GENESIS OF THE HONDSRUG

A SAALIAN MEGAFLUTE, Drenthe, the Netherlands

ASPIRING EUROPEAN GEOPARK

September 2012

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Colophon

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Preface

A proposed European Geopark

This report is the scientific supplement to the application for the Hondsrug region (Drenthe, the Netherlands) to become a European Geopark. For that reason we started a combined geological and glaciological study. Within the context of the northwest European history of glacial landscapes and features the core topic of this study aim is firstly to reconstruct the genesis of peculiar the linear ridges through a detailed glacial geological and glaciological study of the area. Secondly, using this study we postulate how the ice stream might have been initiated. Thirdly, we reconstruct the behaviour of an onshore ice stream (the Hondsrug-Hümmling ice stream), which is a function of ice-marginal processes (glaciological processes, *sensu stricto*), climate (externally triggered glaciological responses of the ice margin) and substratum, and deeper geological structures. The relationship of deeper hydrological and geological elements with the Hondsrug glacial landscape in the past and present is also addressed.

Any contemporary landscape is, of course, the result of a long series of various processes which form that landscape, following each other over time and interacting through the inheritance of substrate and morphology. The imprint of some phases, however, can be more dramatic and may dominate a landscape longer than others. In the case of the northern Netherlands, the penultimate glaciation was the last event to significantly reorganize the landscape, of which the Hondsrug is exemplary. This document serves to answer the question: Why do we need to protect this unique landscape for future generations, apart from its obvious beauty? Obtaining European Geopark status for the Hondsrug area will increase societal awareness of this unique glacial landscape and aid its protection. Ultimately, the level at which we understand the properties and history of this landscape will determine how many functions society will assign to the Hondsrug without depleting it. Below, we present a brief description of how contemporary functions of the "modern" Hondsrug landscape are affected by the Hondsrug's genesis, particularly in relation to integrated groundwater management in part agricultural, part nature conservation 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 that are NNW-SSE oriented and many tens of kilometres long. These were formed by fast flowing ice over the area, a so-called ice stream (e.g. Van den Berg and Beets, 1987; Bennet and Glasser, 2010), 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 reveal a complex build up of till

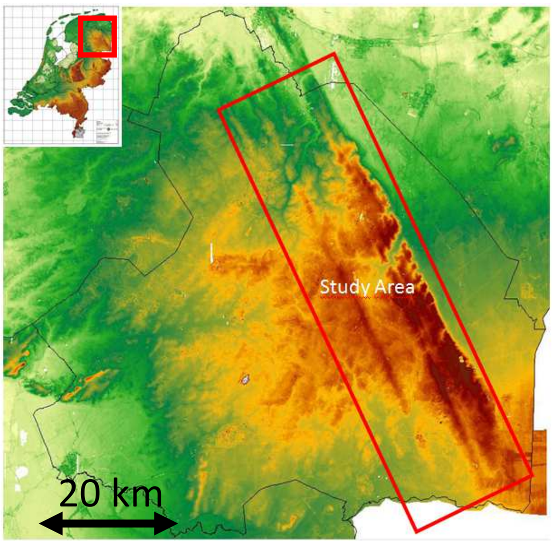

Figure P.1. DEM map showing location of the Hondsrug. *Source*: Dutch Ministry of Infrastructure and glacial and preglacial substrate reworked by megafluting, produced by the Hondsrug ice stream towards the end of the glaciation *c.* 150,000 years ago. During the final glacial period (Weichselian) in the region, the ice sheet did not reach as far south as during the Saalian period. The Hondsrug glacial morphostructure was affected by erosion in the earliest subsequent period (notably in brook valleys), but in the lowland regions in the vicinity of the North Seam this led to localized alteration only, pronouncing rather than destroying the structure and leaving the Hondsrug glacial landscape relatively intact. This allows the study of almost pristine sediments of a former ice stream and the tracing of these over a substantial distance, unlike other parts of the European ice-marginal landscape (IML), where very similar processes are considered to have operated, but where glaciological information has since been lost because these areas are further inland and closer to the Scandinavian ice sheets and were therefore more prone to erosion. Because ice streaming was a common process in former glaciated landscapes and both geologically important (reshaping landscapes) and glaciologically-climatologically important (rapid collapse of the margins of ice sheets) it has been the focus of many studies.

The Hondsrug former ice stream is considered of great importance to such studies. By studying the contact zone between preglacial and glacial sediments, knowledge about the conditions of the formation 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 mark the western side of the ice stream that was responsible for their formation. The source area for the ice stream is sought to the NNW, in the present North Sea, and the terminal zone sought to the SSW, towards the Münster Basin. This study is not limited to the Hondsrug area itself, but includes these source and termination regions, as well as the full length of the area affected by the ice stream in between: partly in the Netherlands, partly in adjacent Germany. We intend to answer questions regarding the ice stream initiation, and the factors that controlled its position and behaviour. Building on earlier studies, we present a new genetic model for the Hondsrug ice stream. We reason that the ice stream had its source in nearby ice that covered the present North Sea and the Hondsrug area itself, while the Münster Basin to the south is considered the main deposition area. We propose that the ice stream was triggered by subglacial overpressure from basal meltwater in the source area due to a higher heat flow density (HFD). An additional trigger mechanism is found in the restructuring of ice-marginal drainage in areas adjacent to the Münster Basin terminal area, notably due to the breaching of Lake Weser (c.f. Winsemann *et al.*, 2011).

This study could not have been done without the cooperation of others and financial support from the Province of Drenthe and the Geopark Hondsrug organization. We would like to thank Dr K.M. Cohen (Utrecht University/Deltares), with whom we had a number of discussions and who also provided editorial comments. Our thanks also go to Dr M.A.J. Bakker (Deltares; GPR data), Dr I. Lüse and dr A.Karpovics (Latvian University; clay mineral analyses and statistics) and H. Huisman for his photographs, his interpretation and description of till types on the Hondsrug complex.

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At the time of writing, knowledge about the unique landscape of the Hondsrug presented in this report is being shared with the ice-age museum in the area (Hunebed Centre, Borger). This is precisely in the spirit of European Geoparks, sharing knowledge of the geoheritage of the region to a broader public, local inhabitants, tourists and other visitors, young and old, from the Netherlands and abroad. I hope this study will further contribute to that aim and shed a new light on a small part of our planet.

E.P.H. Bregman, Assen, 15 oktober 2012

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 1.0), which was formed by a Late Saalian ice stream (MIS 6) (e.g. Van den Berg and Beets, 1987; Zagwijn, 1985; Gibbard and Cohen, 2008). Ice streams are corridors of fast ice flow within an ice sheet (*c*. 0.8 km/yr; Bennett, 2002) or at the margin of ice sheets, which recently are studied in for example Antarctica.

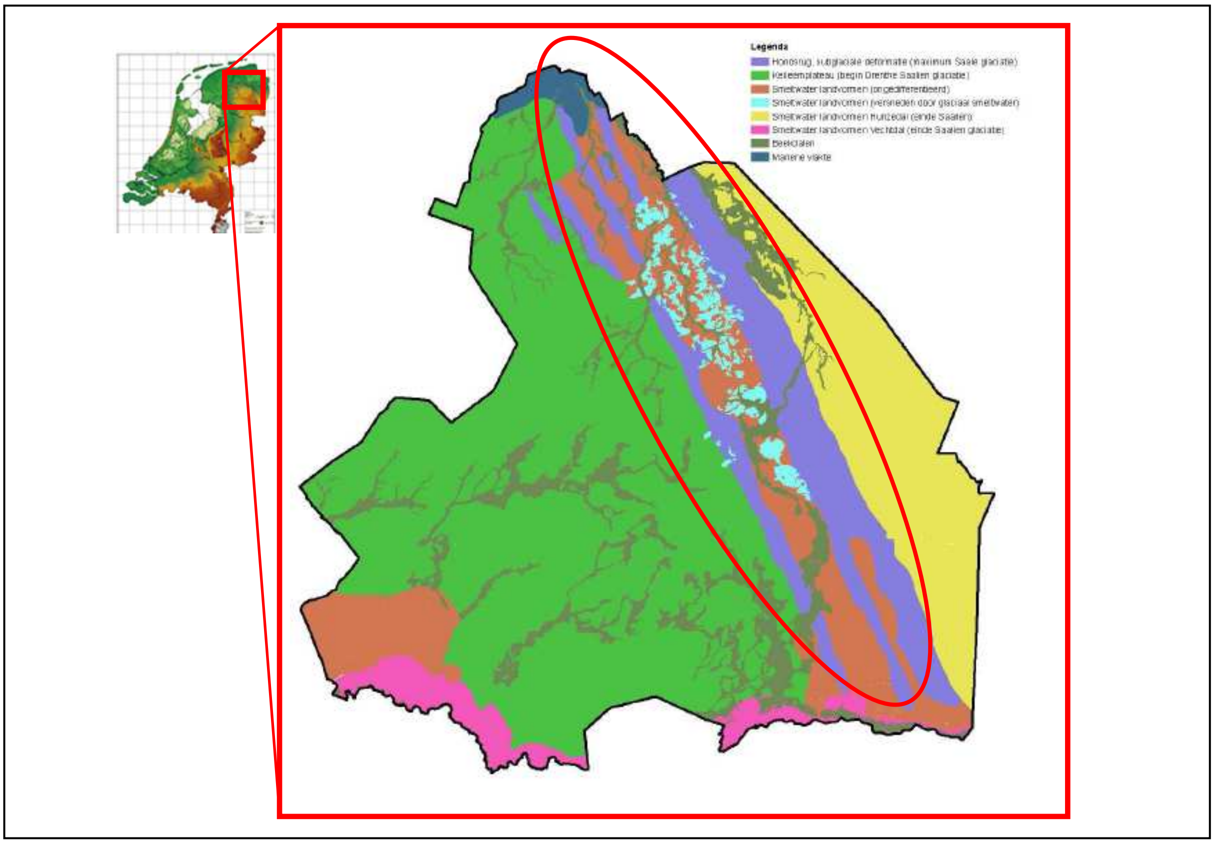


Figure 1.1. Geomorphological Map of Drenthe (2010): main landscapes. The till ridges of the Hondsrug area are well pronounced in the eastern part of the province of Drenthe (pink colour), revealing the NNW-SSE direction of the formation of the Hondsrug complex. The near surface presence of Elsterian deposits (blue colour) are infillings of buried glacial valleys. The lower lying areas (brown colour) are rather peaty areas due to the 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, which are highly variable and dynamic in space and time. Numerous contemporary ice streams have been studied and show behaviour that can be characterized by episodic activity, acceleration, deceleration, migration and changes in ice-flow direction (Winsborrow, 2010). Ice streams control the mass balance in ice sheet margins because they determine the rate of melting (bringing more ice beneath the equilibrium line) and provide more ice to calve off from the margins of the ice sheet into ice lakes, seas or oceans. Knowledge about the controlling factors and thermodynamic or other feedback mechanisms (Stokes and Clark, 2003) of actual ice streams is growing, but there are fewer process-related studies of onshore palaeo-ice streams and most of them are in northwestern Europe and are Weichselian in age.

The focus of this report is the investigation of the mega-scale lineations of the Hondsrug area, extended to the glaciological context of the area, and therefore to the ice-marginal Saalian (MIS 6; ≈150 kyr BP) Hondsrug- Hümmling ice stream as a whole. Undisturbed glacial landforms left by Saalian ice streams are very rare in northwestern Europe due to overprinting by Weichselian ice streams, except in the Netherlands and northwestern Germany. The best expression is the 70 km long and 4 km broad lineation of the Hondsrug. With respect to the morphology of the ridge itself, the key for better understanding of the genesis of the Hondsrug is to focus on the contact surfaces between preglacial and glacial sediments. As is show in figure 1.2 however the object of study the Hondsrug itself is for scientific research important because of positioning in an area where after Late Saalian period the Weichselian glaciation didnot disturbe or removed Saalian glacial features, like the Hondsrug. This makes it possible to study the genesis of a still complete Saalian glacial feature. Together with the peculiar position in the Ice Margin Landscape (IML) of Europe with offers a unique chance to study the impact of glaciations on present landscapes the Hondsrug area has applied for European Geopark status.

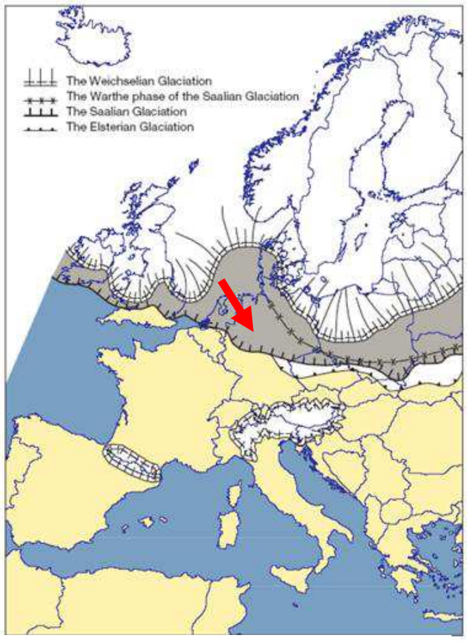


Figure 1.2. The glacial limits of the Pleistocene glaciations. Red arrow shows Hondsrug ice stream position (From Plant *et al.,* 2005)

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 tectonic settings. Because of this, the relief of the province of Drenthe, with its highest points at the Hondsrug, generally reaches a greater height in the eastern part and is lower, dipping more gently in the northwest and southeast.

Ongoing subsidence has caused the deposition of thick sets of unconsolidated shallow Tertiary marine and Pleistocene deltaic deposits (Westerhoff *et al.*, 2003). Most of these (’’Neo’’)-tectonic structures were reactivated during the Tertiary period (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 still ongoining subsidence. The Texel-IJsselmeer High, the Groningen High and the Peel Block are however relative stable blocks. A very tectonically active region occurs around the SE-NW trending Peel faults (Geluk *et al.*, 1994). Tertiary and (Neo)-tectonic activities have however not been recorded in the northern part of the Netherlands (Van Balen *et al.*, 2005), whereas Frikken (1999) states that this complex interplay of predominantly NW-SE oriented wrench tectonics has been active from Carboniferous times to the present. The main deep geological faults connected to the Hondsrug direction are the Hantum graben system, related to the Lauwerszee Trough and the Holsloot fault zone. Rotational displacement has caused antithetic Riedels ('open wrench faults') with significant strike-slip components (up to 750 m) as well as 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 era (as now) there were relatively high numbers of open faults, which could have been activated due to the large shear stresses induced by the vicinity of the Hondsrug area with respect to the forebulge (Figure 1.3). The extensional forces that can 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 the displacement of block structures and other faults, or to the creation of 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) have 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) and Busschers *et al*., (2007) have shown the impact of glaciations on the Rhine-Meuse delta at the distal part of the Weichselian forebulge. Lambeck *et al.,* (1995) refers to the Saalian forbulge, but thus far no studies of the proximal part of the forebulge in the Netherlands have been undertaken.

1.2.2 Salt diapirs

Salt diapirs are also present in the Hondsrug area, which were formed mainly during the Late Jurassic and Early Cretaceous periods 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 northwestern Germany at shallow depths (up to 100 m below the surface). The presence of salt domes may have influenced forebulging 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 preglacial landscape due to updoming. In areas where salt diapirs were located close to the surface, large-scale glacial erosion of the preglacial sediments occurred. Increased glacial erosion above the salt diapirs of Anloo and Schoonlo could be the reason why Elsterian sediments are thinner at these locations and Tertiairy (fluvial) sediments are surfacing (De Gans *et al.*, 2010) as we also found above the salt diaper of Gasselte. The (fluvial) Tertiairy sediments are coarser in comparison with the fine grained lacustrine Elsterian deposits (Peelo formation).

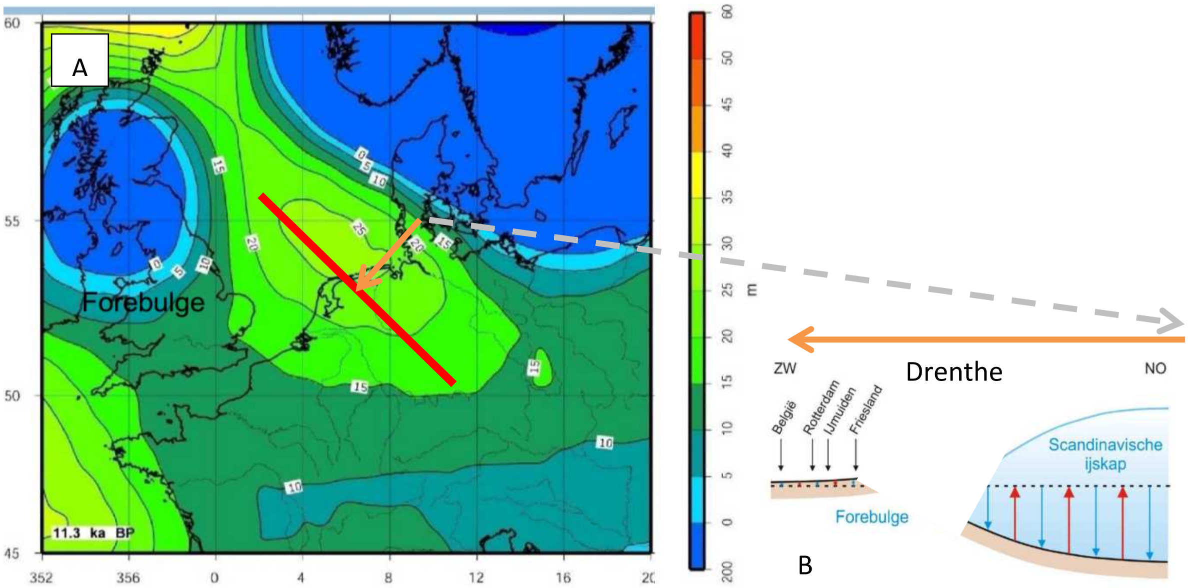


Figure 1.3.(A,B) Positioning of Drenthe on the forebulge 21 kyrs ago (from Steffen, 2006 in Busschers, 2008). The situation presented concerns the change in the earth's surface due to ice pressure (B) with uplift and top near the northern Netherlands. However, in the Weichselian period, land-ice did not reach the Netherlands. In the Saalian era maximum extension was in the central Netherlands. The forebulge lay more to the south. For this reason we assume that the top of the forebulge was positioned in the middle of south Drenthe. The presented Late Glacial forebulge model is indicative for the forebulges in other Scandinavian glacations.

1.2.3 Shallow substratum

Tertiary (Miocene) marine clays and fine sands which were deposited in actively subsiding parts of the North Sea Basin are present in the northern part of Germany, the eastern part of the Netherlands and the adjacent areas north of the Variscan heights. They form a continuous hydrogeological base (Van den Berg and 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 river deposits from the Late Tertiary, Early and Middle Pleistocene periods. 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 and Beets, 1987). In Drenthe these Early Pleistocene 'Eridanos' deposits are covered by sediments from a minor ice-marginal river system which deposited coarse and very coarse, highly permeable sands (Westerhoff *et al.*, 2003). During the Mid Pleisocene Elsterian glaciation (MIS 12; 475-410 ka), which is the earliest extensive glaciation in northwestern Europe, land-ice reached north Netherlands including the Hondsrug area. In this glacial period deep glacial tunnel or buried valleys (BGVs) are formed in the northern part of the Netherlands and in adjacent northern Germany (Figure 1.4). BGVs originated from immense episodic subglacial meltwater 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 of the tunnel valleys were mainly filled with varved silts and clays, known as '*Lauenburger Ton*' (Lauenburger Clay) in Germany (Kuster and Meyer, 1979) and '*Potklei*' (Pottery clay; Peelo Formation) in the northern Netherlands (Ter Wee, 1979; Bosch, 1990; Westerhoff *et al.*, 2003). The Pottery clay forms locally a hydrological barrier of very low permeable sediments in the pre-Saalian subsoil in the northern part of the Netherlands (Van den Berg and Beets, 1987). The pre-Saalian relief, at least in the northern Netherlands and this part of the Hondsrug area near Borger and Anloo, must have been relatively smooth (cf. Van der Wateren, 1985; Van den Berg and Beets, 1987). This is supported by the absence of Elsterian ice-pushed ridges.

Outside the BGVs, the upper part of Elsterian deposits consists of fine sands with mica (Ter Wee, 1979; Bosch, 1990), which is in contrast with locally present coarser sediments on top of the salt diapirs as mentioned in section 1.2.2. It is important to notice contrasts in texture, as we will explain in Chapter 3, because of difference in permeability with impact on subglacial groundwater conditions and on ice stream behaviour.

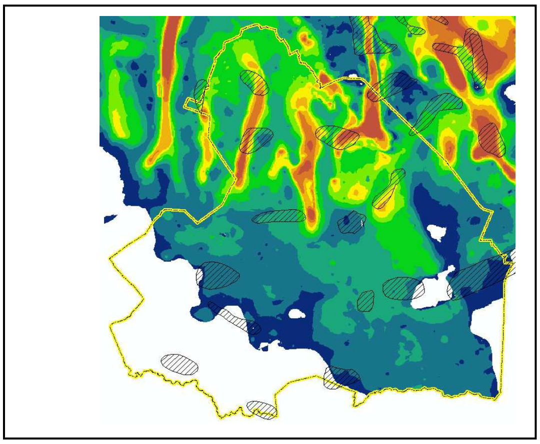
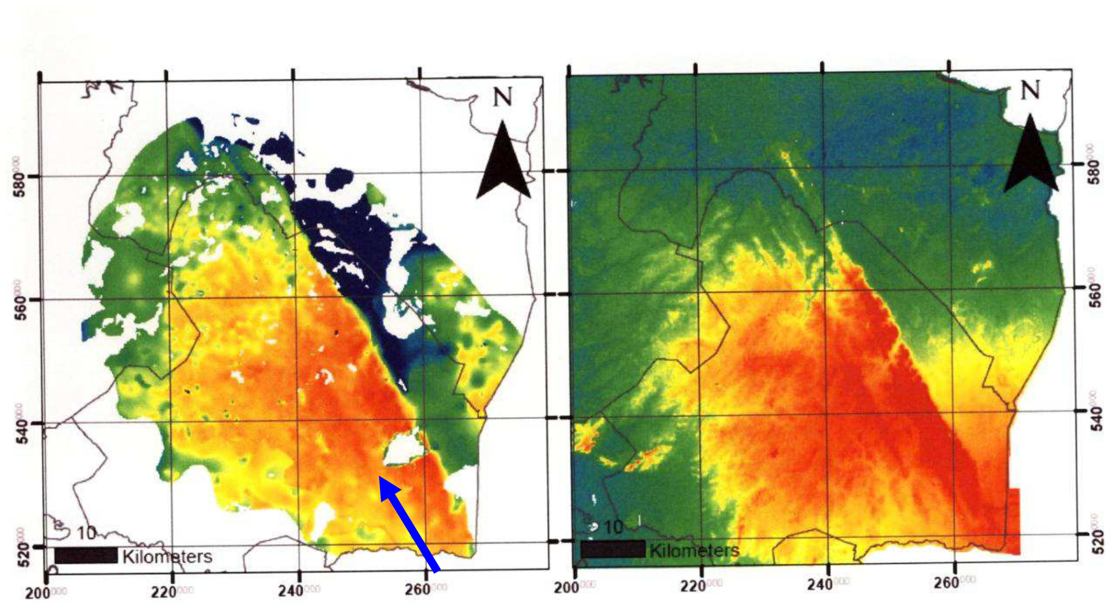


Figure 1.4. Overview of Elsterian deposits in the northern part of the Netherlands with Buried Glacial Valleys (BGVs; darker to brown colour indicates more depth). The hatched areas indicate salt domes. BGVs are sometimes superimposed on salt domes, as in Drouwen and Anloo in the Hondsrug area. (Source: DINO, TNO)

In the Late Saalian period, parts of northwestern Europe were covered by ice sheets from Scandinavia. The ice extended further southwest into the Netherlands than ever before or after. Maarleveld *et al.*, 1958 have proposed that the Peel Horst, with a NNW-SSE orientation, formed an obstacle to advancing ice streams in the central parts of the Netherlands. In the northern part of the Netherlands, we suppose that deep geological features also formed obstacles to Saalian ice streams. More or less similar to the southern part of the Netherlands and also related to the positioning of geological structures, like the Texel-IJsselmeer High, salt ridges and salt diapirs. With a reference to Piotrowski *et al.*, (2007) and others deeper geological structures like salt diapirs could also have influence on ice streams behaviour, because of impact on change of flow direction of groundwater and discharge of meltwater.

The Late Saalian glaciation formed high push moraines and deep glacial basins in the central Netherlands. 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 Drenthe substage of the Saalian glaciation. 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.



A **B**

Figure 1.5. Fig 1.5A indicates the top of the Peelo Formation in Drenthe (REGIS II). Fig. 1.5B represents the relative altitude in Drenthe (RWS-AGI, Delft, 2005). A comparison of the two maps indicates a lower top of the Peelo Formation in the north and easternmost parts of Drenthe. This was caused by Saalian subglacial erosion and erosion discharge of meltwater respectively. In the Hondsrug area, Peelo Formation is also surfacing (Figure 1.1). The top of the Peelo Formation is also subglacially eroded in the Hondsrug area east of the Rolder/Sleenerrug (westernmost ridge in Fig. 1.5A, indicated by blue arrow).

All mentioned aspects combined explains the morphology of the Hondsrug but it makes also clear that the Hondsrug is a key area to study the interaction of different ice streams on glacial landscapes in IMLs as well as to study implications of glacial processes on shallow and surface features like BGVs. This knowledge not only contributes to better understanding of lithostratigrafic questions, to present geoheritage values, but also to get more insight in soilstructure which has influence on processes like positioning of seepage areas (Magri, 2005) and sensibility of peculiar features like salt diapirs for loading. The study of glacial dynamics of the Hondsrug ice stream area inclusive the interaction between deep and undeep geology contributes to fundamental societal questions, like how save is storage of wastedisposal in saltdomes in the IML if we suppose a new glaciation within for example the half time period of nuclear waste. Because of peculiar geographical position the Hondsrug area is an area of interest to study both geological and glaciological scienctific questions as well as to study practice scientific subjects.

1.2.4 Hondsrug ice stream area

The area of interest in this report is the Hondsrug (Figure 1.4) as a part of a larger complex of ridges: the Hondsrug area with a gentle southwesterly dipping topography. The ridges in the Hondsrug area are most pronounced towards the NNW–SSE with a length of 70 km (Groningen to Nieuw Schoonebeek) and a climbing height from 2–28 m in the southeastern part, with the highest point near Weerdinge (Schimmeresch). The higher elevation of the ridges in comparison to the surroundings is the result of a sandy subsurface geology and glacial deposition of tills, whereas the lower parts between the ridges seem to be eroded. This is the conclusion of a study of the topography of Elsterian deposits, whose upper boundary is located significantly lower in the Odoornerveen area between the Hondsrug and the Sleener or Rolder ridge

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 and 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 not covered by marine clays (Rappol, 1987). The till thickness varies between 1–5 m and in former river valleys may be absent but evident from boulder accumulations and stone pavements. Only in the southwestern part of the till plateau is till thickness much greater, partly due to pushing. The push moraine of Havelterberg (19 m above MSL) was formed by an ice stream from an older advance of the ice sheet than that associated with the Hondsrug-Hümmling ice stream, and has 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 oriented forms in the southwest of Drenthe and the NNW-SSE oriented ridges of the Hondsrug complex. These orientations reflect the different directions of ice movement across the Drenthe Plateau (see also Section 1.5 for further explanation). The different directions of till ridges determine the drainage patterns of the rivers. The former rivers have further increased the relief by eroding the valleys, a process which is also influenced by differential postglacial rebound, resulting in a radial drainage pattern in the central part of Drenthe which also influences the drainage pattern in general. This has led 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).

Four major SSE-NNW trending ridges can be observed and are named, from NE to SW (Figure 1.6):

1. The Hondsrug
2. The Tynaarlo Ridge
3. The Rolder Ridge (or Sleener Ridge in the southeaster part)
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 and a western ridge. The till sequences are very different between these two ridges as we will explain in more detail in Chapter 4. The Hondsrug was formed by a NNW-SSE oriented ice stream, the Hondsrug – Hümmling ice stream (e.g. Rappol, 1987; van den Berg and Beets, 1987). The largest obstacles for the advancing Hondsrug-Hümmling ice stream were the high ridges of the Weserbergland (Teutoburgerwald and the Wiehengebirge in Germany), composed of Jurrasic limestone and mudstone. South of the Weserbergland, the ice front reached its maximum extent in the Münsterland and Ruhr regions (Figure 1.8; Winsemann *et al*., 2010).

Our study is the follow up of these studies.

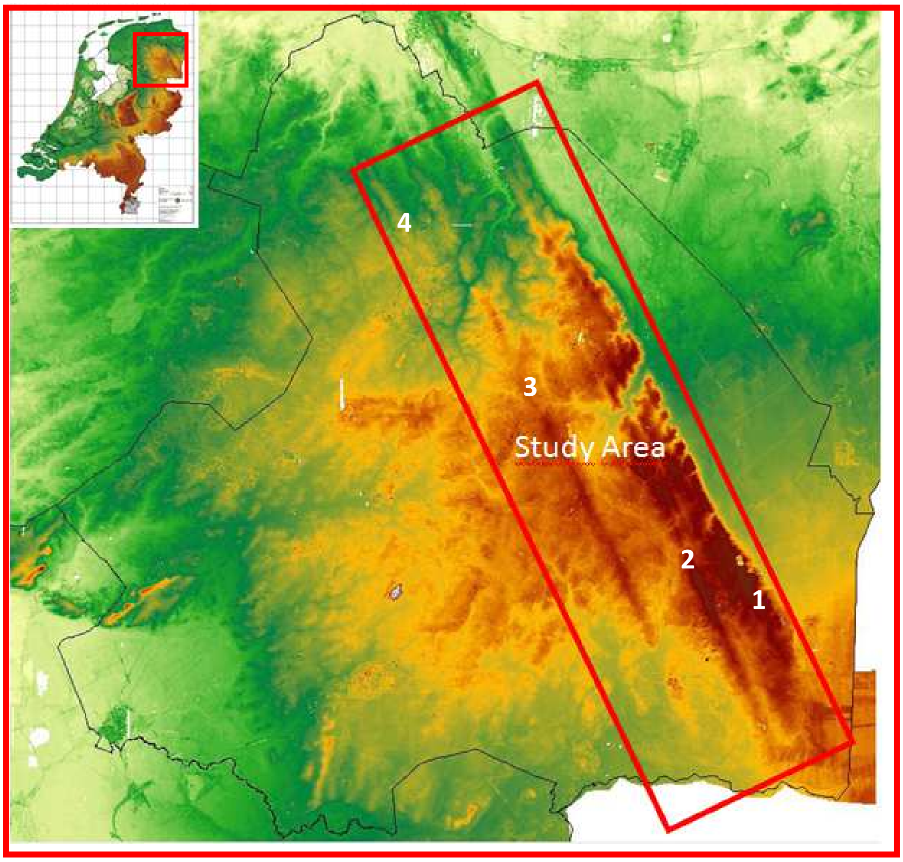


Figure 1.6. Area of interest during this study (Source: DEM of the Netherlands, Rijkswaterstaat 2005). The ridges shown are 1) The Hondsrug, 2) Tynaarlo Ridge, 3) Rolder Ridge, 4) Zeijen Ridge.

1.3 Aim of the research

Within the context of the northwest European history of glacial landscapes including glacial features our main aim is firstly to reconstruct the genesis of the linear ridges through a detailed glacial geological and glaciological study of the area. Secondly, using this study we will postulate how the ice stream might have been initiated. Thirdly, we will reconstruct the behaviour of an onshore ice stream (the Hondsrug-Hümmling 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 focus in our study on the Hondsrug till complex as a collection of genetically related sediments, and subsequently zoom in on outcrops which show contact surfaces between glacial and preglacial sediments, in order to gain insight into the basal contact pressure at the time the sediment was deposited. If the sediment is intensely deformed, the effective pressure must have been very high (and basal water pressure low), while no deformation indicates a lower effective pressure (high basal water pressure) and the possibility that basal sliding may have occurred. No deformation could also be the result of a frozen subsurface (permafrost) below the ice stream. In this way we will describe certain relationships between glacial geology and lateral glacier behaviour across the Hondsrug complex, providing a more detailed understanding of the overall behaviour of the ice stream.

1.4 Hondsrug Regional Research History

1.4.1: 1880–1900 Prof. F.J.P. van Calker: the Hondsrug as an end moraine

Over a period of 20 years, Van Calker published several papers on the origin of the Hondsrug. By means of fieldwork around the town 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 due to the long-lasting stagnation of a glacier (Van Calker, 1901), which 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 glacier folded back the sediments to form the ridges as it retreated to the northeast.

1.4.2: 1902–1907 Prof. E. Dubois vs Dr H.G. Jonker

1902 – Prof. Eugiène Dubois

Dubois 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 stratified layers without intense deformation, as would be expected from the folding mechanism described by Lorié. Therefore, he continued study of the Hondsrug. Data for this research (Dubois, 1902) came from numerous hand-dug pits around the villages of Exloo, Odoorn and Valthe during the construction of a railway from Emmen to Stadskanaal (Figure 1.7). Dubois recognized some typical sedimentary successions and described their spatial patterns.

- *Succession A* contained: i) boulder sand(0.2–0.8 m) on ii) preglacial sediments (Rhine diluvium)
- *Succession B* contained: i) boulder sand (0.8 m) on ii) boulder clay (1–1.5 m thick) on iii) preglacial sediments
- *Succession C* contained: i) peat moss on ii) light-bluish pottery clay (0.4 m thick)

Succession A and B were both found on the Hondsrug, while succession C was found in the valleys (west of Odoorn) between the ridges. Dubois hypothesized about the origin of this spatial distribution based on contemporary ideas about the structure and motion of Greenland's inland ice. According to Dubois, the pattern reflected englacial transported strata, with more coarse debris concentrated in the eastern part of the inland ice and more clay in the western part.

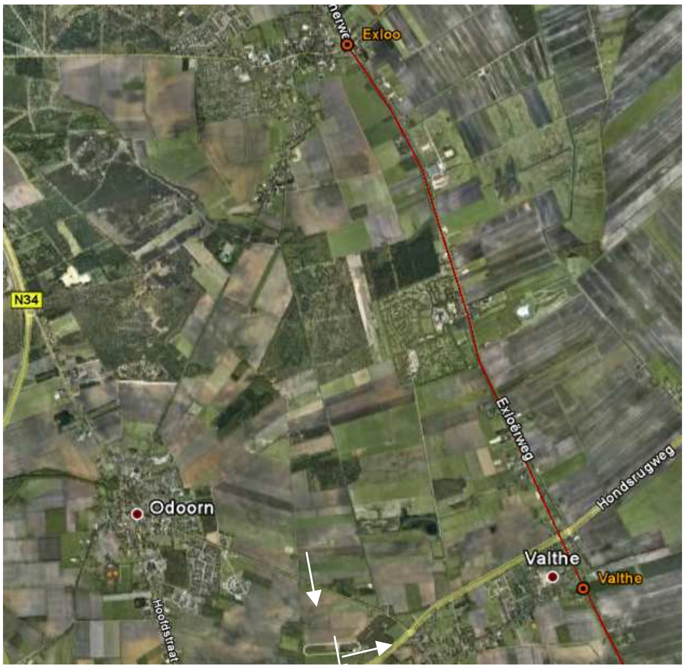


Figure 1.7. Location of the railroad construction (red) by the NOLS (Noord Ooster Locaal Spoorwegen) with its train stations. Dubois collected his observations on the Hondsrug (ridge), corresponding to the region of the GPR location (white). (Source: Google Earth)

Dubois considered that the patterns found in the field were due to melt-out of the glacier and also believed that the western part of the inland ice was more laden with clay, while 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 higher pressure. The low pressure region in the east could then be lifted 5 m relative to the valley. The general concept grasped by Dubois was that elevation of the surface was inversely related to the pressure applied by the ice, and flow rates increase with decreasing pressure. He was also convinced that the inland ice movement was oriented SSE-NNW because the clay layers were deposited in parallel along the ridges, and this flow direction might have been the result of the confluence of the British and Scandinavian icecaps in the North Sea.

1905 –Prof.Dr H.G. Jonker

Jonker was a pupil of Prof. van Calker and strongly opposed Dubois' view on the origin of the Hondsrug. He completely disagreed with Dubois' opinion that 1) a SSE-NNW ice stream formed the ridges, maintaining that ice flowed from the NE, 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. Jonker's attitude (1905) towards Dubois (1902) is almost insulting because he was deeply convinced in the established opinions regarding the origin of the Hondsrug. He was also unpleasantly surprised to hear that Dubois' opinions were about to be taught in 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 a somewhat detailed criticism, explaining why I do not agree with his opinions.'

In this paper (1905), Jonker pointed out that the observations which led Dubois' to his hypothesis –made between Buinen and Emmen– only concern the southern part of the Hondsrug, and that Dubois made an unacceptable generalization by not testing his hypothesis in other parts of the Hondsrug. He added that if the observations of his mentor Prof. van Calker had been taken into account, Dubois would have had to adjust his hypothesis (or refute it completely).

1.4.3: 1950–1980 Maarleveld, Ter Wee, Zonneveld, de Gans

Crommelin and 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 Maarleveld's (1953) model 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 were a continuation of the Rehburg phase from Germany, while the push moraines in the area around Winschoten must have been formed during a more recent 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, both of which were not explained by Ter Wee's (1962) glaciation model. He argued that the retreat of the ice may have been less systematic, with large masses of stagnant ice. He also postulated that the Vecht and Hunze valleys were formed during this stage of dead-ice fields, and that tectonics might have had an influence.

1981: De Gans

In his dissertation, De Gans (1981) assigned the Hondsrug a fluvial origin, with the Drentsche Aa valley further deepening intermediate depressions and crossing perpendicularly to the relative heights. The pattern of straight and cross river valleys are considered to be the reflections of the fault systems in the subsurface that determine river courses. De Gans dismissed a salt tectonic origin, as he claimed that sediments on the ridges were not altered by this process.

1.4.4: 1980–1990 Rappol, Zandstra, Van den Berg and Beets (1987)

Where glacial deposits occur at or near the surface, two distinct orientations of ice flows can be recognized. Firstly, an older NW-SE direction expressed in low ridges in the till and in the fluted shapes of the till ridges. Secondly, this 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. Both Zandstra (1987) and Rappol (1987) came to the conclusion that most of the till in the Netherlands is subglacial in origin.

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

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

3-Phase glacial model

During the first phase, the ice movement in Drenthe was directed N-S and stagnation occurred at the Texel–Wierdingen–Steenwijk–Almeloline. Thick till was deposited. The boulder configuration suggests that the ice originated from the east Baltic. In the second phase, the reactivation of the ice sheet led to its rapid thickening, leading to the formation of pushed moraines at the stagnation lines. The flow direction was NW-SE, with the boulder configuration suggesting that the ice originated from the west and south Baltic.

