Arbeitsbericht NAB 10-33

Deep glacial erosion

Review with focus on tunnel valleys in northern Europe

December 2010

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KEYWORDS

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Summary

Tunnel valleys that formed during the past millions of years have been described from various parts of the world. On a smaller scale, recent tunnel valley formation has been documented. This literature review focuses on tunnel valleys in northern Europe formed during the Pleistocene and describes tunnel valley morphologies, valley distribution, bedrock lithology, formation processes and formation rates.

Tunnel valleys are large, overdeepened incisions that appear as individual several kilometre long segments or as network like systems with total length up to > 150 km. Widths of tunnel valleys range between a few hundred metres and a couple of kilometres, in some cases up to 6 km. Typical depths of tunnel valleys range from a few decametres up to a few hundred metres. In the reviewed literature, only very few tunnel valleys reach depths of more than 500 m, which are cut into very soft sediments in northern Germany and in the North Sea. Tunnel valleys often begin and terminate abruptly and are steep-sided with wide and relatively flat bottoms. The longitudinal profile is often described as undulating, with sills, steps, a reverse gradient, or as concave. There are open and buried tunnel valleys, where open tunnel valleys are occasionally occupied by lakes, bogs or eskers, and buried tunnel valleys are filled with glaciogenic, glacio-fluvial, glaciolacustrine, glaciomarine or non-glacial sediments. Tunnel valleys are oriented in a parallel or radial pattern, and are inferred to be parallel to the hydraulic potential gradient mostly at past ice sheet margins. At notches in the ice margin where two ice lobes meet tunnel valleys develop preferably. Some tunnel valleys in the North Sea possibly formed at an ice sheet central location. Tunnel valleys often end at terminal moraines, where the eroded material is deposited onto an outwash fan or sandur. Formation processes influence the morphology and distribution of tunnel valleys. Several generations of overlying and cross-cutting tunnel valleys have been observed, which formed independently from preexisting tunnel valleys and their infill material. Such cross-cutting tunnel valleys appear as anastomosing valleys systems. The underlying lithology of tunnel valleys in northern Europe consists of unlithified Quaternary sediments and Cenozoic sedimentary rocks, such as sandstone, siltstone, claystone, limestone or chalk. The overall distribution of tunnel valleys roughly relates to the lithology of the substrate, and its mechanical characteristics and ability to modulate pore pressure. Thereby, in general, non-lithified sediments seem to be most susceptible to tunnel valley formation, but also weakly lithified sedimentary rocks often host considerable tunnel valleys. Locally, tectonic features such as salt domes influence bedrock lithology and thereby can (but do not have to) deflect tunnel valleys.

The most important formation processes involve subglacial meltwater erosion, whereby most likely tunnel valleys form by a combination of processes, including direct glacial erosion. The reviewed meltwater erosion processes include time-transgressive formation, catastrophic meltwater drainage, megafloods and sediment deformation. Time-transgressive formation is characterised by temporally transgressing and spatially regressing erosion, in some cases in conjunction with glaciohydraulic supercooling. Catastrophic outburst events or jökulhlaups require a water reservoir that drains suddenly, such as subglacial meltwater that is dammed behind a cold based glacier margin and catastrophically released when the ice margin becomes permeable. Megafloods, though controversial, are thought to produce tunnel valleys as a by-product of widespread subglacial sheet floods that channel temporally. Sediment deformation is based on the liquefaction of sediments that are evacuated by meltwater. The sediments are deformed under low effective pressure either in water-filled subglacial channels causing sediment creep, or in gradually developing pipes. Direct glacial erosion includes quarrying/plucking and abrasion, and is usually considered to contribute to tunnel valley formation only in combination with other processes. Erosion rates are difficult to estimate, on the one hand because they

depend on the considered timeframe and whether phases of inactivity can be identified, and on the other hand because the rare observations concern mainly catastrophic outburst floods.

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1 Introduction

The National Cooperative for the Disposal of Radioactive Waste (Nagra) of Switzerland is responsible for developing safe deep-geological repositories for radioactive waste. In northern Switzerland, potential siting regions for such repositories have been identified and are currently further investigated (Fig. 1; Nagra 2008a, 2008b). Among other criteria such as host rock properties and the tectonic setting, the effects of future glaciations are important aspects when assessing the long-term safety of the potential repository sites. The time of concern is 100 ka for low-/intermediate-level waste and 1 Ma for high-level waste and is based on safety analyses, which – among other factors – take radionuclide transport and decay into account. During the next 1 Ma, several glaciations are expected to reach northern Switzerland, and consequently, the glacial erosion potential has to be investigated particularly for the high-level waste sites. Therefore, Nagra evaluates the possible processes and consequences of deep glacial erosion.

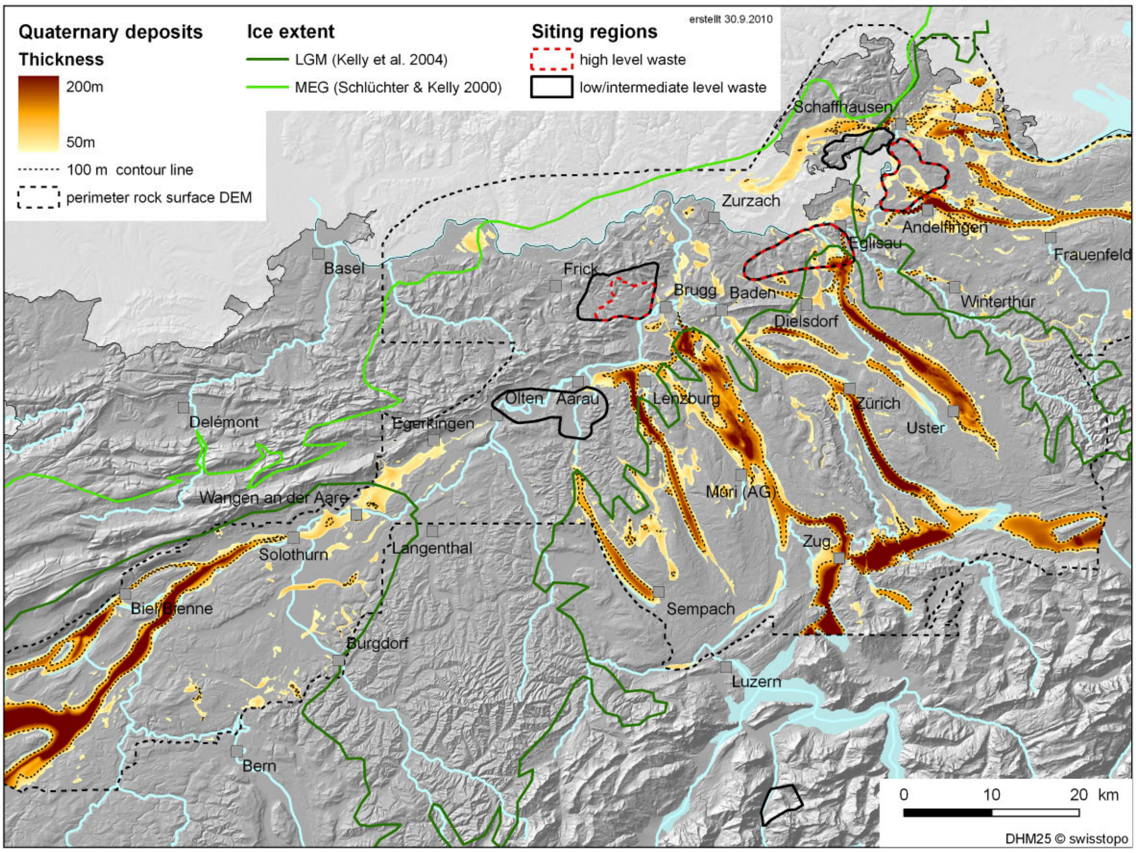


Fig. 1: Thickness of Quaternary sediments in northern Switzerland indicating a system of deep, overdeepened and buried Quaternary valleys in the northern Alpine foreland (modified from Nagra 2008a).

Mapping is based on information from several thousand boreholes and other sources. The ice extent at the Last Glacial Maximum (LGM) and during the Most Extensive Glaciation (MEG) as well as the perimeters of the siting regions for low/intermediate-level and high-level radioactive waste repositories are shown (DEM: Digital Elevation Model).

Recently, a number of new articles have been published on the distribution, depth, sedimentary infill and age of buried glacial valleys in the Alpine foreland (e.g. Jordan 2007, 2010; Graf 2009; Dehnert 2009; Anselmetti et al. 2010; Dürst Stucki et al. 2010; Preusser et al. 2010). Schlüchter et al. (2009) present a new map of the last glacial maximum in Switzerland and Haeberli (2004, 2010) reviewed the climate, extent and characteristics of past glaciations, permafrost conditions, erosion and sedimentation processes of past ice ages for the northern foreland of the Swiss Alps as well as the inferences drawn therefrom for future glaciations. Burki (2009) summarised the main glacial erosion processes in the ice contact zone and their key characteristics, and Fischer (2009) reviewed glacial erosion models. During the "Workshop on Glacial Erosion Modelling" from 29 April to 1 May 2010 in Unterägeri, Switzerland, the state of the art of glacial erosion modelling was assessed and related questions were discussed with leading scientists (see Fischer & Haeberli 2010 for a summary).

Deep glacial erosion features include fjords and glacial troughs, cirques, overdeepened valleys, tunnel valleys and meltwater channels (e.g. Bennett & Glasser 2009). The aim of this report is to complement the studies mentioned above and to review the literature concerning tunnel valleys outside the Alpine foreland. Tunnel valleys have been documented from Pleistocene and ancient glacial sequences in Europe, North America, Africa, Australia and Antarctica (see Chapter 3). However, this report focuses on Pleistocene tunnel valleys in northern Europe (North Sea and adjacent countries) that have been investigated in detail, and in the region of the Great Lakes in North America.

The main questions are:

- Morphology/distribution: What are typical extents, depths and distribution patterns of tunnel valleys and how can they be explained?
- Formation: What are the most common formation processes discussed in the literature?
- Time scales: How long does it take to form tunnel valleys? Are several ice ages required to form deep tunnel valleys? When were the tunnel valleys formed?

This report aims to summarise observations and concepts about the formation of deep glacial erosion outside the Alps. There are similarities as well as differences between the discussed settings and the distal Alpine foreland concerning important factors influencing glacial erosion (e.g. past climate and ice temperature, topography, bedrock geology, tectonics). This report does not draw conclusions about the relevance of the processes proposed in tunnel valley formation to the Alpine foreland, but aims at providing input for such discussions, comparisons and related process-oriented research.

The terminology for tunnel valleys is discussed in Chapter 2. In Chapter 3 the geographical distribution is reviewed and in Chapter 4 the morphology, the substrate and the infill of tunnel valleys are described. In Chapter 5, proposed formation processes and erosion rates are discussed and the findings are summarised in the concluding Chapter 6.

2 Terminology

A variety of terms are used in the literature for the features discussed in this report such as tunnel valley, tunnel channel, overdeepened buried Quaternary valley, palaeovalley, subglacial meltwater channel or (linear or major) incision (Ó Cofaigh 1996; Abed et al. 1993; Clayton et al. 1999; Huuse & Lykke-Andersen 2000a; Sugden et al. 1991; Ehlers & Wingfield 1991; Wingfield 1990). In German, the most common terms are Rinnental or other word constructions associated with the word 'Rinne', Tunneltal or übertieftes Tal, and in rare cases Fördental or Glazielle (e.g. Woldstedt 1952; Grube 1979; Hinsch 1979; Smed 1998). Some of the terms are associated with the formation process or time, whereas other terms are descriptive or neutral without the intention to imply a specific morphology or origin.

Ehlers & Wingfield (1991) and Wingfield (1990) discuss the term for tunnel valleys based on an overview given by Long & Stoker (1986). According to this review, the term 'tunnel valley' was already used early on by Ussing (1903) for features in Denmark that were formed by subglacial meltwater erosion. The term 'tunnel valley' originates from the subglacial drainage channels that form a tunnel at the base of an ice sheet; the resulting linear erosion feature has been referred to as valley (Ehlers 1994). Since the early 20th century, many authors used the term tunnel valley, such as Mooers (1989), Praeg (2003) or Jørgensen & Sandersen (2006). However, Ehlers & Wingfield (1991) use the non-genetic term 'linear incision' and argue that the term 'valley' or 'palaeovalley' refers to a fluvial genesis and should have a falling thalweg. Since these two arguments do not apply to the discussed features, Ehlers & Wingfield (1991) refuse the term tunnel valley. Many authors use 'channel', in some cases specified such as ancestral channels (Hamilton & Smith 1972), sub-bottom infilled channels (Dingwall 1975) or tunnel channels (e.g. Clayton et al. 1999; Beaney 2002; Rains et al. 2002). Wingfield (1990) and Ehlers & Wingfield (1991) write that the term 'channel' indicates a continuous incision rather than an enclosed one. Instead, Wingfield (1990) uses the term 'major incision', which excludes smaller dimensioned features and does not imply assumptions about shape and origin. However, Jørgensen & Sandersen (2006) argue that 'incision' implies that the features have been incised, but according to Boulton and Hindmarsh (1987) the features were possibly formed by the deformation of sediments. Therefore, Jørgensen & Sandersen (2006) prefer the well-known and widely used term 'tunnel valley' for buried and open valleys and 'tunnel channel' for smaller melt-water-occupied, sediment-walled conduits.

Clayton et al. (1999) differentiate between the terms 'tunnel valley', 'tunnel channel' and 'collapsed pipe' depending on the formation process which is reflected in the morphology. Therefore, tunnel valleys are formed either by a subglacial river that was considerably narrower than the valley and meandered over the wide valley bottom, or by fluidised subglacial sediments that flowed into an already existing narrow river channel. They define tunnel channels in a hydrological sense where the channel is in a bank-full condition. Collapsed pipes are depressions caused by collapsing pipes that were well below the glacier bed and initiated by groundwater piping. Clayton et al. (1999) describe tunnel valleys as larger, and more irregular than tunnel channels, with a variable width and often accompanied by eskers. Tunnel channels are smaller with a uniform size, steep-sided, slightly meandering, fewer tributary valleys, and without eskers.

Bennett & Glasser (2009) describe tunnel valleys and tunnel channels as macroscale features (> 1 km) which are large, sinuous, steep-sided valleys or depressions that may contain enclosed basins in their bottom. They specify that tunnel valleys tend to be infilled with sediments, occurring both on continental shelves and in lowland areas, and that tunnel channels are incised into bedrock, glaciogenic sediments or other materials. Since the mentioned characteristics for tunnel valleys and channels are not mutually exclusive, it is assumed that the two terms are used interchangeably.

Bennett & Glasser (2009) categorised subglacial meltwater channels and ice-marginal meltwater channels as mesoscale features (between 1 m and 1 km). They describe subglacial meltwater channels as steep-sided channels with an orientation discordant with the local topography and possibly with an irregular 'up and down' profile. Ice-marginal meltwater channels are described as starting and ending abruptly, amongst other characteristics (Bennett & Glasser 2009).

Many examples of tunnel valleys share characteristics with subglacial meltwater channels, such as abrupt start and end of a valley, irregular and undulating valley bottoms, steep sides or anastomosing pattern (e.g. Huuse & Lykke-Andersen 2000a; Sjogren et al. 2002; Jørgensen & Sandersen 2006). Size is one of the main differences between tunnel valleys and subglacial meltwater channels, although the transition is smooth (Benn & Evans 1998; Bennett & Glasser 2009). Therefore, in some cases mid-sized features are called either subglacial meltwater channels or tunnel valleys (e.g. Sugden et al. 1991).

In the Alps and the Alpine foreland overdeepened features are called overdeepened basins (Schlüchter 1979; Jordan 2010), subglacial channels (Becker & Angelstein 2004), deeply incised troughs and overdeepened valleys (Nagra 2008a; Fischer 2009), overdeepened glacial troughs (Anselmetti et al. 2010), overdeepened valleys, basins and troughs (Preusser et al. 2010). These overdeepened features are produced by subglacial erosion. However, the surrounding topography is mountainous or hilly in contrast to the low relief environment of tunnel valleys in northern Europe (see also Section 4.2 Underlying lithology). The involved formation processes such as direct glacial or meltwater erosion are probably similar as for tunnel valley formation, but the interplay between these are likely to be different.

The discussion of the terminology shows that there is no consensus and a variety of terms is used for different reasons and for tunnel valleys with diverse appearances. Neither is there an agreement about the formation processes with possible resulting morphologies, and many uncertainties remain about the origin of tunnel valleys (e.g. Mooers 1989; Ó Cofaigh 1996; Clayton et al. 1999; Lewis et al. 2006). Some features are named based on processes (Clayton et al. 1999), which seems daring considering the controversy about formation processes. Therefore, in this report we follow the example of Jørgensen & Sandersen (2006) and use the widely known and applied term 'tunnel valley' as a general term without having the claim to imply one specific formation process or resemblance to one specific type of valley.

In this report, tunnel valleys are defined as large, elongated, overdeepened depressions cut into sediments or bedrock (Ó Cofaigh 1996). They occur as individual segments or as an anastomosing network, are often several kilometres long, maximum a few hundred metres deep and hundreds of metres up to a few of kilometres wide (Jørgensen & Sandersen 2006; Hooke & Jennings 2006; Stackebrandt 2009). Usually they are steep-sided with flat undulating bottoms, begin and terminate abruptly and are open or filled with sediments (Huuse & Lykke-Andersen 2000a; Kristensen et al. 2007, 2008, Stewart 2008). Occasionally, eskers and lakes occupy the valleys (Smed 1998). Tunnel valleys are formed below past ice sheets, predominantly at the ice margins, and are generally oriented parallel to the subglacial hydraulic potential gradient. In some cases, the tunnel valleys terminate at major moraines where they may grade into large subaerial ice-contact fans (Clayton et al. 1999).

3 Geographical distribution of reviewed tunnel valleys

Tunnel valleys have been documented on almost all continents, dating from different geological times (Fig. 2 and Tab. 1). The oldest tunnel valleys date from the Upper Ordovician (~ 430 Ma; for stratigraphic chart see Appendix A) in northern Africa and Arabia. Hirst et al. (2002) and Denis et al. (2007, 2010) investigated tunnel valleys in Algeria and in Niger, respectively, and Le Heron et al. (2004) studied tunnel valleys in Libya and compared them to tunnel valleys in Mauretania, Algeria, Saudi Arabia and Jordan (Ghienne & Deynoux 1998; Hirst et al. 2002; Vaslet 1990; Abed et al. 1993; Powell et al. 1994). Visser (1988) studied tunnel valleys in the northern Cape Province in South Africa. In the Late Paleozoic (Late Carboniferous−Early Permian, ~ 310−290 Ma), steep-sided tunnel valleys were formed in Western Australia that were filled with Tertiary and Quaternary strata (Eyles & de Broekert 2001). Sugden et al. (1991) and Lewis et al. (2006) investigated open 'incised channels' in Antarctica in the Dry Valleys from the mid Tertiary (middle Miocene, 11−12 Ma). The channels share typical characteristics of tunnel valleys. They are probably formed by catastrophic drainages of subglacial lakes that were located beneath the East Antarctic Ice Sheet. The tunnel valleys in the Dry Valleys seem very interesting because part of this ancient landscape has been preserved for about 14 million years due to the long-term hyperarid polar climate that essentially freeze-dried the mountain morphology (Denton & Sugden 2005). Therefore, the Dry Valleys are possibly one of very few places where tunnel valleys are still relatively undisturbed preserved in the landscape. The most exotic place where valleys that were inferred to potentially be tunnel valleys is on Mars, described in Benn & Evans (1998). On photographs taken by the Viking Orbiter tunnel valleys were inferred amongst other possible glacial landforms.

The majority and probably best-investigated tunnel valleys are found in northern Europe and in the region of the Great Lakes in North America. Most European tunnel valleys are located in Denmark, northern Germany, the Netherlands, northern Poland and the North Sea, date from the Pleistocene and are assigned to the Elsterian, Saalian and Weichselian glaciations (for stratigraphic chart during Quaternary see Appendix B). Huuse & Lykke-Andersen (2000a) compiled a map of known tunnel valleys in this area with their inferred glaciation affinity and glaciation limits (Fig. 3). Stackebrandt et al. (2003) produced a depth map of the base of Quaternary deposits for the Baltic Sea and adjacent regions (Fig. 4). Lidmar-Bergström et al. (1991) reported tunnel valleys in southern Sweden cut into limestone, and Baltrūnas et al. (2007) identified tunnel valleys in southern Lithuania that are incised into sediments such as claystone, sandstone and limestone from the Upper Cretaceous to the Eocene (35−100 Ma) (Sigmond 2002). Johansson (2003) investigated in western Finnish Lapland up to 4 km long tunnel valleys that are only 50−150 m wide and 30 m deep. Compared to the other northern European tunnel valleys, they are very shallow and narrow. The smaller extent can be explained by the underlying Precambrian bedrock that is much harder than the sediments found in the North Sea and adjacent areas. Because of the smaller scale, it could be argued that the Finnish tunnel valleys are better described as subglacial meltwater channels rather than tunnel valleys.

In North America, tunnel valleys are mainly found in the region of the Great Lakes in Ontario, Minnesota, Wisconsin, Michigan, Washington and New York State (e.g. Mooers 1989; Shaw & Gilbert 1990; Booth & Hallet 1993; Booth 1994; Pair 1997; Clayton et al. 1999; Kehew & Kozlowski 2007). Some tunnel valleys also occur in the southern part of Alberta and in the Sea of Nova Scotia (Boyd et al. 1988; Rains et al. 2002). More tunnel valleys in North America seem to have smaller extents, in particular valley depth, than the tunnel valleys in northern Europe, nevertheless, they are called tunnel valleys rather than subglacial meltwater channels. The underlying lithology consists mainly of Precambrian rocks mantled by glacial deposits (e.g. Pair 1997). Of the reviewed literature in North America, only few buried tunnel valleys were investigated with geophysical methods. Consequently, there is less detailed knowledge about the morphology of the buried tunnel valleys, which can influence the conclusions drawn about the valley formation processes (e.g. Clayton et al. 1999).

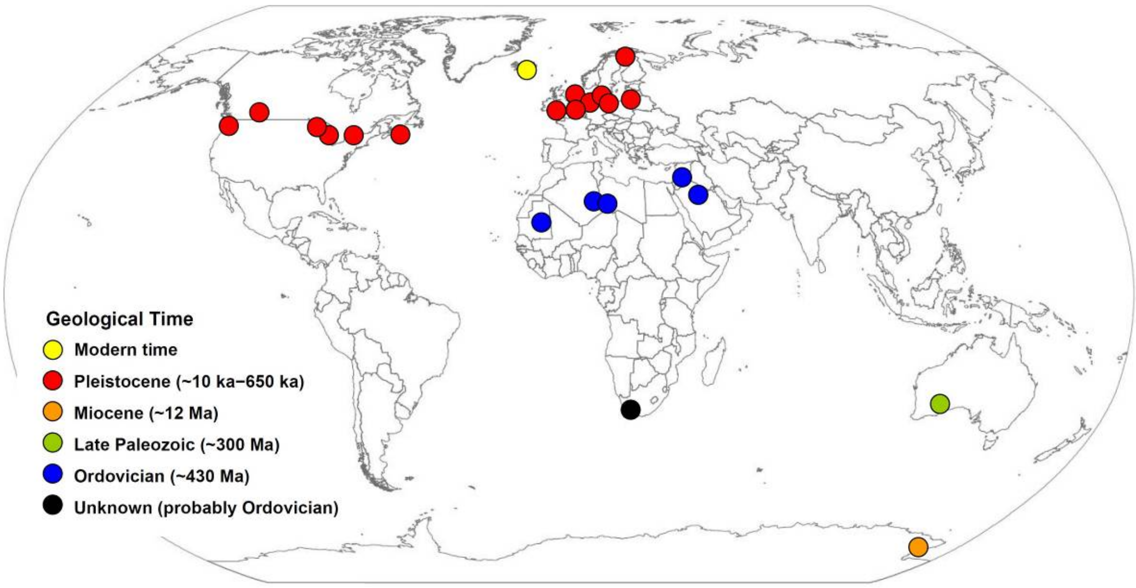


Fig. 2: Worldwide geographical distribution and age of tunnel valleys reviewed in this report (compiled from various sources, see Table 1).

Tab. 1: Worldwide distribution of tunnel valleys reported in the literature.

