A Review of Tunnel Valleys in Northern Europe

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Introduction

The existence of buried Quaternary valleys indicates that glacial erosion is an important process in shaping the landscape of the Swiss Alpine foreland (Fig. 1). Considering the time of concern of 1 Ma for high-level nuclear waste repositories, glacial erosion needs to be addressed for assessing their long-term safety. As one approach to better understand the formation processes of Quaternary valleys, a literature review of tunnel valleys outside the alpine realm was carried out. The focus of the review is on tunnel valleys in northern Europe, which have been investigated in detail. Here we give an overview of observed valley morphologies, their geographical distributions, bedrock lithology and formation process theories.

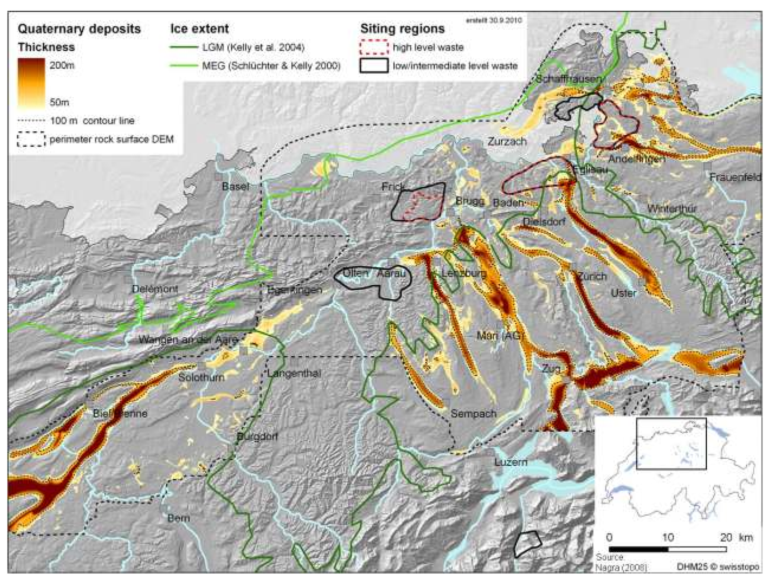


Fig. 1: Thickness of Quaternary sediments in northern Switzerland indicating deep, overdeepened and buried valleys in the northern Alpine foreland. The ice extent at the Last Glacial Maximum (LGM) and during the Most Extensive Glaciation (MEG) as well as the perimeters of the siting regions for low/intermediate-level and high-level radioactive waste repositories are shown (modified from Nagra 2008).

Terminology

Tunnel valley:

- widely known and applied term
- general term without claim to imply one specific formation process or resemblance to one specific morphology
- term originates from subglacial drainage channels that form a tunnel at the base of an ice sheet

Other terms:

- Quaternary valley, paleovalley
- tunnel channel, subglacial meltwater channel
- overdeepend buried valley, linear incision
- German: Rinnental, Rinne, Tunneltal, übertieftes Tal, übertiefte Felsrinne