During the last phase, ice movement originated from the North Sea Basin and flowed towards the SSE between stagnant-ice bodies (Van den Berg and Beets 1987; Rappol, 1991) from the former glaciation phase, creating the Gelderse Valley and the Hondsrug complex. The difference in angle is almost 90 degrees, 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 were formed during the third Saalian glaciation, and the ice must have invaded an open landscape with permafrost (Zagwijn, 1973). The glacier advance over the fine-grained Drenthe till plateau was rapid as a 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 in the central Netherlands were formed during the Rehburg phase.

The ice tongue of the Nordhorn Basin could have overridden the latter's pushed ridge due to the fine-grained Tertiary sediments at Oldenzaal. This could have triggered SSE-NNW ice streaming which created, according to Van den Berg and Beets (1987), the Hondsrug complex. Furthermore, they considered that the Hondsrug-Hümmling ice stream fed an area reaching to the IJssel basin in the west towards the Rheinische Schiefergebirge in the east and the Münster Basin.

The glacial model presented by Van den Berg and Beets (1987) was in the first glacial model which gave an overview of the Saalian glaciation of the Netherlands and northwest Germany and reproduced in a lot of glacial and landscape oriented studies.

1.4.5: 2008–2012 Pierik, Bregman and Cohen

To have a more detailed context for the Hondsrug study and other glacial studies, the authors extended the 3-phase glacial model of Van den Berg and Beets (1987), adding four phases leading to maximum ice extent and a deglaciation complex comprising two phases (Figure 1.8).

Phase 1 and 2: During the onset of the Saalian glaciation, the ice invaded northwest Europe heading south at first but later changing to the 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 in the first phase. The end-line of Phase 2 corresponds to the Rehburg line.

Phase 3: In the Netherlands, the maximum ice extent was reached during Phase 3, with large push moraines formed at the southern border of the ice in the central Netherlands.

Phase 4: Stagnating ice occurred throughout the Netherlands, due to an ice-mass increase in the North Sea Basin. The ice stream protruded between dead-ice masses and flowed towards the Münster 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 and Vecht rivers probably also drained part of the meltwater, causing erosion of their sediments and deepening of their beds.

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

The main phase relevant to the genesis of the present exposed Hondsrug area is Phase 4. The name of the ice stream (Hondsrug-Hümmling ice stream) is based on indications that it extended from the eastern part of Drenthe to the Hümmling, where the ice stream stagnated and partly deformed the latter (Schröder, 1978). Overprinting of the Hondsrug megaflute on the 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. In this study the new glacial model as presented in Figure 1.8 (Phase 4) is the startingpoint.

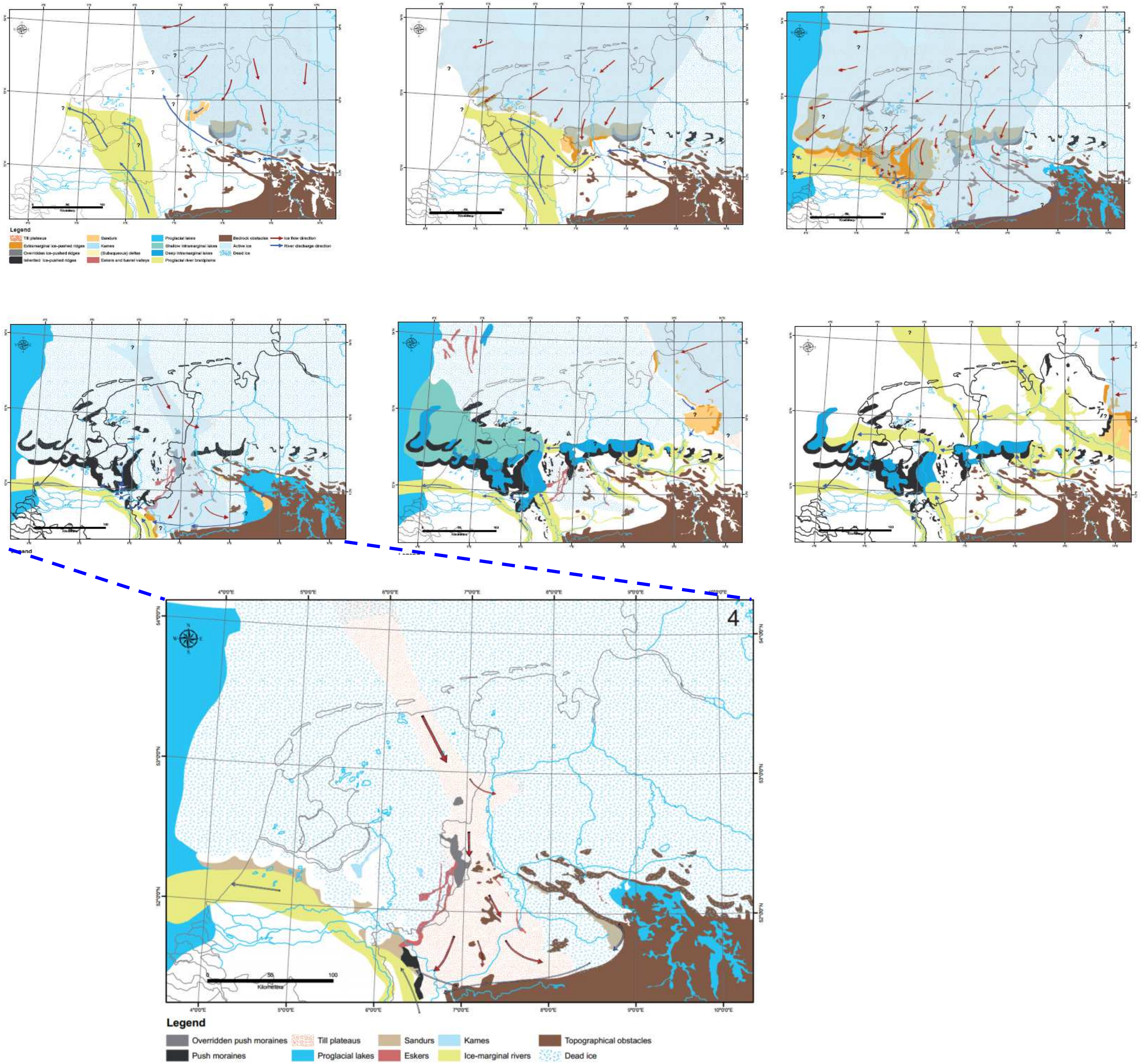


Figure 1.8*; Glaciation model of the Saalian glaciation of the Netherlands* (Pierik, H-J.*et al.,* 2010*). Phase 4 is the last phase at the stagnation – deglaciation stage of the Saalian (MIS 6) Scandinavian ice sheet. The Hondsrug – Hümmling ice stream (light blue) is positioned in between dead or stagnant icefields. Flowdirection is indicated by red arrows.*

2. Methods and materials

2.1 Methods of data collection

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

1. A database of GPS-pinpointed photographs and lithological descriptions of outcrops. The outcrops became accessible during the construction of a road in spring 2010, which was sunk 6 metres underground at Borger (roadcut N34), and in 2011 at Gieten (roadcut N33; Figure 2.1). The pictures were shot digitally and could therefore also be digitally processed (e.g. for inserting formation boundaries, lithofacies codes, etc.)
2. Ground Penetrating Radar (GPR) cross-sections, in addition to outcrop photographs. The GPR survey used a fully bistatic PulseEKKO Pro system (Sensors and Software®), primarily with a 100 MHz antenna but partly with a 400 MHz antenna. Raw data was processed by M.A.J. Bakker (TNO/Geological Survey Netherlands), providing interpretable seismic cross-sections.
3. Hand-core drillings provided lithological insight into the reflected stratigraphy. Drilling was performed with a standard Edelman corer. The classification of the sediment follows Verbraeck (1984 in Berendsen, 2007), who made an adjustment to the classification system of De Bakker and Schelling (1966) (e.g. Berendsen and Stouthamer, 2002).
4. DINO borehole database (source of the Geological Survey Netherlands). Borehole descriptions are available for the whole study area, but are generally less detailed than our borings. The DINO database provided the general sequence for the subsurface, such as the occurrence of till and its thickness.
5. Visual interpretation was done with ArcGIS software applications. In addition, interpreted data (maps, e.g. from the Geological Atlas of the Netherlands) provided detailed information about deeper geological structures.
6. We studied clays composition and deformation structures of tills to test the similarity of tills deposited by different ice streams and also in the Hondsrug area (see Figure 1.8) with, with XRD (Röntgen Diffraction). XRD also provides additional information about the conditions of till formation, local clay mineral formation and weathering conditions in the source area, which can be used with respect to other physical or geochemical soil characteristics. The studied tills are based on classification of the studied tills on the basis of a Turbo Stratism Index (TSI, Reynolds, 1994 in Bregman and Lüse, in prep.; e.g. Scodron, 1999).

2.2 Methods of data interpretation

The structure of this research is represented in Figure 2.1. We also utilized concepts from glaciology and glacial geology to develop our arguments. These include:

1. Outcrop observations at locations in Donderen, Gieten, Gasselte, Borger and Klazienaveen (see Figure 4.1), which are described using a glacial-geological classification system (cf. Kjær and Krüger, 1999).

2. The glacial-geological toolbox (e.g. Benn and Evans, 2001) which 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 the end users of this report are most likely to not be very familiar with these concepts, we include the relevant theory in Chapter 3 so that an understanding of our argument will be easier in subsequent chapters. The importance of the theory for the Hondsrug complex will be highlighted in each section.

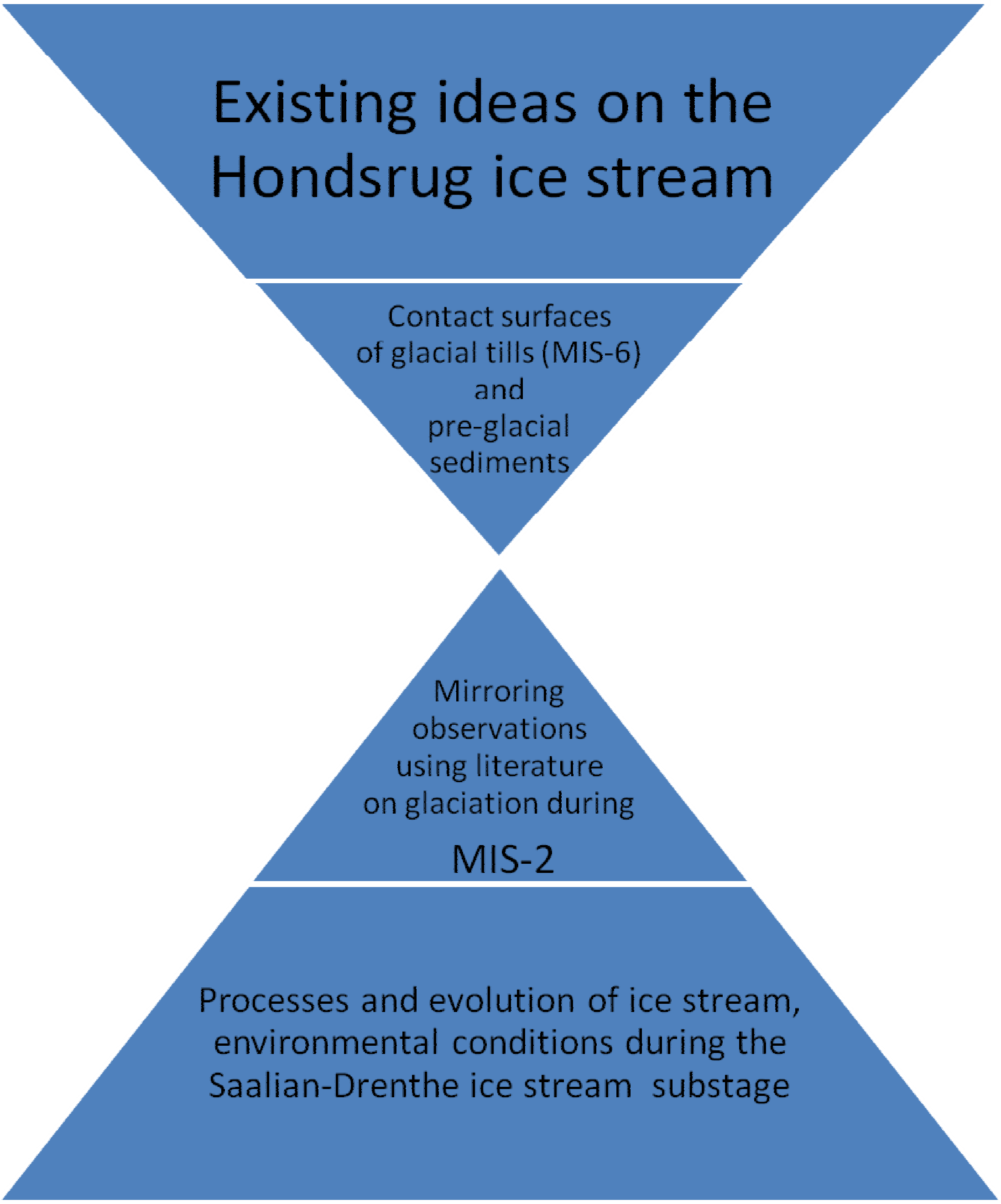


Figure 2.1 General concept of this research. Observations from the Saalian glaciation will be compared to similar sediments described in studies from the last glacial period (Weichselian, MIS-2).

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

4. GPR cross-sections provided spatial information about subsurface structures of a larger area in addition to the point data set (boreholes and outcrops). They also provided information on the extent of subglacial deformation.
5. The genesis of the Hondsrug area was reconstructed on the basis of spatial analyses (DEMs), outcrop data and borehole descriptions. We used data from previous studies and newly interpreted data, e.g. results of a study by Bregman and Lüse (in prep.). These authors tested the new glacial model we developed in the context of the Hondsrug study with XRPD clay minerals analyses of tills in different locations on the Hondsrug. These results will be discussed in Chapter 6. An overview of the study locations and the techniques used is presented in the figure below.

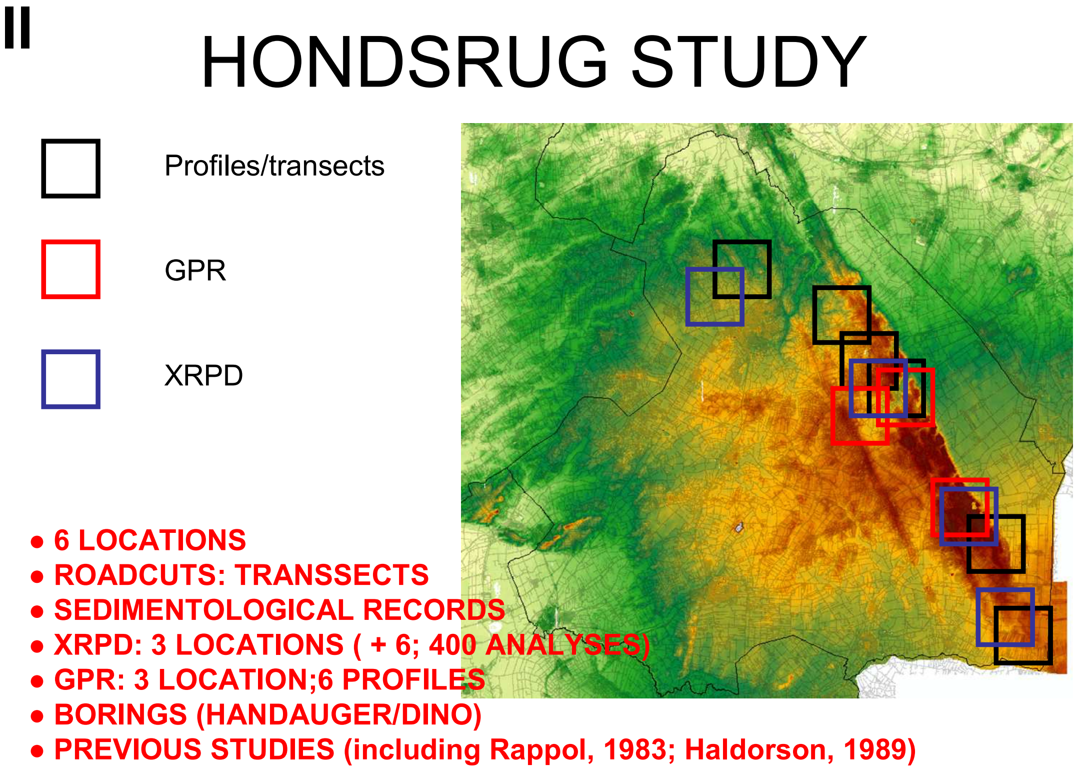


Figure 2.2. Overview of the study locations and techniques used

Following our observations, descriptions and interpretation of the outcrops, this information is used to find patterns along the longitudinal direction of the Hondsrug complex. By doing this, we deduce lateral variations in ice stream behaviour. However to explain all observations we have in our project architecture also planned actions to zoom out to the Hondsrug-Hümmling ice stream to gain an overview and better understanding of the behaviour of the ice stream as a whole.

2.3 Hondsrug area and Study of ice streams

In the last part of the Saalian period, parts of northwestern Europe were covered by ice sheets extending 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 the central Netherlands, and in the north, in Drenthe, it left a till sheet of complex build and morphology. These ridges are seen to be the result of an ice stream event that occurred at the end of the Drenthe substage of the Saalian glaciation. 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 we reviewed in Section 1.7, have developed 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. We used for interpretation of our observations the results of modern glaciological studies (e.g. Winsborrow *et al.*, 2010) which have shed more light on characteristics and the mechanisms that control the flow of ice streams as well as results from studies from late Weichselian (≈25 ka) sediments(e.g. Jørgensen and Piotrowski (2003). These studies describe subglacial processes that determine sedimentation, deformation and erosion and the impact of the glacier on morphology.

Knowledge of contemporary glacial processes occurring under ice streams and ice sheets is the key to the reconstruction of the Pleistocene glacial impact on the landscape in the past and to understanding postglacial processes. With the use of SRTM (Shuttle Radar Topography Mission, NASA) DEM (Digital Elevation Data, Ministry of Infrastructure), regional-scale palaeo-glaciological reconstructions can be made (e.g. Boulton, 2002; Kleman *et al.*, 2006; Clark and Stokes, 2003; Bennett and Glasser, 2009). In addition to previous models we developed with use of SRTM and DEM data a new glacial model for the Netherlands and northwestern Germany (Figure 1.8) to get a better glaciological frame in which we also included several deglaciation phases. In addition, the glacial sedimentary record provided extra information on the basal regime and forms an additional control point in these reconstructions. Techniques such as Ground Penetrator Radar (GPR; e.g. Bakker, 2004), XRPD analyses of clay minerals and the study of sedimentological structures – as used in this study – provide additional small-scale data to supplement more classic data (e.g. clasts, stress analyses). They provide information about deeper structures (deformation or erosion) and the direction of flow of ice streams, whereas offshore palaeo-reconstructions are mainly based on mega-scale geomorphological mapping using remotely sensed data, 2D and 3D seismic records, and multibeam bathymetry and log data (e.g. Andreassen *et al.*, 2009; Winsborrow *et al.*, 2010).

Contemporary studies of basal sediment deformation provide a toolbox to translate glacial sediments back into palaeo-glaciological processes (inversion).Through the efforts 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 typically 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 subsurface. Ice streams can fan out in two settings: they may 1) calve out into the sea, thereby releasing large amounts of glacial debris (high calving rates increase 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.

Studies of ice streams in Antarctica and Svalbard has led to the discovery that ice streams can be initiated and terminated over a period of several hundred years and the merging or capturing of ice streams can often occur over short periods of time (<100 yrs). Even though the upper regions 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.

A distinction has been made between ice surges and ice streams based on the temporal scale of their lifetimes. An ice surge is a relatively short-lived feature (<10 yrs) that occurs 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 its positioning on 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 relatively high velocities and a dynamic character and can even cross older ice streams, as has been shown by many glacial geological studies (Winsborrow *et al.*, 2010, 2010a; Kleman *et al.*, 2007; Stokes *et al.*, 2005).

3. Glacial sediments and subglacial deformation

This chapter provides an overview of the theory required to deduce the glaciological history of an ice stream from sediments. In particular, we focus on the information that can be acquired by studying the contact zones of preglacial and glacial sediments, and any subglacial deformation that may have occurred.

Many studies describe the behaviour of modern glaciers in Svalbard and Antarctica and the sediments deposited under different circumstances. Insight into sedimentation processes gained from modern glaciers may provide a key for understanding glacier behaviour into former glaciated areas, if one follows the uniformitarian, retrospective approach. However, it should be noted that in some cases an analogy between modern and Pleistocene glaciers is not appropriate. The scale of the modern glacier must be equivalent to that of earlier glaciers to prevent scaling problems when taking the inverse approach. The Hondsrug is formed by the Hondsrug-Hümmling ice stream, which dimensions of at least 20 km wide and 120 km in length based on geological evidence are similar to 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. We also refered our description with other glaciological studies (e.g. Jørgensen and Piotrowski (2003). In addition, to extract environmental conditions from the sediments, external influences (salt diapirs) on these conditions were also considered.

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

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

The horizons include:

- A-horizon: sediments which are heavily deformed 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 water pressures, the sediment grains are forced apart more, so that less friction occurs between them, leading to more deformation. With low pore-water pressures, the grains remain more firmly attached to each other, leading to higher friction and less deformation.

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

- Fine-grained sediment has higher pore-water content than coarse-grained sediment
- The permeability of fine-grained sediment is lower than that of coarse-grained sediment

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

3.2 Ice flow affecting the glacier bed

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

Because of this 'rule', the 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 create low temperature gradients (low basal heat exchange), advection of warm ice towards the bed
4. High geothermal heat flux

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

When describing the contact surface of 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. Here we describe the two extremes, with the third lying somewhere between these point of views.

3.2.1 Boulton and Jones' (1979) deformation model

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

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

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

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

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

- The thickness of the overburden ice
- Basal water pressure
- A combination of both

Thickening of the overburden ice can occur when thrust sheets are formed as the ice stream experiences compressional forces (e.g. transition between a warm-based to thaw-based thermal regime or a subtopographic obstacle). The basal water pressure not only depends on the basal melting rate, but also on the drainage of the preglacial aquifer. If drainage is sufficient, meltwater can be discharged and the resulting basal water pressure will be 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-water pressure) and the water film between the ice stream base and the bed. If the permeability of the preglacial aquifer varies laterally 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 generally has lower permeability than coarse-grained sediment, leading to higher basal water pressure. As becomes clear, many combinations of factors that control effective pressure may lead to the same final sediment configuration (the *equifinality* concept) and more proxies are needed to distinguish between the contributions of the different components.

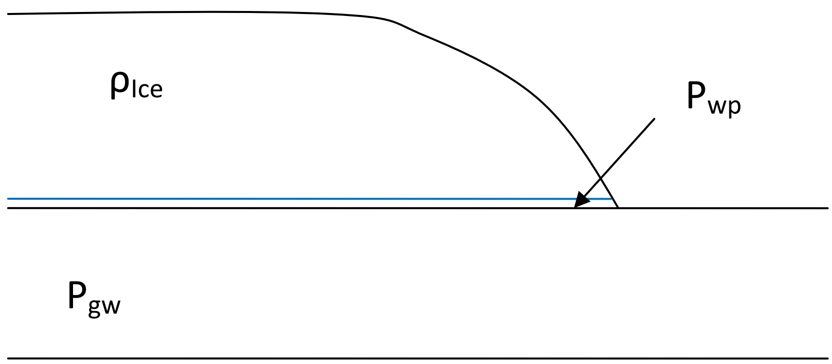


Figure 3.1. Sketch of pressure distribution relevant to ice/bed contact

According to Equation 1, in the 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 the case of $P_{ice} = P_{wp}$, the pressure of the basal water layer becomes sufficiently high 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 the 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 the 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-water pressures will cause the grains to exert less shear stress on each other and become more mobile. With low P_{wp} values, grains exerting more shear stress on each other, leading to more brittle deformation. When the pressure applied is relatively sudden, brittle deformation will occur, whereas with a relatively even pressure increase, ductile deformation will occur. Since fine-grained sediment has a lower permeability than coarse-grained sediment, higher pore-water pressures in fine-grained sediment will more often show ductile deformation due to lower internal friction of the grain contacts. In contrast, lower pore-water pressures in coarse-grained sediment lead to brittle deformation and lower deformation rates due to greater 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 also be partly frozen. The occurrence of this patchy frozen subsurface prevents the 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) considers basal contact pressure to be independent of effective pressure. This model instead assumes that:

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 incorporate them. Therefore, the contact pressure depends on the rate of the ice flow into the bed, forcing the clasts into it. The rate of flow 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

Currently, it now seems that both models can be true in certain cases. The Boulton model works for 'dirty' ice, which contains much 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 rigidly.

3.3 Abrasion models

Abrasion occurs between the basal ice and the bed due to the friction caused by the debris content incorporated into the sole of the ice stream. There are two models: in the case of a high debris concentration, a sandpaper analogy applies, while in the case of a 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
- There is a soft sediment floor
- Sharp rock fragments are present which create deeper incisions into the bed

Both of the deformation models discussed above developed their own abrasion models in accordance with their theory. In Boulton's abrasion model, effective pressure and ice velocity are the controlling factors. The following relationships control abrasion rates:

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

4. Abrasion and lodgement form a part of a continuum

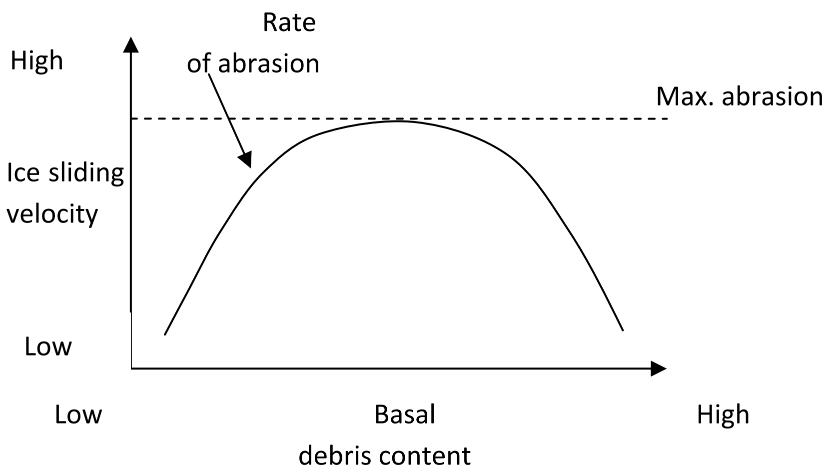


Figure 3.2. Relationship between ice sliding velocity, basal debris content and rate of abrasion *(after Drewry, 1986)*

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

1. Abrasion is highest where basal melting is highest
2. While independent of effective pressure, the abrasion rate is dependent on ice thickness because the latter acts 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 also influences ice stream stability, ice movement mechanisms, sediment and landforms (Piotrowski, 2007). 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 northwestern Germany and Poland and for North America (Breemer, 2007). The loading of the crust by ice leads to a reversed groundwater flow and occurs much faster than in non-glacial periods (Breemer, 2007; up to 30 times faster according to Marczinek *et al.*, 2007).

The impact of reversed groundwater flow can reach up to 200 m in depth and 40 km in front of a glacier margin (Piotrowski, 2007). Old river valleys and buried glacial valley systems, which are found in the entire ice-marginal landscape zone of the European lowland (North Sea area from the Netherlands to Estonia; Smit, in press), functioned as drainage systems for these groundwater flows once formed, and as they were being formed they also secured the stability of the ice sheet by reducing the water pressure (P_w) at the ice/bed interface (Marczinek *et al.*, 2007). Permafrost reduced discharge (*c.* 8%; Marczinek *et al.*, 2007) and led to a more downward groundwater flow, feeding present aquifers, as was shown for northwestern Germany by Koester *et al.* (2008).

Cutler (2007) proposed that water flow through unlithified sediments was probably blocked and that channelized flow did not occur where permafrost reached thicknesses of tens of metres. In such cases, subglacial meltwater cannot drain via the bed but only by episodic outburst (25% of one glacier's meltwater was found to be discharged through groundwater; Piotrowski, 2007). Based upon the sedimentological structures we found in the glacial sediments of the Hondsrug, we can conclude that these kinds of outbursts played an important role in the genesis of the Hondsrug. This would have been possible due to stagnation of the groundwater flow caused by salt diapirs and the occurrence of permafrost in some regions of the Hondsrug area. The impermeable permafrost also leads to a higher P_w. Both processes had a tremendous effect on strong local subglacial deformation and the flotation of the ice stream as well.

3.5 The floting 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 point. The high velocity is the result of the 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 and Piotrowski (2003) undertook glacial geological fieldwork on Funen Island in Denmark on sediments thought to be deposited by an ice stream from the late Weichselian period. They argued that the shear stress applied to the bed by the glacier was in accordance with 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 emphasize that basal water pressure can vary over time, such that different stages of deformation, deposition or erosion can occur. This can be the consequence of larger amounts of meltwater which cannot be drained sufficiently, therefore raising basal water pressure. The increase in meltwater discharge can be the result of seasonal variations in melting rates, increased flow rates (frictional heat) and a thicker ice sheet. Jørgensen and Piotrowski (2003) describe the variation in basal water pressure through time (temporal) at a certain site. This may also be useful in uncovering mechanisms behind 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 the lithology of the preglacial aquifer or increased melting rates due to regional increases in geothermal heat fluxes.

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

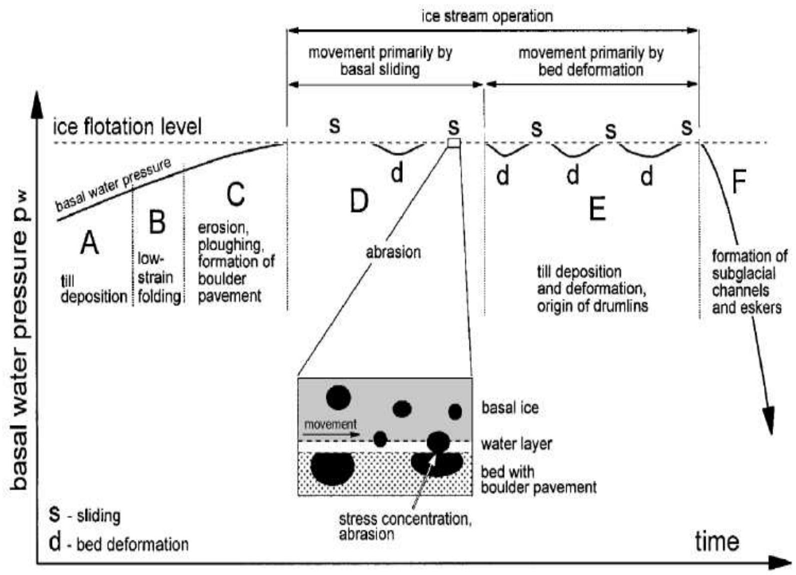


Fig. 10. Sequence of subglacial processes (A–F) in the ice-stream area interpreted in relation to basal water-pressure changes. We envisage that water-pressure conditions decisively influenced the mechanisms of ice movement, sediment deposition/erosion/deformation, and the generation of landforms. During 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. 'Floting Mechanism' from Jørgensen and Piotrowski (2003)

An increase in water pressure can be the result of permafrost, as stated above, but also the result of subtopographic obstacles such as salt diapirs, which occur along the path 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, compressional 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. Diapirs not only have a topographic effect but also a thermodynamic effect, which will be discussed in the next section.

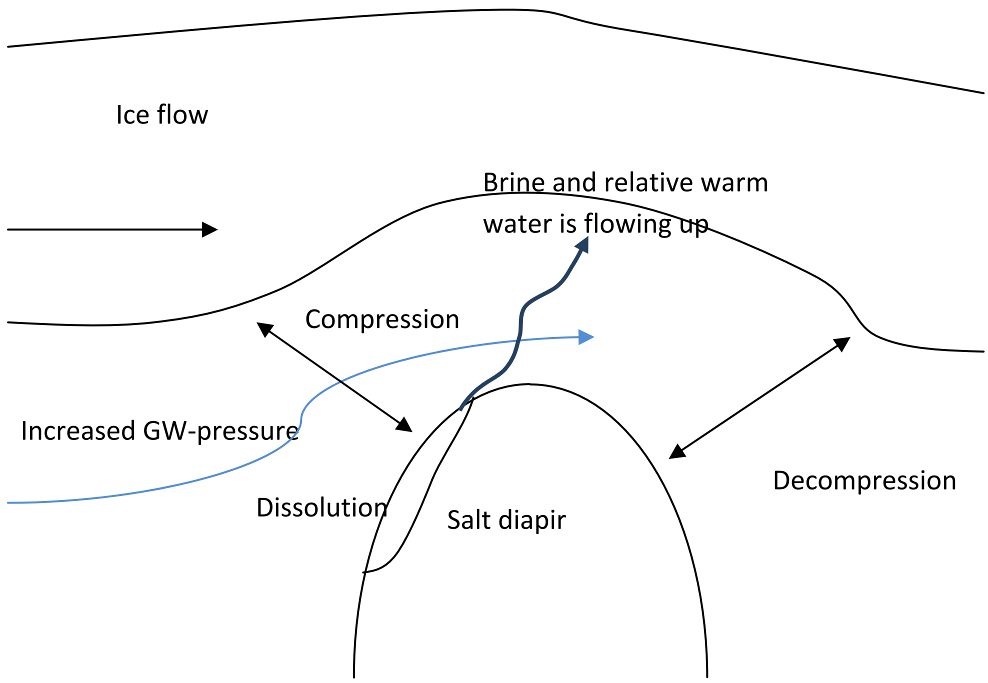


Figure 3.4. Compression and decompression caused by subsurface obstacles (scheme)

3.6 Saltdome geothermal heatflow below ice

Deeply buried rock salt has a smaller density than its surrounding sediments, which leads to a buoyancy force which is exerted on the basal contact zone 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 reactivated) the salt moves close to the surface. A close inspection of a subcrop map (see Chapter 4, Figure 4.5) of the study area shows that the top of the Zechstein formation (which is rock salt) is at very variable depths. It is closest to the surface in Schoonloo (Chapter 4, Figure 4.4), where it occurs 120 m below the surface, but it is also relatively shallow at many other locations. The importance of the shallow occurrence of salt diapirs is twofold: 1) it will influence the salinity of groundwater and 2) the thermal conductivity of rock salt is about $3.63\ Wm^{-1}K^{-1}$, versus $2.2\ Wm^{-1}K^{-1}$ for sand (Delisle *et al.,* 2003).

The waxing and waning of a glacier leads to the loading and unloading of the earth's crust, which creates vertical and horizontal stresses in the latter (Thornson, 2000). Vertical stresses are at their maximum at the top of the forebulge, which can result in reactivation of faults in the deeper subsurface. This can lead to the further mobilization of the rock salt. This process has been important in 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 glaciations (Chapter 1, Figure 1.1) and is still thought to cause vertical (postglacial) movement in Drenthe (Bregman, in prep.). Salt mobilization has significantly uplifted the overlying Tertiary and Quaternary sediments, such that major erosion has occurred in these strata, as is represented in the geological cross-section of the Hondsrug (Appendix A).

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

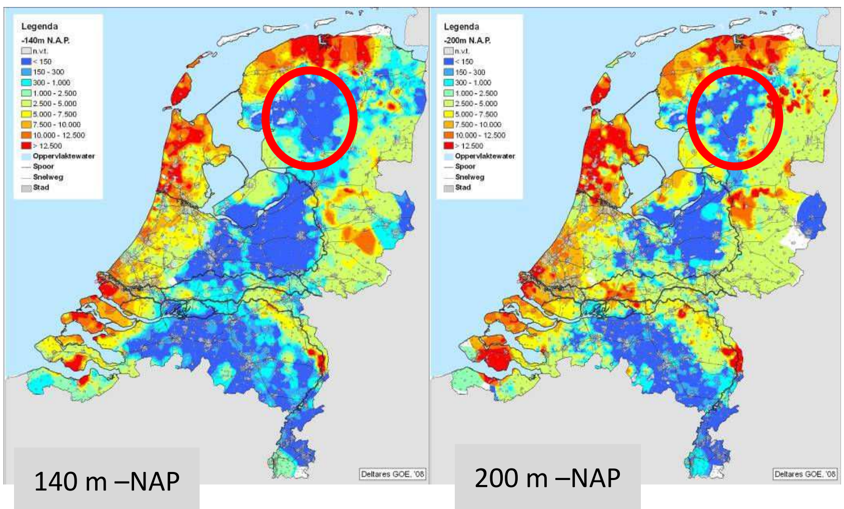


Figure 3.5. *Salinity at present at 140 m – MSL and 200 m – MSL. Salinity above salt domes is > 12.500 mg/l (red circle). These depths are in the vicinity of the depths for modelled reversed groundwater flows (e.g. Piotrowski, 2007; Source: Nationaal Hydrologisch Instrumentarium (NHI) - deelrapport Zoet - zout, TNO, 2008).*

Brine or saltwater will lower the freezing point of the water, which in turn will impede permafrost formation or lift the lower permafrost boundary. This factor may also control the thermal regime at the glacier sole. Impermeable stratigraphic units have been shown to be important barriers to the protrusion of brine water, such that it only penetrates through faults or permeable parts of the aquitard towards the surface hydrological system. The salt obstacle will also force the groundwater flow upward, while the sediment between the glacier and the obstacle will experience higher compression rates due to a greater influence of the velocity component of the glacier on the bed (Piotrowski, 1993). Recent palaeo groundwater modelling studies (e.g. Piotrowski, 2007; Breemer, 2007) have confirmed the previous conclusions of Piotrowski (1993).

Decompression occurs on the lee side of the diapir, 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 release of pressure occurs, this may lead to the formation of subglacial drainage features.

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

Increased external geothermal heat flux also influences internal frictional heat production in the glacier (Mackaay, 2008) and can produce high meltwater fluxes. This can lead to an increase in 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 turn 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 rather than deforming the bed.

Higher salinity content of the subglacial groundwater itself also has an impact on the processes mentioned, by:

1. Lowering the freezing point of the ice
2. Changing the grain sizes of ice crystals in the glacier, thereby strengthening and reducing the hardness of the ice (e.g. Mackaay, 2008)

A higher P_W, as well as the processes mentioned above and other conditions (e.g. lithology), will all have an influence on the velocity of the ice stream, the sliding conditions of the ice stream, and the character of subglacial deposits.

Forebulging and the reactivation of faults could have led to higher HFD during glaciation. Thus, loading of the upper crust not only has an impact on the geoid form of the earth's crust and the distribution of heat in its lower part, and thus also on gravity, but also on the upper crust on a regional scale (e.g. Thorson, 2005). Higher temperatures near salt domes and reactivated faults have not only had an impact on HFD, forced deep groundwater to the surface (e.g. Boulton, 2005; Piotrowski, 2005, Figure 5.1; Breemer, 2005), impact on the permafrost (Marcinek and Piotrowski, 2005), thus leading to a higher amount of meltwater but also to a change in physical-chemical conditions due to a change in groundwater quality also affected the behaviour of the Hondsrug-Hümmling ice stream on a broader scale. The main reasons for this are a reversed groundwater flow and the depth of these flows, found at depths where brinewater concentrations above salt diapirs are relatively high (Figure 3.5). In general, weathering of the cap-rock of salt domes leads to a higher salt content of the groundwater above salt diapirs. A reversed groundwater flow could have an influence on this process, and in combination with groundwater flow could also have an impact on distribution, as is proven by Bregman and Lüse (in prep.), who found newly formed brinewater indicating of new minerals in the lower tills of the Hondsrug. A main point is the link between HFD and a higher basal melting rate. The crux of this relationship is that the pressed up brine to salt groundwater, due to the dissolution of the cap-rock, may cause a lowering of the melting point of basal ice in the order of 5–6℃ (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 ℃; Johnson *et al.,* 1995 in Maaijwwee, 2008) passes or reaches the critical point of melting.