Area [Age]	Country/Region	Source
Europe [Pleistocene, except modern tunnel valleys in Iceland]	North Sea	Wingfield 1989, 1990; Ehlers & Wingfield 1991; Huuse & Lykke-Andersen 2000a; Praeg 2003; Kluiving et al. 2003; Clark et al. 2004; Lonergan et al. 2006; Kristensen et al. 2007, 2008; Stewart 2008; Lutz et al. 2009; Stewart & Lonergan 2011
	northern Germany	Woldstedt 1952; Grube 1979; Hinsch 1979; Kuster & Meyer 1979; Ehlers et al. 1984; Ehlers & Wingfield 1991; Piotrowski 1994, 1997; Gabriel et al. 2003; Stackebrandt, 2009; Tezkan et al. 2009; BURVAL 2009; Rumpel et al. 2009; Götze et al. 2009
	Denmark	Huuse & Lykke-Andersen 2000a; Danielsen et al. 2003; Jørgensen et al. 2003a, 2003b; Sanderson & Jørgensen 2003; Jørgensen & Sandersen 2006, 2009; Larsen et al. 2009; BURVAL 2009; Sandersen et al. 2009; Krohn et al. 2009
	Netherlands	van Dijke & Veldkamp 1996
	southern Sweden	Lidmar-Bergström et al. 1991 (Skåne)
	northern Poland	Ehlers & Wingfield 1991
	United Kingdom	Golledge & Stoker 2006 (Scotland)
	Iceland	Björnsson 1996, Russell et al. 2007
	Lithuania	Baltrūnas et al. 2007
	Finland	Johansson 2003
North America [Pleistocene]	NY State	Pair 1997
	Michigan	Sjogren et al. 2002; Fisher & Taylor 2002; Kehew & Kozlowski 2007
	Wisconsin	Clayton et al. 1999, Cutler et al. 2002
	Minnesota	Mooers 1989; Patterson 1997; Clayton et al. 1999
	Ontario	Shaw & Gilbert 1990; Brennand & Shaw 1994; Pugin et al. 1996; Russell et al. 2003
	Alberta	Rains et al. 2002; Sjogren et al. 2002; Beaney 2002
	Washington	Booth & Hallet 1993; Booth 1994
	Nova Scotian continental shelf	Boyd et al. 1988
	Laurentide ice sheet	Hooke & Jennings 2006
Africa [Ordovician]	South Africa	Visser 1988
	Algeria	Hirst et al. 2002
	Libya	Le Heron et al. 2004
	Niger	Denis et al. 2007, 2010
	Mauritania	Ghienne & Deynoux 1998
Middle East [Ordovician]	Saudi Arabia	Vaslet 1990, Clark-Lowes 2005
	Jordan	Abed et al. 1993; Powell et al. 1994

Area [Age]	Country/Region	Source
Australia [Late Paleozoic]	Western Australia	Eyles & Broekert 2001
Antarctica [Miocene]	Dry Valleys	Sudgen et al. 1991; Lewis et al. 2006

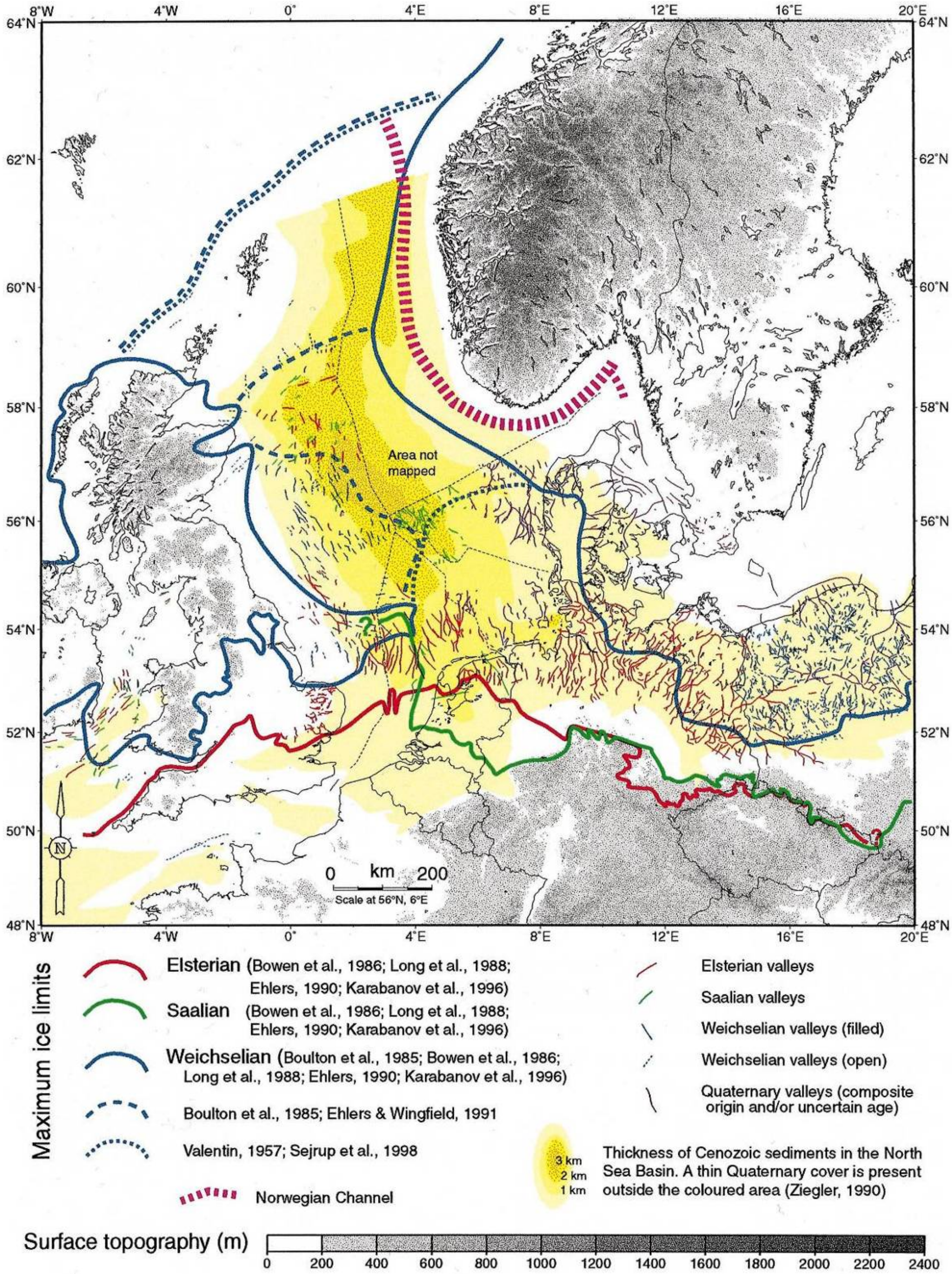


Fig. 3: Overview of tunnel valleys in northern Europe, compiled from various sources (Huuse & Lykke-Andersen 2000a).

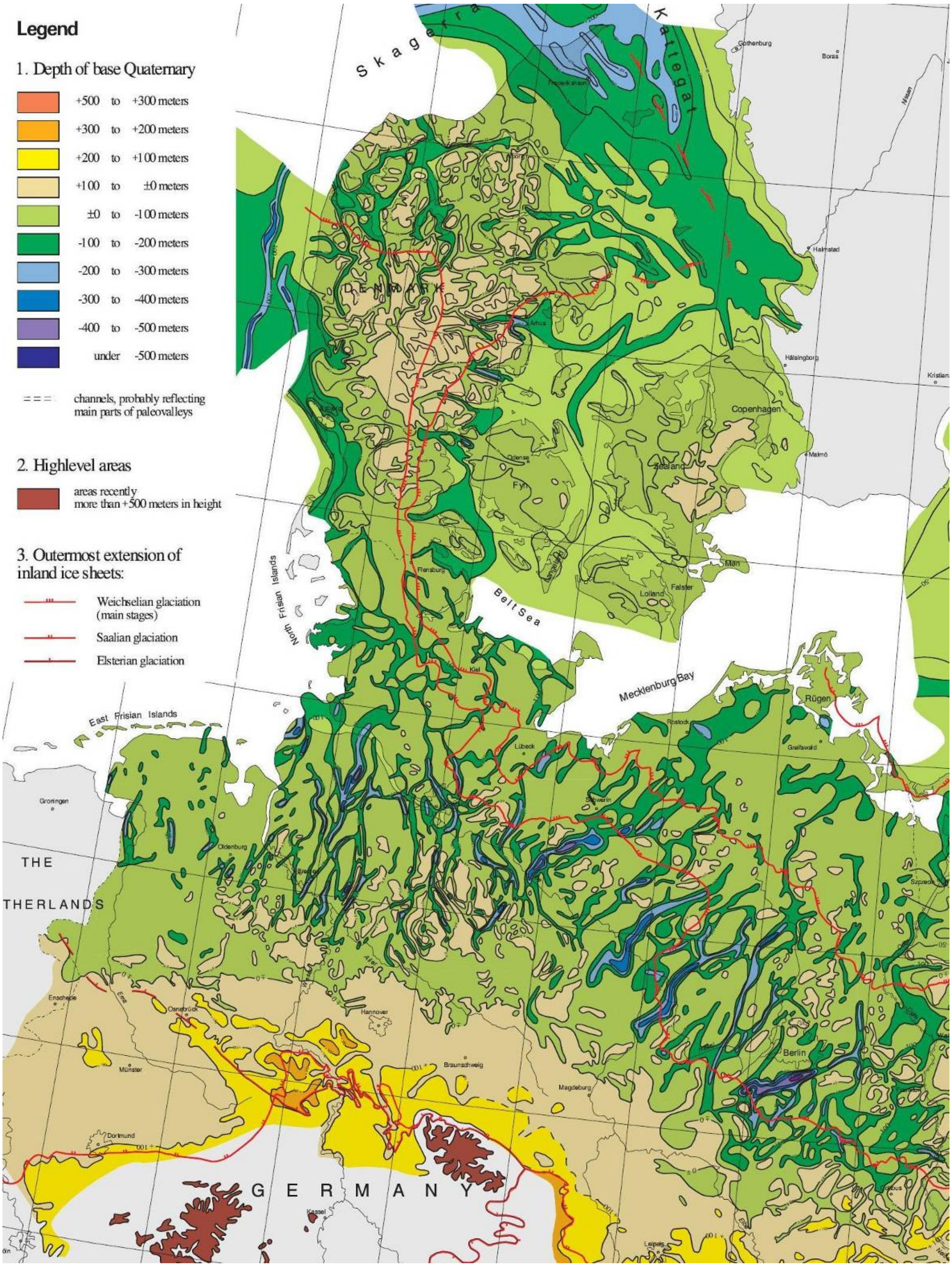


Fig. 4: Map of base of Quaternary deposits in northern Germany and Denmark (modified from Stackebrandt et al. 2003).

Some of the longest and deepest tunnel valleys have been mapped in northern Germany and in the North Sea to the west of Denmark (dark blue and purple colours).

4 Description

Various forms and sizes of tunnel valleys exist that depend on the formation processes and substrate. The description and knowledge about the tunnel valleys depend on the applied exploration methods (e.g. detailed 3D seismic measurements versus simple topographic analyses, Jørgensen & Sandersen 2009; Lutz et al. 2009), which need therefore to be considered. Difficulties arise especially to identify the detailed morphology for buried tunnel valleys, where investigation methods are not or only limited available (e.g. Clayton et al. 1999). For example Rumpel et al. (2009) demonstrated that the description of the tunnel valley 'Cuxhavener Rinne' in northern Germany could be refined significantly by using additional data and 3D modelling techniques (Fig. 5). Therefore, the following descriptions of tunnel valleys are only as good as the data and applied methods allow. In the following Section 4.1 the various forms of tunnel valley morphologies are described. In Section 4.2 the underground into which the valleys are cut is described and in Section 4.3 the valley infill is discussed.

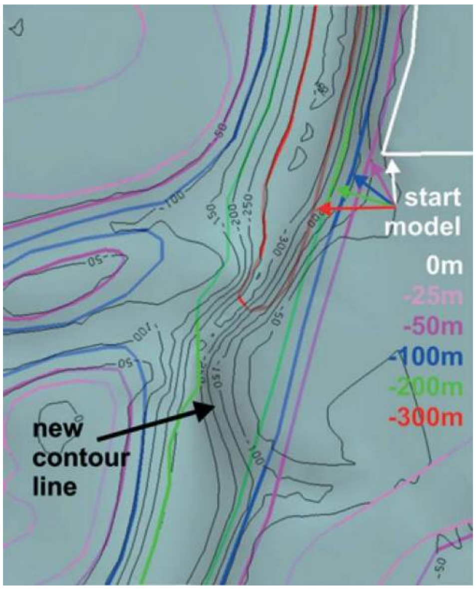
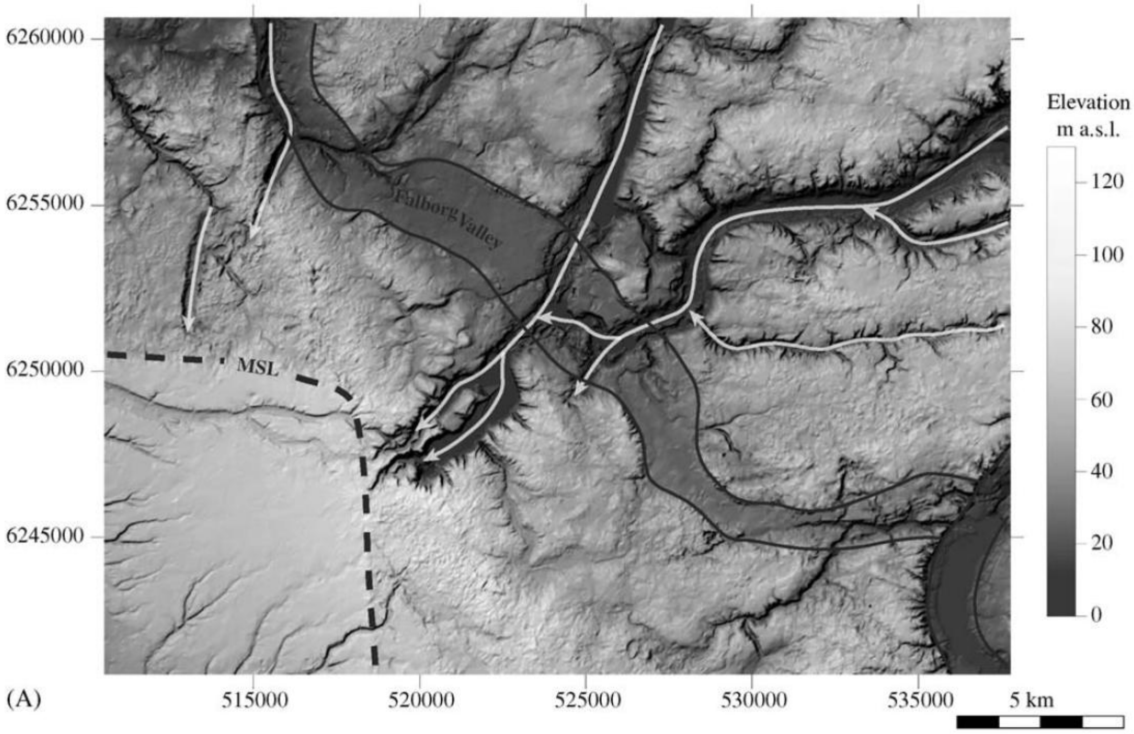


Fig. 5: Map view of the base of the Quaternary surface of the Cuxhavener Rinne before (coloured contour lines) and after (black contour lines) setting up a 3D model using additional geophysical and geological data (Rumpel et al. 2009).

The hill shade of the modelled Quaternary surface (bluish) increases the readability of the black contour lines. The final version of the Cuxhavener Rinne appears narrower and shows a more complex course than before.

4.1 Morphology

There are buried, partly buried and open tunnel valleys, on- and offshore (Fig. 6; Ehlers et al. 1984; Cutler et al 2002; Kluiving et al. 2003; Jørgensen & Sandersen 2006; Kehew & Kozlowski 2007). Jørgensen & Sandersen (2006) studied the dimensions and morphologies of open and buried tunnel valleys in Denmark and concluded based on the shared characteristics that the same processes formed the tunnel valleys. They found that many tunnel valleys from the Weichslian glaciation are open and preserved in the present-day landscape or on the seafloor, whereas tunnel valleys from the older Saalian and Elsterian glaciation are buried (see also Fig. 3 from Huuse & Lykke-Andersen 2000a). In open valleys, overdeepened parts are sometimes occupied by lakes and bogs as it is shown in Fig. 7 on Sjælland Island east of the Danish mainland, where several lakes are lined up along the tunnel valleys (Woldstedt 1952; Smed 1998).



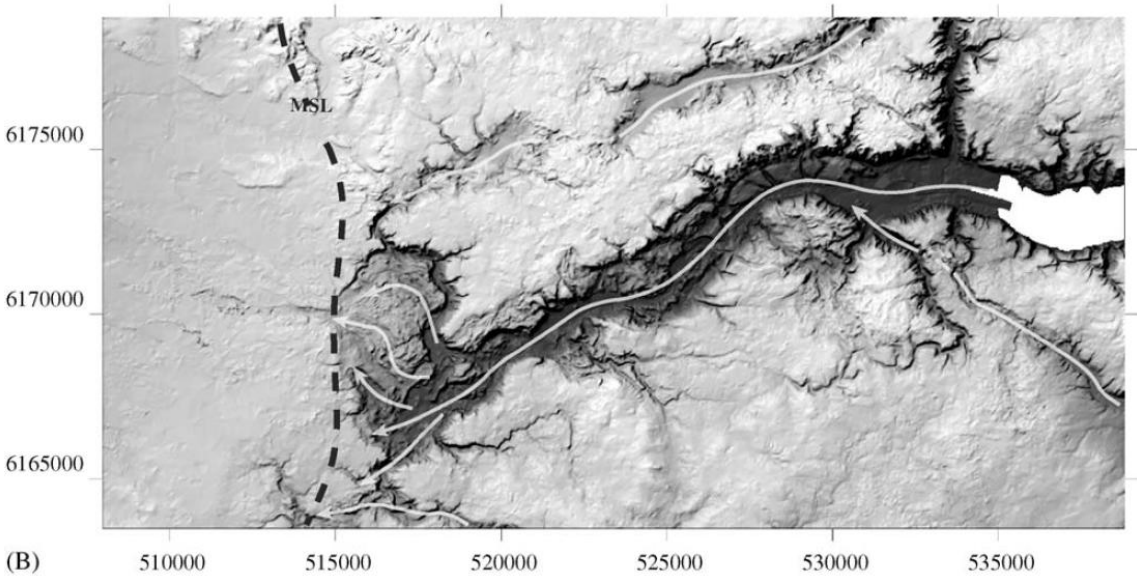


Fig. 6: Digital terrain models showing two examples of open tunnel valleys in Denmark (Jørgensen & Sandersen 2006).

Grey arrow-lines indicate inferred meltwater flow pathways, and MSL (Main Stationary Line) indicates the maximum ice limit during the Last Glacial Maximum. (A) The Hald Sø area. The delineated younger proglacial Falborg Valley formed while the tunnel valleys were still filled with dead ice. (B) Vejle Tunnel Valley, see also Fig. 19.

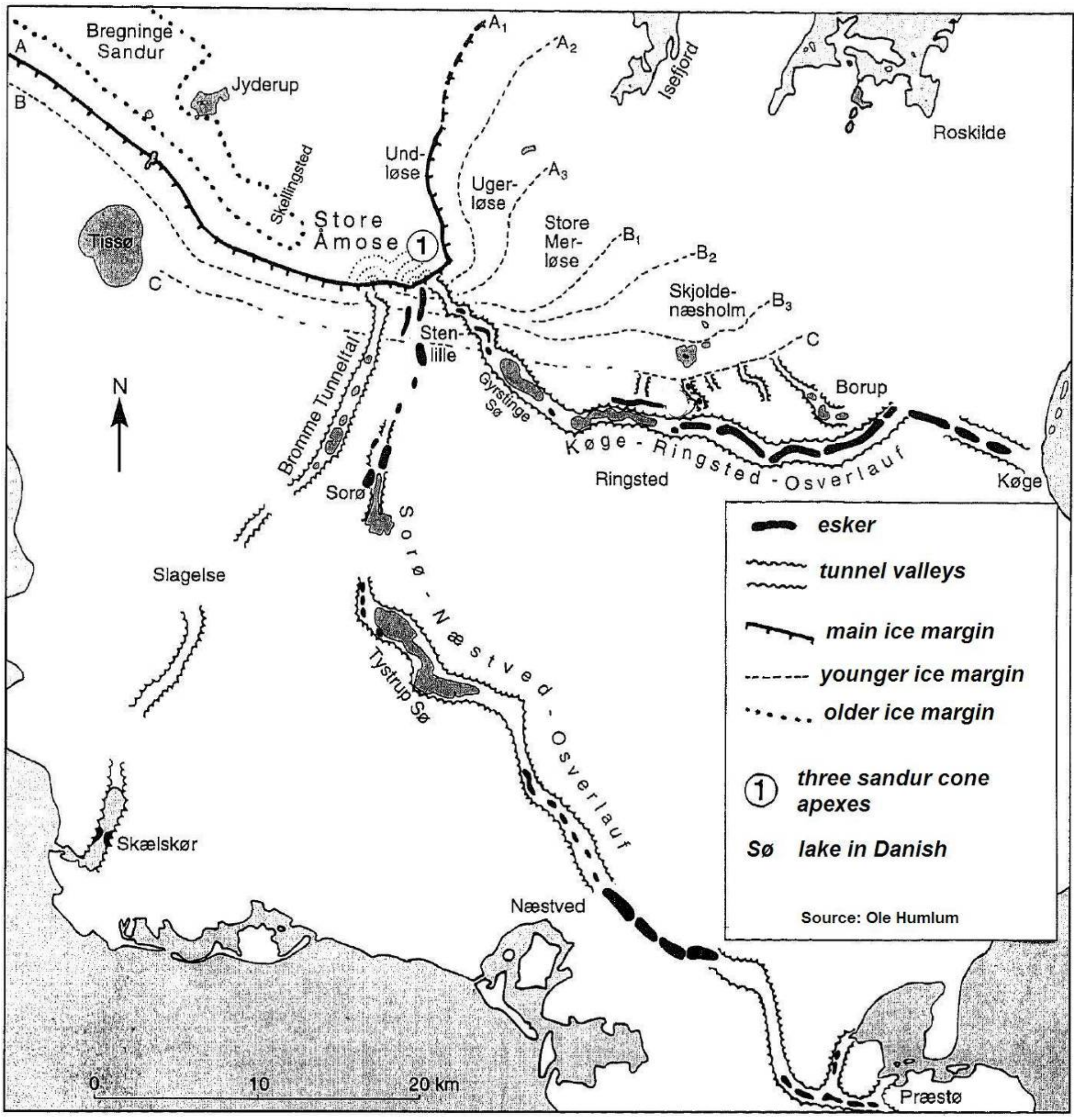


Fig. 7: Three large subglacial streams that were simultaneously active during the Weichselian glacial on Sjælland Island (modified from Smed 1998).

The mouths of the streams were situated close to one another, south of the Store Åmose bog, where three sandur cone apexes are found (1). In the tunnel valleys, several lakes (sø in Danish) are lined up. On the map, the ice sheet covered almost the entire area, leaving only the northwestern corner ice-free. The tunnel valleys drained towards a notch of the ice sheet.

Usually tunnel valleys are found within former glaciation limits, with an orientation parallel to the subglacial hydraulic potential gradient (Kehew & Kozlowski 2007). Therefore, they form a parallel, subparallel to radial pattern, dependent on the shape of the past ice sheet Fig. 8; Beaney 2002; Stackebrandt 2009). Tunnel valleys are also used to define the glaciation limits (Huuse & Lykke-Andersen 2000a). In some cases especially in the region of the Great Lakes in North America, Denmark and Germany, tunnel valleys end at breaches of moraines where outwash fans spread out (Fig. 8 and 9; Clayton et al. 1999; Smed 1998). Wingfield (1990) remarks that tunnel valleys are commonly found in or beneath areas of low relief.

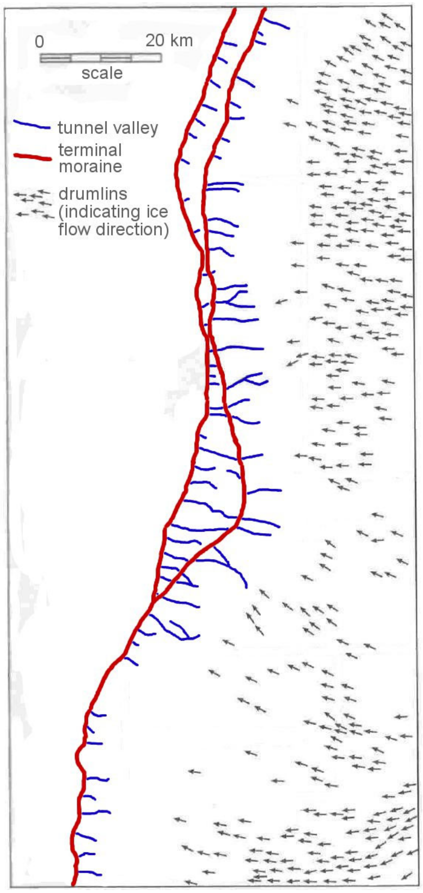


Fig. 8: Tunnel channels (blue) formed in central Wisconsin along the west side of the Green Bay Lobe (modified from Clayton et al. 1999).

The red lines are the Almond moraine (east), which merges southward with the Johnstown moraine, and the Hancock moraine (west). The arrows are drumlins, indicating ice-flow direction. The area west of the moraines is the Driftless Area, which is a region in the American Midwest that escaped glaciation during the last ice age (Albert 1995).

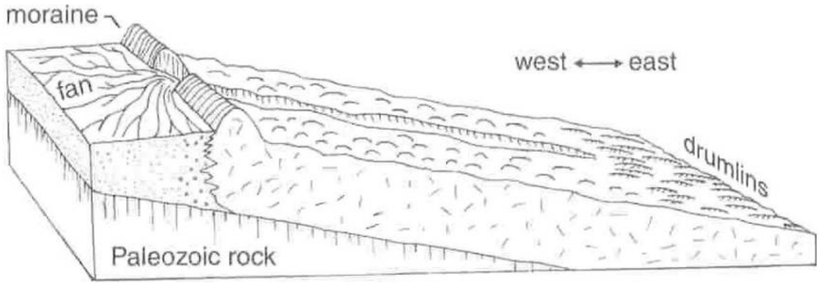


Fig. 9: Stylized block diagram, showing a typical tunnel channel formed along the west side of the Green Bay Lobe of the Laurentide Ice Sheet (Clayton et al. 1999).

A tunnel channel extends from the downglacier edge of the drumlin zone of a hummocky till to a breach in the outermost moraine, with an outwash fan beyond the breach. The dot pattern indicates outwash. The random-dash pattern indicates till and associated sediment. The scale is suggested by the size of the moraine, which is roughly 1 km wide and 5−20 m high.

The longest tunnel valleys of over 150 km length were measured by Stackebrandt (2009) in northern Germany and Huuse & Lykke-Andersen (2000a) in the North Sea west of Denmark (Fig. 4 and 10). Individual tunnel valleys are a few kilometres long reaching up to 20−30 km (Jørgensen & Sandersen 2006). Typical widths are between 0.2 and 1.5 km, but especially in northern Germany, Denmark and in the North Sea up to 6 km wide tunnel valleys have been measured (Fig. 10 and 11; Clayton et al. 1999; Huuse & Lykke-Andersen 2000a; Praeg 2003; Jørgensen & Sandersen 2006; Rumpel et al. 2009; Stackebrandt 2009).

