurface structures of a larger area in addition to the point data set (boreholes and outcrops). GPR cross-sections provide information on the extent of subglacial deformation.
5. The genesis of the Hondsrug area is reconstructed based upon spatial analyses (DEMs), outcrop data and borehole descriptions. We used data of previous studies and new interpreted data, e.g. results of a study by Bregman & Lüse (in prep.) who tested the new glacial model (Pierik, Bregman & Cohen, in prep.) with XRPD clay minerals analyses of tills of different locations also on the Hondsrug. These results will be discussed in Chapter 6. An overview of the study locations with the used techniques is summarized in the figure below.

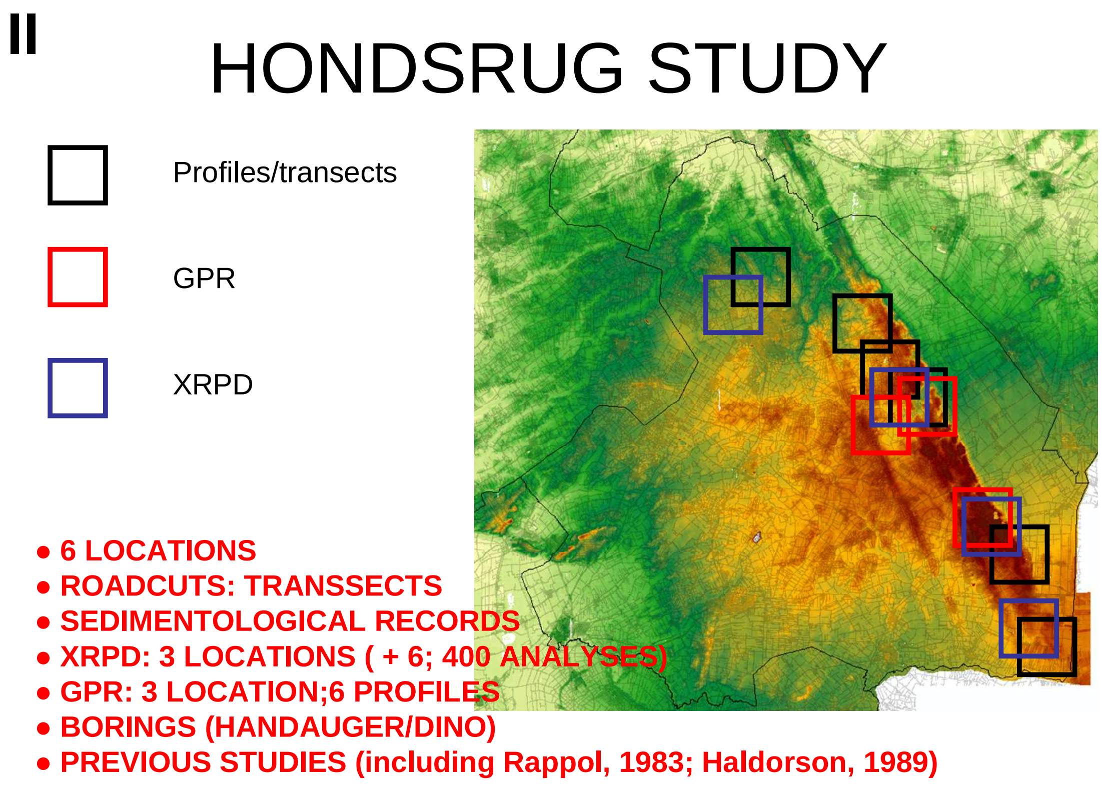


Figure 2.2. Overview of the study locations and used techniques.

3. Glacial sediments and subglacial deformation

This chapter is dedicated to provide the theoretical background that is needed, in order to deduce the glaciological history of an ice stream from sediments. In particular, we are focused on the information that can be acquired by studying the contact zones of preglacial and glacial sediments, and any subglacial deformation that occurred.

Many studies describe the behavior of modern glaciers on Svalbard and Antarctica and the sediments deposited under different circumstances. Insight in sedimentation processes from modern glaciers may provide a key for understanding glacier behavior in former glaciated areas as one follows the uniformitarialistic, retrospective approach. One should bear in mind that in some cases the analogue between modern en Pleistocene glaciers is not appropriate; the scale of the modern and former glacier has to match to prevent scaling problems during the inverse approach. However the Hondsrug-complex is formed by the Hondsrug-Hümmling-Ice stream, with dimensions (min. 20 km wide; 120 km in length based on geological evidence) similar as some ice streams found in modern glacial environments such as Svalbard and Antarctica. Studies from these regions can therefore provide the modern analogue for the processes that occurred during the late-Saalian glaciation of Drenthe. Because of similarity of features we use the floating mechanism as described by Jørgensen and Piotrowski (2003) as a reference. They made a glacial geological model of an ice stream on Funen Island (Denmark). Based on sedimentological observations and integration of results the conclusion was that the mega-scale geomorphological patterns and soil deformation structures only can be the result of Ice stream dynamics related to high temporal fluctuations of basal water pressure. Because of similarity between the glacial geological records of Funen and the Hondsrug we compared results of our study with the Funen study to answer the question in how far the Hondsrug area has been formed by the same mechanism. To extract environmental conditions from the sediments as well, external influences (salt diapirs) on these conditions are described as well.

3.1 Deformation horizons in an unlithified bed according to Boulton (1995)

In glaciotectonically deformed unlithified outcrop (*glacio*=ice; *tectonically*=by shear stresses; thus deformation by shear stresses induced by flowing ice; *unlithified*=not consolidated), horizons may be recognized that may be convenient structural dividers. The boundaries between the horizons are somewhat subjectively, although the degree of deformation is the criterion for a certain horizon and may be recognized easily in the field.

The horizons include:

- A-horizon: sediments which are deformed heavily by the glacier
- B_1-horizon: sediments which are slowly deformed
- B_2-horizon, stable sediment which does not show signs of deformation

The degree of deformation in B_1 depends on the rheology (stiffness) of the sediment and the pore water pressure. With high pore pressures, the grains are expelled more from each other, such that less friction occurs between the grains and therefore more deformation. With low pore pressures, the grains are more firmly attached to each other, leading to higher friction and less deformation.

The type of lithology influences the pore pressures due to the following:

- Fine grained sediment has larger pore water content than coarse grained sediment
- Permeability of fine grained sediment is lower than coarse grained sediment

It follows therefore that fine-grained sediment is more likely to have higher pore pressures than coarse grained sediment. Therefore, fine-grained sediment may deform more intensely.

3.2 Ice flow affecting the glacier bed

The Hondsrug ice stream was located on top of unlithified deltaic plane sediments, Elsterian in age (Bosch, 1990). Therefore, mechanisms controlling the type of movement of an ice stream over these soft sediments are discussed. The theory formally applies to glacier movement which is relatively slow (tens of meters per year), while ice streams move at relatively fast rates (hundreds of meters per year), but the principles are the generally the same. There is one exception to this: the bed of an ice stream is thought to be always unfrozen (cf. Shabtai *et al.* 1987), whereas the bed of a glacier can be frozen. This means that under an ice stream there is always meltwater present.

Because of this 'rule', beds of ice streams always have a warm-based or thaw-based thermal regime (e.g. Eyles, 1983). Warm-based glaciers are molten at their base and basal meltwater flows between the glacier base and bed. Several factors control the melting rate of the basal ice:

1. Rapid ice flow, which releases large amounts of frictional heat
2. Thick ice, which provides insulation of the basal heat which is trapped
3. High ice-surface temperatures, which creates low temperature gradients(low basal heat exchange) iv) advection of warm ice towards the bed
4. high geothermal heat flux

Since we are dealing with a (former) ice stream, basal frictional heat must have been high stimulating high melting rates. Melting rates must also been high during the interstadials, since this creates low temperature gradients. Temperatures during the existence of the ice stream (Late-Saalian) can be inferred from the palaeoclimatic record (e.g. Zachos, 2001). As will be discussed in paragraph 3.5, the shallow occurrence of salt diapirs in the subsurface of Drenthe may increase the geothermal heat flux at some specific spots which may lead to increased meltwater fluxes.

When describing the contact surface between basal ice and the bed, the basal contact pressure is one of the first entities deduced. There are three different schools which stress the importance of basal contact pressure on sedimentation and deformation, for which the two extremes ones are described. The third school is somewhere in between these point of views.

3.2.1 Boulton & Jones (1979) deformation model

In the deformation model of Boulton & Jones (1979), the effective contact pressure is the controlling factor in the deformation process according to equation 1 and Figure 3.1:

$$P_{eff} = P_{ice} - P_{wp}; \qquad (1)$$

$$P_{ice} = hydrostatic\ pressure\ of\ the\ overburden;$$

$$P_{wp} = basal\ water\ pressure$$

According to this deformation model, deformation rates increase with increasing effective pressure. If we assume that the water pressure in the pre-glacial aquifer is constant, the effective pressure depends on:

- Thickness of the overburden ice

- Basal water pressure
- A combination of both

Thickening of the overburden ice can occur when trust sheets are formed when the ice stream experiences compressional forces (e.g. transition between warm-based to thaw-based thermal regime or a sub-topographic obstacle). The basal water pressure does not only depend on the basal melting rate, but on the drainage of the pre-glacial aquifer as well. If drainage is sufficient, meltwater can be discharged and the resulting basal water pressure is low. If drainage is insufficient, meltwater will 'pile up' on the base of the ice stream, leading to high water pressures. The basal water pressure is therefore defined as: the water pressure in the water saturated sediment (pore pressure) and the water film between the ice stream base and the bed. If the permeability of the pre-glacial aquifer laterally varies over the course of the ice stream due to differences in lithology, one can imagine that this affects the basal water pressure as well. Fine-grained sediment has generally lower permeability than coarse-grained sediments, leading to higher basal water pressure. As becomes clear, many combinations of factors controlling effective pressure are possible to obtain the same final sediment configuration (the *equifinality* concept) and more proxies are needed to distinguish between the contributions of the different components.

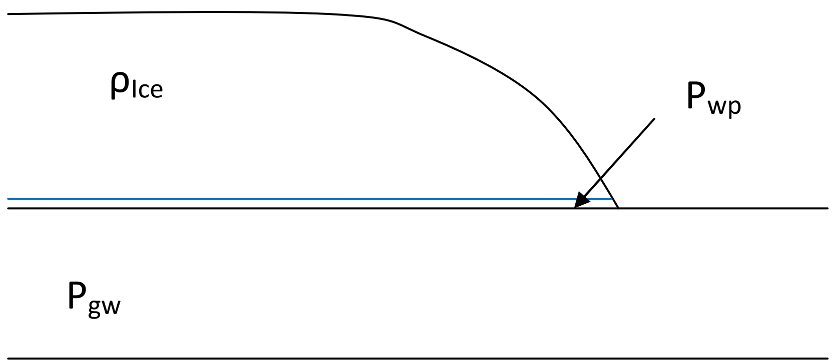


Figure 3.1. Sketch of pressure distribution relevant for ice/bed contact.

According to equation 1, in case of low basal water pressures, a high effective pressure is transferred to the bed. High basal water pressure leads to low effective pressures. In case of $P_{ice} = P_{wp}$, the pressure of the basal water layer becomes sufficient large to lift the glacier from its bed. This is called the flotation point and causes the glacier to slide over its bed without deforming it. In case of a cold-based glacier, P_{wp} will be zero, since the ice is frozen to its bed and no deformation takes place. In case of a warm-based glacier, P_{wp} depends on the basal melting rate and the bed permeability.

The type of deformation also depends on the basal water pressure and the period over which the stress is applied. If P_{wp} is high, ductile deformation will take place, because the high pore pressures will cause the grains to exert less shear stress on each other and become more mobile. With low P_{wp} values, grains are exerting more shear stress on each other, leading to more brittle deformation. When the pressure is applied relatively sudden, brittle deformation will occur, whereas with relatively even pressure increase, ductile deformation will occur. Since fine-grained sediment have a lower permeability than coarse-grained sediments, higher pore pressures in fine-grained sediment will show more often ductile deformation due to lower internal friction of the grain contacts. In contrast, lower pore pressures in coarse-grained sediments lead to brittle deformation and lower deformation rates due to larger internal friction. High normal pressures (due to the weight of the overlying ice-sheet) can result in the expulsion of pore water, leading to higher effective pressures and higher rates of deformation.

Most ice streams are warm- or thaw-based, which means that the surface below the basal contact can be partly frozen too. The occurrence of this patchy frozen subsurface prevents drainage of subglacial meltwater and the formation of drainage channels. The basal water pressure can therefore increase to high values, leading to low effective pressures and low deformation rates.

3.2.2 Hallet's (1996) deformation model

The second school of thought (Hallet's deformation model) thinks that basal contact pressure is independent of effective pressure. This model has instead the following assumption:

> *"Clasts are completely surrounded by ice and can be considered floating in it"*
> (Hallet *et al.* 1996)

Due to the mass of the overburden ice, the ice will flow around the clasts and will incorporate it. Therefore, the contact pressure depends on rate of the ice flowing into the bed, forcing the clasts into it. The rate of flowing depends on:

- Basal melting rate (e.g. rapid ice flow, thick ice, high ice-surface temperatures)
- Presence of extensional flow, which scarps into the bed

It now seems that both models can be true in certain cases. The Boulton model works for 'dirty' ice, which contains lots of debris and behaves as a rigid slab. Hallet's model can be applied to relatively clean ice with some isolated clasts included in the basal layer. This ice tends to behave less rigid.

3.3 Abrasion models

Abrasion occurs at the contact between the basal ice and the bed because of the friction with the debris content incorporated in the sole of the ice stream. There are two modes: in case of high debris concentration a sandpaper analogue applied, in case of low debris content isolated clasts will abrade the bed. Figure 3.2 shows the rate of abrasion in relation to debris content and ice velocity. As the abrasion optimum is reached, the ice velocity decreases because of increasing friction. The most effective abrasion occurs when:

- Hard rock fragments are incorporated, since these are not easily worn down
- Soft sediment floor
- Sharp rock fragments, which creates deeper incision in the bed

Both schools of thought created their own abrasion models in accordance with their deformation models.

In Boultons abrasion model, effective pressure and the ice velocity are the controlling factors. The following relations control abrasion rates:

1. Variations in ice-thickness control abrasion and lodgement via effective normal effective pressure;
2. Variations in basal water pressure (e.g. variations in bed permeability) control the effective pressure and therefore abrasion rate;

3. Ice velocity, increasing ice velocity increases abrasion rate;
4. Abrasion and lodgement form a part of a continuum.

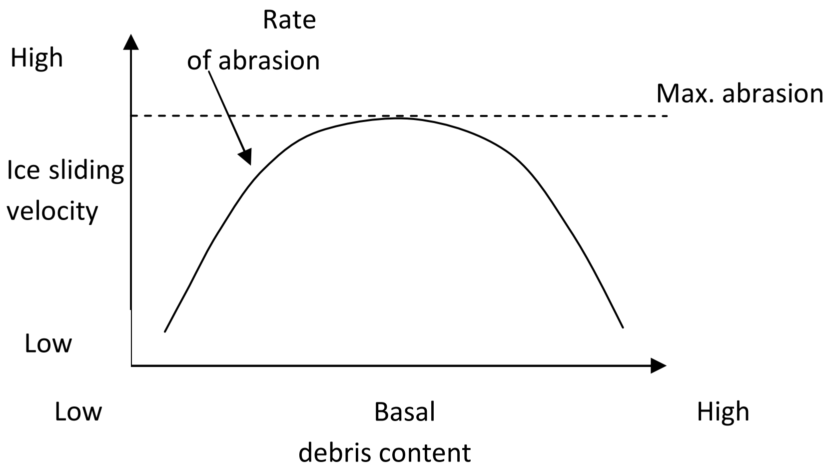


Figure 3.2. *Relation Ice sliding velocity and basal debris content with rate of abrasion (after Drewry, 1986)*

In Hallet's model, rock particles flow hydrostatically in the ice, and the abrasion rate is independent of effective pressure. Abrasion rate depends on the following factors:

1. Abrasion is highest where basal melting is highest
2. Independent of effective pressure, but dependent on ice-thickness because of its role as insulation, which increases the melting rate. Lodgement and abrasion are independent processes.

3.4 Reversed groundwater flows

Groundwater under ice-sheets and ice streams plays an important role in subglacial drainage in soft sediments and rocks, through a system of feedbacks. The groundwater influences also ice stream stability, ice movement mechanisms, sediment and landforms (Piotrowski, 2007). Also the direction of the groundwater flow itself is strongly influenced by the advance or retreat of ice streams and permafrost as is shown by Piotrowski (2007; 2008) and Marczinek *et al.*(2007) for NW Germany and Poland and for North America (Breemer, 2007). Loading of the crust by ice leads to reversing groundwater flow and occurs much faster than in non-glacial time (Breemer, 2007; up to 30 times, Marczinek, *et al.*, 2007).

Impact of reversed groundwater flow reached up to 200 m in depth and 40 km in front a glacier margin (Piotrowski, 2007). Old river valleys and buried glacial valley systems, which are found in the whole Ice Marginal Landscape zone of the entire European lowland (North Sea area/ from the Netherlands to Estonia; Smit, *in press*) functioned as drainage systems of these groundwater flows once formed, whereas when they were formed they secured stability of the ice sheet by reducing the water pressure (P_w) at the ice bed interface (Marczinek *et al.*, 2007). Permafrost reduced discharge (ca. 8%; Marczinek, *et al.*, 2007) and leads to a more downward groundwater flow and fed present aquifers as is shown for NW Germany by Koester *et al.* (2008).

Cutler (2007) proposed that waterflow through unlithified sediments was probably blocked and channelized flow didn't occur, where permafrost reached thicknesses of tens of meters. In that case, subglacial meltwater could not drain by the bed but was drained by episodic outburst (25% of a glaciers meltwater was discharged via groundwater; Piotrowski, 2007). Based upon sedimentological structures we found in the glacial sediments of the Hondsrug, we can conclude that these kind of outbursts played an important role in the genesis of the Hondsrug. This could have been possible due to the occurrence of permafrost in some regions of the Hondsrug area, because the impermeable permafrost led to a higher P_w with tremendous effect on locally strong subglacial deformation and flotation of the ice stream.

3.5 The floating mechanism

The fast movement of ice streams is the result of high basal water pressures, which lead to low effective pressures at the basal contact. The high velocity is the result of deformation of water saturated sediment and/or basal sliding on a thin basal water film. Basal water pressure is therefore a very important parameter in ice-flow.

Jørgensen & Piotrowski (2003) performed a glacial geological fieldwork on Funen Island in Denmark on sediments thought to be deposited by an ice stream from the late Weichselian. The paper argues that the shear stress applied to the bed by the glacier follows the Coulomb criterion:

$$\tau = c + (p_i - p_w) tan\phi$$
$$c = cohesion, \phi = angle\ of\ internal\ friction$$

Increases in P_w will facilitate sediment deformation until the flotation point $(P_{ice} = P_w)$ is reached. At this point the glacier is lifted from its bed by pressurized water and shear stresses are not transferred to the bed. The authors stress that the basal water pressure can vary during time, such that different stages of deformation, deposition or erosion can occur. This can be the consequence of larger amounts of meltwater that cannot be drained sufficiently and therefore the basal water pressure rises. The increase in meltwater discharge can be result of seasonal varying melting rates, increased flow rates (frictional heat) and a thicker ice sheet. The variation in basal water pressure is described by the authors at a certain site through time (temporal). It may also be useful in finding mechanisms for region wide patterns of deformation, non-deposition or erosion (lateral variable).

The basal water pressure can also vary laterally over the path of the ice stream, for example due to changes in lithology of the pre-glacial aquifer or increased melting rates due to regional increases in geothermal heat fluxes.

As the water pressure rises towards the flotation point, successively stages of till deposition, low-strain folding and creation of erosional features occur (Figure 3.3). From the flotation point onwards, basal sliding occurs, leading to abrasion of boulders. As the basal water pressure fluctuates around the flotation level, alternating sliding and deformation occur. When the water pressure suddenly drops sharply below the flotation point, subglacial meltwater features are created.

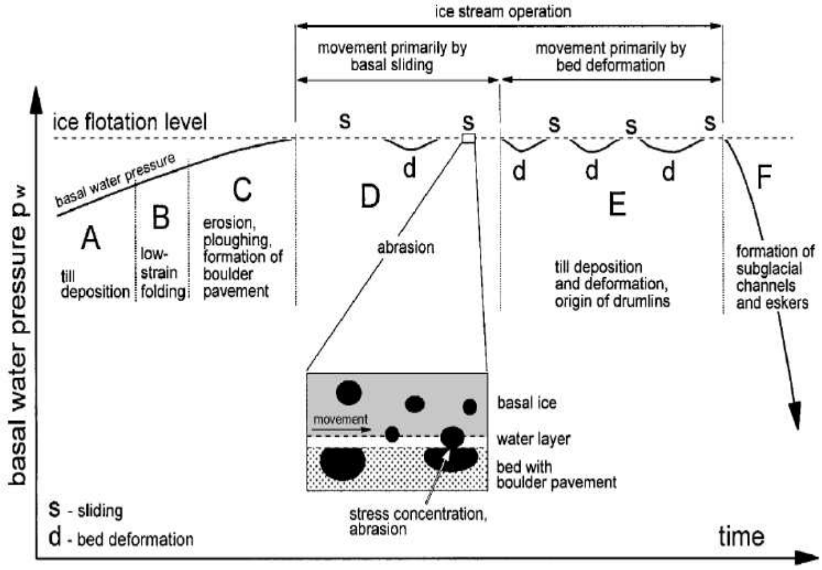


Fig. 10. Sequence of subglacial processes (A–F) in the ice-stream area interpreted in relation to basal water-pressure changes. We envisage that water-pressure conditions decisively influenced the mechanisms of ice movement, sediment deposition/erosion/deformation, and the generation of landforms. During ice streaming, water pressure was in the vicinity of the flotation point, and its fluctuations resulted in switching between basal sliding due to hydraulic decoupling at the ice/bed interface (s) and bed deformation (d). Highest ice-flow velocity is expected at stage D with minimum basal friction due to enhanced sliding on a water film.

Figure 3.3. “Floating Mechanism” from Jørgensen and Piotrowski (2003)

An increase in water pressure can be the result of permafrost as stated before, but also of sub-topographic obstacles, such as salt diapirs, which occur on the pathway of the Hondsrug Ice stream (Figure 3.4). These structures tend to be rigid relative to the surrounding sediments. On the stoss side of the diapir, compresional forces will increase the groundwater pressure because the water is forced upward, over the obstacle. On the lee side of the diapir, decompression occurs, which reduces groundwater pressure. The diapir does not only have a topographic effect, but a thermodynamic effect as well, which will be discussed in the next paragraph.

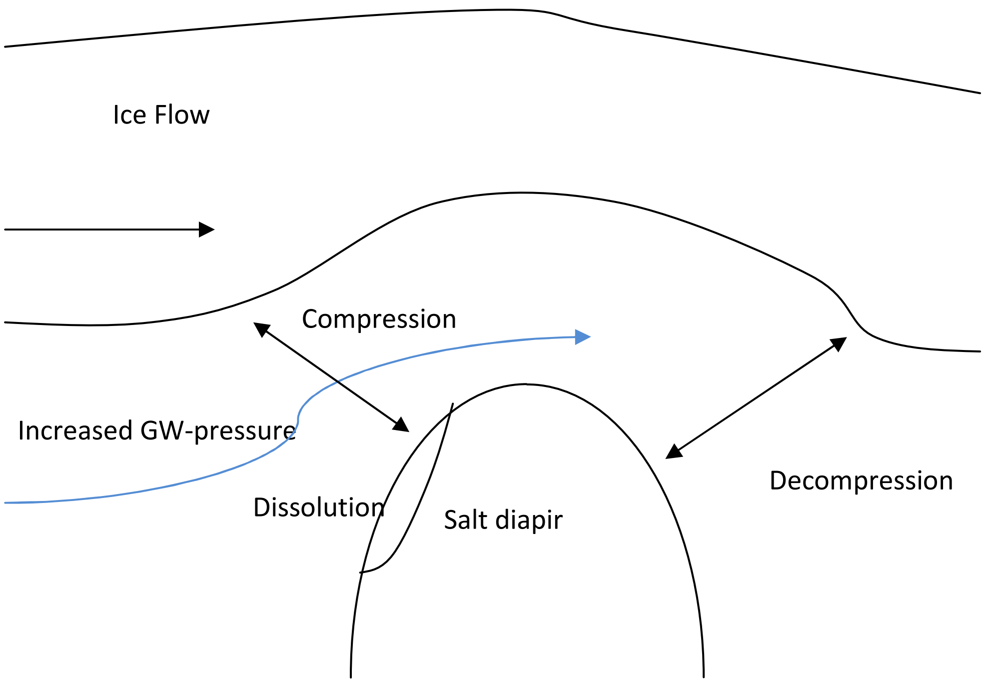


Figure 3.4. Compression and decompression caused by sub-surface obstacles (scheme)

3.6 Role of salt structures on geothermal flux, groundwater and sediments

Deeply buried rock salt has a smaller density than its surrounding sediments, which lead to a buoyancy force which is exerted on the basal contact with the overlying sediments. When a fault cuts down through the overlying sediments into the salt, the buoyancy will make the rock salt move upwards forming a diapir. The extent and activity of the fault will determine the mobility of the diapir. If the fault is large and active (or is often re-activated) the salt can move close to the surface. A close inspection of a subcrop map (Figure 4.5) of the study area shows that the top of the Zechstein formation (which is rock salt) is at very variable depth. It’s closest to the surface in Schoonloo (Figure 4.4) where it occurs 120 m below surface, but at many more locations its occurrence is shallow. The importance of the shallow occurrence of salt diapirs is twofold: 1) shallow occurrence of rock salt will influence the salinity of groundwater and 2) the thermal conductivity of rock salt is about $3.63\ Wm^{-1}K^{-1}$ versus $2.2\ Wm^{-1}K^{-1}$ of sand (Delisle *et al.* 2003).

The waxing and waning of a glacier leads to loading and unleading of the crust, which creates vertical and horizontal stresses in the crust (Thornson, 2000). The vertical stresses are maximum at the forebulge top, which can result in reactivation of faults in the deeper subsurface. This can lead to further mobilization of the rock salt. This process has been important for the area of the Hondsrug, since it lies near or on the top of the forebulge that was initiated during the Late-Saalian and Weichselian [Figure 1.1] and still is thought to cause vertical (post-glacial) movement in Drenthe (Bregman, in prep). Salt mobilization has uplifted the overlying Tertiary and Quaternary sediments significantly, such that major erosion has occurred on these strata as is represented in the Geological cross-section along the Hondsrug [Appendix A].

The shallow occurrence of rock salt (e.g. In Schoonloo 120m below surface) will have two implications for the salinity of hydrological system. The first implication is that dissolution of salt diapirs raises the salinity of the groundwater as is illustrated in Figure 3.5 for present time. We assume that the relaxation time between two glaciations is large enough to return the groundwater flow that was reversed in glacial times to the ‘normal’ non-glacial situation as we have in present time. In other words we suppose that the present positioning of saline and brine groundwater reflects the post-glacial situation very well.

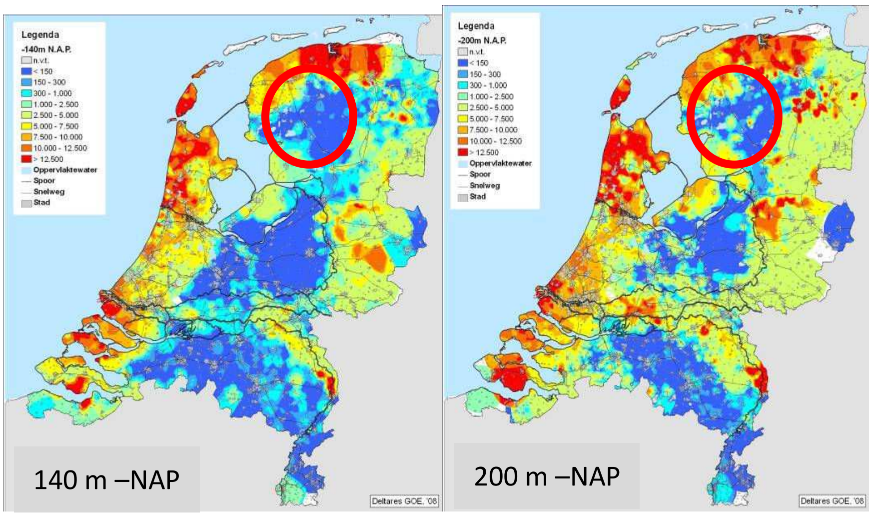


Figure 3.5. *Salinity present time at 140 m – NAP. and respectively 200 m – NAP. Salinity above saltdomes is > 12.500 mg/l (red circle). These depth are in reach of depth of modeled reversed groundwaterflows (e.g. Piotrowski, 2007; source: Nationaal Hydrologisch Instrumentarium (NHI) - deelrapport Zoet - zout, TNO, 2008).*

Brine or saltwater will lower the freezing point of the water, which in term will impede permafrost formation or lifts the lower permafrost boundary. This may be a factor that controls the thermal regime at the glacier sole too. Impermeable stratigraphic units have shown to be important barriers for the protruding brine water, such that it only penetrates through faults or permeable parts of the aquitard towards the surface hydrological system. Secondly, the salt obstacle forces the groundwater flow upward, while the sediment in between the glacier and obstacle experiences higher compression rates due to the increased influence of the velocity component of the glacier on the bed (Piotrowski, 1993). Recent palaeo groundwater modelling studies (e.g. Piotrowski, 2007; Breemer, 2007) confirm the previous conclusions of Piotrowski (1993).

On the lee side of the diapir, decompression occurs which leads to reduced groundwater pressure. According to Jørgensen and Piotrowski (2003), if the basal water pressure is around the ice flotation point (P_w=P_{ice}) and a sudden pressure release occurs, it may lead to the formation of subglacial drainage features.

The thermal conductivity of rock salt is about 1.6 times the conductivity of sand. Delisle *et al.* (2007) have shown in their modelling study, how the occurrence of salt diapirs have a profound effect on the depth of the permafrost. Based on marine proxies and calibrated with mean annual ground temperatures (MAGT), Deslisle *et al.* (2007) estimates a maximum permafrost depth between c. 130 and 170 m in northern Germany. The higher conductivity of rock salt will enhance heat flow and therefore impedes permafrost formation. In between the salt structures, there is a reduced heat flow which results in a deeper penetration of the permafrost. The importance of this observation is that raised geothermal energy fluxes can also have effect on the basal thermal regime of a glacier, as well as the melting rate of the basal ice and distribution of groundwater flows.

Increased external geothermal heat fluxes influences also internal frictional heat production in the glacier (Mackaay, 2008) and can produce high meltwater fluxes. This can lead to an increase basal water pressure if drainage is insufficient or is blocked by the presence of deep permafrost during the advance of the ice stream. This in term will affect the character of the sediment deformation as shown by Jørgensen and Piotrowski (2003). It may even cause the basal contact pressure to exceed the normal pressure exerted by the ice sheet, causing it to slide instead of deforming the bed.

A higher salinity content of the subglacial groundwater itself also has an impact on the above mentioned processes by:

1. Lowering the freezing point of the ice;
2. Changes the grainsizes of ice crystals in the glacier, thereby strengthening and reducing the hardness of the ice (e.g. Maykaay, 2008).

A higher P_W, the processes stated above and other conditions (e.g. lithology) have influence on the velocity of the ice stream, the sliding –conditions of ice streams and also the character of subglacial deposits (clays minerals of tills; Bregman & Lüse, in prep.).

3.7 Types of till on the Hondsrug-complex

Till deposits reflect the glacial history of landscapes and were subject in many previous studies in the Netherlands in the eighties and nineties of the last century (e.g. Rappol, 1983; 1986; 1991; 1992; Kluiving *et al.*, 1991; Haldorson *et al.*, 1989) and more recently by Bregman & Lüse (in prep.).

In general, there are three types of glacial tills (Evans *et al.* 2006, Benn and Evans 1996):

1. *Lodgement till*; a clast located at the basal contact between ice and bed experiences a drag force by the overriding ice and frictional resistance of the bed. If the frictional resistance of the bed becomes larger than the drag force of the glacier, the clast is deposited. Melt-out material makes up the matrix the lodgement till. The shear stresses of the overriding glacier are reflected back as shear planes in the lodgement till.
2. *Deformation till*; this till is characterized by the intense deformation of the subglacial fine material that formed due to subglacial melt-out. Deformation is thought to be the result of the tangential forces exerted by the active ice. The subglacial sediment is deformed into folds, diapirs, breccias and other deformations.
3. *Melt-out till*; deposition of glacial debris due to the melting of stagnant ice, without being transported or deformed after deposition. The till has irregular shape which is the result of the migration of the till during deposition into depressions underneath the ice.

Based on the origin of the crystalline boulder configuration, the flint proportion and calcium content, Zandstra (1976) divided the types of till on the Hondsrug-complex into 4 groups. Rappol (1991) added clast orientations which confirmed meso-scale (regional) orientations of the till types.

In table 1 we summarized the properties of tills found in the field. Six types of till are found on the Hondsrug-complex, three of which are decalcified and three calcified. These are Noordhorn-, Nieuweschoot- and Voorst-type (calcareous) and decalcified counterparts: Assen-, Emmen and Oudemirdum types. In general, two groups of till (stage III; Pierik, Bregman& Cohen, in prep.) are found in the Hondsrug area, which can be distinguished on flint-content and color: 'grey' Assen-group (flint-rich) and 'red' Emmen-group (flint-poor). When not deformed, the Emmen-type overlies the Assen-type. The distinct red color in the Emmen Group is the result of a high fraction of Devonian Old Red Sandstone, originated from Estonia and Latvia and the oxidation of incorporated iron-rich regional deposits (e.g. Haldorson 1989). The color of the Assen till reflects incorporation of German Pleistocene clays, which tend to be grey. It depends greatly on the oxidation/reduction history of a till to still have its distinct color. Oxidized Assen-type till can have the same color as the Emmen-type. In that case, therefore flint content is used as criterion for distinction of the two tills. The tills are based on boulder configuration almost completely identical, only flint content marks the difference of main types very well.

The contrast in flint content is explained by the position of the sediment debris in the ice stream: as the glacier moved towards the Netherlands it came across the Cretaceous limestone formations located in SW-Sweden and Denmark. Therefore the lower part of the ice stream contained flint, while the upper part does only contain the 'original' East-Baltic erratic configuration (Rappol, 1991; Haldorson, 1989). Due to its position low in the ice stream, the Assen-type till is a ground moraine and crushed granites are commonly found at the contact surface with pre-glacial sediment. Emmen till is often associated to be a melt-out till, due to the geometry of its contact surface with the underlying Assen till type (as will be shown in Chapter 4). However, Emmen till is not predestined to be a melt-out till, since local variables can cause lodgement or deformation as well.

At some locations, the Voorst-group is observed as well and is called 'Schollenkeileem' ('thrust sheet-till') since it occurs most of the time as a till lens or thrusted sheets in other till groups. It is a till from an older glaciation phase (first east Baltic phase, Rappol 1991) which has been plastered onto the surface of the Hondsrug area and is also found on top of the Havelterberg in ZW Drenthe (Koster, 2010). Succeeding glaciations deformed the till and mixed it with the other tills, in such a way that its occurrence is highly chaotic and local. The lithological characteristics of this till are reddish, clay-rich and it contains often limestone concretions.