Geographical Distribution

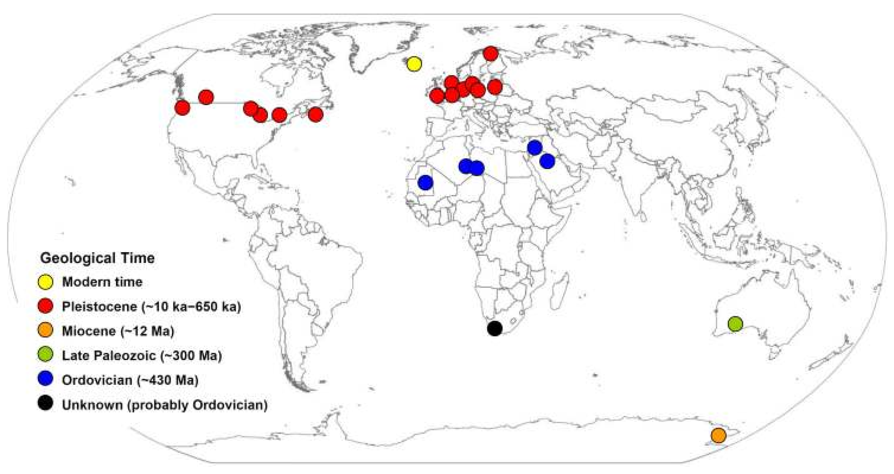


Fig. 2: Worldwide geographical distribution and age of reviewed tunnel valleys

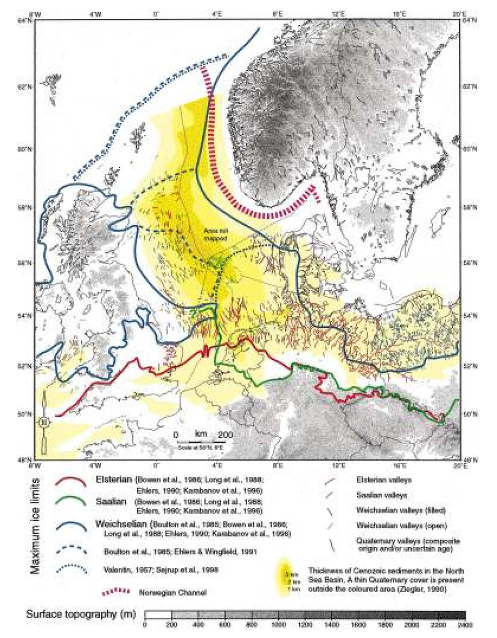


Fig. 3: Overview of tunnel valleys in northern Europe, compiled from various sources (Huuse & Lykke-Andersen 2000).

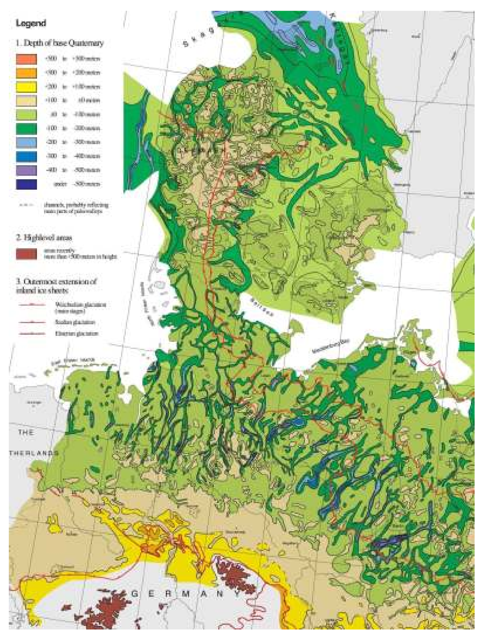


Fig. 4: Map of base of Quaternary deposits in northern Germany and Denmark (Stackebrandt et al. 2003). Some of the longest and deepest tunnel valleys have been mapped in northern Germany.

Lithology

- North Sea, Denmark, northern Germany: sediments, mainly sand-, silt- and claystone from Cenozoic (past ~65 Ma; Fig. 5), epeiric sea
- Northern Denmark: chalk, lime-, sand- and siltstone from Mesozoic (~65- 250 Ma)
- Southern Sweden, north of Scotland: sand- and claystone with some carbonates from Palaeozoic (~250- 540 Ma)
- Northern Scandinavia: hard Precambrian rocks (older than ~540 Ma)

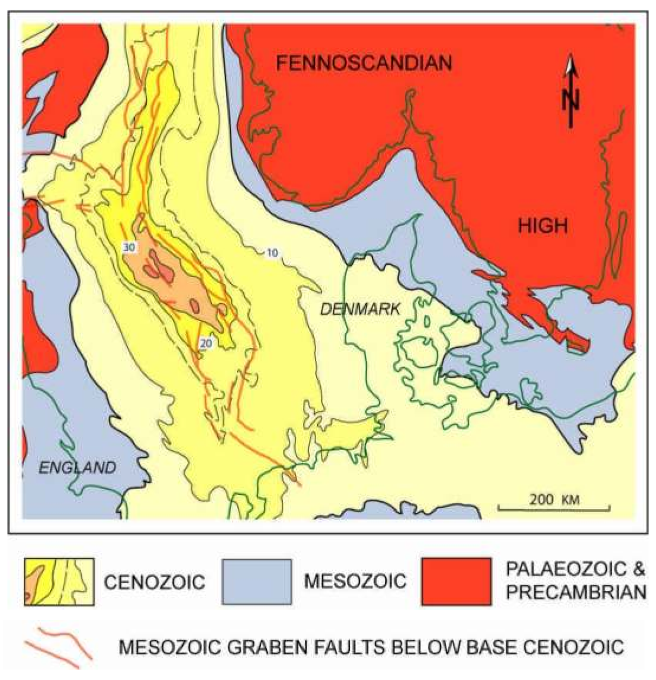


Fig. 5: Geological map of the North Sea Basin (Graversen 2006). The contours are isopachs indicating the stratigraphic thickness of the Cenozoic rock in hundreds of metres.