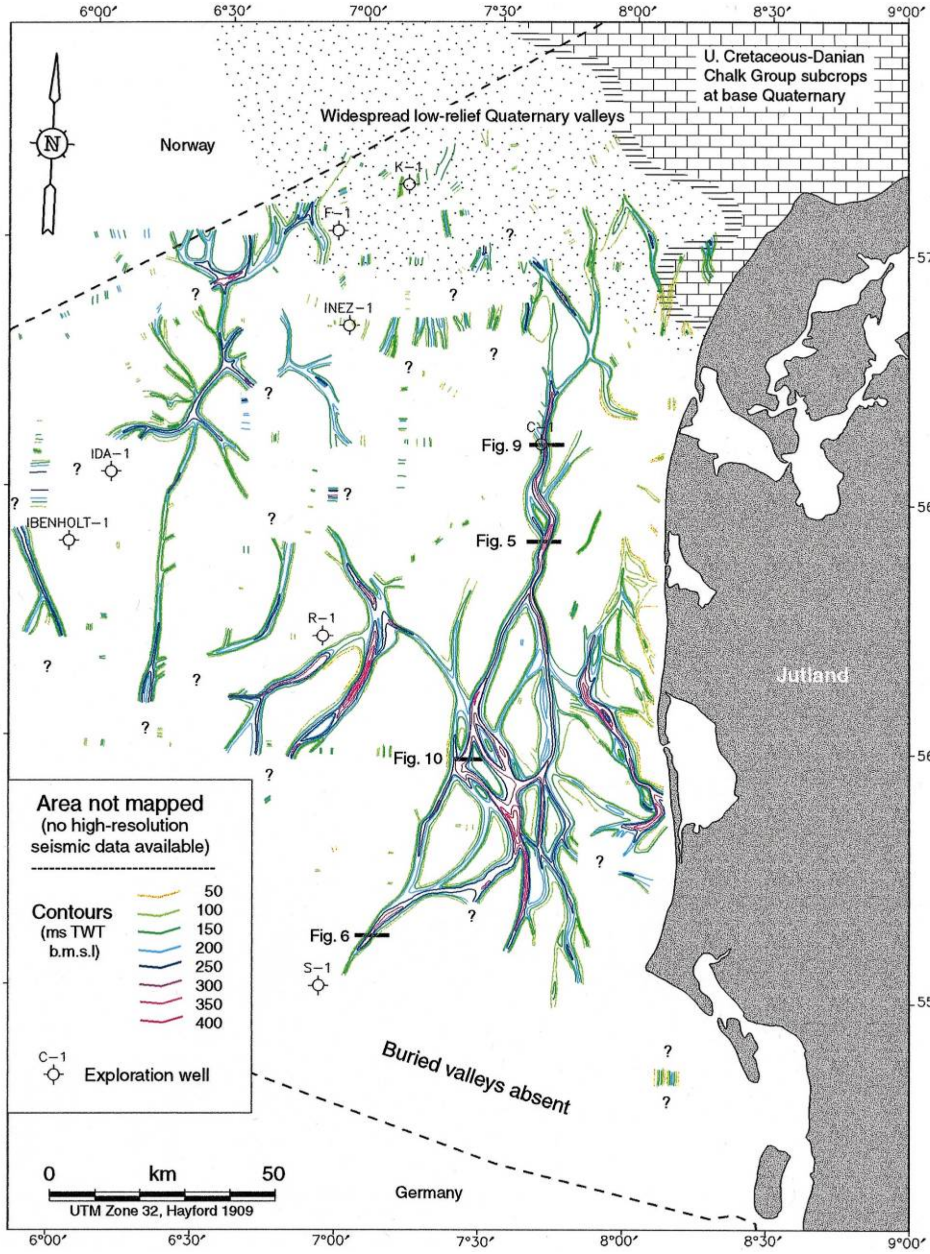


Fig. 10: Buried tunnel valleys in the eastern Danish North Sea (Huuse & Lykke-Andersen 2000a).

Some of the tunnel valleys are more than 300 m deep, several kilometres wide and more than 150 km long.

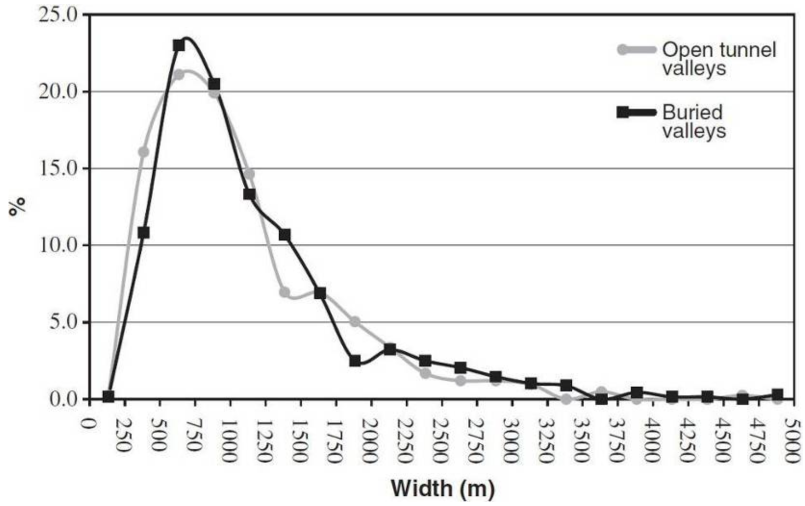


Fig. 11: Frequency distribution of the width of open and buried tunnel valleys in Denmark for intervals of 250 m. Note that narrow valleys may be underestimated (Jørgensen & Sandersen 2006).

Tunnel valleys are typically decametres to a few hundred metres deep (e.g. Kristensen et al. 2007). The greatest depths of more than 500 m have been recorded in northern Germany and in the North Sea where the largest tunnel valleys can be found (Fig. 4; Praeg 2003; Stackebrandt 2009). In northern Germany, the impressive extents can be explained by the underlying lithology that consists of nearly unconsolidated, weakly compacted and water saturated soft sediments. The deposition of this soft sedimentary substrate was favoured by neotectonic subsidence and the related ingression of the sea (Stackebrandt 2009, see Chapter 4.2). Generally, the tunnel valleys recorded in the area of the Great Lakes in North America are shorter, shallower and narrower than the tunnel valleys in northern Europe (Clayton et al. 1999; Hooke & Jennings 2006; Jørgensen & Sandersen 2006). Whether this can be explained by the underlying lithology or duration and type of formation process has not yet been establish. However, Wingfield 1990 studied large tunnel valleys in northern Europe and concluded that their shape and dimensions are comparable regardless of the incised substrate. Andersen (2010) analysed Danish on- and offshore tunnel valleys within various lithologies with statistical tests and found that there are no significant differences regarding depth and shape. As Stackebrandt's (2009) contradicting study concerning the underlying soft substrate of the deep tunnel valleys shows, Wingfield's (1990) and Andersen's (2010) conclusion have to be treated with reservations.

Tunnel valleys often begin and terminate abruptly, especially in front of moraines that form a barrier between the tunnel valley and an outwash fan (Fig. 9; e.g. Clayton et al. 1999; Kristensen et al. 2007). The valley walls are usually steep (Kristensen et al. 2007; Rumpel et al. 2009); Huuse & Lykke-Andersen (2000a) for example measured 10 to 35° steep sides for deep valleys and less than 5° for shallower valleys with more gentle slopes (Fig. 12 and 13, see valley profiles in true scale). Jørgensen & Sandersen (2006) found that the valley steepness varies in general from gentle slopes to sections steeper than 45°. The bottoms have often an irregular undulating or concave longitudinal profile, at times with internal sills, hollows or steps (Fig. 14; Sjogren at al. 2002; Kristensen et al. 2007; Stewart 2008; Rumpel et al. 2009). In some studies (e.g. Wingfield 1990) valley bottoms are described as flat. However, as the study by Rumpel et al. (2009; see also Fig. 5) showed, the applied methods resulted in a higher resolution and the initially streamlined flat valley appears now with a more irregular course and undulating bottom. In the direction of the ice sheet flow, often a reverse gradient has been observed, at times with small steps (Clayton et al. 1999; Rumpel et al. 2009). On the bottom in open as well as in buried tunnel valleys, eskers can sometimes be found (e.g. Sjogren at al. 2002; Jørgensen & Sandersen 2006; Kehew & Kozlowski 2007).

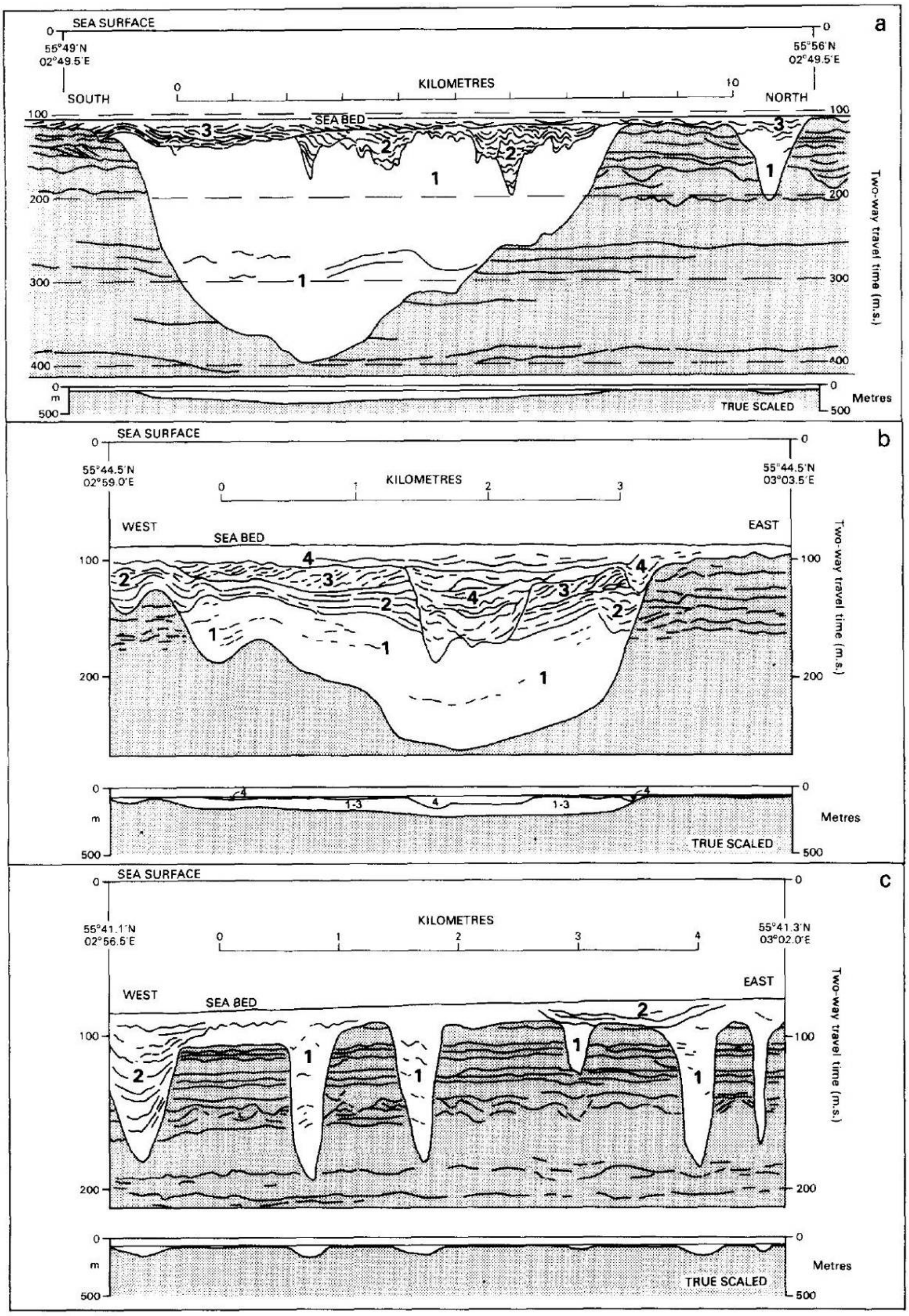


Fig. 12: Profiles and infill of tunnel valleys in the North Sea, interpreted from seismic measurements with and without vertical exaggeration (Wingfield 1990).

The codes for the type facies are (1) chaotic, (2) draped, (3) cross-stratified and (4) variegated.

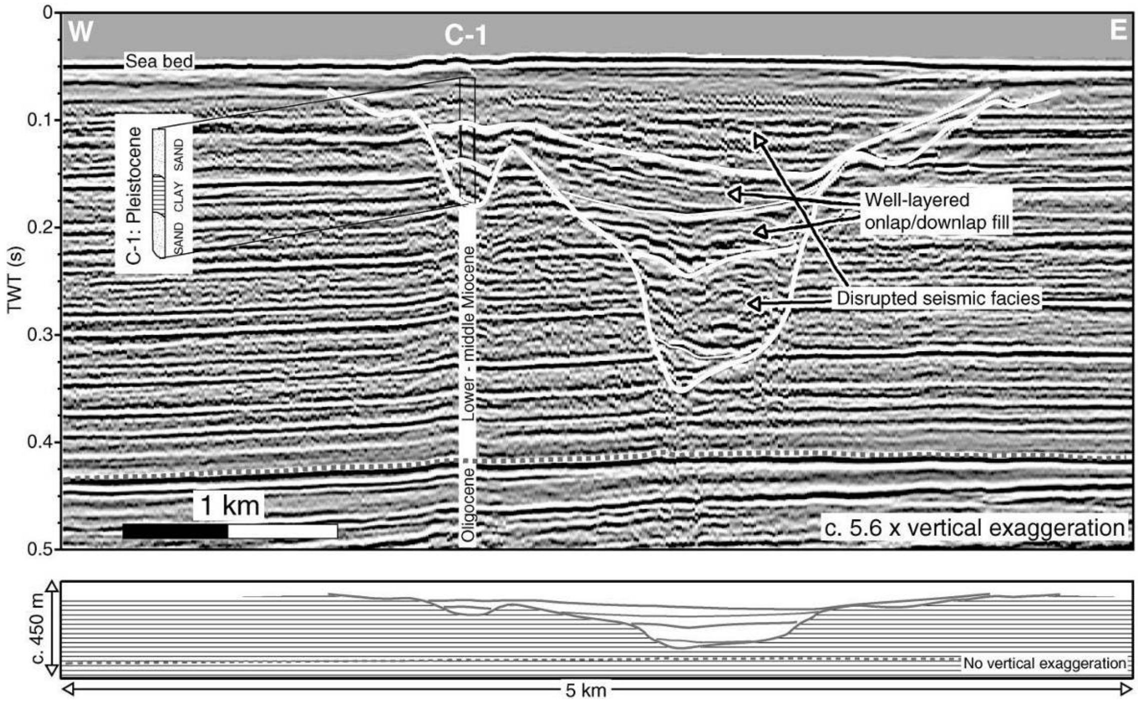


Fig. 13: Interpreted high-resolution multichannel seismic profile across a Quaternary valley with a deep exploration well (C-1), with and without vertical exaggeration (Huuse & Lykke-Andersen 2000a).

The infill is characterized by a lower and upper seismically disrupted/chaotic facies (probably sand and silt), with well-layered on- and downlap fills inbetween (probably silts and clays).

Different generations of tunnel valleys and their geometrical/geochronological relationship have best been described in northern Europe but have also been found in the Great Lakes region (Fig. 12 and 15−18; Wingfield 1989; Piotrowski 1994; Jørgensen & Sandersen 2006; Kehew & Kozlowski 2007; Stewart & Lonergan 2011; Lutz et al. 2009). The tunnel valley generations in northern Europe are generally attributed to the last three glaciations, the Elsterian, Saalian and Weichselian glaciation. Wingfield (1989) developed a scheme of stratigraphic elements based on the Quaternary sequences as they occur under the eastern and western continental shelves (Fig. 18). In the eastern North Sea, Kristensen et al. (2007) found between five and seven valley generations, based on cross-cutting relations, theoretical and palaeogeographical considerations. Whether each generation represents an individual glaciation is undetermined. However, they suggest ice margin oscillations within one or only few glaciations. Jørgensen & Sandersen (2006) suggest that the anastomosing tunnel valley patterns result from valley-re-use effects and related cut-and-fill processes that were not simultaneously active.

In Denmark northwest of Aarhus, Jørgensen & Sandersen (2006) found that some tunnel valleys tend to follow older valley courses, or at least the overall valley pathway. For example, the open Vejle Tunnel Valley in Fig. 19 (and Fig. 6B) southwest of Aarhus follows the course of an older buried tunnel valley. Jørgensen & Sandersen (2006) explain the valley re-use tendency with properties of the underlying tunnel valley that favour repeated tunnel valley formation. Such properties include coarse valley infill or subglacial taliks (layers of year-round unfrozen ground in permafrost areas that form underneath lakes or rivers) that increase groundwater flow and possibly enhance erosion. In addition, the subglacial morphology and the ice flow direction relative to existing valleys influence the re-use tendency of tunnel valleys (Jørgensen & Sandersen 2006).

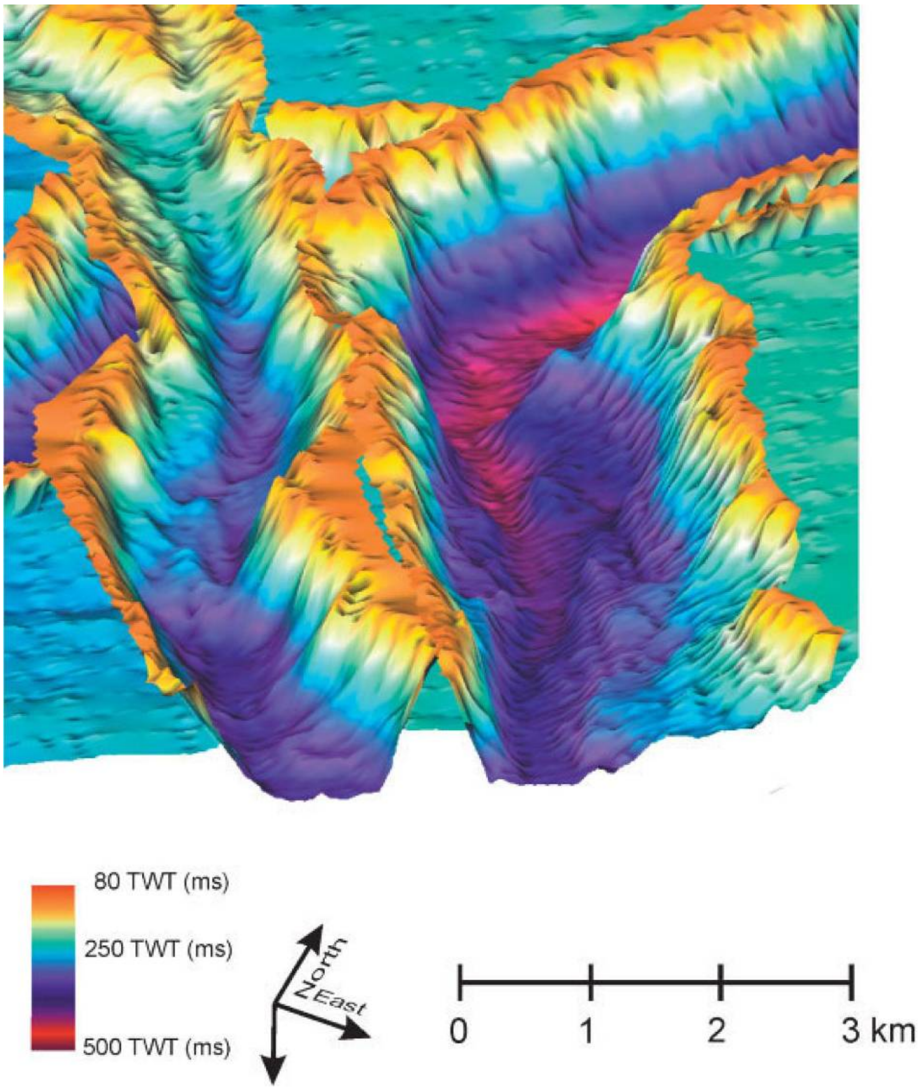


Fig. 14: 3D view of tunnel valleys in the eastern North Sea (Kristensen et al. 2007).

The upper two tunnel valleys cut through a tunnel valley underneath. Note the undulating relief of the valley sides and bottoms. The small scale ripples are likely gridding artefacts. In the background is the horizon map of the Near Base Quaternary surface.

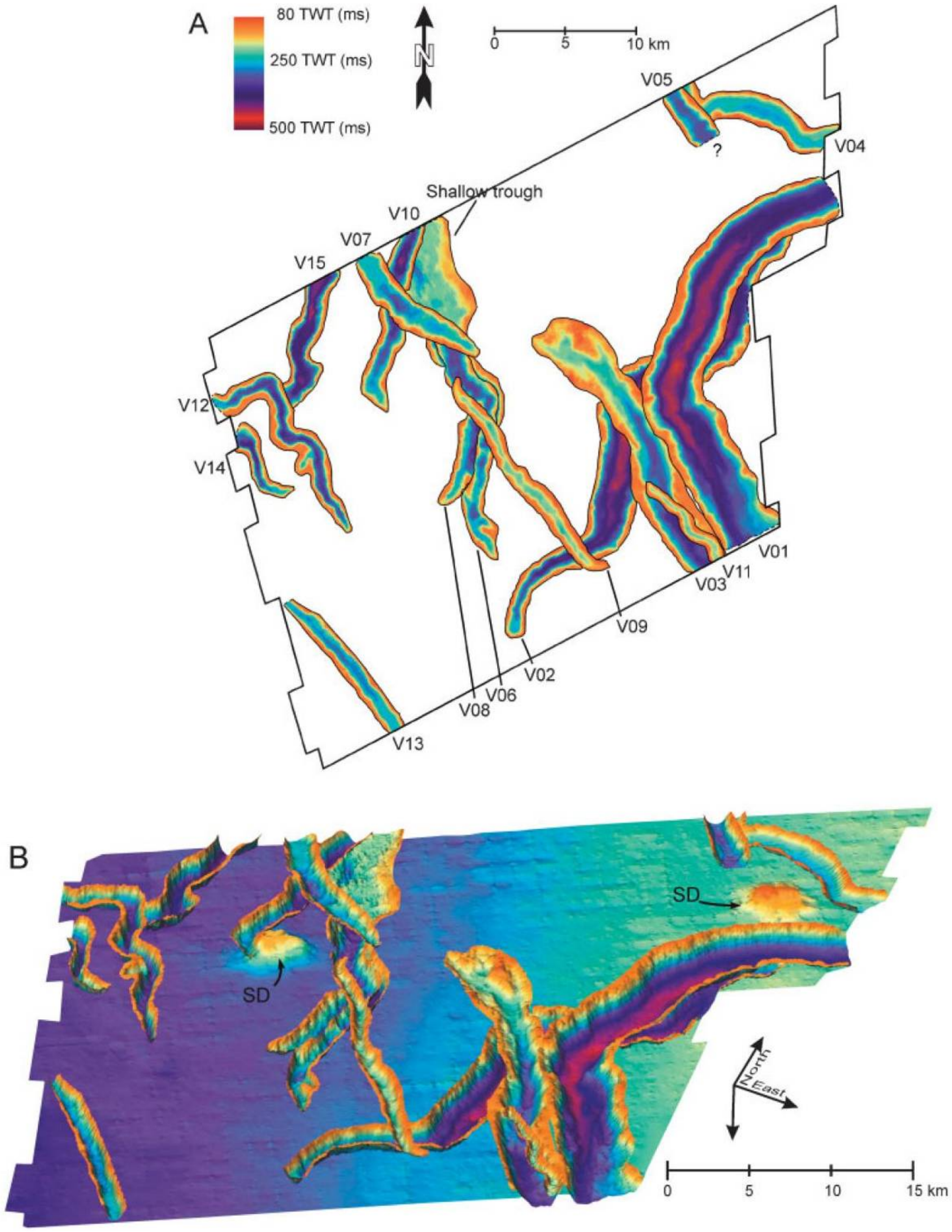


Fig. 15: TWT-structure map of buried tunnel valleys in the eastern North Sea in (A) plan and (B) perspective view (TWT: two-way-travel time; Kristensen et al. 2007).

The seafloor is about 60 m b.s.l. (80 ms TWT) and constitutes the upper limit of the tunnel valleys, and the coloured plane is the Near Base Quaternary (~ top Gelasian) horizon. The tunnel valleys seem to deflect around two salt diapirs (SD) that possibly controlled the local subglacial drainage system.