Clasts in the till fabric show a strong NNW – SSE orientation (Rappol, 1991; c.f. phase 4 in Pierik, Bregman & Cohen, in prep.). These tills overlie an older SW-NE till orientation (c.f. phase 2, 3 in Pierik, Bregman & Cohen, in prep.). This orientation has been largely wiped out by the overriding of the Hondsrug Ice stream. The main characteristics of the tills found on the Hondsrug-complex can be summarized as following:

- The gravel (2-16 mm) fraction is a minor constituent of the tills
- Flint poor tills tend to be richer in the gravel fraction (2-7%, to 1-3% in flint – rich till)
- Calcium rich till is somewhat richer in the gravel fraction

Group	Type	Dir	Calc	Glaciation stage / Hesemann nr.	Characteristics in field	Occurence on Hondsrug
Heerenveen	Heerenveen		—	West-Baltic phase 2350,2260	1. Sandy till 2. Flint-rich 3. Boulder configuration: South Sweden 4. Boulders often homogenized with Assen type of till.	- Western part Rolder Ridge - Has been found in Eext
Emmen	Nieuweschoot		+	Second East-Baltic 10000, 9001	1. Absence of flint 2. Redbrown (unweathered) 3. Limestones are rounded, contain striae 4. Crushed and kitted together as breccias	-North of Noordlaren -On Noordhorn-type normally
	Emmen		—	Second East-Baltic 10000, 9001	1. Redbrown sandy till 2. East-Baltic crystalline boulder configuration 3. Much higher boulder content than Assen 4. Does not contain flint, criterium for Emmen	-South of Noordlaren -Underlain by Assen-type
Assen	Noordhorn		+	Second East-Baltic 7020, 6110	1. Sandy with flint rich boulders, low dolomite cont. 2. Black or grey flint 3. Homogene 4. Dark-grey(reduced); Liver to rusty brown (oxidized)	-North of Noordlaren -Overlain by Nieuweschoot
	Assen		—	Second East-Baltic 7120, 6220	1. Sandy, decalcified Noordhorn till. 2. Liver(dark grey) to rustybrown 3. Low boulder content 4. Distinguish with Emmen: high flint content (10-20%)	-South of Noordlaren -Overlain by Emmen-type
Voorst	Voorst		+	First East-Baltic phase	1. Interbedded with Nieuweschoot: "Schollenkeileem" 2. Orangebrown clayey(90%) till 3. Limestone concretions 4. Low boulder content (polished and striae do occur)	- Exclusvely on northern part of HC
	Oudemirdum		—	First East-Baltic phase	Does not occur at HC	Does not occur at HC

Table 1. Till information according to Zandstra (1976), Rappol (1991) and Huisman (2008) indicates an overview of till types based on classification of erratics

In general, the till thickness (acquired from the DINO database) is largest in the area of Groningen (10-15m) and in the North of Drenthe (5-10m), and in the South of Drenthe near Emmen (20m), due to thrusting of the tills. The area between these regions has till thicknesses varying from absent, to more regularly 2-5 metres. The Hondsrug-complex increases in height from the North (Groningen) towards the southeast (Emmen) (from +2 m +NAP, to 24 m +NAP), where it attains its greatest height. According to Ter Wee (1979), the climbing relief of the Hondsrug coincides with glaciotectonic deformation of the subsurface. Depositions of till is often accompanied by deformation of the subsurface, since coupling of the glacier with its bed occurs. In that case basal water pressures are low (c.f. Boulton *et al.*, 1995), and the effective high. Several deformation structures can be recognized in glacial sediments which can occur syn-depositional or post-depositional.

The timing of events can be determined by the extent to which deformation structures cut across or superimpose the facies and older glacial deposits. Water-escape features, such as liquefaction and fluidization, may also be present. Liquefaction structures include convoluted beds, flame, ball & pillow structures. They mark the presence of abundant meltwater underneath the glacier. Loading structures are the result of density instabilities and are triggered by seasonal thawing and freezing of the ground. Syn- and post-depositional deformation of sediments is very common in glacial sediments due to the dynamic character of an ice-sheet:

1. Removal of ice-support during deglaciation (melting of ice-cored ridges)
2. Pro-glacial or subglacial tectonics (stress due to the loading of the ice)
3. Failure induced by high pore-water pressures (hydro fracturing)
4. Compressional deformation structures show shortening of the sediment piles, which are expressed by thrusts and folds. Extensional deformation structures are typical normal faulting and sag folds.

Publications on the composition of the clay fraction in tills in the Netherlands are from the early 1990's (Rappol, 1983, 1992, 2001; Rappol *et al.* 1989; Haldorssen *et al.*., 1989). Smectitie is absent in flint-poor tills. This indicates, according to Rappol (1992) an East-Baltic source area. The absent of smectite in tills in Drenthe is due to absent of smectitie in Pre-Cambrian and Paleozoïc rocks.

A relatively high illite concentration and a low smectite concentration indicate a cool and dry climate (Ehrmann, 2003). Tills that formed during the Late Saalian in the Hondsrug area, have a high amount of illite in the upper part of the till without any smectite, whereas the lower tills have a higher smectite content due to reworking, whereby southwest Baltic deposits were introduced in the till (e.g. Rappol, 1989; 1992). To test the similarity of tills deposit of different ice streams (c.f. the new glacial model by Pierik, Bregman & Cohen; in prep.), Bregman & Lüse (in prep.) used XRD (Röntgen Diffraction) Analyses to analyse the clay mineral content and could confirm results from previous studies. In addition, XRD also gives additional information about conditions of till formation, local clay mineral formation and weathering conditions in the source area which can be used for other physical or geochemical soil characteristics.

Similarities in studied tills, classified on base of Turbo Stratism Index (TSI, Reynolds, 1994) indicates that the lower tills of the Hondsrug area are similar to the tills in the northern part of Drenthe and the centre of Drenthe; whereas the upper till near Schoonebeek is the same type, indicating that the upper till from the northern part of Drenthe, has been eroded away in Schoonebeek. On well studied tills (Rappol, 1983) Bregman & Lüse (in prep.) showed not only differentiation of clay minerals. They also showed that the tills at the transition zone, 55 cm below the surface, have not any illite reflexes, which could only be explained by shearing of ice streams under high pressure. Because the XRD study showed newly formed minerals like syngenite and halite in lower tills at the Hondsrug area, Bregman & Lüse (in prep) concluded that these tills were formed under saltwater conditions. These newly formed minerals, not formed under weathering conditions or due to use of salt on roads in wintertime, indicates the influence of brines that were pressed up in a pro-glacial and subglacial environment or due to upwelling of deep saline groundwater. These salt- or brinewater intrusions leaked in same till types of northern and central Drenthe, which indicates pro- or subglacial intrusion in the lower till at the last event in the Saalian glacial advance of the Hondsrug-Hümmling Ice stream. This conclusion confirms too that this ice stream must have had impact of reversed groundwater. Its flow characteristics might have be influenced as well by this brine to salt groundwater with implications for its basal melt point, the velocity and erosional processes.

4. Lithological observations at the Hondsrug

This chapter comprises the description of outcrops from five different sites along the Hondsrug-complex (Figure 4.1). Note that the locations are not always located on the same ridge. The sixth location denoted by a square with GPR means that only GPR – cross-sections are available. In all cases, borings from the DINO database are available for the general sequence of the subsurface.

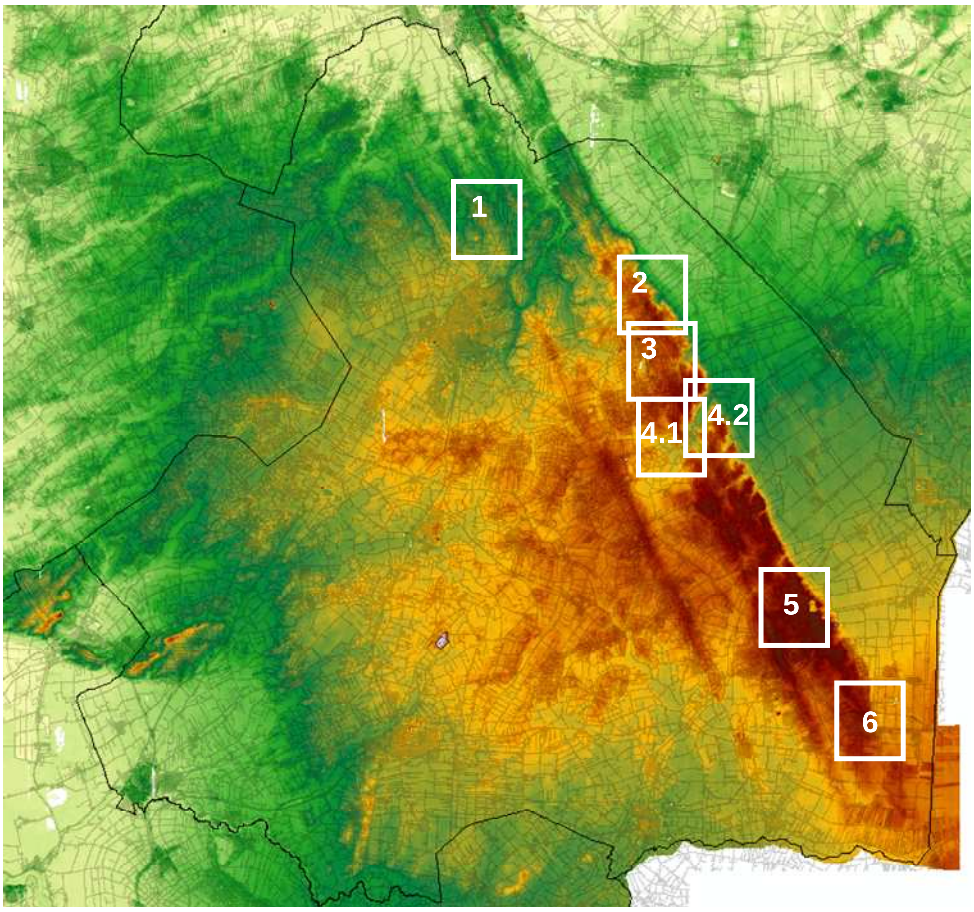


Figure 4.1. Locations of the outcrops: 1. Donderen; 2. Gieten; 3. Gasselte; 4.1 Borger; 4.2 GPR Borger 5 GPR. Odoorn; 6. Klazienaveen (source: DEM of the Netherlands, Rijkswaterstaat 2005).

4.1 Location 1: Donderen area

The northernmost location that provides data for the behaviour of the Hondsrug ice stream is near the small village Donderen [Figure 4.2]. The outcrop is located on the Rolder Ridge, which is only vaguely expressed in the topography in the northern part of Drenthe. A 2.5m by 1.5m outcrop has been dug out by hand and shows the contact surface between the glacial sediments and the pre-glacial sediments [Figure 4.3].

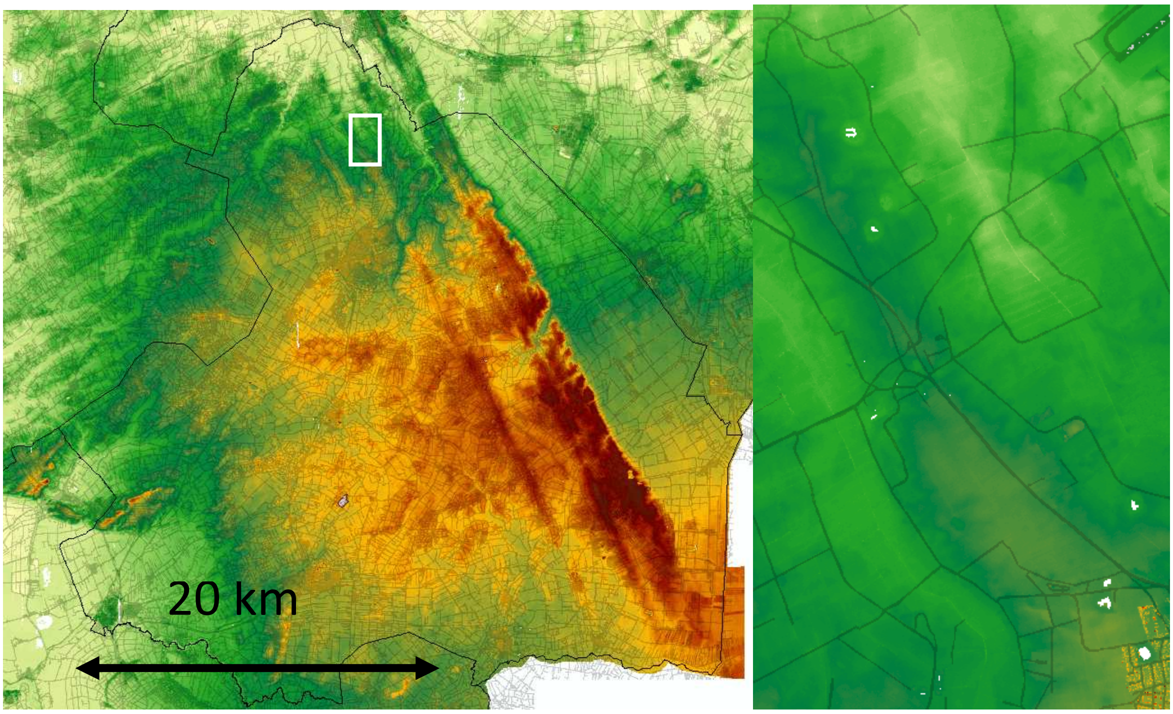


Figure 4.2. A) Location of outcrop 1: Donderen Area; **B)** Detail chart of the relief around Donderen. Rolder Ridge is vaguely expressed in the topography.

4.1.1 Lithostratigraphy

The lithostratigraphy at the outcrop in Donderen consists of

- A 30 cm humus-rich topsoil, underlain by;
- 40 cm fine, well sorted yellow sand;
- 50 cm yellow fine sand with loamy laminations;
- 30 cm of coarse grained sand with pebbles with loamy laminations;
- few centimetres till;
- light-grey fine sand with mica at the bottom of the outcrop.

There exists a disconformity between the light-grey sand and the coarse grained sand.

4.1.2 Structures

At the contact of the remnants of the till and the pre-glacial sediment, till has dropped into the latter sediment or the latter has been injected into the till.

Figure 4.3; Outcrop at the Donderen area. Photo: E.P.H. Bregman

4.2 Location 2: Gieten

Outcrop location 2 is positioned almost perpendicular to the strike of the Hondsrug (e.g. ENE-WSW vs. NNW-SSE) and therefore to the ice stream flow, since these ridges formed parallel to the flow direction (c.f. Boulton *et al.* 2001; Figure 4.4A, B). It shows the lateral variability of the glacier bed across the former ice stream for a length of about 500m. This outcrop cuts through both the east branch of the Hondsrug and the west-branch, where the roundabout is exactly the divide between these two ridges. Since the till sequence is very different between these ridges, they will be described individually and interpreted likewise.

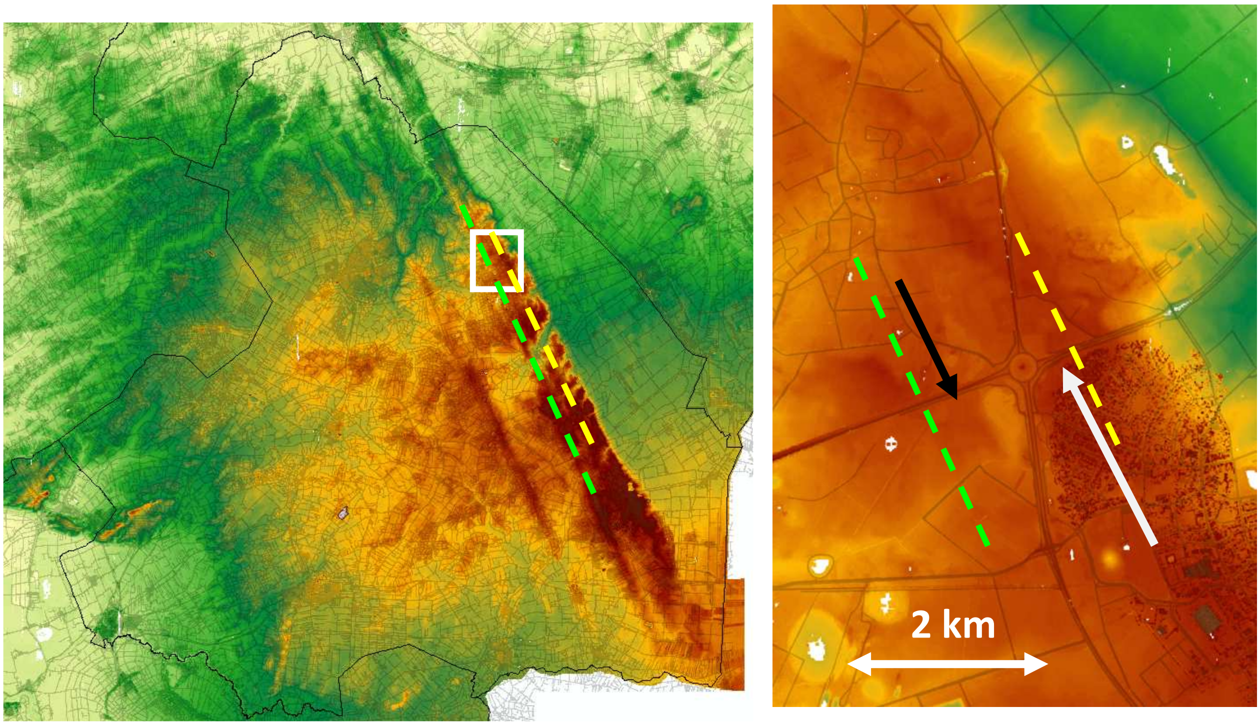


Figure 4.4. A) Location 2 on Hondsrug with west ridge (green dotted line) and east ridge (yellow dotted line) and **B)** detail chart of location 2: white arrow marks the south face east of the round-about, black arrow shows west of the roundabout.

4.2.1 Lithostratigraphy

West side of the roundabout (western ridge of the Hondsrug, Figure 4.8E)

At the bottom of the outcrop fine white sand (150-210μm) is found, that shows intense deformation and drag structures. Although fine sand makes up the bulk, sometimes coarse to very coarse sand with gravel (3 mm) is found as well. These are overlain by a dark-grey to black-green till with a thickness of about 2 m and their contact is of erosional character. A sandy layer (210 – 300μm) sometimes occurs in between the till, whereby the lower till contact is washed out and the upper till contact shows crushed pebbles. Boulder content in the till is low. It is overlain by fine yellow sand (150-210μm) of 30 cm thick; in the contact zone with underlaying tills, with drop stones and pillow structures, a thin accumulation of stones is present. This indicates an erosional phase. On top lies a 0.5 m thick peat succession. The contact zones of the two tills drains ground-water by (diffuse) seepage and pipes (hollow features), which indicates recently intra till erosion.

On the west side of the roundabout, large thrust sheets and recumbent folds have been observed. In pushed and dragged pre-glacial sediment till blobs and coarse grained sand inclusions are observed. The pre-glacial sand shows drag structures [Figure 4.6]. Large dropstones have been found that dropped into the pre-glacial sediment. Intra-till channels have been found in the grey Assen-type till, which contained fine grained sediment with some boulders (Huisman, per. Comm.). The yellow sand on top shows cryoturbation features as well.

East side of the roundabout (East ridge of the Hondsrug, Figure 4.7)

The overall character at the east side of the location is a chaotic sequence of different tills. There have been found six types of till (Huisman, pers. comm., 2011), three of which are calcareous and three decalcified. The intra-till lithology is very diverse, ranging from very loamy to sandy with pebbles, making it hard to distinguish between the tills. We start with the description at the bottom of the outcrop, where white fine sands (150 – 210μm) are found at a depth of about 7 meter (inferred from DINO-database). These sediments are overlain by a sequence of rusty-brown till, with a thickness of about 1,5m [Figure 4.7]. In the till subglacial channels are formed with sometimes very coarse infillings and channel lags. This till is overlain by complex of grey till, sand blobs, and reddish till with a varying thickness between 1.5m to 0.5 m. These sediments are overlain by a red till, about 1m in thickness. At some locations, laminated sandy inclusions are observed in the red till and show drag structures and faults. Upon the red till lays a 40 cm thick layer of yellow fine, well sorted sand (150 – 210μm). The contact between red till and yellow fine sand is first of all cryoturbated, but is erosional in character: the till is somewhat washed out and a boulder accumulation occurs. At the top, a 30 cm thick humus-rich soil is found.

4.2.3 Structures

At the east-side of the roundabout, an undulating contact surface is found between the rusty-brown till and the grey till of the complex. Sand blobs occur directly on top of the lower rusty-brown till or can be found incorporated in the complex. The structure becomes less chaotic from the contact surface of the red till. This till shows cryoturbation features, evident from till that has flown into the grey till complex [Figure 4.7]. The yellow fine sand on top of the outcrop shows cryoturbation features as well: it dropped into the red till. On a smaller scale, we find ductile deformation inside the sand blobs, although brittle deformation occurs as well [Figure 4.9B]. Clastic dykes have also been found: they were filled with pre-glacial sediment and were injected into the grey till [Figure 4.8E]. Although thrust sheets occur, deformation style in the sediment is predominantly ductile. Figure 4.8A shows piping structures that have hydro fractured the till completely (east side roundabout). Figure 4.8D shows a sand lens that is incorporated in the red till.

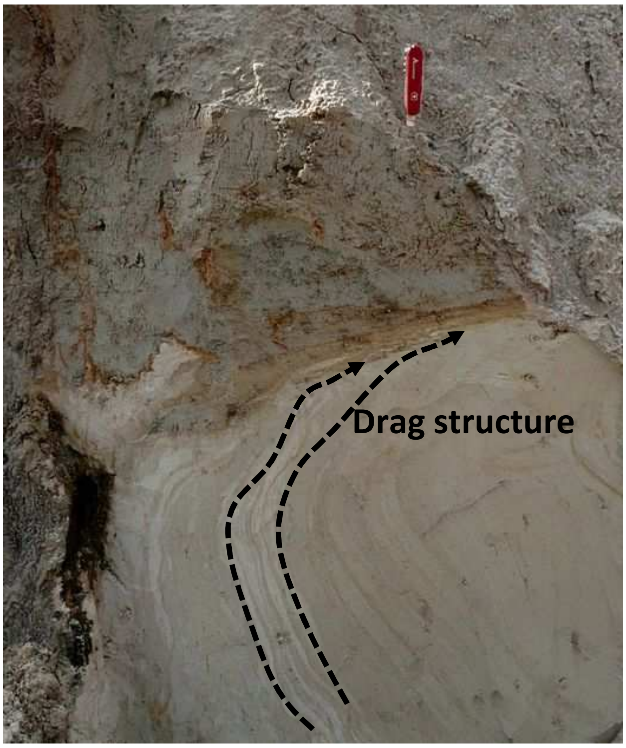


Figure 4.5. drag structures in the pre-glacial sand, ice-movement from left to right (west of the roundabout). (Courtesy of H. Huisman)

Fig

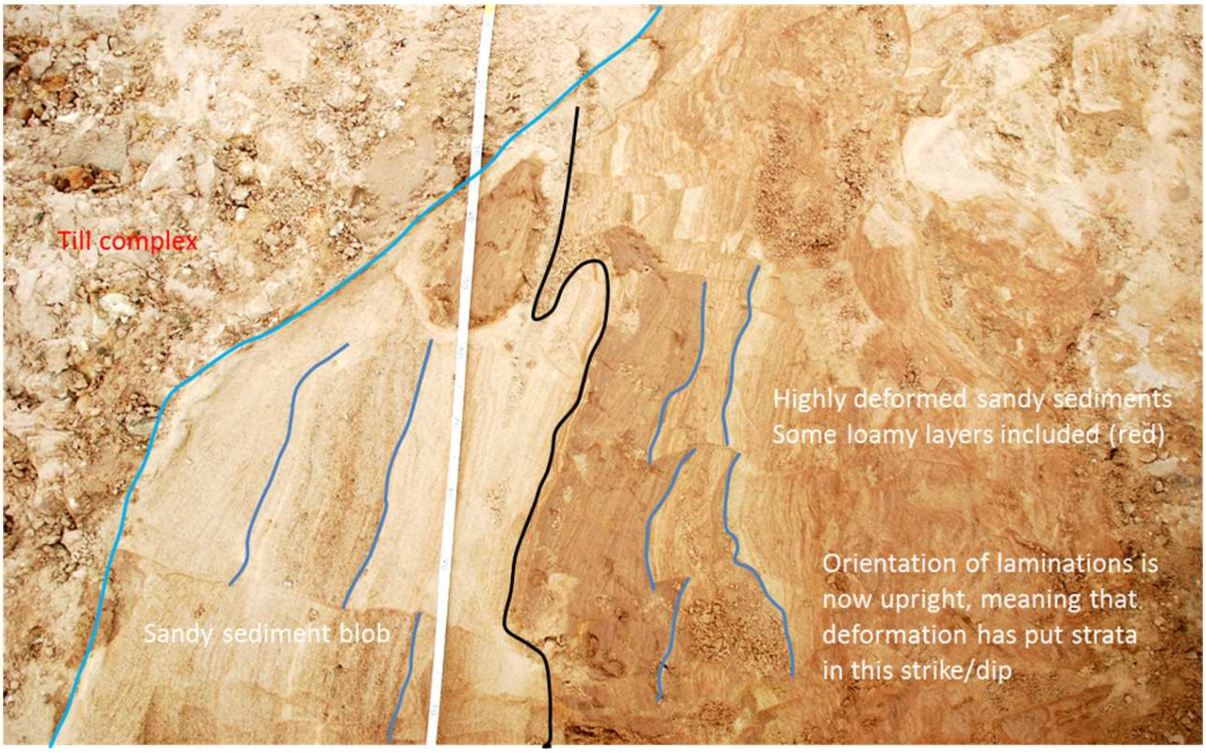


Figure 4.6. Detail of a sand blob of pre-glacial sediment, showing ductile and brittle deformation and the up righted Nieuweschoot-type till.

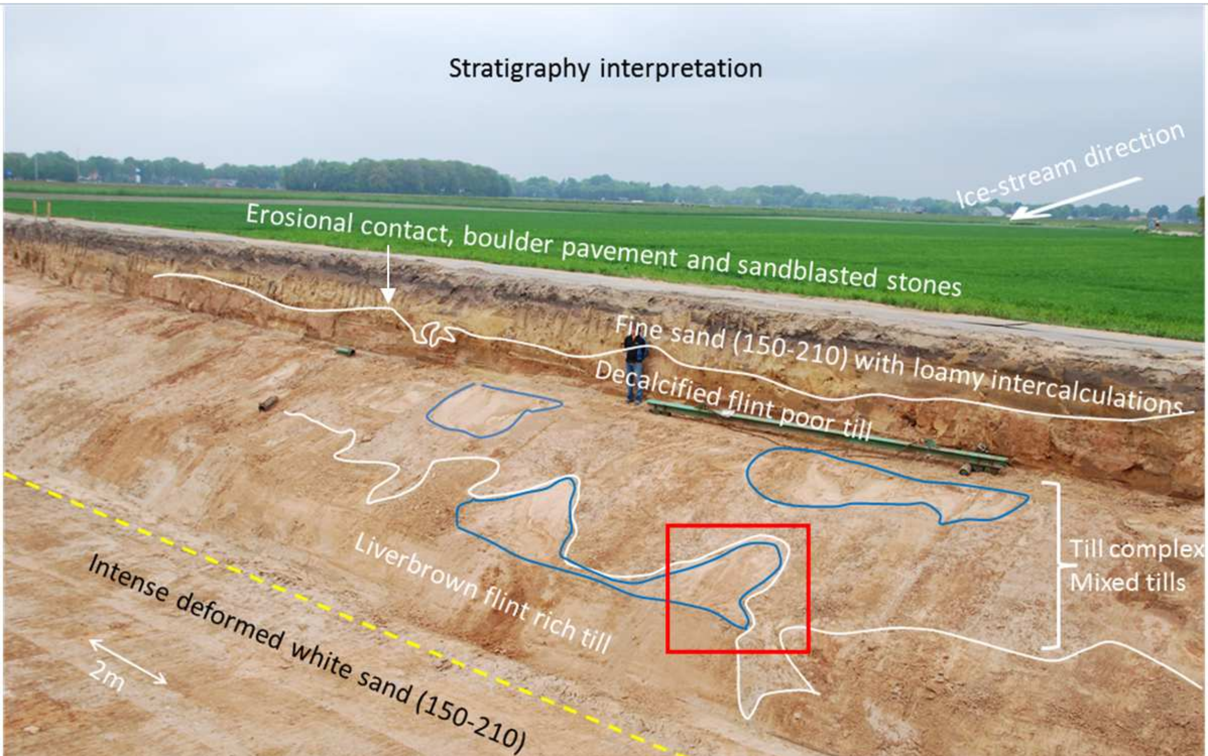


Figure 4.7. South face of the outcrop at Gieten, east of the roundabout. Undulating surface of liver brown flint rich till. Top to bottom is 7 meter. (Red square indicates Figure 4.7) (Photograph: E.P.H. Bregman)

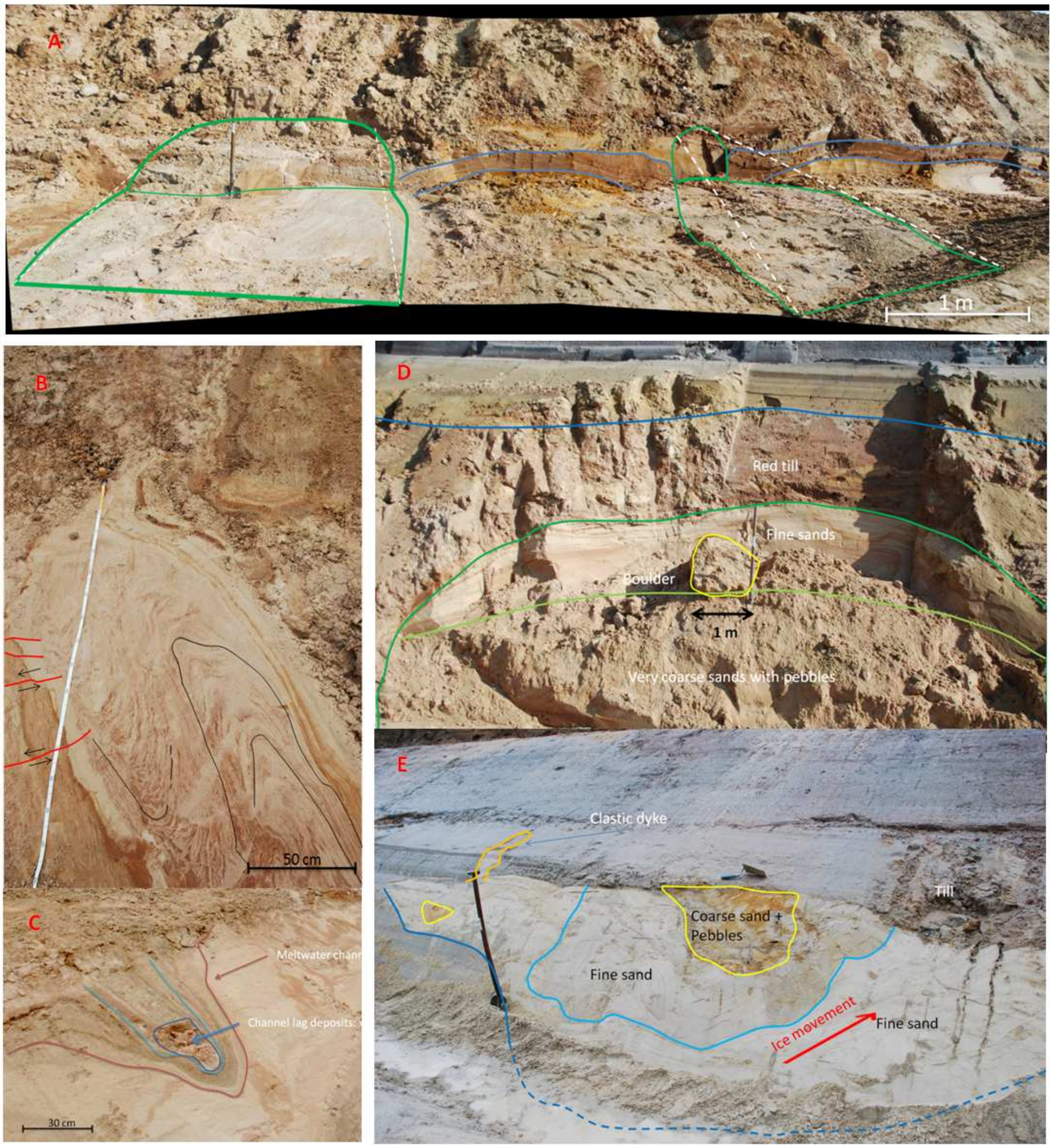


Figure 4.8. Some glacial features from the Gieten site; A) Subglacial piping; B) Dominantly ductile deformation and flow structures in a sand body; C) Meltwater channels in the Emmen-type till; D) Sand lens in Emmen-type till, meltwater deposits; E) Subglacial meltwater channel under Assen – type till in pre-glacial sediment, coarse sand + pebbles (west of roundabout)

4.3 Location 3: Gasselte

The outcrop of location 3 is located 5 km south of Gieten and 5 km north of Borger (location 4), and runs parallel to the Hondsrug [Figure 4.9]. The outcrop became accessible by road cutting.

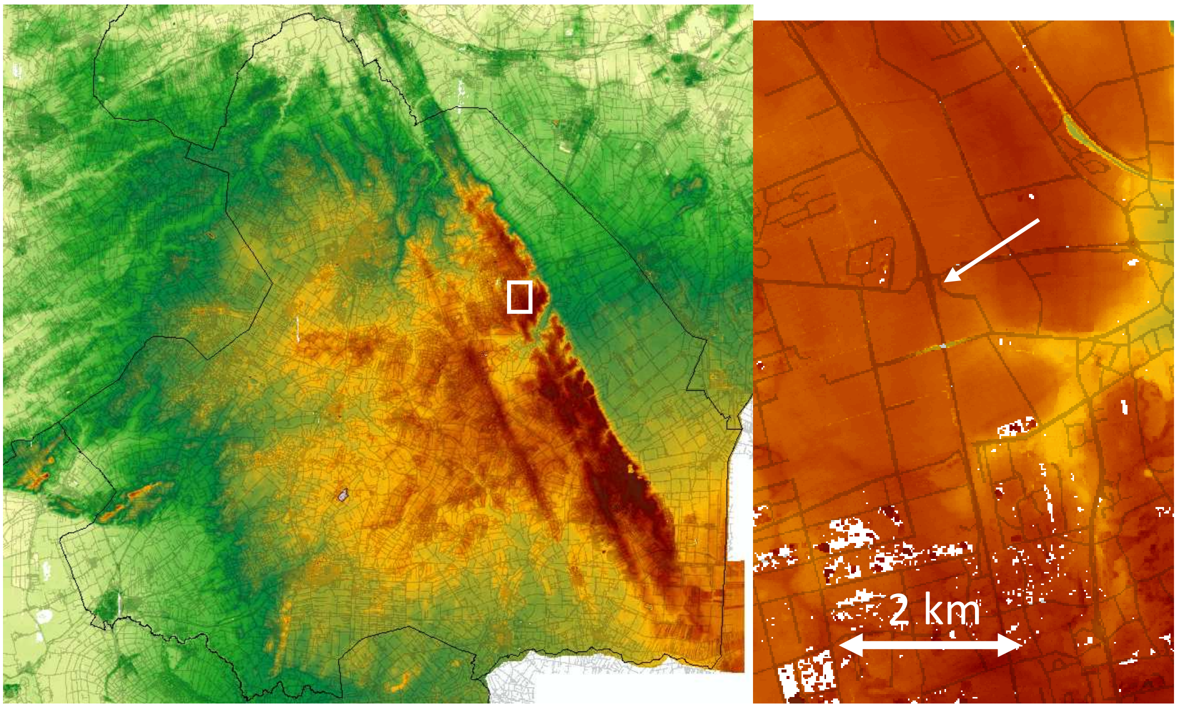


Figure 4.9; A) Location of outcrop 3 on the Hondsrug and B) detail map of outcrop location. White arrow marks the outcrop.

4.3.1 Lithostratigraphy

This site is characterized by the occurrence of very coarse sand (850 – 1400μm) with a high fraction of pebbles. An alternation of coarse grained beds and finer grained beds do occur [Figure 4.10]. These sediments are overlain by a 0.5m thick sequence of red till. The lower boundary of the till has an erosional character, as is evident from the angular unconformity between the two sedimentary units.

4.3.2 Structures

The laminations of the course sand reflect a channel geometry, which is orientated NE – SW and is perpendicular to the ice stream direction NNW-SSE. A closer inspection of the infill (Figure 4.10B) shows that layers are deformed brittle.