Formation Processes

The most important formation processes involve subglacial meltwater erosion that is dependent on the hydraulic potential gradient (Fig. 6). Most likely tunnel valleys form by a combination of processes, including direct glacial erosion.

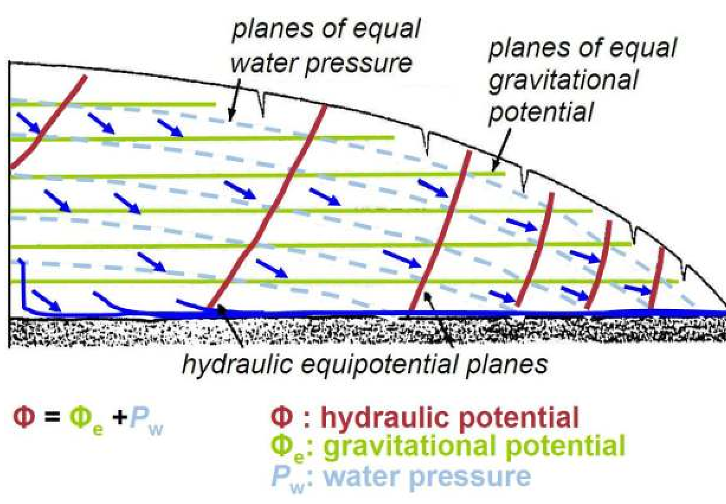


Fig. 6: Construction of equipotential planes through a glacier (Smed 1998). The arrows indicate the flow of water, which is perpendicular to the equipotential planes.

Time-transgressive formation:
Temporally transgressing and spatially regressing erosion (Fig. 7), in some cases in conjunction with glaciohydraulic supercooling (Fig. 8).

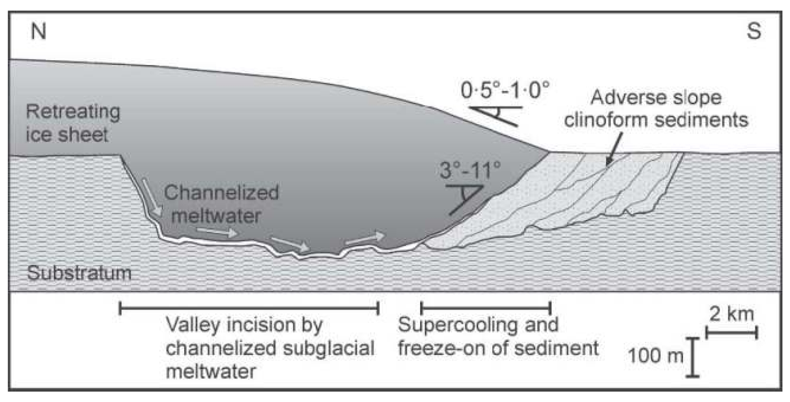


Fig. 7: Conceptual profile along the axis of a tunnel valley showing erosion by subglacial channelised meltwater in the up-ice part of the valley and en-masse freeze-on of sediments due to supercooling beneath the ice margin (Kristensen et al. 2008).