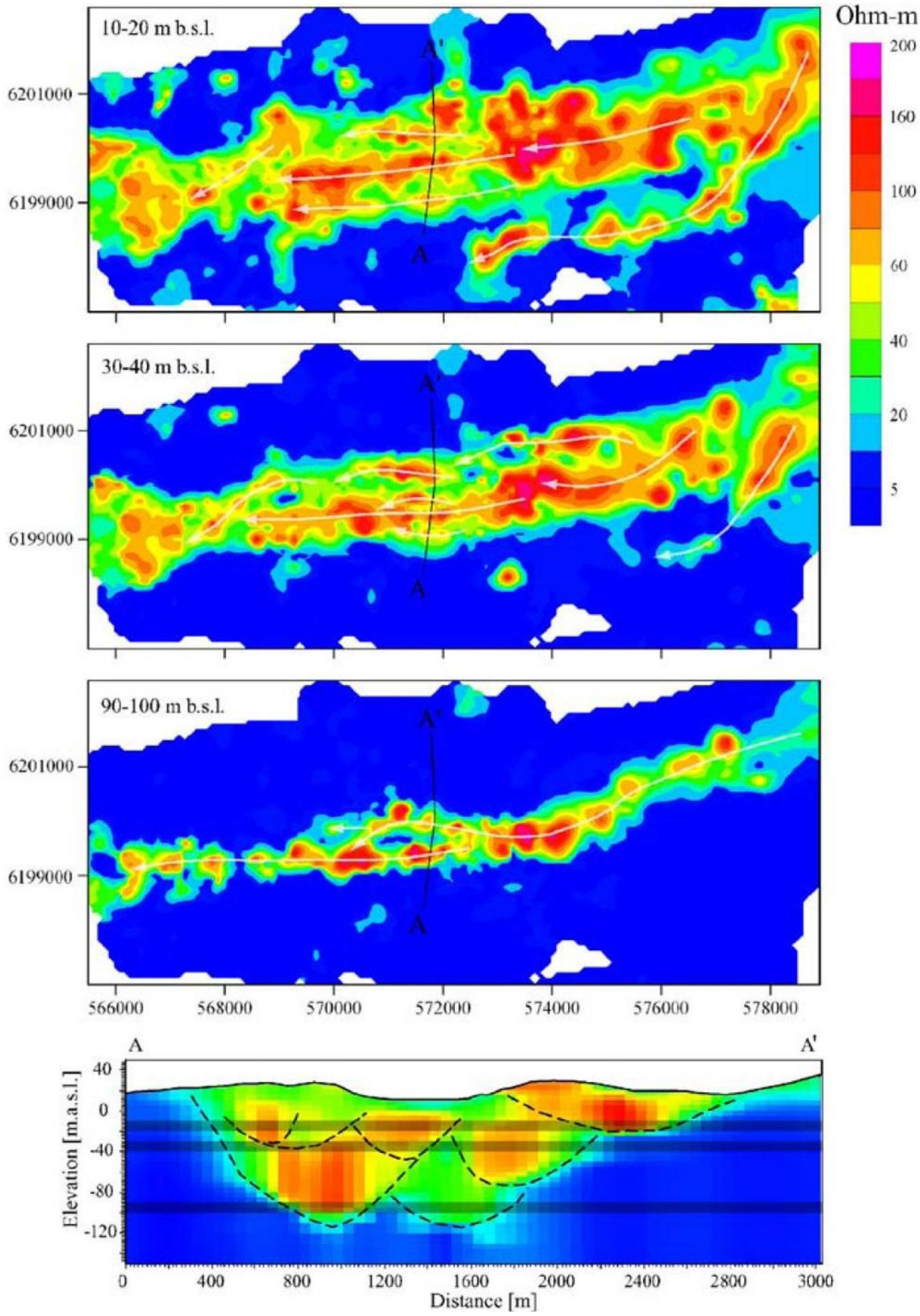


Fig. 16: Interval resistivity maps and a cross-section showing multiple generations of tunnel valleys in Denmark (Jørgensen & Sandersen 2006).

The cross-section A−A' is marked on the maps and shown as shaded lines in the profile. The interval resistivity maps show average resistivities for 10-m intervals calculated from Sky TEM data in the western part and ground-based TEM data in the eastern part (TEM: transient electromagnetic). The cross-section shows the succession of the interval resistivity grids down to 150 m below sea level. The three selected intervals shown by the maps are marked as shaded horizons on the cross-section. Inferred meltwater pathways are shown by white arrow-lines on the maps, and inferred cut-and-fill structures are shown by dashed lines on the cross-section. The composite valley is around 2 km wide and more than 14 km long. At least 5 cut-and-fill structures can be identified both in the maps and the cross-section.

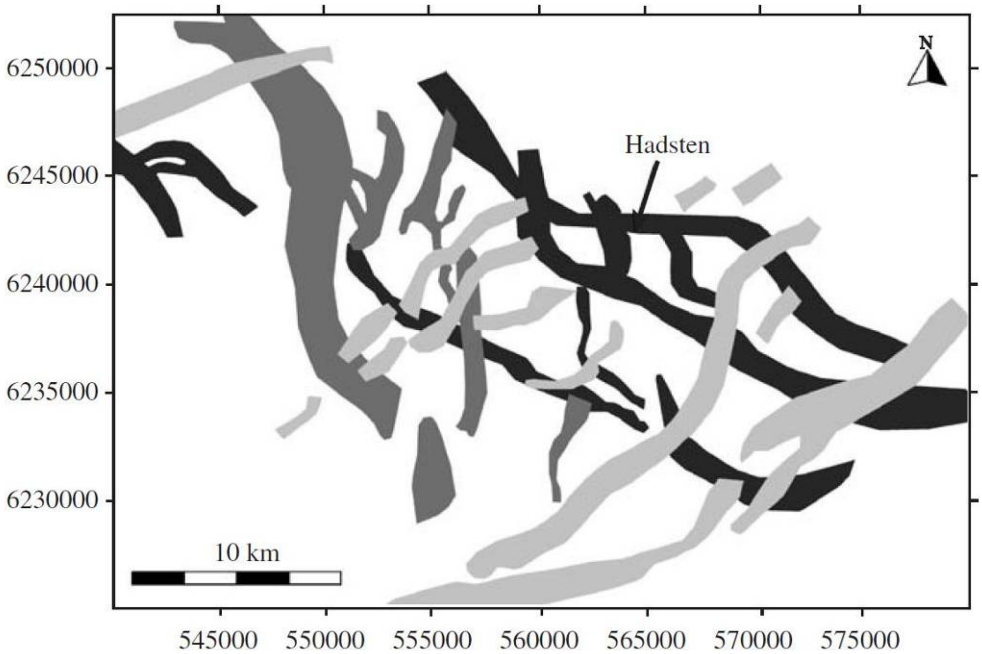
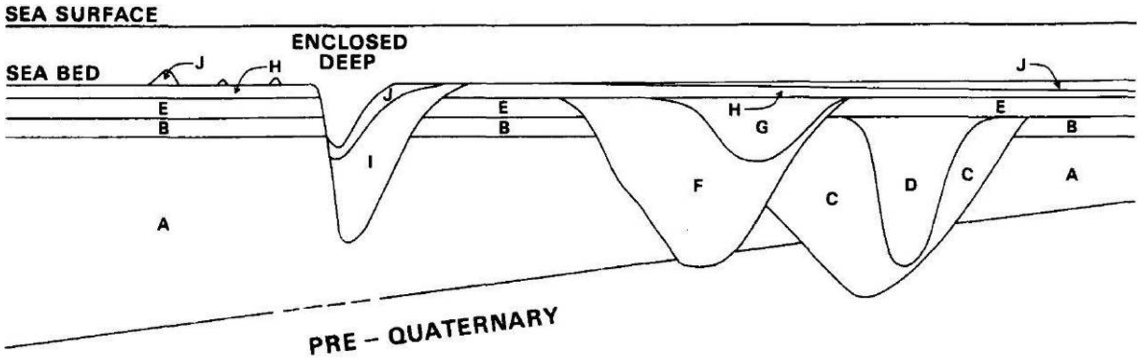


Fig. 17: Three generations of buried tunnel valleys in north-central Jutland, Denmark (Jørgensen & Sandersen 2006).

The orientation of the valleys changes with the generation; from SE−NW for the oldest generation (dark grey valleys), to N−S for a younger genereation (grey valleys) and to SE-NW for the youngest valley generation (light grey valleys).



CODE	AGES	CLIMATE	MAXIMUM THICKNESS OBSERVED (metres)	FACIES
J	Late-Weichselian to Holocene	Temperate	200	Kettle hole infills and sea bed deposits
I	Late-Weichselian	Periglacial	400 ± 50	Incision infills
	GENERATION THREE MAJOR INCISIONS			LATE-WEICHSELIAN
H	Weichselian	*Glacial*	*c.*100	*Till to glacimarine*
G	Late-Saalian, Eemian and early-Weichselian	Temperate	200+	Kettle hole infills
F	Late-Saalian	Periglacial	400 ± 50	Incision infills
	GENERATION TWO MAJOR INCISIONS			LATE-SAALIAN
E	Saalian	*Glacial*	150+	*Till to glacimarine*
D	Late-Elsterian, Holsteinian and early-Saalian	Temperate	200+	Kettle hole infills
C	Late-Elsterian	Periglacial	400 ± 50	Incision infills
	GENERATION ONE MAJOR INCISIONS			LATE ELSTERIAN
B	Elsterian	Glacial	50	Till to glacimarine
A	Pre-Elsterian	Variable	750 ± 50	Fluvial, prodeltaic and marine

Fig. 18: Scheme of the stratigraphic elements applicable to the thick Quaternary successions of the eastern and western continental shelves around Britain (modified from Wingfield 1989).

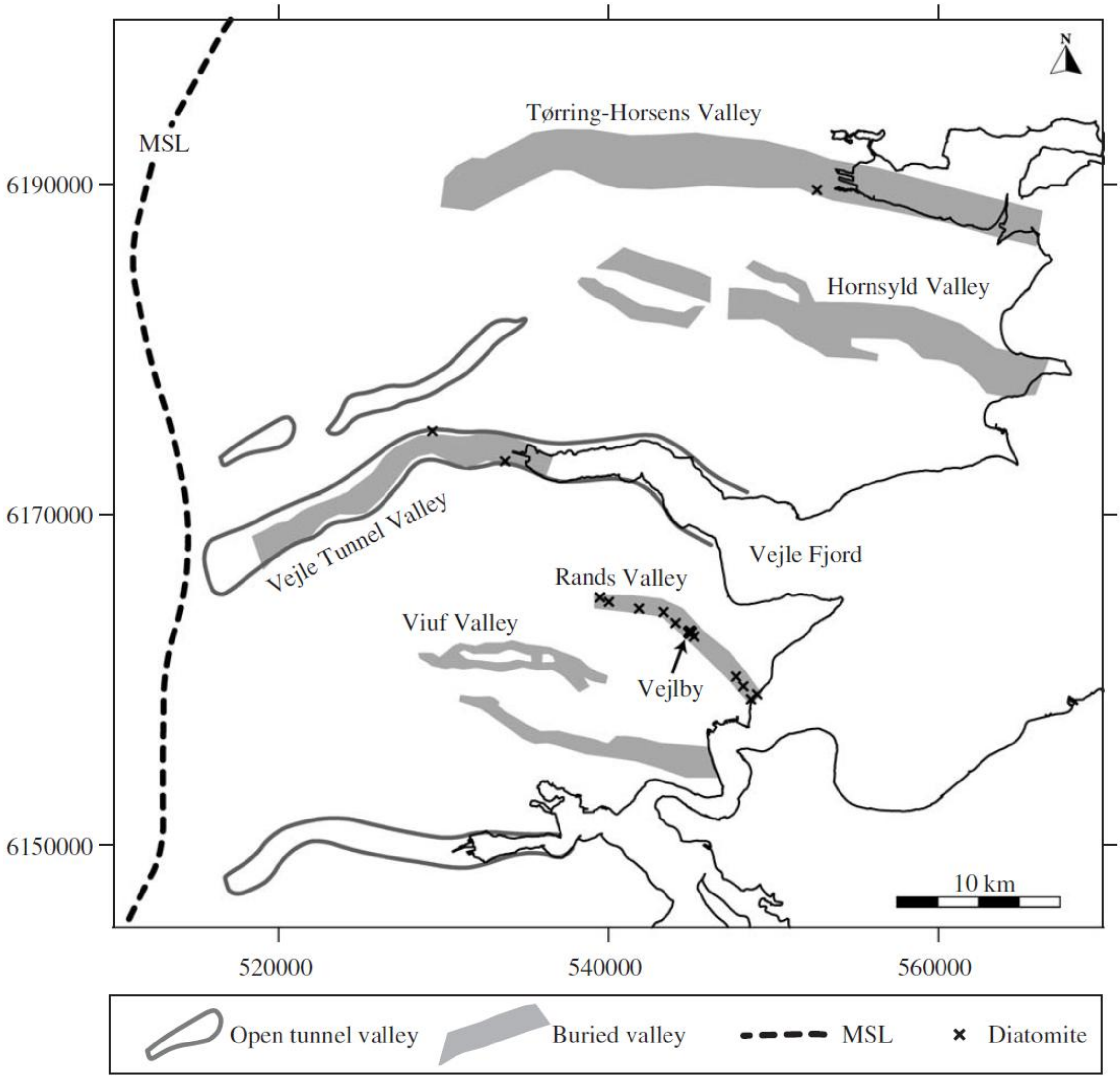


Fig. 19: Map illustrating the tendency of tunnel valleys to re-use older valley courses (Jørgensen & Sandersen 2006).

For example, the open Vejle Tunnel Valley in Denmark re-uses the course of an older buried valley that is of the same generation as the Rands and Hornsyld Valley. The ice sheet was located east of the Main Stationary Line (MSL).

4.2 Underlying lithology

The underlying lithology of tunnel valleys in the North Sea and neighbouring regions consists predominantly of non-metamorphic sediments from the Cenozoic (past ~ 65 Ma) (Fig. 3 and 20; Sigmond 2002). Since the Rupelian stage in the early Oligocene (~ 34 Ma), large parts of the North Sea lowered by more than 1500 m and in northern Germany partly by more than 1000 m (Fig. 21 and 22; Ziegler 1990; Huuse & Lykke-Andersen 2000a; Ludwig 2003a; Evans et al. 2003; Doornenbal & Stevenson 2010). Because subsidence and related sediment deposition were dominant, the onshore topography is generally flat. The northeastern parts of Denmark experienced a slight uplift with erosion.

During the Cenozoic, the North Sea developed as an epi-continental sea (sea extending over parts of a continent) (Ziegler 1990; Huuse & Lykke-Andersen 2000a). In central parts of the North Sea the Cenozoic sediments are more than 3500 m thick, in large areas of the North Sea between 1000 m and 2000 m of Cenozoic sediments accumulated, and in the northern part of Germany they are predominantly more than 500 m thick (Fig. 3 and 20; Ziegler 1990). Towards the margins of the North Sea and on the continent, the accumulation diminishes. The Quaternary sediments in the centre of the North Sea Basin reach a thickness of more than 1 km (Huuse & Lykke-Andersen 2000a, Evans et al. 2003; Doornenbal & Stevenson 2010).

From the Oligocene to the early Pleistocene (~ 34−1 Ma) the North Sea Basin was predominantly filled with marine mudstones and some deep marine, shallow marine and paralic sandstones (Rasser, Haerzhauser et al. 2008, Doornenbal & Stevenson 2010). These sediments are weakly to moderately lithified and erode relatively easily (Tab. 2). In the northern parts of Denmark, the sediments are mainly limestone and chalk, which are older (Upper Cretaceous-Danian) than most sediments in the North Sea and south of Denmark (Fig. 23; Jørgensen & Sandersen 2006). Limestone has a high resistance to mechanical erosion, however, it is prone to chemical erosion, and due to karst it is locally a very good groundwater conveyer (Tab. 2). In the rest of Denmark, the Pre-Quaternary sediments are mainly fine-grained and covered by 5 to 100 m thick Quaternary layers that are easily erodible, and reach about 50 m below and above sea level. The Quaternary layers are glacial, glaciofluvial and interglacial sediments, but also glaciolacustrine and glaciomarine clays from the Late Elsterian glaciation and marine sediments from the Holsteinian interglacial (~ 360,000 a; for Quaternary stratigraphic chart see Appendix B). In northern Germany, interglacial marine and fresh-water sediments were deposited during the Holsteinian and the Eemian (~ 120,000 a) (Fig. 24). The Holsteinian marine sediments are a few metres thick, and in rare cases up to a few decametres (Ludwig 2003b). The Holsteinian fluvial and lacustrine sediments are generally 15 to 30 m thick, and up to a maximum of 75 m. The Eemian marine deposits are several meters up to a maximum of 28 m thick (Ludwig 2003b).

Jørgensen & Sandersen (2006) studied Danish tunnel valleys incised into Upper Cretaceous limestone and Cenozoic sand- and claystone and found that currently in the studied area, it cannot be determined whether the sediment substrate has a significant effect on the morphology, distribution or patterns of tunnel valleys. However, Fig. 3 illustrates well that the majority of the northern European tunnel valleys are incised into Cenozoic sediments. Nevertheless, there are tunnel valleys cut into limestone (Lidmar-Bergström et al. 1991; Jørgensen & Sandersen 2006; Baltrūnas et al. 2007).

Tab. 2: Characteristics of lithology: mechanical resistance to erosion and ability to convey groundwater and modulate pore pressure.

	lithified					unlithified		
			siliciclastic					
	crystal-line rock	lime-stone*	con-glomer-ates	sand-stone	fine grained	gravel	sand-stone	fine grained
mechanical erodibility	**low**							**high**
ability to convey groundwater and modulate pore pressure	**poor**							**good**

* chemical erodibility is high, ability to convey groundwater varies locally.

In Norway and Sweden uplift prevails, and is increased due to the isostatic rebound after the ice ages. Therefore, erosion is the dominating process, old Precambrian lithologies are exposed at the surface and the topography is pronounced compared to southern Denmark and northern Germany. In northern Scandinavia, where Precambrian crystalline bedrock dominates, evidence for subglacial drainage usually manifests itself in eskers (Boulton et al. 2009), while tunnel valleys are exceptions (Johansson 2003). The crystalline rocks are very hard to erode and displays a poor ability to convey groundwater (Tab. 2).

During the Permian (~ 250 Ma) thick salt layers were deposited in an epeiric sea that covered large parts of central and eastern Europe (Grimmel 2004). Over the course of time, the salt deposits were covered by other sediments, such as limestone, sand, silt and clay. Under pressure from the overlying sediments, the salt rose and deformed plastically into salt domes, pillows and diapirs, which deformed the overlying lithified layers (Fig. 25; Jaritz 1973; Grimmel 2004). As a result older lithologies with different erosional properties are often outcropping around the diapirs. In humid climates such as in northern and central Europe, the salt structures cannot reach the surface because the salt dissolves and is removed by groundwater (Grimmel 2004). The insoluble minerals such as gypsum or clay remain as a caprock that seals the salt structures. In Europe during the cold phases in the Quaternary, the frozen ground prevented the dissolution of the salt structures, which ascended and lifted the frozen overlying layers. Later during warm phases, the top layers of the salt structures dissolved and the overlying layers sagged into the resulting so called 'subrosion' depressions (Grimmel 2004).

Hinsch (1979) studied tunnel valleys and salt structures in northern Germany and found that they developed rather independently. Huuse & Lykke-Andersen (2000a) found that tunnel valleys in the eastern Danish North Sea are preferentially located in between salt structures and only a few valleys cut across salt structures. They conclude that the salt pillows, salt diapirs and outcrops of older (and possibly more erosion resistant) strata around the diapirs may have a local influence on the course of the tunnel valleys, but no general rule can be established from that. Piotrowski (1994) studied a tunnel valley lying between two salt diapirs in northern Germany and found that the salt structures influenced the topography and characteristics of the substrate and subsequently also the tunnel valley. Kristensen et al. (2008) observed tunnel valleys seemingly deflected around salt diapirs (Fig. 15). From first principles, one can argue that salt structures affect the immediate substrate of the tunnel valleys by altering subsurface architecture and causing structural deformation (M. Huuse, pers. comm.). As this process can affect erodibility and permeability of the substrate both positively and negatively, each salt structure can affect the local conditions relevant to tunnel valley genesis differently. Whilst most examples seem to indicate that tunnel valleys deflect around salt structures, one can imagine an area of poorly erodible chalk in which salt deformation leads to extensional faulting and thus enhanced tunnel valley formation potential across the structure (M. Huuse, pers. comm.).

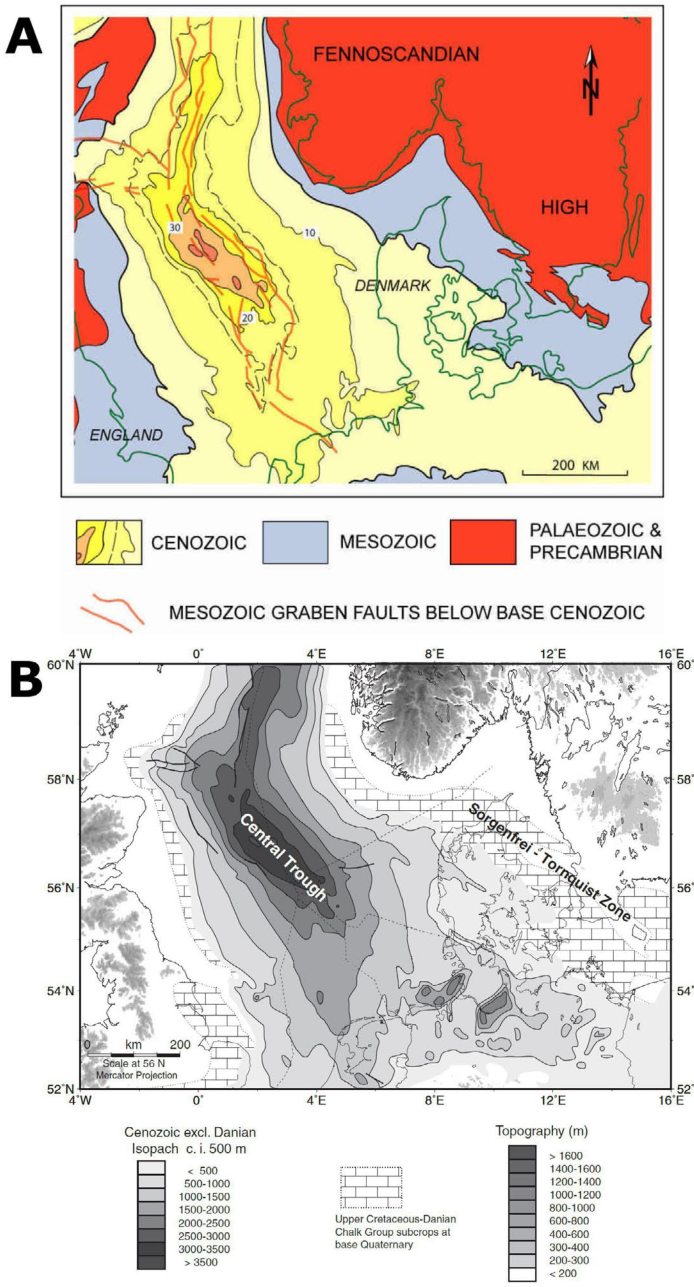


Fig. 20: Geological maps of the North Sea Basin (redrawn from Ziegler 1990 by Graversen 2006 (A) and Huuse & Clausen 2001 (B); see also Fig. 3).

(A) The contours are isopachs that indicate the stratigraphic thickness of the Cenozoic rock in hundreds of metres (e.g. 10 corresponds to 1,000 m). The Cenozoic rocks (past ~ 65 Ma) consist mainly of marine sandstone, claystone and siltstone (yellow to orange colours which indicate increased sediment thickness). The Mesozoic rocks (~ 65−250 Ma) consist mainly of limestone, siltstone and sandstone. In northern Scandinavia, the bedrock consists mainly of hard Precambrian rocks (older than ~ 540 Ma), while the Palaeozoic rocks (~ 250−540 Ma) in the north of Scotland and southern Sweden consist mainly of sand- and claystone with some carbonates.

(B) The Cenozoic isopachs are given in grey shades for 500 m intervalls for the Central Trough, which is surrounded by the Upper Cretaceous-Danian Chalk Group subcrops at the base Quaternary. The topography of the mainland is displayed in gradual shades from white to dark grey.

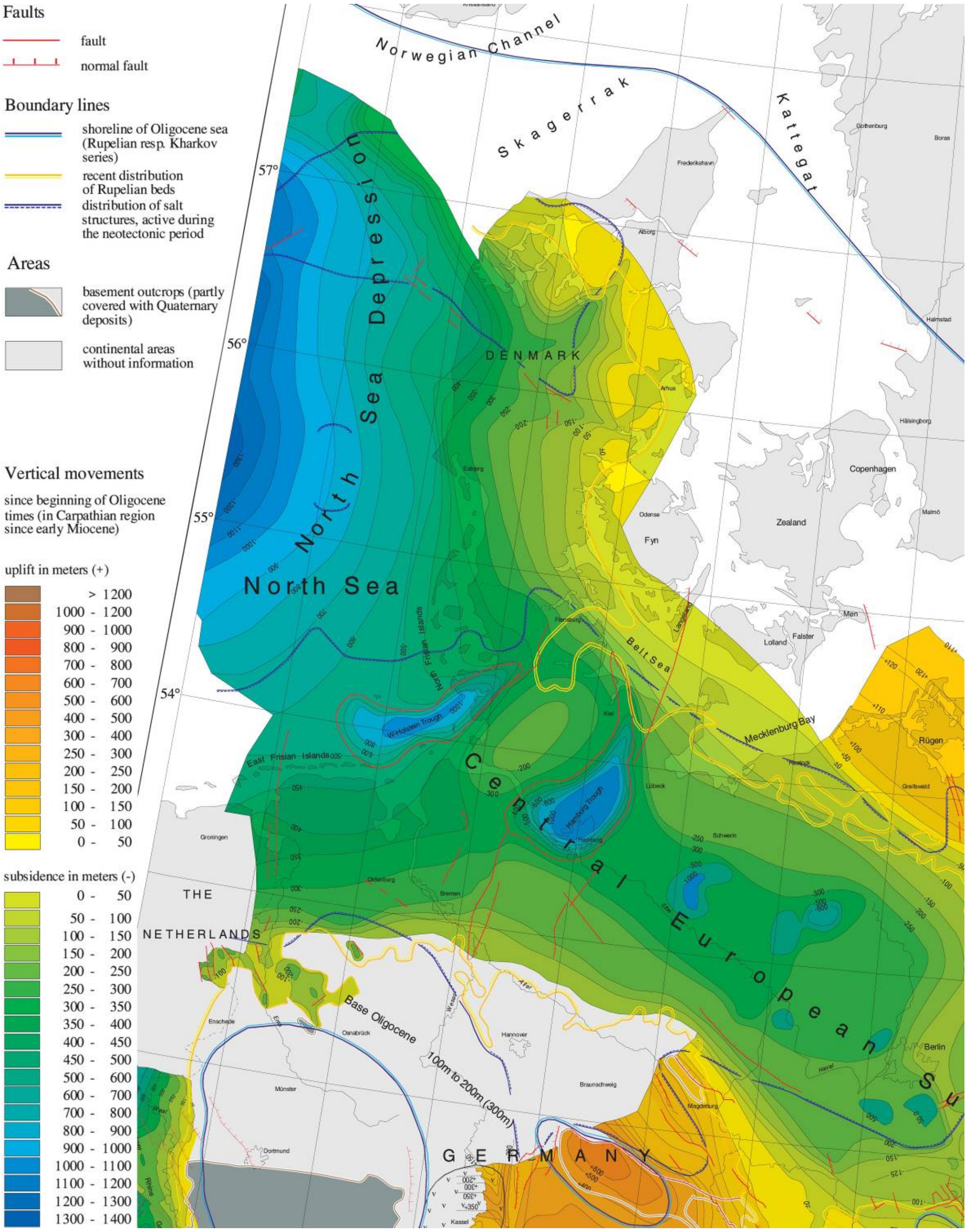


Fig. 21: The vertical movements since the beginning of the Rupelian stage in northern Germany and Denmark (~ 34 Ma) (modified from Ludwig 2003a).