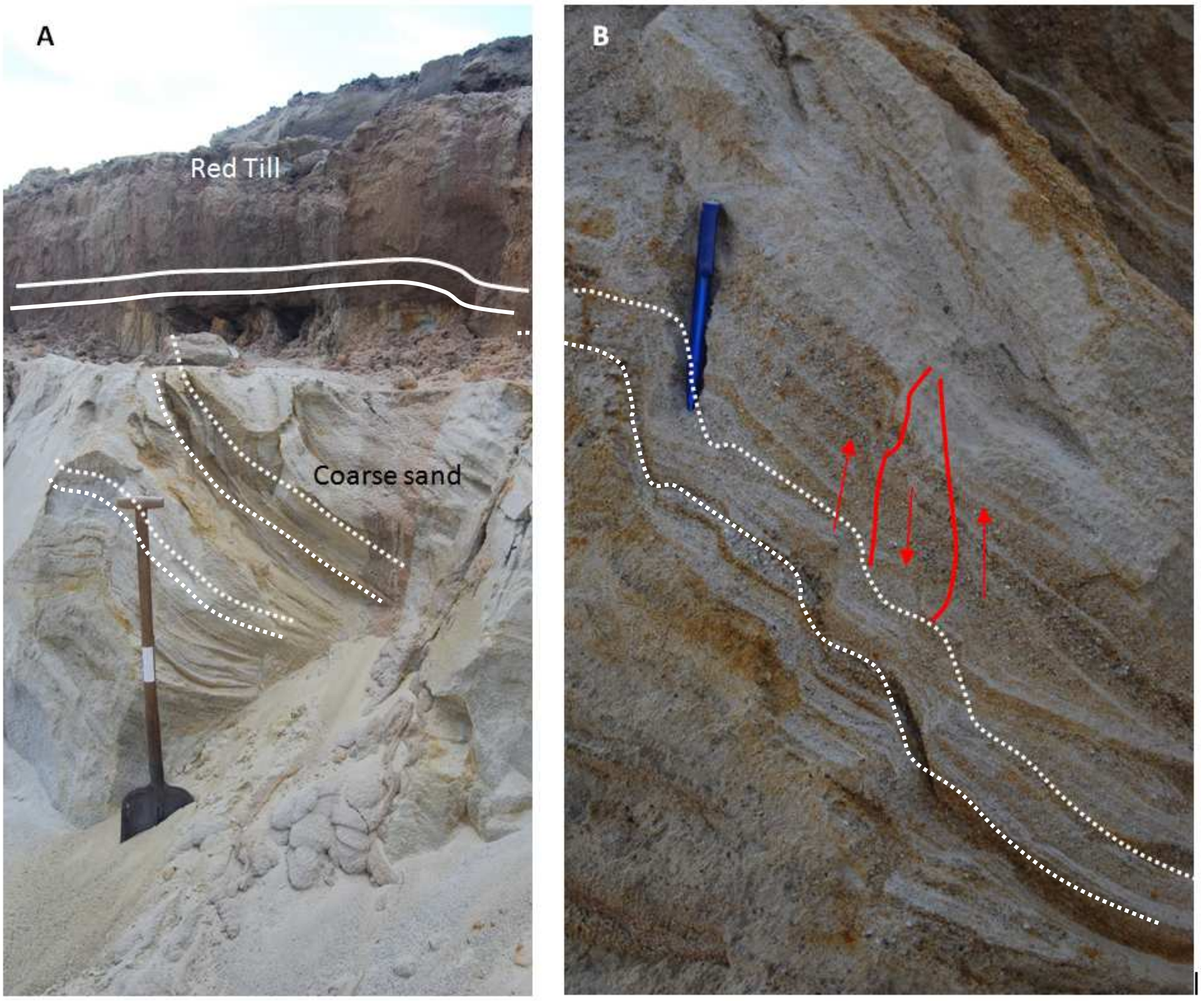


Figure 4.10; **A)** Dipping pre-glacial sediments.. Red arrow is ice –flow direction. **B)** Detail of sandy lithology with dislocations due to stretching of frozen blocks Gasselte roadcut N34 (Photographic copyright by E.P.H. Bregman)

4.4 Location 4: Borger

Location 4 is situated 10 km SW of location 2 (Figure 4.11A). The outcrop is located parallel to the strike of the Hondsrug (Figure 4.11B) and shows the lateral variability of the glacier bed. It is located close to a NE-SW orientated river valley, called the Voorste Diep. GPR-measurements on the slopes of the valley have shown that its orientation is not glaciotectonically determined (insinuating older deformation from NE), since the layers dip towards the NW.

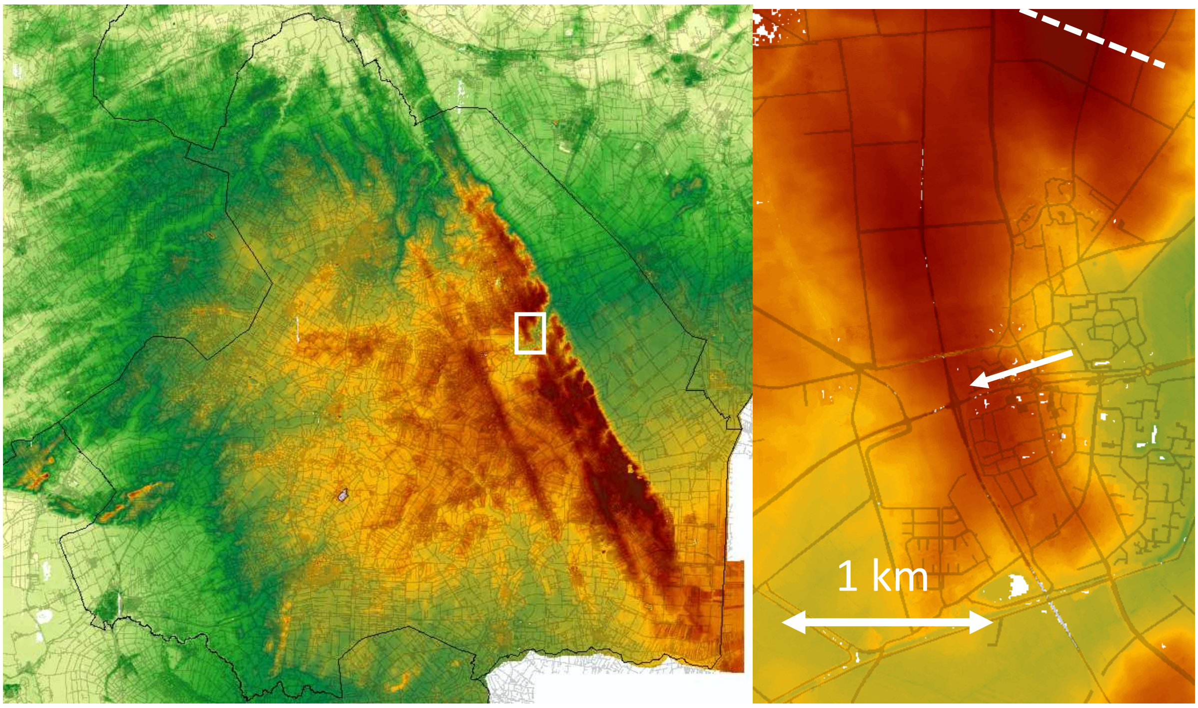


Figure 4.11 A) location of the outcrop in the Hondsrug and B) detail chart of the outcrop at Borger. White arrow marks location of the outcrop. White dashed line indicates GPR transect.

4.4.1 Lithostratigraphy

The stratigraphy contains two major units [Figure 4.13]. At this location, red till is surfacing and has a thickness varying in between 1 and 2 meter. These sediments are underlain by fine white laminated sands and the contact between these units is of erosional character. At some places, boulder accumulations occur at the contact surface between pre-glacial sediments and till.

4.4.2 Structures

Compared to the location of Gieten, which is just situated 10 km north-west of Borger, the outcrop shows very different features and has a completely different stratigraphic sequence. The ductile deformed pre-glacial sediments [Figure 4.12A] reflect compressional forces since shortening is observed. Figure 4.12B shows a thrust sheet of till and the occurrence of recumbent folds, which reflect compression from the NW (parallel to the ice stream movement). At these places, maximum till thickness occurs. Figure 4.14 shows a large subglacial channel, incised into the pre-glacial sediments and its 7 m thick infill is red till. The orientation of this channel is NE-SW, perpendicular to the direction of the ice stream.

In the pre-glacial sediments, ductile folding is the dominant type of deformation. The recumbent folds in the till are cut off by a thrust sheet, which reflects brittle deformation as well.

Locally, boulder accumulations occur on the lee side of an obstacle made up from pre-glacial sediment [Figure 4.12A].

North of viaduct, east face

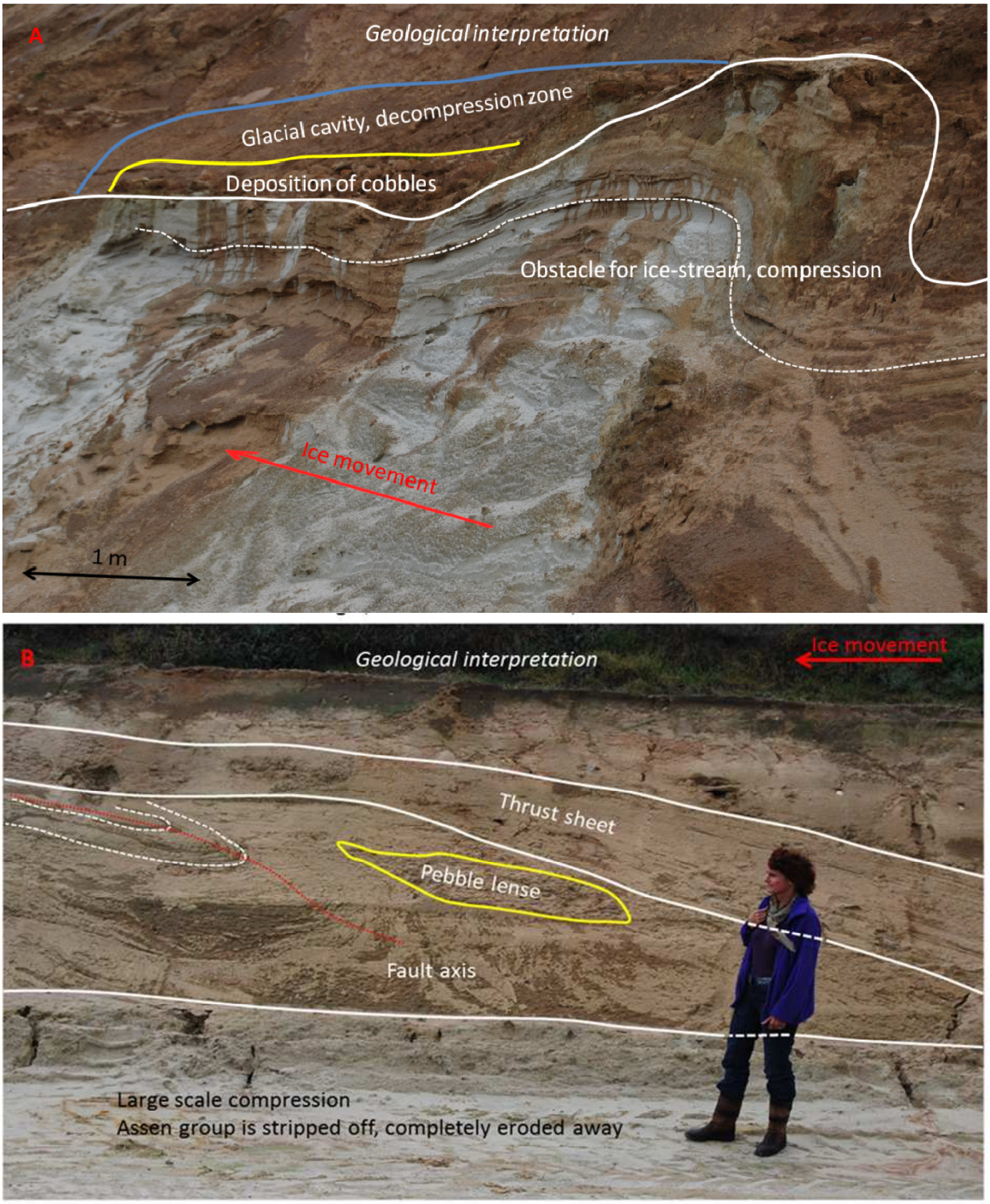


Figure 4.12; A) Boulder accumulations on the lee side of a cavity; B) Large compressional forces are relfected in the sediment: thrust sheets, recumbent faults and incorporated lenses.

Borger: North of the viaduct, East face

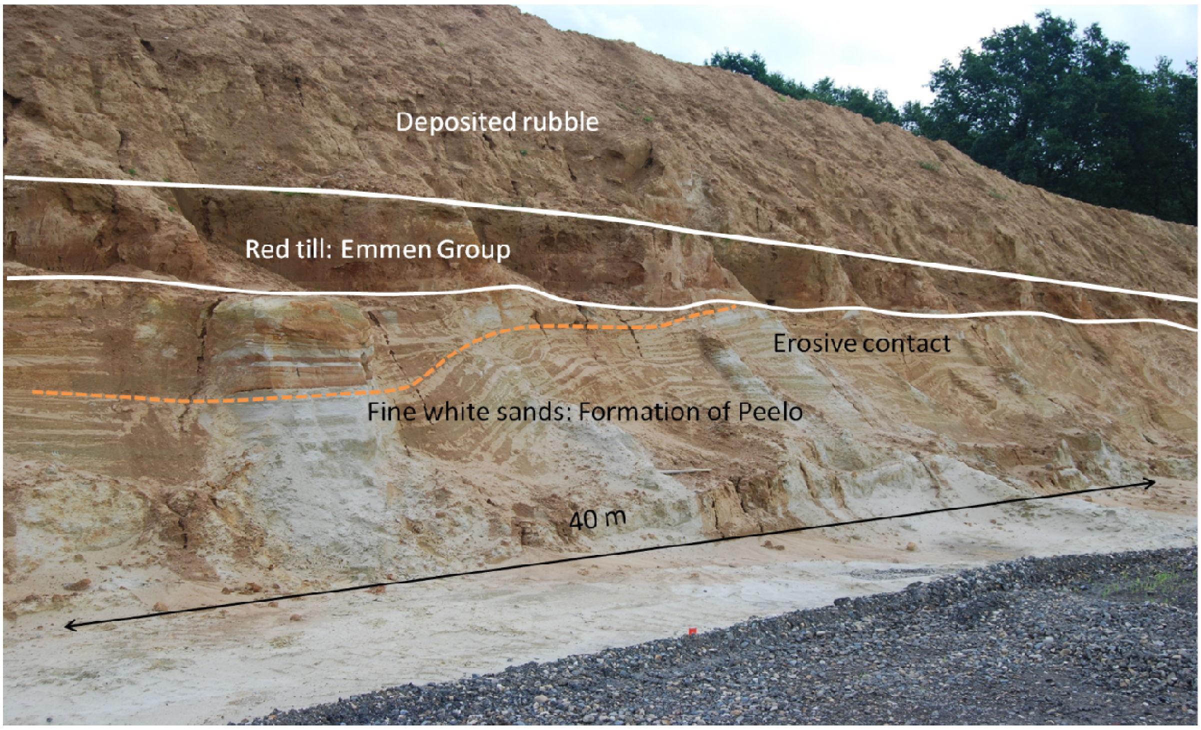


Figure 4.13. Outcrop at Borger (Photographic copyright by E.P.H. Bregman)

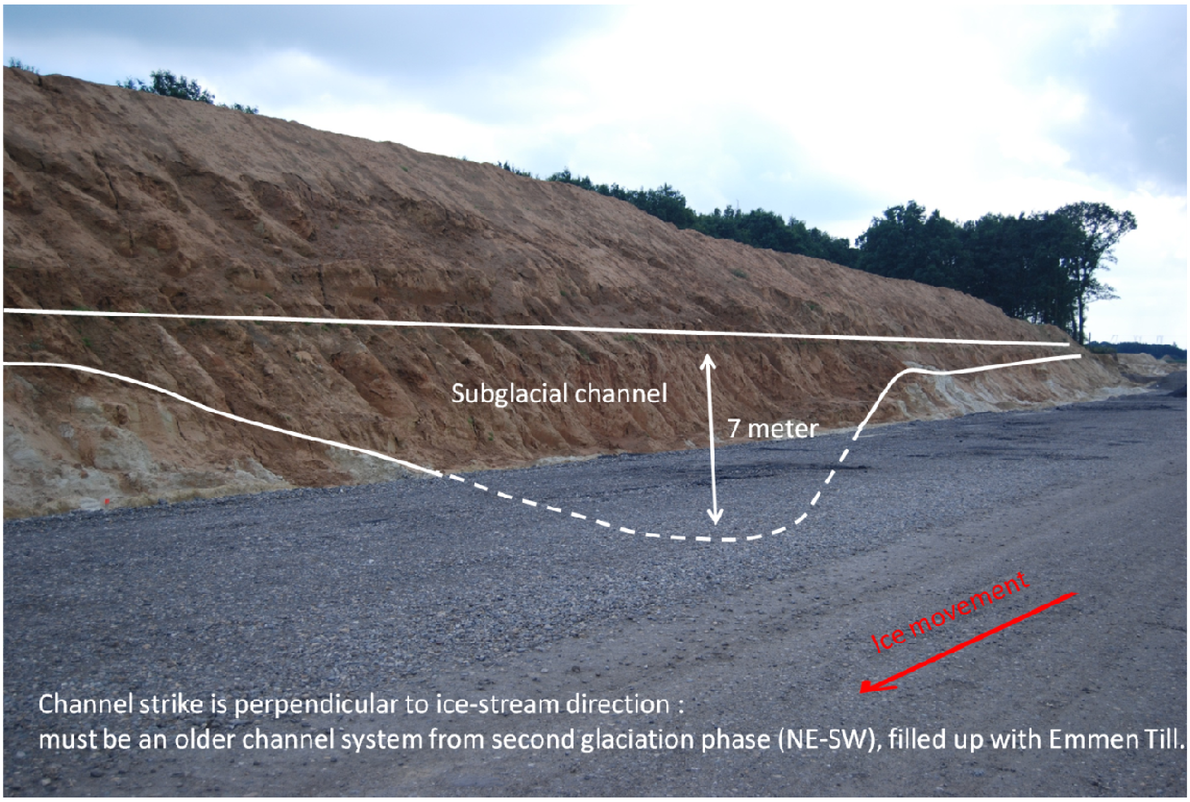


Figure 4.14; A large subglacial meltwater channel, with a perpendicular orientation relative to the ice stream movement. If hydraulic gradient was along the ice stream, this would reflect an older glacial channel. If the hydraulic gradient became lower towards the side of the ice stream, this channel can be formed by the ice stream as well.

4.5 Location 5: Valthe/Odoorn: GPR – measurements

From this area [Figure 4.15], no (recent) outcrop information is available. We performed GPR-measurements to obtain seismic data of the tills and pre-glacial sediments, to extract information from these cross-sections. Main question is to get insight on deformation rate and direction. In addition to the GPR-measurements, hand-core drillings have been performed to obtain lithological information about this region, with a reference to Dubois (1902), who did his fieldwork in the same area, and provides adequate data in addition.

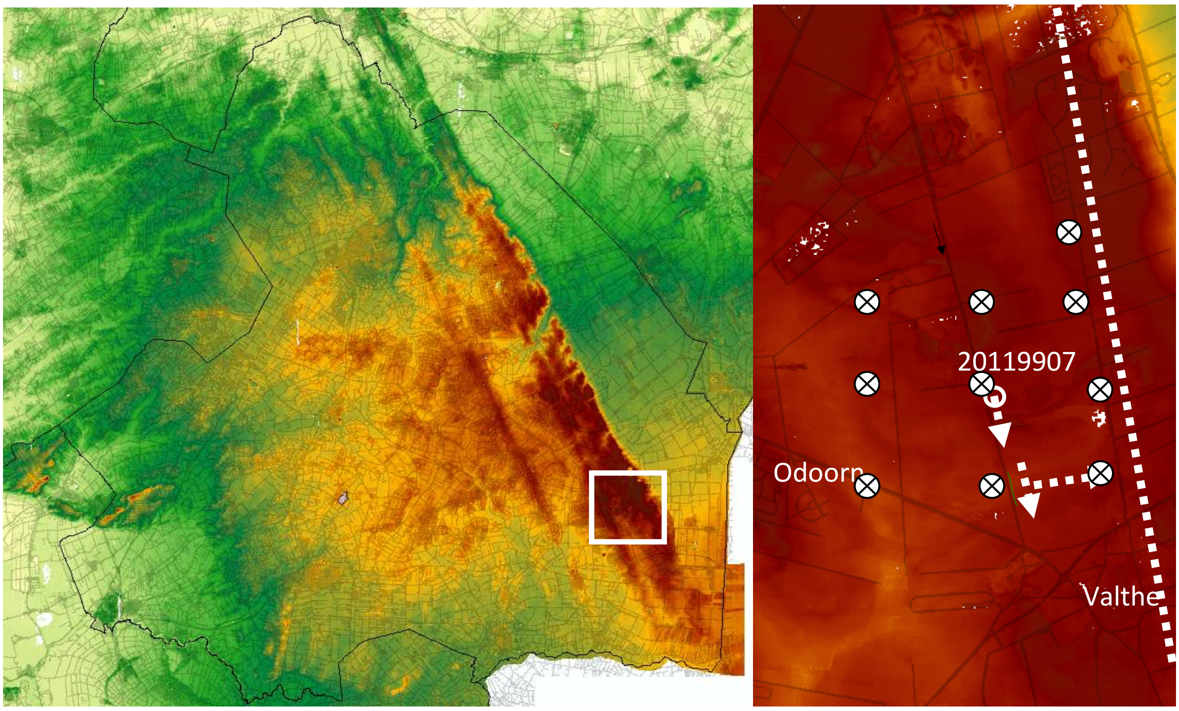


Figure 4.15; A) Location of the outcrop on the Hondsrug and B) Detail chart of the location. White arrows mark GPR-locations. Circle shows bore-hole location. Dotted line shows railroad construction from Dubois (1902) Circle with cross shows locations of the NITG-borehole descriptions.

4.5.1 Lithostratigraphy

From core 20119907 [Figure 4.16], the following lithologies are found from bottom to top: i) between **1.50 – 1.30 m** grey rigid loam which contains crushed pebbles with a diameter of 1 cm. ii) between **1.20 – 0.2 m** yellow extremely loamy to very loamy sand (150-210 μm). From the DINO-database (Table 2) it becomes clear that the thickness of the till in this area is highly variable; it varies from absent to 2.1m thick. Where till is absent, fine sand or silt-rich sand occurs. Dubois (1920) observed the same two types of lithostratigraphy, which corresponds to his succession A (no till, but boulder sand) and succession B (1-1.5m till).

4.5.2 structures

GPR-measurements [Appendix C] show two cross-sections that have been taken near Valthe and are perpendicular orientated. The first cross-section is taken south to North and shows a lightly chaotic pattern. Deformation of the pre-glacial is not easy recognized. At X=90m, a small step in the water table is observed and might indicate a dipping clay layer (pers. comm. M. Bakker TNO). In the West to East cross-section, some thrust sheets can be recognized in the subsurface (depth around 3m) and are located in the pre-glacial sand. Their crests face towards the E, or NE.

Boorpunt: 201199007 Namen: Smit Jaar: 2011 Groep: 99 Datum: 22-3-2011

Coordinaten			Hoogte	Diepte
XCO	YCO	Coord. sys	Z [m +/- NAP]	[cm]
254833	542271	RD	22,4	150

KAARTEENHEID	Geomorfogenetische kaart:
Geologische kaart:	Gondwatertrap:
Begroeiingskaart:	Bodemkaart:

X = 40m langs de dwarsdoorsnede

Diepte	Textuur	Org	Plr	Kleur	RedOx	Grind	M50	Ca	Fe	GW	M	LKL	Strat	Bijzonderheden
10														ger
20	ULZ			orge		1	150-210						D	ger
30	ULZ			orge		1	150-210						D	
40	ULZ			ge		1	150-210						D	spoor FG 1mm
50	ULZ			ge		1	150-210						D	spoor FG 1mm
60	ULZ			ge		1	150-210						D	spoor FG 1mm
70	ULZ			ge		1	150-210						D	spoor FG 1mm
80	ULZ			ge		1	150-210						D	
90	MLZ			ge		1	150-210						D	GGD = 4mm
100	MLZ			ge		1	150-210						D	GGD = 4mm
110	ULZ			ge									D	
120	ULZ			ge									D	Stug, GGD = 1 cm
130	L			gr									D	Stug, GGD = 1 cm
140	Z-L			gr									D	Stug, GGD = 1 cm
150	L			gr									D	Stug, GGD = 1 cm

Einde boring: 201199007

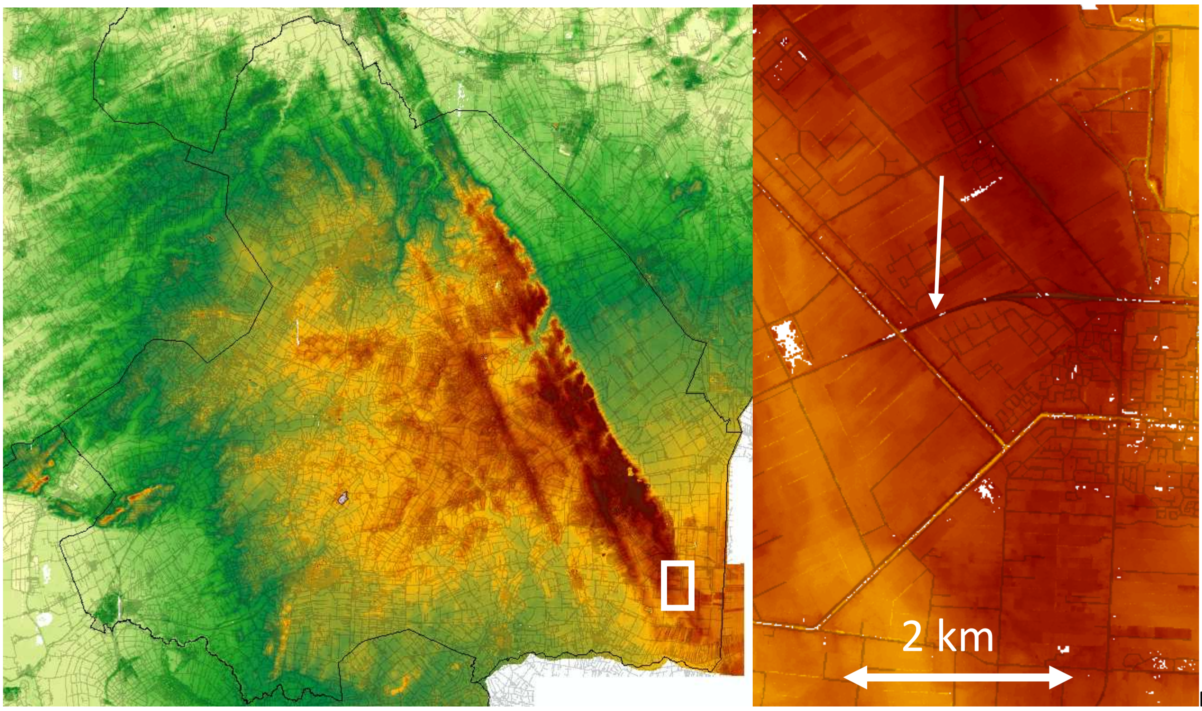
Figure 4.16; *Core 201199007*: location North of Valthe and Odoorn.

NITG-nr	Sand	Till/loam	Till-thickness(m)
B17F0521	0 – 1.6m; 2 – 2.4m	1.6 -2 m	0.4
B17F0522	0 – 0.8m; 0.8 - 1.8m (silt-rich); 1.8 – 2.4m	absent	0
B17F0525	0 - 0.8m ;1.2 – bottom	0.8 – 1.2m	0.4
B17F0526	0 – 1.1m; 1.7 – bottom	1.1 – 1.7m	0.6
B17F0527	0 – 2.4m	Absent	0
B17F0529	0 – 1.45m	1.45 – 3.6m	2.15
B17F0530	0 – 2.4m	Absent	0
B17F0531	0 – 1.3m; 1.7 – 2.2m	1.6 – 2m; 2.2 - 2.5m	0.4, 0.3
B17F0618	0 – 0.3 m; 0.3 – 1.3m (silt-rich); 1.3 – bottom	Absent	0
B17F0621	0 – 1.6m; 2 – 2.4m	1.6 – 2m	0.4

Table 2. NITG-TNO borehole descriptions. Sand is usually fine grained or stated otherwise. Bore-holes are in a radius of 600m from the GPR-location.

4.6 Location 6: Klazienaveen

The outcrop is situated furthest downstream on the ice stream and is located on the Hondsrug [Figure 4.17] .



F

igure 4.17; A) Location on the Hondsrug c; B) detail chart of the region of Klazienaveen. White arrow marks the outcrop location

4.6.1 Lithostratigraphy

At the bottom of the outcrop [Figure 4.18], very fine light-grey sand (105 – 150μm) is found. It is well rounded and well sorted and contains some loamy laminations that show minor ductile deformation. In contrast to the other locations, this sand does not contain mica minerals.

A sharp transition to a purple-grey till occurs; at this contact surface, crushed granites have been observed [Figure 4.19D]. The total thickness of this till is approximately 1.5 m and contains alternations of gravel rich layers (≈30 cm) and more clay rich layers (≈30 cm). The gravel rich layers contain abundant pulverized pebbles. Flint pebbles do occur in this till.

The purple till is overlain by a red till, which is much loamier and contains high concentration of pebbles. The red color is attributed to a high concentration of hematite rich rocks and due to regional uptake of iron rich sediments. Flint is absent in this till. The contact surface is irregular shaped [Figure 4.18] and seems to have flown into depressions in the grey till. Its thickness varies due to the nature of the contact surface, but is generally is around 1 m. At the same location not far from the described outcrop, the contact surface is differently developed: a sandy layer occurs in between the two tills [Figure 4.19C].

The red till is overlain by a 1m thick sequence of yellow fine sand (150-210μm), which is well rounded and well sorted. The contact surface with the underlying till is sometimes irregular [Figure 4.18] and iron concretion occur near the boundary. On top of the yellow fine sand lies a 30 cm thick layer of peat normally, but is dug out at the outcrop.

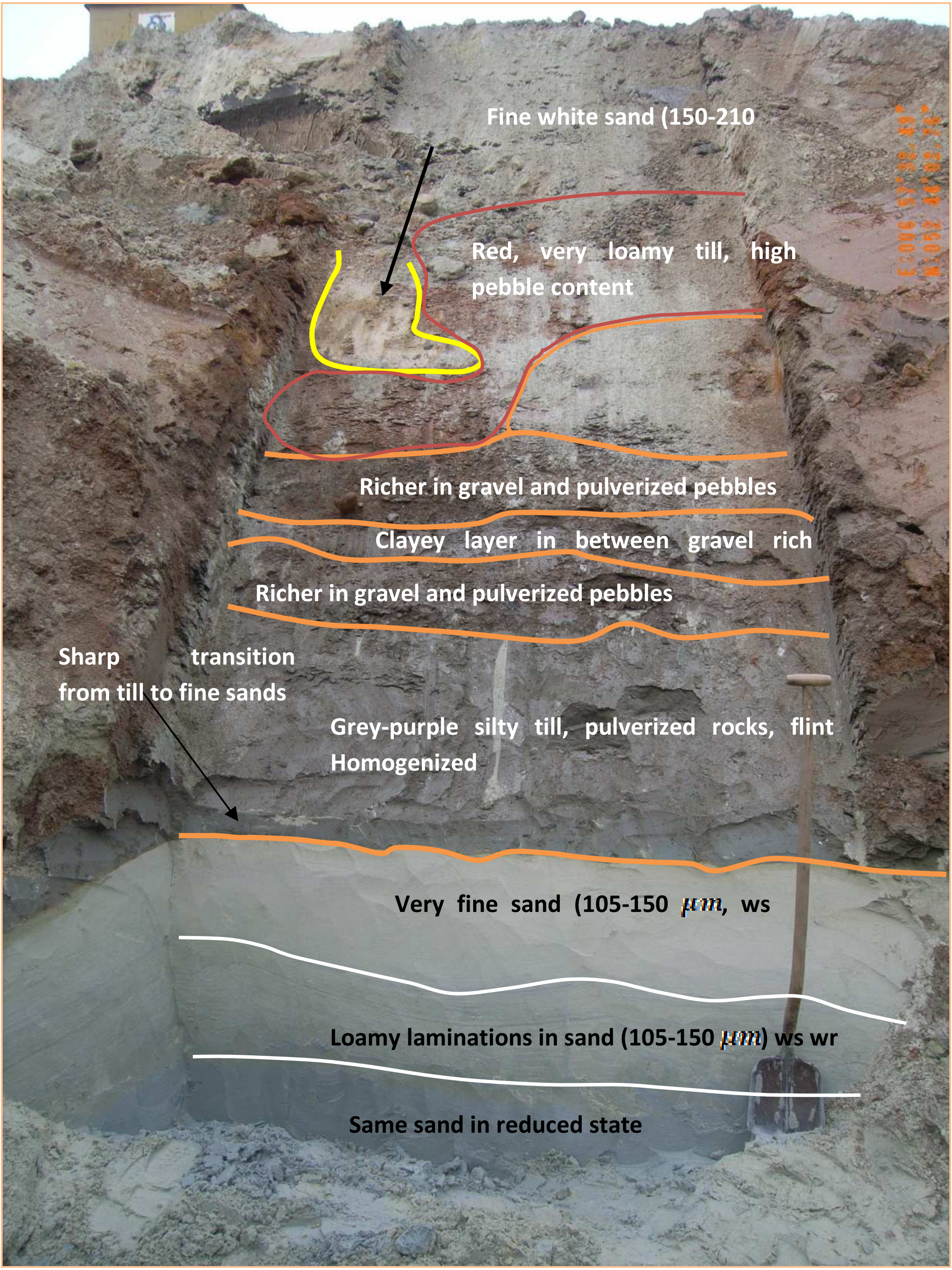


Figure 4.18. Outcrop at Klazienaveen. Note the sharp transition of the till and pre-glacial sand. (Copyright by F.W.H. Smit)

4.6.2 Structures

Characteristic of this outcrop is the sharp transition of the tills with the underlying fine sand and the undisturbed laminations of these latter sediments. The top of the purple till has an undulating surface and filled in with red till, and sometimes a sandy layer occurs in between the tills. The fine yellow sands on top of the red tills are at some locations flown into the red tills. This is the result of cryoturbation processes. The laminations of the very fine light-grey sand show only minor ductile deformation structures. Clastic dykes occur in the grey till, and are filled with very fine white sand. Smaller inclusions of these sands are found in the grey till, but seem not to constitute clastic dykes.