3.7 Types of till on the Hondsrug complex

Till deposits reflect the glacial history of landscapes and were the subject of many studies in the Netherlands in the 1980s and 1990s (e.g. Rappol, 1983; 1986; 1991; 1992; Kluiving *et al.*, 1991; Haldorsen *et al.*, 1989) and more recently by Bregman and 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 the ice and bed experiences a drag force exerted by the overriding ice and frictional resistance from 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 of lodgement till. The shear stresses of the overriding glacier are reflected by shear planes in the lodgement till.
2. *Deformation till*: characterized by the intense deformation of 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, with no transportation or deformation after deposition. Such till is irregularly shaped, which is the result of the migration of the till into depressions underneath the ice during deposition.

Zandstra (1976) divided the types of till in the Hondsrug complex into four groups based on the origin of the crystalline boulder configuration, the flint proportion and calcium content, while Rappol (1991) added clast orientations which confirmed the meso-scale (regional) orientations of the till types. Table 1 summarizes the properties of tills in the northern Netherlands. Zandstra's groups have been further classified into six types of till found on the Hondsrug complex, three of which are decalcified and three calcified. These are the Noordhorn, Nieuweschoot and Voorst types which are calcareous, and the Assen, Emmen and Oudemirdum types, which are decalcified. In general, two groups of till types (stage 3 and 4, Figure 1.8) are found in the Hondsrug area, which can be distinguished in terms of flint content and colour: the 'grey' Assen type (flint-rich) and the 'red' Emmen type (flint-poor). When not deformed, the Emmen type overlies the Assen type.

The distinct red colour in the Emmen type is the result of a high proportion of Devonian Old Red Sandstone, originating in Estonia and Latvia, and the oxidation of the incorporated iron-rich regional deposits (e.g. Haldorsen, 1989). The colour of the Assen till reflects the incorporation of German Pleistocene clays, which tend to be grey. The distinct colour of a till depends greatly on the oxidation/reduction history. Oxidized Assen-type till can have the same colour as the Emmen-type. In this case, flint content is used as the criterion for distinguishing between the two tills. On the basis of boulder configuration the tills are almost completely identical, with flint content the only clear marker of the difference between the main types of till.

The difference 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 Cretaceous limestone formations located in southwestern Sweden and Denmark. Consequently, the lower part of the ice stream contained flint, while the upper part only contains the 'original' east-Baltic erratic configuration (Rappol, 1991; Haldorsen, 1989). Due to its position low in the ice stream, Assen-type till is a ground moraine and crushed granites are commonly found at the contact surface with preglacial sediment. Emmen till is often considered 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 always a melt-out till, since local variables can cause lodgement or deformation as well.

The Voorst type is also apparent at some locations, and is called 'Schollenkeileem' ('thrust sheet till') since it usually occurs as a till lens or in thrusted sheets in other till types. This till comes 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 southwestern Drenthe (Koster, 2010). Succeeding glaciations deformed this Voorst till and combined it with 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 often containing limestone concretions.

Clasts in the till fabric show a strong NNW-SSE orientation (Rappol, 1991; cf. Phase 4 in Pierik, Bregman and Cohen, in prep.). These tills overlie an older SW-NE till orientation (cf. Phases 2, 3; Figure 1.8), which has been largely wiped out by the overriding of the Hondsrug ice stream. The main characteristics of the tills found in the Hondsrug complex can be summarized as:

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

In general, the till thickness (acquired from the DINO database) is greatest in the Groningen area (10–15 m), in northern part of the Hondsrug ridge Drenthe (5–10 m) and in the south of Drenthe near Schoonebeek (7 m), due to thrusting of the tills. The area between these regions has till thicknesses varying from zero to, more regularly, 2–5 m. The Hondsrug complex increases in height from the north (Groningen) towards the southeast (Emmen) (from 2 m above MSL, to 28 m above MSL), where it attains its greatest height. According to Ter Wee (1979), the climbing relief of the Hondsrug coincides with the glaciotectonic deformation of the subsurface. Depositions of till are often accompanied by deformation of the subsurface, since the coupling of the glacier with its bed occurs. In this case, basal water pressures are low (cf. Boulton *et al*., 1995) and the effective pressure high. Several deformation structures can be recognized in glacial sediments, which may be syn-depositional or post-depositional.

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

The timing of events can be determined by the extent to which a deformation structure cuts across or is superimposed on older glacial deposits. Water-escape features, such as liquefaction and fluidization, may also be present. Liquefaction structures include convoluted beds, flame structures, and ball and 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, which includes:

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

Another aspect of tills is clays composition, which gives information about source areas (focus of previous studies) as well about conditions of forming (recent study for the Drenthe and northern Germany by Bregman and Lüse, in prep.). Publications on the composition of the clay fraction in tills in the Netherlands began in the late 1980s (Rappol, 1983, 1992, 2001; Rappol *et al.* 1989; Haldorsen *et al.*, 1989). Smectite is absent in flint-poor tills. This indicates, according to Rappol (1992), an east-Baltic source area. The absence of smectite in tills in Drenthe is due to its absence in Pre-Cambrian and Paleozoic 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 period 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 into the till (e.g. Rappol, 1989, 1992). In relevant Sections 6.1.5. and 7.1 results of the study by Bregman and Lüse are integrated with other results.

4. Lithological observations on the Hondsrug

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

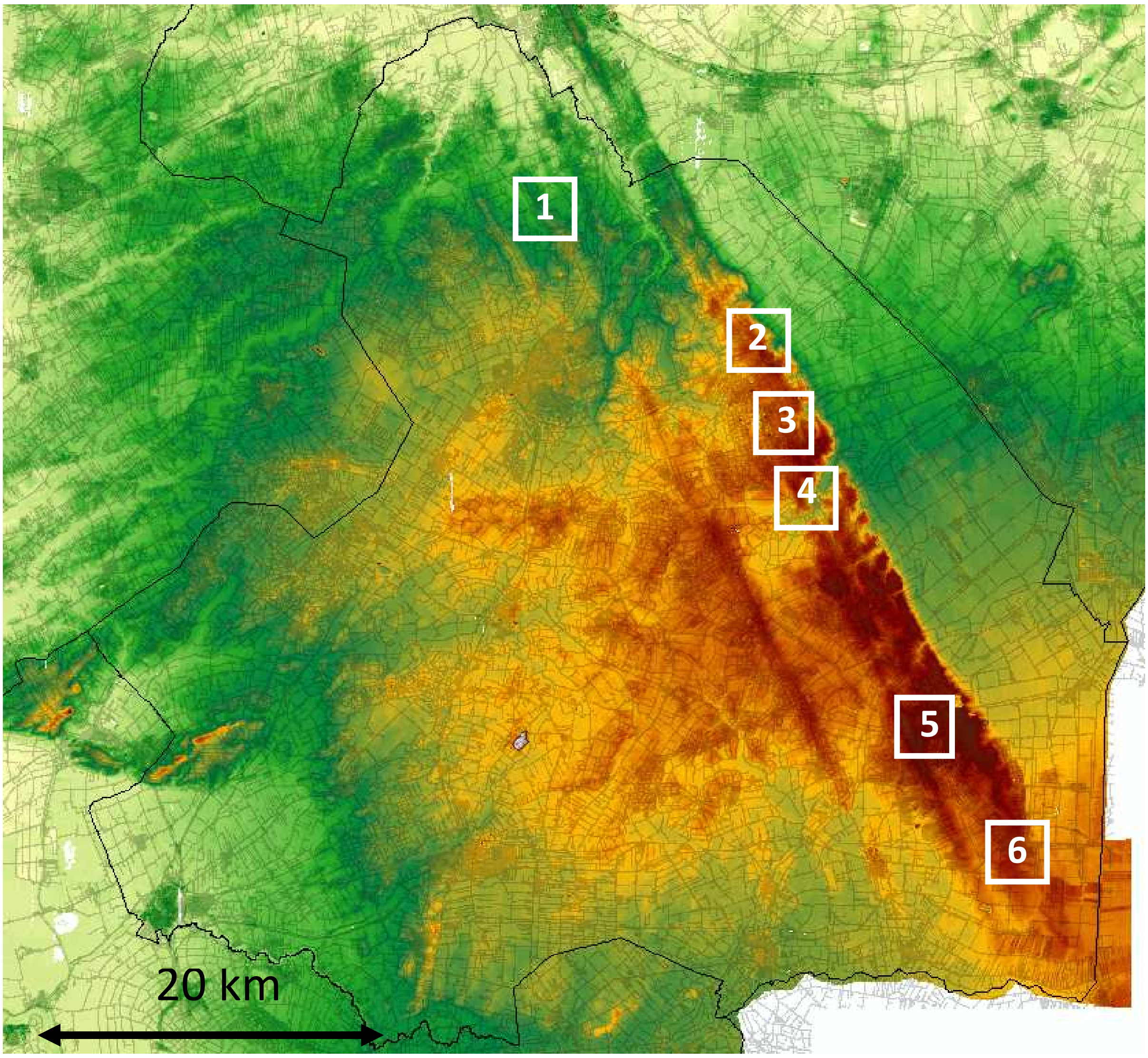


Figure 4.1. Locations of the outcrops: 1. Donderen, 2. Gieten, 3. Gasselte, 4. Borger, 5. Odoorn, 6. Klazienaveen (Source: DEM of the Netherlands, Rijkswaterstaat 2005).

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 of 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 2.5 m by 1.5 m outcrop was dug out by hand and shows the contact surface between the glacial and preglacial sediments (Figure 4.3).

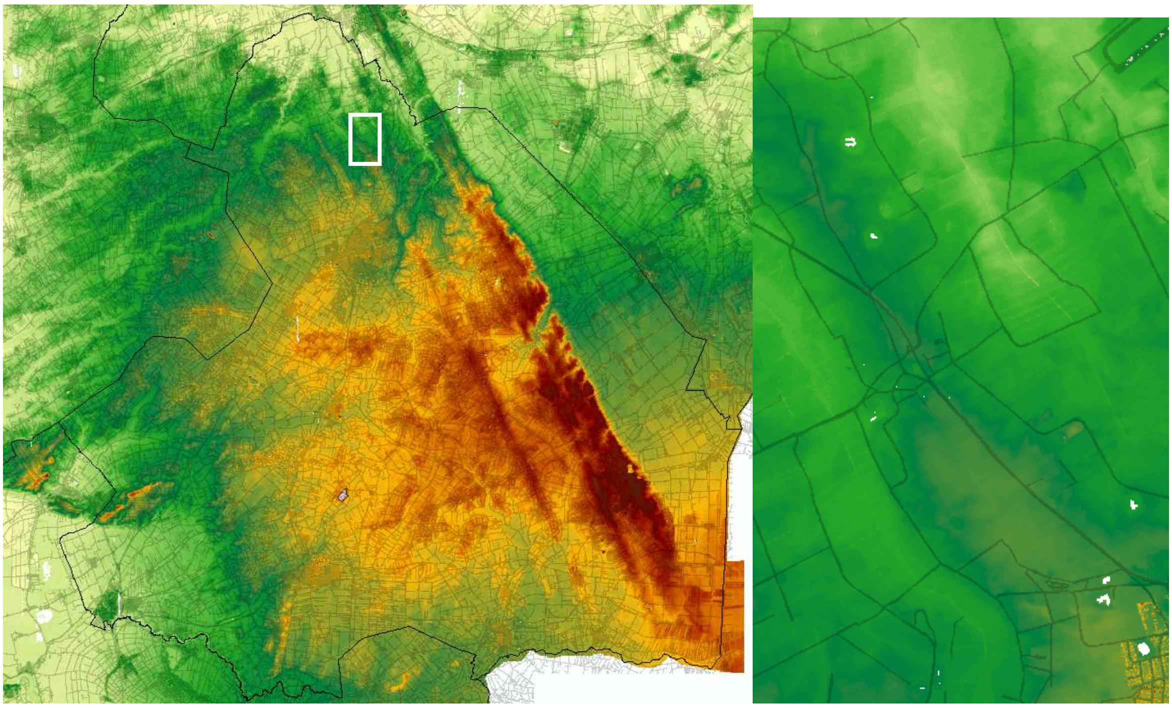


Figure 4.2. A) Location of outcrop 1: Donderen area; **B)** Detail chart of the relief around Donderen. Rolder Ridge is vaguely expressed in the topography.

The lithostratigraphy at the outcrop in Donderen consists of:

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

There is a disconformity between the light-grey sand and the coarse-grained sand. At the point of contact between the remnants of the till and the preglacial sediment, either the till has dropped into the sediment or the sediment has been injected into the till.

Figure 4.3. Outcrop at the Donderen area.

4.1.1 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 the fines being washed out. The fine, well-sorted yellow sands with loamy laminations can be interpreted as snow meltwater deposits. They belong to the Boxtel Formation and were deposited during the Weichselian glaciation. The fine yellow sand on top of these loamy laminations is considered to be aeolian coversand from the late Weichselian period. The organic-rich topsoil is anthropogenic in origin ('plaggen soil') as it occurs next to an 'esdorp'. Thus, in general, the outcrop contains four major units based on the deposition environment. These are (from top to bottom): aeolian sand (Boxtel Formation), snow meltwater deposits (Boxtel Formation), residue of glacial till (Drenthe Formation, Gasselte Member) and fluvioglacial sand (Peelo Formation).

4.2 Location 2: Gieten

Outcrop location 2 is positioned almost perpendicularly to the strike of the Hondsrug (e.g. ENE-WSW vs NNW-SSE) and therefore to the ice stream flow, as these ridges formed parallel to the flow direction (cf. Boulton *et al.*, 2001; Figure 4.4A, B). The outcrop shows the lateral variability of the glacier bed across the former ice stream for a length of about 500 m. This outcrop cuts through both the east and west branches of the Hondsrug, with a roundabout lying exactly on the divide between these two ridges. Strikingly, the ridges seem to disappear in the northern part of Drenthe, although very thick sequences of till can still be found here which are in fact much thicker than generally observed on the Hondsrug. The mosteastern ridge is much more stoney then the moste mostwestern ridge. Since the till sequence for each of these ridges is very different, they will be described and interpreted individually.

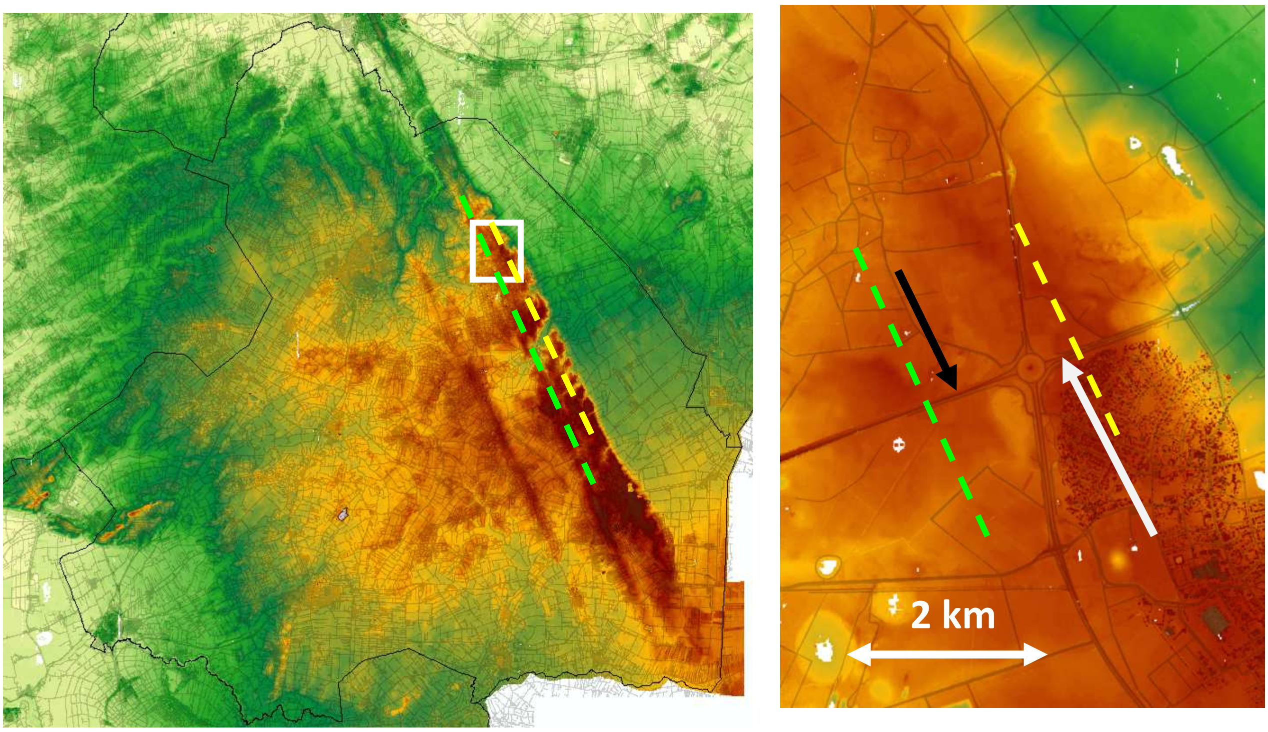


Figure 4.4. A) Location 2 on Hondsrug with west ridge (green dotted line) and east ridge (yellow dotted line) and; **B)** Detail chart of location 2: white arrow marks the south face east of the roundabout, black arrow shows location west of the roundabout. Note that white and black arrows only indicate study locations. The Hondsrug forming ice flow had a NNW - SSE direction.

At the Gieten location the west side is different of the mosterneast side. We describe both locations as following.

The *western branch* of the Hondsrug, Figure 4.8E) consist of fine white sand (150–210 μm) which shows intense deformation and drag structures is found at the bottom of the outcrop. Although fine sand makes up the bulk, sometimes coarse to very coarse sand with gravel (3 mm) is also found. These are overlain by a dark-grey to black-green till with a thickness of about 2 m and their contact is of an erosional character. A sandy layer (210–300 μm) 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 (150–210 μm), 30 cm thick. In the contact zone with underlying tills a thin accumulation of stones is present, which includes dropstones and pillow structures. This indicates an erosional phase. On top lies a 0.5 m thick peat succession. The contact zones of the two tills drain groundwater by diffuse seepage and pipes (hollow features), which indicates recent intra-till erosion.

On the west side of the roundabout, large thrust sheets and recumbent folds were observed. Till blobs and coarse-grained sand inclusions were observed in pushed and dragged preglacial sediment. The preglacial sand shows drag structures (Figure 4.6). Large dropstones were found in the preglacial sediment. Intra-till channels were found in the grey Assen-type till, which contained fine-grained sediment with some boulders (Huisman, personal communication). The yellow sand on top also shows cryoturbation features.

The overall character of the *east side* of the location (Figure 4.7) is a chaotic sequence of different tills. Six types were found (Huisman, pers. comm., 2011), three of which were calcareous and three decalcified. The intra-till lithology is very diverse, ranging from very loamy to sandy with pebbles, making it difficult to distinguish between them. We start the description at the bottom of the outcrop, where fine white sands (150–210 μm) are found at a depth of about 7 metres (inferred from DINO database). These sediments are overlain by a sequence of rusty-brown till, with a thickness of about 1.5 m (Figure 4.7). Subglacial channels in the till have formed, with sometimes very coarse infillings and channel lags. This till is overlain by a complex of grey till, sand blobs, and reddish till with a varying thickness between 0.5–1.5 m. These sediments are overlain by a red till, about 1 m in thickness. At some locations, laminated sandy inclusions can be observed in the red till and show drag structures and faults. A 40 cm thick layer of fine yellow, well-sorted sand (150–210 μm) lies on top of the red till. The contact between red till and fine yellow sand is first of all cryoturbated, but is erosional in character: the till is

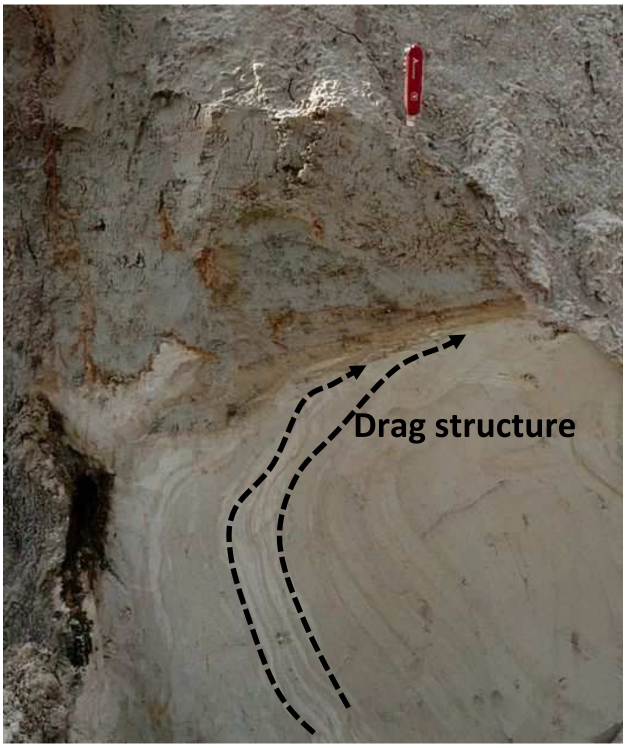


Figure 4.5. Drag structures in the preglacial sand, ice movement from left to right (west of the roundabout). (Courtesy of H. Huisman)

somewhat washed out and a boulder accumulation occurs. At the top, there is a 30 cm thick layer of humus-rich soil.

4.2.1 Structures

On 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 into 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 flowed into the grey till complex (Figure 4.7). The fine yellow sand on top of the outcrop also shows cryoturbation features: it has 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 were also found: they were filled with preglacial sediment and injected into the grey till (Figure 4.8E). Although thrust sheets occur, the deformation style in the sediment is predominantly ductile. Figure 4.8A shows piping structures that have hydrofractured the till completely (east side of the roundabout). Figure 4.8D shows a sand lens that is incorporated into the red till.

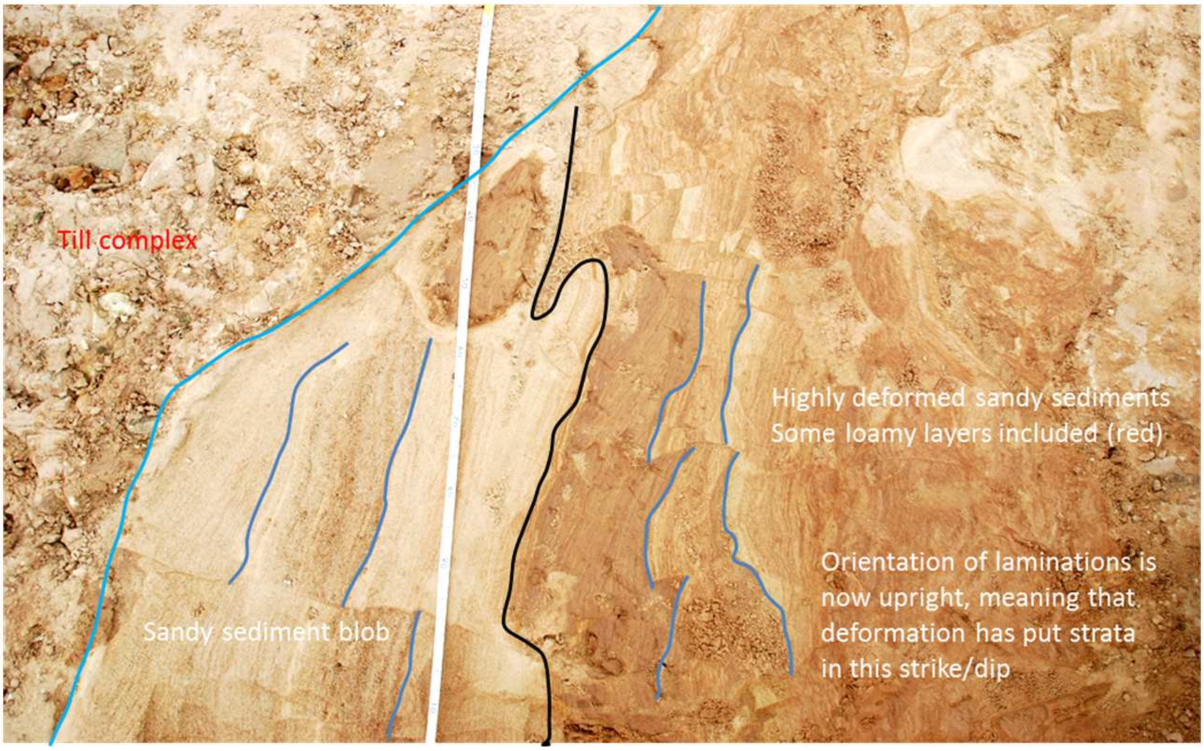


Figure 4.6. Detail of a sand blob of preglacial sediment showing ductile and brittle deformation and the uprighted Nieuweschoot-type till.

4.2.2. Geological interpretation

At the *eastern branch of the Hondsrug ridge* the tills show an extremely varied lithology and different colours compared to west of the roundabout, which makes interpretation in terms of till types very difficult. Colour, as a criterion for attributing the diamict to a till type, as described in Section 3.6, cannot be utilized at this outcrop, since oxidation has tended to make all the tills rusty brown. Flint content allows the division of the Emmen from the Assen type, while the distinction from the Voorst type is based on geometry and the occurrence of limestone concretions.

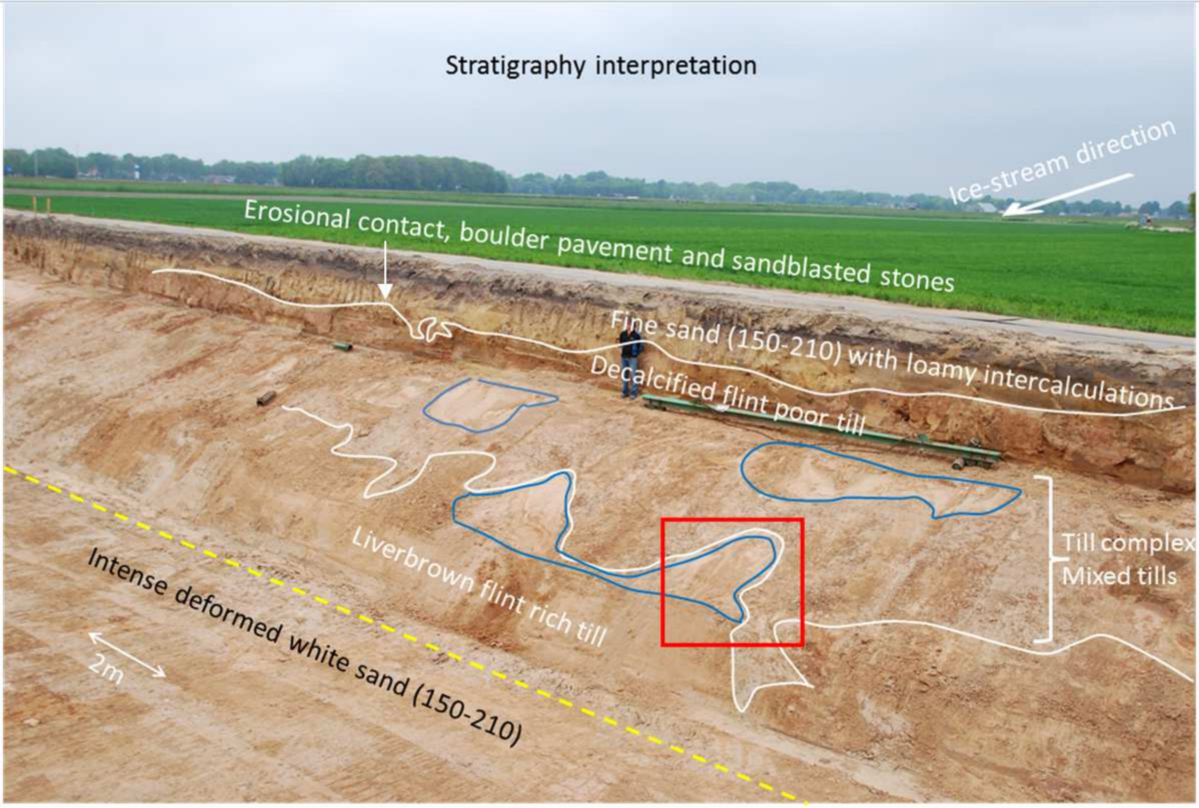


Figure 4.7. South face of the outcrop at Gieten, east of the roundabout. Undulating surface of liver-brown flint-rich till. Top to bottom is 7 m. (Red square indicates Figure 4.7)

The white sand at a depth of 7 m 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, as these layers were uplifted by the underlying salt diapir (Appendix A) and may have been further pushed by the glacier and 2) washed out older till. The rusty-brown till at the bottom of the outcrop contained flint and was calcareous, it can therefore be classified as Noordhorn-type till. This till is a ground moraine and plastered onto the land by lodgement. Its contact surface with the overlying sediment undulates between 0.5 m and 1.5 m is the result of glacial scour or subglacial deformation. The complex of grey till, sand and red loamy sediments can be considered a deformation till, which includes Voorst-type till, preglacial sand of the Peelo Formation and some 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 ebris as no pebbles were found to have another genetic origin. The fine yellow sand on top of the sequence can be interpreted as periglacial sediment from the Weichselian glaciation (Boxtel Formation).

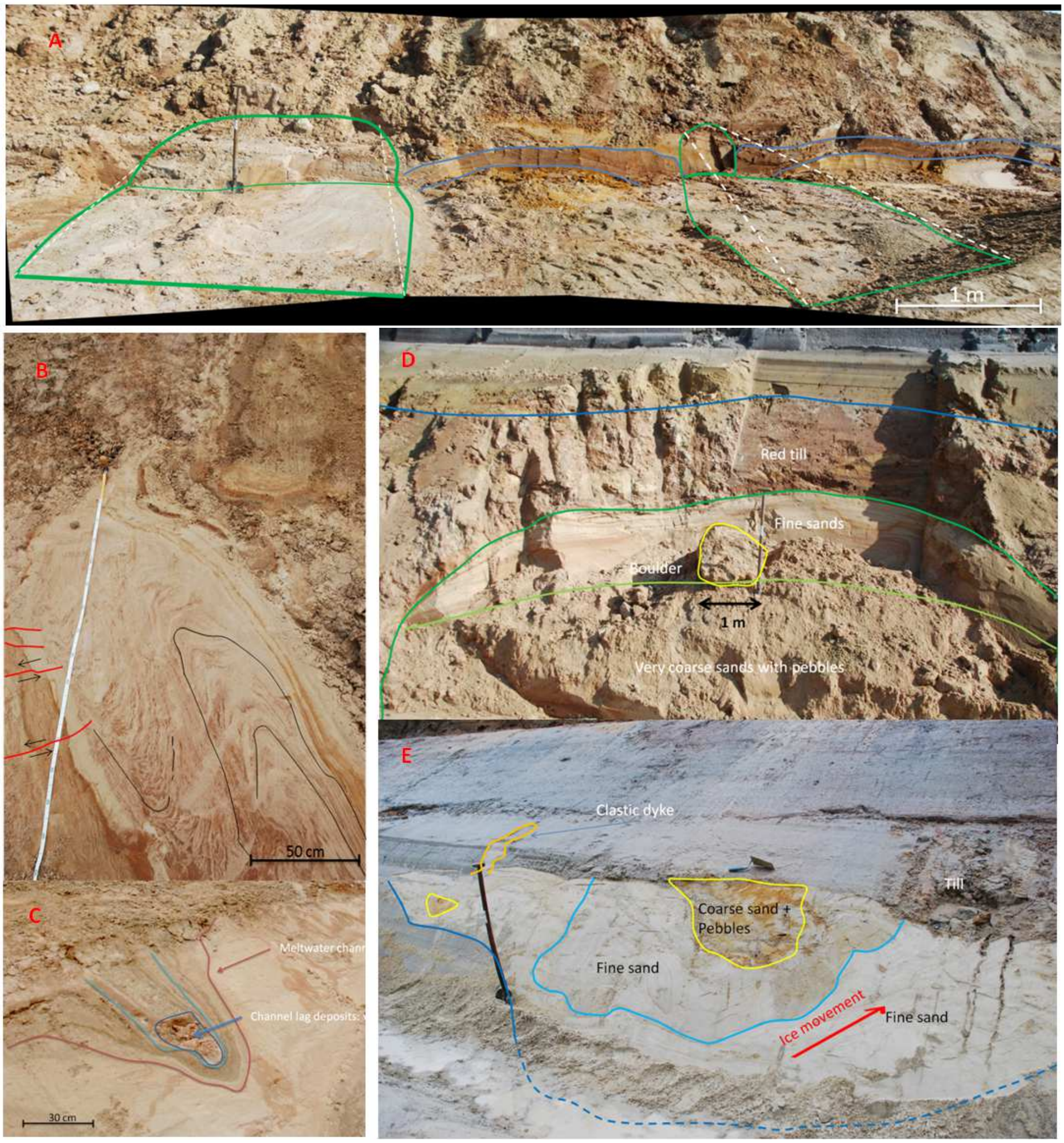


Figure 4.8. Some glacial features from the Gieten site, A) Subglacial piping, B) Predominantly ductile deformation and flow structures in a sand body, C) Meltwater channels in the Emmen-type till, D) Sand lens in Emmen-type till, meltwater deposits, E) Subglacial meltwater channel under Assen-type till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

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

4.3 Location 3: Gasselte

The outcrop at location 3 lies 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.

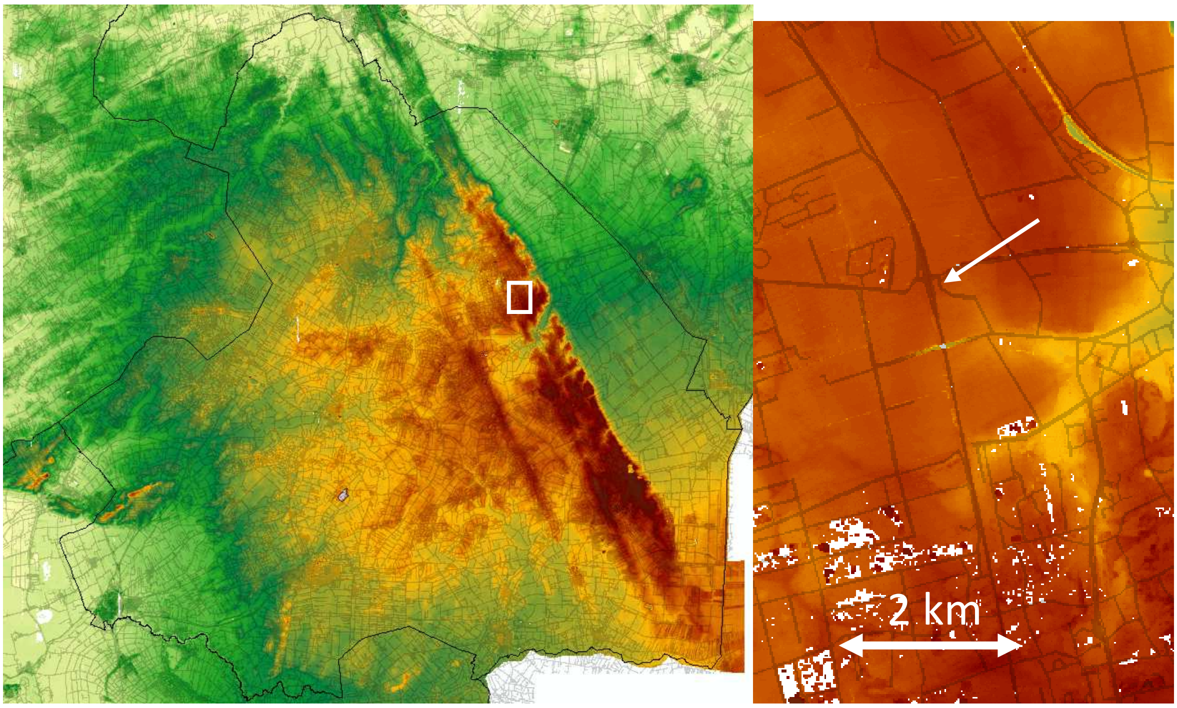


Figure 4.9. A) Location of outcrop 3 on the Hondsrug and B) Detail map of outcrop location. White arrow marks the outcrop.

This site is characterized by the occurrence of very coarse sand (850–1400 μm) with a high proportion of pebbles. An alternation of coarse-grained beds and finer grained beds also occurs (Figure 4.10). These sediments are overlain by a 0.5 m 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.

4.3.1. Structures

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

4.3.2 Geological interpretation

The coarse sand below the red till has a glacial origin, with the occurrence of pebbles and a large grain median reflecting this origin. Since grey till is absent at this outcrop, the coarse sand can be considered to be the erosional remnant of Assen-type till (and perhaps a fraction of Emmen-type till). It therefore belongs to the Gasselte Member of the Drenthe Formation, a type which can be found not far from this outcrop’s location. The angular unconformity also reflects the erosional character of the site.