For the Central Baltic Sea region, the base of the Quaternary has been accepted as the main reference level for establishing the neotectonic movements because Tertiary deposits are absent there. The reference level used for the determination of vertical movements changes from west to east, i.e. to younger stratigraphical horizons. It is, therefore, a diachronous plane.

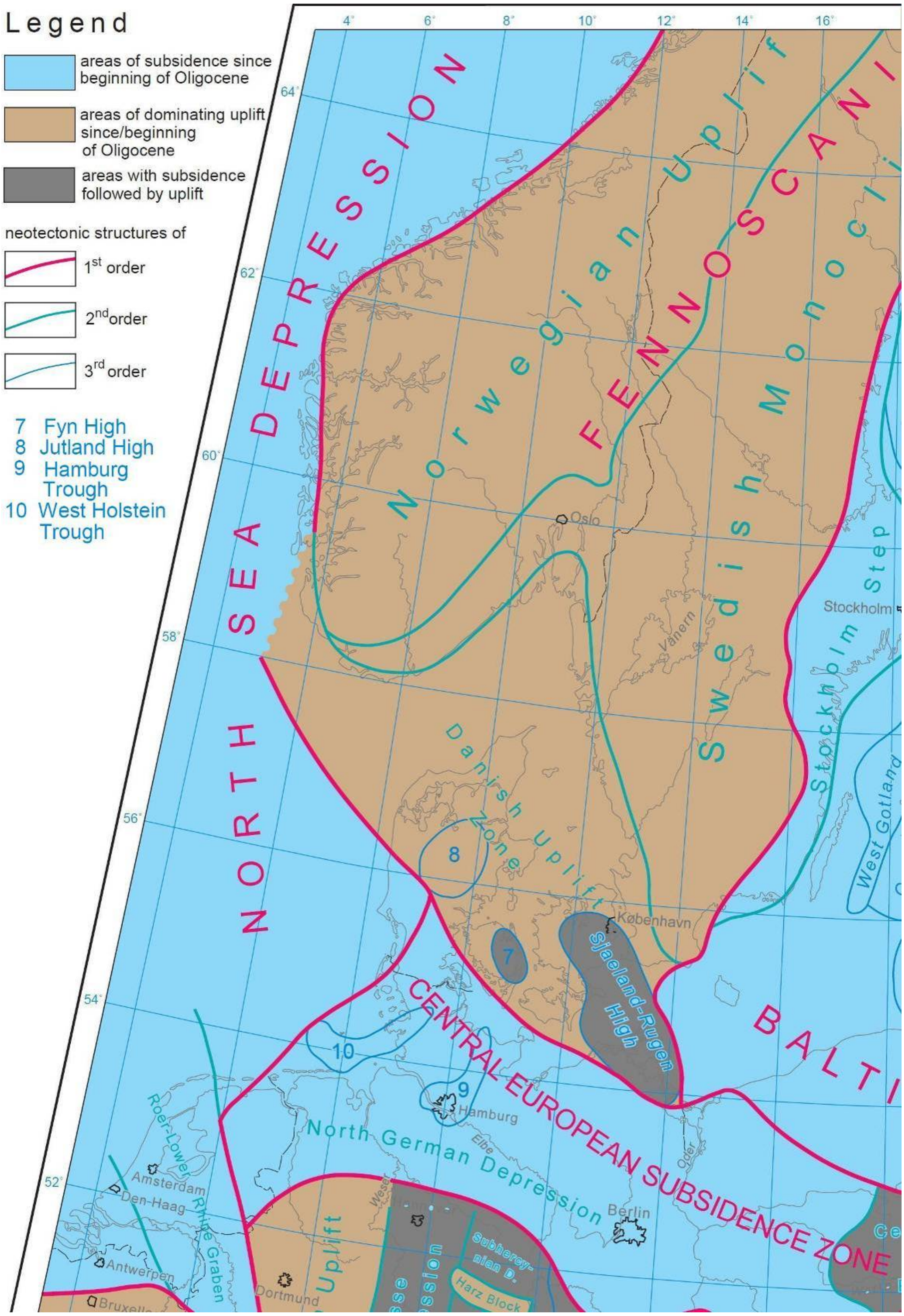


Fig. 22: The neotectonic structural subdivision with uplift and depression zones since the beginning of Oligocene until recent (past ~ 34 Ma) in northern Europe (modified from Garetzky et al. 2003).

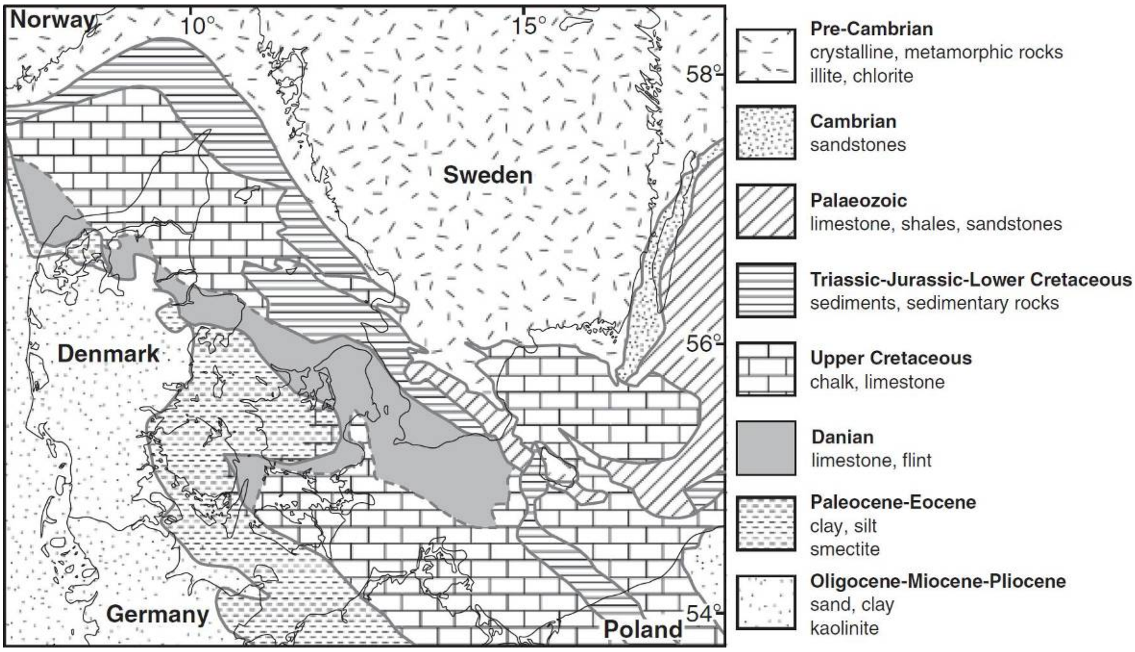


Fig. 23: Bedrock map of southwest Scandinavia (Krohn et al. 2009).

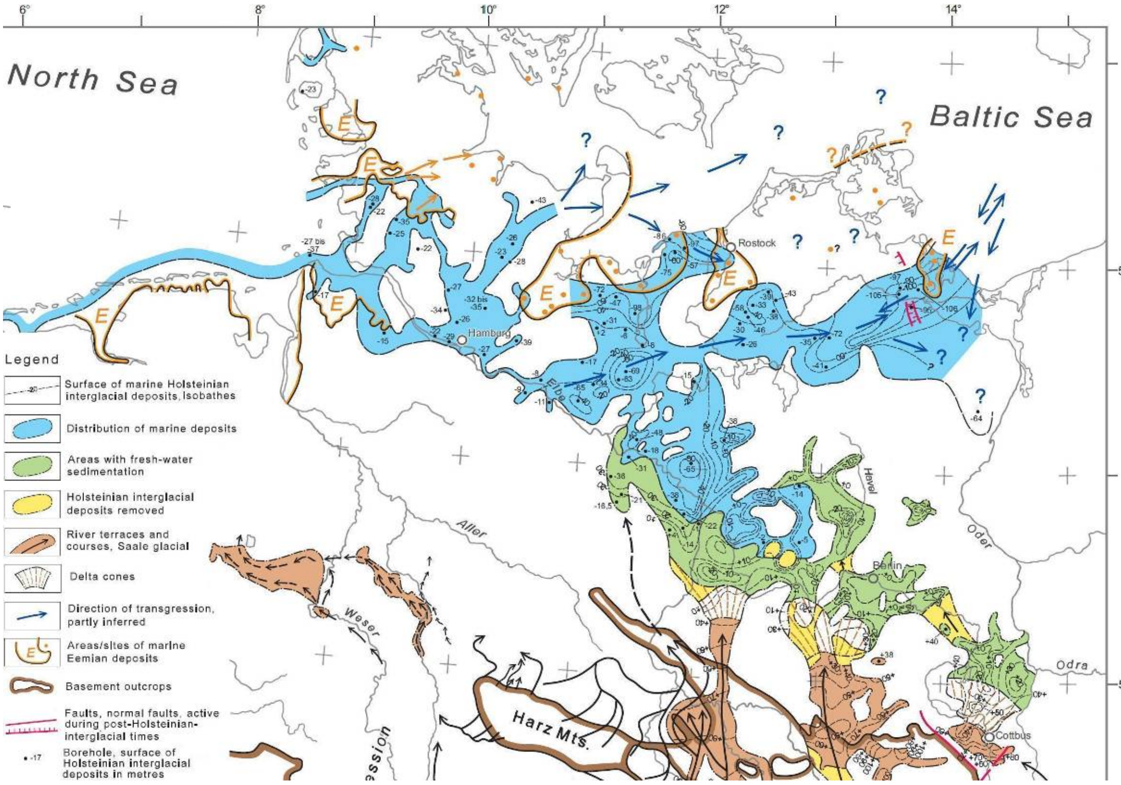


Fig. 24: Distribution and surface contours of Holsteinian interglacial sediments and river terraces from the Saalian glaciation in northern Germany. Marine Eemian deposits are indicated separately (modified from Ludwig 2003b).

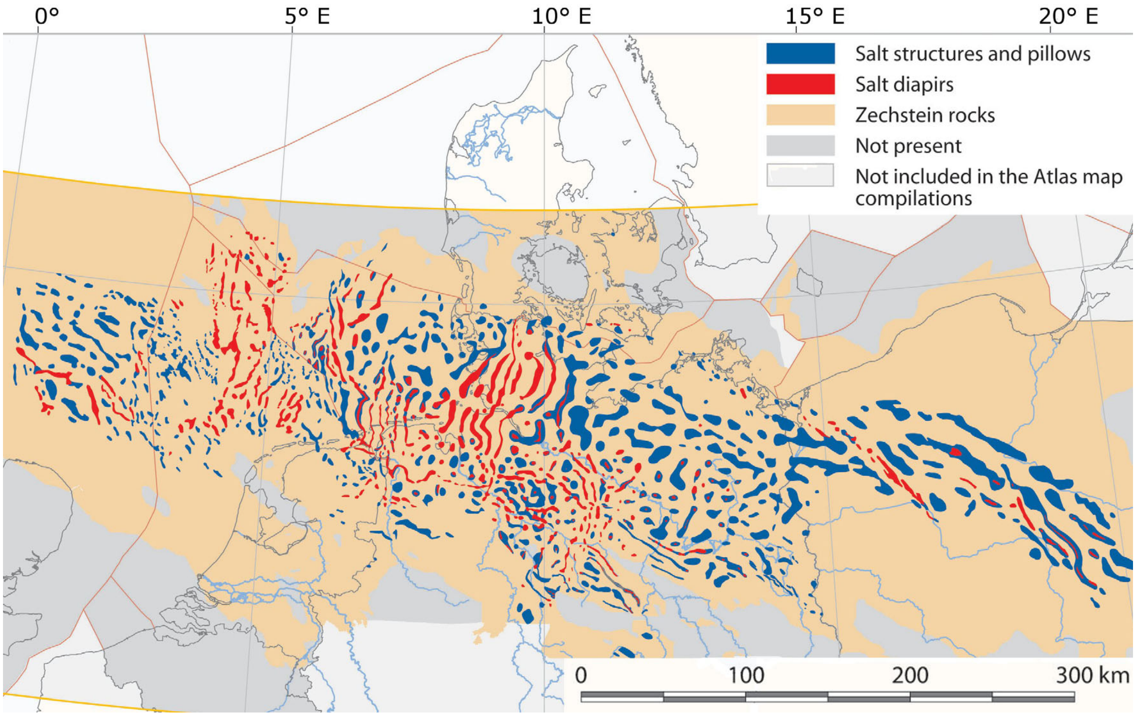


Fig. 25: Salt diapirs and pillows in the Southern Permian Basin in the area of a former epeiric sea (modified from Doornenbal & Stevenson 2010).

4.3 Tunnel valley infill

Tunnel valleys are filled with sediments associated with glacial deposition processes, glaciofluvial, glaciolacustrine, glaciomarine sedimentation, as well as with sedimentation processes during warm interglacial conditions (Ó Cofaigh 1996). The sediments are often deposited with layers of glaciogenic and non-glacial sediments, in many cases with complicated cut-and-fill relationships (Fig. 12, 16 and 18). The varying valley fill reflects the changing hydrological and sediment transport environment of the tunnel valleys, and locally the incised substrate is reflected in the valley infill (Jørgensen & Sandersen 2006). For example in a tunnel valley with a clayey underlying lithology, more clay can be found in the valley infill. The valley infill distribution is usually identified with seismic data whilst borehole data are important to validate and calibrate the seismic interpretation (Huuse & Lykke-Andersen 2000a; Kluiving et al. 2003; Kristensen et al. 2008).

In some cases, eskers can be found at the bottom of tunnel valleys; they represent subglacial sedimentation shortly after or even during the formation of the tunnel valley (Fig. 7; e.g. Mooers 1989; Smed 1998; Sjogren et al. 2002; Jørgensen et al. 2003b). Thick or thin layers with mixed mud-, sand- and gravel-sized material is often interpreted as till that is subglacially deposited (Jørgensen & Sandersen 2006). Many tunnel valleys are filled with coarse-grained deposits that are characterised by a high resistivity in TEM soundings (e.g. Fig 16), which are often interpreted as meltwater sediments (Jørgensen & Sandersen 2006). In some cases, dead ice remained in the tunnel valleys and prevented the valley from filling with glaciofluvial deposits, or only thin layers of outwash sediments were deposited on top of dead ice, collapsing on a lower level after the ice melted (Huuse & Lykke-Andersen 2000a; Jørgensen & Sandersen 2006). In seismic cross-sections, sand and silt appear often as chaotic and disrupted seismic facies, and silt and clay as well-layered seismic facies (Fig. 12 and 13; Huuse & Lykke-

Andersen 2000a). Praeg (2003) found in tunnel valleys in the North Sea sandy glaciofluvial sediments overlain by lacustrine to marine muds. In the eastern Danish North Sea Huuse & Lykke-Andersen (2000a) recorded a well-layered seismic facies, which represents silt and clays that are possibly glaciolacustrine, glaciomarine or interglacial sediments. Jørgensen & Sandersen (2006) found most commonly sand and gravel from glacial meltwater, glaciolacustrine clay, silt and clay till, but also heterogeneous, sandy diamictons, marine clay and peat. Fig. 24 shows Holsteinian and Eemian deposits that is substrate for Saalian and Weichselian tunnel valleys, but also tunnel valley infill for Elsterian and Saalian tunnel valleys.

In seismic measurements, glacially thrusted infill sediments and rafts of Pre-Quaternary material in the glacial sediments were identified that indicate glaciotectonic activity following valley formation and burial (Jørgensen & Sandersen 2006). In some cases, the tunnel valleys intersect glaciotectonic thrust structures, which can thus help constrain the dating of the tunnel valleys (Fig. 26; Huuse & Lykke-Andersen 2000a, 2000b). Praeg (2003) and Kristensen et al. (2007, 2008) describe clinoforms along tunnel axes that are argued to have developed contemporaneously with the erosion and backfilling of the tunnel valley (Fig. 27 and 28; see also Subchapter 5.1.2 Time-transgressive formation).

The knowledge about tunnel valley extents, underlying lithology and especially valley infill is important for groundwater hydrology (BURVAL 2009). The sequences of permeable porous layers such as sand and gravel and impermeable layers like clay and silt in the valley infill form ideal groundwater reservoirs and traps (Gabriel et al. 2003; Jørgensen et al. 2003a, 2003b; Sandersen & Jørgensen 2003). Porous layers serve as conduits between aquifers on different levels and impermeable layers in between protect in many cases lower aquifers from surface pollution. Coarse-grained parts of Quaternary sediments that fill tunnel valleys effectively clean the water running through and therefore provide good quality drinking water (Danielsen et al. 2003).

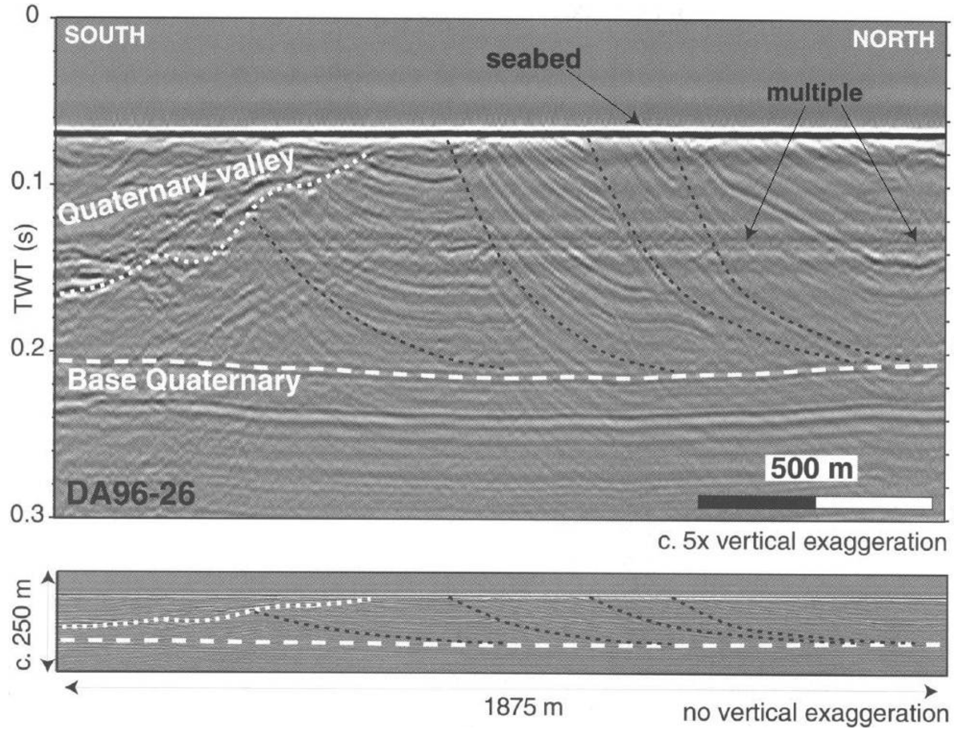


Fig. 26: High-resolution multichannel seismic profile showing detached thrust structures intersected by a tunnel valley (Huuse & Lykke-Andersen 2000b).

The detachment surface roughly coincides with the base Quaternary. The Quaternary succession is largely sandy (permeable), whereas the underlying Pliocene and Miocene succession consists mainly of silty clay (impermeable).

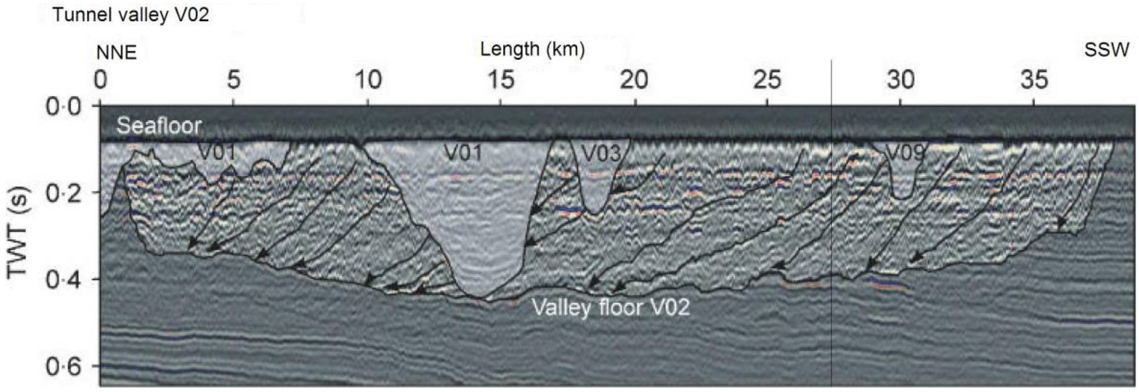


Fig. 27: Vertical profile along the valley axis of tunnel valley V02 filled with northward prograding clinoforms (Kristensen et al. 2008).

The clinoforms are marked with black arrow lines. Several generations of tunnel valleys are visible cutting through the tunnel valley V02. The thin line indicates roughly where the profile intersects with the profile from Fig. 28A. The position of the tunnel valleys V01, V02, V03 and V09 is given in Fig. 15.

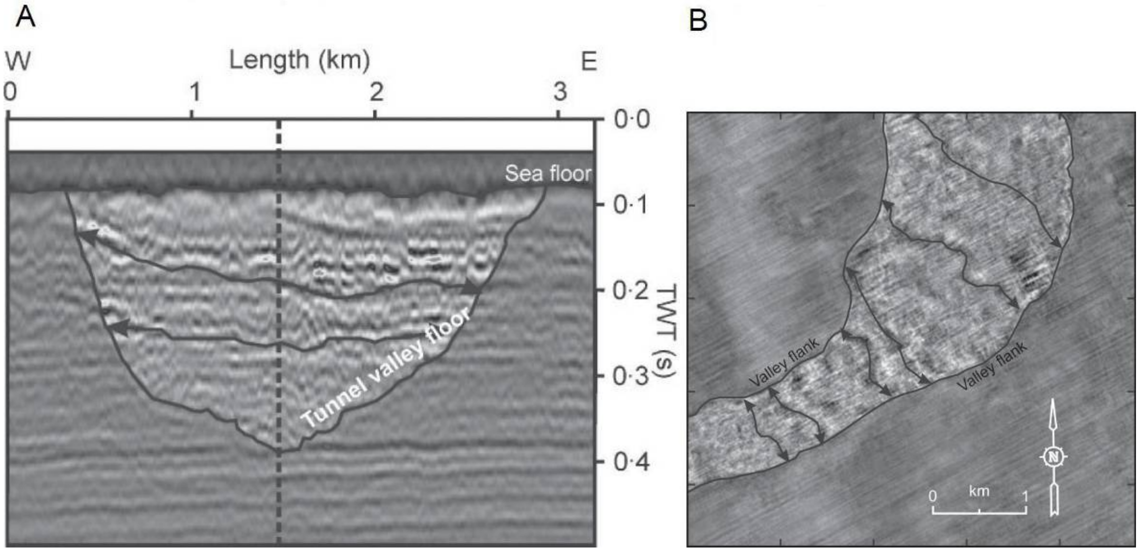


Fig. 28: Cross-sectional profile (A) and plan view (B) of tunnel valley V02 showing the structure of the clinoform infill (Kristensen et al. 2008).

The dashed line in the cross-sectional profile indicates roughly where the profile intersects with the profile in Fig. 27. The plan view is from the southern end of the tunnel valley. The position of the tunnel valley V02 is given in Fig. 15.

5 Formation processes

In the past, glacial and non-glacial formation processes have been discussed for tunnel valleys. However, in the current literature there is a general agreement that tunnel valleys formed subglacially by meltwater. Although most tunnel valleys are inferred to form predominantly at the ice margin (e.g. Mooers 1989; Piotrowski 1994; Smed 1998; Kristensen et al. 2008), Lonergan et al. 2006 and Stewart 2008 suggested that some tunnel valleys in the North Sea possibly formed subglacially at a central location of the ice sheet.

The most important formation processes involve meltwater. Here, four concepts for tunnel valley formation involving meltwater are presented, which are the time-transgressive tunnel valley formation (Section 5.1.2), formation by catastrophic outbursts (jökulhlaups) (Section 5.1.3), by megafloods or sheet floods (Section 5.1.4) and by steady-state sediment deformation (Section 5.1.5) (Ehlers 1994; Piotrowski 1994; Boulton & Hindmarsh 1987; Smed 1998; Shaw 2002; Kristensen et al. 2008). Direct glacial erosion is another process that many authors consider as subordinate and usually occurring in combination with other formation processes. The formation concepts share elements and could be classified in many different ways. For example, it could be argued that most tunnel valleys form time-transgressively, or that megafloods are also catastrophic outburst events (e.g. Ó Cofaigh 1996; Kehew & Kozlowski 2007). Some authors suggest that the degree of catastrophism of the water drainage depends on the time scales of observation, and it is feasible that tunnel valleys might form due to pulsed or repeated meltwater outbursts forming the deep valleys incrementally due to daily, seasonal or even decadal time scales (Huuse & Lykke-Andersen 2000a, Huuse pers. comm. 2010). In this literature review, different theories have been condensed to the four presented concepts, whereas terms from the literature have been used to describe the concepts. For the concepts involving subglacial meltwater it is a premise that the ice base is temperate, which means that the glacier is not frozen to its bed and meltwater can penetrate and circulate through the glacier. Such conditions prevailed towards the end of ice ages when temperatures rose and ice margins retreated (Mooers 1989). Therefore, it is often argued that tunnel valleys form during glacier retreat or in a stagnant phase (e.g. Piotrowski 1994; Kristensen et al. 2008, Sandersen et al. 2009).

Many authors suggest a combination of processes (e.g. Piotrowski 1994; Huuse & Lykke-Andersen 2000a, Stewart 2008). Jørgensen & Sandersen (2006) suggest that preglacial fluvially eroded valleys were re-used by the tunnel valleys. Usually, formation theories are developed for specific tunnel valleys or regions, and therefore, it is difficult to generalise them (Van Dijke & Veldkamp 1996). Authors categorise formation theories in several ways, which depend on the emphasised aspects of the formation process. However, there is still controversy about the tunnel valley genesis (Ó Cofaigh 1996). It can be argued that much of the controversy is caused by the search for a single formation process that explains the entire range of tunnel valley morphologies (Huuse & Lykke-Andersen 2000a).