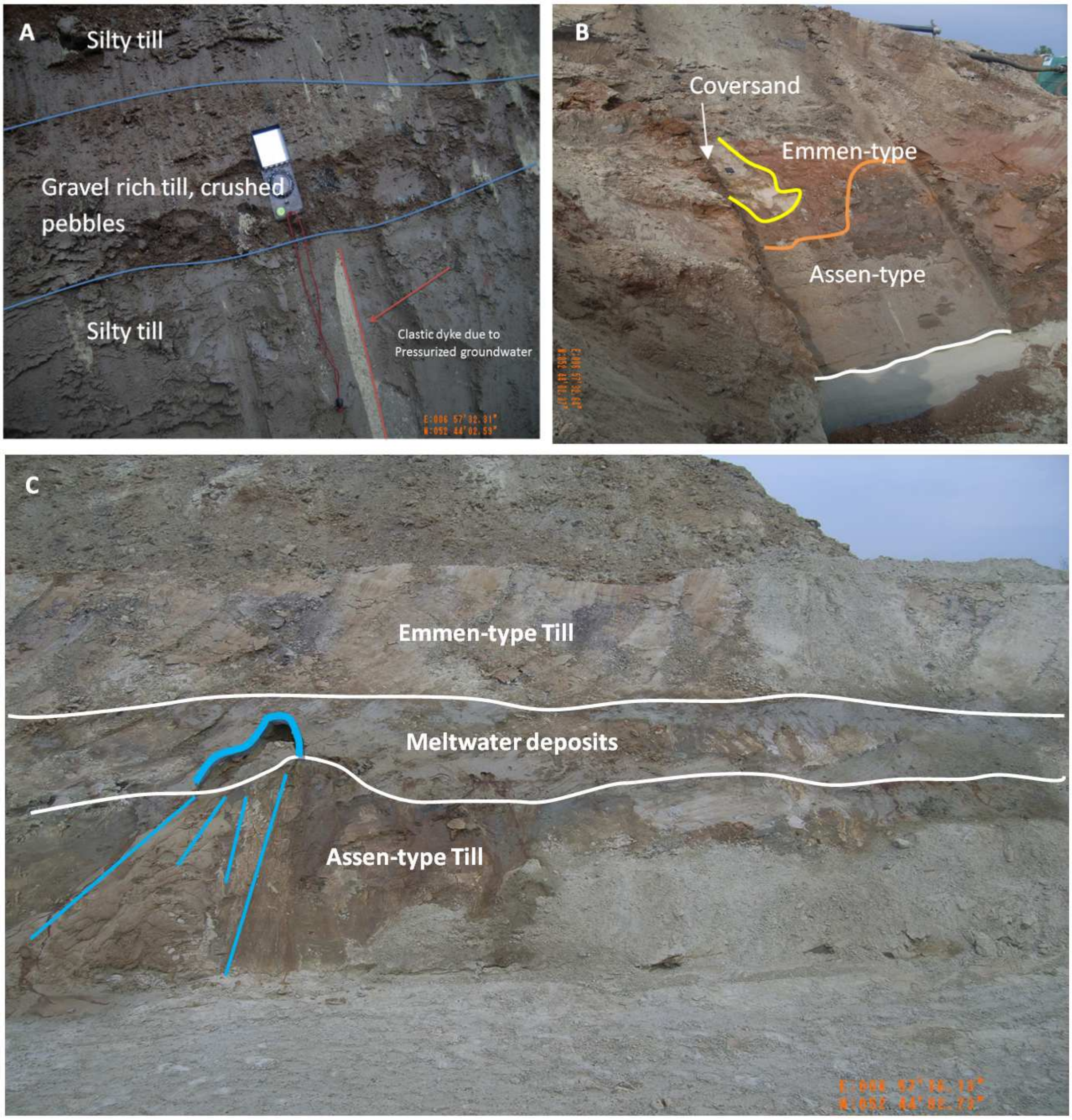


Figure 4.19; A) Alternations of silt content of the till and a clastic dyke containing sand from the underlying sand body; B) Detail of the nature of the contact between Assen-type Till and Emmen-type Till; C) Sandy ('meltwater deposits') in between the Assen and Emmen-type till. These layers are highly permeable compared to tills, making them important in groundwater flow. This is reflected in the seepage of groundwater during excavation (blue lines); D) Crushed granite at the contact surface of Assen-type till and the Drachten Fm.

5. Interpretation

First, the geological interpretation will be discussed of each of the described locations, thereafter followed by the glaciological interpretation. We will relate the situation at the location to the classification of glaciological processes occurring under a flowing ice stream with the system of Jørgensen and Piotrowski, 2003; Figure 3.3: divide it into subglacial processes A t/m F.

5.1 Location 1: Donderen

5.1.1 Geological interpretation

The fine white sand at the bottom of the outcrop belongs to the Peelo Formation. These sediments formed during the last phase of the Elsterian glaciation and are fluvioglacial in origin. The coarse sand with loamy alternations is interpreted as the remnants of glacial till, as is evident from the pebbles within the sediment. These sediments belong to the Drenthe Formation, since they have a glacial origin. More specifically, they belong to the Gasselte Member of the Drenthe Formation since they are the result of washing out of the fines. The fine, well sorted yellow sands with loamy laminations can be interpreted to be snow meltwater deposits. They belong to the Boxtel Formation and are deposited during the the Weichselian glaciation. The yellow fine sand on top of these loamy laminations is interpreted to be aeolian coversand from the late-Weichselian. The organic rich topsoil may be anthropogenic of origin, since it occurs next to an 'esdorp'. Thus in general, the outcrop contains four major units based on deposition environment. These are (from top to bottom): aeolian sand (Boxtel Formation), snow meltwater deposits (Boxtel Formation), residue of glacial till (Drenthe Fm., Gasselte Member) and fluvioglacial sand (Peelo Formation.)

5.1.2 Glaciological interpretation

The remnants of glacial tills at Donderen reflect a large basal water pressure which can be the result of large meltwater fluxes or insufficient drainage via groundwater discharge. Major erosion occurs just before the flotation point is reached (Jørgensen and Piotrowski, 2003; Figure 3.3). Remnants of tills, implicates presence of till deposition in a previous stage when basal water pressure was somewhat lower (category subglacial process: A). An increase in basal water pressure has occurred through time in this region. There are some mechanisms to describe that would result in an increase of basal water pressure.

The permeability of the aquifer underneath the ice stream was low, since it was made up from fine sands and clays of the Peelo Formation. Therefore, basal water pressure could increase readily, since the aquifer was quickly water saturated (see paragraph 3.1). In addition, the occurrence of salt diapirs downstream of this location (Anloo; Gasselte; Drouwen), meant a sub-topographic obstacle for the ice stream movement leading to compressional forces. The formation of brine water impeded groundwater to freeze near the surface, such that it could facilitate an increase in basal water pressure as well in the area of Donderen to Borger.

The glaciological reconstruction can be summarized as following: basal water pressure was low in the earliest phase, leading to high effective pressure and till deposition. It increased rapidly due to the saturation of the underlying fine grained aquifer, leading to the erosion phase (category subglacial process: C). The till sequence was almost completely eroded away, leaving behind its remnants consisting of coarse grained sediment with pebbles, which belongs to the Gasselte Member of the Drenthe Formation.

5.2 Location 2: Gieten

5.2.1 Geological interpretation (East branch of the Hondsrug)

The tills show an extremely varying lithology and different colours compared to west of the roundabout, which makes interpretation in terms of till types very difficult. Colour as criterion for attributing the diamict to a till type, as described in paragraph 3.6, cannot be utilized at this outcrop, since oxidation tends to make all the tills rusty brown. Flint content provides the division of Emmen- to Assen-Group, while the distinction with the Voorst-group is based on its geometry and the occurrence of limestone concretions.

The white sand at a depth of 7 meters belongs in general to the Peelo Formation. Since the sand is intensely deformed, the occurrence of very coarse sand with gravel at this location may indicate 1) outcropping of (older) Peize formation, since these layers have been uplifted by the underlying salt diapir [Appendix A] and may further pushed by the glacier; 2) washed out older till. The rusty-brown till at the bottom of the outcrop contained flint and was calcareous, therefore can be classified as the Noordhorn-type till. This till is a ground moraine and plastered onto the land by lodgement. Its contact surface with the overlying sediment is undulating between 0.5 m and 1.5 m as the result of glacial scour or subglacial deformation. The complex of grey till, sand and red loamy sediments can be thought to be a deformation till which includes Voorst-type till, pre-glacial sand of the Peelo Formation and part of the Nieuweschoot-type till. The red till on top of this infill belongs to the Emmen-type and its erosional contact has been cryoturbated. The sandy inclusions that are faulted could be transported as englacial debris since no pebbles have been found that suggest another genetic origin. The fine yellow sand on top of the sequence can be interpreted as periglacial sediment from the Weichselian (Boxtel Formation).

5.2.2 Geological interpretation (West branch of the Hondsrug)

On the other side of the roundabout, the stratigraphic sequence is different. Fine white sands do occur at the bottom of the outcrop, and belong to the Peelo Formation. On top of these sediments, grey till is found which can be assigned to the Assen-type till, since it was decalcified (pers. comm. Huisman, June 2011). Inside the grey till, the sandy layers and the till below reflect that meltwater has washed out the fines. The till on top of this sandy layer showed crushed pebbles, suggesting high effective pressures were applied. Above the grey till, fine loamy sand was found, which can be interpreted to be periglacial, glaciofluvial or aeolian in origin and belong to the Boxtel Formation. The peat layer on top of these sediments are formed in a round depression (Geomorphological Map, 2010), which may have been part of a Pingo-ruin. The peat layer belongs to Nieuwkoop Formation.

5.2.3 Glaciological interpretation (East branch of the Hondsrug)

In contrast to the area of Donderen, the stratigraphy of the area around Gieten contains thick sequences of till. Till deposition occurs when the friction between the debris carpet at the glacier sole and the glacier bed becomes so large that the basal debris is deposited: a lodgement till. The Noordhorn till at the bottom of the outcrop can be thought to be a lodgement till, since it makes up the ground moraine deposit. Till deposition occurs at the moment that effective pressure is relatively large, and thus basal water pressure is low. In the model of Jørgensen and Piotrowski (2003) this occurs at some point in time when basal water pressure is relative low (A in the category of subglacial processes). The undulating surface of the Noordhorn till suggests glacial scour and deformation of the lodgement till during further overriding.

The sediment complex reflects a succeeding phase of large scale deformation and mixing. Undisturbed melting of the till from the ice stream would lead to Emmen on Assen till (as is observed in Klazienaveen, paragraph 4.6). The occurrence of other sediment that is located in between the tills, suggest another stage in glacial scour occurred. The occurrence of pre-glacial sediments and Voorst-type till in the complex suggests that the ice stream has scraped off the sediments from the bed upstream (maybe from North of Drenthe, Donderen, paragraph 4.1) and transported it towards Gieten, where it was mixed together and deposited in the previously scoured depressions. This phase was succeeded by deposition of the Nieuweschoot-type till. Since the contact surface of this till with the overlying periglacial sand contains a boulder accumulation, erosion must have occurred by snow meltwater from the last glacial or during the final meltdown of the ice stream (since ice is relatively 'clean' higher up the glacier). The fact that these tills are mostly calcareous is due to 1) the thick sequence of till that is almost impermeable to rain water and 2) the fast covering of freshly scraped surfaces by new deposits.

5.2.4 Glaciological interpretation (West branch of the Hondsrug)

Drag-structures in the pre-glacial sand indicate that the ice stream was coupled to its bed and large shear strains were applied to it. This led to erosion as well, since the contact surface of Assen-type till and the pre-glacial sediment is very sharp. As the effective pressure reached levels where till deposition was favoured, the Noordhorn-type till was deposited as lodgement till (later on, decalcification made it an Assen-type till). A channel occurred beneath the grey till which was filled in with very coarse sediments. It may therefore be a subglacial meltwater channel, which formed during deposition of the grey till and as a result of insufficient drainage. The deformation till (sediment complex) is absent at the west branch of the Hondsrug, suggesting either non-deposition or erosion.

Since the Emmen-type till does occur on the west branch, but in isolated patches on the highest points of the Hondsrug, erosion might be the process that led to the absence of the tills that are found on the east branch (sediment complex, Emmen group). But erosion of such thick sequences including the boulder rich Emmen group would at least leave a trace of a boulder pavement on top of the Assen group, but this is not observed at this location. The suggestion of locally non-deposition of Emmen till is may be related to the ice flow from the direction of Norg (see also Chapter 6.2). At other places on the western branch, erosional remnants of the Emmen-type till (this till contained the largest boulder concentrations) did indeed show up in a more downstream direction.

Due to the occurrence of thick (impermeable) till sequences, basal water pressures might have risen to levels where erosion is the most important process (region C of subglacial processes). On the eastern branch, friction with the dead-ice body could have led to slower movement and more compressional forces in this part of the ice stream, while the ice stream a bit west could continue flowing due to lesser friction. These marginal ridges are sometimes observed at the frictional borders of ice streams and dead-ice bodies, where internal friction within a small zone leads to higher meltwater production, erosion and sedimentation as well. That explains why in these so called ice-contact marginal ridge (Bennet & Glasser, 2007) of the western branch at Gieten do have islands of till deposits of the Assen type, where till concretions of the so called "schollen-till" (thrust-sheeted till) of the Oude Mirdummer-type occur in the upper parts of the till, which is a non-calcareous, very clay-rich till type, with erratics similar the calcareous Voorst type.

5.2.5 Palaeo-reconstruction (eastern branch)

In one of the first phases, erosion of the older tills and pre-glacial sediments occurred, since Noordhorn-till lies directly on the pre-glacial sediments. Deformation of the pre-glacial sediments is inherited from previous glaciations, since it dips towards the NE. Effective pressures raise to levels at which deposition of lodgement till (Noordhorn-type, Assen Group) occurred due to a decrease in basal water pressure or increase in ice weight. Subglacial scour into the till led to an undulating surface of the Noordhorn till. Subsequent deposition and deformation of subglacial/englacial debris led to the sediment complex. Degradation of the ice stream led to the deposition of the Nieuweschoot till on top of the complex. Due to (meltwater) erosion of the top of this till, a boulder pavement formed. Periglacial deposits from the last glaciation covered this surface, and were cryoturbated during the Pleniglacial. Soil- forming processes started during the Holocene, when climate was more favourable.

Hydraulic piping has occurred at this location as well [Figure 4.8A], which means that the pressure in the underlying aquifer (at the bottom of the till) was elevated to a critical point where it became larger than the pressure at the top of the till. This has led to hydro fracturing of the till and the injection of pre-glacial sediment upwards. More indicators of insufficient drainage are the formation of subglacial meltwater channels [Figure 4.8E] into the Peelo Formation and ductile deformation structures in the pre-glacial sand that indicate high pore-water pressures.

5.2.6 Palaeo-reconstruction (western branch)

The main difference with the eastern branch is the absence of Emmen-type till and the sediment complex, and the decalcified parts of the grey till. As described, flotation may have led to non-deposition from the Assen-type till onwards. The fact that the till is decalcified can be explained (partly) by this absence as well, because rainwater may have been able to infiltrate into the till. The occurrence of a thick peat sequences (3m thick) few meters south of this location may have helped decalcification as well by producing acid water. The peat is deposited in a depression which was located at the spring of a meltwater valley (Geomorphological map of Drenthe, 2009). The observation that the till was in a reduced state can be explained by the occurrence of this peat sequence as well, since it consumes all the oxygen from the water.

An important conclusion that can be drawn on the basis of the outcrops in Gieten is that the glacier bed was not frozen. The occurrence of meltwater deformation and flowing structures, indicate an unfrozen bed and very high waterpressures ($P_{w's}$).

5.3 Location 3: Gasselte

5.3.1 Geological interpretation

The coarse sand below the red till has a glacial origin and the occurrence of pebbles and a large grain median reflect this origin. Since the grey till is absent at this outcrop, the coarse sand can be thought as the erosional remnant of the Assen-type till (and maybe a fraction of the Emmen-type till). It therefore belongs to the Gasselte Member of the Drenthe Formation, which type locality is not far for the outcrop location. The angular unconformity reflects this erosional character of the site as well.

5.3.2 Glaciological interpretation

Till deposition must have occurred in an early phase (Region A), when basal water pressure was low (e.g. Van der Meer, 2003).

An explanation for the formation of these structures could be that after saturation of the aquifer, basal water pressure increased rapidly to levels that major erosion took place (C in subglacial processes). The deposited till suffered high rates of meltwater erosion, which transported away the fine fraction and leaving behind the coarse grained sediments. These sediments could drain the meltwater more efficient, leading to a decrease in basal water pressure and brittle deformation of these layers. Further lowering of the basal water pressure led to renewed till deposition and (part of) the Emmen-type Till was deposited. In this case, it could be possible that the Gasselte outcrop is part of a sub-glacial drainage system, with NNE –WSW direction (e.g. perpendicular to the ice stream direction) which channel infillings are also found in the sandpits west of the described outcrop in the Gasselterveld. This explanation supposes a very high basal water pressure and transport of meltwater from the east.

5.4 Location 4: Borger

5.4.1 Geological interpretation

The red till surfaces at this location is classified to the Drenthe Formation and more specific as the Emmen-type till (c.f. Zandstra, 1976). The contact surface with the underlying fine sands of the Peelo Formation has an erosional character as it reflected by the cut-off of laminations. The Assen-type till (grey till) is missing at this location, as well as coversand from the Weichselian.

5.4.2 Glaciological interpretation

Till deposition occurred during times of low basal water pressure (region A in subglacial processes; e.g. Van der Meer, 2003). Increasing basal water pressure led to a shift in ice stream behaviour from region A to region C (from deposition to erosion). The grey tills of the Assen-type were completely eroded away. This could have happen in one event, or in multiple stages through time. No remnants of the till have been found at the location of the outcrop, but further downstream large accumulations of glacial rubble have been observed, which might constitute the former till. The ice stream may have reached flotation point several times, but deformation was the dominant mechanism. This is reflected in the ductile deformation of the pre-glacial sediments, which have been deformed in such a way that they locally act as subglacial obstacles. This has led to the formation of subglacial cavities and the occurrence of boulder accumulations on the lee side of this obstacle [Figure 4.12A]. Preglacial sediments are found as frozen blocks in the tills, which indicates a (partly) frozen glacier bed. This contributed to higher deformation of the glacier sole too.

GPR measurement in transects from Buinen to Drouwen and from Drouwen to Borger [Figure 4.15, Appendix B/C] showed that the pre-glacial sediments still dip towards the NE (perpendicular to the ice stream direction) to ca. 12 – 18 m – s.l. and indicates an older glaciation phase, with relative shallow deformation by the Hondrug-Hümmling Ice stream at the top of the sequence. Cryoturbation during the last glacial could also have altered the structures.

5.5 Location 5: GPR – measurements at Valthe/Odoorn

5.5.1 Geological interpretation

The DINO-database borehole descriptions have shown that the till thickness varies extremely at this location. Observations from Dubois (1902) confirm the occurrence of two types of stratigraphy on the ridge (a third is defined for the valley in between the ridges; see paragraph 1.5.2). Moreover, the geological cross-section of 1977 shows that the Drenthe Formation largely disappears at this site (B17H113).

The GPR-measurements have shown only minor deformation of the pre-glacial and were dipping towards NE [Appendix C]. The DINO-database boreholes often show a stratigraphy with medium/fine sand with some pebbles which can be interpreted as boulder sand. From the geomorphological map (2010), it becomes clear that in this the area glacial meltwater valleys occur and drift-sand areas. This explains the variation in till thickness and the occurrence of boulder sand, since erosion of the till took place. The lower pre-glacial sediment belongs to the Drachten Formation (Eindhoven Fm. on the geological cross-section of Appendix A). It is overlain by brown-yellow fine grained (150-210μm) that can be interpreted as Weichselian coversand: Boxtel Formation. In borehole 201199007, very loamy yellow sand is found with pebbles on top of a grey till. Both types of sediments do belong to the Drenthe Formation since they have a glacial origin. The grey till must belong to the Assen-type, while the yellow loamy sediments may be partly washed out Emmen-type till or loose deposition of basal debris from the glacier sole.

5.4.2 Glaciological interpretation

Till deposition has occurred at the location of Valthe/Odoorn as is witnessed by the occurrence of tough lodgement till. From the GPR-measurements it became clear that the pre-glacial surface has not suffered (glaciotectonic) deformation from the ice stream, since the pre-glacial sediments still dip towards the NE (category subglacial process: A). This is conform the GPR measurements in the transects near Drouwen, which indicates an older glaciation phase and relative shallow deformation of the Hondsrug-Hümmling Ice stream. This might indicate that basal water pressures were high at both locations during most time and might have reached flotation point.

High basal water pressures may have been the result of permafrost occurring at this location, and the initial deposition of till might have impeded drainage even further. Permafrost decreases the permeability of the sediment with several orders of magnitude compared to the unfrozen state (Boulton *et al.,* 2001). This leads to insufficient drainage of the meltwater, which can elevate basal water pressure to the point that it exceeds the pressure of the overburden ice. As the flotation point is exceeded, the ice stream begins to slide on the pressurized water layer and deformation stops. Till deposition has shown to be rather uneven distributed, which could be the result of subglacial erosion of the till by the pressurized water layer.

5.6 Location 5: Klazienaveen

5.6.1 Geological interpretation

The very fine light-grey sands could belong to the Peelo Formation, based on grain size, but the lack in micas is in general a clear indicator that they belong to another formation. They can therefore be interpreted to belong to the Drachten Formation, which are interpreted as aeolian deposits from the Early Saalian (≈200 kyr BP). This is confirmed in the geological cross-sections along the Hondsrug from the Geological Survey of 1977 (Appendix A, Rijks Geologische Dienst, 1977), showing that the Peelo Formation ceases to exist south of Emmen.

Due to the occurrence of flint in the purple-grey till, this till can be interpreted to be the Assen-type till. The contact surface with the underlying strata is very sharp and crushed granites occur at this boundary. Moreover, lower part of the grey till contains a high fraction of pulverized pebbles that indicate that the sediment has been exposed to very high pressures. This can thus be interpreted as a ground moraine and the sediment as a deformation till, since the lower 1 meter of till has been homogenized [Figure 4.18]. The sharp transition with the underlying pre-glacial sediments is often observed with deformation tills, which tend to act as a shear strain buffer for the underlying strata (Boulton *et al.* 2001). The stratification in the upper part of the grey till (e.g. the alternation of gravely and more clayey sediments) suggest homogenization did not occur in this part. This would argue for a lodgement till or a (subglacial) melt-out till. In case of the latter, it reflects englacial stratification of debris. But since these sediments do contain completely crushed granites as well, it can only be a lodgement till.

The red tills do not contain flint, and can be interpreted to be the Emmen-type till. Two types of contact surfaces have been observed, one in which the till lays immediately on the Assen-type till and one where a sandy layers divides the two tills. Where it lies immediately on the Assen till, the structures reflect that it has flown into the depressions of the Assen till, suggesting a melt-out till. The sandy layer in between the tills may be interpreted as a meltwater deposit and may reflect high meltwater discharge during the degradation of the ice stream. This pattern has been observed elsewhere on the Hondsrug-complex (such as Gieten) as well, suggesting that such event might occurred time-transgressive.

The fine yellow sand (150 – 210μm) that overlies the red till, may be interpreted as coversand from the Weichselian and belongs to the Boxtel Formation. It has been deposited during the coldest parts of the last glaciation and has been cryoturbated during periglacial conditions. The occurrence of iron-concretions is the result of stagnating water due to the occurrence of relative impermeable tills.

On top of the yellow sand lies a 30 cm thick sequence of peat. Its thickness only shows the remnants of a much thicker peat sequence that grown during the Holocene as a result of rising groundwater levels. This peat belongs to the Nieuwkoop Formation and due to its specific plant content (*Sphagnum palustre)* to the Griendtsveen Member. The impermeable subsurface (e.g. the tills) has facilitated wet conditions that favour peat formation.

5.6.2 Glaciological interpretation

The relative undeformed tills and pre-glacial sediment and the sharp transition reflect that the glacier had not much interaction with the bed (category subglacial process: A). If that would have been the case, large scale deformation should have occurred, such as observed in the subsurface of Emmen (Zandstra, 1976). Sharp transitions between glacier bed and glacial till often reflect erosion (Boulton *et al.* 2001).

Erosion takes place during times of large basal water pressures (category subglacial process: C), and the underlying fine-grained aquifer could readily facilitate this. Basal water pressure must have dropped towards category subglacial process: A, during which the ice stream deposited the lower part of the grey till. During low basal water pressure, interaction between glacier and its bed homogenized the till. Deposition of the grey till continued, but changed to lodgement rather than deformation till, as is reflected from the stratification.

The occurrence of sandy meltwater deposits in between the two tills reflects an increase in meltwater discharge that could be the result of a degradation phase of the ice stream. This layer occurs throughout the outcrop at about the same height indicating the large scale of this event. The fact that meltwater channels did not form in reaction to this event indicates that basal meltwater could be drained sufficiently in a thin film of water beneath the glacier sole.

After this event, red till was deposited which is interpreted as a melt-out till and might reflect further degradation of the ice stream. These sediments are not washed out, which indicate a small decrease of meltwater discharge.

5.7 Geology versus glaciology

In this chapter we are linking deeper geology to surface processes (in this case flowing ice).

5.7.1 Location 1: Donderen/Zeijen

The area of Donderen lies upstream (relative to the ice stream movement) of a height in the top of the Zechstein Formation [Figure 6.1], which is located in the area surrounding Anloo. This diapir is also visible on the geological cross-section of the Geological Survey [Appendix A, 1977]. The sediments that are overlying the salt are lifted by halokinese, which creates an obstacle for ice-flow. This will lead to compressional forces [Figure 3.4] that resulted in erosion of the Urk – Enschede – and – Harderwijk Formation. Large glacial channels, which have possibly their origin from the Elsterian glaciation as subsurface drainage channels, can be seen in the area of Donderen up to a depth of 120m; the infill of which belongs to the Peelo Formation, containing fine sands and clays. Elsterian deposits are in this area surfacing now [Figure 1.2]. The lowest tills near Borger and central Drenthe are of the same type as the tills located in Zeijen, as indicated by XRPD analyses (Bregman & Lüse, in prep.) and correspond to an older phase (pre-dating the Hondsrug ice stream). In Donderen and the tills near Zeijen are strongly eroded.

5.7.2 Location 2: Gieten

The outcrop is located just downstream of a salt diapir, and may be interpreted as a decompression zone. Basal water pressure did not reach the point where large scale erosion took place (subglacial process classification: C), since this is not reflected in the sediments. This may be due its location downstream of this salt diapir of Anloo [Figure 6.1]. Delisle *et al.* (2007) have demonstrated that geothermal fluxes around salt diapirs show a pattern of anomalously high fluxes above salt diapirs and anomalously low fluxes in between. Since geothermal fluxes influence basal melting rate of a glacier, the location of Gieten in between salt diapirs may have resulted in lower meltwater fluxes, leading to lower basal water pressures. On the contrary we observed a lot of features related to drainage of subglacial meltwater and in between the west – and the east branch (paragraph 5.2) strong deformation. The absence of Emmen till on this location is maybe related to a divergent of a more westerly ice flow from the Assen type. Divergent of ice flow may be related to the deeper subsurface. South of Assen, we find a deep tectonic basin [Figure 6.1.], which is still present around Geelbroek and Eleveld: a lower area then surroundings [Figure 6.2]. We suppose that differential lowering of the area may be related to loading of the salt-ridge near Hooghalen during ice coverage, creating post-glacial compensational vertical movements. It is the same area, where in post-glacial time [Figure 6.4 A.; see also Chapter 7) differentiate rebound formed the actual river pattern of the Drentsche Aa river. This means that local lowering of the area and may be differentiate resistance of the crust by loading might have had influence on the ice flow behaviour. As we will argue in paragraph 6.3, it is in fact the same kind of interaction that we suppose for the ice stream south of Emmen, where the ice stream dipped in a steep and very deep part of the German Permian Basin (Itterbeck Basin).

5.7.3 Location 3: Gasselte

Figure 4.4 reveals that the outcrop of Gasselte is situated closely upstream to the diapir of Gasselte. In this region, one can expect to have elevated geothermal fluxes which results in a larger basal melting rate. Secondly, the occurrence of this sub-topographic obstacle will force groundwater upwards. The ice stream may experience an increased normal force since it has to overcome the obstacle, which could elevate basal water pressure further. These factors may provoke a readily increase in high basal water pressure, which led to the erosion of the tills.

5.7.4 Location 4: Borger

The outcrop of Borger is just located downstream of the diapir, where geothermal fluxes still are anomalously higher than the surroundings. This might have facilitated higher basal melting rates and higher basal water pressures that are reflected in the sedimentary record south of Borger, near the present roundabout. In the area near the bridge (Koesteeg), deformation is very strong. The present GPR measurements at the location east of Borger show no deformation of older deformational structures with NE – SW direction, which indicate floating. Higher meltwater amounts explain the situation south of Buinen: most stony soils are found in this part of Drenthe (Soil map of the Netherlands, Alterra, : 12W; 12O;17O;18W;22O;22W). We suggest that these stony soils are washed out (stone-rich) Emmen till by meltwater, which gives accumulation of these erratics near surface.

5.7.5 Location 5: Klazienaveen

The Zechstein thickness map shows that no diapirs occur around the area of Klazienaveen. The base of the Zechstein drops to great depths just south of Klazienaveen (the lowering of the base between Itterbeck – Klazienaveen is around 1 km; South Permian Basin Atlas of NW-Europe) We suggest that this strongly influenced the behaviour of the Hondsrug – Hümmling Ice stream as will be explained in paragraph 6.3, and which is a reason why this ice stream dropped very thick amounts of tills near Schoonebeek (which is partly in the Itterbeck Basin).

Salt diapirs are not present in the Hondsrug area from Borger to Valthe/Odoorn. Delisle *et al.* (2007) showed that geothermal fluxes are lower further away from salt diapirs and that permafrost would occur to greater depth or could form more easily. We reason therefore, that deformation in this area didn't occur by the ice stream, due to the occurrence of permafrost creating: 1) stiff rhyolite and 2) an impermeable layer, so that the flotation point is easily reached. This in contrast to the northern part of the Hondsrug area, where melt was much higher due to the occurences of salt diapirs.

In the southern part of the Hondsrug area Bregman & Lüse (in prep) found newly formed minerals (paragraph 3.7) which indicate influences of brine or saline groundwater. This proves not only the presence of ascending groundwater with a reversed flow direction from NNW to SSE, but also the position of the brine/salt source The source of can be deeper located marine deposits (Breda Formation) or from groundwater in areas with salt diapirs. The latter source is favored, since Bregman & Lüse (in prep) didn't found newly formed minerals in tills outside the Hondsrug area and in area between Borger and Schoonebeek.

One of the main conclusions we now can draw from our geological and glaciological interpretations of the studied locations (see also Chapter 5) deeper geology geological structures had

had a strong impact on the behavior of the Drenthian part of Hondsrug-Hümmling Ice stream. We've shown that in order to better understand genesis of the Hondsrug ridges, as well as positioning and dynamics of Hondsrug – Hümmling Ice stream, the role of deeper geology should be taken into account as well.

5.8 Summary

An overview of observations and interpretation of subglacial processes of previous chapter is given in table 3 and Figure 5.1.

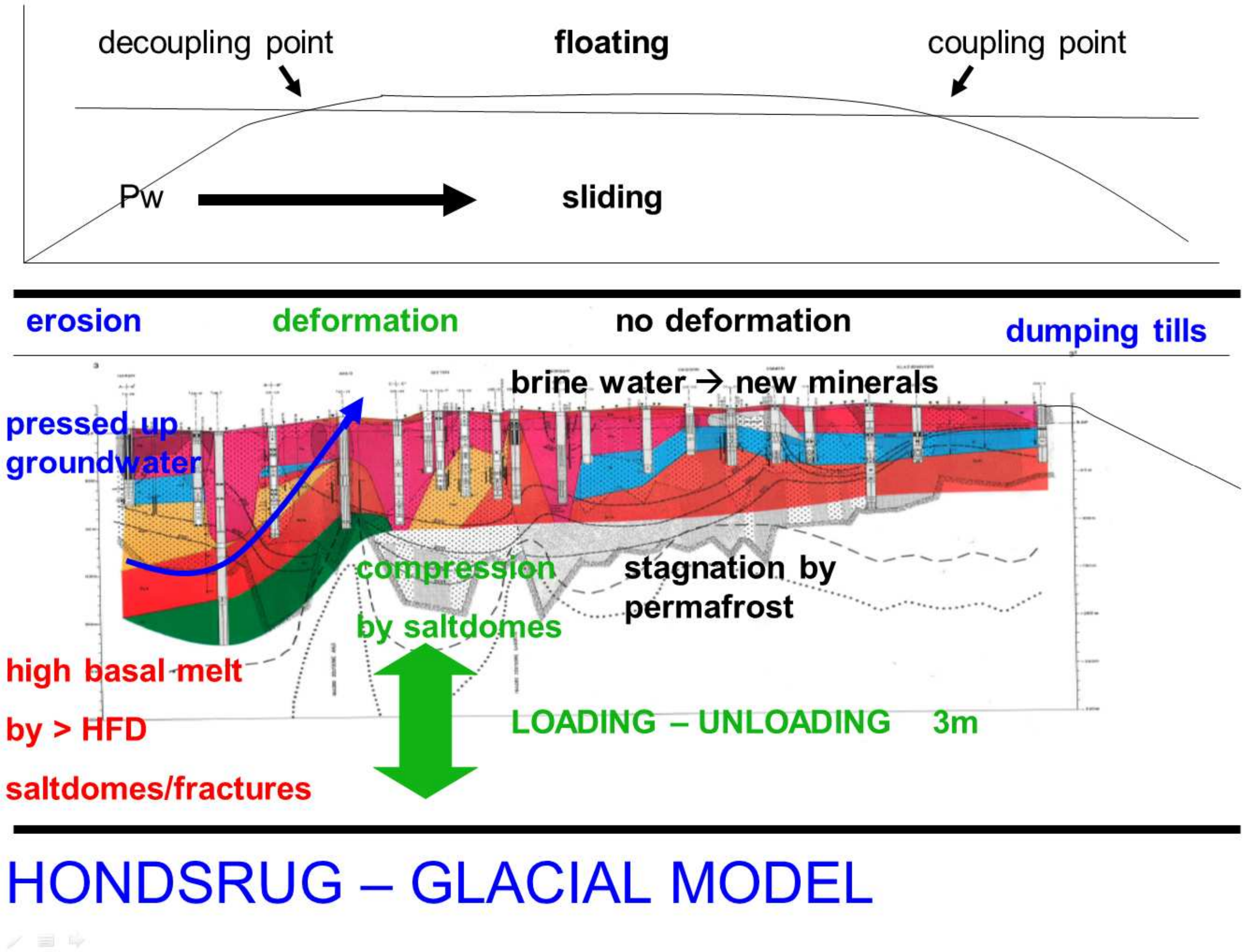


Figure 5.1. A) the theoretical correlation between water pressure (P_w) and time is given. With increasing P_w there will be a transition from no bed deformation, via erosion to deformation and above floating point to floating. In B), the impact of increasing P_w and groundwater flow and glacial processes are given for the Hondsrug area

In the area of Donderen, large scale erosion took place after till deposition had occurred, as is reflected by washed out sediments. In Gieten, two branches of the Hondsrug show complete different features but have two things in common: 1) both branches do show deformation of the pre-glacial sediments in the same direction from the NE, the older phase pre-dating ice stream coverage. 2) Both branches show a lodgement till (interpreted to be of the Assen Group) at the top of the pre-glacial sand. The main difference is the occurrence of a large deformation till in between Assen Group and Emmen group on the eastern branch, while only the lodgement till occurs on the western branch. Stronger erosion in the dead ice on the western branch has been proposed to explain the observations.

	Pw	Flotation	Perma-frost	Sub-glacial proces	Features
Donderen	-/+	-	-	A → C	- STRONG ERODED TILL - NO-DEFORMATION FEATURES
Gieten Oost	++	-	-	C	- SUBGLACIAL- AND INTRA-GLACIAL CHANNELS - PIPING - STRONG DEFORMATION FEATURES
Gieten West	+	-	-	A	- SUBGLACIAL CHANNELS - ERODED TILL , OR ABSENT - SCHOLLEN TILL
Gasselte	++	-	-	A → C	- SUB GLACIAL DRAINAGE SYSTEM (INDICATED)
Borger	+++/-	-/+	+/-	A → C	- STRONG DEFORMATION FEATURES - NO DEFORMATION
Valthe - Odoorn	+++	++	+	A	- NO DEFORMATION - THIN TILL DEPOSIT
Klazina-veen	-/+	+/-	-	A →C → A	- NO DEFORMATION

Tabel 3; Overview of main glacial processes and features of 7 locations at the Hondsrug area. Subglacial processes are according to Jørgensen and Piotrowski, 2003. See also Figure 3.3.

Gasselte is characterized by large scale erosion, and the Assen till does not occur at this location. It may never has been deposited, or it has been eroded away completely, both indicate that basal water pressure exceeded Region A and was likely to be in Region C or above flotation point (Jørgensen & Piotrowski, 2003). Thrust sheet orientation in the coarse grained sand dipped towards NE, suggesting that the older phase glaciation was preserved. It's hard to think other explanations for preserved thrusts in coarse sand that is overridden by an ice stream that moved almost perpendicular, than to conclude that the sand was solidly frozen. High basal pressures led to minor coupling between glacier and bed.