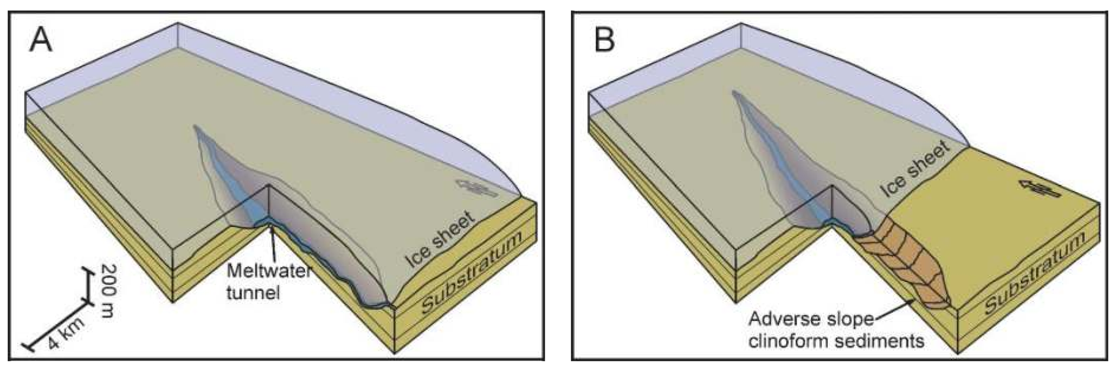


Fig. 8: Conceptual model of tunnel valley erosion and infilling processes (Kristensen et al. 2008). (A) Subglacial erosion by channelised meltwater. (B) Deposition of adverse slope clinoform sediments by en-masse freeze-on of supercooled meltwater during ice-sheet retreat.

Catastrophic outburst events/jökulhlaups:
Water reservoir that drains suddenly, e.g. subglacial meltwater dammed behind a cold based glacier margin that is released catastrophically when the ice margin becomes permeable (Fig. 9 and 10).

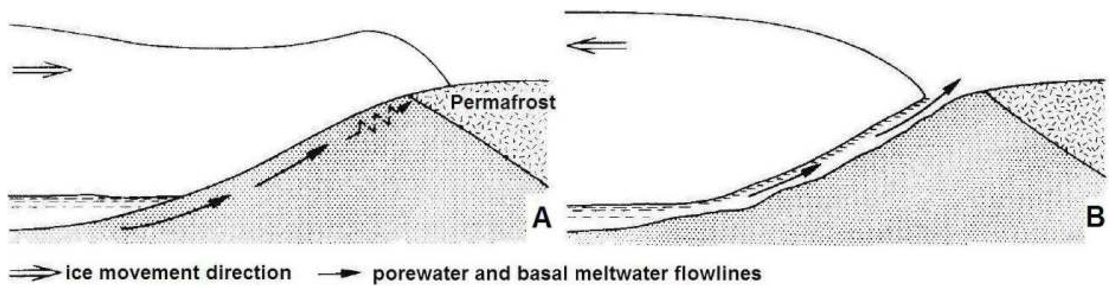


Fig. 9: Schematic representation of mechanism controlling subglacial meltwater dynamics (Piotrowski 1994). (A) Ice margin overrides permafrost, which then prevents the drainage of subglacial meltwaters. (B) As the ice margin retreats exposing unfrozen bed, a rapid outburst of subglacial waters occurs and erosion by a high-pressure water initiates tunnel valley formation.

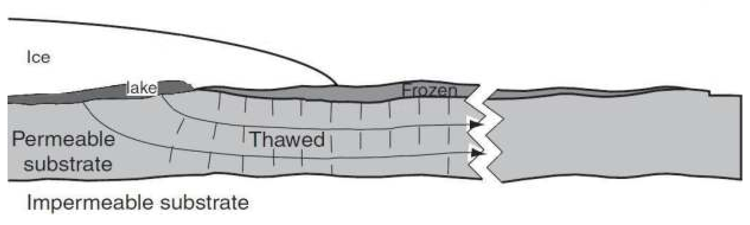
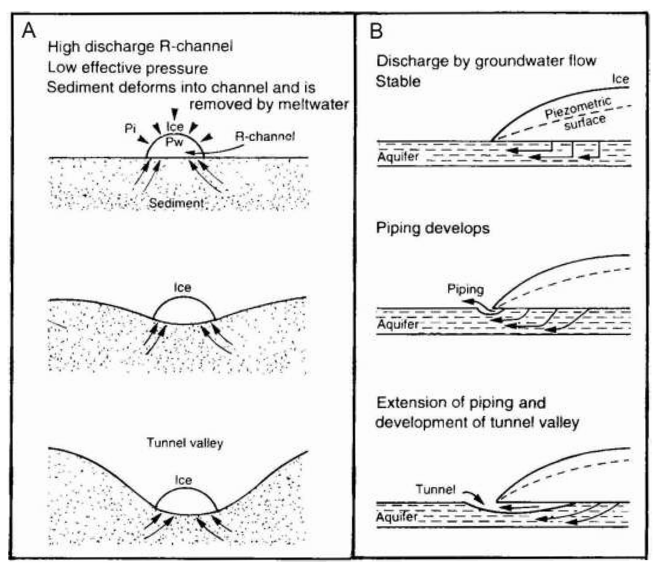


Fig. 10: Schematic illustration of a subglacial lake dammed behind an ice margin that is frozen to the bed (Hooke & Jennings 2006). The approximate equipotential lines (dashed) and flowlines (solid with arrowheads) that allow seepage are shown.