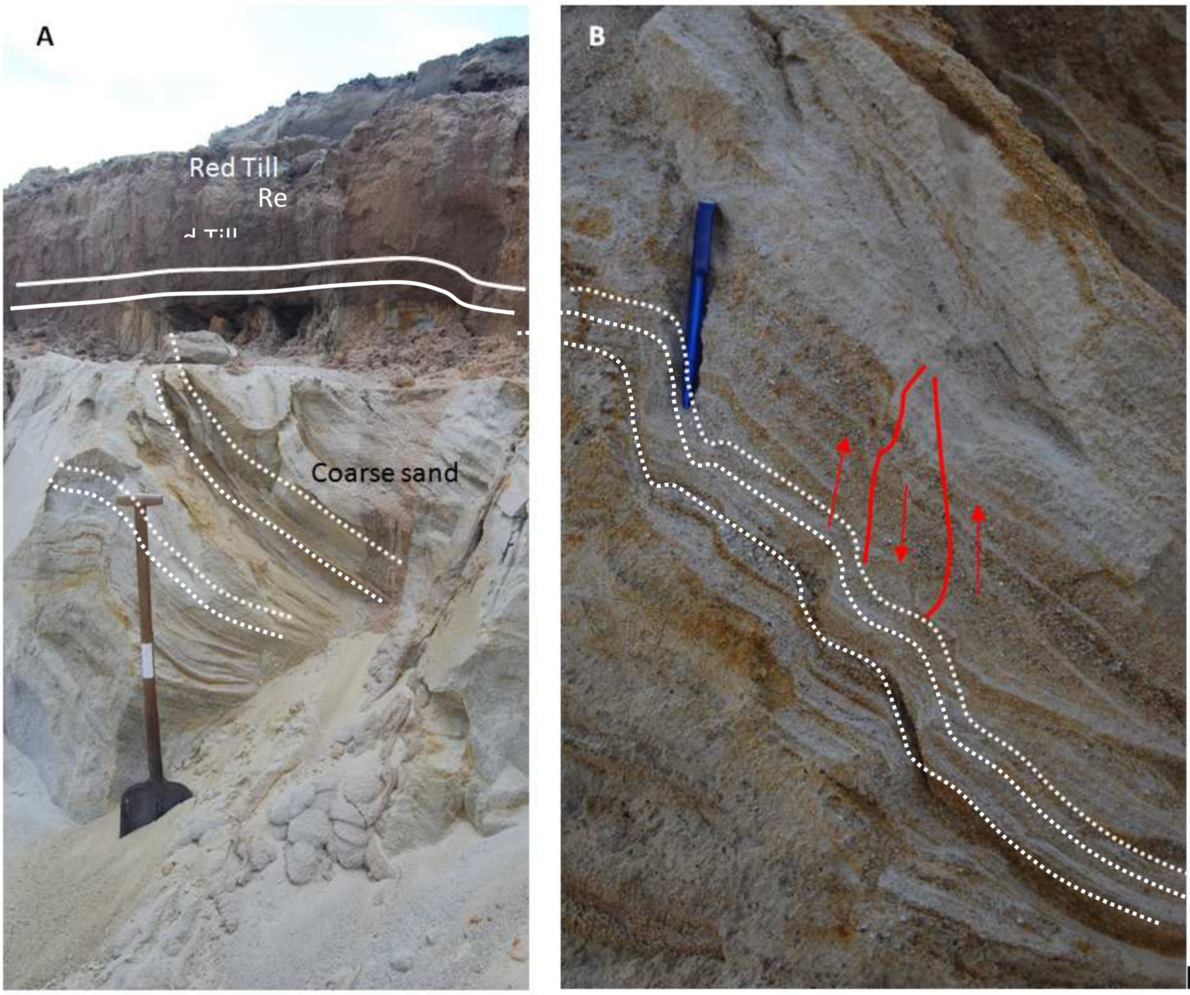


Figure 4.10. **A)** Dipping preglacial sediments. Red arrow is ice-flow direction. **B)** Detail of sandy lithology with dislocations due to stretching of frozen blocks, Gasselte roadcut N34.

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 oriented 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 the NE), as the layers dip towards the NW.

The stratigraphy contains two major units (Figure 4.13). Red till surfaces at this location and has a thickness varying between 1 and 2 m. These sediments are underlain by fine white laminated sands and the contact between these units is of an erosional character. At some places, boulder accumulations occur at the contact surface between preglacial sediments and the till. Southeast of Borger accumulation of gravel in the soil (we observed till 4 mBSL). Gravel-pavement is surfacing in the forests at different locations in that area.

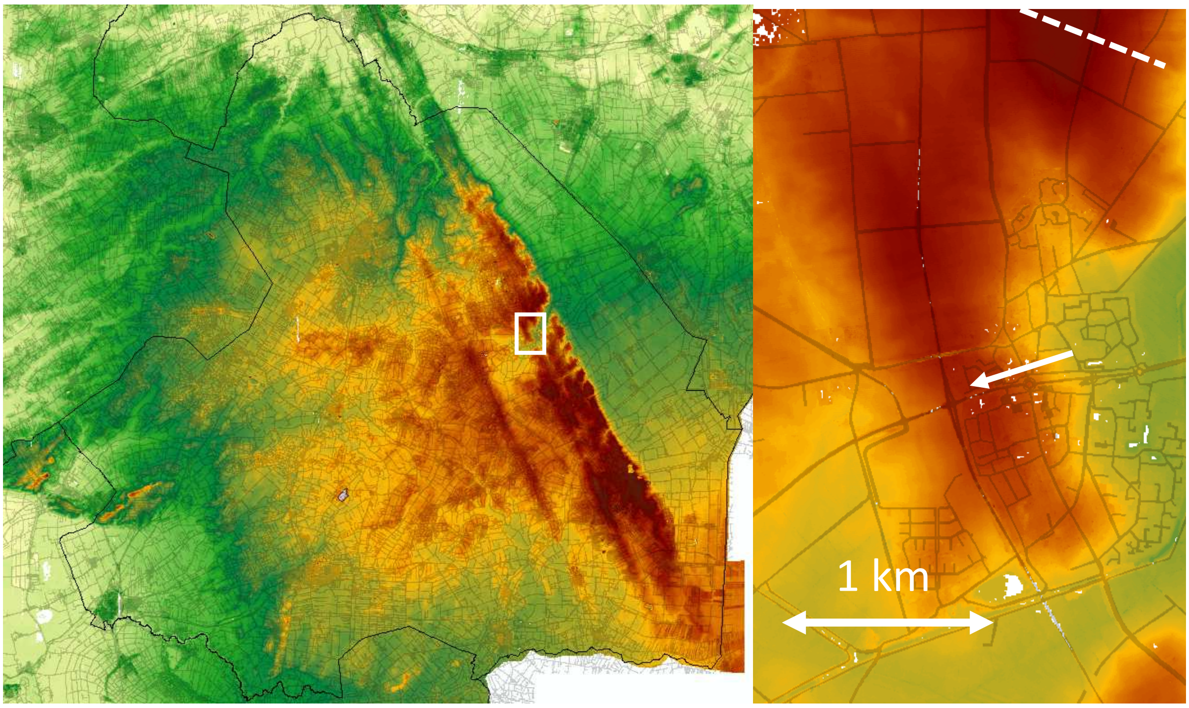


Figure 4.11 A) location of the outcrop in the Hondsrug and B) Detail chart of the outcrop at Borger. White arrow marks location of the outcrop. White dashed line indicates GPR transect.

4.4.1 Structures

Compared to the location at Gieten, which is situated just 10 km northwest of Borger, the outcrop shows very different features and has a completely different stratigraphic sequence. The ductile-deformed preglacial sediments (Figure 4.12A) reflect compressional forces, as shortening can be 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 preglacial 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 preglacial sediments, ductile folding is the predominant type of deformation. The recumbent folds in the till are cut off by a thrust sheet, which also reflects brittle deformation. Locally, boulder accumulations occur on the lee side of an obstacle consisting of preglacial sediment (Figure 4.12A).

North of viaduct, east face

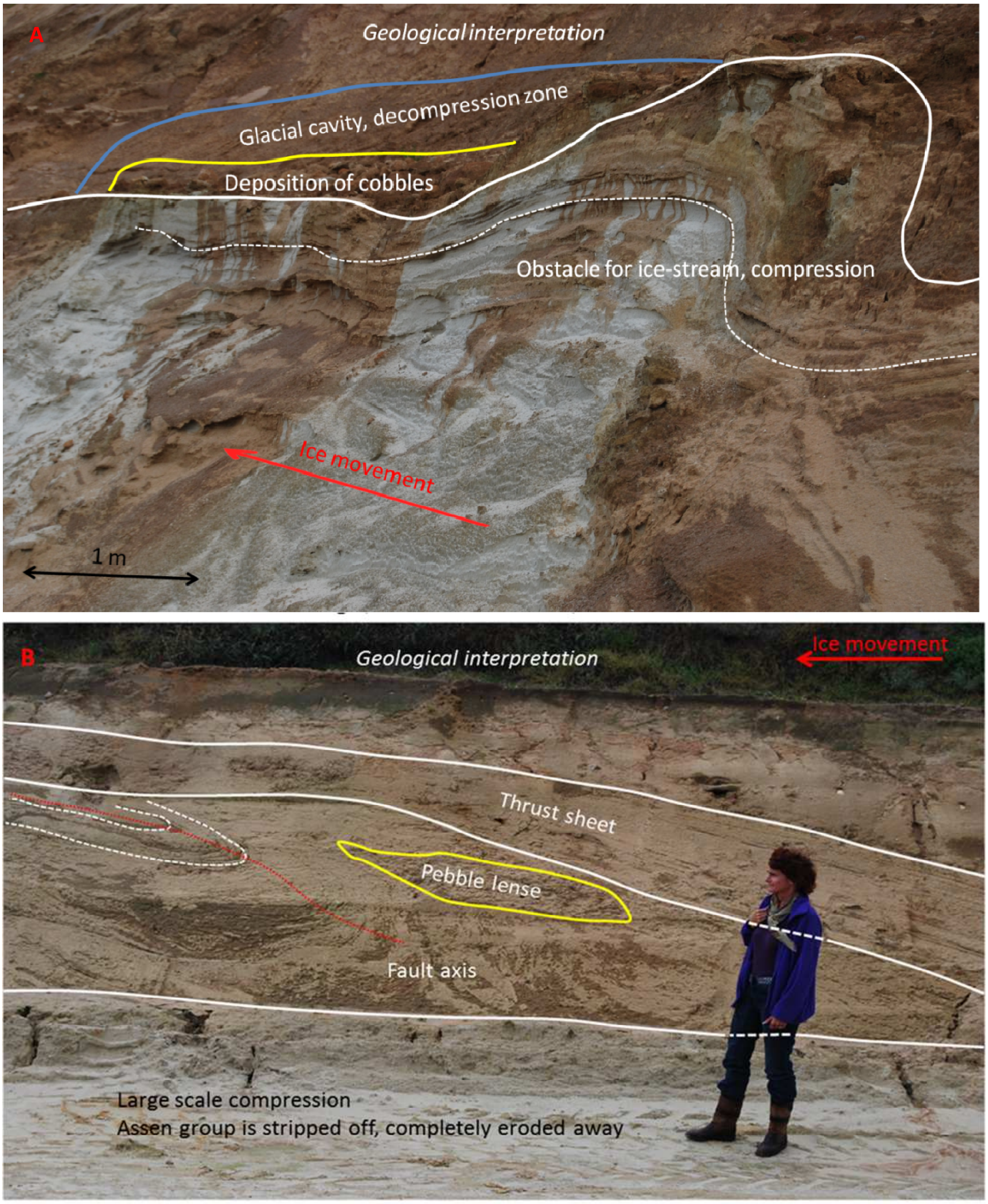


Figure 4.12. A) Boulder accumulations on the lee side of a cavity; B) Large compressional forces are relfected in the sediment: thrust sheets, recumbent faults and incorporated lenses.

Borger: North of the viaduct, East face

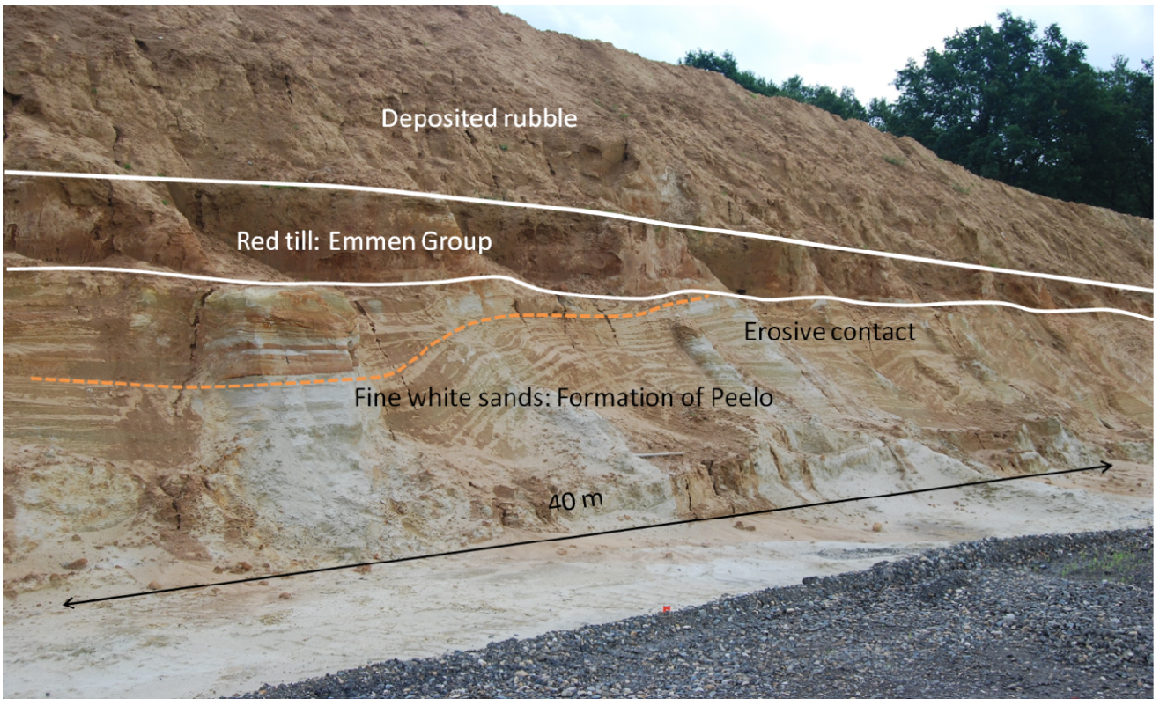


Figure 4.13. Outcrop at Borger

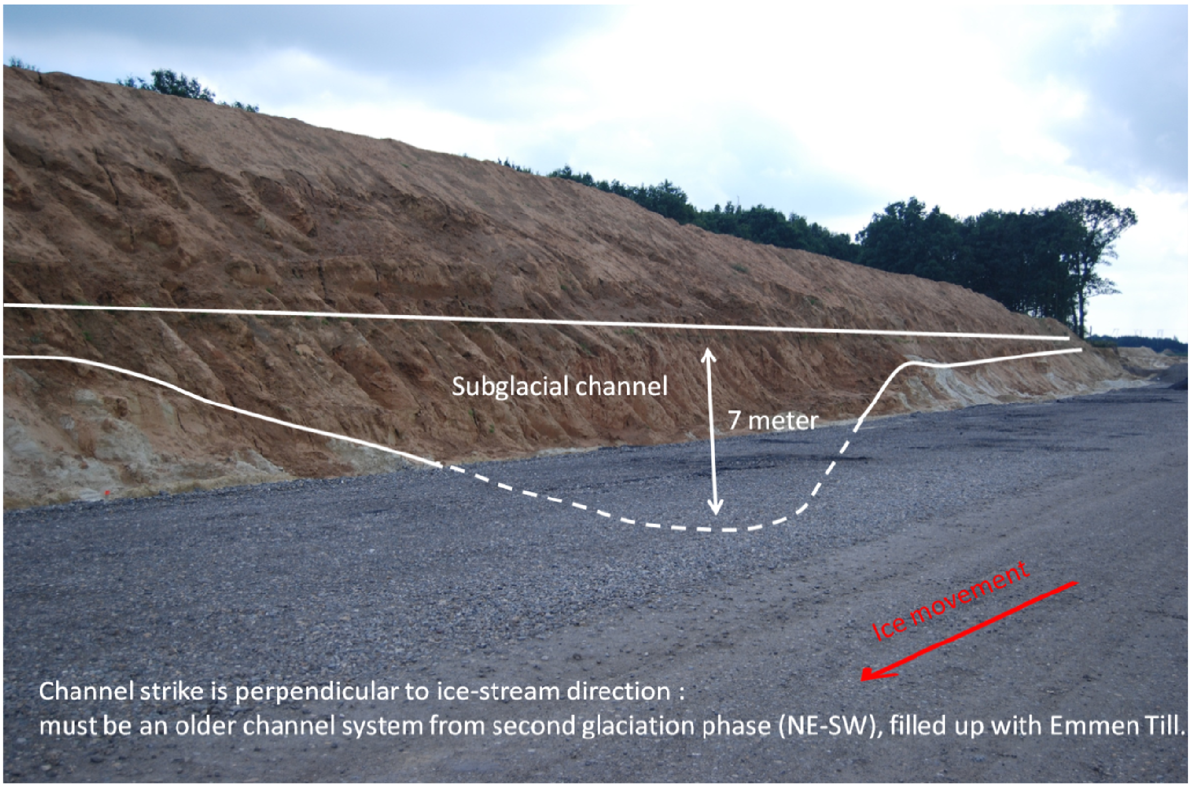


Figure 4.14. A large subglacial meltwater channel, with a perpendicular orientation relative to the ice stream movement. If the hydraulic gradient was along the ice stream, this would reflect an older glacial channel. If the hydraulic gradient was lower towards the side of the ice stream, this channel may also have been formed by the ice stream.

4.4.2. Geological interpretation

The red till surfaces at this location are classified as Drenthe Formation and more specifically as Emmen-type till (cf. Zandstra, 1976). The contact surface with the underlying fine sands of the

Peelo Formation has an erosional character, as is reflected by the cut-off of laminations. Assen-type till (grey till) is absent from this location, as is coversand from the Weichselian period. The accumulation of gravels and surfacing of gravel-pavement south east of Borger indicates wash out by meltwater and accumulation of gravel (and stones).

4.5 Location 5: Valthe/Odoorn: GPR measurements

No recent outcrop information is available from this area (Figure 4.15). We performed GPR measurements to obtain seismic data on the tills and preglacial sediments and thereby extract information from these cross-sections. The main issue is to gain an insight into the deformation rate and direction. In addition to the GPR measurements, hand-core drillings were performed to obtain lithological information about this region, with reference to Dubois (1902), who did fieldwork in the same area, providing adequate additional data.

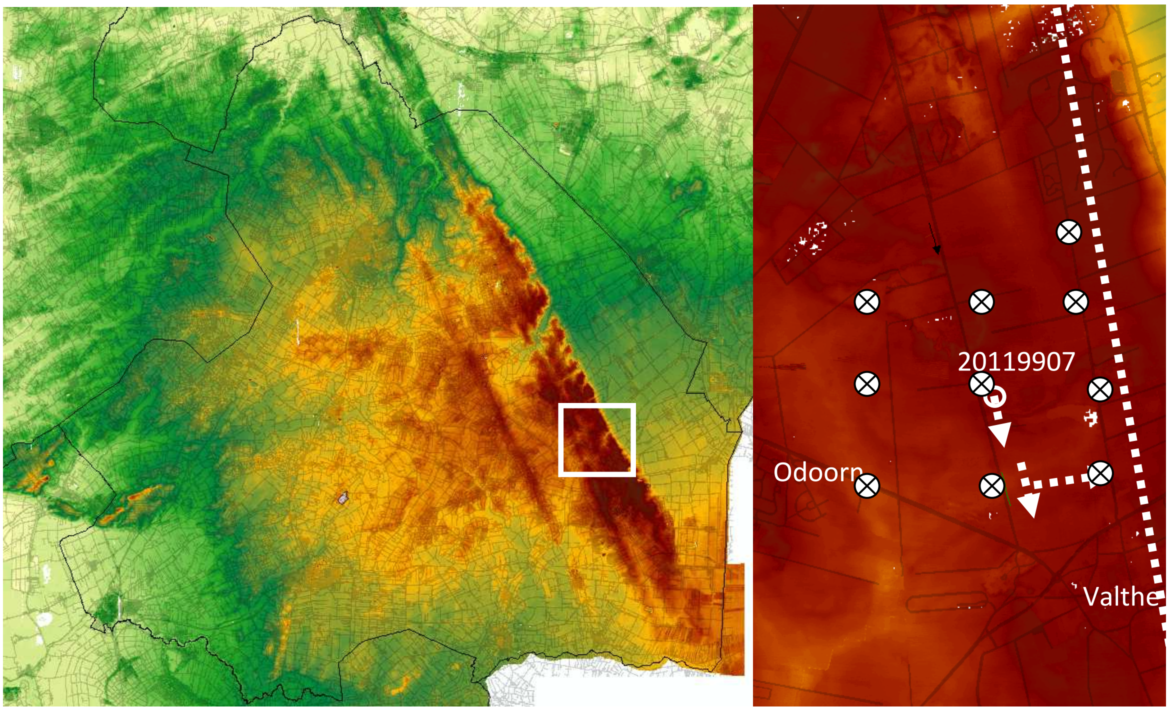


Figure 4.15. A) Location of the outcrop on the Hondsrug and B) Detail chart of the location. White arrows mark GPR locations. Circle shows borehole location. Dotted line shows railroad construction (from Dubois, 1902). Circle with cross shows locations of the NITG borehole descriptions.

The following lithologies are found from bottom to top in core 20119907 (Figure 4.16): i) between 1.50–1.30 m of grey rigid loam which contains crushed pebbles with a diameter of 1 cm, ii) between 1.20–0.2 m of 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: from absent to 2.1 m thick. Where till is absent, fine sand or silt-rich sand occurs. Dubois (1902) observed the same two types of lithostratigraphy which correspond to his succession A (no till, but boulder sand) and succession B (1–1.5 m till).

4.5.1 Structures

GPR measurements (Appendix C) show two cross-sections near Valthe which are oriented perpendicularly. The first cross-section is taken south to north and shows a lightly chaotic pattern. Deformation of the preglacial layer is not easily recognizable. At X = 90 m, 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 3 m) and are located in the preglacial sand. Their crests face towards the east or northeast.

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

Coordinaten			Hoogte	Diepte	KAARTEENHEID		Geomorfogenetische kaart:	
XCO	YCO	Coord. sys	Z [m +/- NAP]	[cm]	Geologische kaart:		Gondwatertrap:	
254833	542271	RD	22,4	150	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 no.	Sand	Till/loam	Till thickness (m)
B17F0521	0–1.6 m; 2–2.4 m	1.6–2 m	0.4
B17F0522	0–0.8 m; 0.8–1.8 m (silt-rich); 1.8–2.4 m	Absent	0
B17F0525	0–0.8 m ; 1.2–bottom	0.8–1.2 m	0.4
B17F0526	0–1.1 m; 1.7–bottom	1.1–1.7 m	0.6
B17F0527	0–2.4 m	Absent	0
B17F0529	0–1.45 m	1.45–3.6 m	2.15
B17F0530	0–2.4 m	Absent	0
B17F0531	0–1.3 m; 1.7–2.2 m	1.6–2 m; 2.2–2.5 m	0.4, 0.3
B17F0618	0–0.3 m; 0.3–1.3 m (silt-rich); 1.3–bottom	Absent	0
B17F0621	0–1.6 m; 2–2.4 m	1.6–2 m	0.4

Table 2. NITG-TNO borehole descriptions. Sand is usually fine grained unless stated otherwise. Boreholes lie within a radius of 600 m from the GPR location.

4.5.2. Geological interpretation

The DINO database borehole descriptions have shown that the till thickness is extremely varied 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 Section 1.5.2). Moreover, the geological cross-section from 1977 shows that the Drenthe Formation largely disappears at this site (B17H113).

The GPR measurements revealed only minor deformation of the preglacial layer, dipping towards the northeast (Appendix C). The DINO database boreholes often show a stratigraphy composed of medium/fine sand with some pebbles, which can be interpreted as boulder sand. From the geomorphological map (2010), it becomes clear that in this area glacial meltwater valleys and drift-sand areas occur. This explains the variation in till thickness and the occurrence of boulder sand, since erosion of the till took place. The lower preglacial sediment belongs to the Drachten Formation (Eindhoven Formation on the geological cross-section of Appendix A). It is overlain by brown-yellow fine-grained sand (150–210 μm) that can be interpreted as Weichselian coversand; in other words, Boxtel Formation. In borehole 201199007, very loamy yellow sand was found, with pebbles on top of a grey till. Both types of sediment 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.

4.6 Location 6: Klazienaveen

This outcrop is situated furthest downstream on the ice stream and is located on the Hondsrug (Figure 4.17).

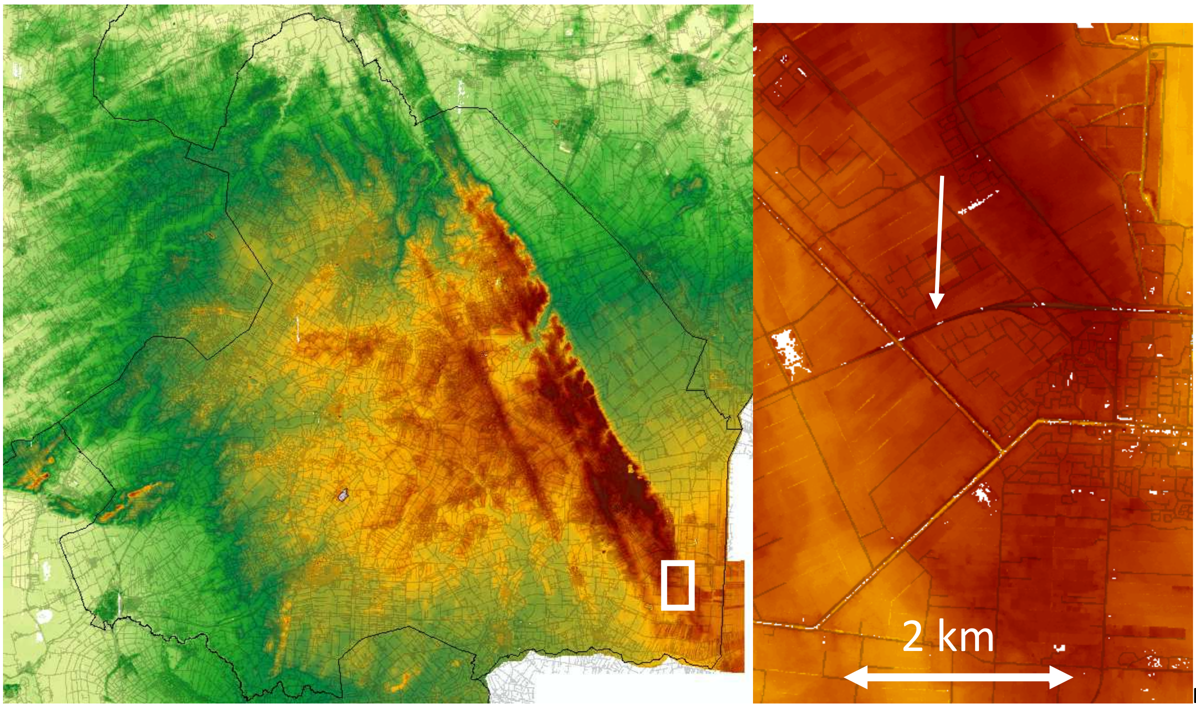


Figure 4.17. A) Location on the Hondsrug and B) Detail chart of the region of Klazienaveen. White arrow marks the outcrop location.

Very fine light-grey sand (105–150 μm) is found at the bottom of the outcrop (Figure 4.18). 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.

There is a sharp transition to a purple-grey till. At this contact zone, crushed granites are observed (Figure 4.19D). The total thickness of this till is approximately 1.5 m and it 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 also occur in this till.

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

The red till is overlain by a 1 m thick sequence of fine yellow sand (150–210 μm) which is well rounded and well sorted. The contact surface with the underlying till is sometimes irregular (Figure 4.18) and iron concretion occurs near the boundary. Generally, a 30 cm thick layer of peat lies on top of the fine yellow sand, but this has been dug out at the outcrop.

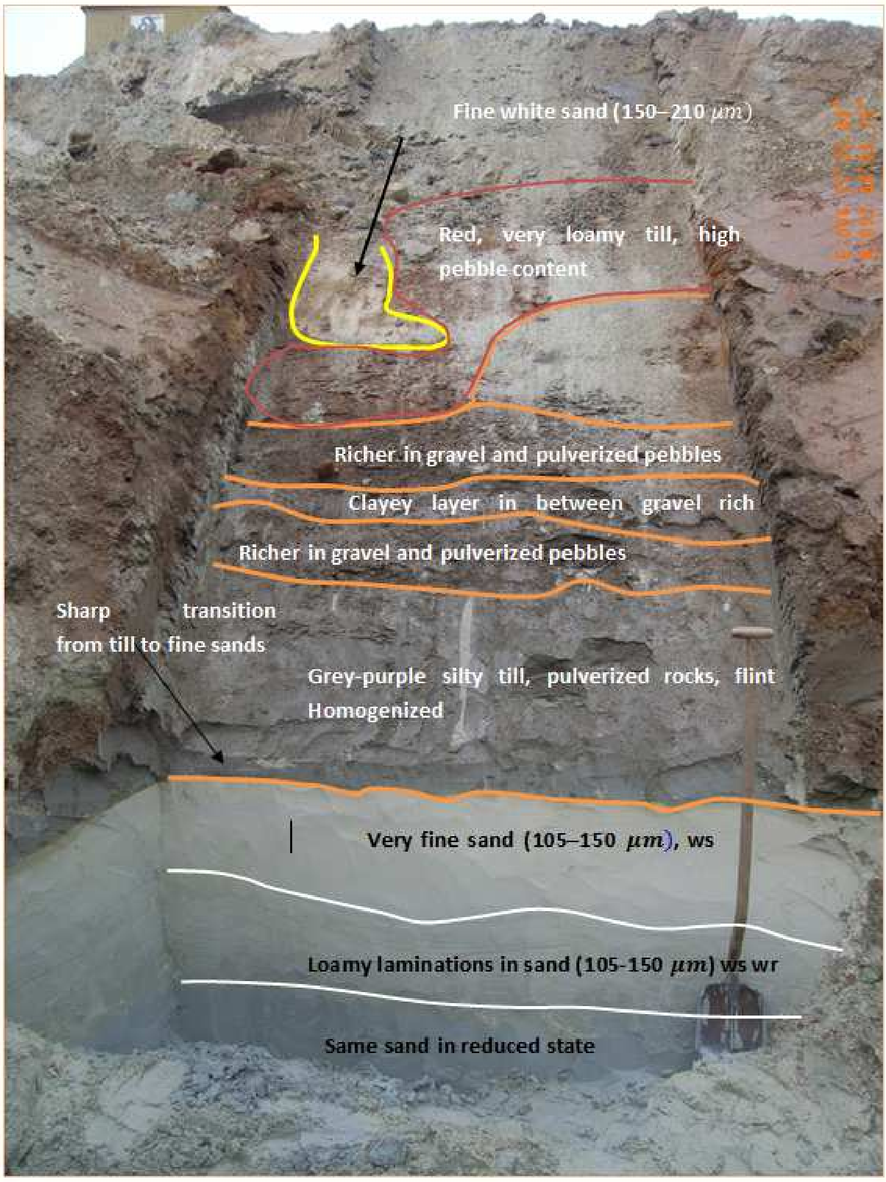


Figure 4.18. Outcrop at Klazienaveen. Note the sharp transition between the till and the preglacial sand.

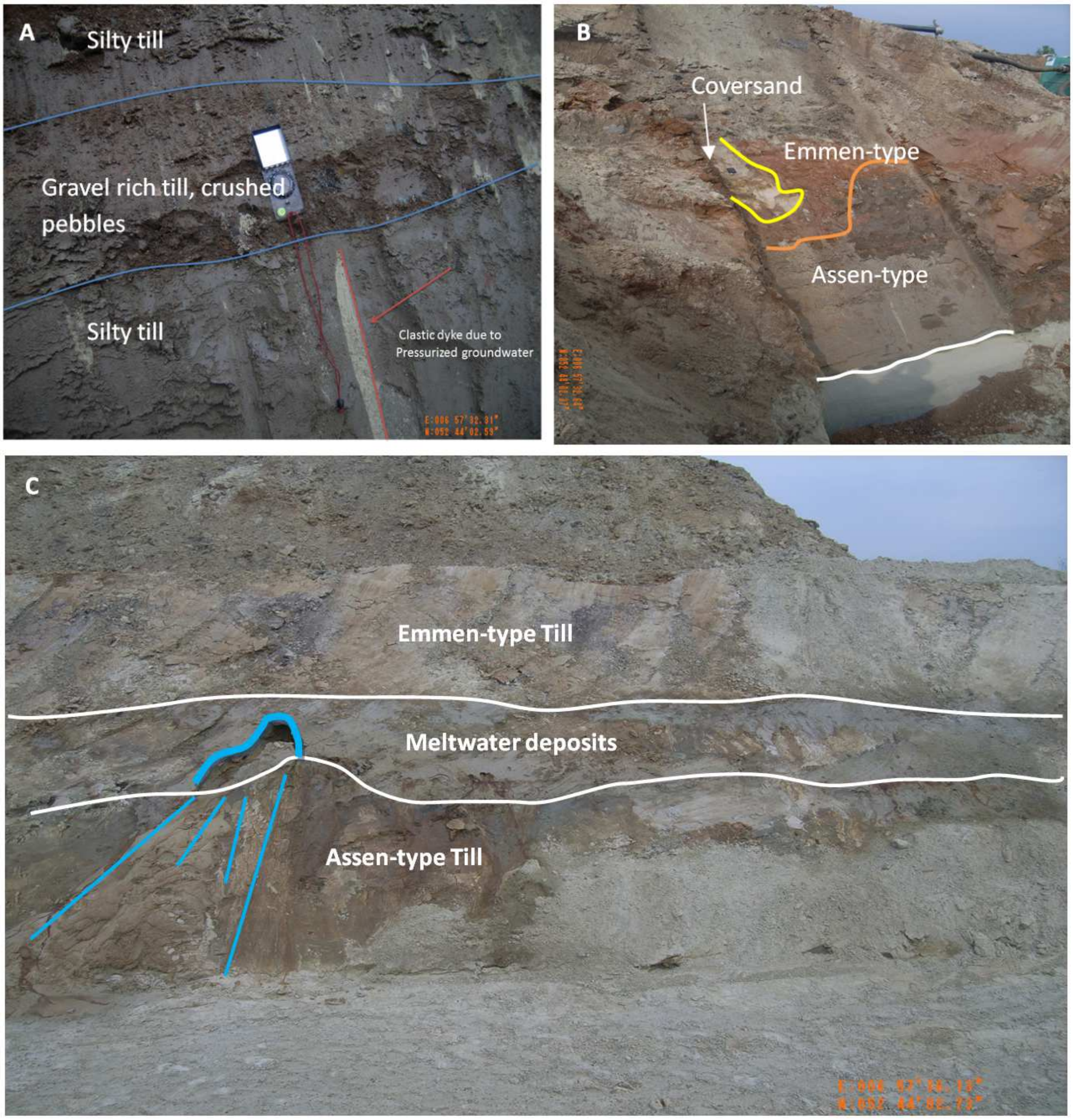


Figure 4.19. A) Alternations of silt content of the till and a clastic dyke containing sand from the underlying sand body, B) Detail of the nature of the contact between Assen-type till and Emmen-type till, C) Sandy 'meltwater deposits' in between the Assen and Emmen-type tills. These layers are highly 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 Formation.

4.6.1 Structures

This outcrop is characterized by the sharp transition between the tills, between the underlying fine sand and between the undisturbed laminations of these latter sediments. The top of the purple till has an undulating surface and is 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 have flowed into the red tills at some locations. 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 do not appear to constitute clastic dykes.

4.6.2 Geological interpretation

The very fine light-grey sands could belong to the Peelo Formation, based on grain size, but the lack of micas is in general a clear indicator that they belong to another formation. They can therefore be interpreted as belonging to the Drachten Formation; in other words, 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) which shows that the Peelo Formation ceases south of Emmen.

Due to the occurrence of flint in the purple-grey till, it can be interpreted to be Assen-type till. The contact surface with the underlying strata is very sharp and crushed granites occur at this boundary. Moreover, the lower part of the grey till contains a high fraction of pulverized pebbles, indicating 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, as the lower 1 m of till has been homogenized (Figure 4.18). A sharp transition to underlying preglacial 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) suggests homogenization did not occur in this part. This would suggest a lodgement till or a subglacial melt-out till. However, in the case of the latter, this would reflect englacial stratification of debris, and since these sediments also contain completely crushed granites, it can only be a lodgement till.

The red tills do not contain flint and can be interpreted as Emmen-type till. Two types of contact surfaces were observed, one in which the Emmen-type till lies directly over Assen-type till, and one where a sandy layer separates the two tills. Where the Emmen-type till lies directly over the Assen-type till, the structures reflect that the former has flowed into the depressions in the latter, 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 also been observed elsewhere in the Hondsrug complex (such as Gieten), suggesting that such an event might have been time-transgressive.

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

A 30 cm thick sequence of peat lies on top of the yellow sand. It is the remnant of a much thicker peat sequence that developed during the Holocene period 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) facilitated wet conditions that favour peat formation.

Southeast of Nieuw Schoonebeek the till dips in the former valley of the Vecht and the Itterbeck Basin and is just like in Groningen more than 7 m thick which make clear that tillthickness on the Hondsrug has a high variability. Locally the tills are thicker or absent. In general the tills are 3–4 m thick on Hondsrug.

5. Glaciological interpretation

In this chapter, of each of the studied locations (Figure 4.1) we will describe at first the the glaciological interpretation (Sections 5.1 to 5.6). We relate the situation at the location to the classification of glaciological processes occurring under a flowing ice stream using Jørgensen and Piotrowski's system (2003), which distinguishes subglacial processes A to F (as shown in Figure 3.3). In Chapter 5.7 we zoom in on the relation between glaciological interpretations and 'deeper'geology. In Chapter 5.8 finally we summarize and integrate results of geological and glaciological interpretations.

5.1 Location 1: Donderen

The remnants of glacial tills at Donderen reflect a high basal water pressure which could 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 suggest the presence of till deposition in a previous stage when basal water pressure was somewhat lower (subglacial process A). An increase in basal water pressure has occurred through time in this region. A number of mechanisms can be described which would result in such an increase.

The permeability of the aquifer underneath the ice stream was low, since it was made up of fine sands and clays of the Peelo Formation. Therefore, basal water pressure could increase readily, as the aquifer was quickly saturated with water (see Section 3.1). In addition, the occurrence of salt diapirs downstream from this location (Anloo, Gasselte, Drouwen) meant the presence of a subtopographic obstacle to the ice stream movement, leading to compressional forces. The formation of brinewater impeded groundwater from freezing near the surface, which could also facilitate an increase in basal water pressure in the area from 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 (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

In contrast to the area of Donderen, the stratigraphy of the area around Gieten at *the most eastern branch of the Hondsrug ridge*, 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 great that the basal debris is deposited as a lodgement till. The Noordhorn till at the bottom of the outcrop can be considered a lodgement till, since it makes up the ground moraine deposit. Till deposition occurs when effective pressure is relatively high, and thus when basal water pressure is low as Jørgensen and Piotrowski's (2003) model suggests (subglacial process A). 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 form tills of the Emmen type above tills of the Assen type (as is observed in Klazienaveen, Section 4.6). The occurrence of other sediment in between the tills, suggests that another stage of glacial scour occurred. The occurrence of preglacial sediments and Voorst-type till in the complex suggests that the ice stream scraped off sediments from the bed upstream (perhaps from north of Drenthe, Donderen, Section 4.1) and transported it towards Gieten, where it was mixed with and deposited in the previously scoured depressions. This phase was succeeded by deposition of 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 period 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 rapid covering of freshly scraped surfaces by new deposits.

Erosion of the older tills and preglacial sediments occurred in one of the first phases, as Noordhorn till lies directly on the preglacial sediments. Deformation of the preglacial sediments is inherited from previous glaciations, since it dips towards the northeast. Effective pressures must have risen to levels at which deposition of lodgement till (Noordhorn type, Assen group) could occur 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 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 Eemien and in the Weichselian but we observed no paleaosoils. Probably by deflation in the Weichselian.