The stratigraphy in Borger did not contain the Assen-type till, but only fine pre-glacial sand and some Emmen-type till. Large scale channels were observed that are orientated perpendicular to the ice stream direction in the pre-glacial sand and would suggest formation during the first phase of ice-coverage (NE-SW). The channel infill has been eroded away by the ice stream since a 7 m thick sequence of Emmen-type till is deposited in the channel.

GPR-measurements (Appendix C) from Valthe and Odoorn show that, compared to deformation at Bronneger (Borger), there is only minor deformation of pre-glacial sediments. The dip angle of these thrusts is NE, suggesting that the sediments were deformed during the older glaciation from the NE. A striking feature of this region is the large variations in till thickness. It varies from absent to 2 meter thick, and two explanations can be given for this which can be true at the same time: 1) subglacial till deposition is not homogenous, variations of pre-glacial topography, glacier sole relief and ice-velocities all have their impact on the thickness of the till; and 2) The location is situated near a meltwater-valley, where running meltwater has eroded into the till and left behind its remnant, 'keizand'.

The outcrop at Klazienaveen showed no major deformation over a great length in the pre-glacial sediments. Laminations in the till show that the layers lay horizontal. This is in contrast to the study of Rappol (Figure 9, 1984), who found large scale deformation in the pre-glacial sediment at Klazienaveen. It shows that although large scale patterns may be observed, local differences may exist that could alter interpretations of ice stream behaviour in to such extent, that opposite conclusions may arise. The till pattern of the Hondsrug is patched and highly complex because of spatially and temporally highly variable deformed beds (e.g. Van der Meer *et al.,* 2003).

The general till thickness distribution along the Hondsrug-complex shows that near Groningen it's rather thick and becomes thinner towards the southeast near Haren. Around Donderen the till is completely absent, only an accumulation of boulders remain; while thickness increases towards Gieten (around 5-7 m till), decreases again towards Gasselte and Borger(partly absent) and increases towards Emmen and Klazienaveen.

A palaeo-reconstruction, based upon the interpretation of the differences in till thickness alone, is dangerous, since many local conditions (e.g. non-deposition and erosion) will control the final thickness of the till. But by utilizing many more proxies, such as stress measurements, erratics counts, micro-morphology of the glacial sediments and insight in clay mineral species and structures, will lead to a much better delineation of the reconstruction. Our focus in the next chapter is to use these detailed analysis of parts of the Hondsrug area, and fit them into a more regional scale (paragraph 6.2) to understand how this ice stream has formed the Hondsrug landscape. We then focus on initiation of the ice stream in the source region (paragraph 6.3) and put our detailed interpretation in a broader context. In Chapter 7, we reach the largest scale and place our results in the context of marginal ice streams and ice sheet behaviour. And on this level, we'll present a new glaciation model of the Hondsrug-Hümmling Ice stream.

6. The role of ‘deeper’ geology on the behaviour of the glaciers.

6.1 Introduction

The behavior of an ice stream is highly dynamic and many factors control the interaction between an ice stream and its bed. For a large part, the dynamics of an ice stream are determined by surface properties such as lithology of the glacier bed and the supply of ice from the source regions.

Previous glaciological studies (e.g. Rappol, 1987; Van den Berg & Beets, 1987), which reconstruct the formation of the Saalian glacial deposits and morphology in the Netherlands, are built upon single datasets, like lithology and clast orientation. In more recent studies, which will be referred to in the following parts of this chapter, the positioning of ice streams and glacial behavior is, in more linked to deeper geological features (sub-topographic obstacles) and processes (geothermal anomalies) that may have played an important role on different time- and spatial scales.

In the coming paragraphs we’ll argue why deeper geology also has played an important role in the formation of the Hondsrug landscape, besides the glaciological processes sensu stricto. We’ll start off at the lowest scale, interpreting the observations from Hondsrug area with respect to deeper geology and will zoom out to larger scales in subsequent paragraphs. In paragraph 6.3, we’ll place our conclusions in a broader (regional) context with reference to other observations outside the Hondsrug area.

6.1.1 Detailed explanation (the Netherlands/NW Germany)

In relation to previous studies on the Hondsrug, our research has a high focus on deeper geology that influences surface processes. We think that in order to explain the patterns we find at the Hondsrug (till thickness, deformation intensity, river patterns and fauna), deeper geology provides a part of the answer as well, in contrast to many previous studies that neglected the substratum upon glacier movement occurred. Several other reasons for our rather high focus on deeper geology is summarized below:

- In the last century, Zonneveld (1964) and Ter Wee (1979) noticed that the Hondsrug ridges are aligned to deeper fault systems, but did not have the tools (Ground Penetrating Radar, model simulations, GIS) to further investigate this possible relation. Since we have these tools available and more studies have focused on the relation between deeper geology and surface processes, we are able to investigate it further.
- More studies have now related the movement of the upper crust, invoked by the forebulge (uplift and collapse) and ice loading. and the dynamic interaction with this movement of a glacier than decennia before.

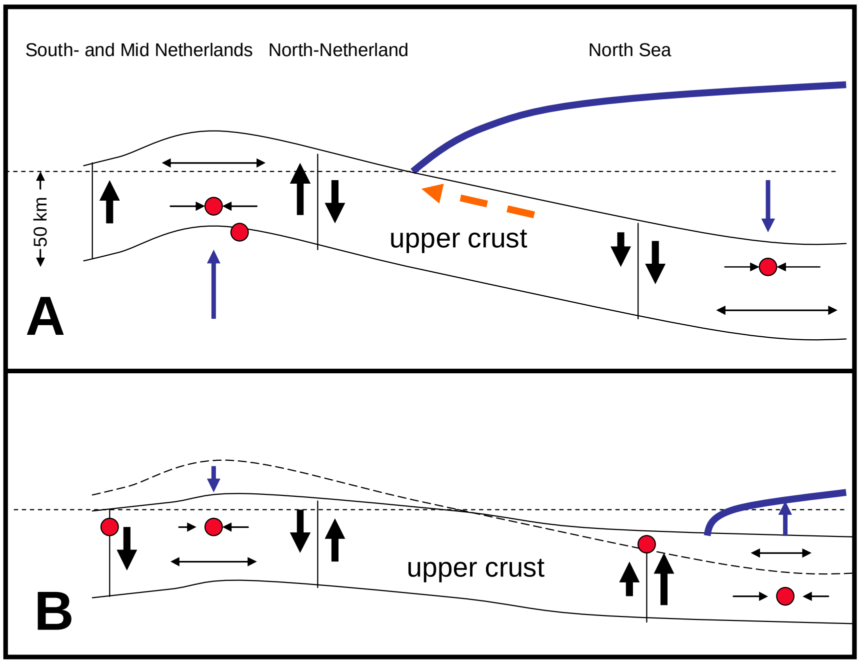
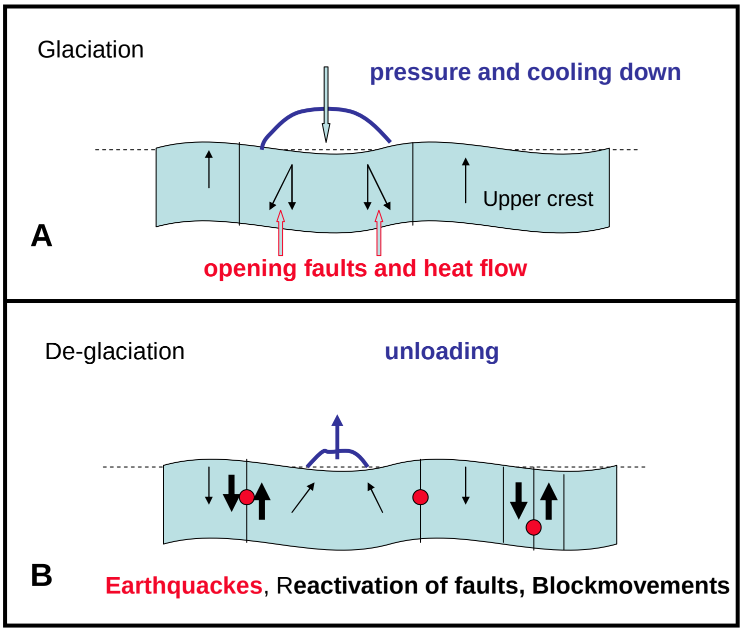


Figure 6.1 Glacio-isostatic impact of advance (A) and retreat of an icesheet (B) on the upper earth crust in relation to the Netherlands (Late Pleistocene/ Early Holocene). Source: Houtgast (2003) and Cohen *et al.* (2009), modified. Blue arrows indicate … fferential tectonic movem… see text.



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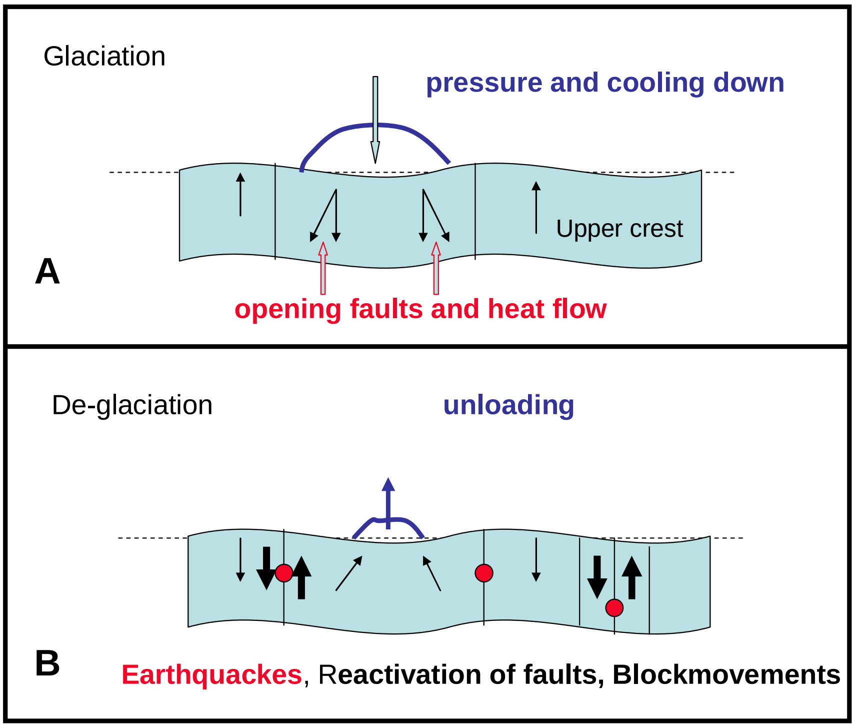


Figure 6.2. Glacio-isostatic impact of loading (A) and unloading(B) of an ice stream on the upper earth's crust related to respectively glaciation and de-glaciation. After James (1998), modified.

6.1.2 The correlation of surface morphology and deeper geological structures (such as tectonic highs, faults and graben systems)

6.1.2.1 General observations

We suppose that flow paths of ice streams or even flow direction are predestined by topographic troughs as one of the most strong favorable pathways (Winsborrow *et al.,* 2010). However (deep) geological structures are also important. The positioning of marginal ice streams in tectonic weaker zones (graben systems) in the IML is evident in the Baltic, where ice streams followed in the Weichselian glacial weaker zones in the area of the Gulf of Gdansk, the Gulf of Riga and Gulf of Kaliningrad. Ice streams penetrated this area and formed push-moraines far inland.

In the Netherlands, during the stagnation phase (Phase 2 in Figure 1.5, according to Pierik, Bregman & Cohen, in prep.) of the Saalian glaciation, the pushed moraines of Texel, Wierdingen, Steenwijk and Almelo formed. The stagnation line of ice streams coincides approximately with the Texel-IJsselmeer structural high [Figure 6.8B].

More in general, there is a connection between tectonic highs and lows and glacial features. These sediments are much more consolidated than the infill of the surrounding lows, and these might provide a sub-topographic obstacle for an advancing glacier. Since the impact of ice-coverage protrudes towards upper crust of the lithosphere, we suppose that stiffer or weaker deeper geological structures has influence on (horizontal) forebulge motion because of compaction and decompression such as occurs on the local scale [e.g. Figure 3.4]. Glacier advance may therefore terminate temporarily, until enough stress was build up to overcome the 'friction' the obstacle provides. This event predates the formation of the Hondsrug.

We assume that the landscape in Drenthe what was a continuation of the NW German landscape. Sediment deformation in the province of Groningen was probably caused stagnation of the ice due to the occurrence of an sub-topographic obstacle: the Groningen. So even before the Rheburgphase we suggest that deformation of locations in Groningen near Slochteren, Noordbroek en Alteveer near Pekela (overridden push moraines) is linked with the position of the Groningen High Deep deformation of the Elsterian deposits with NE – SW directions found in the northern part of the Hondsrug are also evident for deformation. Remarkable is that the glacial basins, related to the maximum extention of the ice advance in the Netherlands, all are positioned in the Central Netherlands Basins and push moraines have been formed in line with the Kijkduin High (Table 3; Wong *et al.*, 2007).

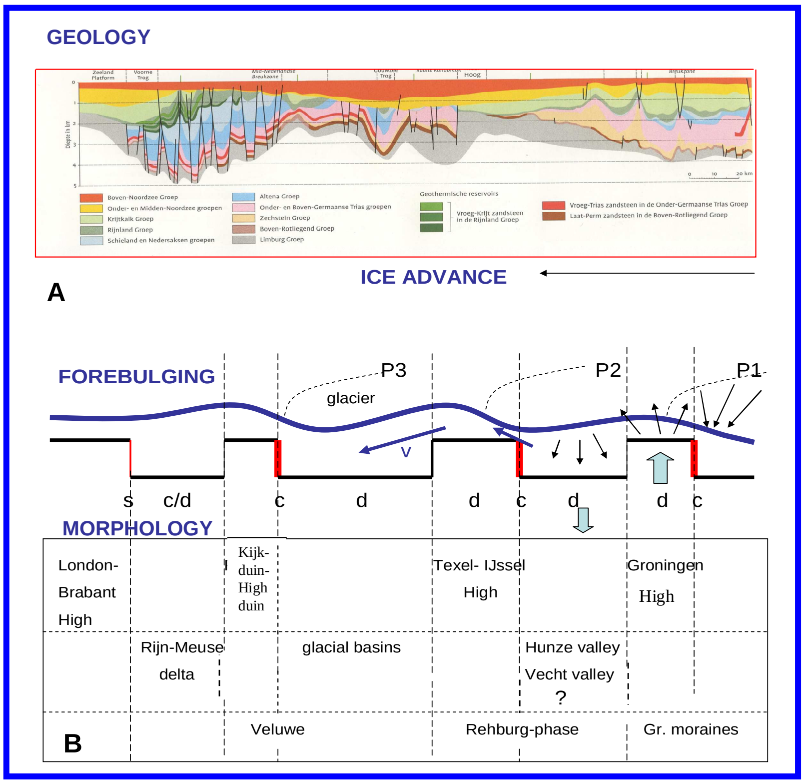
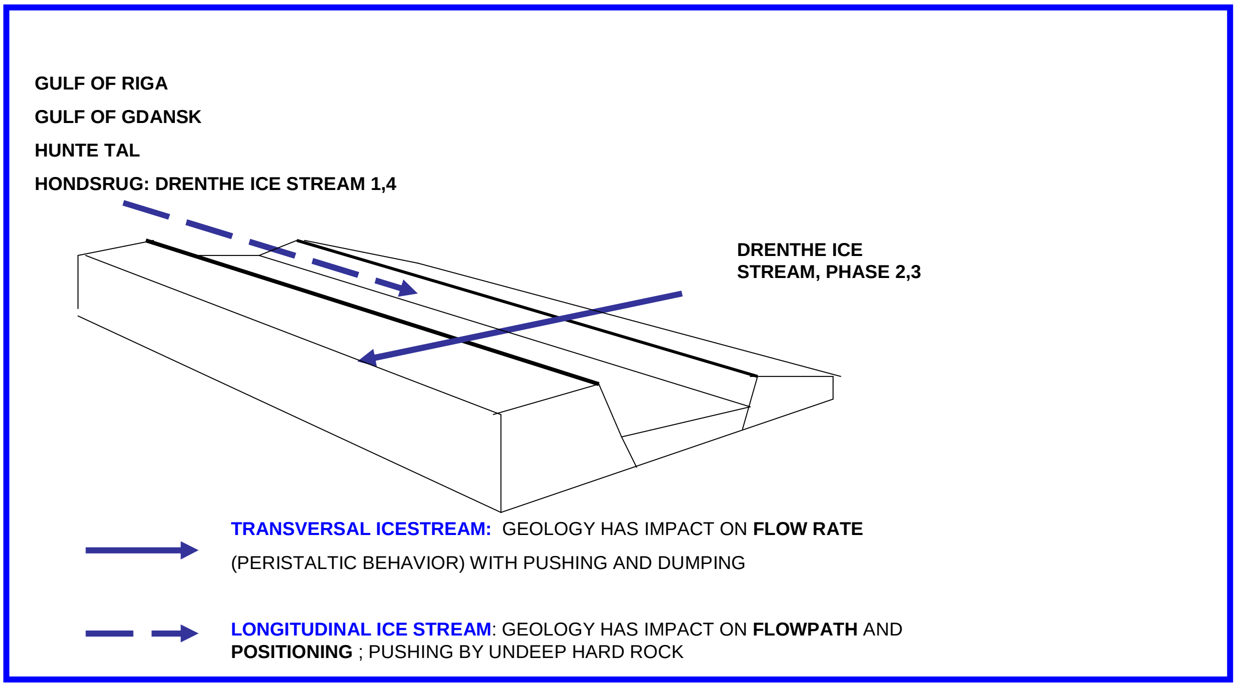


Figure 6.3 Ice sheet advance and behavior in a schematic cross section from the NW to the SW part of the Netherlands at different Saalian MIS-6 phases (P1 t/m 3) are related to structural features of deep geology highs and lows in the Netherlands (cross-section **A; TNO**) and glacial morphology. Black arrows indicate compression c) and stagnation (short blue arrow) and decompression (d) and sliding (large blue arrow) indicating pulsing behaviour of glacial advance.

Basin	Length	Width	Depth
Beverwijk	?	?	-112?
Haarlem	15	10	-120
Amsterdam	25	15	-125
Amersfoort (Gelderse Vallei)	50	20	-130
Deventer (IJssel valley)	90	25	-140

Table 4: Correlation of length, width and depth of glacial basins (REGIS II) formed at the LGM in the Netherlands and superposed on the Central Netherlands Basin (Wong *et al.*,2007)



In Figure 6.4, the correlation between geological structures, ice stream flow direction and -behaviour is given. Because of passing stiffer and weaker geological structures ice streams which crosses geological structures do have different resistant in flowing and do have a more peristaltic behaviour than ice streams which are flowing in longitudinal direction, because of less resistance. The flow path is controlled by geological structures as we suppose for the Hondsrug - Hümmling Ice stream

6.1.2.2 Present observations in the Netherlands and NW Germany.

Glacial induced tectonic reactions are caused by unloading at the proximal and distal side of the forebulge. In the Netherlands the studies of Houtgast (2003) and Cohen (2003) indicates impact of rebound on deeper geology and geomorphology at the distal side of the forebulge. Glacial unloading created additional extensional stresses, superimposed on the far field regional stresses indicated by increased fault activity of the Roer Valley Graben in the initial phase of unloading around 10 – 15 ka (Houtgast, 2003;. Cohen *et al.,* 2002). Cohen *et al.* (2009) demonstrated that the fluvial dynamic of the rivers Rhine and Meuse correlates with structural lowering of the North Sea Basin and Neotectonic movements as well as is influenced by late Pleistocene loading and unloading as an interaction of advance or retreat of ice sheets. Both "nearby" studies at the distal side of the forebulge demonstrate postglacial induced tectonic activity. Differential rebound morphology has been shown West of Bremen by Sirocko *et al.* (2004,2005; block movements and terraces) and in Drenthe by de Gans (2010; radial river pattern).

We'll show how glacial features and (deduced) glaciological processes might be linked to geological features like salt diapirs, patterns of geophysical features like gravity and/or the combined effect of heat distribution of the upper earth crust and heat flow density (HFD; e.g. Wang *et al.*, 1965) and possible implications on glacial processes (like basal melt) and glacial dynamics (amount of subglacial meltwater and meltwater discharge in closed system with rising water pressure, e.g. Piotrowski, 2007). We assume that open fault systems or spots with higher Heat Flow Densities (HFD) release anomalously higher geothermal fluxes, which can increase basal melting rates of the ice. Ice streams may be 'pulled towards' these favorable pathways since sliding will be facilitate by these higher geothermal fluxes. The salt diapirs formed partly along this faults as well, and due to the higher heat conductivity of rock salt compared to surrounding unconsolidated sediments, they create higher geothermal gradients as well. Thus, in addition to the faults, the occurrence of salt diapirs can create higher geothermal heat fluxes and thereby providing a favourable pathway for glacier flow. Several salt diapirs occur shallow in the subsurface [Figure 6.4A] of Drenthe such as Anloo (-350m), Gasselte (-200m) and Schoonlo (-120m).

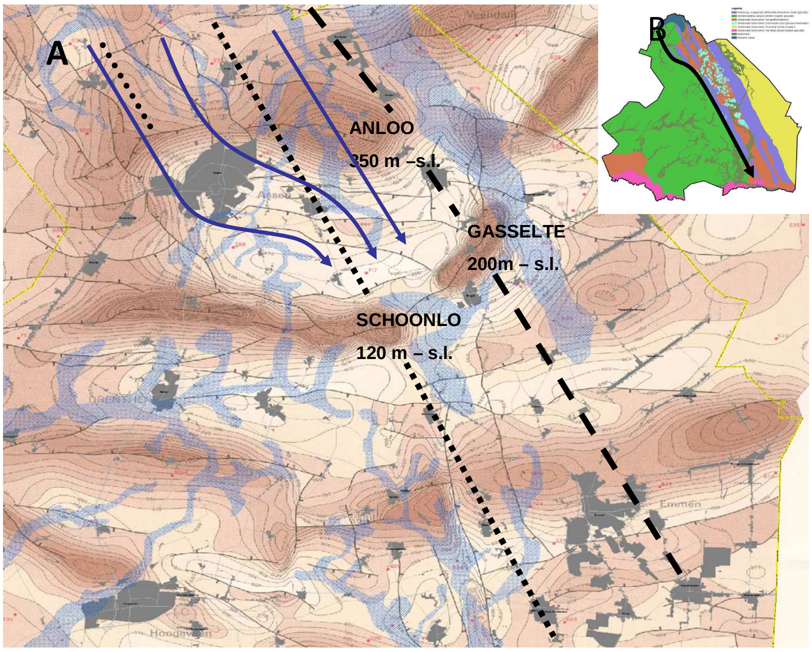


Figure 6.5. Thickness of the Zechstein Formation (rock salt) with saltdiapirs and –ridges in Drenthe (red-brown color) and position of main near surfacing diapirs with depth in m's under surface level (s.l.). In blue colors, modern river valleys (for explanation: see Chapter 7 Discussion and Chapter 8 Conclusions). The black dashed line is the Hondsrug; the black square dotted line the Sleener- , Rolder and Zeijer ridge; the black dotted line: the Norger ridge. Thin blacklines indicate faults, including tecktonic blockstructures. The blue arrows indicate ice stream direction, based on morphology as is shown in Figure 6.1 B. the Hondsrug – Hümmling Ice stream has its most western limit near Norg.

Rock salt has a thermal conductivity which is 1.6 times larger than the surrounding unconsolidated sand (e.g. Durham, 1979). This implicates higher soil temperature at the deeper subsurface and near the surface as well, so that they salt diapirs/ridges hotspots. Conductivity of heat has a different impact on overlain formations by different heat conductivity rates. Heat transport occurs further more by groundwater displacement and will be easier near fractures. If so, then it is to expect that heat exchange to shallower formations will have a higher rate if there are open faults. The following three examples show higher soil temperatures near surface in areas with salt diapirs:

Soil temperatures have been measured in the province Friesland at 100, 150 and 200 m's depth (Iwaco, 1998; Figure 6.6), and are at 100 – 150 m depth 2-2,5 ˚C higher than the surroundings and which are caused by heat emission of the saltdome near Pieterburen. Delineation of shallow salt diapirs and surface faults by temperature measurements at a depth of approximately 2 meters depth in Groningen, the Netherlands (Poley and Van Steveninck, 1970), clearly indicate several temperature anomalies with differential temperatures of about 1˚C with excellent correlation of a prepared thermal contour map and seismic and well data. Piotrowski (2007) showed in NW Poland also a positive correlation between soil temperatures (2 m – s.l.) and positioning of salt diapirs.

Delisle *et al.,* (2007) modeled implications of heat transport through sediments and along faults in the subsurface in NW Germany. Their conclusions are a larger quantity of heat can be transported to the surface where salt diapirs occur due to their higher heat conductivity, which can impede permafrost formation significantly (Delisle et al. 2007). In between these regions, anomalously low heat fluxes occur and can aid permafrost formation or the deeper penetration of it (Delisle et al. 2007).

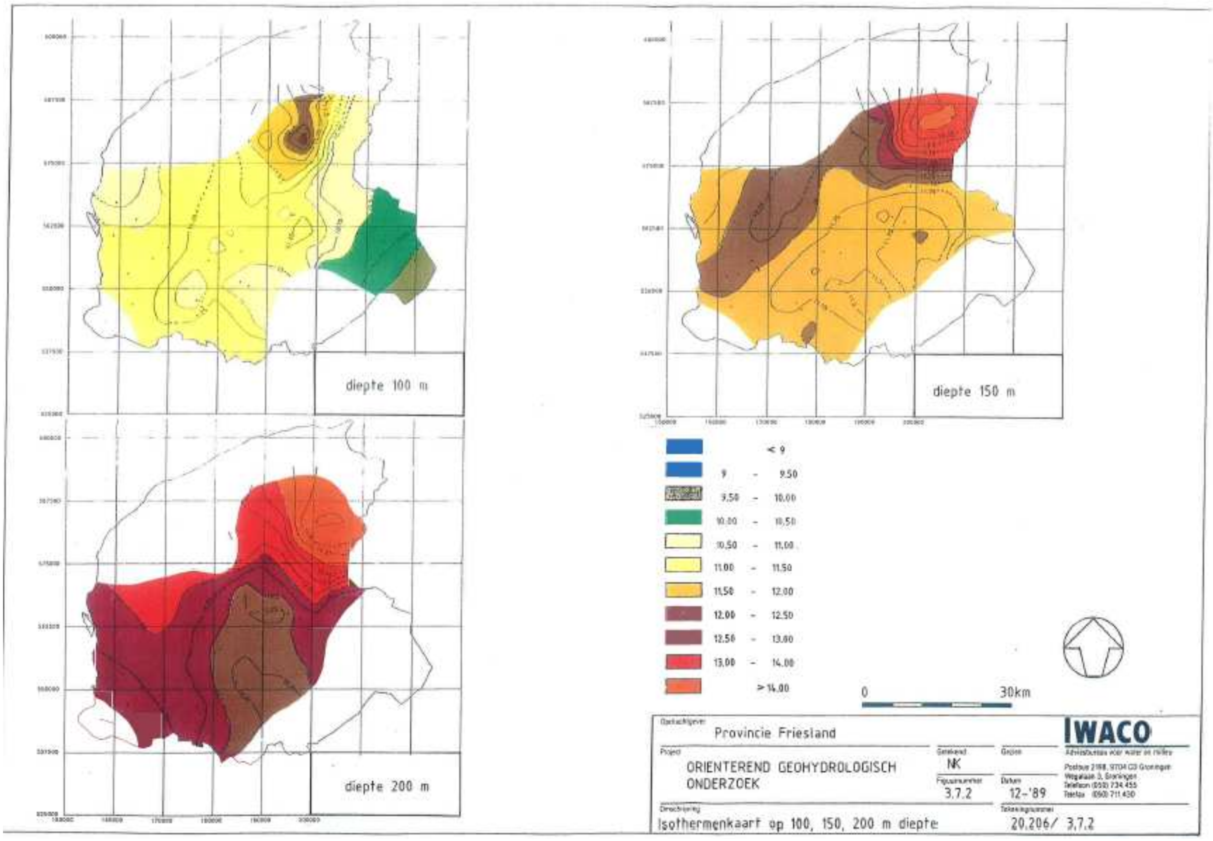


Figure 6.6 Isotherms at 100, 150, and 200 m –s.l. in the Province of Friesland (Iwaco, 1989)

Deep soil temperature and Heat Flow Density are independent from glacial processes, or might slightly be influenced by crustal loading through forebulging. This crustal movement is a reflection of vertical, horizontal and 3D adaptions of the lithosphere by re-distribution of magma and the lithosphere itself (e.g. Lund 2005, Thorson, 2000). We suppose that present locations of heat sources even by loading of ice streams are a relative stable heat source with more or less same position.

Because of reversed groundwater flow, caused by ice streams (e.g. Piotrowski, 2007; Koesters *LBEG Annuals*; Saks, 2012), and double diffuse convection (DDC), heat sources have impact on temperature of deeper groundwater and heat distribution too and based on the same principles as in present time (e.g. Magri, 2005; Bregman & Magri, in preparation). Both processes influence subglacial basal temperatures in the flow direction of ice streams in a direct fashion or indirect in a combination (see also Chapter 3). Subglacial groundwater that has been pressed up under the ice stream results in deformation, subglacial erosion or in case high water pressures occur, to decoupling of the ice stream and its bed (floating; Chapter 3.5; Figure 3.3).

6.1.2.3 Deep – temperatures versus gravity.

Close inspection of the temperature at a depth of 2000m [Figure 6.9B] in the Netherlands shows an increase in temperature in the North Sea and around the Lauwersmeer Trough. In Figure 6.7 Heat Flow Densities(HFD) are given.

Remarkable is the position of the Texel IJsselmeer High (see for position also Figure 6.8A/B)). The HFD 30 mW/m^{-2} isotherm in the center of the North Sea basin connects with the pattern related to the Hangstum Graben and the part of the German Permian Basin near Itterbeck with HFD > $40mW/m^{-2}$ and low gravity, indicating thinner earth crust locally. It is also the area with a branch of the North Sea trough (Figure 6.6.A), with faults and salt diapirs (red circles in fig 6.5 and fig.6.6B).

The increase in HFD above the Wadden Islands, around the Louwersmeer Trough with connection to the Itterbeck region as is shown in figure 6.6 is the combined result of presence of saltdomes and thermal leakage of heat through faults (e.g. Stein, 1995).

We project the position of the Hondsrug-complex on the maps of fig.6.2, 6.3 and 6.6, and striking comparisons can be seen. The pathway the ice stream took is approximately along the fault systems and highest salt thickness. Poley and Van Steveninck (1970) demonstrated in several cases that strong thermal anomalies indeed coincided with known deep faults, but for shallow faults, however, lack of subsurface detail prevented any unambiguous correlation with observed thermal anomalies. North of the Hondsrug, there is a general anomalously high temperature (Figure 6.2A), but warm and cold spots are observed as well that locally might play a role in the amount of meltwater production.

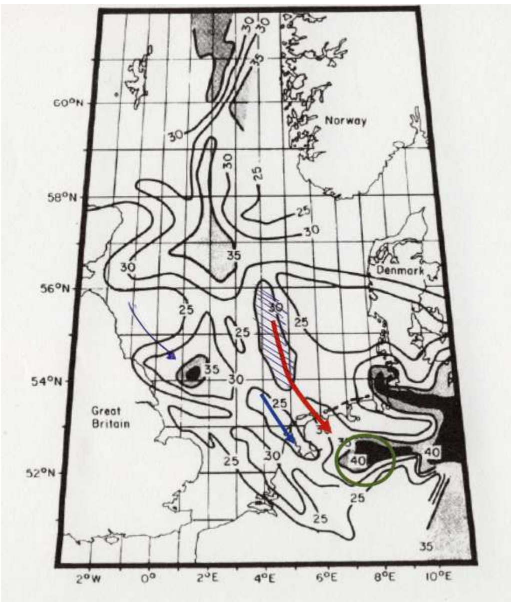


Figure 6.7. Heat Flow Densities (mW/m^{-2}) of the North Sea area, the Netherlands and NW Germany.. Remarkable is the position of the Texel IJsselmeer High (see for position also fig.6.2B), blue arrow and in red the connection of > HFD. For paleao-climate reconstruction the colder climate reduces temperatures according Jõeleht e.a (1996) at surface 10 – 15 mW/m^{-2} and 5 – 7 mW/m^{-2} at 150 – 150 m – s.l. From Rider, 2002

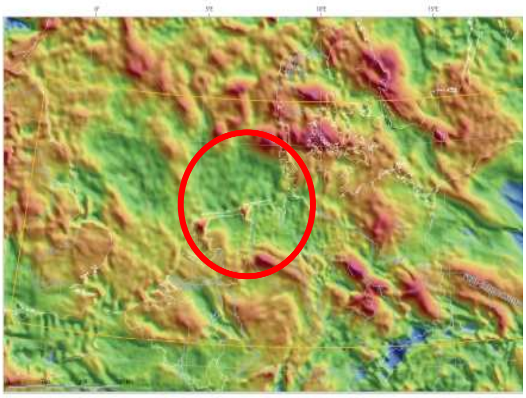


Figure 6.8. Gravity map of the Netherlands, NW Germany and the Central part of the North Sea (Atlas SPB, 2011). In red colour high positive values (mGal/s) indication for thick colder material with low heat flow and in green low values (mGal/s) indicating lighter and hotter material (Wang, 1965;fig. 6.3). Red circle indicates positioning of saltdomes [Figure 6.5B] with low gravity because of specific mass weigth and with high HFD caused by high conductivity of salt rock

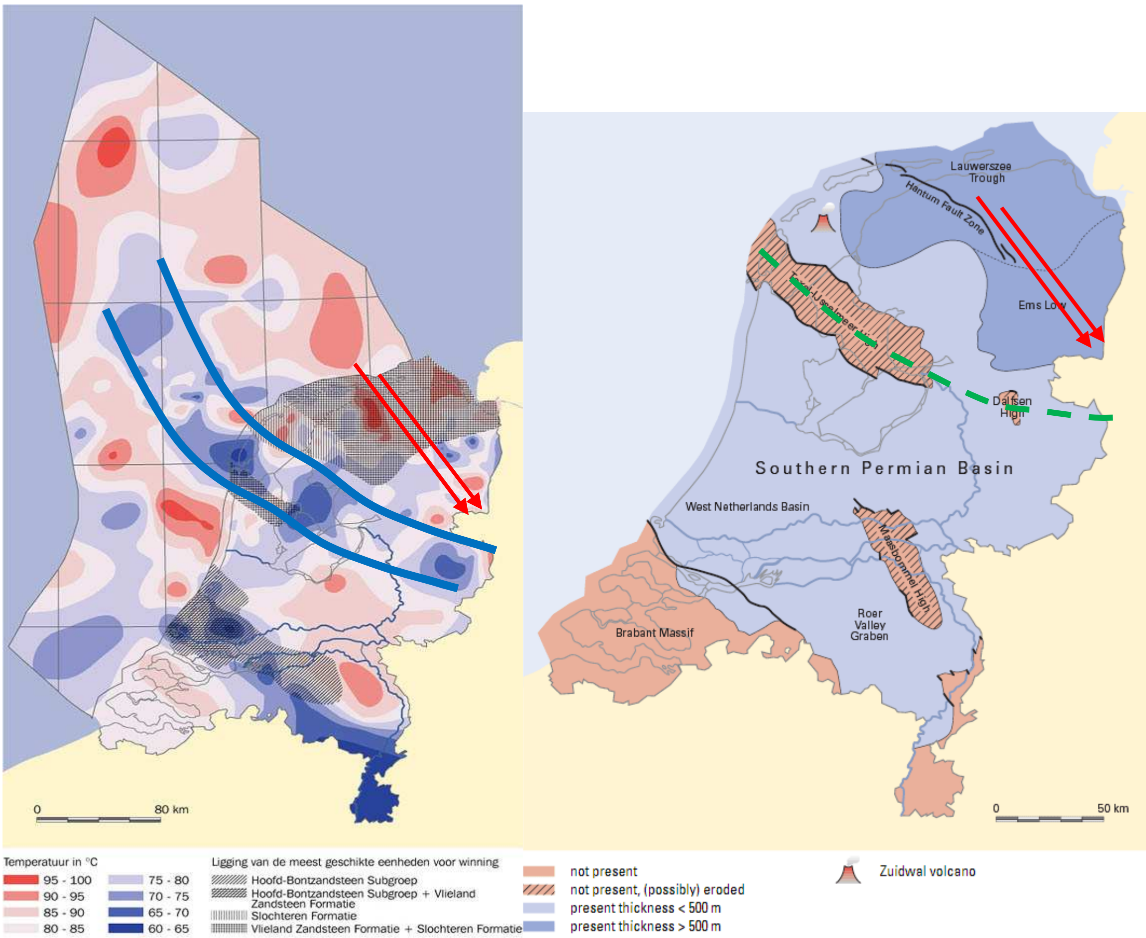
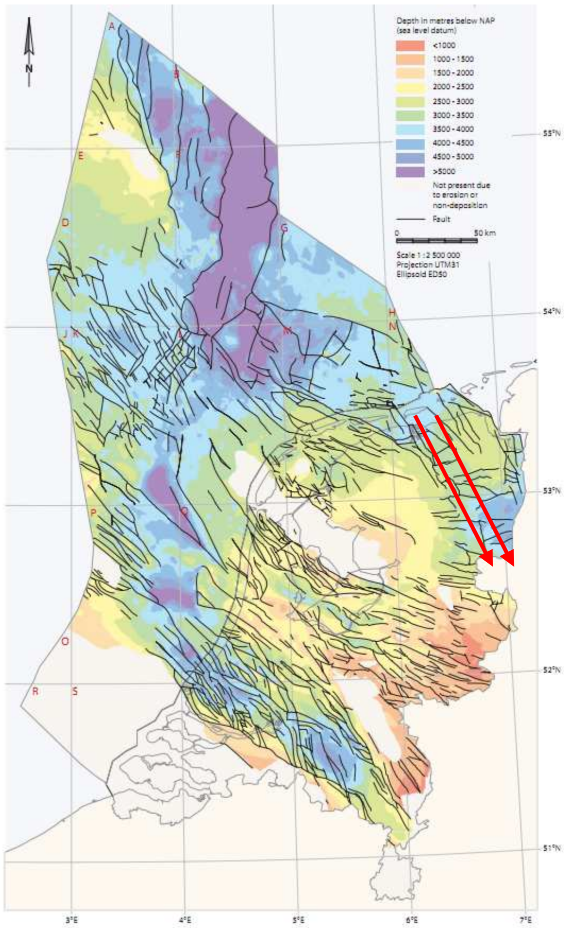
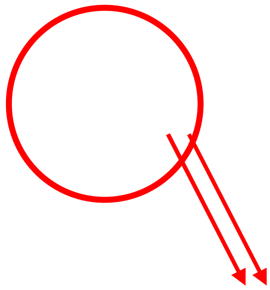


Figure 6.9 A) Map showing temperatures at 2000 m depth. Red arrows mark Hondsrug ice stream movement. Blue lines represent temperature minimum zone which coincides approximately with the Rehburg Phase stagnation line. B) Structural highs and lows of the Permian Zechstein Formation. Green dashed lines mark Rehburg stagnation phase.