Megafloods:
Tunnel valleys produced as a by-product of widespread subglacial sheet floods that channel temporally (very controversial).

Sediment deformation:
Based on liquefaction of sediments that are evacuated by meltwater. Sediments deform under low effective pressure either in water-filled subglacial channels causing sediment creep, or in gradually developing pipes (Fig. 11).

Fig. 11: Tunnel valley formation by sediment deformation in unconsolidated substrate (Boulton & Hindmarsh 1987, Ó Cofaigh 1996). (A) High discharge Röthlisberger-channels (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. High discharge liquifies the unconsolidated sediments and pipes develop, which eventually grow into tunnel valleys at the ice margin.



Direct glacial erosion:
Quarrying/plucking and abrasion (Fig. 12), usually considered to contribute to tunnel valley formation only in combination with other processes.

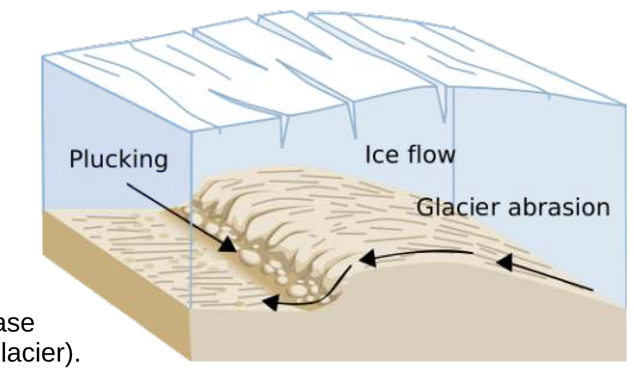


Fig. 12: Plucking and abrasion at the base of the ice (Source: Wikipedia, School: Glacier).

Erosion rates:

- can be high in unlithified sediments:
  - decametres during days by catastrophic outburst floods (Fleisher et al. 2010; Russell et al. 2007)
  - up to 300 m depth during 200- 300 years (e.g. Björnsson 1996; Sandersen et al. 2009)
- apply only to limited time periods and can therefore not be extrapolated over longer times
- rare observations concern mainly catastrophic outburst floods

Morphology

Tunnel valley characteristics:

- open, buried or partly buried
- geometry (Fig. 4 and 13):
  - length individual segments: several km long
  - length valley systems: up to 150 km long
  - width: 0.2-1.5 km; up to 6 km
  - depth: decameters up to 350 m; max. 500 m in northern Germany
- begin and terminate abruptly (Fig. 13)
- undulating bottom, overdeepened (Fig. 13)
- steep-sided (Fig. 13)
- often several generations of tunnel valleys (Fig. 13 and 14)
- often terminate at terminal moraines with outwash fan/sandur (Fig. 15 and 16)
- inferred to be parallel to hydraulic potential gradient (Fig. 15)
- usually cut into weakly to moderately lithified sediments
- open tunnel valleys: often occupied by lakes, bogs or eskers
- filled with glaciogenic, glaciofluvial, glaciolacustrine, glaciomarine or non-glacial sediments (Fig. 14)

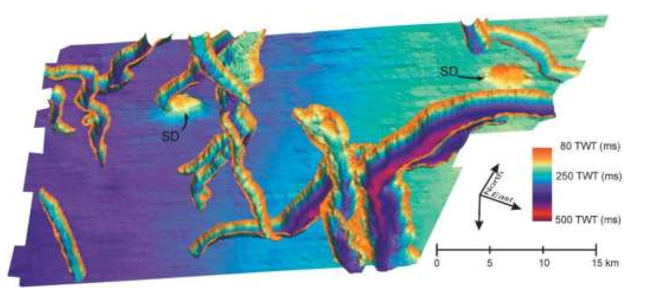


Fig. 13: TWT-structure map of buried tunnel valleys in the eastern North Sea (TWT: two-way-travel time; Kristensen et al. 2007). The seafloor is about 60 m b.s.l. (80 ms TWT) and constitutes the upper limit of the tunnel valleys. The coloured plane is the Near Base Quaternary horizon (SD: salt diapir).