In the past, it has been argued that the conditions and setting of current glaciers and ice sheets differ from those during past ice ages, and that currently tunnel valley formation cannot be observed (e.g. Wingfield 1990; Shaw 2002; Jørgensen & Sandersen 2006). However, in modern times glacier outburst floods eroding subglacial overdeepenings, albeit mostly on a smaller scale, have been observed in Iceland and Alaska (Björnsson 1996; Smed 1998; Russell et al. 2007; Fleisher et al. 2010).

5.1 Meltwater drainage

Many formation processes are based on meltwater drainage, which is driven by hydraulic potential gradients. The well-known principle of the hydraulic potential and its implications for tunnel valley formation and distribution are described in Section 5.1.1. The undulating and overdeepened bottoms of tunnel valleys can be explained by the subglacial flow of pressurised meltwater and sedimentation processes (Beaney 2002; Sjogren et al. 2002; Benn & Evans 1998).

5.1.1 Hydraulic potential

Shreve (1972) describes the hydraulic potential Φ:

$$\Phi = \Phi_e + P_W , \tag{1}$$

where Φ_e is the gravitational potential due to the elevation above some datum and P_w is the water pressure (Shreve 1972). The gravitational potential Φ_e can be written as:

$$\Phi_e = \rho_W g z , \tag{2}$$

where ρ_w is the density of water (1000 kg m^{-3}), g is the acceleration due to gravity and z is the elevation of the point considered (Shreve 1972). In Fig. 29 planes of equal water pressure and gravitational potential as well as the resulting hydraulic potential are displayed. The flow of water is perpendicular to the hydraulic equipotentials and always directed towards the decreasing hydraulic potential (Smed 1998). Therefore, in a subglacial overdeepening with a decreasing hydraulic potential towards the ice margin water can flow and erode uphill.

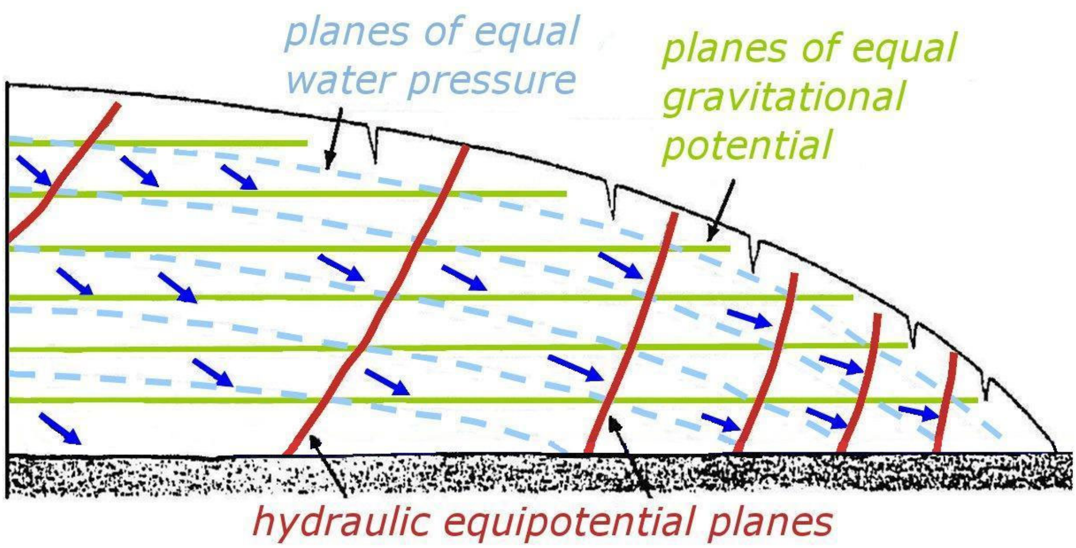


Fig. 29: Construction of equipotential planes through a glacier. The arrows indicate the flow of water, which is perpendicular to the equipotential planes (modified from Smed 1998).

The hydraulic equipotential planes dip upglacier (note minus sign in following equation) with an average angle α of:

$$\alpha = -\tan^{-1}\left(\frac{\rho_i \, \nabla H}{\rho_w - \rho_i}\right), \tag{3}$$

where ∇H is the gradient of the ice surface, and ρ_i is the density of ice (916 kg m^{-3}) (Shreve 1972; Hooke 2005). Therefore, the slope of the hydraulic equipotential planes are approximately eleven times the slope of the ice surface (Shreve 1972). The example of Hald Sø (Hald Lake) in an open tunnel valley in Jütland (see also Fig. 6A) illustrates the minimum slope the ice sheet surface must have had at this location (Smed 1998). To form the tunnel valley, the water had to flow 103 m uphill over a distance of 2 km, which results in a slope of the hydraulic equipotential of at least 2.86° which corresponds to a gradient of 1:20. Consequently, at this location the ice surface must have had a slope of more than 0.26° (∇H of 1:220). This example demonstrates the low ice-surface angle required to allow water to flow uphill. However, for the water to have the capacity to erode and evacuate sediments from the tunnel valley bottom the ice-surface slope presumably must have been larger than 0.26°.

In a more complex environment, the undulating topography influences the hydraulic potential (Smed 1998). For example the hills under the ice sheet in Fig. 30 increase the gravitational potential and also alter the hydraulic potential gradient through dynamic effects associated with iceflow over the hills that impact the water pressure (e.g. Shreve 1972), which results in a diversion of the water around the hills. Such hills or ridges slow down the ice flow and form often ice lobes behind the ridges. In the middle of the lobes, the ice is thicker which increases the hydraulic potential. Therefore, the subglacial meltwater drains preferably at the notches where the hydraulic potential is lower (Fig. 6A, 7, 8 and 30). At the glacier portal the hydraulic potential decreases rapidly, the meltwater emerges from the glacier and deposits the debris load onto outwash fans or so-called sandurs (Fig. 7 and 9; Smed 1998).

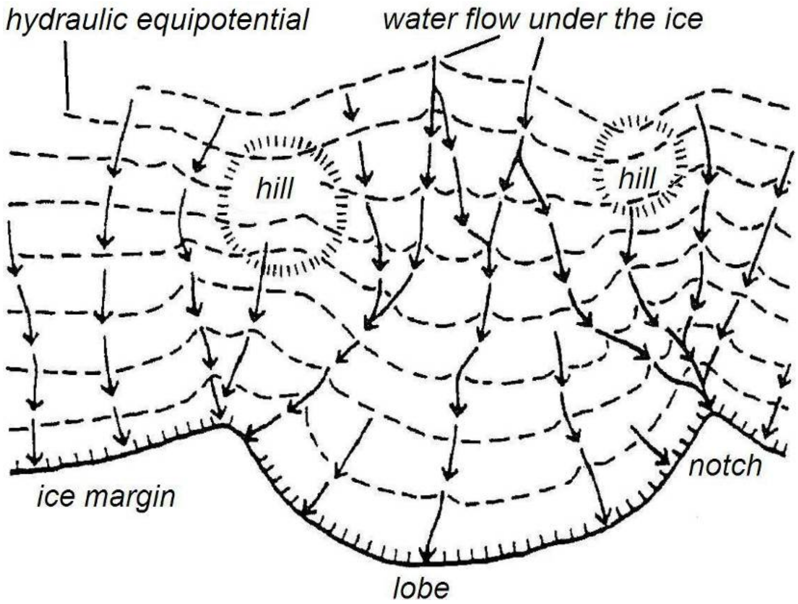


Fig. 30: Plan view of an ice margin overlying a hilly pre-glacial surface, modifying the hydraulic equipotential lines and the ice front morphology (modified from Smed 1998).

The hills cause the ice to form an ice lobe with notches. The water flow is diverted around the hills because of the higher hydraulic potential, which decreases towards the notches where the ice is thinner than in the middle of the ice lobe.

5.1.2 Time-transgressive formation

Time-transgressive tunnel valley formation is characterised by spatially regressing erosion that occurs over a period of time (Mooers 1989; Ó Cofaigh 1996; Praeg 2003; Jørgensen & Sandersen 2006; Kehew & Kozlowski 2007; Kristensen et al. 2008). Such tunnel valleys typically form during ice sheet retreat, occasionally interrupted by phases of stagnation or advance. Kristensen et al. (2008) and Praeg (2003) describe time-transgressive tunnel valley erosion with contemporaneous sediment re-deposition and Wingfield (1990) suggests regressing erosion initiated at the ice sheet margin.

Mooers (1989) investigated tunnel valleys in Minnesota and proposes a seasonal and time-transgressive formation process. Further, he specifies that, based on geomorphological features such as eskers and outwash fans, the tunnel valleys formed during ice sheet recession and stagnation of the Superior lobe. Eskers coexist often with tunnel valleys (e.g. Mooers 1989; Smed 1998; Sjogren et al. 2002; Jørgensen et al. 2003b) and are accepted to form time-transgressively, according to an established model in which surface meltwater recharges the bed via englacial conduits that migrate with the ice margin during its recession (Praeg 2003). Mooers (1989) suggests that towards the end of ice ages, the warming initiated the ice sheet retreat and led to an increased amount of surface meltwater that promoted tunnel valley formation. The duration of the formation process with surface and subglacial meltwater could be much shorter than if subglacially produced meltwater was the only source of water. Smed (1998) explains tunnel valleys, and especially the large width with a successive and seasonal origin. In the winter, meltwater is reduced and ice creeps into the tunnel. In the spring, the meltwater increases while the constricted tunnels cannot accommodate the meltwater. Therefore, the meltwater erodes a new tunnel next to the previous tunnel and subsequently widens the tunnel valley. This process repeats every year and the tunnel valley increases in depth and width. However, Smed (1998) argues that the erosion is strongest during the ice sheet advance when the slope of the terminus is steepest and consequently the subglacial hydraulic potential gradient the largest. A similar description of seasonal erosion is offered by Van Dijke & Veldkam (1996). However, they and Jørgensen & Sandersen (2006) explain widening of the tunnel valleys by the direct glacial erosion due to the ice pressure on the slopes, and lowering of the tunnel valleys by fluvial erosion due to high water pressure. They argue that rising air temperature increase meltwater production, which results in a higher water pressure and subsequently higher erosion rates.

Based on detailed seismic investigations in the North Sea, Praeg (2003) and Kristensen et al. (2008) propose a time-transgressive formation during ice retreat, whereby sediments erode from the top end of the tunnel valley. The sediments are re-deposited along the adverse slopes beneath the ice margin in clinoforms (Fig. 27 and 28). Kristensen et al. (2008) refined and described the backfill process based on the theory of glaciohydraulic supercooling when the re-deposited sediments freeze on the adverse slope (Fig. 31 and 32). The theory of glaciohydraulic supercooling states that subglacial meltwater at the pressure melting point ascending up the adverse slope can be supercooled (freeze instantaneously due to the pressure drop in the ascending water-sediment mix) (Hooke 1991; Alley et al. 1998, 2003). Such subglacial meltwater is in a drainage system at the ice-bed interface and becomes supercooled when the gradient of the ice-bed slope exceeds the gradient of the overlying ice-surface slope by a factor of 1.2−1.7. When meltwater becomes supercooled thick sections of sediment-laden platy and frazil ice accrete on the sediment substrate (Kristensen et al. 2008). If the conditions for supercooling are fulfilled, sediment-rich ice could potentially freeze-on. Subsequently the ice-bed slope may lower, reaching again the supercooling threshold, which leads to sediment erosion and steepening of the ice-bed slope. The cycle of sedimentation and erosion based on glaciohydraulic supercooling also includes periods of standstill. The clinoforms in the North Sea are interpreted as thawed remnants of the sediments frozen onto the substrate during the formation process (Fig. 27 and 28; Kristensen et al. 2008). Considerable field evidence from modern glaciers in Alaska support the notion of active glaciohydraulic supercooling (Alley et al. 1998; Lawson et al. 1998). However, it is unclear whether super-cooling would have taken place at the scale of the clinoforms observed in the North Sea (hundreds of metres high, several tens of km along the tunnel valley lengths (M. Huuse, pers. comm.).

Wingfield (1990) describes a regressing erosion process that starts at the ice margin and migrates backwards to a subglacial lake that drains catastrophically. Initially, a subglacial lake is dammed by the frozen ice toe. Water leaks through an ice tunnel, which grows by frictional melting. The ice creeps into the tunnel and the roof of the tunnel may collapses, which creates a breach along the tunnel line. The draining water enlarges the breach, which migrates backwards and eventually results in a catastrophic outburst of the subglacial lake.

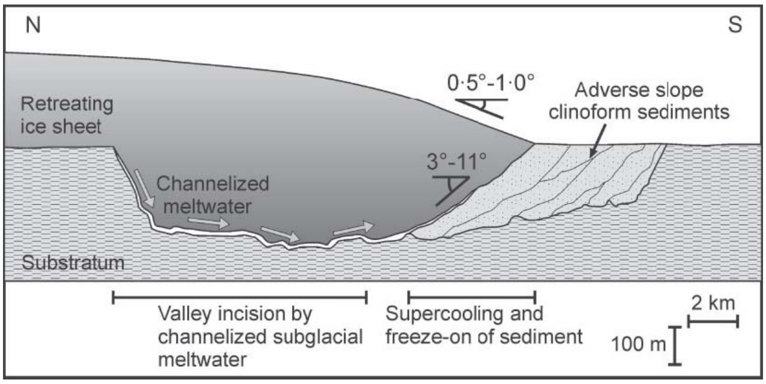


Fig. 31: Conceptual profile along the axis of a tunnel valley showing erosion by subglacial channelised meltwater in the up-ice part of the valley and en-masse freeze-on of sediments due to supercooling beneath the ice margin (Kristensen et al. 2008).

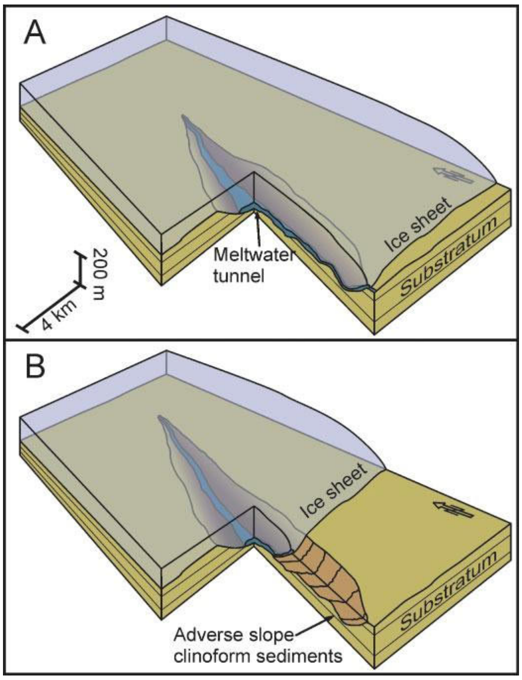


Fig. 32: Conceptual model of tunnel valley erosion and infilling processes.

(A) Subglacial erosion by channelised meltwater. (B) Deposition of adverse slope clinoform sediments by en-masse freeze-on of supercooled meltwater during ice-sheet retreat (Kristensen et al. 2008).

5.1.3 Catastrophic meltwater drainage (jökulhlaups)

For the Bornhöved tunnel valley in northern Germany, Piotrowski (1994) suggests a polygenetic origin with catastrophic subglacial meltwater drainage as main process involving a sequence of steps. During the ice advance, the ice sheet was cold-based and caused little erosion. With the ice build-up, the base thawed and created water reservoirs that were hampered from drainage by the frozen ice margin (Fig. 33 and 34). When the glacier retreated from the frozen margin into a zone of temperate basal conditions the water reservoirs drained in short and spontaneous outbursts initiating the tunnel valley formation. The process of ice advance and retreat from cold-based to warm-based areas repeated several times and deepened the tunnel valley (Piotrowski 1994).

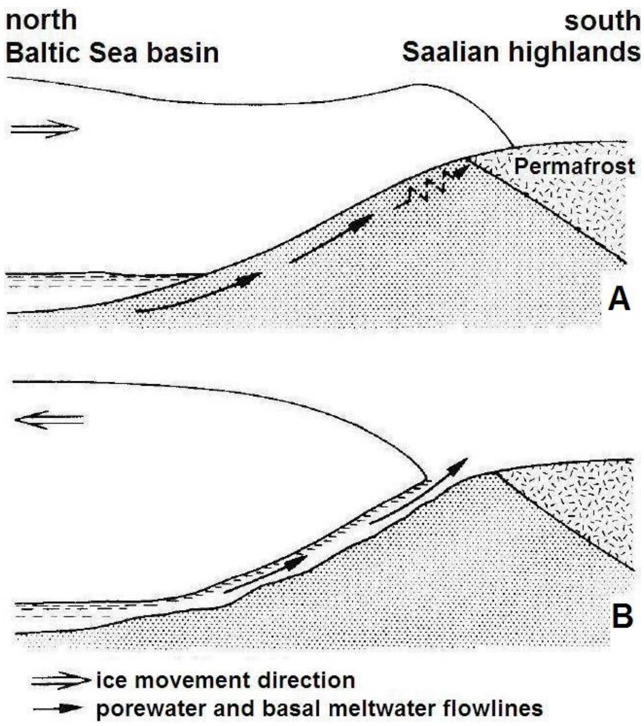


Fig. 33: Schematic representation of mechanism controlling subglacial meltwater dynamics (modified from Piotrowski 1994).

(A) Ice margin overrides permafrost, which then prevents the drainage of subglacial meltwaters and causes a water-pressure build-up.

(B) As the ice margin retreats from the outermost extent and the unfrozen bed is exposed, a rapid outburst of subglacial waters occurs and erosion by a high-pressure water jet initiates the erosion of a tunnel valley. For this mechanism, the area in front of the ice sheet can also be flat or down sloped; highlands as shown in the scheme are not a precondition.

For the southern Laurentide ice sheet, North America, Hooke & Jennings (2006) propose a similar periodic process for tunnel valley formation with a warm-based ice sheet and a frozen ice sheet margin. However, for Hooke & Jennings (2006) the frozen ice sheet margin is a precondition during the meltwater outbursts. If drainage through permeable sediments was insufficient (Darcian flow), basal meltwater formed subglacial lakes under high pressure that may have remained undisturbed for several decades (Fig. 34). Over time, water seeped under high pressure through the permeable layers under the glacier and the permafrost layers at the front of the glacier. The meltwater carried soil particles away, melted the permafrost by friction and initiated piping. Subsequently, the pipe eroded headwards until the subglacial lake was tapped, which led to a catastrophic meltwater outburst with the erosion of a tunnel valley. After emptying the water reservoir, the roof might collapse closing the conduit, and a new subglacial lake formed restarting the process.

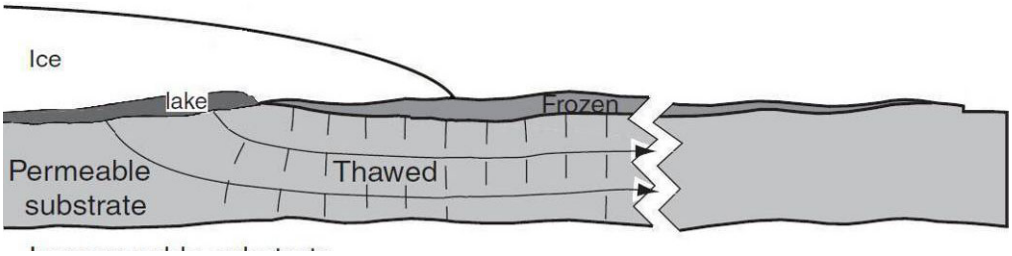


Fig. 34: Schematic illustration of a subglacial lake dammed behind an ice margin that is frozen to the bed (modified from Hooke & Jennings 2006).

The approximate equipotential lines (dashed) and flowlines (solid with arrowheads) that allow seepage are shown. At the upstream end, the flowlines are normal to an equipotential surface in the ice rather than to the bed.

5.1.4 Megafloods – sheet floods

Various authors regard tunnel valleys as a by-product of megafloods (e.g. Shaw & Gilbert 1990; Brennand & Shaw 1994; Shaw 2002; Beaney 2002; Munro-Stasiuk et al. 2009). The megaflood or sheet flood hypothesis is based on the analogy between the mould of erosional marks at the base of turbidites and drumlins that formed supposedly in the same way by water on different scales (Fig. 35; Shaw 1983; Brennand & Shaw 1994; Shaw 2002). Drumlins are thought to have formed by infilling sediments into inverted erosional marks that were cut into the base of ice sheets by subglacial meltwater (Fig. 36; Shaw 1983; Fisher & Shaw 1992). The meltwater flowed as a sheet flood covering the glacier bed and forming subglacial landforms such as drumlins, flutes or eskers. At some locations, parts of the sheet floods were channelised and tunnel valleys formed under the pressurised meltwater. The meltwater erosion at the tunnel valley bottom is described as happening during catastrophic outbursts events under bankfull conditions (Brennand & Shaw 1994; Beaney 2002; Munro-Stasiuk et al. 2009).

The megaflood hypothesis is criticised for several reasons (Walder 1994; Ó Cofaigh 1996; Clarke et al. 2005; Benn & Evans 2005, 2010). The hypothesis rests ultimately on an analogy of forms, such as drumlins and other streamlined features (Benn & Evans 2010). However, streamlined features are observed in various environments such as cloud formations, windblown sand dunes, riverbeds, snow, and glacier beds. Ó Cofaigh (1996) criticises that an enormous amount of water is needed to produce megafloods, and to fill large tunnel valleys to the banks, such as the tunnel valley described by Beaney (2002) that is up to 100 m deep and 5 km wide. Shaw (2002) assumes that the storage of such tremendous quantities of water is possible. Walder (1994) argues that a sheet flood would not remain stable and collapse to form channels, whereas Shaw (2002) responds that sheet floods have been observed at Skeiðarárjökull in Iceland that were stable for several tens of hours (Russell et al. 2007). Clarke et al. (2005) criticise that for the megaflood theory an incredible enormous volume of sub- or supraglacial water needs to be available that is released suddenly. On a physical basis, they explain that it is unlikely for sub- or supraglacial water reservoirs to remain stable until they are filled with the huge amount of water required for megafloods. Calculations of melt rates, reservoir filling rates and reservoir volumes demonstrate that the assumed sources and volumes of meltwater are unrealistic. Benn & Evans (2005) criticise that the hypothesis has not been treated in a Popperian sense that can be tested against new observations. Instead, the megaflood theory was adjusted to new contradicting evidence. For example, initially drumlins were interpreted as cavity fills. After till-cored drumlins were discovered, they were interpreted as remnants of eroded material. In the end, both types of drumlins were used as evidence for megafloods.

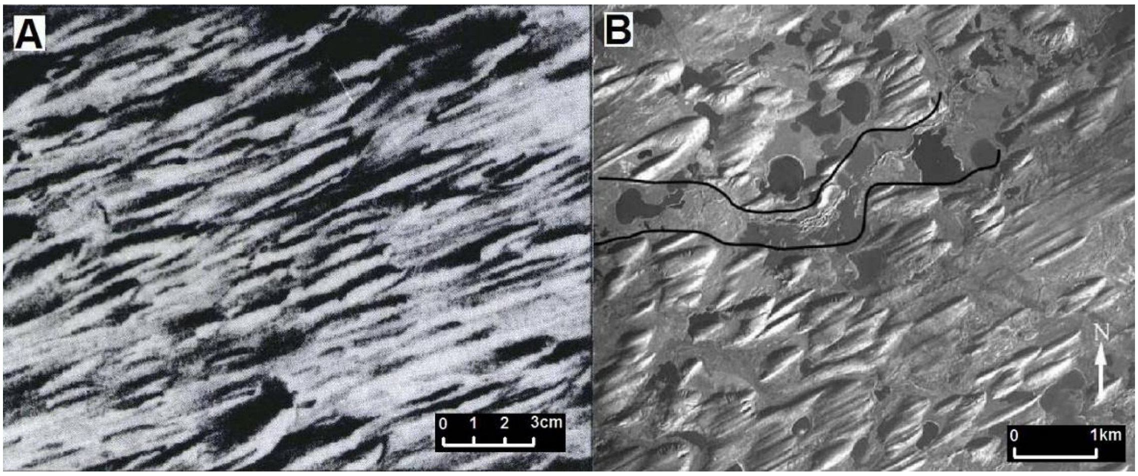


Fig. 35: Similarities in shape of (A) erosional marks at the base of turbidites (Shaw 1983) and (B) drumlins (Munro-Stasiuk et al. 2009).

In (B) a tunnel valley containing eskers is outlined with black lines. The meltwater flow was from northeast to southwest.

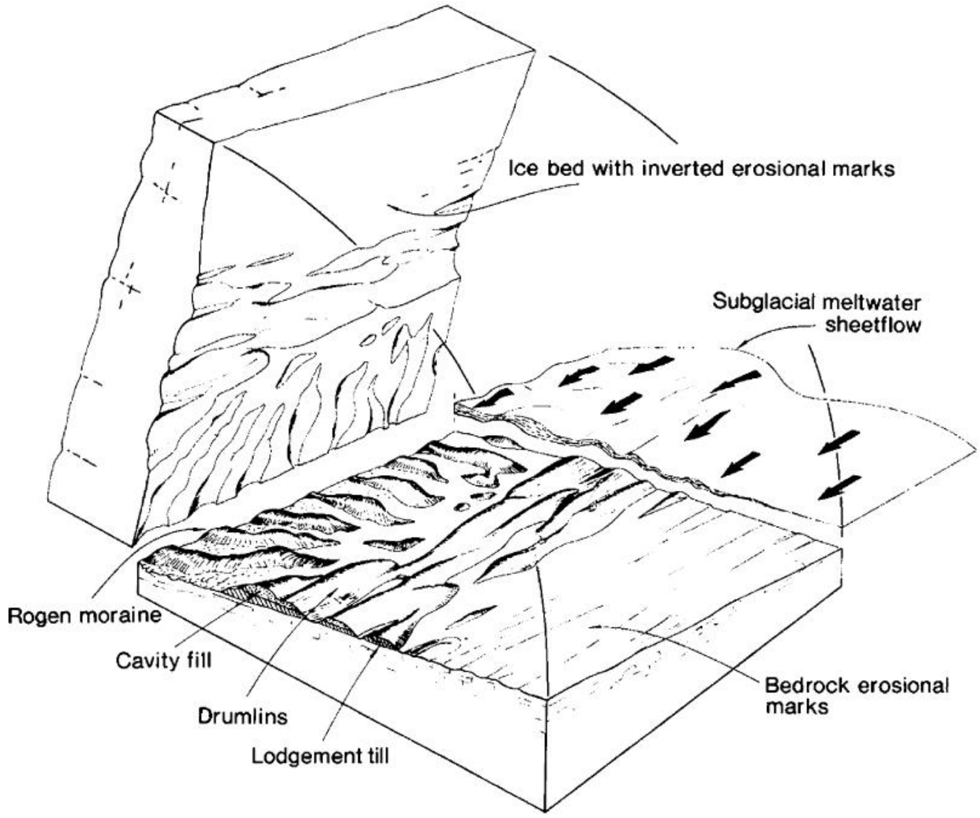


Fig. 36: Model for subglacial landforms produced by meltwater floods (Fisher & Shaw 1992).