N
Depth in metres below NAP (sea level datum)
<1000
1000 - 1500
1500 - 2000
2000 - 2500
2500 - 3000
3000 - 3500
3500 - 4000
4000 - 4500
4500 - 5000
>5000
Not present due to erosion or non-deposition
Fault
0
50 km
Scale 1 : 2 500 000
Projection UTM31
Ellipsoid ED50
55°N
54°N
53°N
52°N
51°N
3°E
4°E
5°E
6°E
7°E



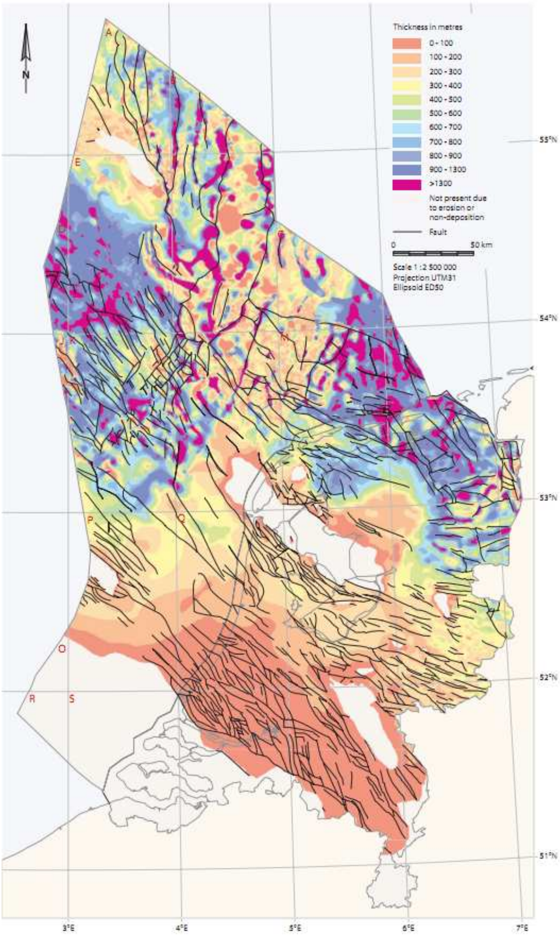


Figure 6.10. A) Depth map of the base of the Zechstein Group (Late Permian) and B) Thickness map of the Zechstein Group (Late Permian) with in pink the saltdiapirs. Red arrows mark the position of the Hondsrug – Hümmling Ice stream. Note the striking comparison between position of faults and maximum thickness of Zechstein and Hondsrug – Húmmling Ice- Stream orientation. (From: Duin, 2006)

6.2. Overview IML

The question is are we talking about a coincident or do we recognize these kinds of correlations also in other locations of the IML? To give an answer to that question we made two compilations of different information:

As shown in Figure 6.11, the stagnation line of the Rehburger phase continues eastwards to Germany north of Braunschweig through the Ankümer Høhe, Dammerberge and Rehburger Berge. Stagnation might not only occur because of presence of hard rock that might formed an obstacle to glacier flow, but remarkable is that hotspots (yellow – red dots in Figure 6.11) are highest on places where glacial basins are formed (black shades in Figure 6.11). In figure 6.2 we see for the Netherlands in fact the same situation near the glacial basin of the IJssel and Montferland.

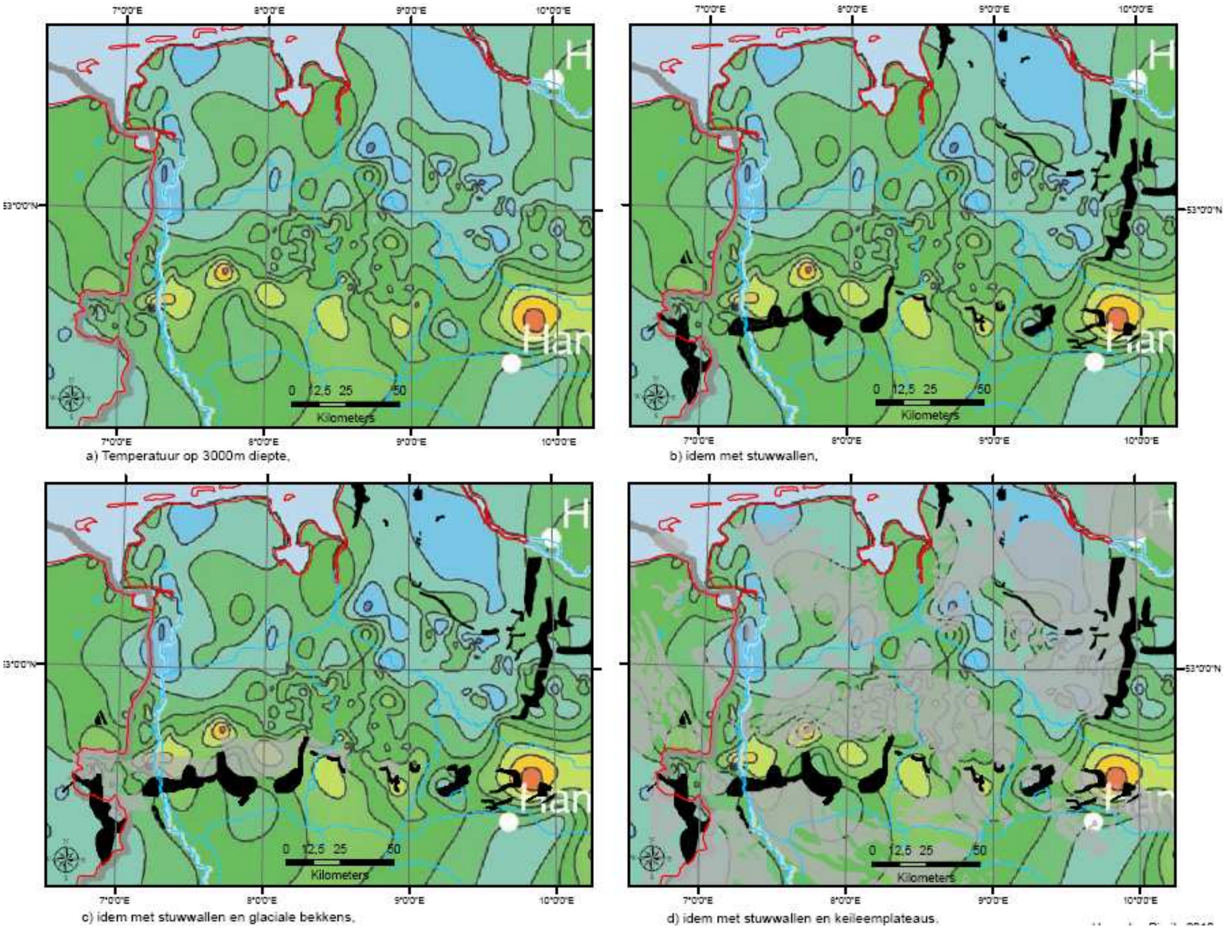


Figure 6.11. A) temperature at 3000m depth; B) T at 3000m depth + push moraines; C) Figure B + Glacial basins; D) Figure C + till plateaus

Figure 6.12 shows the correlation of the gravity map of the IML and positioning of different glacial features. Areas with low gravity, indication for tectonic weaker zones (unconsolidated sediments, salt rock etc.) and fault systems are positive correlated to positioning of ice streams.

6.3 General conclusions

Related to the role of 'deeper' geology on the genesis of the Hondsrug – Hümmling Ice stream we can first of all conclude that we found strong indications of (i) ice streams may re-activate faults and salt mobilization (due to crustal loading and forebulging), thus surface processes influencing deeper geology. The otherway around might occur as well: sub-topographical obstacles can influences the behavior of ice streams and determine stagnation positions and (ii) soil temperature influences ice stream behavior as well (higher geothermal fluxes in areas of faults or salt rock diapirs/ridges/domes).

The Texel IJsselmeer High region coincides with a temperature minimum (blue lines, Figure 6.8A), that could decrease meltwater production and stagnation of movement. Hotspots caused by positioning of saltdomes with higher HFD's north of the present Northern Dutch coast on the contrary must have had impact on basal melt rate of the ice, which could have led to higher subglacial water pressure in the relative lower area of the branch of the North Sea basin and the Louwersmeer Trough.

A second main conclusion is that hotspots may have a different impact on ice streams. We suppose that (i) an increase of subglacial melt in the more central part of the ice sheet, might have influence on basal meltwater pressure and that this process is much stronger in the deglaciation phase where fractures and moulins form in the degrading ice sheet, provide meltwater pathways towards subglacial lakes and contribute herewith to higher basal water pressure (e.g. Evans, 2005) and (ii) hotspots have as well influence on the melt of ice lobs and influences ablation with impact on ice sheet velocity, which can be seen as a part of the feedback mechanism of the degradation of ice sheets to stay in balance.

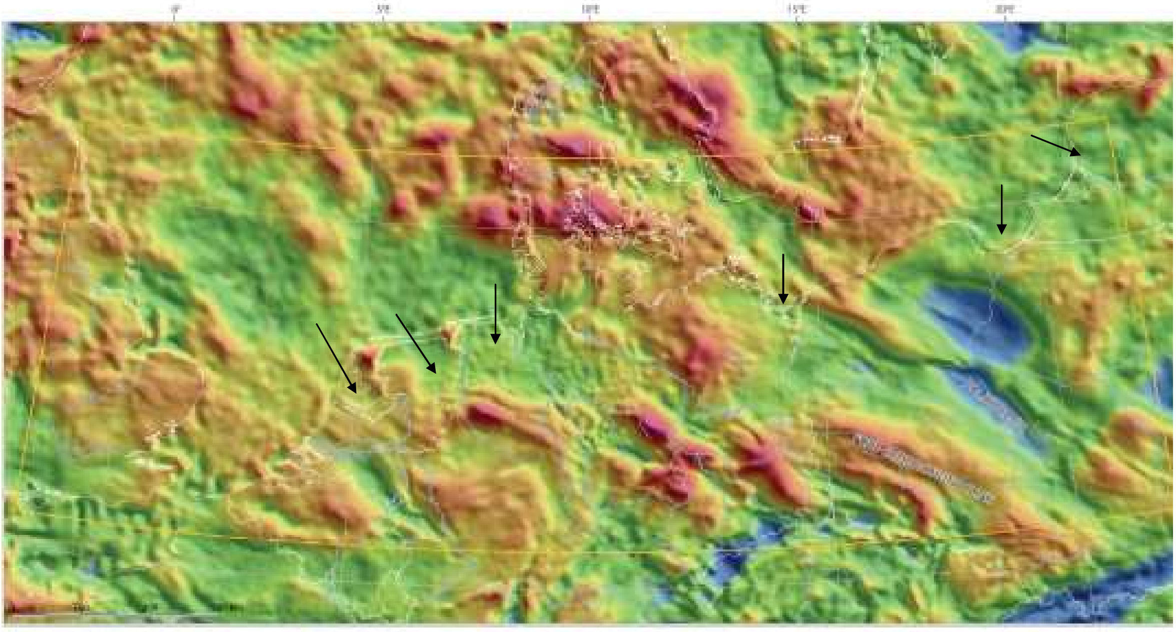


Figure 6.12. Correlation of gravity patterns in the IML and glacial features. Black arrows indicates positioning of marginal ice streams. Source: Duin (2006)

Hotspots in NW Europe are related to position of salt diapirs, mains fault zones and thinner parts of earth's crust. It has been shown for the Rehburg phase in Germany and the supposed onset zone of the Hondsrug – Hümmling Ice stream confirmed this relationship as well. It is remarkable that one of the main hotspots in the Rehburgphase is found just at the position of the Porta Westfalica: the entrance to the Weser Bergland, where melt water formed in Saalian Lake Weser (Winsemann, *et al*., 2011). We explain later in more detail that this lake played an important role in the genesis of the Hondrug – Hümmling Ice stream (Chapter 7). The subglacial hotspot in the onset zone of the Hondsrug – Hümmling Ice stream contributes to geothermal heating and higher subglacial melt of the icesheet and we suggest that a Jökulhlaup occurred by a burst out of a hydrostatically sealed subglacial lake in the North Sea area.

A breach of a proglacial Lake Weser Bergland to Lake Münster (Winsemann *et al.,* 2011) formed another main reason which triggered an ice flow. This NNW – SSE ice flow (the Hondsrug – Hümmling Ice stream) overprinted in a part of the Hondsrug older deformations (with NE – SW direction), while in other parts it left the older deformation undisturbed, which indicate permafrost in these regions. This in contrary to the northern part of the Hondsrug, where our observations confirm impact of the combined process of reversed groundwater flow with a high basal water pressure, indicate a higher meltwater production because influence of brine water and higher HFD due to the presence of salt diapirs. Indeed, numerical models have shown that variations in the geothermal fluxes can have a significant impact on the depth of permafrost (e.g. Delisle *et al.*, 2007) and so can influence glacier flow by influencing basal water pressure (permafrost raises basal water pressure highly because it acts as an impermeable barrier and thus is a closed system; while higher geothermal fluxes lead to higher basal melt rates, thereby transporting more water to the bed; e.g. Grasholm, 2008).

High geothermal anomalies in the north of the present northern coast of the Netherlands in the North Sea [Figure 6.8A] could have acted as the onset zone for the Hondsrug-Hümmling Ice stream, where basal melting rates were higher and basal water pressure were raised as well. Such situation of high basal melting rates and high basal water pressures could have triggered fast ice flow towards other favorable (high geothermal fluxes) locations, which were located along the Hondsrug transect where salt diapirs and faults occurred. This implicates too that it will not be necessary to have a connection between Scottish and Scandinavian ice sheets (e.g. Dubois, 1902; Van den Berg & Beets, 1987) to explain change of ice stream flow direction from NE – SW to NNW –SSE direction.

7 Palaeo-reconstruction of the Hondsrug area

Based upon acquired data and foregoing discussions, we developed a new glacial model of the genesis of the Hondsrug. To start off, we'll focus on the Hondsrug area itself in Chapter 7.1. In Chapter 7.2 we scale up our observations and the central questions are why this ice stream started in an degrading ice field and why just at this location. In this chapter we will also describe the pathway of the ice stream with respect to main parameters that influenced the path way. More in detail, the question what controlled the Honds- Hümmling Ice stream will be explained In Chapter 7.3.

7.1 Genesis of the Hondsrug

Our observations on studied locations are as follows to summarise (see also tabel 3):

A generalized pattern which is found on the Hondsrug:

1. **Groningen**: Thrusted tills, thick sequences. Slow movement of the ice stream in this region.
2. **Donderen**: No till, lots of erosion. Extensional forces due to acceleration of the ice stream towards the Hondsrug region where salt diapirs could increase basal melt rates
3. **Gieten**: thick till sequences and deformation tills. Local compressional forces (east branch), other extension forces (west branch). This might have to do with friction with the dead-ice body east of Gieten and the formation of ice-contact moraines. This might explain the occurrence of thick deformations tills on the east-branch of the Hondsrug. Less friction was felt at the location at the western branch, leading to higher flow velocities.
4. **Gasselte**: No till, large scale erosion, orientation of the thrust sheets of coarse pre-glacial sand (NE) not altered by overriding ice stream (NNW). High basal water pressure. Coarse grained sediment solid frozen.
5. **Borger:** Minor till deposition, large scale erosion.
6. **Odoorn/Valthe:** Lodgement till, undisturbed pre-glacial sediments that reflect thrusting from NE, older phase.
7. **Klazienaveen:** Thick sequences of till. Meltwater deposit in between Assen en Emmen Group. Glacier bed not deformed. Till thickness increases towards Itterbeck.

Based upon the interpretations from the studied locations (Chapter 5) and the correlative analyses (Chapter 6) we come up with the following synthesis:

In between dead ice fields (Van den Berg & Beets; Rappol, 1991) an ice stream, with more substreams, developed with NNW - SSE direction (phase 4, Pierik, Bregman & Cohen, in prep.) overprints an older glacial Saalian (MIS 6) landscape with glacial deposits with a NE – SW direction (phase 3, Pierik, Bregman & Cohen, in prep.). The onset zone of the ice stream is located in the North Sea area, NW of the province of Groningen.

Stagnation, caused by a stiffer geological block (Groningen High), resulted in thick till deposits in Groningen due to the slow movement of the Hondsrug – Hümmling Ice stream and due to thrusting of older sediment till.

In between Donderen and Emmen, salt diapirs and permafrost favour high ice-velocities, and therefore thinner sequences of till are deposited or movement and melt water erosion has stripped off the till completely. In the northern part, north of Borger, basal melting was high because of higher

HFD near salt diapirs and supposed opening of main faultsystems of the Hangstum graben and the occurrence of brine water lowered melting rate and resulted in a subglacial high meltwater content of a reversed groundwater flow. Meltwater drainage through the subglacial aquifer, which is the main subglacial drainage system, reached depths where brine water occurred The flow path of this groundwater was – as we assume – controlled by Elsterian buried glacial valleys and subsurface obstacles (salt-pillows and –diapirs of Hooghalen, Schoonlo and Gasselte), where saddles formed the main flow. Groundwater flow was blocked by permafrost in the area between Buinen/Eext and Valthe. Stagnation of the groundwater flow north of Borger caused high water pressure and contribute to floating of the ice stream south of Borger whereas north of Borger it founds its way in a complex system of subglacial channels, canals or pipe flow structures which penetrated older and new formed relative (related to the eastern part of Hondsrug area near Gieten) thick tills. This mechanisme forms water escape structures (WES's; van de Meer *et al.*, 2003) and agrees with our observations of hydro-fracturing features and that indicate always high water pressures according to van der Meer *et al.* (2003) (combined pressure of ice overburden and water pressure) and the forming of thick tills. Although we have not studied the thicker Groningen tills, this conclusion is not in contradiction with the mechanism of stagnation and by that of compression as we suppose the main reason for thickening of the Groningen tills. Deformation in this part of the Hondsrug area is probably also influenced by locally coarser grained texture of in this part of the Hondsrug, (near salt diapirs surfacing of Tertiary deposits due to older uplift or probably higher erosion due to forbulging).

At the most eastern part of the Hondsrug, a relative higher content of erratics are present in the upper tills of the Hondsrug, indication of a very stone-rich sub-stream with a relative high amount of East Baltic erratics. The western substream, linked to the Tynaarlo Ridge contains more Mid- and South East Baltic erratics and till deposits are thinner, which we can explain by three processes according Bennett and Glasser (2009).

One explanation is that environments are not static through time and that during a shift in ice streams position, will shift the position of sedimentary facies in such a way that they succeed each other in a vertical profile (e.g. Walther's Law, in Bennett and Glasser, 2009). In other words, upper tills of an older stage (Phase 3; Pierik, Bregman & Cohen, in prep.) shift over younger tills, as we have seen indeed in the Gieten outcrop.

A second process is related to the positioning of the western substream in the contact-zone of –not moving– 'dead ice' and the active fast moving ice stream. In this contact zone, which is a zone of maximum three km broad, high internal friction causes extra heat production that leads to more meltwater and thereby more erosion of glacial till, so that it will be absent or partly present in thin sections [Figure 7.0]. By the same process, there is a relative enrichment of erratics of an older phase too.

The third explanation is also related to the formation of ridges, which is caused by relative high pressures at the lower part that will invoke an upward shift of debris because of a lower pressure zone occuring at the top of the ridge (the same process is observed in smaller scale ridge formation; Benn and Evans, 2007). This process is probably also the reason that in the western part the top of the Peelo formation has been eroded in the area of Odoornerveen (a former peatbog), in linear direction parallel to the Hondsrug (Figure 1.2; Chapter 1.2).

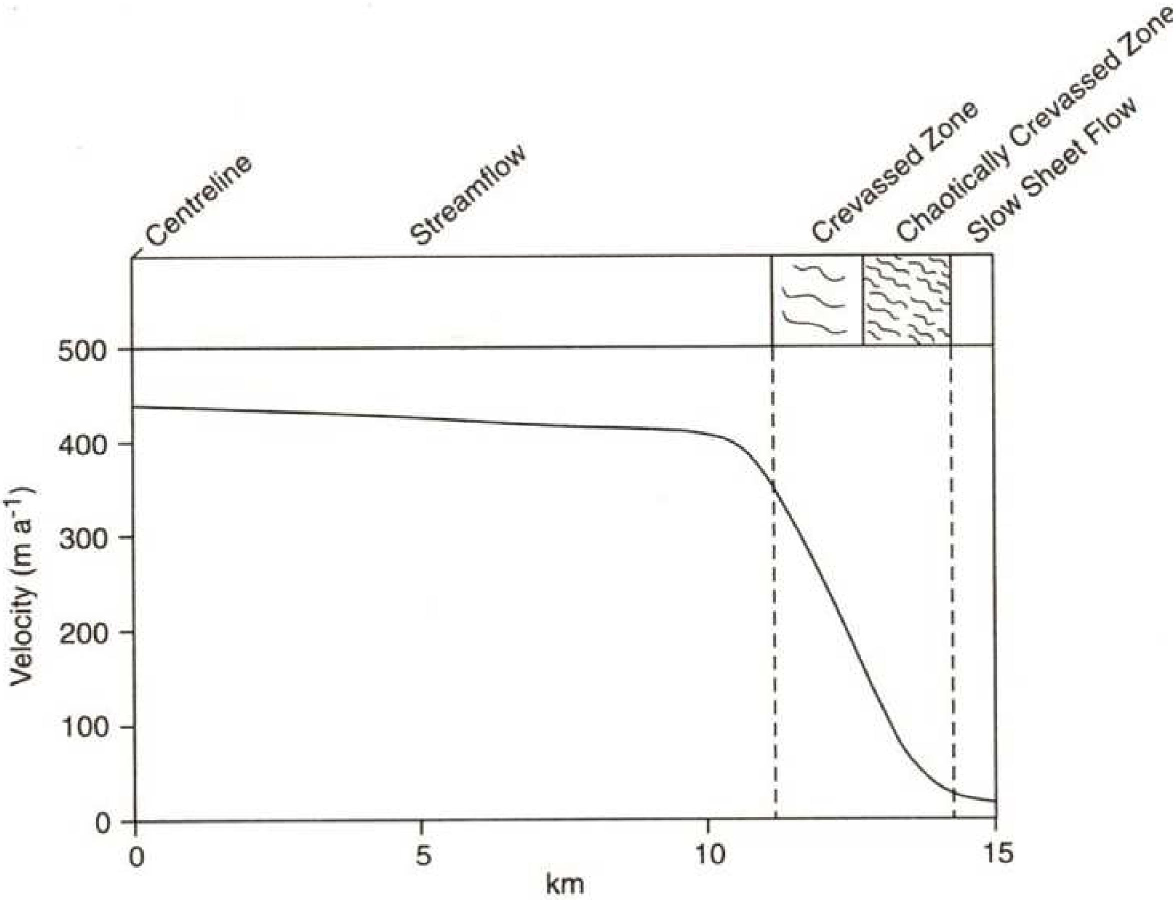


Figure 7.0. Variation of velocity across an ice stream with a dramatically lowering in the friging zone of the part of the ice stream with high velocity to the part with slow sheet flow. In the zone because of internal melt water production is high and due to occurrence of frigging crevasses (From: Evans, 2003)

South of Borger/Buinen, tills are partly absent and erratics and pebbles are surfacing as is indicated on soilmaps (the only area in Drenthe with a depth up to 4 meter (own observation)). This indicates strong erosion of the tills due to a release of a large amount of meltwater which eroded the tills and washed out the finer material. There is a remarkable difference with the strong deformed glacier bed north of Borger to Gieten and the area between Exloo and Valthe. In this area, tills are very thin and are superposed on NE – SW deformed (older) subglacial sediments indicating phase 3 according to Pierik, Bregman & Cohen (in prep.). Glacial erosion caused by the Hondsrug – Hümmling Ice stream did not occur, because of two reasons: firstly, we suppose the presence of permafrost and secondly we suppose the presence of high water pressures above the flotation point. The thin tills indicate less water content during their formation and fast flow (e.g. Van der Meer, *et al.,* 2003); whereas in the lowest tills (near Borger, Emmen and Schoonebeek) newly formed minerals (like syngenite, and halite; Bregman & Lüse in prep.) indicate the influence of brine water which penetrated from the north into the lowest tills from water above the permafrost layer. This agrees with indications of groundwater being forced up from the subglacial aquifer towards the surface (e.g. presence of pipes) in the northern area, north of Borger. We suggest basal decoupling of the ice stream in the area between Exloo and Valthe, due to (i) the occurrence of thin tills deposit upon undeformed subglacial sediments indicating fast flow; (ii) brine water intrusion in the till and (iii) indications of a high P_w (due to permafrost and by the occurrence of finer grained texture of the (preglacial) Peelo formation; Van den Berg & Beets, 1987)

While flowing over the Hondsrug transect, the ice stream loses its energy near Valthe and Emmen where finer grained deposits build up the megaflute with thicker sequences of till. According to this, it indicates a change in water content (van der Meer, *et al.,* 2003), maybe because permafrost was absent or penetrated less deep and due to stagnation as we described before. We suppose that a main reason for stagnation at Emmen is related to denudation of a previously formed push moraine from an older glaciation (probably connected to the Rehburg phase; phase 2; Pierik, Bregman & Cohen, in prep.) is evident from the pushed subsurface. Related to height and positioning of till types and clayminerals to present surface however the push moraine was not very high: at 55 cm – s.l. they found different till types. The lowest one is, based upon a study of erratics (Rappol, 1981) and XRPD analyses; Bregman& Lüse (in prep.), the same till-type as in south west Drenthe (phase … the Hondsrug – Hümr …

N … ost its energy
probab … d dumping of
tills int … e depression.
Subseq … ase 2: Pierik,
Bregma … uiving, *et al.,*
1994). … ide this area,
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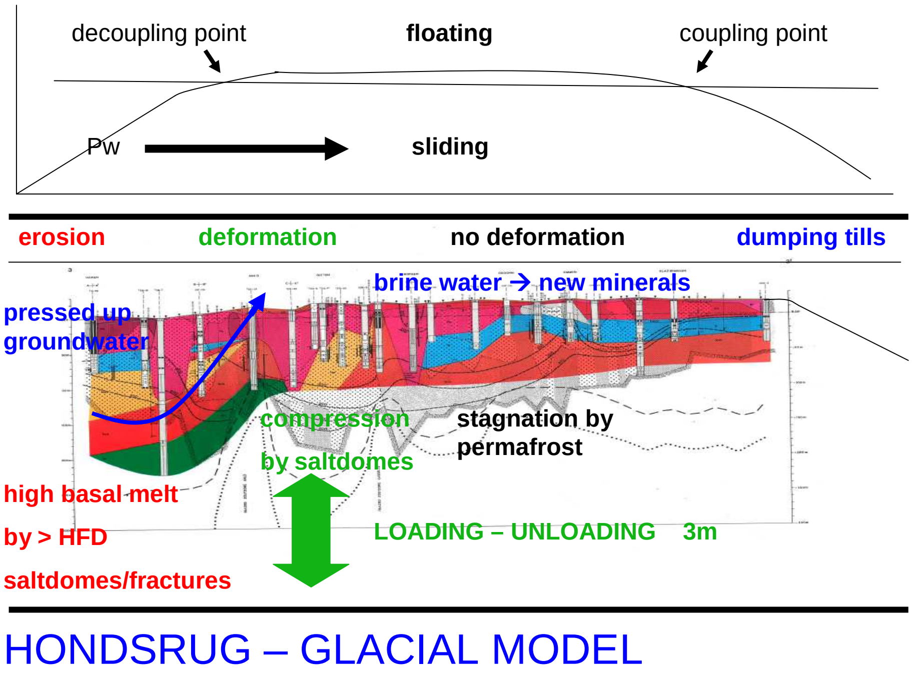


7.2 Genesis of the Hondsrug – Hümmling Ice stream

In this chapter the central question to answer is why the Hondsrug – Hümmling Ice stream started in a degrading ice field and why just at this location. In this chapter we will also describe the pathway of the ice stream with respect to main parameters which influenced the path way.

On base of interpretation of (6) studied locations (Chapter 5) and correlative analyses (Chapter 6) we come to the next synthesis.

The Hondsrug – Hümmling Ice stream is a Saalian marginal ice stream which extented from North Sea area, north of Groningen to the Münster Basin [Figure 7.1]. The Hondsrug - Hümmling Ice stream as well as an ice lobe which formed the Gelderse Valley (e.g. Rappol, 1991) are the only known ice streams that formed in our region. Both are formed after the Saalian glacial maximum in the Netherlands in the beginning of phase 4 (Pierik, Bregman & Cohen, in prep.) in the IML of North Western Europe. The features formed by the ice stream of the Gelderse Vallei are mainly push moraines with no indications of forming a megaflute, which makes the Hondsrug an unique Saalian glacial feature.

Marginal ice streams occur in margins of ice-fields and have an important internal feedback function in the icefield: to keep mass-balance in equilibrium in the degradation phase. In the Netherlands and NW Germany the Saalian (MIS 6) glaciation was the last one that covered the land with ice. In the northeast a reactivation of ice movement occurred between the Elbe and the Weser forming several push moraines. Some of these push moraines were overridden and large sandurs formed on the Lüneburger Heide. The ice came from the northeast. This re-advance can be linked to the Middle Drenthe phase of Ehlers (1990). A second re-advance probably occurred, somewhat further to the east around Hamburg. This re-advance can be linked to the Younger Drenthe phase or Warthe. The Weichselian glaciation did not reach this area.

Previous studies (e.g. Van den Berg & Beets, 1987; Rappol, 1991) proved, based upon palaeo-reconstruction of glacial landscapes, that after the Saalian glacial maximum in most of the area deglaciation started by stagnation and melting of parts of the ice field. Dead ice fields exist at the same time as ice streams are active. After the ice advance reached its maximum, a fast retreat of the ice caused imbalance in the mass-balance. As a response to this condition, an internal reorganisation within the ice-field forms an ideal starting point for the genesis of ice streams. In fact this period is the beginning of further degradating of the ice field, and starting point too of a very dynamic landscape where processes like rebound because of unloading started to play a fast growing role with impact for example on positioning of drainage systems with alternating positions as is proven for example for the Rhine – Meuse after last glaciation (e.g., Cohen, 2003), response on drainage and infilling of proglacial lakes and shoreline development with changes of the erosion base were the main processes at the end of this phase, which will be explained more in detail at the end of this chapter.

The extension of the Hondsrug – Hümmling Ice stream with NNW – SSE direction is described by Speetzen and Zandstra (2009) on base of (similarar) erratics, which are found in the Hondsrug area, as well as in the Münster Basin. The ice flow which affected the western edge of the Hümmling (Rappol, 1991a) and, although not corresponding to assemblages of erratics noticed by Speetzen and Zandstra (2009), continued according to (Kluiving *et al.,* 1991; Skupin *et al.,* 1993) in eastern Twente into the Münsterland (Van den Berg & Beets, 1987). In other regions dead ice fields formed, clearly preserving the morphology from earlier phases (e.g. Pierik, Bregman & Cohen, in prep.; Van den Berg & Beets, 1987).

On base of our correlative analyses (Chapter 6) we conclude that the ice stream is triggered in two areas by a jökulhlaup in the Münster Basin and a hotspot in the North Sea area:

(i) The jökulhlaup has been caused by a breach of Lake Weser Bergland in the Münster Basin [Figure 7.1, point 1]. Winsemann *et al.* (2011) describes how a breach of the Weser Bergland Lake rose the waterlevel of the Münster Lake, with an depth of 130 m. (ckecken) and triggered calving of the ice scheet.

(ii) The hotspot with a higher HFD rose basal melting and formed a hydrostatically sealed subglacial lake in the North Sea area with high waterpressure which pulled the ice mass towards SSE. But also a mass surplus probably caused by patchy accumulation as is show by modeling due to regional differences in climatological conditions (e.g. van den Berg, 2007) could be a reason for mass flow.

The jökulhlaup pulled by overpressure of the subglacial water probably the process, whereas deeper geological structure as we assume, formed the pathway to drain overpressed subglacial lake-water from the North Sea area, pushed the ice stream when started (Figure 7.1 point 2).

A zone with higher temperatures (HFD) from the North Sea area trough the Hangstum Graben and Louwersmeer Trough to Groningen (e.g. fig 6.8 A) raised higher basal melt of the ice field. The subglacial meltwater drained from the source area by a (reversed) groundwaterflow to SSE direction. We assume that the ice flow direction is influenced by deep geological structures. But probably the direction of the ice stream is also influenced by the position of an older (Elsterian) valley system or drainage of the Weser. During the onset of phase 1 (Figure 1.5; Klostermann, 1992; Pierik, Bregman & Cohen, prep.) the Weser was still able to drain between the Wiehengebirge and the “Maarleveld line”. At the end of this phase the Weser was probably blocked and deflected towards the west to follow the ice margin to the north, which formed probably by erosion a lowering of the surface, which could be one of the reasons for ice- stream flow in the Hondsrug area in phase 4.

The most eastern side of the ice stream is marked by the Hümmling (Figure 7.1 point 4), well studied by Schröder (1978). The Hümmling is pushed from two directions from an N – NNE direction and a NNW direction. Most of the Hümmling is not deformed by pushing of this ice mass.