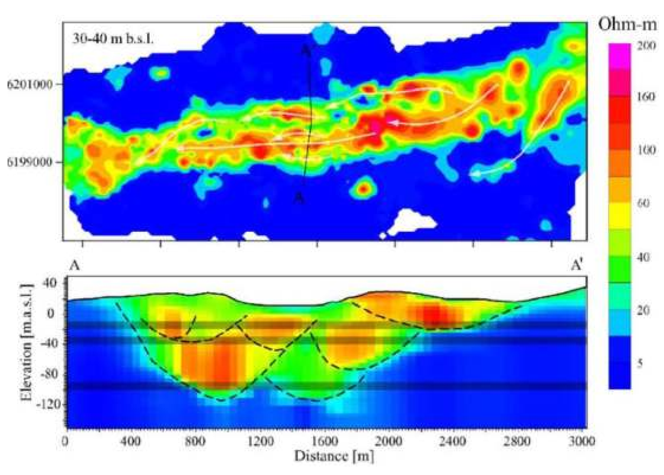
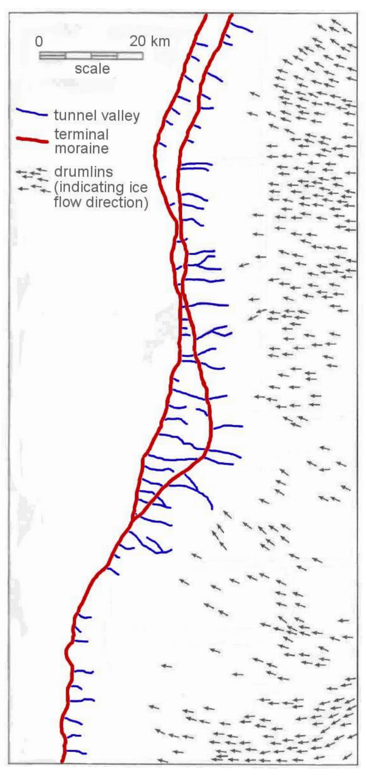


Fig. 14: Interval resistivity map (top) for 30-40 m b.s.l. and cross-section (bottom) showing multiple generations of tunnel valleys in Denmark calculated from Sky TEM and ground-based TEM data (TEM: transient electromagnetic; Jørgensen & Sandersen 2006). The cross-section A- A' is marked on the interval map. (White arrow-lines: inferred meltwater pathways; dashed lines: inferred cut-and-fill structures).

Fig. 15: Tunnel channels formed in central Wisconsin along the west side of the Green Bay Lobe (Clayton et al. 1999). The area west of the moraines is the Driftless Area, a region in the American Midwest that escaped glaciation during the last ice age.



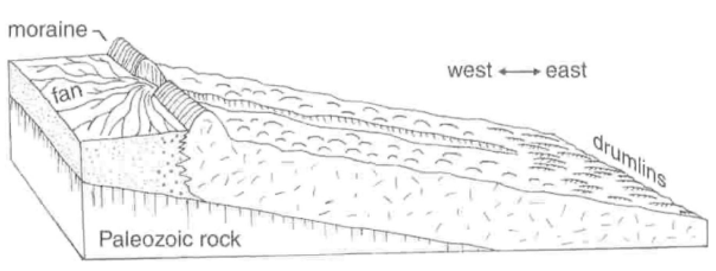


Fig. 16: Stylized block diagram, showing a typical tunnel channel formed along the west side of the Green Bay Lobe of the Laurentide Ice Sheet (Clayton et al. 1999). A tunnel channel extends from the downglacier edge of the drumlin zone of a hummocky till to a breach in the outermost moraine, with an outwash fan beyond the breach. (Scale suggested by the size of the moraine: roughly 1 km wide and 5- 20 m high)

Conclusions

- Diverse characteristics identified, range of extents
- Underlying lithology is relevant (e.g. unconsolidated sediments)
- Meltwater is important for formation process
- Most likely combination of formation processes
- Predominantly formation at ice sheet margin
- Erosion rates depend on considered time frame (phases of inactivity)
- Process rates can be high

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Further Reading

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