The bedforms result from interactions between the ice base and the ground surface; for example drumlins are ice cavities filled with sediments.

5.1.5 Subglacial sediment deformation

Boulton & Hindmarsh (1987) propose subglacial sediment deformation as a tunnel valley formation process, where unconsolidated sediments are liquified by high water pressure, deformed and subsequently evacuated by subglacial meltwater. Two distinct processes are described that use different drainage systems, which are R-channels (or Röthlisberger channels; Paterson 1994) and pipes. R-channels can form in the ice at the glacier bed (Fig. 37A). The discharge of subglacial meltwater in R-channels is assumed to be high due to the hydraulic potential gradient, but the effective pressure is low. Therefore, sediments are weak and they creep into the channel; they are then removed by the meltwater. The sediment bed, and subsequently the ice and R-channels lower into the newly formed depression and the sediment deformation and evacuation continues to form a tunnel valley (Boulton & Hindmarsh 1987). Piping can develop near the ice margin of a temperate glacier with a sediment bed of low hydraulic transmissibility and under low effective pressure. If the friction between sediment particles is small due to the low effective pressure, the sediments may liquify and flow to the proglacial zone of the glacier, producing subglacial pipes (Fig. 37B; Boulton & Hindmarsh 1987). Over time the subglacial pipes enlarge and eventually form tunnel valleys.

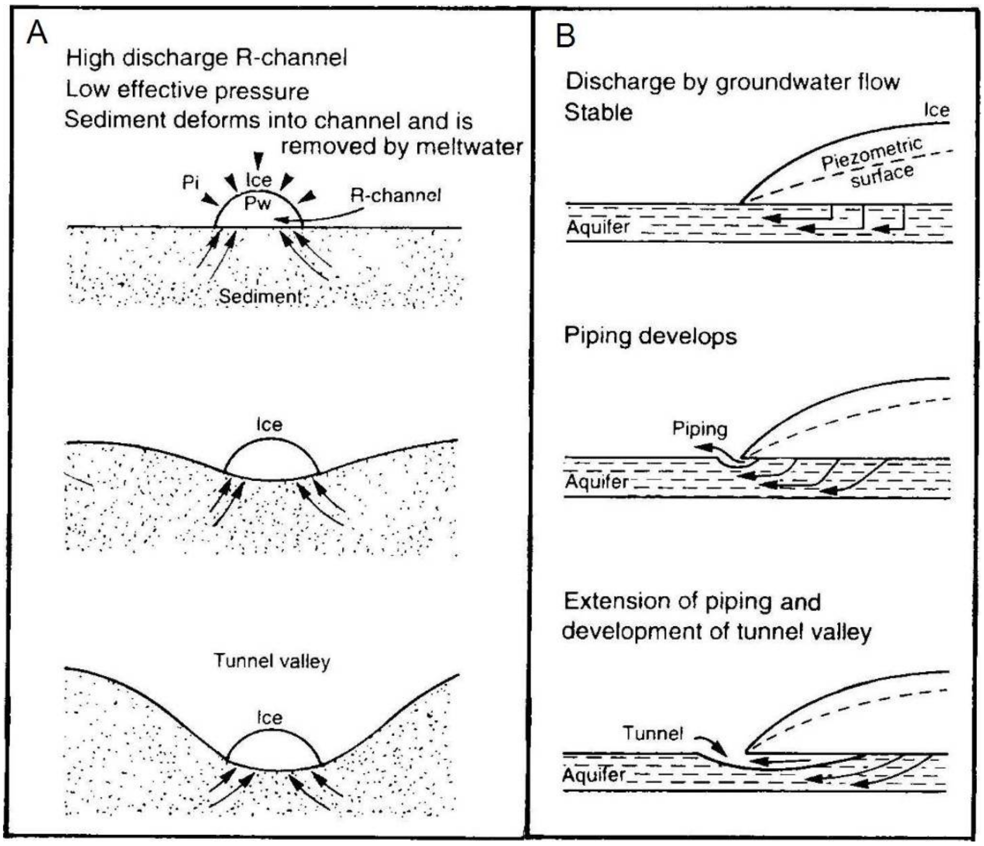


Fig. 37: Tunnel valley formation by sediment deformation in unconsolidated substrate (modified from Boulton & Hindmarsh 1987, by Ó Cofaigh 1996).

(A) High discharge R-channels develop with low effective pressure and unconsolidated sediments creep towards the tunnel and deform into it. The sediments are evacuated by the meltwater flow. The tunnel valleys develop by the R-channels migrating into the newly formed depression.

(B) Initially, the subglacial meltwater is discharged with the groundwater flow through a subglacial aquifer (top). High discharge liquifies the unconsolidated sediments and pipes develop, which eventually grow into tunnel valleys at the ice margin (middle and bottom).

According to Boulton & Hindmarsh (1987), sediment deformation, pipes and tunnel valleys may help to maintain the stability of large ice sheets flowing over deformable beds by allowing excess meltwater drainage. In this context, it is interesting to note that in the North Sea the largest tunnel valleys developed under the largest ice sheets, which date possibly from the Elsterian and Saalian glaciation (Boulton & Hindmarsh 1987).

Ó Cofaigh (1996) criticises the approach from Boulton & Hindmarsh (1987) in several ways, for example, that it is unclear why sediments should deform towards the channels if there is high water pressure. He rather would expect the opposite with the glacier decoupling from its bed due to the high water pressure that would reduce the stress on the bed and therefore result in a lower sediment deformation rate.

Piotrowski et al. (1999; 2002) investigated deformed sediments in and below a small subglacial channel (about 5 m deep and 3 m wide at the bottom) in eastern Germany, and found that they support the concept of subglacial sediment deformation. However, Piotrowski et al. (2001)

postulate that subglacial sediment deformation happens only at a small spatial and temporal scale, which cannot explain large tunnel valleys. Boulton et al. (2001) disagree referring to a tunnel valley studied by Björnsson (1996), which is 300 m deep and 20 km long under Breiðamerkurjökull and formed during the Little Ice Age (~ 1730−1890; Section 5.3).

5.2 Direct glacial erosion

The processes here referred to as direct glacial erosion are quarrying/plucking and abrasion (e.g. Benn & Evans 1998; Bennett & Glasser 2009; Burki 2009). Glacial troughs and fjords are typical geomorphological features formed by direct glacial erosion on a macroscale. However, direct glacial erosion is also a process attributed to the formation of tunnel valleys. In most studies, direct glacial erosion is considered being one of a combination of formation processes (Van Dijke & Veldkamp 1996; Smed 1998; Huuse & Lykke-Anderson 2000a; Jørgensen & Sandersen 2006). Studies by Woldstedt (1952) and Carlson et al. (1982) are cited by authors as examples of direct glacial erosion forming tunnel valleys (Ehlers & Wingfield 1991; Ó Cofaigh 1996; Huuse & Lykke-Anderson 2000a). However, as outlined below, the conclusions of Woldstedt's study from 1952 seem questionable, and Carlson et al. (1982) described valleys as troughs or submarine valleys, which share only few characteristics of tunnel valleys. In the following, these two studies are discussed in detail to explain why the studies are considered as unsuitable examples of tunnel valleys formed by direct glacial erosion.

Woldstedt (1952) investigated tunnel valleys in northern Germany and concluded in earlier studies that the tunnel valleys formed by subglacial meltwater erosion. In the study from 1952, Woldsted revised his opinion and concluded that direct glacial erosion was the predominant formative process. Woldstedt (1952) argues that the axial profile of the tunnel valleys is composed of individual segments of basins and ridges as they are found in the former glaciated alpine areas that are directly glacially eroded. Additionally, the tunnel valleys narrow towards the ice margin, which would contradict the increasing amount of meltwater that would form deeper and wider tunnel valleys at the ice margin. Woldstedt (1952) accepts that erosion by subglacial water driven by the pressure distribution under the glacier possibly explains the formation of local overdeepenings or kettle holes but not entire tunnel valleys. He disagrees that water close to the ice margin is under pressure because the margin is heavily crevassed and comparable to karst regions. Woldstedt (1952) describes the ice coverage as a continuous ice sheet with lobes and considers narrow glacier tongues to be an exception (Fig. 38). However, at an earlier stage of the glaciation, Woldstedt assumes that the ice filled and eroded preexisting valleys. Only at a later stage, the ice would form an ice sheet and continue to erode the underlying valleys. Further up the glacier in the 'original main basin' ('Stammbecken' in Fig. 38), there would be area-wide erosion because of higher ice velocities and thicker ice cover. The sandur and outwash plains are located in front of the tunnel valleys. This relationship he explains by the glacier portal, which lies at the lowest point of the glacier base at the ice margin where the tunnel valley is located. Because of high meltwater drainage the ice melts and the glacier portal retreats back, forming notches at the ice margin and depositing sediments on the outwash plains.

However, several aspects of Woldstedt's explanations are out-dated such as the idea of a 'original main basin' ('Stammbecken'), or the formation of notches in the ice margin by retreating glacier portals due to melt. The effective force produced by the hydraulic potential gradient is underestimated. The distribution of tunnel valleys in relation to the terminal moraines and sandurs (Fig. 38) suggest subglacial meltwater erosion based on the hydraulic potential gradient being the more likely formation process. Especially the location of the tunnel valleys at the notches of the ice margin, indicated by the terminal moraines, can be explained by an increased hydraulic potential gradient (see also Fig. 30 in Subchapter 5.1.1).

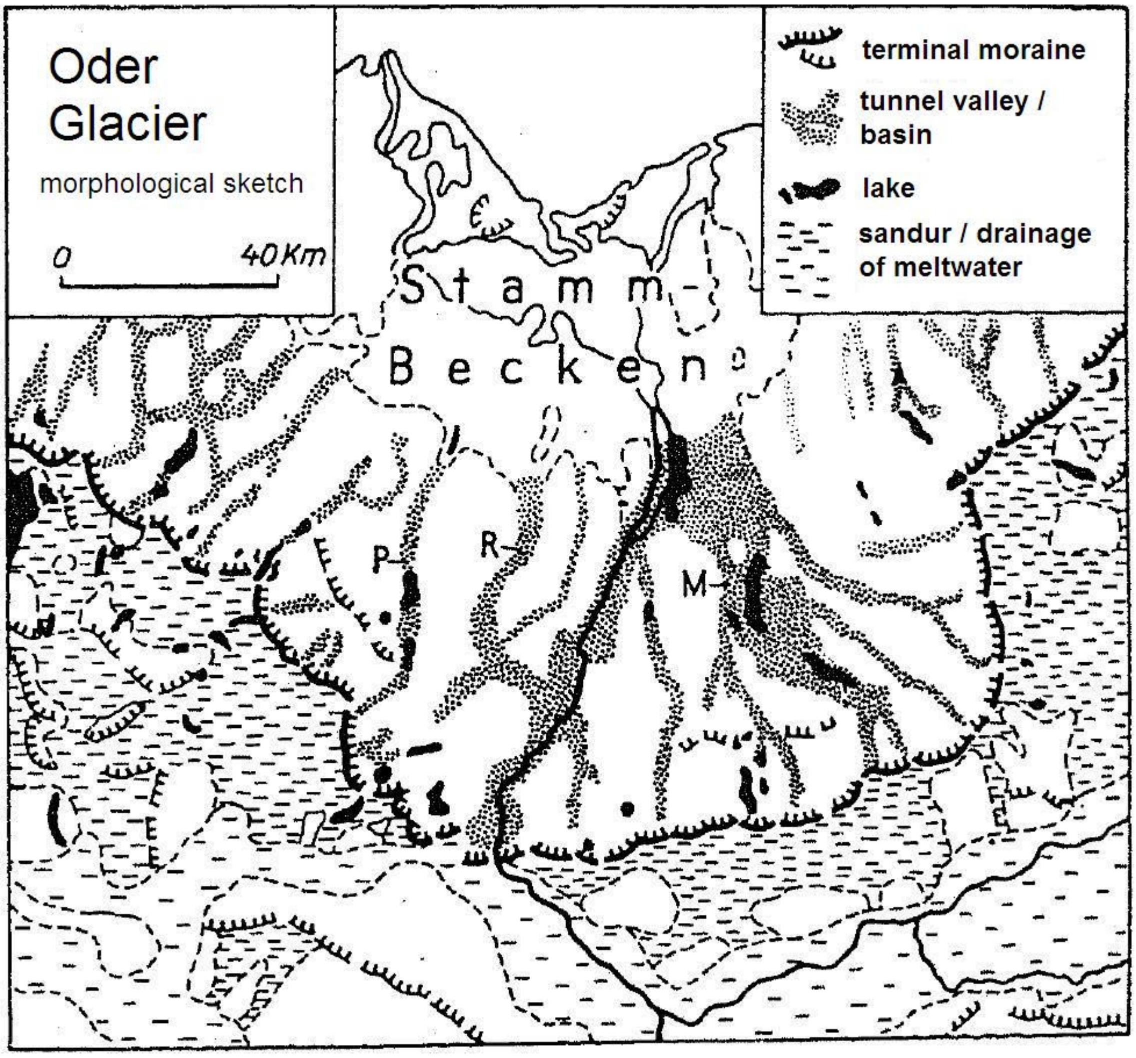


Fig. 38: Morphological sketch of Oder Glacier at the Pommerian Stadium during the last glaciation (modified from Woldstedt 1952).

The tunnel valleys are mainly located at the notches along the ice margin, depositing the sediments on sandurs. P = Prenzlauer Basin, R = Randow Basin, M = Madü-Plöne Basin.

5.3 Erosion rates

The northern European tunnel valleys are widely believed to date from the Elsterian, Saalian and Weichselian glaciation within the Pleistocene (e.g. Ehlers et al. 1984; Grube 1979; Ehlers & Wingfield 1991; Huuse & Lykke-Andersen 2000a; Larsen et al. 2009; Krohn et al. 2009). Dating tunnel valleys and constraining the duration of tunnel valley formation is difficult because often only relative ages can be determined. Usually there is no or only little organic material available for absolute radiocarbon dating of Pleistocene tunnel valleys (Wingfield 1989), and valley fills predating the last (Weichselian) glaciation are beyond the age range covered by this method. Other absolute dating methods include optically stimulated luminescence (OSL) and thermoluminescence (TL). Although these methods have a high potential for dating Quaternary valley fills (also of pre-Weichselian age), they have been applied only rarely in the reviewed literature (e.g. Krohn et al. 2009). In general, the younger tunnel valleys are, the easier they can be dated, the duration of formation constrained and erosion rates calculated.

Erosion rates depend on the length of the timeframe considered and on whether inactive intervals can be identified or not. It is likely that there are times of intense tunnel valley erosion separated by phases of inactivity. Therefore, it is difficult to project erosion rates into the future because the phases of erosion and inactivity are difficult to assess. In the following section, rates of deepening are described for tunnel valleys in Denmark that were confined by dating methods (Sandersen et al. 2009; Krohn et al. 2009) and erosion is described for overdeepenings formed in Washington State (Booth & Hallet 1993; Booth 1994). Additionally, timeframes are discussed for overdeepenings, which formed in modern times by subglacial meltwater (Björnsson 1996; Post & Motyka 1995; Motyka et al. 2006; Fleisher et al. 2010; Russell et al. 2007). However, these overdeepenings vary in size, surrounding topography and are influenced by various processes. Therefore, not all described overdeepenings are necessarily tunnel valleys.

Sandersen et al. (2009) and Krohn et al. (2009) used transient electromagnetic (TEM) and borehole data to determine Late Weichselian ice-marginal positions, defining timing and duration of the tunnel valley formation in northern Denmark. The incised substrate consists mainly of unconsolidated Quaternary sediments and in the lowest layers Upper Cretaceous chalk. The age of the tunnel valleys were dated relatively, and have been constrained together with absolutely dated borehole data to the deglaciation of the Late Weichselian Main advance and re-advance within the time interval of about 20 to 18 ka BP. Based on the distribution of at least eight generations of tunnel valley systems and the topography, four successive ice-marginal positions were attributed to the deglaciation of the Main ice advance, and seven ice-marginal positions were assigned to the deglaciation following the re-advance (Fig. 39; Krohn et al. 2009). Consequently, the tunnel valleys formed within a few thousand years, narrowing down the duration of the formation of the tunnel valley systems at each ice-marginal position to only a few hundred years or less. Sandersen et al. (2009) suggest that repeated catastrophic subglacial meltwater outbursts eroded these tunnel valleys, which are up to 190 m deep, 2−13 km long and between 0.5 and 2 km wide.

In western Washington State, the Puget ice lobe advanced into the Puget Lowland about 15'000 years ago, and deposited voluminous sediments on a prograding, proglacial outwash plain during 2000 or 3000 years (Booth 1994). Subsequently, the ice sheet advanced over the outwash plain and excavated deep linear troughs similar to tunnel valleys described in northern Europe (Booth & Hallet 1993). The subparallel troughs are up to 400 m below the surface of the glaciated uplands (Booth 1994). For the excavation of the troughs and small upland valleys in the Puget Lowland, a net transport of nearly 1000 km^3 of sediments was required, where well over three-fourth are accounted to trough erosion. The troughs formed primarily by subglacial water and probably mainly during ice occupation (Booth 1994).

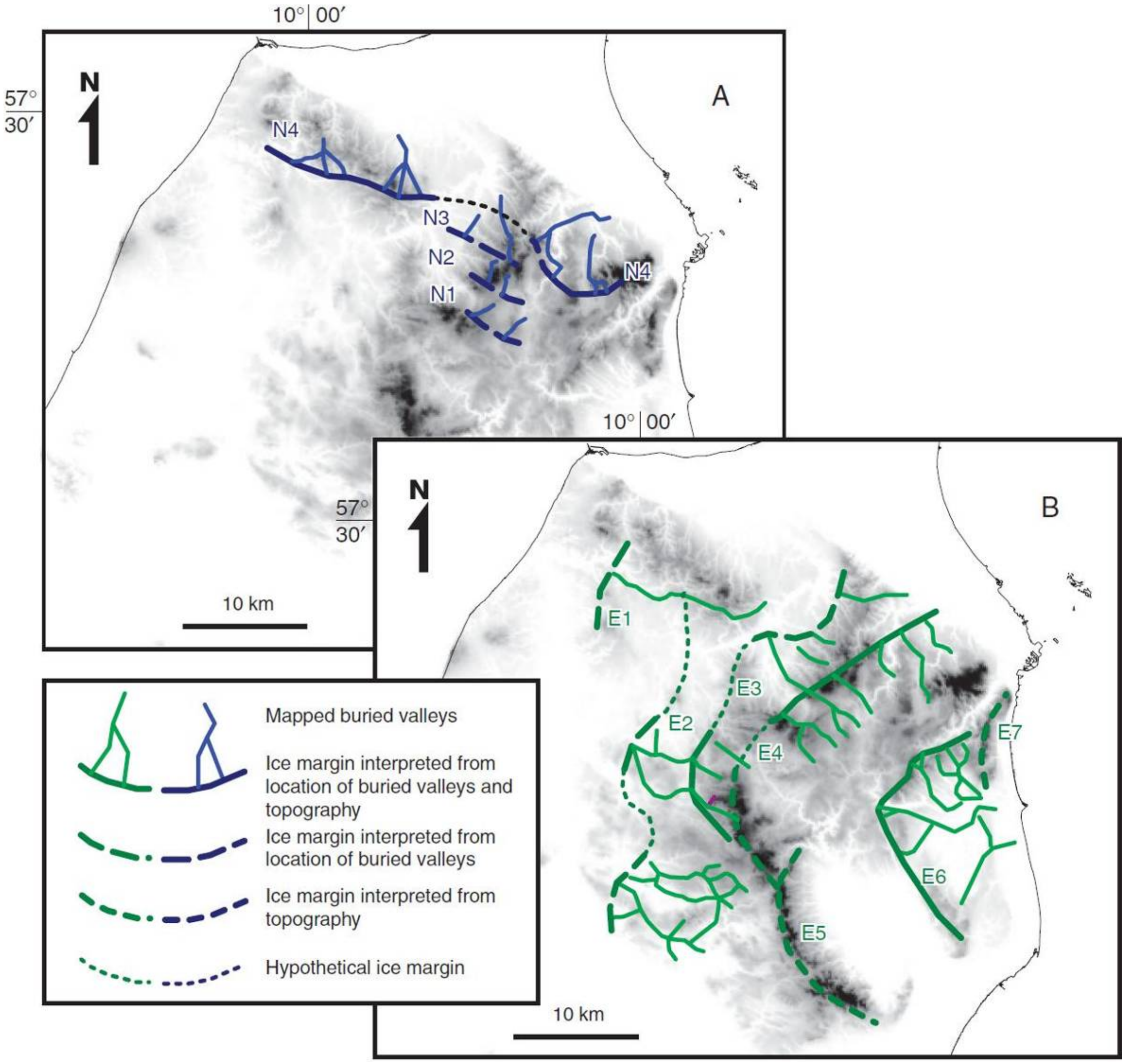


Fig. 39: Ice-margin positions inferred from buried tunnel valleys and the topography in northern Denmark (Sandersen et al. 2009).

Ice-margin positions during deglaciation of (A) the Late Weichselian Main advance and (B) re-advance. The topography is shown as background with dark grey colours representing the highest areas (up to 136 m a.s.l.).

Written historic records document the advance of Breiðamerkurjökull, Iceland, by about 10−15 km onto farmland, destroying vegetation and farms between the Middle Ages and the post-glacial maximum in 1890 (Little Ice Age; Björnsson 1996). During the 20th century, the glacier retreated and a proglacial lake developed. Beneath the glacier, radio-echo soundings revealed glacial landforms such as a 20 km long tunnel valley 2−5 km wide and 300 m deep. The tunnel valley must have eroded into the unlithified sediment substrate (believed to be from the Late Weichselian and Holocene) within a maximum of 260 years between the advance in 1732 and 1990 when the tunnel valley was detected under the ice. Björnsson (1996) calculated the sediment flux within the ice, subglacial till and subglacial streams and found that the fluvial processes evacuated an order of magnitude more sediments than the two other processes together. Additionally, several surge events (periodically accelerated glacier advances) and drainages of ice-dammed marginal lakes by jökulhlaups have been observed at Breiðamerkurjökull in the past (Björnsson 1996). The observed jökulhlaups and very high precipitation rates make repeated outburst events a likely formation process for the tunnel valley.

Extraordinary erosion and sedimentation rates have been documented for Taku Glacier that is the principal outlet glacier from the Juneau Icefield in southeast Alaska (Motyka & Post 1995; Post & Motyka 1995; Nolan et al. 1995; Hallet et al. 1996; Motyka et al. 2006; Truffer et al. 2009; Pelto et al. 2008). Subglacial meltwater processes are considered being the main processes (e.g. Hallet et al. 1996). Additionally, Taku Glacier is in principal a tidewater glacier that is accompanied by an extraordinary advance and retreating behaviour, which can also explain the exceptional erosion and sedimentation rates. The glacier follows the typical cycle of a grounded tidewater glacier, where the glacier terminus is initially in a stable phase at the head of the fjord, followed by a slow advance phase until another stable phase with maximum extent is reached, and ends with a rapid glacier retreat (Fig. 40) (Meier & Post 1987; Criscitiello et al. 2010). High calving rates associated with high water depth indicate that glaciers can advance into deep waters only by keeping a moraine shoal at the glacier terminus, which moves slowly forward by eroding material at the proximal side, and depositing it at the distal side (Fig. 41) (Meier & Post 1987). Motyka et al. (2006) compared early bathymetric surveys of Taku Glacier (1890, 1937, 1952) and repeat ice-penetrating radio echo soundings (RES; 1989, 1994, 2003−2005). They found that between 1890 and 2005, Taku Glacier advanced by about 7.5 km and lowered the sediment bed by about 100 m. They documented the continuing sedimentation and erosion process with a resulting progressing overdeepening (Fig. 41), and found that the erosion rate increases as ice thickens, and that soft sediment erosion of 1−4 m a^{-1} can occur for valley glaciers in maritime climates. Hallet et al. (1996) calculated for the 99 year long period (1890−1989) a sediment evacuation of roughly about 0.5−0.6 km^3, resulting in an evacuation rate of about $5x10^6$ m^3 a^{-1}.

From 1993−95, three outburst floods were observed at Bering Glacier in Alaska in conjunction with a glacier surge (Fleisher et al. 2010). In the following ten years, the glacier wasted down and retreated, revealing two overdeepend basins several decametres deep resulting from the outburst floods, and new sub- and proglacial landforms such as eskers, lakes and new terraces. The conduit draining the outburst floods was already in place during a previous surge event in 1965−67 and was located in the notch between two ice lobes.