Although Schröder (1978) did not found evidence for an ice mass which caused the deformation of the Hümmling, we suppose that the partly overridden deformated Hümmling marks the most eastern flow of the ice stream, which could partly override the Hümmling as well. We estimate on base of height of topography (highest point of the Hümmling 72,7), base of fluvioglacial and glaciolacustrine sediments (LBEG, 2012; hydrostratigaphical profile; Schwan & Casse, 1997) and base of groundmoraine (Schröder, 1978) height of ice stream at ca. 80 meters at the eastern side of the ice stream.

Evidence for the most western part of the Hondsrug – Hümmling Ice stream (Figure 7.1 point 5 and 6) is obvious and reflects in morphology, but also in erratic assemblages (Chapter 5, 6). In the most northern part divergent of ice flows is may be related to the deeper subsurface. South of Assen we find a deep tectonic basin (Figure 6.1), which is still present around Geelbroek and Eleveld a lower area then surroundings (Figure 5.2). We suppose differential lowering of the area, which is may be related to loading of the saltridge near Hooghalen. It is the same area, where in post-glacial time (Figure 5; see also Chapter 8) differentiate rebound formed actual riverpattern of the Drentsche Aa. This means that local lowering of the area and may be differentiate resistance of the crust by loading might have influenced the ice flow behavior. In the most southeasternpart part of Drenthe, the Hondsrug ends and the ice stream dropped thick tills in the Itterbeck Basin. This glacial basin connects with the push moraine of Itterbeck connected with the Rehburd phase and which has in the northern part stagged slab, caused by ME – SW pushing.

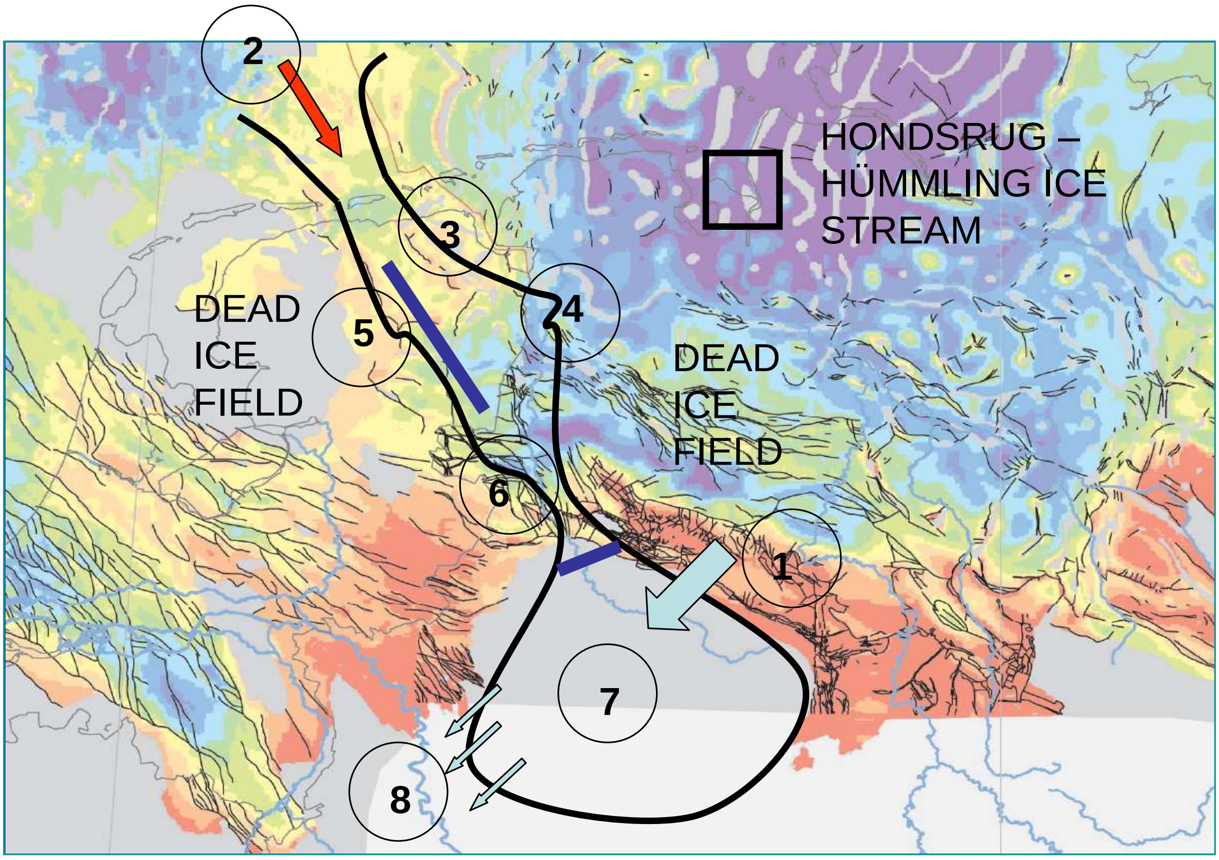


Figure 7.1. Positioning of the Hondsrug – Hümmling Ice stream (Saalian, MIS 6; phase 4: Pierik, Bregman & Cohen, in prep.). Background map: Lower Trias (PBA, 2011) indicating also tectonic structures. Main are South Permain Basin with salt structures (pink color; deep base); Devonian hardrock (red color; near surfacing). Correlation with glacial surface features, which will be explained in the text for locations 1 to 8. In blue in the north the Hondsrug area; in the south the ice margin (deglaciation phase; indicative). Red arrow: flow direction of the ice stream.

Trusting is influenced by Tertiary clays (Middle Oligocene; Ruppel formation), which formed glaciotectonic nappes because of high pore water pressures which contributed to sliding and overtrusting (Kluiving, 1993). In addition also deeper surface geology plays a role. Maybe a higher HFD (Figure 6.10), but most remarkable is the positioning of the glacial basin (depth 60 – 80 m. – N.N.) on a depression which connects to the South Permian Basin. The ice stream dipped into this a part of the South Permian Basin, a clearly structural weaker stron faulded zone (Figure 7.1), pushed against the Itterbeck Push moraine but could not pass it, as we conclude because of missing tills on top of the moraine. Height reaches to 50 m + s.l. Maximum ice thickness in the glacial basin reached to ca. 120 meter. Height and depth data are from LBEG (2012).

On base of hydrostratigraphical profiles (LBEG, 2012) our conclusion is that surface height of Tertiary clays, Mesozoic sandstones and Lower-Creteaceous formations, form in longitudinal direction of the Northwestfalian Lippische High (e.g. Walter, 2007, a to NW direction gradual dipping ridge, east of the Itterbeck basin). Between this ridge and the eastern part of the Itterbeck Push moraine (with EW glacial deformations; Kluiving,1993) the top of the Tertiary clays is 80 m – N.N. Top of plain, not glacial defromed areas in the Hunzedal and near Meppen reaches up to 40 m – N.N.. When we take this as a reference then we estimate height of the Hondsrug – Hümmling Ice stream near Drenthe in the most western part ca. 80 m. just like at the eastern rim of the ice stream. In the central part of the ice stream ice thickness amounted to 120 m. Another conclusion is that it could be that the Itterbeck Basin related to for example the glacial basins connected to the Lingener Hohe, the Ankumer and the Dammer Berge (e.g. van de Wateren, 1995) relative deep is and in an active phase of the Hondsrug – Hümmling Ice stream thick tills dropped. The flow of this ice stream stagnated in the Itterbeck Basin and prograded on the east side in between the Itterbeck Push moraine and the in SE direction updipping hard-rock ridge. Just in this area subglacial erosion deepend out subsurface to 80 m- s.l.

The ice stream probably pushed for second time (after forming in Rehburg phase) the eastern part of the Itterbeck push moraine. This is conform insights of Van de Wateren (1995) who has shown that lateral pressure gradients plays an important role in ice pushing as Bakker (2003) also demonstrated for the eastern part of the Veluwe. By consequence the ice flow is forced to the east, but blocked in the east by a dead ice mass with some tens of m's higher top surface then the ice stream. That is what we conclude with respect to respectively depth (80 to 90 m –N.N) in the glacial basin, height of the Dammer Berge (137 m above N.N), height of eastern push moraines of the Rehburg phase and top of northern not glacial deformed area (40 m – N.N.).

We assume that the dead ice field, east of the Hondsrug – Hümmling Ice stream was melting because of relative high HFD (Figure 6.10). This meltwater feeded a glacial lake in between the Wiehengebirge and the ice field and also Lake Weser (e.g. Herget, 1997; Klostermann, 1992) by passing the Porta Westfalica, a natural low with High HFD too (Figure 6.10)

We conclude on presence of erratics (*et al.,* Speetzen & Zandstra, 2009) that the ice stream passes Nordhorn where the Ems had already in that time its position where a deeper graben system probably contributed to a natural passage.

The breach of Lake Weser into Lake Münster, which caused (inland-) calving of the ice front somewhere near Nordhorn, caused not only the flow of the Hondsrug – Hümmling Ice stream (e.g. Winsemann *et al.,* 2011), but also raised the water level of the Münsterlake [Figure 7.1, point 7] and probably a breach at different locations to the Rhine valley, where deposits may be formed the UM 3 terrace (Untere Mittelterasse 3), which is mapped in the Rhine valley north of Duisburg to Montferland (Figure 7.1 point 8). This ca. 8 m. high terrace is build up by very stone rich, middle to coarse fluvioglacial sediment, indicating a high energy depositional environment. Klostermann (1992) describes how the base of the UM 3 terrace nearly almost a strong erosion discordance layer forms with underlying sediments and when formed often deep incised in older sediments even into Tertiary sediments. On base of lithostratigraphy UM 3 Klostermann (1992) concluded that the UM 3 is formed at the end of the Drenthe stadium. Positioning of the UM 3 terraces, west of the Münsterbasin, deposits which indicate dramatically impact of fast release and immense amounts of meltwater and chronology are that way that it will be of interest to study in future the possible connection with events in the Münster Basin triggered by a breach of Lake Weser.

7.3 What controlled the Saalian MIS 6 ice stream?

In this chapter we give an answer to the question of what controlled the Hondsrug – Hümmling Ice stream. In table 5 we summarise our conclusions and it will be evident that geographical positioning of the ice stream in the margin of a degrading icefield is a very important conditional factor, but positional conditions related to specific regional circumstances are the main reasons the ice stream started to flow. The ice stream is triggered by an event at the (inland) shoreline by forced calving and pushed by high pressured subglacial amounts of meltwater. The positioning of the source area, pathway and behaviour of the ice stream depends strong of "deep" and "warm" where to our opinion loading and unloading caused by forebulging and collapse reactivated and triggered changes in the earth crust, which influenced not only the positioning of the ice stream, but also postglacial processes. Deep geology influenced discharge of meltwater strongly, but is locally also influenced by permafrost, substrate characteristics, whereas the pathway of the ice stream is mainly controlled by an interaction of "deep" and "shallow" obstacles. In Chapter 8.3 we will discuss our hierarchy in relation to a proposed hierarchy of controlling factors for marine-ice streams (Winsborrow *et al.,* 2010).

Controls	Feature/parameter	Process/ impact
- Geographical position	- Ice marginal zone	- Deglaciation phase with strong ablation - Internal correction unbalance
- Margin type	- Inland "ice margin"	- Calving
- Subglacial geology	- Hotspot; higher HFD; - Basement temperature (Tb) - Graben and fault structure - Elsterian channel system - Salt domes, - ridges - Base of groundwater system with underground topography	- Spatial variation by local higher Tb - Raise of amount of sub-glacial meltwater - Fore bulging - Vertical and horizontal stress - Reactivation of faults - Halokinese - Spatial variation reversed groundwater flow, probably - Impact on ground-water quality (salinization of meltwater caused by pressed up groundwater flow with influence on new formed minerals in tills)
- Topography	- Ancient proglacial drainage of meltwater/ the Ems	- Less resistance surging, the more in combination of impact of loading on deeper geological structures
- Abundant meltwater	- P_w (basal water pressure)	- Overpressure leads to deformation, subglacial erosion (specific features: e.g.: * subglacial channels, *dykes and floating - (Sub-) glacial erosion
- Soft bed	- Fine sands and Tertiary clays	- Less resistance sliding ice stream - Raising Pw

- Smooth bed	- Roughness - Outcrops (hardrock)	- Lower basal slipping - Resistance, blockage - Stream velocity - Pushing (
- Controlled pathway	- Flow path control - Hotspot; higher HFD (in combination with positioning of main faults/graben systems)	- (Lateral) resistance caused by outcrops, older push moraines - Higher thermal gradient promotes ice stream flow

Table 5: Controlling parameters of the terrestrial Saalian Hondsrug – Hümmling Ice stream, Drenthe, the Netherlands. In the table hierarchy of controlling parameters are given from top to down.

Is

8. Discussion

8.1 Ice streams in the IML

We studied in detail the central part of a Saalian MIS 6 glacial feature and zoomed out to the onset and ablation zone of the ice stream for better understanding reasons of forming, positioning, and ice streams behaviour.

Positioning of marginal ice streams in North Western Europe is strongly related to deeper geological (graben-) structures [Figure 6.6] and are - as well as most studied Weichselian ice streams (e.g. Winsborrow *et al.,* 2009; 2010; Andreassen *et al.,* 2009; Winsborrow (a) *et al.* 2009) and recent ice streams (e.g. Bennett, 2005) - very dynamic systems which play an important role to control mass-balance in equilibrium, as well as discharge of the majority of ice and sediment (e.g. Bennett and Glasser, 2009). On the contrary to recent marginal or peripheral (Bennett and Glasser, 2009) ice streams positioning of on shore ice streams, even of Weichselian age, are in North Western Europe not studied very well in relation to control factors, although there are to our opinion good reasons to do it. The correlation of positioning of the Gulfs of Gdansk, Riga and Kaliningrad and inland formed push moraines is only studied superficial, correlated these ice streams with deeper geological structures (graben sytems). But post glacial processes are just of huge impact on shoreline development and occupation in the delta systems (Bregman & Druzhinina, 2012) which developed in these now high populated areas and more on general on river systems like Rhine and Meuse (e.g. Cohen, 2003; 2009).

More in general we conclude that in the Netherlands and North Western Europe (on contrary to the Baltic) post glacial rebound studies are not done at the distal side of the forebulge, with exception of studies of the Hunte-valley west of Bremen (Sirocko, 2005, Lehné and Sirocko ,2005 and Szeder and Sirocko, 2005.

We conclude too that relicts of glacial ice streams of Saalian age on shore are also not studied very well. The most logic main reason is a natural one because in North Western Europe the Weichelian ice advance removed Saalian features or reduced coverage to local relicts covered by younger Weichselian depositis. For that reason the Hondsrug area is a unique well to study Saalian feature, which we classify on base of feature (composed of more lineation's, 60 km length, spacing between lineation's) as a megaflute, a streamlined subglacial feature (Bennett and Glasser, 2009).

8.2 The newly Hondsrug model unique?

Saalian Lineations and megaflutes like the Hondsrug are in literature well described, but less studied from a genetical point of view. A main reason in the NW European context is that Weichselian glaciation in most areas removed older glacial features. Also Weichselian ice streams were not object of study. One of the exceptions is a study by Jørgensen and Piotrowski (2003) who describe how several stages of ice-sheet covering on Funen Island in Denmark can be extracted from the glacial sedimentary record. Secondly they describe how to classify and structuralize glacial sediments exposed in gravel pits in a convenient way for palaeoglaciological reconstruction. And last, they provide a glacial model for the behavior of an ice stream on its bed based on the basal water pressure (Figure 3.3). Our results, where we assume different phases in ice stream behavior (erosional phase, deformation- and floating phase) in the Hondsrugarea are confirmed by their study. Although glacial features and chrononology are different (Funen: late Weichselian; Hondsrug: Late

Saalian) the sequences of events and principe of floating, caused by high waterpressures above floating point is clear and seems to be in both cases important for ice stream behaviour in both areas. Similar are sedimentary records indicating same processes as we studied on detail in the Hondsrug area. Remarkeble however is the difference in subglacial features. At Funen for example eskers and drumlins are subglacial formed by the Weichselian ice stream. In the model of Pierik, Bregman & Cohen (in prep.) the Hondsrug – Hümmling Ice stream these features are missing, on the contrary of the third ice advance as mapped by Skupin *et al.,* (1993) which covers a broader area, inclusive a western part in the Netherlands with an esker in Twente and the Achterhoek. A weak point in the model of Pierik, Bregman & Cohen (in prep) as well as our study, which relates with our aim and focus on the Hondsrug itself, is that both studies are based on interpretation of previous studies and needs field control. Our conclusion is that as well as the onset zone as the termiinal zone of the Hondsrug – Hümmling Ice stream needs much more attention in future. In that case both studies will be totally different in approach. In the onset zone seismic data and interpretation of deep well logs are very important for palaeo reconstruction, whereas in the terminal zone much more attention will be given to lithostratigraphy with attention to fluvioglacial deposits (e.g. Herget, 2008), impact of dumping of the Hondsrug – Hümmling Ice stream of debris and implications of the breach of Lake Weser in the former Münster Lake. An interesting point of discussion is the question about dumping of debris from the Hondsrug area in the former Münster Lake. Debris could be transported by ice bergs in the lake and may be this is one the reasons why in the Münster Basin the lithostratigraphy is complicated, as described by Herget (2008). Stokes and Clark (2003; 2007) describe this kind of ice stream with a reference to the Dubawnt Lake Paleao-Ice Stream in the northwestern portion of the Laurentide Ice Sheet during late glacial times. Just like the Hondsrug – Hümmling Ice stream the Dubawnt Lake Paleao-Ice stream has:

(i) Appropriate dimensions;
(ii) Converging – trunk – diverging flow;
(iii) Abrupt lateral margins;
(iv) Mega scale glacial lineations
(v) Inferred velocity field as we have shown for the Hondsrug area.

According to Evans (2005) the Dubawnt Lake Palaeo Ice stream is very rare and to him the only known terrestrial ice stream. This implicates that the Hondsrug – Hümmling Ice stream a good and unique example is of such type of terrestrial ice stream too, but even more described in detail and different too from the late glacial Funen ice stream, which can be classified by the system of Evans (2005) as a marine-based ice stream. The process of calving of the terminal zone and transport of debris by ice bergs is however the same. To make a difference with the terminus of marine- based ice streams and terrestrial calving zone we proposed to call the terrestrial ice margin: inland ice margin (Table 5).

8.3 What controlled the Hondsrug – Hümmling Ice stream?

In Chapter 7.4 we have given in Table 5 an overview of parameters which controlled the terrestrial Hondsrug – Hümmling Ice stream. The parameters in Table 5 are ranked from top to bottom reflecting their importance. Leaving aside the first two parameters: geographical position and inland ice margin, to our opinion the ranking is different as presented by Winsborrow *et al.* (2010). In Figure 8.1 the overview is given. To our opinion, sub glacial geology processes (reactivation of faults; shifting mantleflow/ HFD) influenced by forebulging plays an important role in the onset zone and in combination with ice margin calving, these both parameters are the main reasons to start flowing of the terrestrial ice stream. In the ranking of Winsborrow *et al.* (2010) [Figure 8.1] deep geological processes don't play a very strong role or are not well studied.

It is well known that differential shoreline development caused by rebound is strongly connected with (regional) geological structures. Rebound already starts in the ice field degradation and could be a good addition to the model of Winsborrow *et al.,* (2010). In both set of parameters topography, subglacial meltwater and bed conditions are important and more or less equal in ranking. However, in combination with deep geology, the pathway of the reversed groundwater flow is to our opinion in the Hondsrug area very dominant regional condition as seems to be also geothermal heat. This combination is to our opinion a strong one, which has strong influence on basal melt conditions as well as the pathway of the subglacial meltwater. In the examples of Winsborrow (hard)rock topography is most favourable for ice flow condition, while the occurrence of thick sedimentary deposits in the Hondsrug area makes a world of difference with Winsborrows' models, since these deposits favour deep groundwater flow and interaction with ''deep'' geology.

STRONG

Winsborrow, e.a.(2010)	This study
Topographic trough	Subglacial geology - faults, saltomes, geothermal heat flux (HFD)
Calvin ice margin	Calvin ice margin (inland)
	Topography
Soft bed	Abundant meltwater - waterpressure
Abundant meltwater	Soft bed
Smooth bed	Smooth bed - roughness
Geothermal heat flux	Controlled pathway - obstacles
Topographic step	

WEAK

Figure 8.1. Hierarchy of controls of ice streams by Winsborrow *et al.*(2010) and our study. The most favourable parameters are given. Unfavourable conditions are according to Winsborrow *et al.*(2010) respectively: flat bed/topography, land terminating, hard bed, scarce meltwater, rough bed, low geothermal heat and flat bed/without topographic steps. Related to our study Land terminating is obvious not an unfavourable condition for ice streams of the inland ice margin type (Hondsrug – Hümmling Ice stream).

In hierarchy, changes exist between the two studies with "shallow" geology playing a role in the pathway of the ice streams, because of topography, topographic steps or presence of surfacing obstacles (our study).

8.4 Correlation with deeper geology

We have in this study for the first time in Northern Netherlands attention for the impact of forebulging on glaciological processes and conclude that till now there is an underestimation of the implication of forebulging as an important glaciological process in our region. One of the implications is that in studies like ours, deeper formations and processes within the earth crust have to be considered in addition to the surface processes (glaciology), therefore a need for good cooperation between different disciplines and needs an inter-disciplinary or holistic approach. In the Netherlands, the importance of forebulging as a glaciological process has been correlated to-date to specific regional quaternary geological events (delta development) and studies by Stouthamer, *et al.* (2002); Cohen (2003, 2009); Houtzagers (2003) and Busschers (2008) [Figure 8.2]. All studies were done at the distal side of the forebulge; whereas in North Western Germany impact of rebound has been studied for the Hunte Valley, west of Bremen (e.g. Lehné and Sirocko, 2005).

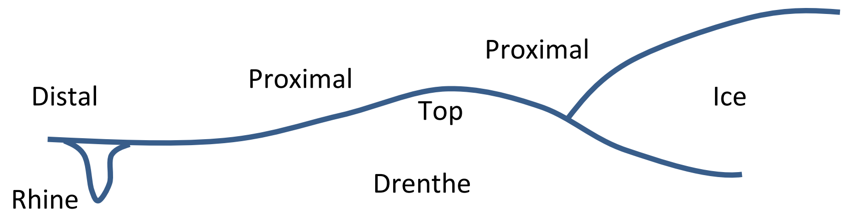


Figure 8.2. Location of Drenthe and Quaternary geological studies (e.g. Stouthamer *et al.,* 2002). Hondsrug area is in the proximal part of the forebulge influence area, while the Quaternary geological studies have been performed in the distal part of the forebulge, where vertical movements are much less.

However, since 2007 the deeper subsurface is getting more attention in the Northern Netherlands, because of the growing need of regulation of subsurface activities, mainly related to soil energy and a sustainable policy for its use. This implicated also the need of weighting of best practice use which forces interdisciplinary approach and for example to get more insight in stability of the subsurface for save practice use like storage of waste disposal (e.g. Beleidsplan voor de ondergrond, Provincie Drenthe, 2010).

Related to the impact of forebulging on the shallow earth crust, we conclude that impact of glaciations reaches not only deeper and needs therefore attention (see the follow up), but also that we have strong arguments that the base of Perm or lower Trias will be a good reference level for correlation of pre-, sub- and post glacial impact on landscape forming processes.

A central point of discussion in our approach is the correlation of spatial distribution of features, e.g. a correlation between “deep” geological structures, glacial features and properties of the earth crust as a result of forebulging we have shown in Figure 6.3 for the Netherlands. The strong point is that to our opinion that we can explain in the Netherlands that positioning of glacial events is related to a systematical relationship between stiffer parts of the earth crust, tectonic highs, and stagnation of the advancing Saalian ice flow. A correlation between the positioning of fault systems (northwestern part of the Kijkduin High; Wong, *et al.,* 2007) and positioning of Saalian end-moraines in the Netherlands (e.g. het Gooi; de Veluwe) is already mentioned by Edelman & Maarleveld (1958). Although correlations in that part of the Netherlands are very positive, it is never been studied in detail. Even glacial basins related to the push moraines are all situated in the Mid Netherlands low. And in the Northern Netherlands, it is to our opinion obvious that the a-synchronic continuation of the Rehburg phase in the Netherlands (tills near Texel, Rode Klif and the Havelterberg; phase 3 according to Pierik, Bregman& Cohen, in prep.) correlates with the positioning of the Texel-IJsselmeer High and the moraines in Groningen with the Groningen High.

Another example concerns a positive correlation between “deep” geology, glacial features (in this case thickness of tills) (Figure 8.3) and the positioning of higher HFD values (e.g. Figure 6.5 and Figure 6.8A).

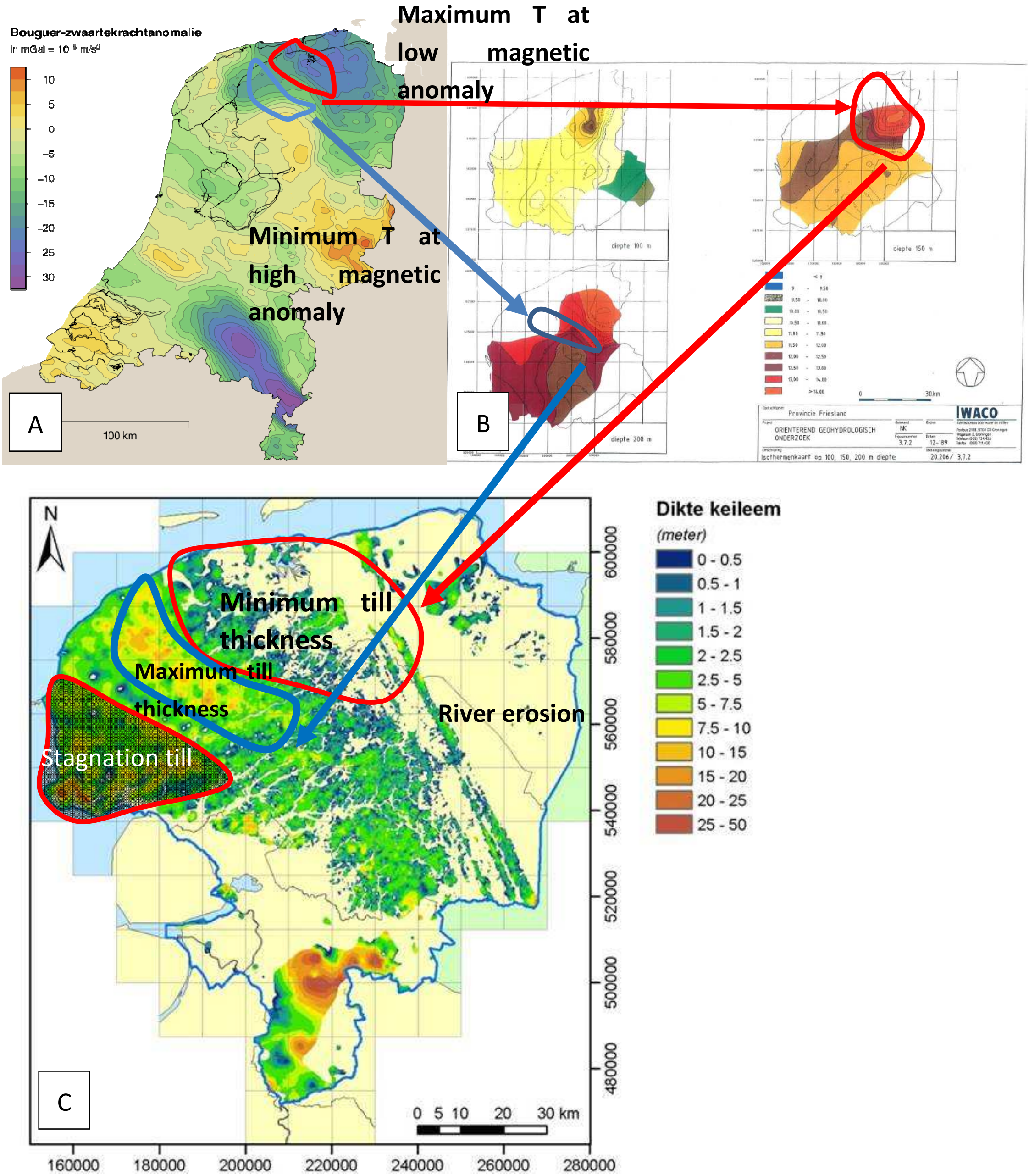


Figure 8.3. A) Deep geology: gravity anomalies in the Netherlands. Low values correspond to: 1) occurrence of thick unconsolidated sediments in subsiding basin (Roergraben, south Netherlands) or 2) Occurrence of rock salt (since the density is lower than the surrounding sediments, northern Netherlands) (Bouguer-anomaly of gravity in mGal. From: Atlas van Nederland, 1971). The occurrence of rock salt in the northern part of the Netherlands results in rather high geothermal gradients (**B**, source: IWACO report, 1989). Glacial erosion occurred in the north Frysian area due to the occurrence of a salt dome that lead to large compressional forces. South of this region, increased heat fluxes led to higher basal melting rates and therefore thick till deposits (**C**). C) Till thickness in northern Netherlands. The till is also thicker in SW Friesland, since at

this location stagnation of the land ice occurred due to the occurrence of the Texel-IJsselmeer structural high and therefore in a conveyer belt fashion, till was brought towards this front. (Source: TNO, 2012)

Most thick till deposits are in the Hondsrug area found near Groningen and Schoonebeek and in north Netherlands furthermore in the middle of Friesland and areas related to the Rehburg-phase (Chapter 6.2; Figure 6.3).

Two processes might be the main reason for thicker till deposits:

(i) Stagnation, because of influence of tectonic highs (near Groningen; Rheburg–line with Texel-IJsselmneer High) or surface obstacles (Hondsrug – Hümmling Ice stream near Emmen/ Nieuw Schoonebeek and an older pushmoraine near Itterbeck)

(ii) Higher basal melt because of a higher HFD value. The last is possible reason for dumping of tills in central Friesland as a result of a combination of stagnation and presence of a hotspot: the salt diapir of Pieterburen.

Both processes, stagnation and basal melt (and a combination) results in dumping of (melt out) tills. The main conclusion for the Hondsrug area is that thick tills correlates with stagnation because of positioning of deeper geological structures, but our approach is rather bold correlation of different parameters and is in need of modelling and more glaciological interpretations of deposits and detailed analyse with help of new techniques like GPR and XRPD.

8.5 Geothermal heat and basal temperature

In our model, Heat Flow Density (HFD) is an important controlling factor (see also Figure 8.1) and we assume that forebulging and reactivation of faults could have had impact on a higher HFD during glaciation. So loading of the uppercrust not only has impact, to our opinion, on the geoid form of the earthcrust and distribution of heat in the lowerpart of the earthcrust and so on gravity, but also on the regional scale in the uppercrust (e.g. Thorson, 2005). Higher temperatures near saltdomes and reactivated faults have not only impact on HFD, but must have also forced deep groundwater to surface (e.g. Boulton, 2005; Piotrowski, 2005, Figure 9.1; Breemer, 2005) with impact on permafrost (Marcinek & Piotrowski, 2005) and so on a higher rate of meltwater. We suppose that also a change in physical-chemical conditions due to a change in groundwater quality effected the behaviour of the Hondsrug –Hümmling Ice stream in a broader area. The main reasons are a reversed groundwater flow and the depth of these flows to depths where brine water concentrations above saltdiapirs are relative high (Figure 3.5). In general weathering of the cap-rock of saltdomes leads to a higher salt content of the groundwater above salt diapirs. A reversed groundwater flow could have influence on this process, and in combination with groundwater flow also have impact on distribution, as is proven by Bregman & Lüse (in prep.) who found newly formed brine water indicating the formation of new minerals in the lower tills of the Hondsrug. This knowledge could be of interest, when salt diapirs will be used for storage, since on the longer term dissolution of rock salt by groundwater could create a risk of waste entering the hydrological cycle. Besides dissolution, loading and unloading of the crust can re-activate faults and rock salt re-mobilization, leading to an unstable host rock for waste disposal.

The position of saltdiapirs indicates a turn-over point from basal erosion and deformation (northern and middle part of the Hondsrug) to deposition of sediments. In our opinion, a main point of discussion is the link between HFD and a higher basal melting rate. The crux of this relationship is to our opinion that the pressed up brine to salt groundwater due to dissolution of the capcrock may cause a lowering of the meltpoint of basal ice in the order of 5-6 □C (pers. comm. prof. Séglins, Latvia University). A lowering of the melting point of ice in this range means that the basal temperature of the ice sheet (2-8 °C; Johnson *et al.,* 1995 in Maaijwwee, 2008) passed or becomes at the critical point of melting. In our opinion this is the main reason of higher meltwater fluxes in the northern part of the Hondsrug, which could be an important input for testing our model in combination with reversed groundwater flow, subglacial pathways and permafrost.

8.6 The need to test our model

Contrary to previous studies we had the opportunity to study the internal structure of the Hondsrug in lengths direction and rectangular in profiles at different locations the because of deep road cuttings and due to the use of new and modern techniques like XRPD analyses and GPR. The results of our observations, combined with modern glaciological knowledge, created for the first time the opportunity to make process related interpretations of different aspects and to combine these. As a result we developed a model of the genesis of the Hondsrug area.

A weak point in our study however is our proposal about the location of the source area and relation with deep geological structures in the whole area influenced by the Hondsrug – Hümmling Ice stream. Our conclusions are strongly based on correlations of geological structures, pattern of geophysical phenomena and similarity between our observations and studies in other areas. New insights for example, based on XRPD analyses and GPR measurements, underline coherence and made our model strong and ready for geophysical, geohydrological and glaciological – preferably integrated - modelling in future. We see this kind of modelling as the next step, i) to prove our model ii) to get more insight in for example stability of saltdomes and iii) the effect of a reversed groundwater flow on groundwater- and soil quality which might be influenced by a new glaciation. The possible impact of glaciations on these phenomena and more in general impact of rebound on landscape forming processes as we demonstrated in our study will be important in case of permanent waste disposable and use of saltdomes for other functions, like storage of compressed air (CO_2 sequestration).

The correlations between “deep and shallow” and impact of glaciations will be of scientific interest in the IML, to understand ice flow and positioning of ice streams better for palaeo-reconstruction in other countries or even for actual processes in glaciated parts of the world. We haven’t tested our model to consistency in other situations, but we have strong indications that better insight in comparable situations will improve glacial models for example in the Baltic. Therefore, our study can be seen as indicative, and as first to repeat a similar study in other countries. This makes the Hondsrug study of scientific interest for quaternary geological studies related to palaeo-reconstruction of glacial landscapes in IML’s of Europe, Eurasia and North-America. A follow up study not only contributes to the improve of palaeo-reconstructions, but to our opinion it will contribute to better insight in genesis and dynamics of ice streams themselves and on landscape forming processes as well with important geographical and temporal variations.

The coupling of a glacier flow model and a geological model (which includes parameters as loading, stiffness of the upper earth crust, geothermal flux, salinity of groundwater and unloading) could provide a quantitative estimate on the influence the deeper geology on subsurface and surface processes such as subglacial groundwater flow and ice stream behaviour. It will be of scientific interest to have such studies in interdisciplinary teams in areas (i) with hardrock and (ii) without hardrock and (iii) with Weichselian ice advance and (iv) without.

8.7 The new model of genesis of the Hondsrug versus previous ones

In Chapter 1.5 an overview is given of previous studies that studies the origin of the Hondsrug area. With a reference to our results it is obvious that the ridges of the Hondsrug area are not formed by glacio-tectonic folding (Van Calker, 1901; Lorié, 1891; Jonker, 1905), nor by retreat of an ice sheet (Ter Wee, 1979). Observations on tills indicating different ice streams (NE-SW and NNW – SSE); e.g. Dubois, 1902) are conform modern insights (e.g. Van den Berg & Beets, 1987; Rappol, 1987; Bregman & Lüse, in prep.; Pierik, Bregman & Cohen, in prep.) and are confirmed by our study.