Hydraulic piping also occurred at this location (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 greater than the pressure at the top of the till. This led to hydrofracturing of the till and the injection of preglacial sediment upwards. Other indicators of insufficient drainage are the formation of subglacial meltwater channels (Figure 4.8E) in the Peelo Formation and ductile deformation structures in the preglacial sand, which indicate high pore-water pressures.

Drag structures in the preglacial sand at *the most western branch of the Hondsrug ridge* indicate that the ice stream was coupled to its bed and large shear strains were applied to it. This also led to erosion, since the contact surface of the Assen-type till and the preglacial sediment is very sharp. As the effective pressure reached levels where till deposition was favoured, Noordhorn-type till was deposited as lodgement till (decalcification at a later stage 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 the 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.

While Emmen-type till does occur on the west branch, it is only found in isolated patches on the highest points of the Hondsrug. It could be argued that erosion led to the absence of these tills, which are still found on the east branch (sediment complex, Emmen type). However, the erosion of such thick sequences, including the boulder-rich Emmen till, would at least leave a trace of a boulder pavement on top of the Assen till type, but this is not observed at this location. The suggestion of local non-deposition of Emmen till 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 Emmen till (this till contained the largest boulder concentrations) did indeed appear in a more downstream direction.

Due to the occurrence of thick (impermeable) till sequences, basal water pressures might have risen to levels where erosion became the most important process (subglacial process C). 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 little to the 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. This explains why these so called ice-contact marginal ridges (Bennet and 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 to the calcareous Voorst type.

The main difference of the most western branch of the Hondsrug ridge with the most eastern one 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 also be explained partly by the absence of Emmen-type till, because rainwater may have been able to infiltrate into the till. The occurrence of a thick peat sequences (3 m thick) a few metres south of this location may also have helped decalcification 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 also be explained by the occurrence of this peat sequence, as it consumes all the oxygen from the water. Related to till observations in the Emmen area the Gieten tills indicate weathering; whereas the lower tills in the Emmen area indicate by higher kaolinite content that they are formed in a not by weathering influenced closed system in a uninfluenced closed sytem kaolinitization continues (e.g. Nguyen, et al. 2008). Because of this the tills of the Emmen area are very suitable to study till formation conditions (Bregman and Lüse, in prep.).

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 water pressures (P_w).

5.3 Location 3: Gasselte

Till deposition must have occurred in an early phase (subglacial process 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 at which major erosion took place (subglacial process C). The deposited till suffered high rates of meltwater erosion, which transported the fine fraction away leaving behind the coarse-grained sediments. These sediments could drain the meltwater more efficiently, 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 some part of the Emmen-type till was deposited. In this case, it is possible that the Gasselte outcrop is part of a subglacial drainage system, flowing in a NNE-WSW direction (e.g. perpendicular to the ice stream direction), whose channel infillings are also found in the sandpits west of the outcrop in the Gasselterveld. This explanation assumes very high basal water pressure and transport of meltwater from the east.

5.4 Location 4: Borger

Till deposition occurred during times of low basal water pressure (subglacial process A; e.g. Van der Meer, 2003). Increasing basal water pressure led to a change in ice stream behaviour between subglacial process A and subglacial process C (from deposition to erosion). The grey tills of the Assen type were completely eroded away. This could have happened in one event, or as a result of multiple processes through time. While no remnants of the till were found at the location of the outcrop, further downstream large accumulations of glacial rubble were observed, which might constitute the former till. The ice stream may have reached flotation point several times, deformation was the predominant mechanism. This is reflected in the ductile deformation of the preglacial sediments, which were 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 indicate a partly frozen glacier bed. This also contributed to higher deformation of the glacier sole.

GPR measurement in transects from Buinen to Drouwen and from Drouwen to Borger (Figure 4.15, Appendix B/C) showed that the preglacial sediments towards the northeast (perpendicular to the ice stream direction) still dip to *c*. 12–18 m deep, indicating an older glaciation phase, with relatively shallow deformation by the Hondsrug-Hümmling ice stream at the top of the sequence. Cryoturbation during the last glacial phase could also have altered the structures.

5.5 Location 5: GPR measurements at Valthe/Odoorn

Till deposition has occurred at the location of Valthe/Odoorn, evidenced by the occurrence of tough lodgement till. From the GPR measurements it became clear that the preglacial surface has not suffered (glaciotectonic) deformation from the ice stream, as the preglacial sediments still dip towards the northeast (subglacial process A). This conforms with the GPR measurements in the transects near Drouwen, which indicate an older glaciation phase and relatively shallow deformation of the Hondsrug-Hümmling ice stream. This might indicate that basal water pressures were high at both locations most of the 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 by 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 appears to be rather unevenly distributed, which could be the result of subglacial erosion of the till by the pressurized water layer.

5.6 Location 6: Klazienaveen

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

Erosion takes place during times of high basal water pressures (subglacial process C), and the underlying fine-grained aquifer could readily facilitate this. Basal water pressure must have dropped towards that associated with subglacial process A, during which the ice stream deposited the lower part of the grey till. During a period of low basal water pressure, interaction between the glacier and its bed homogenized the till. Deposition of the grey till continued, but changed to lodgement rather than deformation till, as is reflected in 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 response to this event indicates that basal meltwater could be sufficiently drained 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 indicates a small decrease in meltwater discharge.

5.7 Geology *and* glaciology

In this section we will link 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 overlie the salt were lifted by halokinese, which creates an obstacle to ice flow. This led to compressional forces (Figure 3.4) that resulted in erosion of the Urk, Enschede and Harderwijk Formations. Large glacial channels which possibly originated from the Elsterian glaciation as subsurface drainage channels can be seen in the area of Donderen up to a depth of 120 m, the infill of which belongs to the Peelo Formation, containing fine sands and clays. In this area Elsterian deposits are surfacing (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 and Lüse, in prep.) and correspond to an older phase (pre-dating the Hondsrug ice stream). In Donderen and near Zeijen the tills are heavily 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 C), since this is not reflected in the sediments. This may be due its location downstream of the Anloo salt diapir (Figure 6.4). Delisle *et al.* (2007) found 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 the 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. However, we observed many features related to drainage of subglacial meltwater, and strong deformation between the west and the east branches (Section 5.2). The absence of Emmen till at this location may be related to the divergence of a more westerly ice flow from the Assen type. Divergence of ice flow may be related to the deeper subsurface.

South of Assen, we find a deep tectonic basin (Figure 6.4), which is still present around Geelbroek and Eleveld as an area lower than the surroundings (Figure 4.1). We suggest that the differential lowering of the area may be related to a loading of the salt ridge near Hooghalen during ice coverage, creating postglacial vertical compensational movements. In the postglacial period

(Figure 6.4.; see also Chapter 7) differential rebound formed the actual river pattern of the Drentsche Aa river in this area. This means that a local lowering of the area may be due to differential resistance of the crust to loading, which might have had an influence on the behaviour of the ice flow. As we will argue in Section 6.3, it is in fact the same kind of interaction that we propose for the ice stream south of Emmen, where the ice stream dipped into 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 Gasselte outcrop is situated close to and upstream of the Gasselte diapir. In this region, elevated geothermal fluxes can be expected, which result in a higher basal melting rate. In addition, the diapir is a subtopographic obstacle which will force groundwater upwards. The ice stream may have experienced an increased normal force since it had to overcome the obstacle, which could elevate basal water pressure further. These factors may have readily provoked an increase in already high basal water pressure, which led to the erosion of the tills.

5.7.4 Location 4: Borger

The Borger outcrop is located just downstream from the diapir, where geothermal fluxes were still anomalously higher than the surroundings. This might have facilitated higher basal melting rates and higher basal water pressures, which are reflected in the sedimentary record south of Borger near the present roundabout. In the area near the bridge (Koesteeg), deformation is very strong. Present GPR measurements at the location east of Borger show no deformation of older deformational structures with a NE-SW direction, which indicates 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: 12 W; 12O; 17O; 18W; 22O; 22W). We suggest that these stony soils are stone-rich Emmen-type till washed out by meltwater, which explains the accumulation of these erratics near the surface.

5.7.5 Location 6: 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 and Klazienaveen is around 1 km; South Permian Basin Atlas of northwestern Europe). We suggest that this strongly influenced the behaviour of the Hondsrug-Hümmling ice stream as will be explained in Section 6.3, and which is one reason why this ice stream dropped very thick amounts of till near Schoonebeek (on the transient zone to 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 when further away from salt diapirs and that permafrost would occur to a greater depth or form more easily. On this basis, we reason that deformation by the ice stream did not occur in this area because the permafrost created: 1) stiff rhyolite and 2) an impermeable layer, so that the flotation point was easily reached. This is in contrast to the situation in the northern part of the Hondsrug area, where melt was much higher due to the occurrence of salt diapirs.

In the southern part of the Hondsrug area, Bregman and Lüse (in prep.) found newly formed minerals (Section 3.7), which indicates the influence of brine or saline groundwater. This not only proves the presence of ascending groundwater with a reversed flow direction from NNW to SSE, but also the position of the brine/salt source, which may be in deeper marine deposits (Breda Formation) or from groundwater in areas with salt diapirs. The latter source is considered more likely because no newly formed minerals were found in tills outside the Hondsrug area or in the area between Borger and Schoonebeek (Bregman and Lüse, in prep.).

One of the main conclusions that can now be drawn from our geological and glaciological interpretations of the locations studied (see also Chapter 6) is that deeper geological structures have had a strong impact on the behaviour of the Drenthian section of the Hondsrug-Hümmling ice stream. We have shown that in order to better understand the genesis of the Hondsrug ridges, as well as the positioning and dynamics of the Hondsrug-Hümmling ice stream, the role of deeper geology should be taken into account.

5.8 Summary

An overview of observations is presented in Tabel 3.

	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

Table 3. Overview of main glacial processes and features of 7 locations in the Hondsrug area.

The interpretation of subglacial processes is presented in Figure 5.1., which leads to the following description of coherent processes:

● In the area of Donderen, large-scale erosion took place after till deposition had occurred, as is reflected by washed-out sediments. In Gieten, the two branches of the Hondsrug have completely different features but have two things in common: 1) both branches do show deformation of the preglacial sediments in the same direction from the NE, the older phase pre-dating ice stream coverage, and 2) both branches show a lodgement till (interpreted to be of the Assen type) on top of the preglacial sand. The main difference is the occurrence of a large deformation till in between Assen and Emmen groups 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 as an explanation for these differences.

● Gasselte is characterized by large-scale erosion and Assen till does not occur at this location. It may never have been deposited, or has been eroded away completely, both possibilities indicate that basal water pressure exceeded that associated with subglacial process A and was likely to be in the region of C or above flotation point (Jørgensen and Piotrowski, 2003). The thrust sheet's orientation in the coarse-grained sand, dipping towards the northeast, suggests that an older phase of glaciation was preserved. With respect to thrusts preserved in coarse sand that has been overridden by an ice stream which moved almost perpendicularly to its orientation, it is difficult to conclude otherwise than that the sand was frozen solid. High basal pressures led to minor coupling between glacier and bed.

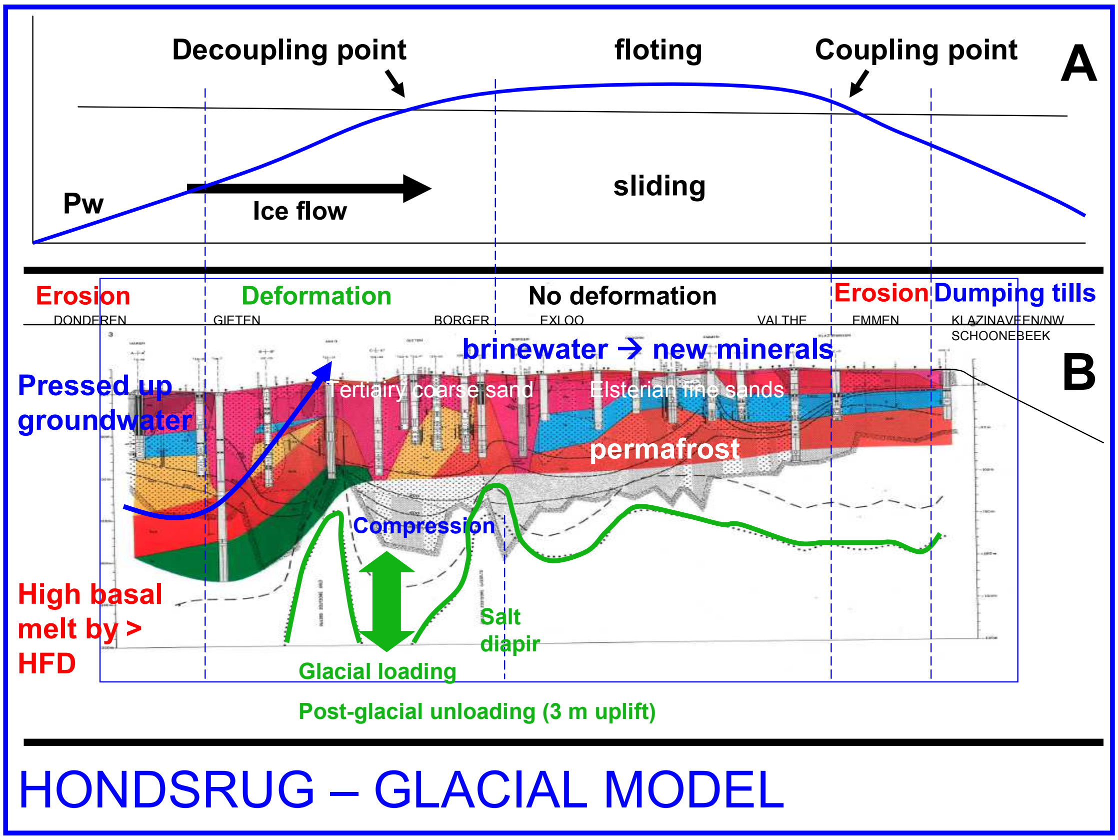


Figure 5.1. A) The theoretical correlation between water pressure (P_w) and time is given. With increasing P_w there will be a transition from no bed deformation, via erosion to deformation and above floting point to floting. B) The impact of increasing P_w and groundwater flow and glacial processes for the Hondsrug area is influenced by deeper geological structures (geothermal heat; salt diapirs), texture of the bed and permafrost. Legend of the geological profile in Figure 5.1B: see Appendix A.

● The stratigraphy in Borger does not contain Assen-type till, only fine preglacial sand and some Emmen-type till. Large-scale channels were observed, oriented perpendicularly to the ice stream direction in the preglacial sand, suggesting formation during the first phase of ice coverage (NE-SW). The channel infill has been eroded away by the ice stream, as a 7 m thick sequence of Emmen-type till was 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 preglacial sediments. The dip angle of these thrusts is NE, suggesting that the sediments were deformed during the older glaciation period from the NE. A striking feature of this region is the large variation in till thickness, from absent to 2 m thick. Two explanations can be given for this, both of which may be true: 1) subglacial till deposition is not homogenous; variations in preglacial 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 the till and left its remnant, 'keizand'.

● The outcrop at Klazienaveen showed no major deformation in the preglacial sediments over a great length. Laminations in the till reveal that the layers lay horizontally. This is in contrast to the study by Rappol (Figure 9, 1984), who found large-scale deformation in the preglacial sediment at Klazienaveen. It shows that although large-scale patterns may be observed, there may also be local differences that could alter interpretations of ice stream behaviour to such an extent that opposite conclusions may arise.

6. The role of 'deeper' geology in the behaviour of glaciers

Our focus in this chapter is to bring detailed analyses of parts of the Hondsrug area as we decribed in Chapter 4 and 5 into a discussion of the landscape on a more regional scale (Section 6.2), with the aim of understanding how this ice stream formed the Hondsrug landscape. We then focus on the initiation of the ice stream in the source region (Section 6.3) and place our detailed interpretation in a broader context. Chapter 7 examines an even larger scale, with our results placed in the context of marginal ice streams and ice sheet behaviour. It is at this level that we will present a new glaciation model of the Hondsrug-Hümmling ice stream.

6.1 Introduction

The behaviour 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.

Some previous glaciological studies (e.g. Rappol, 1987; Van den Berg and Beets, 1987) reconstructed the formation of the Saalian glacial deposits and morphology in the Netherlands on the basis of single datasets, such as lithology and clast orientation. In more recent studies, which will be referred to in the following sections of this chapter, the positioning of ice streams and glacial behaviour were linked to deeper geological features (subtopographic obstacles) and processes (geothermal anomalies) that may have played an important role at different times and on various spatial scales.

With regard to ice flow, it is in glaciology common to assume that ice flows follow some most favourable path (Winsborrow *et al.,* 2010). It is either the shallow subsurface alone, or the combination of it with deeper geology that determined what flow path were favourable to paleo-ice streams. The positioning of marginal ice streams in tectonically weaker zones (graben systems) in the IML is evident in the Baltic, where ice streams flowed in the weaker zones of the Weichselian glacial system 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 our study the focus is on the Netherlands and northwestern Germany related to the Saalian glaciation. To understand impact of glaciations on landscape forming processes of the study area it is critical to study the relation between deep tectonics and glaciology in this area of subdued topographic expression, because it makes it easier to separate the classic tectonic-topographical from the deep geology hydrological, heat flow, glacio-isostasy factors.

6.1.1 Implications of forebulging in the Hondsrug area

In relation to previous studies of the Hondsrug, this chapter has a greater focus on the deeper geology that influences surface processes. Rather than shallow processes alone, also structures and processes inherited from the deeper geology to a certain extent can explain the spatial diversity we find along the Hondsrug paleao ice stream (variations in till thickness, deformation intensity, river patterns and fauna). To consider these links with deeper geology is relative new: earlier studies typically neglected the deeper substrate and only consider deposits in the shallow subsurface to have interacted with glacier ice stream movement occurred. The reasons to put emphasis on deeper geology are summarized below:

- Previous studies by Zonneveld (1964) and Ter Wee (1979) noted that the Hondsrug ridges are aligned with deeper fault systems but the tools were not available at the time (Ground Penetrating Radar, model simulations, GIS) to further investigate this possible relationship. As we now have these tools and more studies have focused on the relationship between deeper geology and surface processes, we are able to investigate this alignment further.
- More studies have now related the movement of the upper crust to forebulge (uplift and collapse) and ice loading, and the dynamic interaction with such glacial movements.

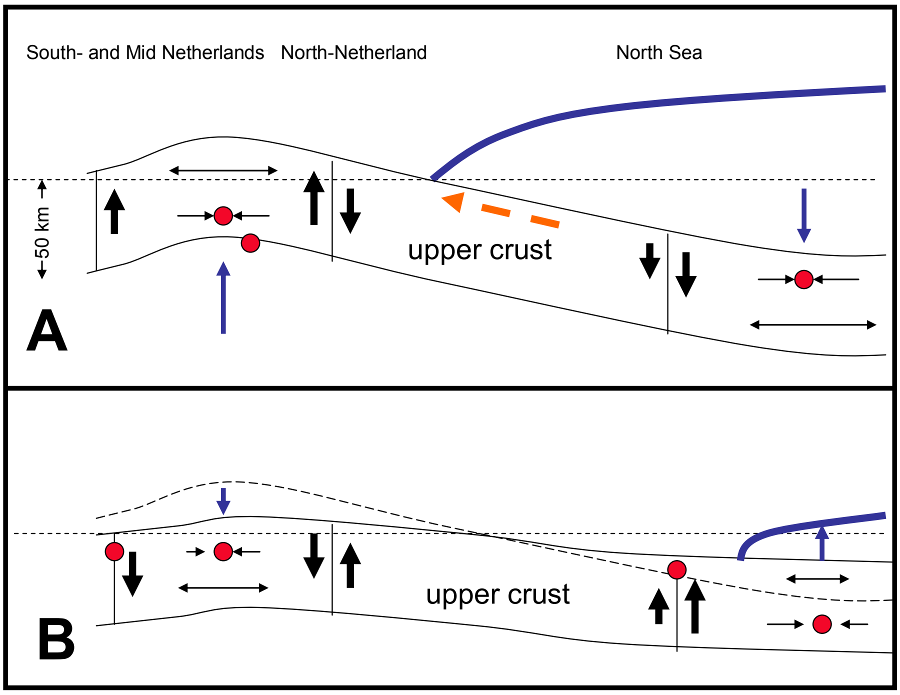


Figure 6.1. Glacio-isostatic impact of (A) advance and (B) retreat of an ice sheet on the upper earth's crust in the Netherlands (Late Pleistocene/Early Holocene). Blue arrows indicate loading (A) and unloading (B). Thin black arrows indicate crust movements which lead to differential tectonic movements, the opening of faults or compaction with possible earthquakes (red bullets). Note that the figure is not on scale. For explanation see text.

Figures 6.1 present schematic the positioning of the northern Netherlands almost on top of the Weichselian forebulge (see also Figure 1.3). The literature differs as to the positioning of the top (and area with maximum collapse), which remains a point of discussion (cf. Lambeck *et al.,* 1996; Kiden *et al*., 2002; Busschers *et al.*, 2007), but as we concluded in Chapter 1 the top of the Saalian forebulge was positioned in the middle or near the south of Drenthe. This means that in the northern Netherlands (and thus in Drenthe) maximum effective vertical stress and horizontal stress (Thorson, 2000) could have influenced deeper geological structures, while horizontal stress may have had an effect at the surface and upper part of the earth's crust in terms of crustal movement of the top of the forebulge, which could be up to a metre per year (Thorson, 2000). This explains why in the Netherlands we observed processes triggered by loading and unloading, such as extensional and compressional stress (Figure 6.1, 6.2; Houtgast, 2003), the reactivation of faults and block displacements (e.g. Cohen, 2003; Cohen *et al.*, 2009), the distribution and redistribution of heat and heat transport along fault zones (e.g. Wang, 1965), and earthquakes triggered by unloading (e.g.

Houtgast, 2003; Houtgast *et al.,* 2005), as occurs occasionally in areas with retreating ice sheets (Mörner, 2004).

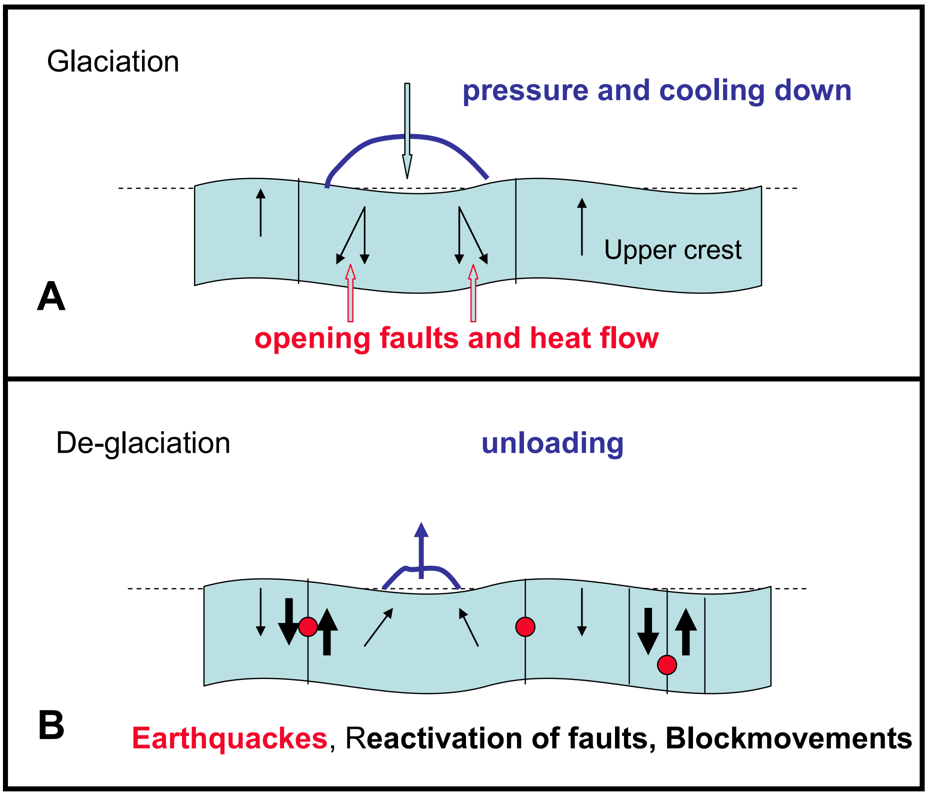


Figure 6.2. Glacio-isostatic impact of (A) loading and (B) unloading of an ice stream on the upper earth's crust related to glaciation and de-glaciation respectively. Note that the figure is not on scale. (Source: James, 1998, modified).

Glacially induced tectonic reactions are caused by unloading at the proximal and distal side of the forebulge. In the Netherlands, studies by Houtgast (2003) and Cohen (2003) indicated the impact of rebound on deeper geology and geomorphology on the distal side of the forebulge. Glacial unloading created additional extensional stresses, which were superimposed on the far-field regional stresses, indicated by increased fault activity in the Roer Valley Graben, occurring in the initial phase of unloading, around 10–15 ka (Houtgast, 2003; Cohen *et al.*, 2002; Cohen *et al.*, 2009). This demonstrates that the fluvial dynamics of the Rhine and Meuse rivers correlates with the structural lowering of the North Sea Basin and neo-tectonic movements, as well as being influenced by late Pleistocene loading and unloading due to the advance or retreat of ice sheets. Two studies nearby on the distal side of the forebulge demonstrate postglacially 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 studied in cooperation with TNO seven locations in Drenthe (amongst them two in the Hondsrug area) the correlation between till base and underlaying faults and position of saltdomes (Figure 6.3.). At five locations the slope of topography and till base are the same indicating no postglacial uplift or lowering above the faults or saltdomes on contrary to two locations in the At two locations on the Hondsrug area. Above the saltridge of Hooghalen and the saltdome at Gasselte (Borger) we observed uplift of the till base and in the area of the valley of the Sleenerstroom above a major faultsystem a lowering (in both cases with a mean displacement of 2 meter). In the area of

Hoohalen – Gasselte the surface level is much higher then the sourroundings, the fact that we found terraces above saltdomes and shift of watershed (van Kammen *et al*., 2010) and makes clear that differential postglacial rebound i.c. updoming of the saltridge an saltdome occurred after the Saalian glaciation. We cannot explain the lowering of the valley of the Sleenstroom very well, because of leacking evidence. Lowering of the till base in this area could be the result of glacial erosion, but also be the results of (local) postglacial displacement. Anyway it is remarkable all locations with displacment are situated at the Hondsrug area, which indicate a connection with the impact of the Hondsrug-Hümmling ice stream.

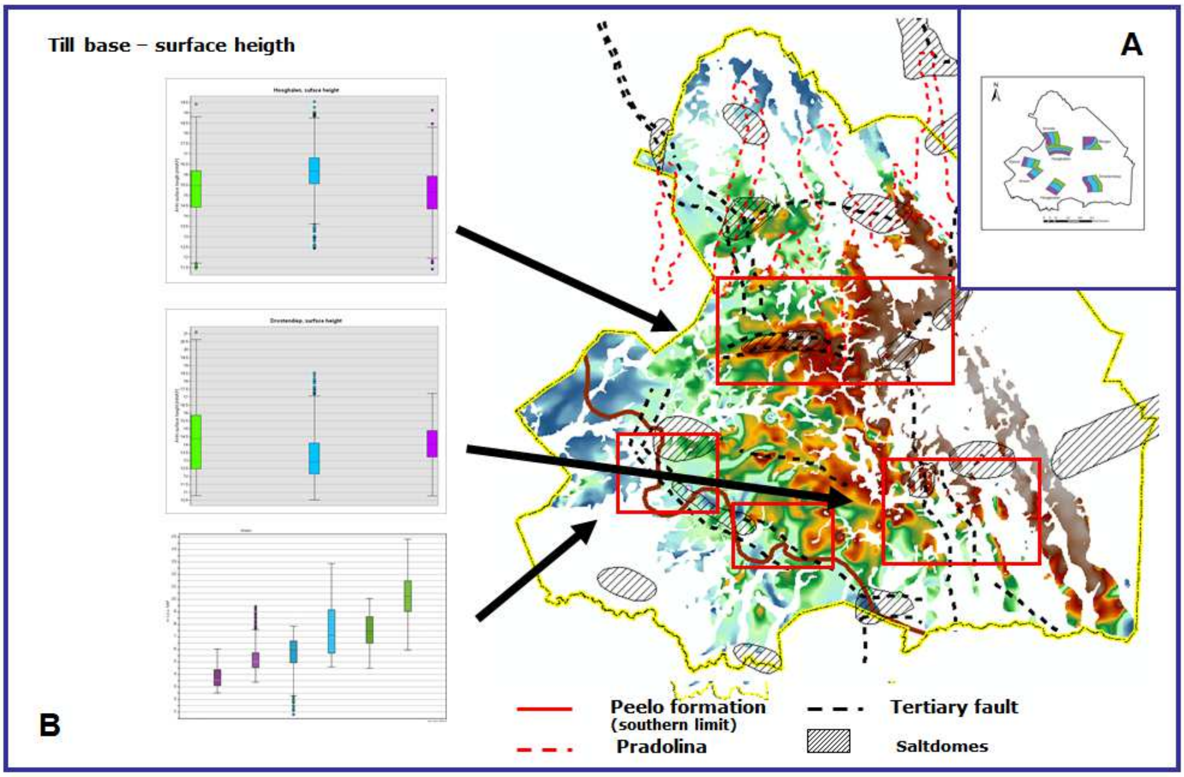


Figure 6.3. Correlation between Saalian till base, Tertiary faults and saltdomes. A)Overview studies seven lacations. B) The height of the till base (in mBGL) is related to surface level in box-whisker diagrams (e.g. Hunter 2008). Profiles are from higher (green part in diagrams, Hunt 2008) to lower part (pink in diagrams) of the relief. Central part (in blue in diagrams) is above fault zones and or saltdomes. The upper diagram is Borger; the middle the Sleenerstroom area and the lowest diagram is near Ansen and similar to other locations.

A convincing proof of postglacial rebound in the Hondrug area is in Figure 6.5 with the strong correlation of thickness of Permian Zechstein, faults at the Permian base and the pattern of the Holocene riverpattern. It is logic that the pattern of brookvalley systems in the mosteastern part of Drenthe connects with the Hondsrug ridges, but details of curves of these drainage sytems connects strongly with the deeper faultsystems of the Permian base, indicating postglacial rebound. In the Hondsrug area this correlation is very strong and ice stream induced reactivated faultszones are to relate with locations of seepage areas (e.g. Magri, 2011). Forbulging in the phases 1 and for sure 2 and 3 (Figure 1.8.) with character of an ice sheet had strong impact on loading (and so on unloading) because of high mass weight of the ice on the study area, whereas the impact of the Hondsrug-Hümmling ice stream was minor.

6.1.2 Surface morphology and deeper geological structures in the Netherlands

The Saalian glaciation over the Netherlands produced several glacial limit lines, e.g. the overridden line depicted as Phase 2 (Figure 1.8.) and the maximum limit of phase 3. The lines do coincide with deeper geological tectonic structures, e.g. the Texel-IJsselmeer -structure and the Peel Horst/Maasbommel High– structure (Figure 6.4.). This could also go for earlier overridden ice limits in the Northeastern Netherlands and adjacent Northernmost Germany. The landscape at Drenthe was a continuation of the northwestern German landscape and sediment deformation in the province of Groningen was probably caused by the stagnation of the ice due to a subtopographic obstacle: the Groningen High. With this new insight we suggest that the deformation of locations in Groningen near Slochteren, Noordbroek and Alteveer near Pekela (overridden push moraines) is linked with the position of the deep deformation of the Groningen High before the Rehburg-line.

To the southeast, the Rehburg limit in adjacent Germany (Phase 2 in Figure 1.8.) also coincides with deep geological structures. In that southeastern area, the tectonics have topgraphical expression in the form of bedrock ridges separating Quaternary and Tertiary depocentres. In the rest of the study area the topographic expression of deep tectonics is much more subdued, but the structures are strong in the basin fill architectures. In this case it is in the Dutch situation remarkable that the glacial basins related to the maximum extension of the ice advance in the Netherlands are all positioned in the Central Netherlands Basin and that push moraines were formed in line with the Kijkduin High (Table 4; Wong *et al.*, 2007). In general, tectonic highs and lows link to glacial still stand and acceleration features respectively (see Figure 1.3). On top of tectonic highs, sequences are more condensed and relative more consolidated at shallower depth than in the infills of surrounding tectonic lows, and might provide subsurface obstacles for an advancing glacier.

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

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

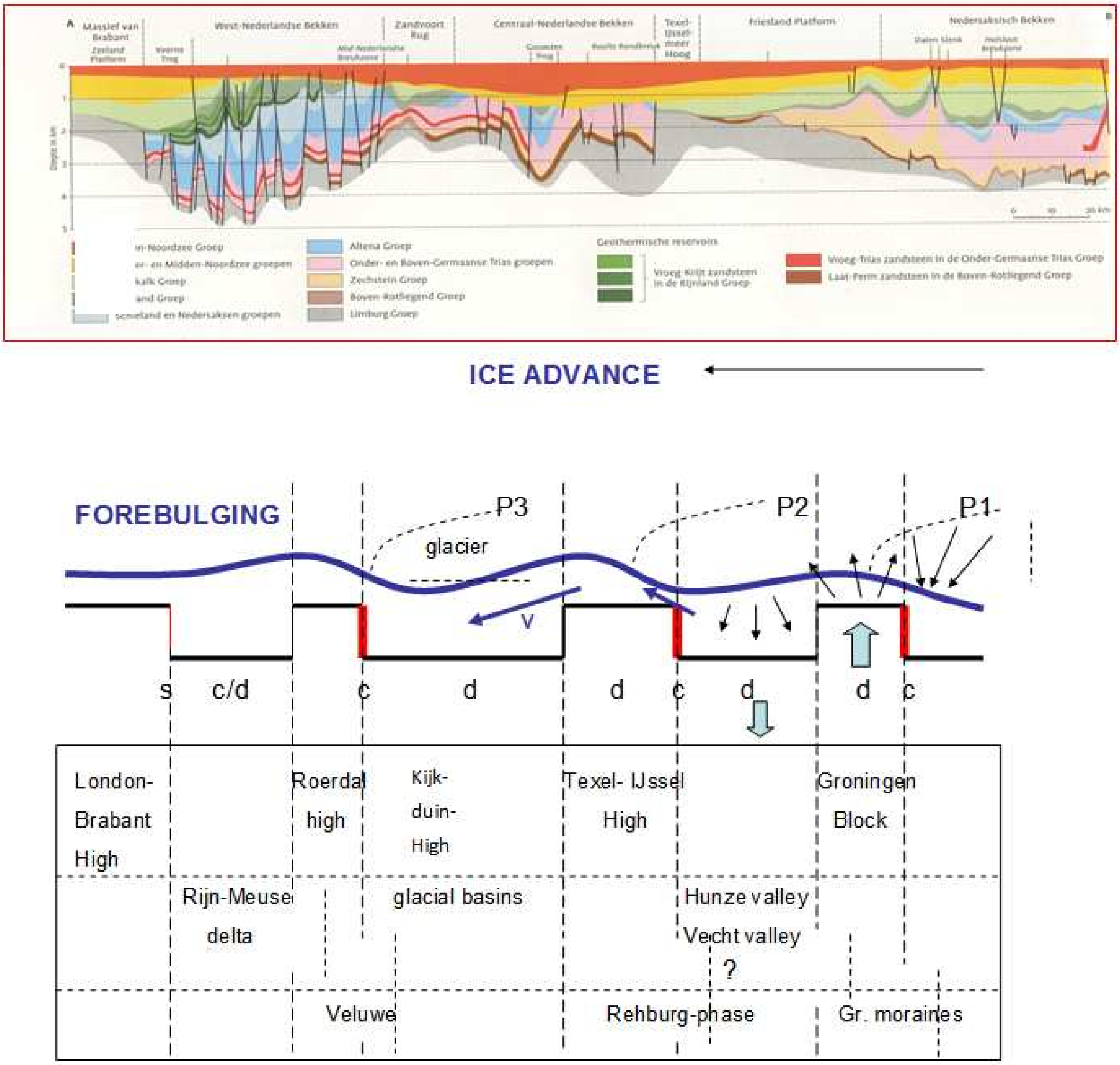


Figure 6.4. Ice sheet advance and behaviour in a schematic cross-section from the NW to the SW part of the Netherlands at different Saalian MIS-6 phases (P1 to 3) are related to structural features of deep geology (highs and lows in the Netherlands) (cross-section **A; TNO**) and glacial morphology. Black arrows indicate compression c) and stagnation (short blue arrow) and decompression (d) and sliding (large blue arrow). Note that the the schemes about forbulging and morphology are not on scale.

6.1.3. Geothermal heat fluxes

Open fault systems or spots with higher heat flow densities (HFD) release anomalously high geothermal fluxes, which can increase the basal melting rate of the ice. Ice streams may be ‘pulled towards’ these favourable pathways, as sliding will be facilitated by these higher geothermal fluxes. Salt diapirs formed partly along these faults as well, and due to the higher heat conductivity of rock salt compared to surrounding unconsolidated sediments they also create higher geothermal gradients. Thus, in addition to the faults, the occurrence of salt diapirs can also create higher geothermal heat fluxes, thereby providing a favourable pathway for glacier flow. Several salt diapirs occur at shallow depths in the subsurface (Figure 6.5) of Drenthe, such as those at Anloo (350 mBGL [metres below ground level]), Gasselte (200 mBGL) and Schoonlo (120 mBGL).

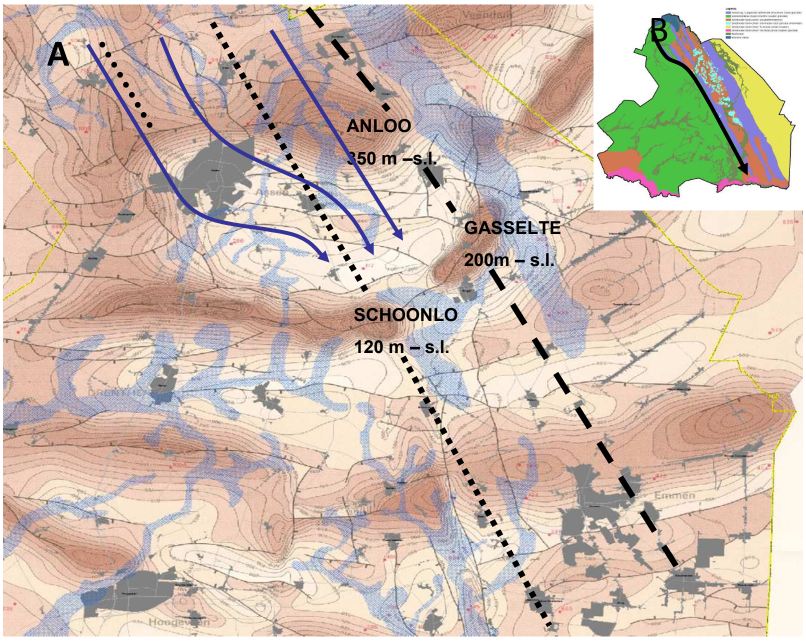


Figure 6.5. Thickness of the Zechstein Formation (rock salt) with salt diapirs and ridges in Drenthe (red-brown colour) and position of main near-surfacing diapirs with depth in metres below ground level (mBGL). In blue, modern brook-valleys. The black dashed line is the Hondsrug ridge; the black square dotted line the Sleener, Rolder and Zeijer ridges; the black dotted line, the Norger ridge. Thin black lines indicate faults, including tectonic block structures. The blue arrows indicate ice stream direction, based on morphology, as in Figure 6.1 B. The ice stream has its most western limit near Norg.