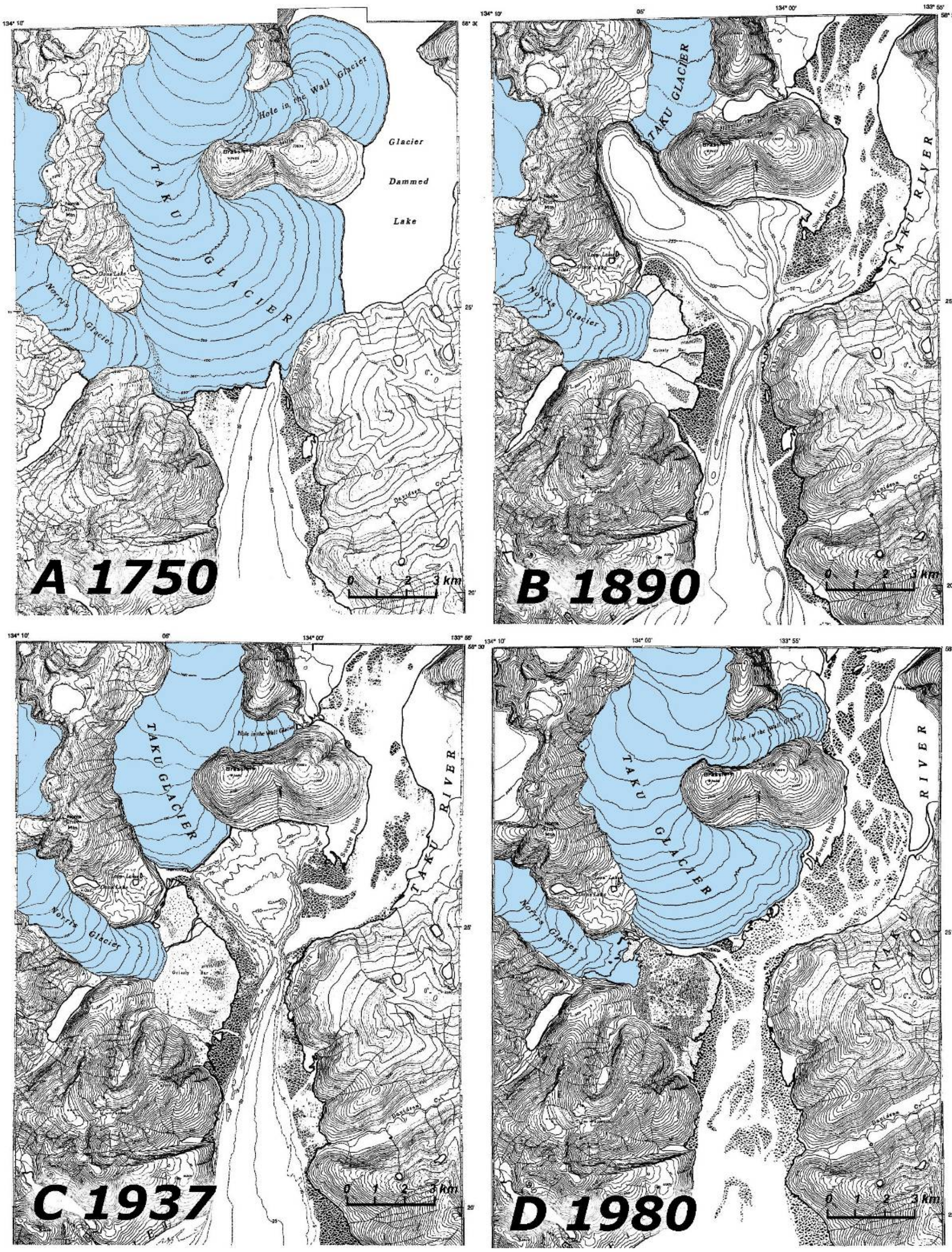


Fig. 40: Ice extents of Taku and Norris Glacier with bathymetry of Taku Inlet (depth in feet; modified from Post & Meier 1995).

(A) Taku and Norris Glacier in 1750 approximately as they were at the most recent maximum advance. (B) Taku Glacier in its furthest retracted observed historic position with large tidal basin with depths of more than 100 m (330 ft) below sea level in 1890. (C) Advancing Taku Glacier with moraine shoal with maximum depth of 6.7 m in 1937. (D) By 1980, Taku Glacier pushed the terminal moraine shoal above sea level, and filled Taku Inlet with sediments.

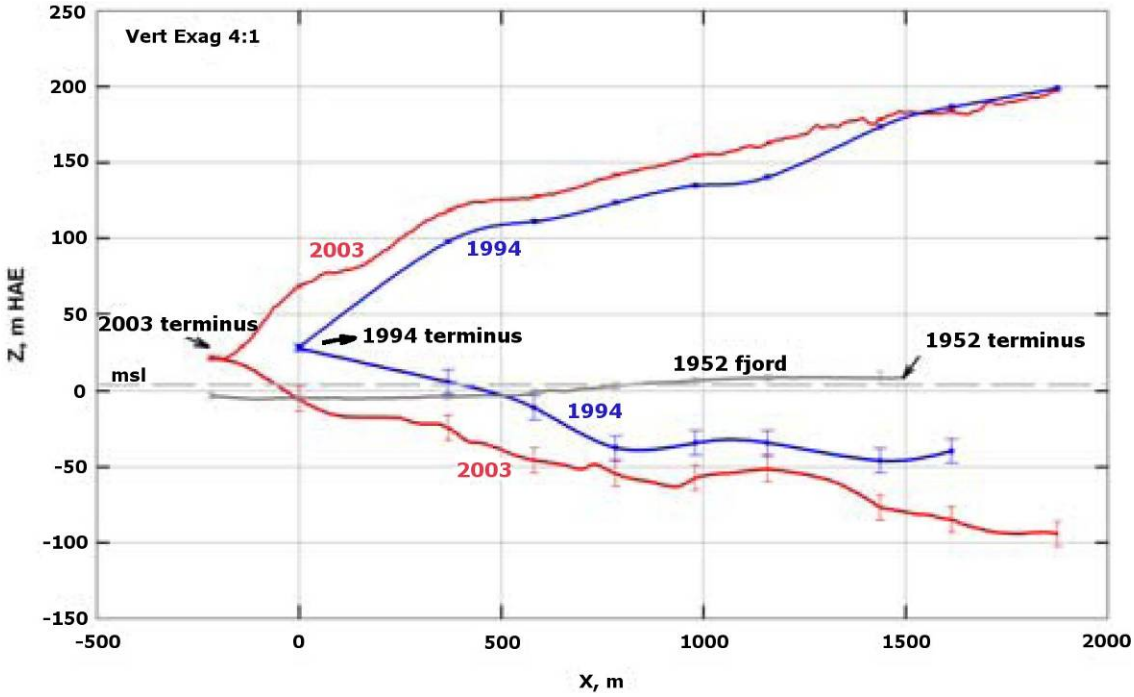


Fig. 41: Longitudinal transect from terminus of Taku Glacier (Motyka et al. 2006).

Blue (red) lines indicate glacier bed and ice surface in 1994 (2003) with 1σ error bars. Fjord bathymetry for 1952 (grey line) is also shown.

Russell et al. (2007) studied the formation of and discharge rates from a tunnel valley at Skeiðarárjökull, Iceland, which was formed by a jökulhlaup from 4−7 November 1996 (Smith et al. 2000). The jökulhlaup was conspicuous for its record magnitude and short duration, and was the result of ice melted by a volcanic eruption under the Vatnajökull ice cap (Smith et al. 2000). The meltwater flowed subglacially to the subglacial lake Grímsvötn from where it was released once a critical level was reached (Russell et al. 2007). The floodwater burst from several outlets across the 23 km wide ice margin, channelising progressively into major conduits. The tunnel valley formed beneath the margin of the eastern end of the ice lobe, cutting into the sediments of a surrounding moraine rather than into the ice. A preexisting proglacial lake with temporarily raised water levels influenced the routing of the tunnel valley by acting as a hydraulic dam, which deflected the subglacial jökulhlaup flow to the side. After subsequent glacier retreat in the following years, the tunnel valley appeared at the surface. Over a distance of 160 m, the tunnel valley ascended with a reverse gradient 11.5 m up to the former ice margin, where sediments were deposited on a proglacial outwash fan. Rip-up clasts on the proglacial outwash fan were evidence for the major subglacial excavation by the jökulhlaup. Russell et al. (2007) emphasise that proglacial lakes influencing the subglacial meltwater routing require greater attention.

The erosion by catastrophic outburst events observed in modern times demonstrates the excavation power of water, and suggests erosion on the order of decametres within the short duration (days) of outburst events (Fleisher et al. 2010; Russell et al. 2007). The studies of Björnsson (1996), Sandersen et al. (2009) and Krohn et al. (2009) suggest that tunnel valleys as deep as 300 m can form within about 200−300 years. These studies document erosion rates predominantly for catastrophic outburst events for unconsolidated sediment beds. However, very little is known about erosion rates of bedrock (lithified substrates) and of sediments by continuous processes such as fluvial sediment transport or sediment deformation or time-transgressive erosion, and the relative contribution of rare extreme erosion events and more continuous processes to tunnel valley formation is not well understood.

6 Conclusions

Tunnel valleys have been described from various parts of the world. The oldest tunnel valleys are Ordovician (~ 430 Ma) and are located in northern Africa (Hirst et al. 2002; Le Heron et al. 2004). Tunnel valleys in West Australia and Antarctica date from the late Paleozoic (~ 300 Ma) and Miocene (~ 13 Ma), respectively (Eyles & Broekert 2001; Sugden et al. 1991; Lewis et al. 2006). Pleistocene tunnel valleys (~ 10 ka − 650 ka) have been described in North America and Europe. The European valleys are associated with the Elsterian (~ 370 ka−475 ka), Saalian (~ 128 ka−210 ka) and Weichselian ice age (~ 10ka−15 ka) (Mooers 1989; Clayton et al. 1999; Ehlers et al. 1984; Huuse & Lykke-Andersen 2000a; Jørgensen & Sandersen 2006). In modern times, tunnel valley formation has been observed in Alaska and Iceland (Björnsson 1996; Russel et al. 2007; Fleisher et al. 2010). This literature review focused on tunnel valleys in northern Europe and North America. The results concerning tunnel valley morphology, valley distribution, bedrock lithology, formation processes and formation rates are summarised below.

Tunnel valleys are large, overdeepened depressions that appear as individual several kilometre long segments or as network like systems with total length up to > 150 km (Ó Cofaigh 1996; Stackebrandt 2009). Widths of tunnel valleys range between a few hundred metres and a couple of kilometres, in some cases up to 6 km (e.g. Clayton et al. 1999; Praeg 2003; Jørgensen & Sandersen 2006). Typical depths of tunnel valleys range from a few decametres up to a few hundred metres. In the reviewed literature, only very few tunnel valleys reach depths of more than 500 m, and these are typically cut into very soft sediments in northern Germany and in the North Sea (Praeg 2003; Stackebrandt 2009). Tunnel valleys often begin and terminate abruptly and are steep-sided with wide and relatively flat bottoms (Huuse & Lykke-Andersen 2000a). The longitudinal profile is often described as undulating, with sills or steps with a reverse gradient, or as concave (Sjogren et al. 2002; Kristensen et al. 2007; Rumpel et al. 2009). There are open and buried tunnel valleys, where lakes, bogs or eskers occasionally occupy the open tunnel valleys. Buried tunnel valleys are filled with glaciogenic, glaciofluvial, glaciolacustrine, glaciomarine or non-glacial sediments (Benn & Evans 1998; Jørgensen & Sandersen 2006; Praeg 2003). Tunnel valleys are oriented in a parallel or radial pattern, and are inferred to be parallel to the hydraulic potential gradient at past ice sheet margins. At notches in the ice margin where two ice lobes meet tunnel valleys develop preferably (Smed 1998). However, Lonergan et al. 2006 and Stewart 2008 argue that some tunnel valleys possibly formed at a central location of the ice sheet. Tunnel valleys often end at terminal moraines, where some of the eroded material is deposited onto an outwash fan or sandur (Clayton et al. 1999; Rumpel et al. 2009).

The underlying substrate of tunnel valleys in northern Europe and North America consists largely of unlithified sediments and weakly to moderately lithified sedimentary rocks (particularly sandstones, siltstones, claystones and marls). Extraordinary excavation locally exceeds 500 m in soft and water-saturated sediments in northern Germany. In the North Sea, tunnel valleys of such depths are a rare exception (Praeg 2003). In Germany and in the North Sea tunnel valleys deflecting around salt diapirs have been observed (e.g. Piotrowski 1994; Kristensen et al. 2007, 2008) indicating that tectonic features, such as folds and diapirs can have a local influence on the course of tunnel valleys. However, also tunnel valleys cross-cutting salt structures have been observed and therefore indicate that salt structures can exert opposite controls on the erodibility on the substrate (Hinsch 1979; Huuse & Lykke-Andersen 2000a).

The most important formation processes is evidently subglacial meltwater erosion, whereby most likely tunnel valleys form by a combination of processes (Stewart 2008), including direct glacial erosion. Subglacial meltwater erosion is dependent on the subglacial discharge and hydraulic potential gradient, both of which increase at the ice sheet margin and leads to tunnel valley formation. In temperate ice masses, meltwater is produced supraglacially, englacially and/or subglacially. Supraglacial melting is enhanced by warming air temperatures, which is typical for warming phases that initiate deglaciation. Subglacial meltwater forms at the base of ice sheets, when it is at the melting point in part because of the thermal insulation provided by the overlying ice and the depression of the melting point by the pressures beneath the ice; warm mean air temperatures are also conducive to the basal ice being temperate. However, during cold phases of the ice ages the glacier margins were cold based and therefore frozen to the ground. Warming air temperatures could lead to a temperate base at the ice sheet margin, considerable meltwater production and possibly ice sheet retreat. Therefore, many formation theories suggest that tunnel valleys form predominantly during deglaciation or stagnant phases, which is supported by preserved glacial geomorphological features that are not overridden by the ice sheet, such as eskers or terminal moraines (e.g. Piotrowski 1994; Kristensen et al. 2008, Sandersen et al. 2009). However, the studies on Taku Glacier (e.g. Post & Motyka 1995; Motyka et al. 2006) indicate that overdeepening also happens during glacier advance. Additionally, the hydraulic potential gradient increases with a steep glacier terminus as occurring during glacier advance (Smed 1998). Sediment analysis of the tunnel valley infill could potentially give further indication in which glacier phase tunnel valleys formed.

The reviewed meltwater erosion processes include time-transgressive formation, catastrophic meltwater drainage, megafloods and sediment deformation. Time-transgressive formation is characterised by temporally transgressing and spatially regressing erosion usually associated with deglaciation (Mooers 1989; Praeg 2003; Kehew & Kozlowski 2007). Kristensen et al. (2008) describe time-transgressive erosion in conjunction with contemporaneous sedimentation caused by glaciohydraulic supercooling. The time-transgressive erosion described by Wingfield (1990) is initiated at the ice sheet margin and migrates headwards, where it can result in the catastrophic outburst of a subglacial lake. Catastrophic outburst events or jökulhlaups require a water reservoir that drains suddenly. It is often assumed that subglacial meltwater tends to dam up behind the cold based glacier margin before being released by either the ice sheet margin that becomes permeable when retreating into zones with temperate conditions, or meltwater that seeps through the permafrost layers, developing pipes that eventually tap the subglacial lake (Piotrowski 1994; Hooke & Jennings 2006). Megafloods have been hypothesised to produce tunnel valleys as a by-product (Shaw 2002; Munro-Stasiuk et al. 2009), but the hypothesis is controversial (e.g. Clarke et al. 2005; Benn & Evans 2005), and accepted by only a few Quaternary scientists and glaciologists (Shaw 2002; Munro-Stasiuk et al. 2009). Sediment deformation and subsequent evacuation by meltwater may contribute to tunnel valley formation (Boulton & Hindmarsh 1987). The sediments are deformed under low effective pressure either in water-filled subglacial channels causing sediment creep, or in gradually developing pipes. However, Ó Cofaigh (1996) criticises that it is unclear why sediments would creep into subglacial channels, and Piotrowski (1994) claims that sediment deformation happens only on small scales. Direct glacial erosion includes quarrying/ plucking and abrasion, and is usually considered to contribute to tunnel valley formation only in combination with other processes (Benn & Evans 1998; Bennett & Glasser 2009).

Formation processes influence the morphology and distribution of tunnel valleys. At the ice margin, the rapidly decreasing hydraulic potential could possibly cause increased meltwater erosion and would explain the frequently observed reverse gradient of the valley bottom and the abrupt termination of tunnel valleys. The undulating overdeepened valley bottoms are an indicator for subglacial erosion by pressurised meltwater (Beaney 2002; Sjogren et al. 2002; Benn & Evans 1998). Laterally shifting meltwater erosion processes or direct glacial erosion due to the ice pressure on the slopes help account for the widening of tunnel valleys (e.g. Smed 1998; Van Dijke & Veld-kamp 1996; Jørgensen & Sandersen 2006). Valley re-use tendencies and possibly the re-use of preexisting fluvial valleys can be explained by the topography that reinforces erosion patterns (Jørgensen & Sandersen 2006), particularly where relief is high. Additionally, the hydraulic conductivity and the kinematic resistance of the valley infill influence the erodibility. However, several generations of overlying and cross-cutting tunnel valleys have been observed, which formed independently from preexisting tunnel valleys and their infill material (Jørgensen & Sandersen 2006, 2009; Kristensen et al. 2007, 2008; Stewart & Lonergan 2011; Lutz et al. 2009; Sandersen et al. 2009). Anastomosing tunnel valley systems are explained by cross-cutting relationships of several generations of tunnel valleys (Jørgensen & Sandersen 2006), or by a time-transgressive formation during the gradual retreat of ice sheet lobes (Mooers 1989).

Studies indicate that erosion rates can be very high, particularly in unlithified sediments. Recent well-documented erosion by catastrophic outburst events demonstrates the excavation power of water, and suggests on the order of decametres of erosion within the short duration (days) of outburst events (Fleisher et al. 2010; Russell et al. 2007). The studies of Björnsson (1996), Post & Motyka (1995), Motyka et al. (2006), Sandersen et al. (2009) and Krohn et al. (2009) suggest that tunnel valleys as deep as 300 m can form within about 200−300 years. These studies document erosion rates predominantly for catastrophic outburst events for unconsolidated sediment beds. However, as the rates inferred in these case studies only apply to limited time periods they cannot be extrapolated over a longer time. Moreover, little is known about erosion rates of bedrock (lithified substrates) and of sediments by continuous processes such as fluvial sediment transport or sediment deformation.

More quantitative observational data would help to improve process understanding, and characterisation and dating of valley fills may help to better identify phases of activity and inactivity. An estimation of the depth of future glacial erosion should be based on a good understanding of the morphology and depth of existing valleys. Potential processes and parameters controlling maximum valley depth (e.g. ice thickness, inclination of ice at the ice front, glaciohydraulic supercooling) should be further investigated.

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Appendix

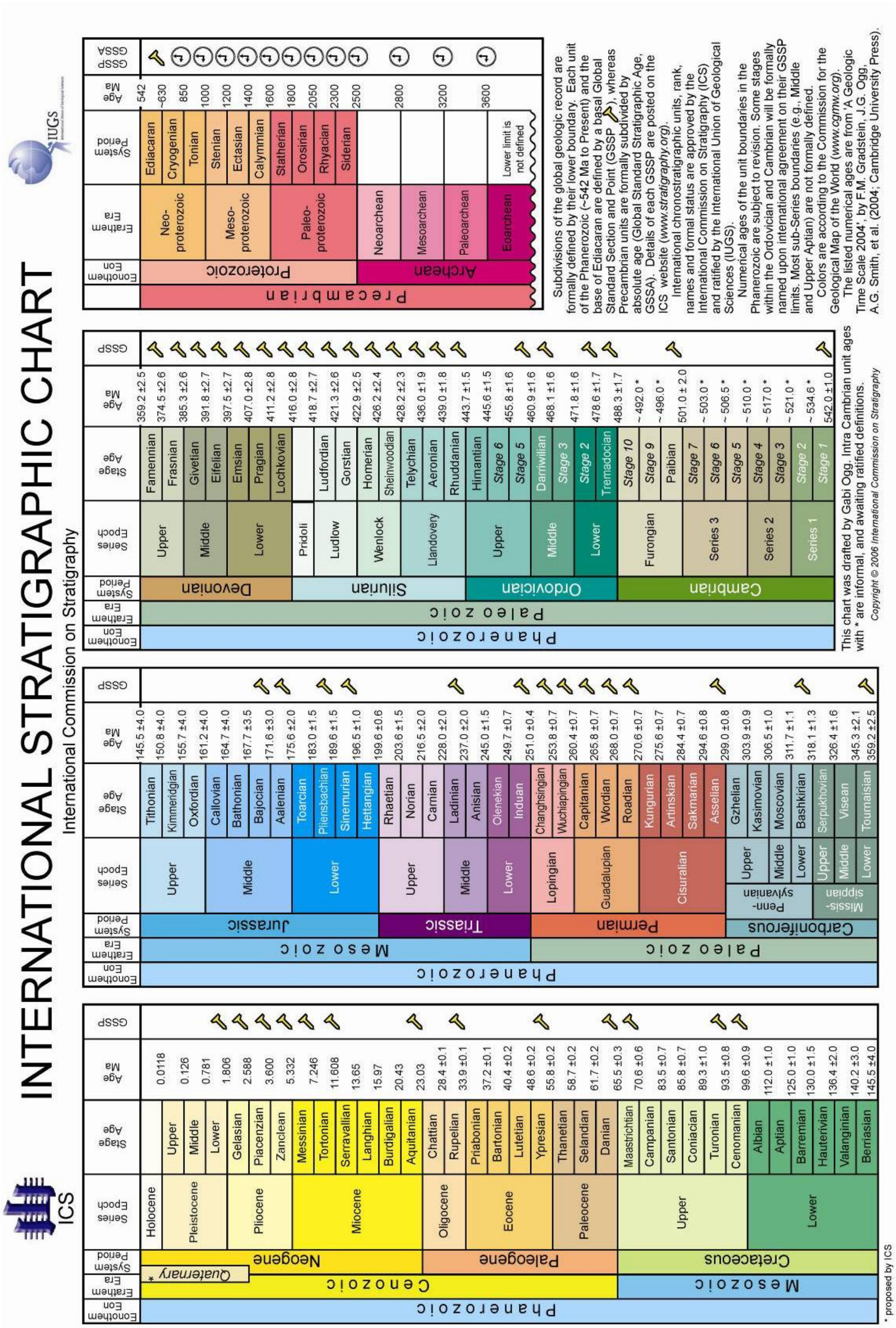

Fig. A-1: International stratigraphic chart by the International Commission on Stratigraphy (ICS 2006).

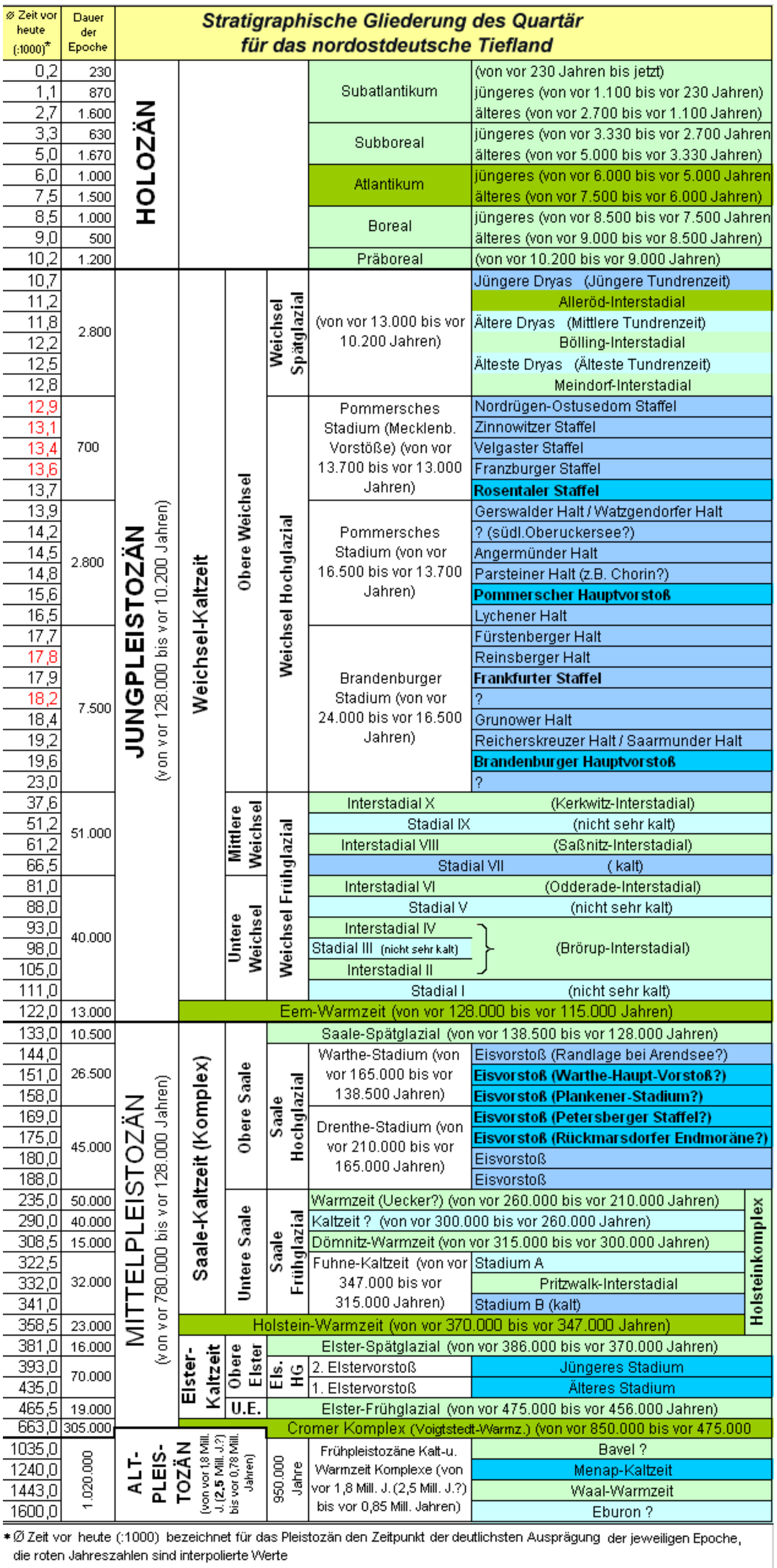

Fig. A-2: Stratigraphic chart during the Quaternary for northern Germany (Source http://de.academic.ru/pictures/dewiki/113/quartaer.png accessed on 15 April 2010).

Blue colours indicate cold periods and green colours indicate warm periods.