Related to present insight about the impact of forebulging (this study), Dubois (1902) had already ideas about the role of loading (and unloading), although his explanation of the difference in height between the Hondsrug and the valley of the Hunze at the eastern side of the Hondsrug was totally wrong and as we now know is mainly lowered by glacial and post-glacial erosion. Zonneveld (1975) and de Gans (e.g.1981) also related the origin of the Hondsrug with deeper geological structures, but did not formulate their ideas as concretely as Van den Berg and Beets (1987), who described the relation between the occurrence of fine and coarse grained subglacial bed deposits (Tertiary, clays; Rhine sediment) on the glacier's behaviour.

Whereas previous studies and related discussions are mainly focussed on a few themes, our approach is integrating different aspects, based on recent records and involves as well "deep" geology and modern insight on subglacial meltwater discharge as classical themes related to till type, and erratics. We have in our model of reconstruction – based on recent observations – a sharp difference in the chronology of events and we show the differences in events. Processes related to the formational phase of the Hondsrug are: i) strong erosion in the north and ii) deformation in the middle part of the Hondsrug area, whereas iii) in the southern part no deformation is caused by the ice flow. So partly previous observations, which are confirmed in our study, are a result of a former glaciation phase and are even related to a former different glacial landscape (phase 2 according Pierik, Bregman & Cohen, in prep.).

A major issue of debate, since beginning of the nineties century, is how the Hondsrug – Hümmling Ice stream is initiated, due to a almost 90 degrees shift in ice-flow direction (the older phase had a NE-SW direction, whereas the Hondsrug had a NNW-SSE direction). According to Rappol (1987; 1991) the NNW direction of the ice flow implies that it was induced by the collision of the Fennoscandian ice sheet and the British ice sheet as was already proposed by Dubois (1902). Busschers *et al.* (2008) concluded that the British and Fennoscandian ice sheet must have been in contact, because their presence is the most likely explanation for damming off the northern edge of the North Sea proglacial lake. This does not necessarily mean that this collision actually caused the Hondsrug – Hümmling Ice stream. In fact it is very unlikely, because such a collision would yield a much larger scale ice stream than the Hondsrug – Hümmling Ice stream. An alternative explanation is the initation of an ice stream in a stagnant ice field as proposed by Rappol (1987) and Van den Berg & Beets (1987), which we linked to a source of geothermal heat in the onset zone and combined with a weaker zone related to heat flow and the positioning of the pathway because of existing (reactivated?) geological structures.

The flow of the ice is to our opinion triggered by these two conditions (high geothermal heat flux and geological structures), but another reason could be that in the onset zone ice thickness was higher because of locally higher precipitation and stagnation because of obstacles (e.g. Groningen High and Texel Ijsselmeer High). Above all, we suggest that in the ice field local conditions triggered ice flow.

On contrary, we suggest in the northern part of the Münster Basin that the breach of Lake Weser acted as a pulling force as suggested by Bregman (2008) and confirmed by Winsemann *et al.,* (2010). These kinds of pull induced ice streams are also described by (Stokes and Clark, 2005) for the Dubawnt Lake Ice stream in Northern Keewatin, Canada (see also Chapter 8.2). We suggest therefore to introduce a name for these ice streams that occur due to these phenomena: push and pull ice streams.

8.8 More attention to dynamics ask new paradigms

We conclude that the deglaciation phase, after stagnation of the ice advance, is a very dynamic one. Instead of what classical models suggest during the retreat of an ice front, our study of the Hondsrug area is a "show case" which demonstrates that advance and retreat could occur at the same time. We assume as well that i) loading and unloading at the same time occurs in different parts of the glaciated terrain, and that ii) changes in groundwater flow occur and that iii) the impact of extreme superficial groundwater pressures in combination with permafrost have influence on till formation. We suppose that this dynamic point of view has impact on interpretation of glacial processes and models which might contribute to new paradigms (Bitinas, 2008).

Based upon recent work (Pierik, Bregman & Cohen, in prep.) our proposal is to focus on two paradigms in processes occurring in ice marginal landscapes:

- One line of revision should be to pay more attention to the dynamics and variations during the formation of an ice stream, with more attention to local patchy zones with differences of ice thickness, precipitation and windshield conditions (e.g. van den Berg *et al.,* 2007), but also on the impact of local stagnation of ice flow (e.g. Pierik, Bregman & Cohen, in prep.) which both creates differences of accumulation of ice in the IML and ablation too.
- We also have the opinion that dynamics of the deglaciation phase needs more attention, to better understand landscape development as a dynamic and holistic entity. In other words: glacial landscape studies needs to comprise the glaciation as well as the deglaciation phases, including dynamic pro-, sub, and post glacial processes. Pierik, Bregman & Cohen (in prep.) demonstrated that glacial dynamics, including deglaciation, must be studied on the "level of the playing field". That means, in other words, that local and regional glacial studies must always be observed in the context of geographical spatial and time scales. Smaller scale (in space and time) processes always occur superposed onto larger scale processes (in space and time). Larger scale processes include forebulging, which has a long relaxation time, since magma is rather inert to move. Superposed on forebulging movement is for example the remobilization of rock salt, that can both occur in a constructive and destructive fashion. On the local scale, specific conditions can occur, that could influence ice streams behaviour at this specific spot (occurrence of salt diapir that result in compression of the ice stream). Glacial rebound can occur heterogeneously in space, where some areas are more susceptible to rebound than others. And as we showed for reversed groundwater flow in the area between Gieten and Borger [Figure 3.4], blockage of subglacial meltwater by deeper salt structures and permafrost downstream, led to very strong deformation and specific features like pipes.

The Impact of rebound on the Holocene river pattern is another example as is demonstrated in Figure 6.4. The actual river pattern in the area with Permian salt formations is correlated to the fault systems and block structures even on the base of the Perm formation. Rivers change flow pattern passing tectonic blocks (highs and grabens) or where strike-slip faults occur. Our conclusion is that this correlation is related to differential displacement of the faults and tectonic blocks by rebound indicating an important influence of Permian anhydrite salt formations (e.g. Geluk, 2005) in the subsurface of Drenthe. Anhydrite is brittle when it is thicker than 1 m whereas halite is plastic under pressure (Geluk, *et al.,* 2007). Because of halokinesis, an enrichment of halite in the surroundings when salt diapirs were formed could be an explanation why tectonics structures of the Permian base are related to surface morphology. But this is never been studied very well (oral conf. E. Duin/ L. Kramer).

8.9 Postglacial implications

We have explained the origin of the Hondsrug, the aim of our study. But after Saalian landscape processes forming processes caused by for example Weichselian glaciiation and a process like rebound had even till present impact on the Hondsrug landscape as well.

Rebound causes postglacial uplift of saltdomes and a radial river pattern in Drenthe, which is described by de Gans (e.g. 2011) and has also impact of a shift of the main waterdivide in Drenthe to the north of 800 meter. That is the conclusion of fieldwork we did in the area of Schoonlo were we found a deeper (older) riversystem of the Drentsche Aa on top of the saltdiapir.

More in general, one of the main post glacial implications of glaciations is related to the interaction of glacial (induced or formed) features and groundwater flow. Figure 6.4 is a good example and indicates that the present river pattern in Drenthe is related to deep geological structures, which must be the result of post glacial rebound as we concluded. This implicates a displacement of faults, which leads to influence of deep groundwater flows and to fixed positions of deep seepage areas in Drenthe. These areas are also areas where peat soils have highest thickness. This correlation is stronger where Elsterian buried glacial valleys exist and where double diffuse convection (DDC) has also influence of groundwater flow systems and positioning of seepage areas with differences in groundwater quality (Magri, 2011; Bregman & Magri, in prep.). Untill now, these correlations and conclusions, which are based on modelling, are not used in nature and landscape management systems.

Our study at the road cuts N34 and N33 offers a good insight in the deeper structure of the Hondsrug. With regard to the hydrology it is very clear now that (i) till sequences, (ii) deformation of the subsoil and (iii) subglacial features have a huge impact on hydrology.

We observed that interlayering of tills with very variable permeability (from very sandy to very stiff clayey) are common, whereas in literature (e.g. Bosch 1990) general statement is that different (more or less homogenous) tills are superposed. But even in the case where thick tills packages occur, drainage in between that tills is common (Figure 8.2) by means of piping, due to the occurrence of coarse material that fills up (Weichselian) frostwedges that penetrate these tills. Subglacial channels (meltwater channels) might also be influenced by iron pans (e.g. Figure 4.9). This means that for example that, for the calibration of hydrological models, parameterizing the permeability for the tills as homogeneous is not sufficient due to these piping features. Local knowledge of a till formation is thus indispensable, also for construction works like road cuttings, and measures taken to protect and improve nature- and landscape values.

Understanding of the complex geometry of glacial (eroded and deformed) sediments may be very difficult, but with techniques like GPR (Bakker, 2004) and XRPD analyses (Bregman & Lüse, in prep.) a superior insight is provided compared to borings alone.

9. Conclusions

Based upon previous studies and newly acquired data, we suggest a new glacial model of the Hondsrug area: a complex of megaflutes as a result of a Late Saalian ice stream with subflows with a NNW – SSE flow direction. The Hondsrug is formed by an ice stream, the Hondsrug – Hümmling Ice Stream, with the onset zone NNW of the province of Groningen in the present North Sea and was triggered by a breach of subglacial Lake Weser into Lake Münster, which pulled the ice masse to flow. Because of this, we propose to call this kind of ice stream a push – pull ice stream. With reference to Stokes and Clark (2005), this kind of terrestrial ice stream is the second known in the world and as we know the best studied one.

In the study area, stagnation related to deeper geological structures led to deposition of thick tills in the most northern part of the Hondsrug at a height of 6 m above sea level. In this portion also older sediments of Elsterian age are surfacing because of a high amount of melt water that resulted in large scale erosion of tills that were deposited, which was caused by basal melting due to high geothermal heat fluxes. In the middle of the Hondsrug area strong subglacial deformation occurs, caused by brine groundwater that were pressed up towards the surface, and stagnation of the ice flow due to the occurrence of shallow salt diapirs. These structures blocked the groundwater flow (forced over the salt diapirs) thereby raising groundwater pressure and this forced discharge of groundwater by subglacial channels and piping. In the southern part of the Hondsrug area no deformation of deposits of an older NE – SW ice flow occurs by the Hondsrug – Hümmling Ice stream. No deformation of older tills and sediments occurred (only a thin ice stream till cover) indicate the occurrence of permafrost and fast ice flow due to flotation of the ice stream in this part of the Hondsrug. By a lateral selection and building up of glacial sediments and tills, the megaflute reaches its maximum height of 28 m above mean sea level. The ridges, which are classified as mega-scale glacial lineations, formed in a similar way as their smaller scale counterparts (flutings) [Figure 9.1]. The glacial lineations make up an alternation of ridges and lows and this implicates a difference in pressure between the ridges and lows. The ice thickness is smallest at the highest point of the ridges, and largest at the bottom of the lows, thus the pressure of the ice is largest in the lows and lowest at the ridges. This will push sediment from the higher pressure zones in the lows, towards the lower pressure zones located at the ridges .

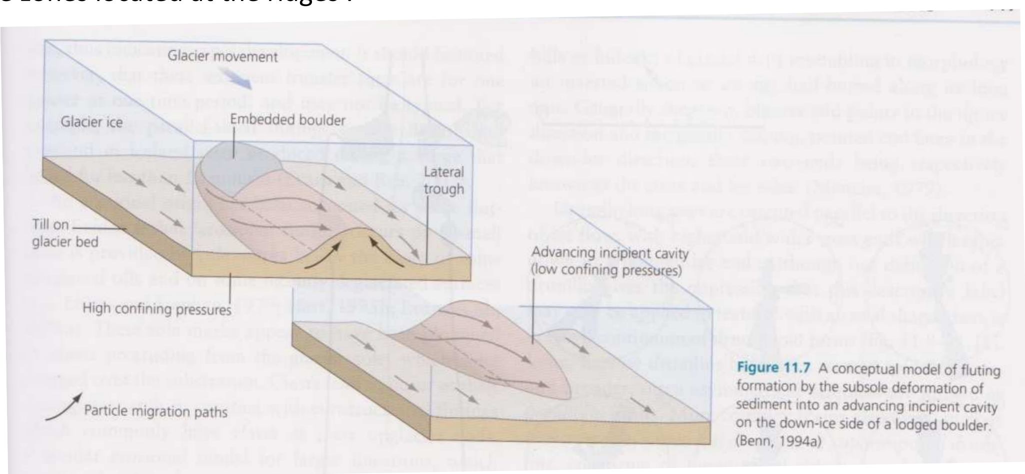
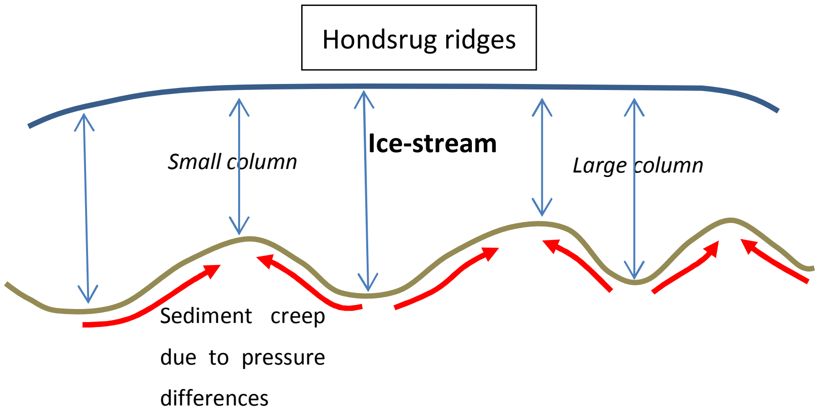


Figure 9.1. A conceptual model of fluting formation by the subsole deformation of sediment into an advancing incipient cavity on the down-ice side of a lodges boulder. Once the ridges exist, sediment will be pushed towards the low pressure

cavity. The ridges of the Hondsrug are classified as mega-scale glacial lineations and form with the same principles. (Benn and Evans, 2007).



Pressure = Density × Gravity acceleration × Height of column

Figure 9.2. Sediment creep due to differences in pressure at the glacier bed, since topographic highs and lows occur. Since the density and gravity acceleration are the same at the ridges and lows, only the difference in column of ice is creating a pressure difference. At the ridges, the ice column is several meters lower, while at the lows, the ice column is several meters higher. Therefore a lower pressure can be found at the ridges and a higher pressure at the lows, promoting sediment creep towards the ridge (from high to low pressure).

A bit further downstream, tills are dumped in the Itterbeck Basin, where the ice stream changed its flow direction, through a tectonic lower area into the Münster Basin, where most glacial debris was dumped in the proglacial Lake Münster (indicated by Bregman, 2008 and worked out by Winsemann, *et al.,* 2011).

Results of our study are comparable with flotation model for ice streams, developed by Jørgensen and Piotrowski (2003), although different in chronology. Instead of the Late Weichselian Funen ice stream with different glacial features, the magaflute of the Hondsrug is a Late Saalian feature and not deformed by the last glaciation. That makes the Hondsrug a unique (Saalian) glacial feature. In most parts of Europe, the Weichselian ice advance overprinted and eroded Saalian features (mostly) completely.

The Hondsrug as well as the Hondsrug – Hümmling Ice Stream are formed after the maximum Saalian ice advance in a degrading marginal ice field. We described the controlling parameters and compared these with a hierarchy of controlling parameters given by Winsborrow *et al.* 2010. To our opinion, sub glacial geology processes (reactivation of faults; shifting mantle flow/HFD) influenced by forebulging plays an important role in the onset zone and in combination with ice margin calving. Both these parameters are the main reasons to start the flow of the terrestrial ice stream.

In the future, the newly model of the Hondsrug – Hümmling Ice stream needs testing and improvement as well, as the onset zone as the terminal zone needs much more attention in future. In that case, both studies will be totally different in approach. In the onset zone, seismic data and the interpretation of deep well logs are very important for palaeo reconstruction, whereas in the terminal zone much more attention must be given to lithostratigraphy with attention to fluvioglacial deposits (e.g. Herget, 2008), impact of dumping of the Hondsrug – Hümmling Ice stream of debris and implications of the breach of Lake Weser in the former Lake Münster with possible implications for the formation of the Untere Mittelterasse 3 (UM3; Klostermann, 1992) in the Rhine valley.

We defined as a main point of discussion the link between HFD and a higher basal melting rate, which could be an important key question for testing our Hondsrug model in combination with reversed groundwater flow, subglacial pathway and permafrost. Another point of attention should be the correlation between stagnation and basal melt (and combination) which results in dumping of (melt out) tills. We have strong indications that in the Hondsrug area thick tills correlates with stagnation due to the occurrence of deeper geological structures. But, our approach is a very rough one and the proposed link between 'deep' geology and surface processes needs more attention with modern insight based upon glaciological interpretations of glacial deposits and detailed analysis of these sediments with new techniques like GPR and XRPD.

Finally we conclude that the glaciation and the deglaciation phase are very dynamic and need more attention in the future and could be seen as a new paradigm (Bitinas, 2008). To our opinion, we have to pay more attention to the dynamics and variation during the formation of ice streams, for example in local patchy zones with differences of ice thickness, precipitation and windshield conditions (e.g. van den Berg, *et al.* 2007). To our opinion, also the impact of local stagnation of ice flow (e.g. Pierik, Bregman & Cohen, in prep.) deserves more attention with a variation in the amount of accumulation of ice in the IML. These variations have to our opinion also impact on regional and local variations of events in the deglaciation phase, which leads to a-synchronic developments in time and space. The resulting differences in dynamics in the deglaciation phase need more attention. Glacial landscape studies need to include glaciation as well as deglaciation phases, including dynamic pro-, sub, and post glacial processes. Glacial dynamics however, including deglaciation, must be studied on the "level of the playing field". That means, in other words, that local and regional glacial studies always must be related to the context of different geographical spatial and time scales. To our opinion, these kind of researches need an integrated approach and can only be successful based upon interdisciplinary cooperation of different fields of studies of Earth sciences due to its high complexity.

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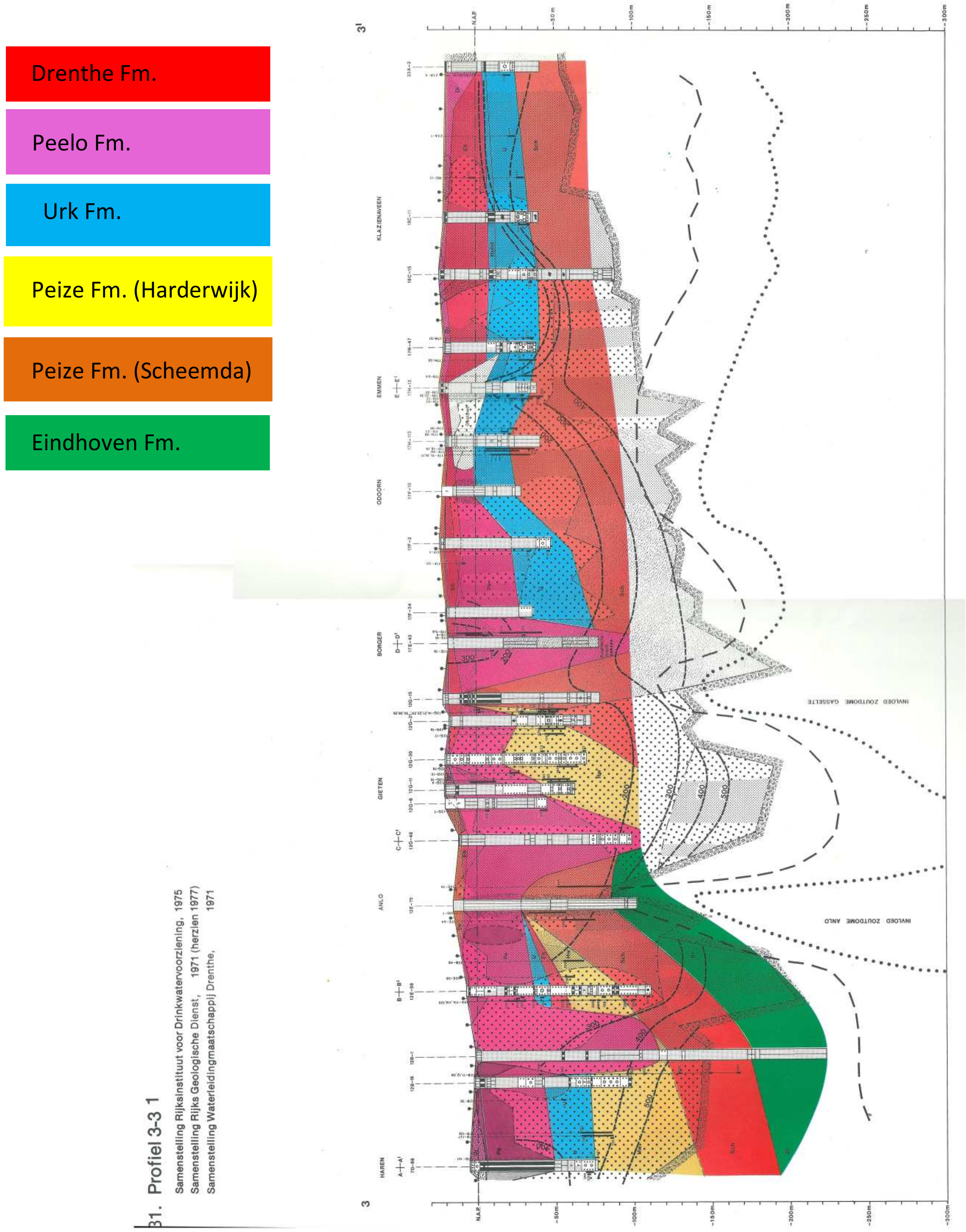
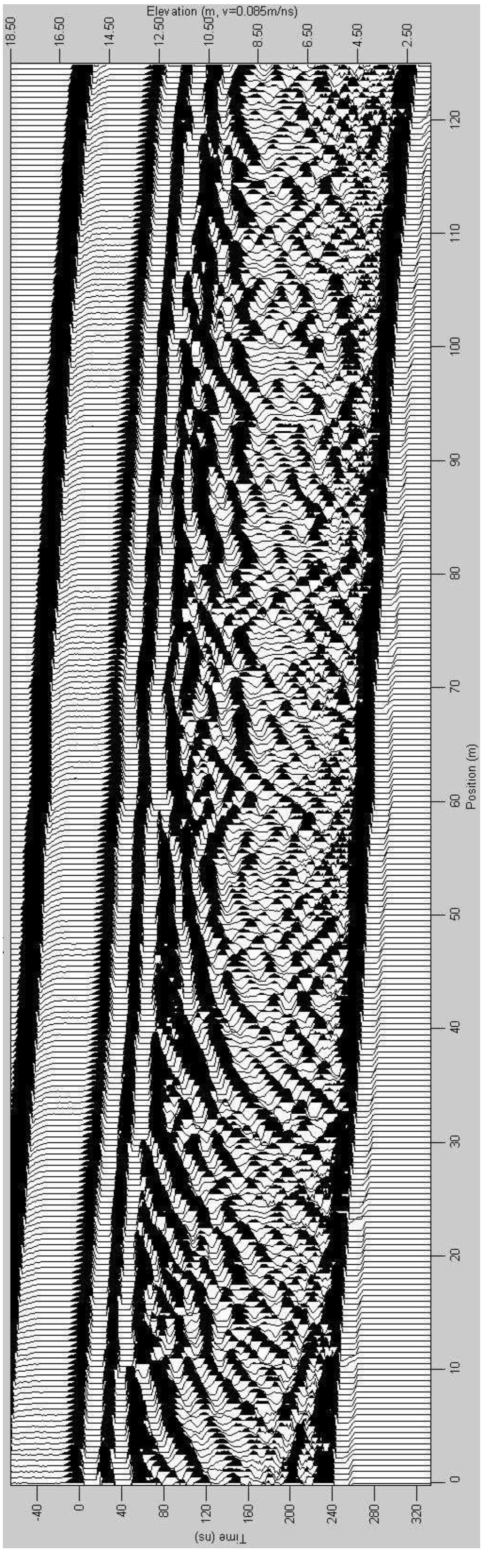
Appendix A

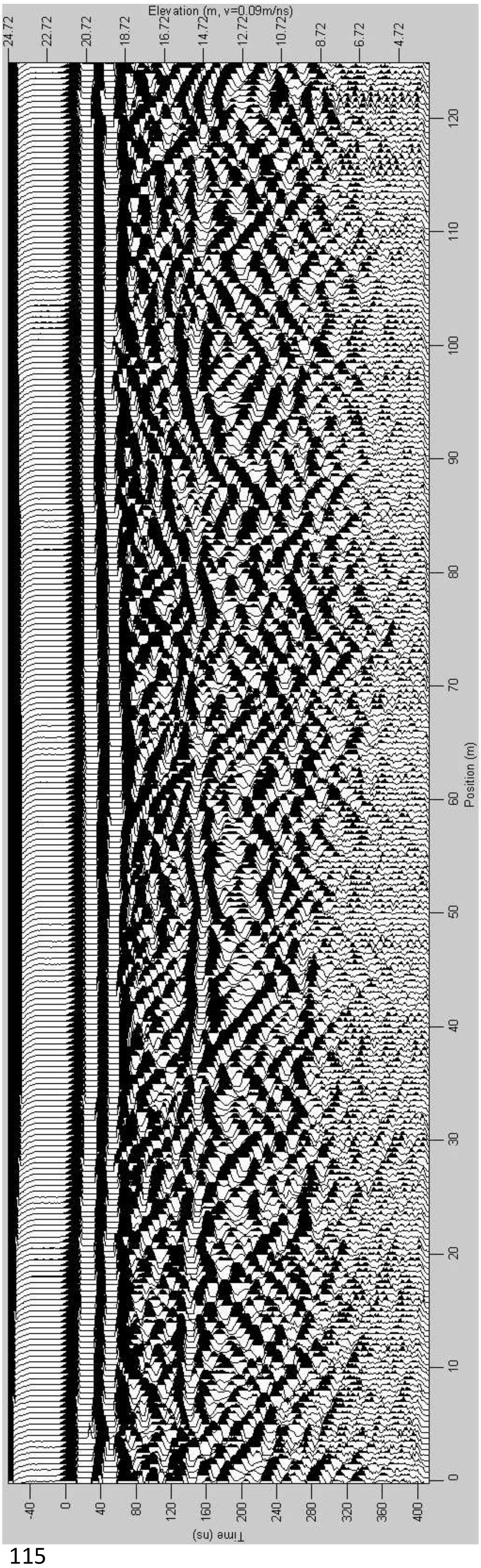
Geological NNW – SSE profile of the Hondsrug, indicates impact positioning of saltdomes and deformation of Tertiary sediments. In the northern part coarse grained river deposits are surfacing or covered by Saalian tills and Late Glacial coversands. In the southern area subglacial sediments (Formation of Peelo) are not deformed.

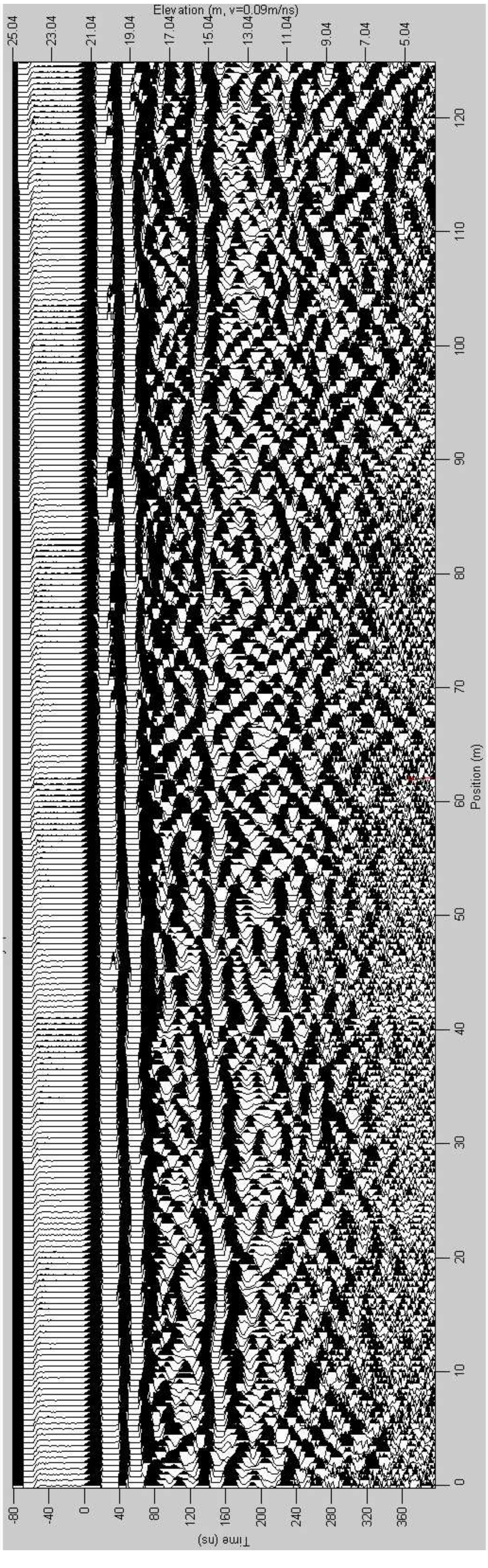


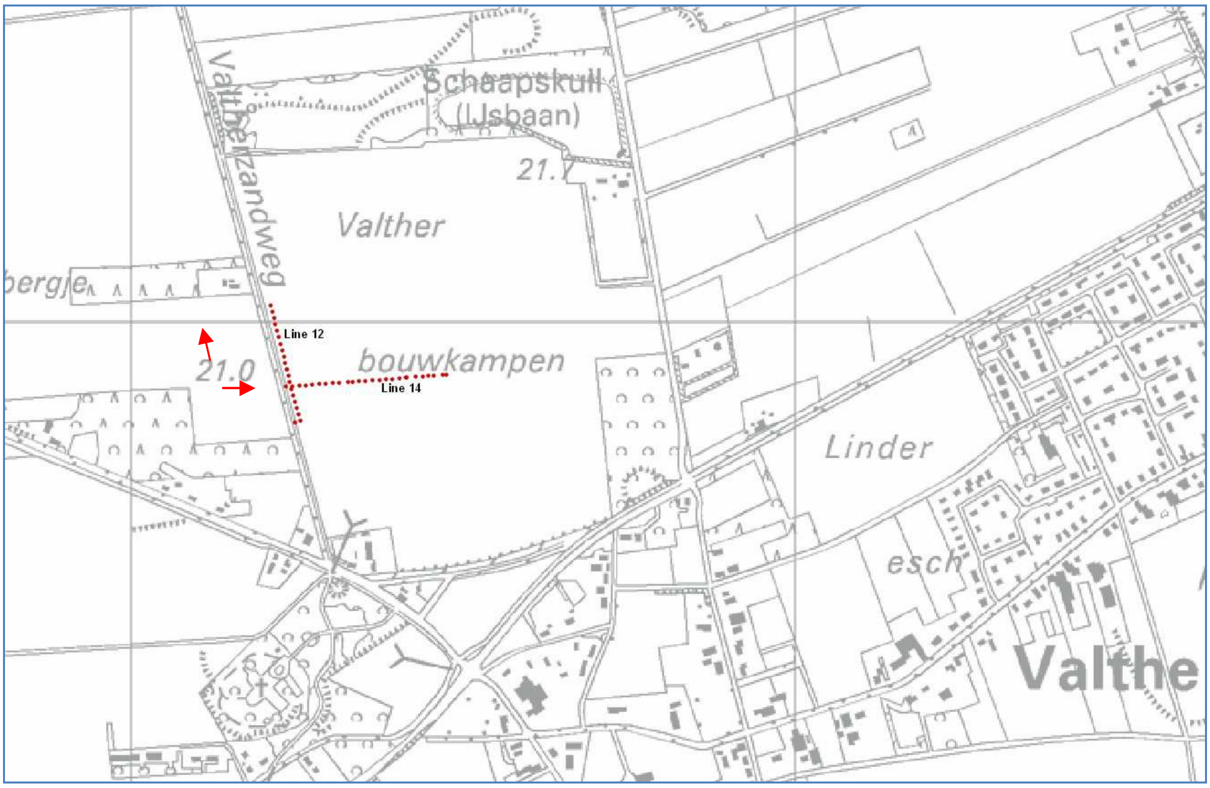
Appendix B: GPR - Bronneger



Appendix C : GPR – Odoorn / Valthe (See map on next page)

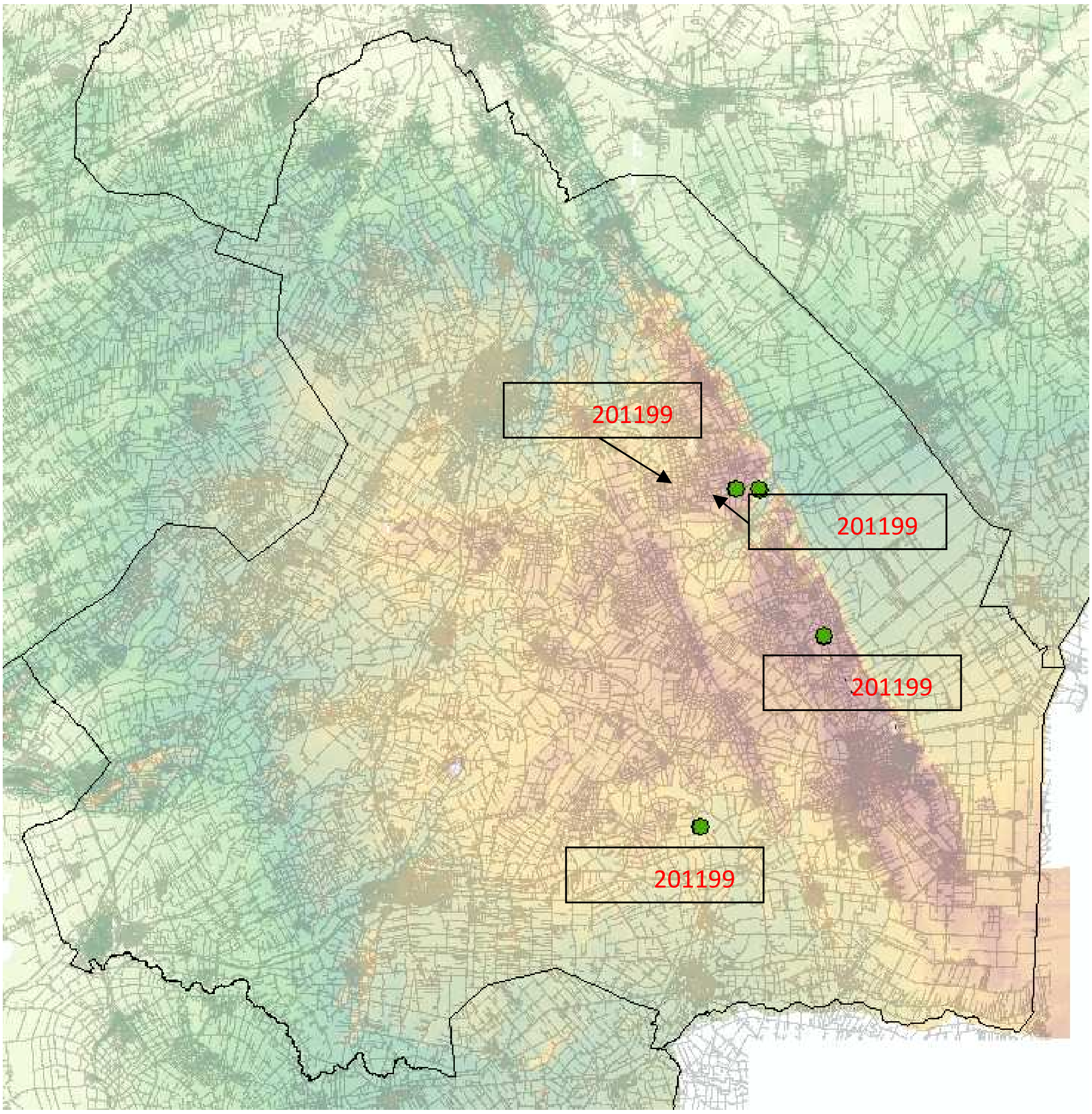






Location map of the GPR-cross-sections. The first cross-section shown is W-E, second S to N.

Appendix D: Bore-hole descriptions



Locations of the borehole descriptions