The thermal conductivity of rock salt is 1.6 times greater than the surrounding unconsolidated sand (e.g. Durham, 1979). This means that there will be higher soil temperatures both in the deeper subsurface and near the surface, with the salt diapirs and ridges forming hotspots. These will have a different impact on overlaid formations by introducing different heat conductivity rates. In addition, heat transport also occurs by groundwater displacement and will occur more easily near fractures. Under such conditions, it is to be expected that heat exchange with shallower formations will occur more often if there are open faults. The following three examples show higher soil temperatures near the surface in areas with salt diapirs.

Firstly, subsurface temperatures were measured in the province of Friesland at 100, 150 and 200 m deep (Iwaco, 1998; Figure 6.6.). At 100–150 m the temperatures were 2–2.5˚C higher than the surroundings, caused by heat emission from the salt dome near Pieterburen. Secondly, the delineation of shallow salt diapirs and surface faults using temperature measurements at a depth of approximately 2 m in Groningen (Poley and Van Steveninck, 1970) clearly indicates several temperature anomalies, with differential temperatures of about 1˚C showing excellent correlation with a thermal contour map and seismic and well data. Thirdly, Piotrowski (2007) also demonstrated a positive correlation between soil temperatures (2 mBGL) and the position of salt diapirs in northwestern Poland.

Delisle *et al.* (2007) modelled the implications of heat transport through sediments and along faults in the subsurface in northwestern Germany, concluding that a larger quantity of heat can be transported to the surface where salt diapirs occur due to their higher heat conductivity, which can significantly impede permafrost formation (Delisle *et al*., 2007). In between such regions, anomalous low heat fluxes occur and can aid permafrost formation or its deeper penetration (Delisle *et al.*, 2007).

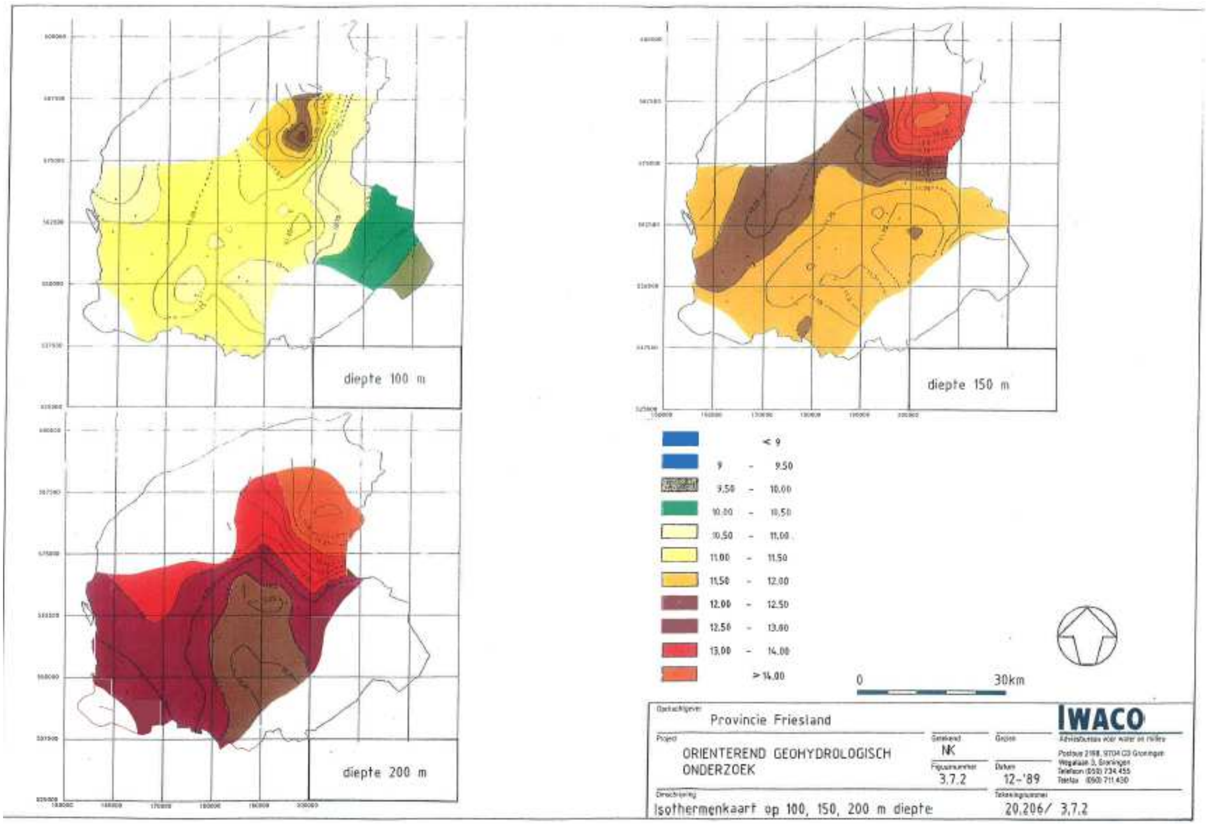


Figure 6.6. Isotherms at 100, 150 and 200 mBGL in the Province of Friesland (Iwaco, 1989)

Deep subsurface temperature and heat flow density are independent of glacial processes, or might be slightly influenced by crustal loading through forebulging. This crustal movement is a reflection of vertical, horizontal and 3D adaptations of the lithosphere caused by redistribution of magma and the lithosphere itself (e.g. Lund, 2005; Thorson, 2000). We suggest that the present locations of heat sources are relatively stable, with more or less the same position despite any loading by ice streams.

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

6.1.4. Deep temperatures versus gravity

In the Netherlands, close inspection of the temperature at a depth of 2000 m (Figure 6.8B) shows an increase in temperature in the North Sea and around the Lauwersmeer Trough. Figure 6.7 provides heat flow densities (HFD).

The position of the Texel-IJsselmeer High is notable (see also Figure 6.9A/B). The HFD 30 mW/m^{-2} isotherm in the centre of the North Sea Basin connects with the pattern related to the Hantum Graben and a part of the German Permian Basin near Itterbeck with an HFD > 40mW/m^{-2}(Figure 6.7) and low gravity(Figuyre 6.8), indicating a thinner earth's crust locally. It is also the area where we find a branch of the North Sea trough (Figure 6.10.A), with faults and salt diapirs (red circles in Figure 6.8 and Figure 6. 10B).

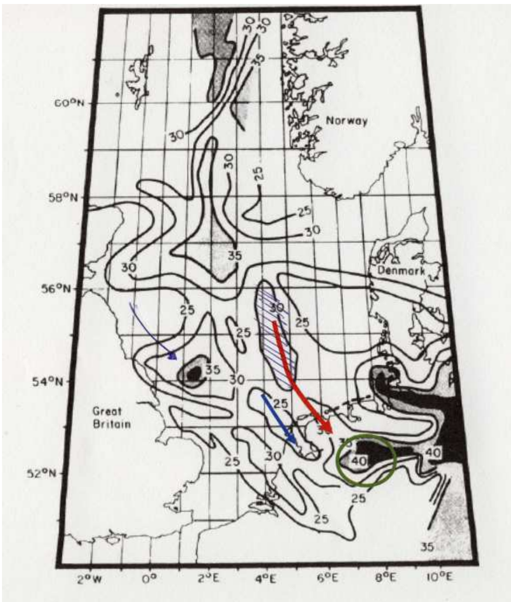


Figure 6.7. Heat flow densities (mW/m^{-2}) for the North Sea area, the Netherlands and NW Germany. The position of the Texel-IJsselmeer High is of note (see also Figure. 6.2B), blue arrow and in red the connection of > HFD. For paleaoclimate reconstruction, a colder climate reduces temperatures, according Jõeleht *et al*. (1996), at surface 10–15 mW/m^{-2} and 5–7 mW/m^{-2} at 150–150 mBGL. (Source: Rider, 2002)

The increase in HFD above the Wadden Islands, around the Lauwersmeer Trough with a connection to the Itterbeck region, as shown in Figure 6.9, is due to the combined presence of salt domes and thermal leakage of heat through faults (e.g. Stein, 1995).

When we project the position of the Hondsrug complex onto the maps of Figures 6.7, 6.9 and 6.10, striking comparisons can be seen. The pathway taken by the ice stream approximately follows the fault systems and highest salt thicknesses. Poley and Van Steveninck (1970) demonstrated in several cases that strong thermal anomalies indeed coincided with known deep faults; however, for shallow faults, a lack of subsurface detail prevented any unambiguous correlation with observed thermal anomalies. North of the Hondsrug, there is generally an anomalously high temperature (Figure 6.7), but warm and cold spots can also be observed that might have played a role in the amount of local meltwater production.

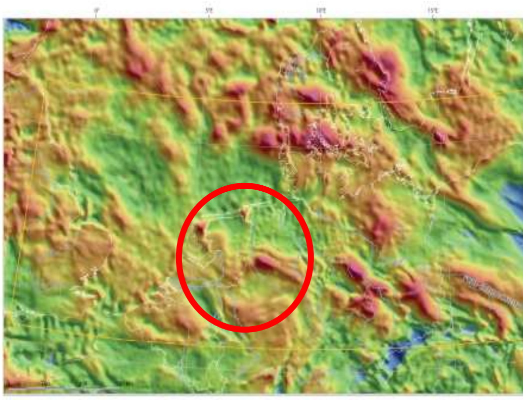


Figure 6.8. Gravity map of the Netherlands, NW Germany and the central part of the North Sea (Atlas SPB, 2011). High positive values as shown in red (mGal/s), indicate thick colder material, with low heat flow and low values in green (mGal/s), indicating lighter and hotter material (Wang, 1965; Figure 6.9AB). The red circle indicates the positioning of salt domes (Figure 6.10B), with low gravity due to specific mass weight and high HFD due to high conductivity of salt rock.

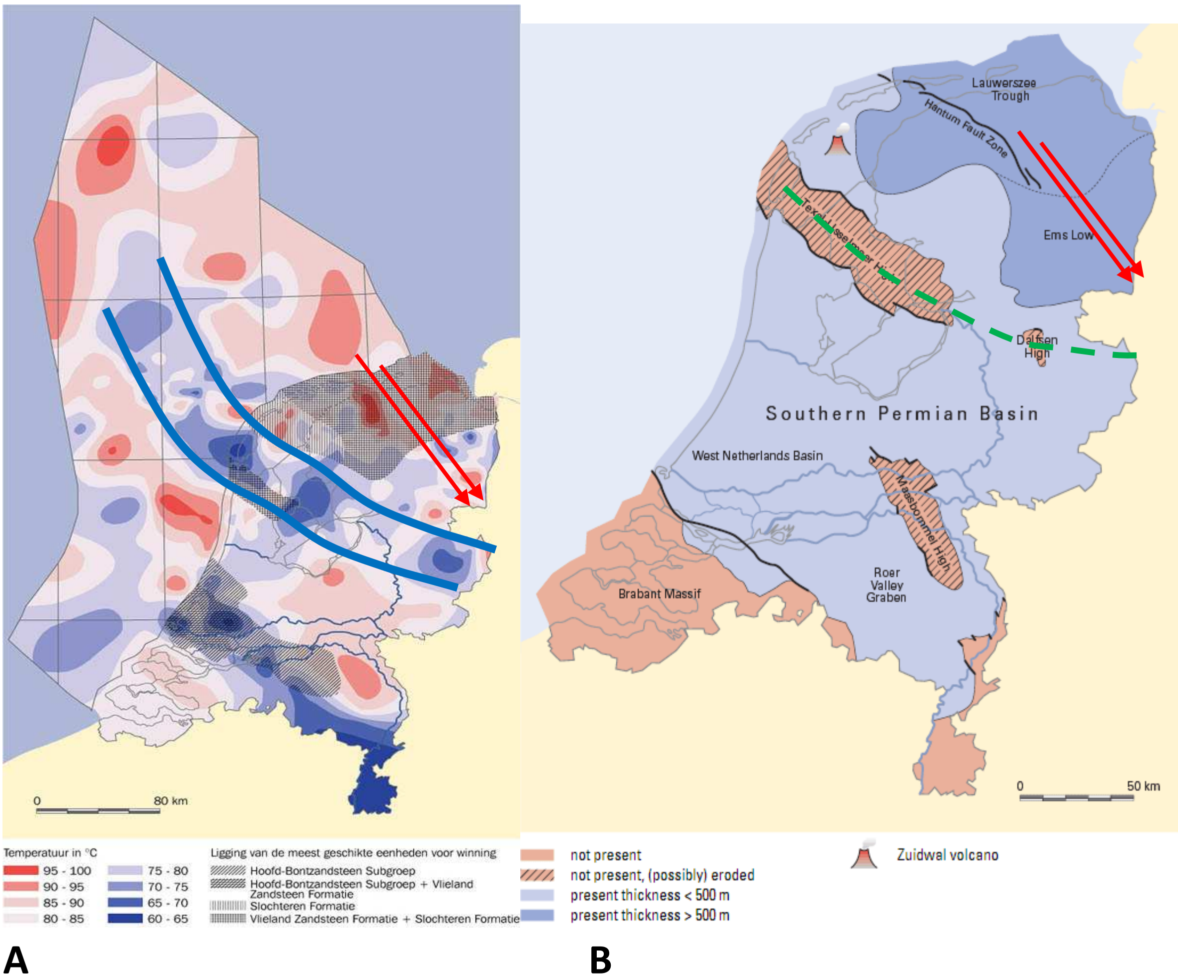


Figure 6.9. A) Map showing temperatures at 2000 m deep. Red arrows mark the Hondsrug ice stream movement. Blue lines represent minimum temperature zone, which coincides approximately with the Rehburg phase stagnation line. B) Structural highs and lows of the Permian Zechstein Formation. Green dashed lines mark Rehburg stagnation phase. Maps from Wang, 1995.

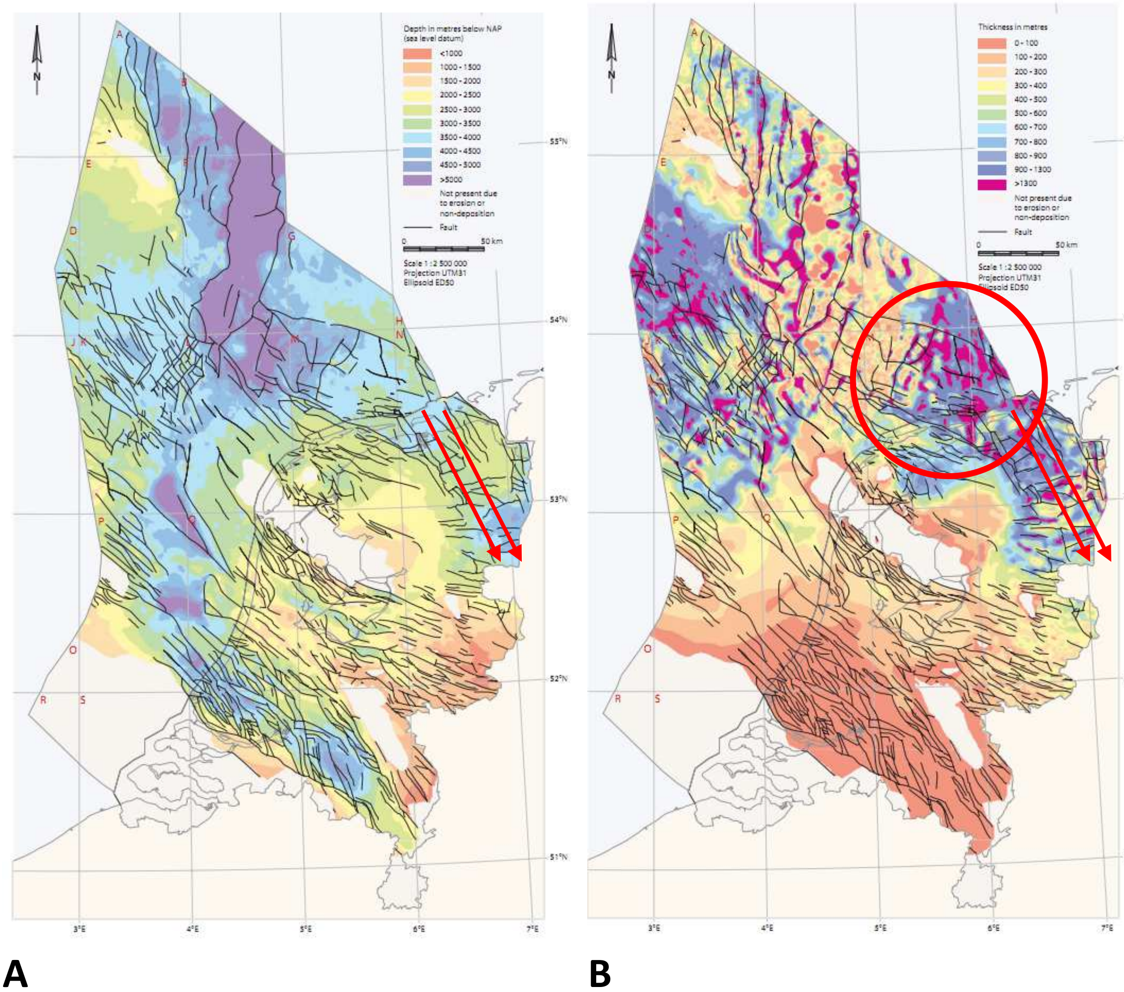


Figure 6.10. A) Depth of the base of the Zechstein Group (Late Permian) and B) Thickness of the Zechstein Group (Late Permian) with the salt diapirs in pink. Red arrows mark the position of the Hondsrug-Hümmling ice stream. Note the striking relationship between the position of faults and the maximum thickness of the Zechstein and Hondsrug-Hümmling ice stream orientation. (From: Duin *et al*., 2006)

6.1.5. Thickness of tills, 'deep'geology and sub-surface temperatures

To our observation (Chapter 4) the till pattern of the Hondsrug is patched and highly complex due to 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 is rather thick and becomes thinner towards the southeast near Haren. Around Donderen, the till is completely absent, with only an accumulation of boulders remaining, while its thickness increases towards Gieten (around 5–7 m), 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 however is dangerous, since many local conditions (e.g. non-deposition and erosion) will control the final thickness of the till. However, by utilizing many more proxies, such as stress measurements, erratics counts, micro-morphology of the glacial sediments and insight into clay mineral species and structures, a much better delineated reconstruction can be made.

Both processes, stagnation and basal melt (or a combination of the two), result in the dumping of melt-out tills. The main conclusion for the Hondsrug area is that thick tills correlate with stagnation because of the positioning of deeper geological structures, but our approach is a rather bold correlation of different parameters. In Figure 6.11 an other example, which makes clear that till as well as erosion and deposition of tills is correlated to deeper structures. Glacial erosion occurred, just like in the north Drenthe Hondsrug area also in the north Frysian area due to the occurrence of a salt dome that led to large compressional forces (Figure 6.11). South of this region, increased heat fluxes led to higher basal melting rates and therefore thick till deposits (Figure 6.11.**C**). 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 till was brought towards this front in a conveyer belt fashion.

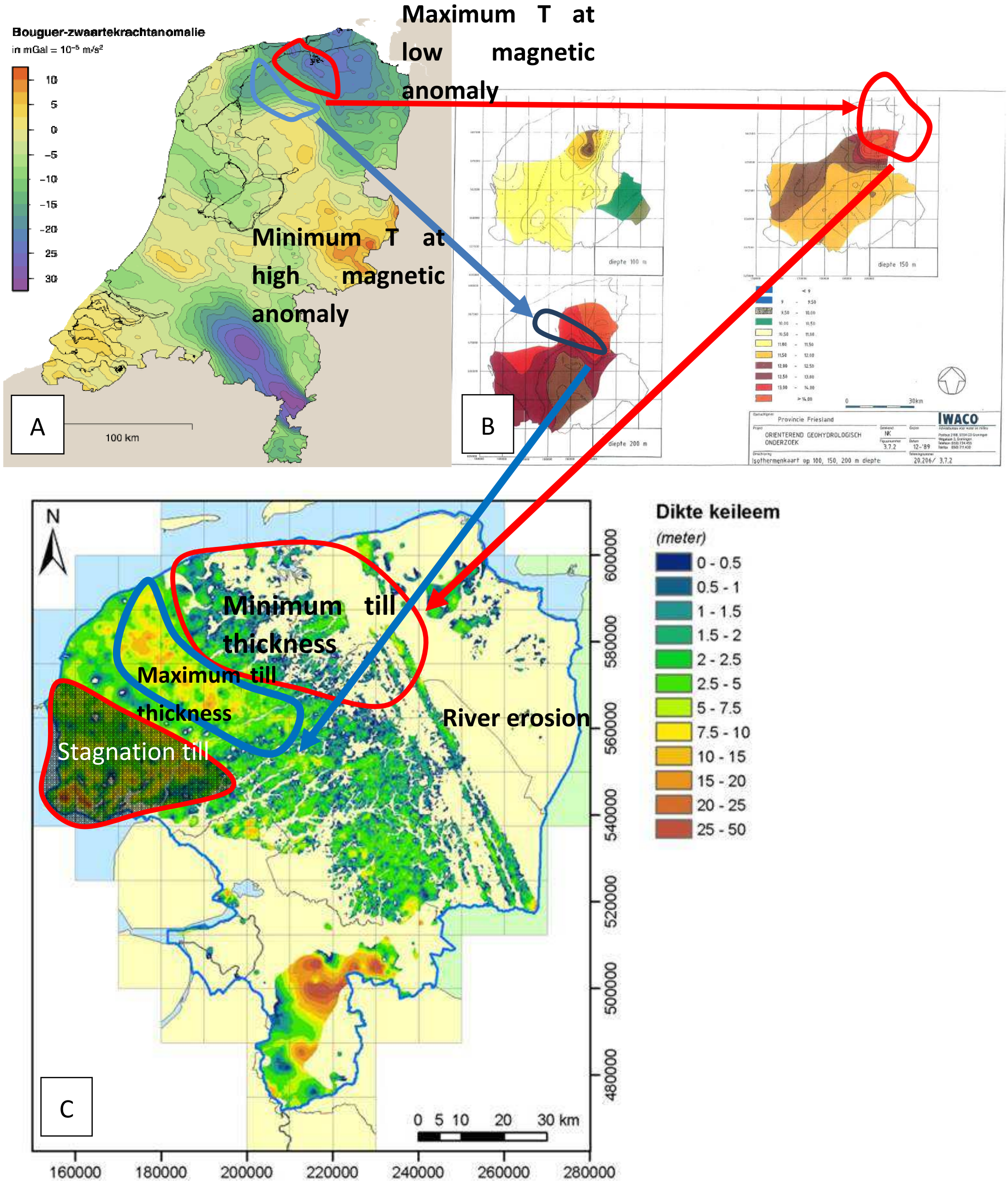


Figure 6.11. Impact of high geothermal fluxes on till deposition. **A**) Deep geology: gravity anomalies in the Netherlands. Low values correspond to: 1) Occurrence of thick unconsolidated sediments in subsiding basin (Roergraben, south Netherlands) or 2) Occurrence of rock salt (since the density is 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). C) Till thickness in northern Netherlands (Source: TNO, 2012).

6.1.6 . Ridges that formed

The glacial lineations make up an alternation of ridges and lows and this implies a difference in pressure between the ridges and lows. Main reason is that the density and gravity acceleration are the same at the ridges and lows, so only the difference in the column of ice creates a pressure difference. At the ridges, the ice column is lower, while at the lows, the ice column is 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). Figure 6.12 presents the conceptual model in longitudinal direction; Figure 6.13 presents the crosssection (schematic, not on scale).

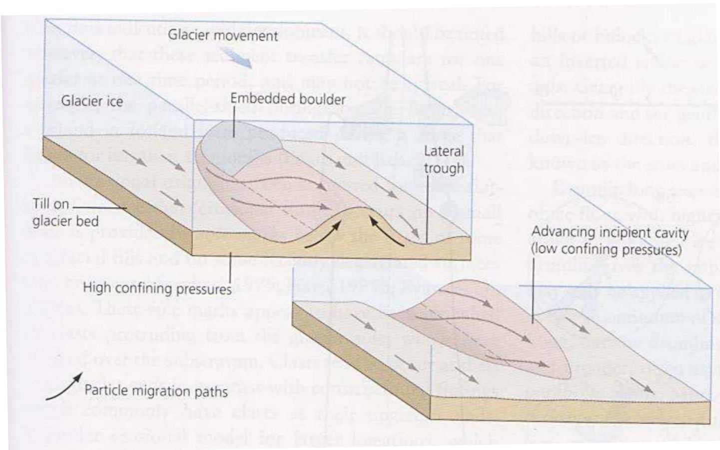


Figure 6.12. A conceptual model of fluting formation due to the subsole deformation of sediment into an advancing incipient cavity on the down-ice side of a lodges boulder. (From Benn and Evans, 2007)

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 were formed on the same principles.

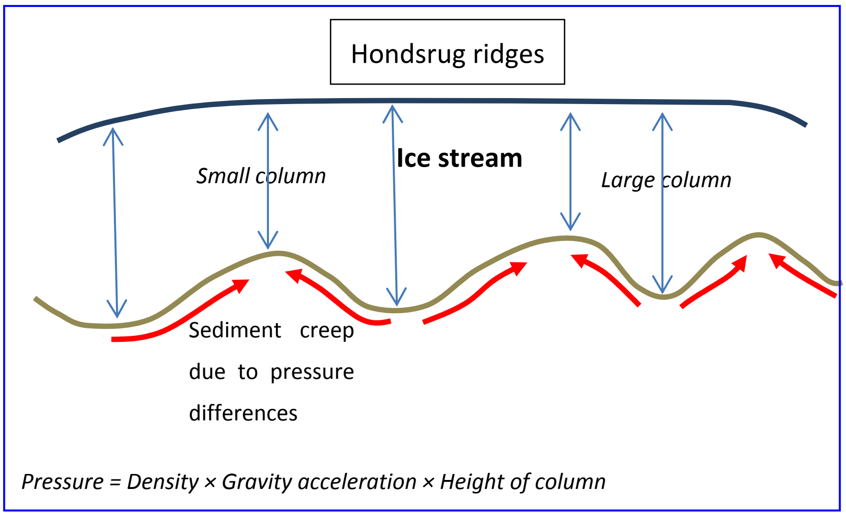


Figure 6.13. Crosssection of Sediment creep due to differences in pressure at the glacier bed, as topographic highs and lows occur.

6.2. Overview of the IML

The question to be considered here is whether these conditions are coincidental or whether these kinds of correlations can also be found at other locations on the IML. To answer this question we examined two further sources of information.

As shown in Figure 6.14, the stagnation line of the Rehburg phase continues eastwards to Germany north of Braunschweig through the Ankümer Høhe, Dammerberge and Rehburger Berge. The presence of hard rock, forming an obstacle to glacial flow, might not be the only cause of stagnation as, remarkably, the hotspots (yellow-red dots in Figure 6.10) are highest in places where glacial basins have formed (black shading in Figure 6.11). In Figure 6.2, we see the same situation occurring in the Netherlands near the glacial basin of the IJssel and Montferland.

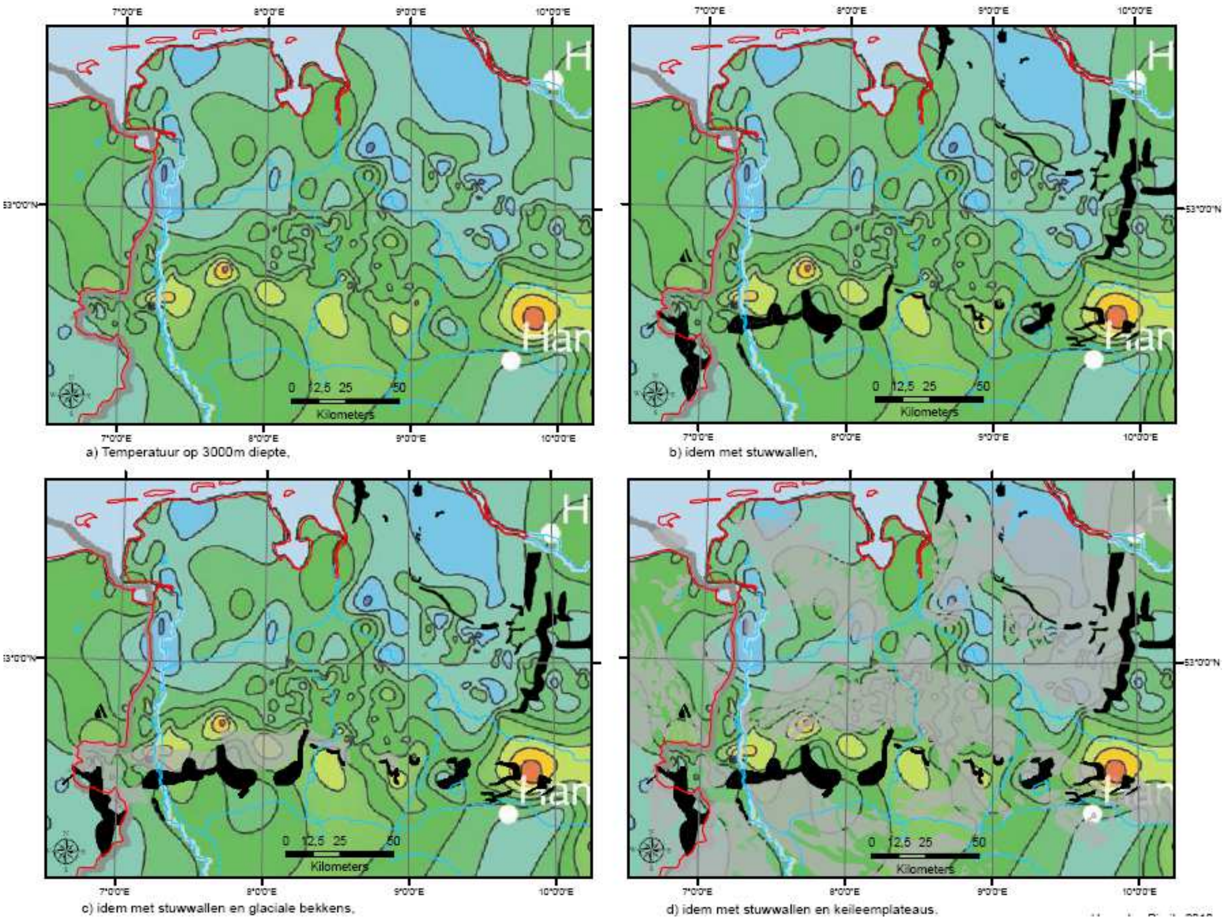


Figure 6.14. A) Temperature at 3000 m; B) T at 3000 m + push moraines; C) Figure B + glacial basins; D) Figure C + till plateaus. Geothermal maps from Hurtig *et al*. (1992)

Figure 6.15. shows the correlation of the gravity map of the IML and positioning of different glacial features. Areas with low gravity, an indication of tectonically weaker zones (unconsolidated sediments, salt rock, etc.) and fault systems, are positively correlated with the positioning of ice streams as we concluded also for the Hondsrug area. In other words on base of the Hondsrug study we now know that positioning of icestreams in the IML is strongly correlated with deep geological structures and geothermal heat and for further study (e.g. modelling) about icestreams like the Hondsrug geophysical indicators have to be involved.

6.3 General conclusions

With respect to the role of 'deeper' geology in the genesis of the Hondsrug-Hümmling ice stream, we can firstly conclude that we found strong indications that the Saalian glaciation had, although different impact on reactivation faults and salt mobilization (due to forebulging, crustal loading and and unloading). Forbulging in the phases 1 and for sure 2 and 3 (Figure 1.8.) with character of an ice sheet had strong impact on loading (and so on unloading) because of high mass weight of the ice on the study area, whereas the impact of the Hondsrug-Hümmling ice stream was minor. Surface processes thus influenced deeper geology and the opposite also occured: subtopographical obstacles influenced the behaviour of ice streams and determine stagnation positions. Subsurface temperatures also influence ice stream behaviour (higher geothermal fluxes in areas of faults or salt rock diapirs/ridges/domes) at different ways:

The Texel-IJsselmeer High region coincides with a temperature minimum (blue lines, Figure 6.9A) that could reduce meltwater production and induce stagnation. Hotspots caused by the positioning of salt domes with higher HFDs north of the present northern Dutch coast, on the contrary, must have had an impact on the basal melt rate of the ice, which could have led to higher subglacial water pressure in the relatively lower area of the branch of the North Sea Basin and the Lauwersmeer Trough.

Hotspots may have a different impact on ice streams. We suggest that (i) an increase in subglacial melt in the more central part of the ice sheet might influence basal meltwater pressure and this process is much stronger in the deglaciation phase, where fractures and moulins could be formed in the degrading ice sheet, providing meltwater pathways that flow towards subglacial lakes, and contributing thereby to higher basal water pressure (e.g. Evans, 2005) and (ii) hotspots also influence the melt of ice lobs and ablation, with an impact on ice sheet velocity, which can be seen as a part of the feedback mechanism by which the degradation of ice sheets remains in balance.

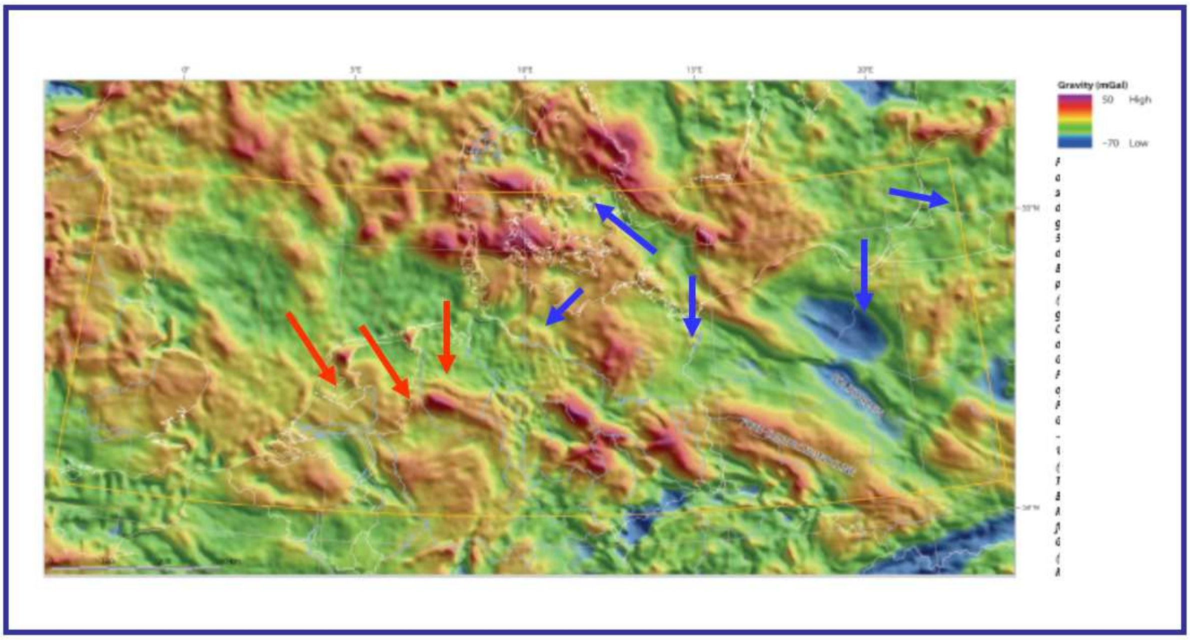


Figure 6.15. Correlation of gravity patterns in the IML and glacial features. Red arrows indicate positioning of Saalian marginal ice streams. Blue arrows indicate Weichselian marginal ice streams. Source gravity map: Duin (2006). For explanation of the legend of the map: see Figure 6.8.

Hotspots in northwestern Europe are related to the position of salt diapirs, the main fault zones and thinner parts of the earth's crust. This has been shown for the Rehburg phase in Germany, while study of the supposed onset zone of the Hondsrug-Hümmling ice stream also confirmed this relationship. It is remarkable that one of the main hotspots in the Rehburg phase is found precisely at the position of the Porta Westfalica: the entrance to the Weser Bergland, where meltwater formed in the Saalian Lake Weser (Winsemann *et al*., 2011; Meinsen *et al*., 2011). We will explain in more detail below how this lake played an important role in the genesis of the Hondsrug-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 ice sheet and we suggest that a jökulhlaup occurred through a burst out of a hydrostatically sealed subglacial lake in the North Sea area.

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

High geothermal anomalies in the North Sea, north of the present northern coast of the Netherlands (Figure 6.9A), could have acted as the onset zone for the Hondsrug-Hümmling ice stream, where basal melting rates were higher and basal water pressure was also raised. Such conditions could have triggered fast ice flow towards other favourable (high geothermal flux) locations along the Hondsrug transect where salt diapirs and faults occurred. This also suggests that the occurrence and direction of the Hondsrug-Hümmling ice stream is not indicative for large scale coaelescence of the Scandinavian and British ice sheets (contra Dubois, 1902; Rapol, 1987; Van den Berg and Beets, 1987). Better arguments for such coalescence in the Saalian are found in the proglacial sediments of Phase 2 and 3 (Figure 1.8.) when the directions and types of ice flows differed from that of the Hondsrug-Hümmling ice stream. The ice-sheets remained coalescent during the Hondrugs ice-stream phase (Phase 4), but those that hold the Hondrug ridge direction for that at the current state of knowledge are right for the wrong reason.

7. Reconstructed Hondsrug ice stream mechanics

Based upon the data acquired and the interpretations above, we developed a new glacial model of the genesis of the Hondsrug. In this regard, in Section 7.1 we will firstly focus on the Hondsrug area itself. In Section 7.2 we will scale up our observations, with the central questions being why this ice stream began in a degrading ice field and why this occurred only at this location. In this chapter we will also describe the pathway of the ice stream with respect to the main parameters that influenced it. What controlled the Hondsrug-Hümmling ice stream will also be explained in more detail in Section 7.3.

7.1 Genesis of the Hondsrug-ridge complex

Correlative analysis of various observational evidence and process knowledge (Chapters 4-6), lead to the following synthesis on the relevance of the Hondsrug area to a Saalian ice stream and the recording of the dynamics of this ice-stream in morphology and deposits:

A kilometres-wide ice stream, with marginal substreams, developed between stagnant dead-ice fields, just after the maximum glaciation phase of the Saalian glaciation (Van den Berg and Beets, 1987; Rappol, 1991; Phase 4 in Figure 1.8). This stream flowed with a NNW-SSE and overprinted and remodelled subglacial landforms created during advancing phases of the same glaciation had a contrasting NE-SW direction (Phase 2 and 3, Figure 1.8.). The source area and onset zone of the ice stream should be sought to the North, in the North Sea area, relative close to the modern coast line (Chapter 6). The outflow region was the Munster Basin to the SE (Van den Berg and Beets, 1987; Chapters 2 and 6). The Hondsrug area has preserved the deposits and morphology of the western margin of the ice stream over a large and continuous enough area to study variations in ice-bed interaction along the ice stream path, indicative for acceleration and deceleration in response to overran structures.

In summary, our observations at the locations studied reveal a generalized pattern found on the Hondsrug, from the north to the south:

1. **Groningen**: Thrusted tills, thick sequences. Slow movement of the ice stream in this region.
2. **Donderen**: No till, extensive erosion. Extensional forces due to acceleration of the ice stream towards the Hondsrug region where salt diapirs increased basal melt rates.
3. **Gieten**: Thick till sequences and deformation tills. Local compressional forces (east branch), other extensional forces (west branch). These might be due to friction caused by the dead-ice body east of Gieten and the formation of ice-contact moraines. This activity might explain the occurrence of thick deformation tills on the east branch of the Hondsrug. Less friction was found to occur at the location on the western branch, leading to higher flow velocities.
4. **Gasselte**: No till, large-scale erosion, the orientation of the thrust sheets of coarse preglacial sand (NE) not altered by overriding ice stream (NNW). High basal water pressure. Coarse-grained sediment frozen solid.
5. **Borger:** Minor till deposition, large-scale erosion.
6. **Odoorn/Valthe:** Lodgement till, undisturbed preglacial sediments that reflect thrusting from the northeast, older phase.

7. **Klazienaveen:** Thick sequences of till. Meltwater deposit in between the Assen and Emmen till type. Glacier bed not deformed. Till thickness increases towards south of Schoonebeek where it is dumped in the Itterbeck Basin.

● The tectonic block (Groningen High) influenced ice sheet and ice stream flow at different ways. An older ice flow with NE – SW direction stagnated in Groningen which resulted in thick tills. The Hondsrug-Hümmling ice stream when started to flow stagnated due to this older tills, resulted in the slow movement of the Hondsrug-Hümmling ice stream, deposition again of tills thrusting of till sediments of different phases (2,3 and 4; Figure 1.8)

● Between Donderen and Emmen, salt diapirs and permafrost favoured high ice velocities, and therefore thinner sequences of till were deposited or, alternatively, movement and meltwater erosion stripped off the till completely.

● In the northern part, north of Borger, basal melting was high because of higher HFD near salt diapirs and the supposed opening of the main fault systems of the Hantum graben as well as the occurrence of brinewater, which lowered the 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 the depths of the brinewater. The flow path of this groundwater was – we assume – controlled by Elsterian buried glacial valleys and subsurface obstacles (salt pillows and diapirs at 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 contributed to the floating of The ice stream south of Borger, whereas north of Borger it found its way into a complex system of subglacial channels, canals or pipe flow structures which pe.etrated older and newly formed relatively thick tills (in relation to the eastern part of Hondsrug area near Gieten). This mechanism formed water escape structures (WESs; Van de Meer *et al.*, 2003) and agrees with our observations of hydrofracturing features which always indicate high water pressures according to Van der Meer *et al.* (2003) (the 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 does not contradict the hypothesis that the mechanism associated with stagnation was compression, which we suggest was the main reason for the thickening of the Groningen tills. Deformation in this part of the Hondsrug was probably also influenced by a coarser grained texture occurring locally (near the salt diapirs there is a surfacing of Tertiary deposits due to older uplift or probably higher erosion due to forebulging).

● The easternmost part of the Hondsrug reveals a relatively higher content of erratics in the upper tills, indicating a very stone-rich substream with a relatively high amount of east-Baltic erratics. The western substream, linked to the Tynaarlo Ridge, contains more mid- and southeast Baltic erratics and the till deposits are thinner, which according Bennett and Glasser (2009) can be explained by three processes:

Firstly, environments are not static over time and a shift in an ice stream's position at localities where this causes deposition will result in a facies shifts hat record in a vertical profile (e.g. Walther's

Law, in Bennett and Glasser, 2009), whereas at adjacent locations it will cause deformation and erosion.

Firstly, environments are not static over time and a shift in an ice stream's 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 a later stage shift - without erosion - over earlier tills, as we have seen in the Gieten outcrop.

Secondly, another process is related to the positioning of the western substream in the contact zone of the stagnant 'dead ice' and the active fast-moving ice stream. In this contact zone, which was a maximum of 3 km wide, high internal friction caused extra heat production that led to more meltwater and thereby to more erosion of glacial till, such that it is absent or only partly present in thin sections (Figure 7.1). By the same process, there was also a relative enrichment from erratics of a later phase.

Thirdly, the final explanation is also related to the formation of ridges, which is caused by relatively high pressures at the lower part that will invoke an upward shift of debris because of a lower pressure zone occurring 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 why the top of the Peelo Formation on the western side has been eroded in the area of Odoornerveen (a former peatbog), in a linear direction parallel to the Hondsrug (Figure 1.5; Section 1.2).

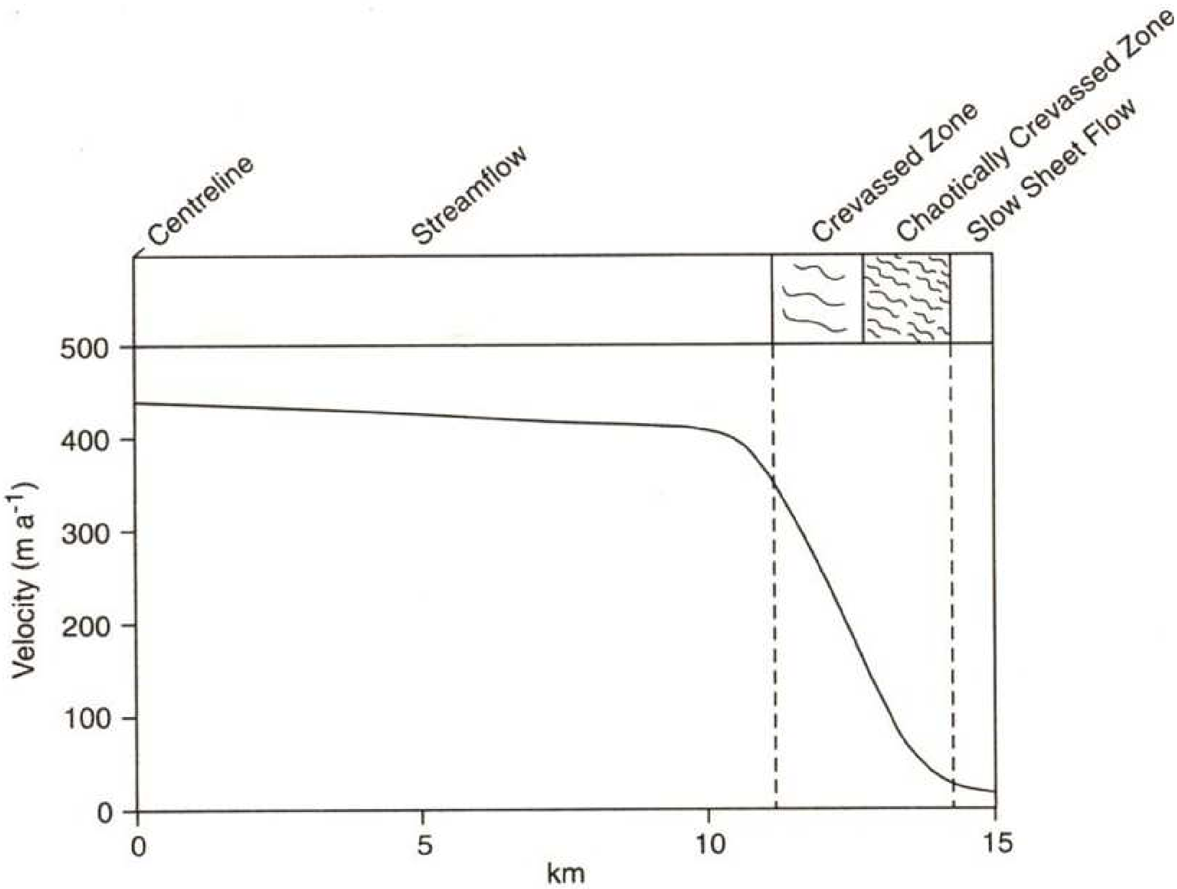


Figure 7.1. Variation in velocity across an ice stream, with a dramatic lowering in the fringing zone between the part of the ice stream with high velocity and the part with slow sheet flow. Internal meltwater production is high in such a zone due to the occurrence of internal fringing and fringing of crevasses. (Source: Evans, 2003)

● South of Borger/Buinen, tills are partly absent and erratics and pebbles are surfacing as indicated on soil maps (this is the only area in Drenthe with a depth of up to 4 m [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 between the strongly deformed glacier bed north of Borger to Gieten, and the area between Exloo and Valthe. In the latter area, the tills are very thin and are superposed on NE-SW deformed (older) subglacial sediments, indicating Phase 3, Figure 1.8). Glacial erosion caused by the Hondsrug-Hümmling ice stream did not occur for two reasons: we suggest firstly, the presence of permafrost and, secondly, 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).

● Results of the recent till study (Bregman and Lüse, in prep.; see also Chapter 2) it is apparent that the lower tills of the Hondsrug area are similar to the tills in the northern and central areas of Drenthe, while the upper till near Schoonebeek is also the same type, indicating that the upper till from the northern part of Drenthe has been eroded away in Schoonebeek. Our results of till study have not only shown a differentiation of clay minerals on well-studied tills (Rappol, 1983), but also that the tills at the transition zone, 55 cm below the surface, do not have any illite reflexes, which can only be explained by the shearing of ice streams under high pressure. Because the XRD study revealed newly formed minerals such as syngenite and halite in the lower tills in the Hondsrug area we conclude that these tills were formed under saltwater conditions. These newly formed minerals, which were not formed due to weathering conditions or due to the use of salt on roads in winter, indicates the influence of brines that were pressed up in a proglacial and subglacial environment or due to the upwelling of deep saline groundwater. These salt or brinewater intrusions leaked into the same till types in northern and central Drenthe, which indicates pro- or subglacial intrusion in the lower till during the last event in the Saalian glacial advance of the Hondsrug-Hümmling ice stream. This conclusion also confirms that this ice stream must have caused a reversed groundwater flow. Its flow characteristics might also have been influenced by this briny to salty groundwater, with implications for its basal melting point, velocity and erosional processes. The newly formed minerals indicate the influence of brinewater which penetrated from the north into the lowest tills from sources above the permafrost layer. This accord 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 till deposits on undeformed subglacial sediments, indicating fast flow, (ii) brinewater intrusion in the till, and (iii) indications of a high P_w (due to permafrost and the finer grained texture of the preglacial Peelo Formation; Van den Berg and Beets, 1987; Figure 5.1).

● While flowing over the Hondsrug transect, the ice stream loses its momentum near Valthe and Emmen, where finer grained deposits build up the megaflute with thicker sequences of till. This indicates a change in water content (Van der Meer *et al.,* 2003), perhaps because permafrost was absent or penetrated less deeply and due to the stagnation we described above. We suggest that one main reason for stagnation at Emmen is related to denudation of a previously formed push moraine from an older period of glaciation (probably connected to the Rehburg phase; Phase 2, Figure 1.8), which is evident from the pushed subsurface. However, relative to the height and positioning of till types and clay minerals of the present surface, the push moraine was not very high with different till types found at 55 cm below sea level. Based on a study of erratics (Rappol, 1981) and XRPD analyses (Bregman and Lüse, in prep.), the lowest till type is the same as that found in southwest Drenthe (Phase 3, Figure 1.8), which could mean that glacial erosion by the Hondsrug-Hümmling ice stream in the Valthe – Emmen area was not very strong.

● Near Emmen, the ice stream gradually built up thicker tills in an ESE direction and probably lost its momentum under different conditions, indicating a higher amount of subglacial water and dumping of tills into the Itterbeck depression, into which the ice stream partly 'slumped'. Subsequent stagnation occurred and deformation of an older (Rehburg phase; Phase 2, Figure 1.8) push moraine at Itterbeck (now north staggered slabs; Kluiving *et al.,* 1994). The ice stream did not have enough kinetic energy left to denude or override this area, and subsequently dipped over the edge of the German Tectonic Basin and flowed in the direction of Nordhorn (a tectonically weak zone; edge of German Permian Basin), dropping glacial debris that had been taken up along the Hondsrug transect in the Münster Basin (e.g. Speetzen and Zandstra, 2009; Winsemann *et al*., 2011).

● Once the the Hondsrug-Hümmling ice stream flow had been triggered, the ice stream's behaviour was determined by the interaction between 'deep' geology, subglacial hydrology and proglacial environmental conditions (coarse/finer subglacial sediments and permafrost). From north to south there is a sequence of subglacial erosion, followed by strong deformation of the subglacial bed and glacial deposits, and the floating and dumping of glacial debris.

7.2 What triggered the ice stream to form

● The advancing ice field of Phase 3 (Figure 1.8) show two flow directions. In the north of Drenthe the ice flow had a NE-SW direction and in SW Drenthe the ice flow was more to the south in the direction of the IJssel valley and east of the Münster Basin (Van den Berg and Beets, 1987). This ice lob stagnated and blocked ice flow to the south.

● stagnated ice fields exist at the same time as ice streams are active. After the ice advance reached its maximum, a rapid retreat of the ice caused an imbalance in the mass balance. As a response to this condition, an drainage reorganization within the ice field is an ideal starting point for the genesis of ice streams (e.g. Cohen, 2003; Busschers et al. 2007; Hijma et al. 2009) and for the penultimate glaciation (Cohen et al. 2002; Busschers et al. 2007; 2008)

● On the basis of our correlative analyses (Chapter 6) we conclude that the ice stream was triggered in two areas: by a jökulhlaup in the Münster Basin freeing an outflow area, and by a geothermal hotspot in the North Sea area, providing an ice source area, with the presence of stagnant ice over the North sea, the Northern Netherlands and Northern Germany, accumulated in the earlier part of the glaciation was a prerequisite.

(i) Ice source area. Raised subglacial basal melting on a hotspot, with a higher HFD, that formed a hydrostatically sealed subglacial lake in the North Sea area with high water pressure, which pulled the ice mass towards the SSE. However, a mass surplus, due to regional differences in climatological conditions, probably caused by patchy accumulation as is shown by modelling (e.g. Van den Berg, 2007), could also be a reason for mass flow.

(ii) Outflow area. By a breach of Lake Weser Bergland in the Münster Basin a jökulhlaup was caused (Figure 7.1, point 1). Winsemann *et al.* (2011) describe how a breach of the Lake Weser raised the water level of the Münster Embayment by 130 m and triggered calving of the ice sheet.

● The jökulhlaup, pulled by overpressure from subglacial water, is the most probable process, while we assume deeper geological structures, which formed the pathway draining overpressed subglacial lake water from the North Sea area, pushed the ice stream once it had started (Figure 7.2, point 2).

● The WNW - SSE pathway of the Hondsrug- Hümmling ice stream is because of:

(i) Direction of a zone with higher temperatures (HFD) from the North Sea area through the Hantum graben and Lauwersmeer Trough to Groningen (e.g. Figure 6.8 A). The subglacial meltwater drained from the source area through a reversed groundwater flow in that SSE direction. We assume that the ice flow direction wasinfluenced by deep geological structures.

(i) Stagnation of the southern IJssel lob forced the ice stream when forced to SSW direction.

● The extension of the Hondsrug-Hümmling ice stream with a NNW-SSE direction is described by Speetzen and Zandstra (2009) on the basis of the discovery of similar erratics in the Hondsrug area similar to the Münster Basin. The ice flow affected the western edge of the Hümmling (Rappol, 1991a) and, although not corresponding to assemblages of erratics noted by Speetzen and Zandstra (2009), continued (Kluiving *et al.,* 1991; Skupin *et al.,* 1993) through eastern Twente into Münsterland (Van den Berg and Beets, 1987). Based on geological evidence the dimensions of the ice stream are at least 40 km wide and 120 km in length, with extension from the North Sea area north of Groningen to the Münster Basin (Figure 7.1).

● The easternmost side of the ice stream is marked by the Hümmling (Figure 7.2 point 4), well studied by Schröder (1978). The Hümmling was pushed from two directions: from a NNE direction and a NNW direction. Most of the Hümmling is not deformed by pushing of this ice mass.

Although Schröder (1978) did not find any evidence for an ice mass which caused the deformation of the Hümmling, we suppose that the partly overridden deformed Hümmling marks the easternmost flow of the ice stream, which could also partly override the Hümmling. We estimate, on the basis of the height of the topography (highest point of the Hümmling 72.7 m), on the basis of the fluvioglacial and glaciolacustrine sediments (LBEG, 2012; hydrostratigraphical profile; Schwan and Casse, 1997) and on the basis of the ground moraine (Schröder, 1978) that the height of the ice stream was *c*. 80 m on its eastern side.

● Evidence for the westernmost part of the Hondsrug-Hümmling ice stream (Figure 7.2, point 5 and 6) is obvious and reflects morphology, but also in erratic assemblages (Chapters 5, 6). In the northernmost part the divergence of ice flows 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 area lower than the surroundings (Figure 5.2). We propose differential lowering of the area, which may be related to the loading of the salt ridge near Hooghalen. In this area (Figure 6.5; see also Chapter 8) differential rebound determined the actual river pattern of the Drentsche Aa in the postglacial period. In other words, local lowering of the area may be the result of differential resistance of the crust due to loading and this might have influenced ice flow behaviour. The Hondsrug ends in the southeasternmost part of Drenthe, where the ice stream dropped thick tills in the Itterbeck Basin. This glacial basin connects with the push moraine of Itterbeck, related to the Rehburg phase, and in the northern part reveals staggered slabs caused by NE-SW pushing.

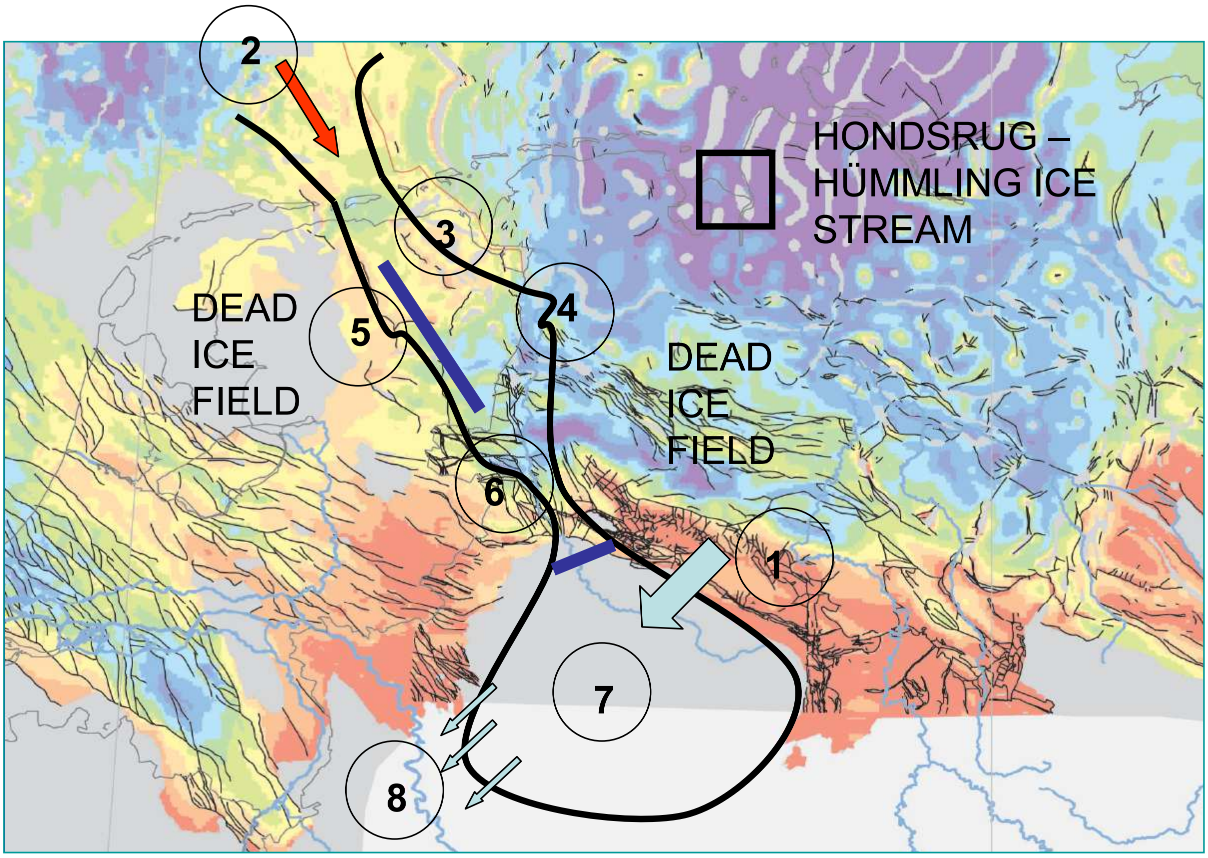


Figure 7.2. Positioning of the Hondsrug-Hümmling ice stream (Saalian, MIS 6; Phase 4, Figure 1.8.). Background map: Lower Trias (PBA, 2011) also indicating tectonic structures. Primarily the South Permain Basin with salt structures (pink colour; deep base); Devonian hard rock(red colour; near surfacing). Correlation with glacial surface features, which will be explained in the text for locations 1 to 8. The Hondsrug area in blue in the north; in the south, the ice margin (deglaciation phase; indicative). Red arrow: ice stream flow direction.

● Thrusting is influenced by Tertiary clays (Middle Oligocene; Ruppel Formation), which formed glaciotectonic nappes due to high pore-water pressures which contributed to sliding and overthrusting (Kluiving, 1993). In addition, deeper surface geology also plays a role. There may have been a higher HFD (Figure 6.10), but most remarkable is the positioning of the glacial basin (depth 60–80 m below MSL) on a depression which is connected to the South Permian Basin. The ice stream dipped into this part of the South Permian Basin, a heavily folded zone which is clearly structurally weaker (Figure 7.1), and pushed against the Itterbeck push moraine but could not pass it, as we conclude from the lack of tills on top of the moraine. The height reaches to 50 m above ground level.

The ice thickness in the glacial basin reached to a maximum of *c*. 120 m (height and depth data are from LBEG, 2012).

● On the basis of hydrostratigraphical profiles (LBEG, 2012) our conclusion is that the surface height of Tertiary clays, Mesozoic sandstones and Lower-Creteaceous formations, follows the longitudinal direction of the Northwestfalian Lippische High (e.g. Walter, 2007, a ridge dipping gradually in a NW direction, 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 below MSL. The top of the plain, constituted by non-glacially deformed areas in the Hunze valley and near Meppen, reaches up to 40 m below MSL. When we take this as a reference we can estimate the thickness of the Hondsrug-Hümmling ice stream near Drenthe in its westernmost part to be *c*. 80 m, similar to the eastern rim of the ice stream. In the central part of the ice stream the ice thickness was *c*. 120 m.

● The ice stream probably pushed the eastern part of the Itterbeck push moraine for a second time (after forming in the Rehburg phase). This conforms with the insights of Van de Wateren (1995), who has shown that lateral pressure gradients play an important role in ice pushing, as Bakker (2003) also demonstrated in the eastern part of the Veluwe. Consequently, the ice flow was forced to the east, but was blocked there by a dead-ice mass with top surface tens of metres higher than the ice stream. This would explain the depth of the glacial basin (80–90 m below MSL), the height of the Dammer Berge (137 m above MSL), the height of eastern push moraines of the Rehburg phase, and the top of the northern non-glacially deformed area (40 m below MSL). We assume that the dead-ice field east of the Hondsrug-Hümmling ice stream was melting because of a relatively high HFD (Figure 6.7). This meltwater fed a glacial lake between Wiehengebirge and the ice field, as well as Lake Weser (e.g. Herget, 1997; Klostermann, 1992; Winsemann, *et al*., 2011), bypassing the Porta Westfalica, a natural low also with high HFD (Figure 6.11).

● On the basis of the presence of erratics (Speetzen and Zandstra, 2009), we conclude that the ice stream passed Nordhorn, where the Ems already existed at the time in a 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, not only caused the flow of the Hondsrug-Hümmling ice stream (e.g. Winsemann *et al.,* 2011; Meinsen *et al*., 2011), but also raised the water level of Lake Münster (Figure 7.2, point 7) and probably led to breaches at different locations into the Rhine valley, where deposits perhaps formed the UM 3 Terrace (Untere Mittelterasse 3), which is found in the Rhine valley north of Duisburg to Montferland (Figure 7.2, point 8). This *c*. 8 m high terrace is built up of very stone-rich, middle to coarse fluvioglacial sediment, indicating a high energy depositional environment. Klostermann (1992) has described how through strong erosion a discordance layer with underlying sediments nearly always formed at the base of the UM 3 Terrace, and during its formation often incised deeply into older sediments, even Tertiary sediments. On the basis of lithostratigraphy of the UM 3 Terrace, Klostermann (1992) concluded that it was formed at the end of the Drenthe stadium. The positioning of the UM 3 Terrace west of the Münster Basin, showing deposits which indicate the dramatic impact of the fast release of immense amounts of meltwater, and the chronology of events, is a topic for future research concerning the possible connection between the events in the Münster Basin being triggered by a breach of Lake Weser (e.g. Meinsen, *et al.*, 2011)

7.3 What caused the ice stream to follow the Hondsrug path?

This section addresses the question of what factors controlled the Hondsrug-Hümmling ice stream. Table 5 presents a summary of our conclusions.

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, salt ridges - Base of groundwater system with underground topography	- Spatial variation due to local higher Tb - Rise in amount of subglacial meltwater - Forebulging - Vertical and horizontal stress - Reactivation of faults - Halokinesis - Spatial variation reversed groundwater flow (probably) - Impact on groundwater quality (salinization of meltwater caused by pressed up groundwater flow with influence on newly formed minerals in tills)
- Topography	- Ancient proglacial drainage of meltwater/the Ems	- Less resistance to surging, more in combination with 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 to sliding ice stream - Raising Pw

- Smooth bed	- Roughness - Outcrops (hard rock)	- 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 for the terrestrial Saalian Hondsrug-Hümmling ice stream, Drenthe, the Netherlands. The table shows the hierarchy of controlling parameters from the top down.

It is evident that the geographical positioning of the ice stream in the margin of a degrading ice field 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 was triggered by an event at the inland shoreline due to forced calving and was pushed by raised levels of high pressured subglacial meltwater. The positioning of the source area, pathway and behaviour of the ice stream depended strongly on 'depth' and 'warmth'. We consider that such conditions were due to loading and unloading caused by forebulging and collapse, reactivating and triggering changes in the earth's crust, which not only influenced the positioning of the ice stream, but also the postglacial processes. Deep geology strongly influenced the discharge of meltwater, but this was also influenced locally by permafrost and substrate characteristics, while the pathway of the ice stream was mainly controlled by an interaction of 'deep' and 'shallow' obstacles.

8. Discussion

8.1 Cases of ice streams in the wider European ice marginal landscape

Having studied the central part of a Saalian glacial ice stream in detail, we then zoomed out to its onset and ablation zones for a better understanding of the reasons behind the formation, positioning and behaviour of the ice stream. Here we locate the Hondsrug-Hümmling ice stream in the ice-marginal landscape (IML) of northwestern Europe.

The positioning of marginal ice streams in northwestern Europe is strongly related to deeper geological (graben) structures (Figure 6.6), as is the case with most Weichselian ice streams (e.g. Winsborrow *et al.*, 2009, 2010; Andreassen *et al.,* 2009; Winsborrow *et al.*, 2009a) and recent ice streams (e.g. Bennett, 2005). All of these ice streams are very dynamic systems which play an important role in maintaining the mass balance of a glacier in equilibrium, as well as in the discharge of the majority of the ice and sediment (e.g. Bennett and Glasser, 2009). However, unlike recent marginal or peripheral (Bennett and Glasser, 2009) ice streams, there is a lack of studies of onshore ice streams found in northwestern Europe, even of Weichselian age, particularly with respect to the factors determining their onset, position and behaviour. There are, in our opinion, good reasons to undertake such studies. The correlation between the positioning of the Gulfs of Gdansk, Riga and Kaliningrad and push moraines formed inland has only been studied superficially, correlating the associated ice streams with deeper geological structures (graben systems). However, postglacial processes have had an equally huge impact on the development of the shoreline and delta systems (Bregman and Druzhinina, 2012) which are now highly populated areas, and more generally on river systems such as the Rhine and Meuse (e.g. Cohen *et al*.,2002; Busschers *et al*., 2007; Hijma and Cohen, 2011).

In general, we have found that in the Netherlands and northwestern Europe (contrary to the Baltic), postglacial rebound studies have not been done on the distal side of the forebulge, with the exception of studies of the Hunte valley west of Bremen (Sirocko, 2005; Lehné and Sirocko, 2005; and Szeder and Sirocko, 2005). Moreover, there are relatively few studies of the relicts of onshore glacial ice streams of Saalian age. The most logical reason for this is a natural one, because in northwestern Europe the Weichselian ice advance removed Saalian features or reduced coverage to local relicts which were then covered by more recent Weichselian deposits. We argue that it is precisely this geological history which makes the Saalian features of the Hondsrug area unique (see also Figure 1.2). On the basis of its composition of many lineations, approximately 70 km length, and the distance between the lineations, we have classified it as a megaflute, which is a streamlined subglacial feature (Bennett and Glasser, 2009).

8.2 Is the new Hondsrug ice stream case unique?

While Saalian lineations and megaflutes such as the Hondsrug have been described in the literature, they are rarely studied from a genetic point of view. As mentioned above, one main reason for this in the northwestern European context is that in most areas Weichselian glaciation removed older glacial features. At the same time, however, Weichselian ice streams are also rarely the object of study. One of the exceptions is a study by Jørgensen and Piotrowski (2003), who, on the basis of glacial sedimentary records, described several stages of a ice stream cover on Funen Island in Denmark. In addition, they classified and structured the various glacial sediments exposed in gravel pits, allowing for a convenient palaeo-glaciological reconstruction. Finally, they created a glacial model of the behaviour of an ice stream at its bed, based on the basal water pressure (Figure 3.3). Our results, which also assume different phases in ice stream behaviour (erosional phase, deformation and floating phases) in the Hondsrug area, are confirmed by their study. Although the glacial features and chronology are different (Funen: Late Weichselian; Hondsrug: Late Saalian) the sequence of events and the principle of floating caused by high water pressures is clear and seems to be a significant factor in ice stream behaviour in both areas. The sedimentary records for Funen are also similar, indicating the same processes as those which we studied in detail in the Hondsrug area. However, the differences in subglacial features are notable. At Funen, for example, eskers and drumlins were formed subglacially by the Weichselian ice stream. In the model of the Hondsrug-Hümmling ice stream these features are missing. This also stands in contrast to the third ice advance as mapped by Skupin *et al.* (1993), which covers a greater area, including a western part in the Netherlands, with an esker in Twente and in the Achterhoek.

A weak point of present study – relating to our aim and focus on the Hondsrug itself – is that our model of the Hondsrug-Hümmling ice stream is based on the interpretation of fieldwork carried out by previous studies and thus are still in need of further field control. Our conclusion is that in the future, both the onset zone and the terminal zone of the Hondsrug-Hümmling ice stream require much more attention. Furthermore, a study of the onset zone would require a completely different approach to a study of the terminal zone, as in the onset zone seismic data and the interpretation of deep well logs are very important for palaeo-reconstruction, while in the terminal zone much more attention needs to be given to lithostratigraphy, specifically with respect to fluvioglacial deposits (e.g. Herget, 2008), the impact of dumping of debris by the Hondsrug-Hümmling ice stream and the implications of the breach of Lake Weser into the Münster Embayement. An interesting point of discussion would be the dumping of debris from the Hondsrug area into the proglacial Lake Münster. Debris may have been transported by icebergs in the lake, and perhaps this is one of the reasons why the lithostratigraphy is complicated in the Münster Embayment, as described by Herget (2008). Stokes and Clark (2003, 2007) describe this kind of ice stream with a reference to the Dubawnt Lake palaeo-ice stream in the northwestern section of the Laurentide ice sheet during late glacial times. As with the Hondsrug-Hümmling ice stream, the Dubawnt Lake palaeo-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 also shown for the Hondsrug area

According to Evans (2005), the Dubawnt Lake palaeo-ice stream is very rare and the only known terrestrial ice stream. This overlooks the Hondsrug-Hümmling ice stream, but thereby confirms it as a very rare and unique example of a terrestrial ice stream. Furthermore, it has been described in greater detail, which according to Evans (2005) would be classified as a marine-based ice stream. Nevertheless, we must acknowledge that the process of calving in the terminal zone of the Hondsrug-Hümmling ice stream and the transport of debris by icebergs is the same. Thus, to distinguish the terminus of marine-based ice streams and a terrestrial calving zone we propose calling the terrestrial ice margin the 'inland ice margin' (Table 5).

8.3 What controlled the Hondsrug–Hümmling ice stream?

Section 7.4, Table 5, provided an overview of the 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 – the ranking is different in our opinion to that presented by Winsborrow *et al.* (2010). Figure 8.1 provides an overview. We consider that subglacial geological processes (reactivation of faults, shifting mantle flow/HFD) influenced by forebulging play an important role in the onset zone, in combination with calving on the ice margin. Both parameters are the main reasons behind the start of the flow of the terrestrial ice stream. For Winsborrow *et al.* (2010) (Figure 8.1), deep geological processes do not 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 starts during ice-field degradation and could be a good addition to the model presented by Winsborrow *et al.* (2010). In both sets 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 in our opinion a very significant regional condition in the Hondsrug area, along with geothermal heat. We consider this combination to be important, having a strong influence on basal melt conditions, as well as influencing the pathway of the subglacial meltwater. In Winsborrow's examples, (hard)rock topography is a most favourable condition for ice flow. However, the occurrence of thick sedimentary deposits in the Hondsrug area contrasts significantly with such topography, with these deposits favouring deep groundwater flow and interaction with 'deep' geology.

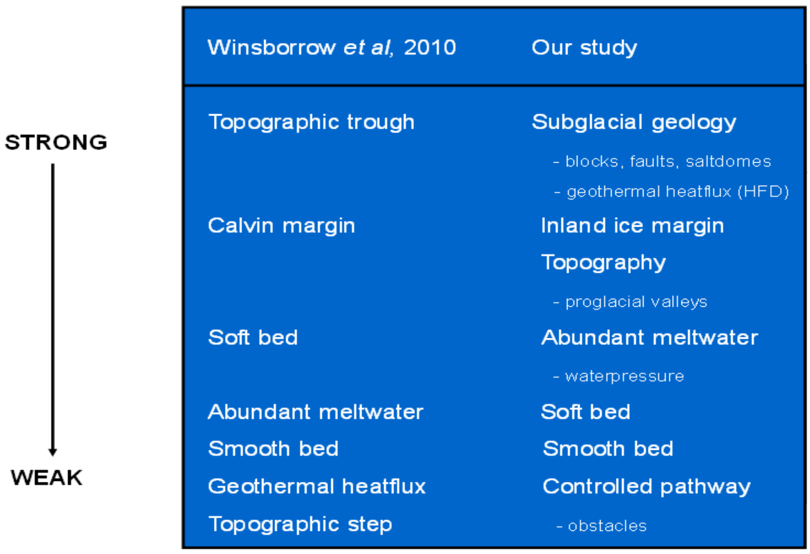


Figure 8.1. Hierarchy of controlling factors for ice streams according to Winsborrow *et al.* (2010) and our study. The most favourable parameters are presented. According to Winsborrow *et al.* (2010), the most unfavourable conditions are: flat bed/topography, land terminating, hard bed, scarce meltwater, rough bed, low geothermal heat and flat bed/without topographic steps. In relation to our study, 'land terminating' is obviously not an unfavourable condition for ice streams of the inland ice margin type (Hondsrug-Hümmling ice stream).

Clearly there are differences in the rankings of ice flow conditions of the two studies. In the Hondsrug area 'shallow' geology and geothermal heat plays an much more important role in basal melt and the onshore pathway of the ice stream depending on topography and presence of surfacing obstacles, then in marine ice streams studied by Winsborrow et al. (2010). This explains the positioning of the Hondsrug – Hümmling ice stream, and so the positioning of the Hondsrug.

8.4 Impact of forebulging

This study examined the impact of forebulging on glaciological processes for the first time in the northern Netherlands and concluded that there has been an underestimation of the implications of forebulging, as we found it to be an important glaciological process in our region. One of the implications is that in studies such as ours, deeper formations and processes within the earth's crust must be considered in addition to surface processes (glaciology), and thus there is a need for cooperation between different disciplines and an interdisciplinary or holistic approach. In the Netherlands, the importance of forebulging as a glaciological process has thus far been correlated to specific regional quaternary geological events (delta development) All of these studies were done on the distal side of the forebulge, while in northwestern Germany the impact of rebound was studied with respect to the Hunte Valley, west of Bremen (e.g. Lehné and Sirocko, 2005).

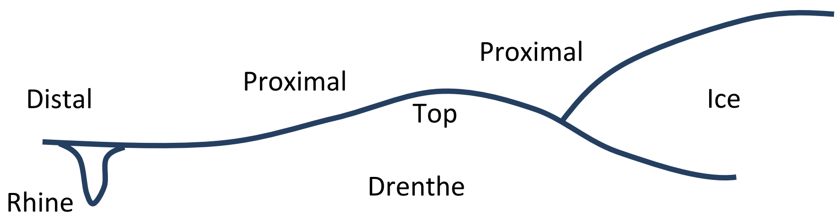


Figure 8.2. Location of Drenthe and quaternary geological studies. The Hondsrug area is in the proximal part of the forebulge area of influence, while the quaternary geological studies were performed on the distal part of the forebulge, where there are fewer vertical movements.

However, since 2007 the deeper subsurface has been receiving more attention in the northern Netherlands because of the growing need to regulate subsurface activities, mainly related to soil energy and a sustainable policy for its use. This also implies the need to weigh best practice with respect to use, which also demands an interdisciplinary approach. Such an approach will allow us, for example, to gain greater insight into the stability of the subsurface, which is of significance in relation to developing safe practices for use such as storage and waste disposal (e.g. 'Beleidsplan voor de ondergrond', Province of Drenthe, 2010).

In relation to the impact of forebulging on the shallow earth's crust, we conclude that the impact of glaciations not only reaches deeper and thus also needs attention (see also Chapter 9), but that a Permian or Lower Trias base would be a good reference level for the correlation of preglacial, subglacial and postglacial influences on landscape forming processes.

A central point of discussion in our approach is the correlation of the spatial distribution of features. Figure 6.3 presents a correlation between 'deep' geological structures, glacial features and properties of the earth's crust as a result of forebulging in the Netherlands. What is important is that we can demonstrate that in the Netherlands the positioning of glacial events is related to systematic relationships between stiffer parts of the earth's crust, tectonic highs and the 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 the positioning of Saalian end moraines in the Netherlands (e.g. Het Gooi and Veluwe regions) has already been mentioned by Edelman and Maarleveld (1958). Although correlations in those parts of the Netherlands are very positive, this has never been studied in detail. Even glacial basins related to the push moraines are all situated in the mid-Netherlands Low. In the northern Netherlands, in our opinion, it is obvious that the asynchronic continuation of the Rehburg phase (tills near Texel, Rode Klif and the Havelterberg; Phase 3, Figure 1.8 correlates with the positioning of the Texel-IJsselmeer High, while the moraines in Groningen correlate with the Groningen High.

The correlation between 'deep' geology, thickness of tills) (Figure 8.3) and the locations with higher HFD values (e.g. Figure 6.7 and Figure 6.9A).

Most thick till deposits in the Hondsrug area are found near Groningen and Schoonebeek, while elsewhere in the northern Netherlands they are found in mid-Friesland and areas related to the Rehburg phase (Section 6.1.2.1; Figure 6.3).

Two processes might explain these thicker till deposits:

(i) Stagnation due to the influence of tectonic highs (near Groningen; Rehburg line with Texel-IJsselmeer High) or surface obstacles (Hondsrug-Hümmling ice stream near Emmen/Nieuw Schoonebeek and an older push moraine near Itterbeck)

(ii) Higher basal melt due to higher HFD values. This is also a possible reason for the dumping of tills in central Friesland, or perhaps even as a result of a combination of stagnation and the presence of a hotspot at the salt diapir of Pieterburen.

8.5 Geothermal heat and basal temperature

Heat flow density (HFD) is an important controlling factor in our model (see also Figure 8.1). Forebulging and the reactivation of faults could have led to higher HFD during glaciation. Thus, loading of the upper crust not only has an impact, in our opinion, on the geoid form of the earth's crust and the distribution of heat in its lower part, and thus also on gravity, but also on the upper crust on a regional scale (e.g. Thorson, 2005). Higher temperatures near salt domes and reactivated faults have not only had an impact on HFD, but must have also forced deep groundwater to the surface (e.g. Boulton, 2005; Piotrowski, 2005, Figure 5.1; Breemer, 2005) with an impact on the permafrost and thus leading to a higher amount of meltwater as we described in Section 3.6.

We hypothesized that a change in physical-chemical conditions due to a change in groundwater quality also affected the behaviour of the Hondsrug-Hümmling ice stream on a broader scale. The main reasons for this are a reversed groundwater flow and the depth of these flows, found at depths where brinewater concentrations above salt diapirs are relatively high (Figure 3.5). A reversed groundwater flow could have an impact on distribution of brine saltwater. Bregman and Lüse (in prep.) found indeed newly formed brinewater indicating new minerals in the lower tills of the Hondsrug. This knowledge could be of interest should areas containing salt diapirs be considered to be used for waste storage, since in the longer term the dissolution of rock salt by groundwater could create a risk of waste entering the hydrological cycle. In addition, dissolution, loading and unloading of the earth's crust can reactivate faults and rock salt remobilization, leading to an unstable host rock for waste disposal. In the glacial history of the northern part of the Netherlands saltdomes playen an important role, not only on glaciers behaviour, but also on change in groundwater flow and distribution of groundwater with a different quality to surface. This process not only eccelerate basal melt, but can lead also to dispersion of polluted groundwater. This knowledge should be important input when testing our model in combination with reversed groundwater flow, subglacial pathways and permafrost but also in modelling environmental impact of storage of wastedisposal in saltdomes in relation to longterm predictions and risk assessments of impact of glaciations on stability of saltdomes

8.6 The need to test our model

Contrary to previous studies, we had the opportunity to study the internal structure of the Hondsrug along its length using profiles at different locations thanks to recent deep road cuttings and due to the use of new and modern techniques such as XRPD analyses and GPR. The results of our observations, combined with modern glaciological knowledge, allowed us to develop process-related interpretations of different aspects and to combine these for the first time. This led to a new model of the genesis of the Hondsrug area.

A discussion point in our study, however, is our proposal about the location of the source area and its relationship to deep geological structures in the entire area influenced by the Hondsrug-Hümmling ice stream. Our conclusions are strongly based on correlations of geological structures, patterns of geophysical phenomena and similarities between our observations and studies in other areas. New insights, for example based on XRPD analyses and GPR measurements, can further strengthen and support the model, which is ready for additional geophysical, geohydrological and glaciological – preferably integrated – modelling in the future. We consider that this kind of modelling is the next step, not only i) to test our model, but also ii) to gain more insight into such issues as the stability of salt domes and iii) the effect of reversed groundwater flow on groundwater and soil quality, which might have been influenced by another later glaciation. The possible impact of glaciations on these phenomena and, more generally, the impact of rebound on landscape-formation processes as demonstrated in our study, will be important to land use decisions such as in the case of permanent waste disposable and the use of salt domes for other functions such as storage of compressed air (CO_2 sequestration).

The correlations between ‘deep and shallow’ and the impact of glaciations will be of scientific interest to those studying the IML. Our study will also assist in understanding ice flow and the positioning of ice streams better with respect to palaeo-reconstruction in other regions or even for understanding present processes in glaciated parts of the world. We have not tested our model’s applicability to other situations, but we have strong indications that better insight into comparable situations will improve glacial models, for example in the Baltic. Therefore, our study can be seen as indicative, and the first step would be to repeat similar studies in other countries. This makes the Hondsrug study of scientific interest for quaternary geological studies related to palaeo-reconstruction of glacial landscapes in the IMLs of Europe, Eurasia and North America. A follow-up study would not only contribute to the improvement of palaeo-reconstructions, but would also contribute further insight into the genesis and dynamics of ice streams themselves and their effect on landscape-formation processes, including important geographical and temporal variations.

The coupling of a glacier flow model and a geological model (which includes parameters such as loading, stiffness of the upper earth’s crust, geothermal flux, the salinity of groundwater and unloading) could provide a quantitative estimate of the influence of deeper geology on subsurface and surface processes such as subglacial groundwater flow and ice stream behaviour. It will be of scientific interest to undertake such studies in interdisciplinary teams in areas (i) with hard rock and (ii) without hard rock and (iii) with Weichselian ice advance and (iv) without Weichselian ice advance. This means that the Hondsrug (without hard roch and Weichselian ice cover) will be one of the key areas for further (comparatively) study.

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

Section 1.5 provided an overview of previous research on 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 glaciotectonic folding (Van Calker, 1901; Lorié, 1891; Jonker, 1905), or by the retreat of an ice sheet (Ter Wee, 1979). Observations on tills indicating different ice streams (NE-SW and NNW-SSE) (e.g. Dubois, 1902) concur with modern insights (e.g. Van den Berg and Beets, 1987; Rappol, 1987; Bregman and Lüse (in prep.) and are also confirmed by our study.

With respect to present insights into the impact of forebulging (this study), Dubois (1902) had already considered the role of loading and unloading, although his explanation of the difference in height between the Hondsrug and the Hunze valley on the eastern side of the Hondsrug was completely wrong, as we now know that it was primarily lowered by glacial and postglacial erosion. Zonneveld (1975) and De Gans (e.g. 1981) also related the origin of the Hondsrug to deeper geological structures, but did not formulate their ideas as concretely as Van den Berg and Beets (1987), who described the relationship between the occurrence of fine and coarse-grained subglacial bed deposits (Tertiary clays; Rhine sediment) and the glacier's behaviour.

While previous studies and related discussions mainly focused on specific themes, our approach integrates different aspects based on recent records and also involves 'deep' geology and modern insights into subglacial meltwater discharge as classic themes related to till types and erratics. Our model of reconstruction – based on recent observations – reveals a sharp difference in the chronology of events and the different nature of the 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, while iii) in the southern part there is no deformation caused by the ice flow. Thus, some previous observations, which are confirmed by our study, concern the results of a former glaciation phase and are even related to a former, different glacial landscape (Phase 2, Figure 1.8).

A major issue of debate, which has been ongoing since the beginning of the nineteenth century, concerns how the Hondsrug-Hümmling ice stream was initiated, due to an almost 90 degree 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 the damming of 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 initiation of an ice stream in a stagnant ice field as proposed by Rappol (1987) and Van den Berg and Beets (1987), which we linked to a source of geothermal heat in the onset zone, 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 was in 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 local conditions triggered ice flow in the ice field.

The breach of Lake Weser in the northern part of the Münster Embayment acted as a pulling force (Winsemann *et al.* (2010). These kinds of pull-induced ice streams have also been described by Stokes and Clark (2005) in relation to the Dubawnt Lake ice stream in Northern Keewatin, Canada (see also Section 8.2). We therefore suggest a new name for such ice streams that occur due to these phenomena: push-pull ice streams.

8.8 More attention to dynamics demands new paradigms

We conclude that the deglaciation phase, after stagnation of the ice advance, is very dynamic. In contrast to classic models of the retreat of an ice front, our study of the Hondsrug area is a 'showcase' which demonstrates that advance and retreat can occur at the same time. We also assume that i) loading and unloading can occur at the same time but in different parts of the glaciated terrain, that ii) changes in groundwater flow occur and that iii) the impact of extremely superficial groundwater pressures in combination with permafrost have an influence on till formation. We consider that this dynamic point of view will have an impact on the future interpretation of glacial processes and models which might contribute to new paradigms (Bitinas, 2008).

Based upon this study our proposal is to focus on developing two paradigms with respect to processes occurring in ice marginal landscapes:

- One line of revision should entail paying more attention to dynamics and variations during the formation of an ice stream, with more attention to local patchy zones exhibiting differences in ice thickness, precipitation and windshield conditions (e.g. Van den Berg *et al.,* 2007), but also on the impact of local stagnation of the ice flow, both of which also lead to differences in the accumulation of ice in the IML and ablation.
- We also consider that the dynamics of the deglaciation phase need further research to better understand landscape development as a dynamic and holistic entity. In other words, glacial landscape studies should include the glaciation and the deglaciation phases, as well as dynamic proglacial, subglacial and postglacial processes. We have demonstrated that glacial dynamics, including deglaciation, must be studied on a 'level playing field'. In other words, local and regional glacial studies must always be undertaken in the context of broader geographical spatial and time scales. Smaller scale (in space and time) processes always occur in the context of and superposed on larger scale processes (in space and time), such as forebulging, which has a long relaxation time, since magma is rather inert. The remobilization of rock salt for example may be superposed on forebulging movement in both a constructive and destructive fashion. On the local scale, specific conditions may occur that influence an ice stream's behaviour at that specific spot (occurrence of a salt diapir that results in compression of the ice stream). Glacial rebound can occur heterogeneously in space, where some areas

are more susceptible to rebound than others. Moreover, as we have shown for reversed groundwater flow in the area between Gieten and Borger (Figure 3.4), the blockage of subglacial meltwater by deeper salt structures and permafrost downstream can lead to very strong deformation and specific features such as pipes.

8.9 Postglacial implications

We have explained the origin of the Hondsrug, the aim of our study. However, following the Saalian landscape forming processes, other processes, caused by Weichselian glaciation for example, and processes such as rebound, also had an impact on the present Hondsrug landscape.

Rebound has caused the postglacial uplift of salt domes and a radial river pattern in Drenthe, as described by De Gans (e.g. 2011), and also shifted the main water divide in Drenthe 800 metres to the north. This is the conclusion of our fieldwork in the area of Schoonlo, where we found a deeper (older) river system related to the Drentsche Aa on top of the salt diapir.

More generally speaking, one of the main postglacial implications of glaciations is related to the interaction between glacially induced or formed features and groundwater flow.

The impact of rebound on the Holocene river of the importance of large-scale processes, as is demonstrated in Figure 6.4 is another example of postglacial implications of glaciation on the present landscape. The actual river pattern in the area with Permian salt formations is correlated to the fault systems and blocking structures even on the base of the Permian formation. Rivers change their flow patterns as they pass tectonic blocks (highs and grabens) or where strike-slip faults occur. Our conclusion is that this correlation is related to the 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). Due to halokinesis, an enrichment of halite in the surroundings when salt diapirs were formed could be an explanation for why the tectonic structures of the Permian base are related to surface morphology. However, this is yet to be thoroughly studied (oral confirmation E. Duin/L. Kramer). This implies a displacement of faults, which leads to the influence of deep groundwater flows and to fixed positions of deep seepage areas in Drenthe. These areas are also areas where peat soils have the greatest thickness. This correlation is even stronger where Elsterian buried glacial valleys are found and where double diffuse convection (DDC) has also influenced groundwater flow systems and the positioning of seepage areas, with differences in groundwater quality (Magri, 2011; Bregman and Magri, in prep.). To date, these correlations and conclusions based on modelling are not being used in nature and landscape management systems.

Our study of the roadcuts N34 and N33 offers a good insight into the deeper structure of the Hondsrug. With regard to the hydrology, it is now very clear that (i) till sequences, (ii) deformation of the subsoil and (iii) subglacial features have a huge impact on hydrology. We observed that the inter-layering of tills with very variable permeability (from very sandy to very stiff clay) is common, whereas the general view in previous literature (e.g. Bosch, 1990) is that different (more or less homogenous) tills are superposed. However, even in the case where thick till packages occur, drainage in between the tills by means of piping is common (Figure 8.2), due to the occurrence of coarse material that fills up (Weichselian) frost wedges that penetrate these tills. We have indications that the tills in the Emmen region are more suitable to study conditions of forming then the tills in the Gieten-Borger area, which have more indications of weathering (see also Sections 5.2 and 5.7.5).

Subglacial channels (meltwater channels) might also be influenced by iron pans (e.g. Figure 4.9). This means, for example that, for the calibration of hydrological models, using parameters which assume that the permeability of the tills is homogeneous is not sufficient, due to these piping features. Local knowledge of a till formation is thus indispensable, also for construction works such as road cuttings and to improve the measures taken to protect nature and landscape.

An understanding of the complex geometry of glacial (eroded and deformed) sediments may be very difficult, but with techniques such as GPR (Bakker, 2004) and XRPD analyses (Bregman and Lüse, in prep.) a superior insight is gained compared to that which relies on borings alone.

9. Conclusions

Based upon previous studies and newly acquired data, we presented a new glacial model of the Hondsrug area as a complex of megaflutes which are the result of a Late Saalian ice stream with subflows in a NNW-SSE direction. The Hondsrug was 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. The flow was triggered by a breach of subglacial Lake Weser into the proglacial Lake Münster, which pulled the ice mass causing it to flow (Meinsen, 2011). We propose calling this kind of ice stream a push-pull ice stream. With reference to Stokes and Clark (2005), this kind of terrestrial ice stream is only the second known in the world and as far as we know the best studied.

In the study area, stagnation related to deeper geological structures led to the deposition of thick tills in the northernmost part of the Hondsrug at a height of 6 m above sea level. In this section, older sediments of Elsterian age are also surfacing because of a high amount of meltwater that resulted in large-scale erosion of the tills that were deposited. This 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 was pressed up towards the surface and by 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 the discharge of groundwater through subglacial channels and piping. In the southern part of the Hondsrug area, the Hondsrug-Hümmling ice stream did not cause any deformation of deposits of an older NE-SW ice flow (a thin ice stream till cover). This indicates the occurrence of permafrost and fast ice flow due to flotation of the ice stream in this part of the Hondsrug.

Through a lateral selection and build 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 to their smaller scale counterparts (flutings).

A bit further downstream, tills were dumped into the Itterbeck Basin, where the ice stream changed its flow direction through a tectonically lower area into the Münster Embayment, where most glacial debris was dumped in the proglacial Lake Münster (Winsemann *et al.*, 2011).

The results of our study are compatible with the flotation model of ice streams developed by Jørgensen and Piotrowski (2003) on the basis of a study of a Late Weichselian ice stream at Funen (Denmark), although different in chronology. Rather than the Late Weichselian Funen ice stream, which has different glacial features, the megaflute of the Hondsrug is a Late Saalian feature and not deformed by the last glaciation. This makes the Hondsrug a unique (Saalian) glacial feature. In most parts of Europe, the Weichselian ice advance overprinted and eroded Saalian features almost completely.

The Hondsrug and the Hondsrug-Hümmling ice stream were formed after the maximum Saalian ice advance in a degrading marginal ice field. We have described the controlling parameters and compared these to a hierarchy of controlling parameters developed by Winsborrow *et al.* (2010). In our opinion, subglacial geological processes (the reactivation of faults; shifting mantle flow/HFD) influenced by forebulging played an important role in the onset zone and in combination with ice margin calving. Both these parameters are the main reasons why the flow of the terrestrial ice stream began.

In the future, the new model of the Hondsrug-Hümmling ice stream will require testing and further improvement, as both the onset and the terminal zones need much more attention. However, we suggest that studies of the onset and terminal zones should take different approaches. 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 paid to lithostratigraphy, and particularly to fluvioglacial deposits (e.g. Herget, 2008), as well as the impact of the dumping of debris by the Hondsrug-Hümmling ice stream. The implications of the breach of Lake Weser into the former Lake Münster and its possible influence on the formation of the Untere Mittelterasse 3 (UM 3; Klostermann, 1992) in the Rhine valley must also be addressed.

We consider that the main point of discussion is the link between HFD and a higher basal melting rate, which could be an important key question when testing our Hondsrug model in combination with reversed groundwater flow, the subglacial pathway and the presence of permafrost. Another point of attention should be the correlation between stagnation and basal melt (and their combination) which results in the dumping of melt-out tills. We have strong indications that in the Hondsrug area the presence of thick tills correlates with stagnation due to the occurrence of deeper geological structures. However, our approach was provisional to some extent and the proposed link between 'deep' geology and surface processes requires more attention using modern insights based on glaciological interpretations of glacial deposits and detailed analyses of these sediments using new techniques such as GPR and XRPD.

We conclude that both the glaciation and deglaciation phases are very dynamic and require more attention in the future and could be seen in terms of a new paradigm (Bitinas, 2008). In our opinion, we must pay more attention to the dynamics of and variations that occur during the formation of ice streams, for example in local patchy zones which exhibit different ice thicknesses, precipitation and windshield conditions (e.g. Van den Berg *et al.*, 2007). Moreover, the impact of local stagnation of the ice flow also deserves more attention, with variations in the amount of accumulation of ice in the IML. We consider that these variations also influence regional and local variations in events during the deglaciation phase, which lead to asynchronic developments in time and space, and a patchy pattern of tills which confirm the viewpoint of Piotrowski et al (2004) that glacial reflections on soft beds result in a mosaic of deforming and stable spots.

Furthermore we conclude that the resulting differences in dynamics in the deglaciation phase requires more attention. Glacial landscape studies should include both the glaciation and deglaciation phases, as well as dynamic proglacial, subglacial and postglacial processes. Glacial dynamics, however, including deglaciation, must be studied on a 'level playing field'. In other words, local and regional glacial studies must be related to broader geographical spatial and time scales. We consider that these kinds of studies must take an integrated approach and will only be successful if based upon interdisciplinary cooperation between different fields in the Earth Sciences due to the high complexity of the topic.

A summary of the most important conclusions:

- In most parts of the Ice Marginal Landscapes (IMLs) in Europe, the Weichselian ice advance overprinted and eroded Saalian features almost completely.The megaflute of the Hondsrug is a Late Saalian feature and not deformed by the last glaciation. This makes the Hondsrug a unique (Saalian) glacial feature.

- With respect to the forming processes the Hondsrug is formed by an ice stream triggered by pushing in the onset zone and the breach of Lake Weser in the northern part of the Münster Embayment (Winsemann *et al.* (2010) acted as a pulling force. These kinds of pull-induced ice streams have also been described by Stokes and Clark (2005) in relation to the Dubawnt Lake ice stream in Northern Keewatin, Canada. We suggest a new name for such ice streams that occur due to these phenomena: push-pull ice streams.

- The Hondsrug- Hümmling ice stream and the Dubawnt ice stream are so far we know the only in the world known two inland terrestrial ice streams induced by calving of the terminal zone in a lake(e.g. Clark and Stokes, 2005).

- The unique Saalian glacial feature of Hondsrug is a as well as the described forming processes of interest for fundamental further scientific research to understand impact of glaciations on landscape forming processes, inclusive impact of loading (and postglacial unloading) on stability of deep and shallow geological structures like salt diapirs and the earth crust.

- Further research with focus on geo-hydrological and geo-physical modelling of the presented newly developed concepts related to the origin of the Hondsrug contributes to better palaeo-reconstructions of terrestrial ice streams and glacial features, and to better understanding of geoheritage values.

- Our study generated practice focussed knowledge related to glacial impact on sub- and postglacial groundwater flow and for example to stability of salt diapirs in the IML of northwestern Europe which are used or will probably be used for storage of nucleair waste disposal with half-life time longer then the reiteration time of a new glaciation.

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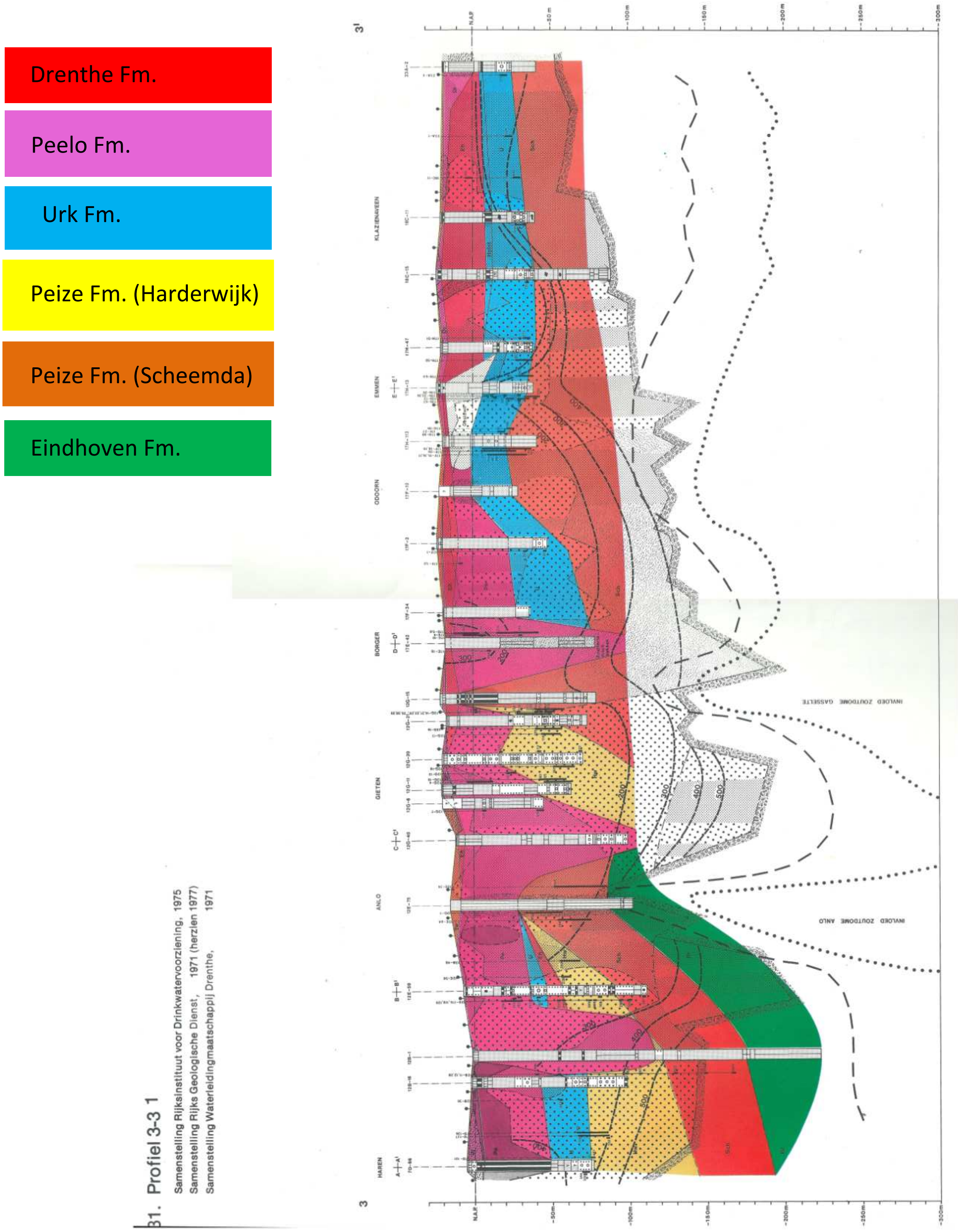
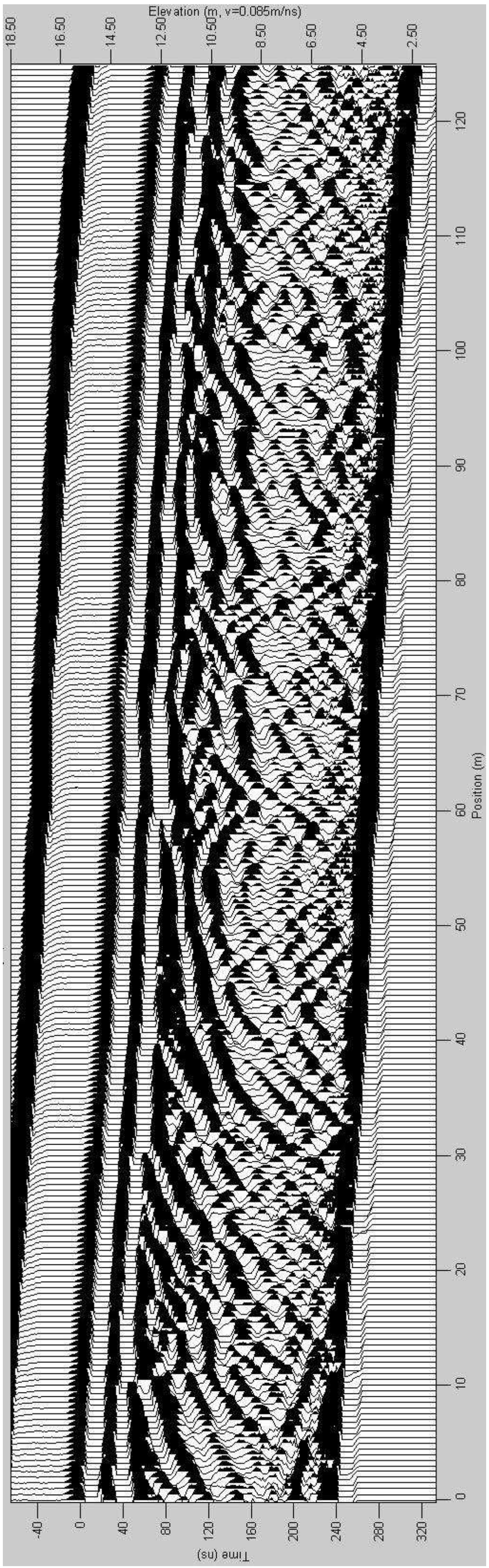
Appendix A

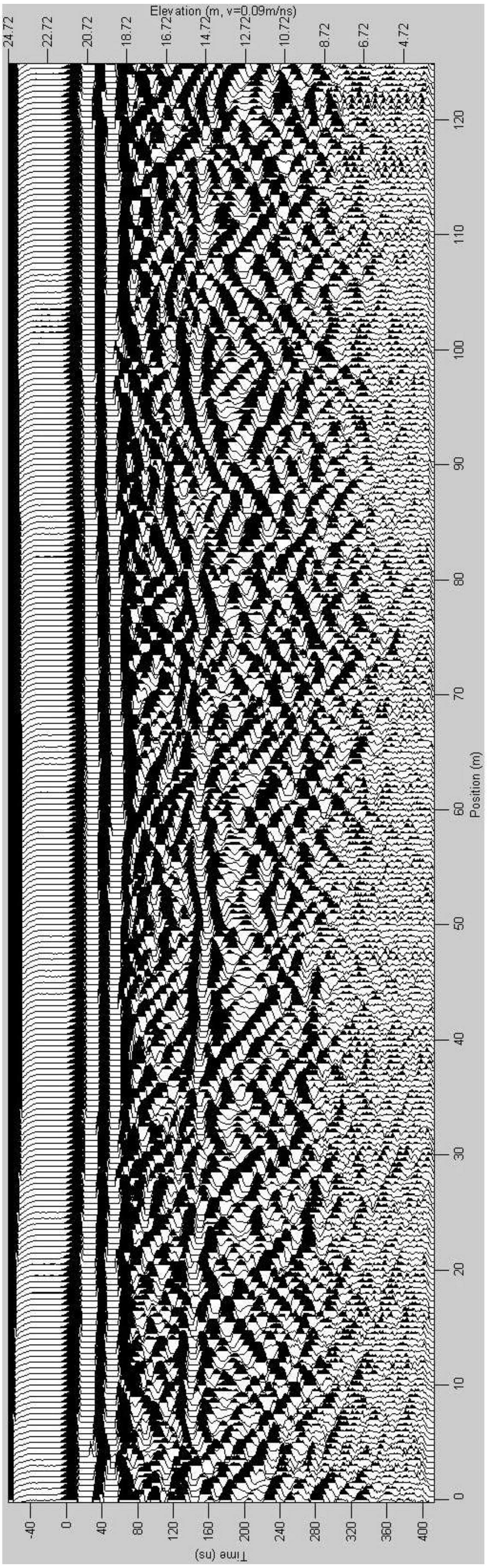
Geological NNW-SSE profile of the Hondsrug indicating impact positioning of salt domes and deformation of Tertiary sediments. In the northern part, coarse-grained river deposits are surfacing or covered by Saalian tills and late-glacial coversands. In the southern area, the subglacial sediments (Peelo Formation) are not deformed.

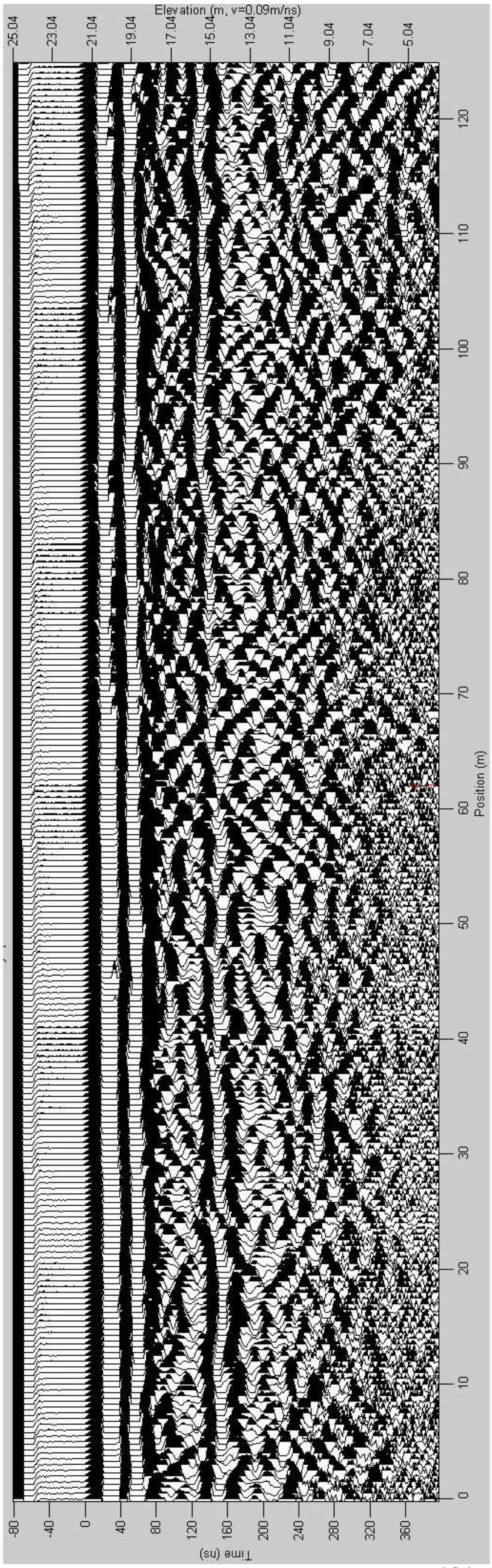


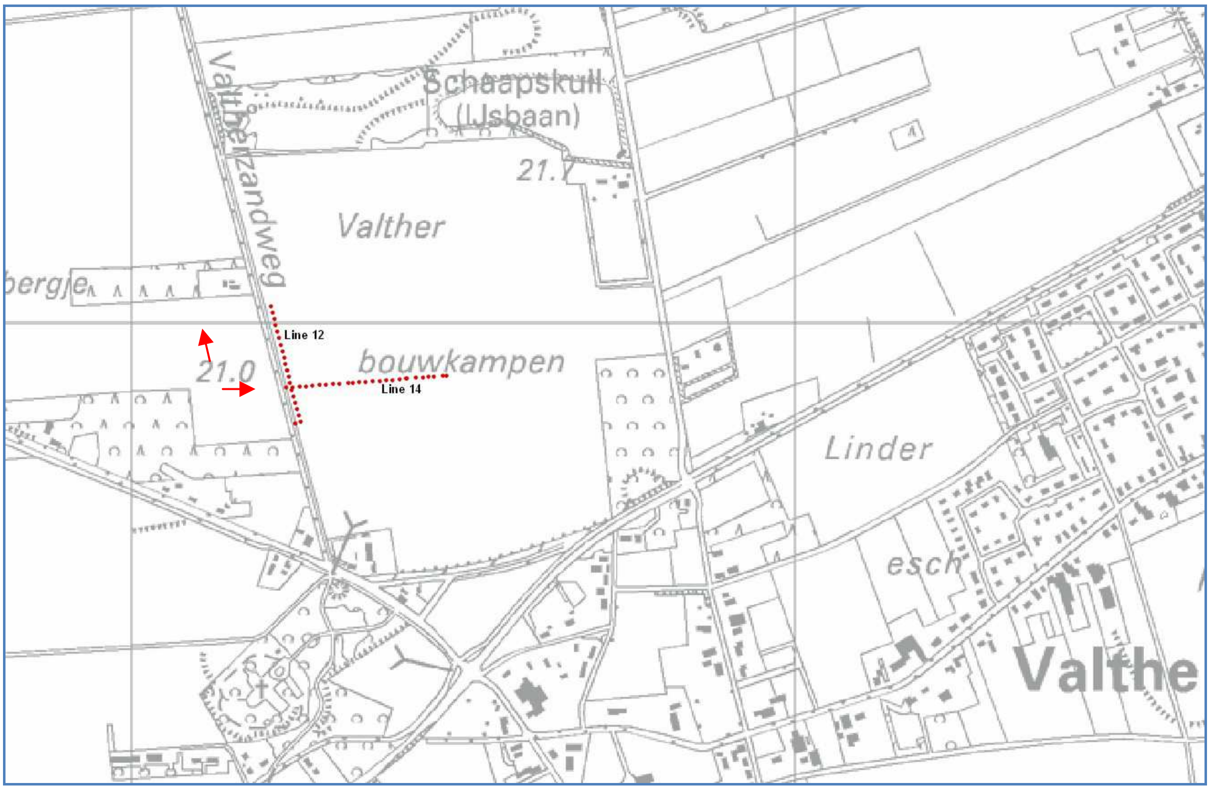
Appendix B: GPR – Buinen – Drouwen- Borger



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

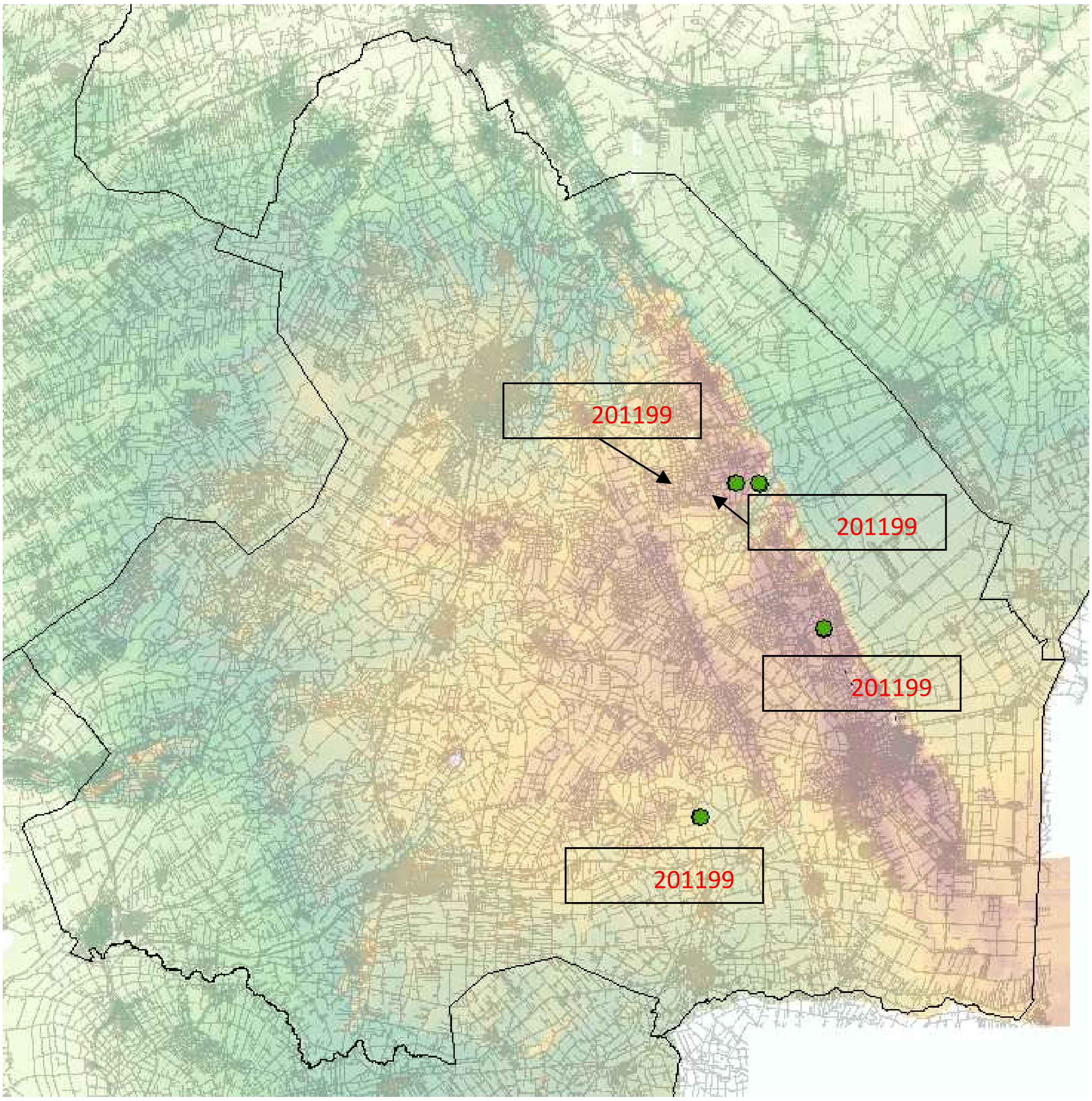






Location map of the GPR cross-sections. The first cross-section shown is W-E, second S-N.

Appendix D: Borehole descriptions



Locations of the borehole descriptions