Excursions ARCPaC 2026, Aarhus

Day 1 (27 May 2026)

Site 1 (Figs 3 – 6)

Weichselian outwash deposits and Grenå Till at Balle

Several gravel pits in the area between Tirstrup and Balle in Djursland provide insight into the deposits of the last two ice advances in this area during the Weichselian glaciation. The oldest exposed unit is Tebbestrup Formation consisting of upward-coarsening outwash sand deposited in front of the ice sheet advancing from NE. It is discordantly overlain by Grenå Till deposited by the NE ice that reached its outermost extent at the Main Stationary Line ~90 km to the west around 23-21 ka ago. The till is discontinuous, up to 3 m thick, massive or structurally diversified with finely laminated sand stringers occurring in places. Both these units belong to the Djursland Group. Grenå Till is truncated by an erosional surface on top of which meltwater sediments of Mols Group occur. These sediments were deposited in front of the East Jutland ice margin during the Young Baltic advance at around 18 ka. This ice moved into the area from SE and was characterized by a pronounced lobate margin that created, among others, the spectacular glaciotectonic landform assemblage of Mols Hills. The outwash deposits of Mols Group are up to ~8 m thick coarse-grained, massive to crudely stratified, matrix-supported or open-work pebbly gravels. They often host well-rounded boulders up to around 1 m in diameter. Further to the west, the gravels grade into parallel stratified to cross-bedded sand with evidence of bedform accretion and migration given by current ripples and delta foresets. The Mols Group indicates rapid, possibly catastrophic release of substantial volumes of meltwater at the ice margin and fast reduction of flow competence some distance into the outwash plain. Numerous frost-cracked pebbles occur at the top of Mols Group documenting permafrost conditions in the area after the ice retreat.

Site 2 (Figs 9 – 18)

Weichselian till at Ebeltoft

A cliff section at the SW part of Ebeltoft peninsula reveals an up to 9 m thick Ebeltoft Till. The till has a high content of pebbles and boulders, some of which are striated (orientation ~330°) on their flattened upper surfaces. The till contains thin, horizontal layers and smudges of meltwater sand. These sand layers often coat the pebbles or are sagged beneath them, suggesting compaction during passive release of material from stagnant ice. Several meltwater channels filled with stratified sand occur within the till, and this sand has yielded a large spread of poorly zeroed OSL dates (15-32 ka). The channels are interpreted as subglacial meltwater conduits. The till is not overconsolidated, has a uniform grain-size and petrographic composition, and the elongated clasts show variable orientation with some clustering around the SW-NE direction. The till, which is called Ebeltoft Till, has been deposited during the Young Baltic advance by an ice lobe occupying the Ebeltoft Bay at around 18 ka. It is interpreted as a hybrid of traction till and melt-out till whose deposition was interrupted by events of meltwater drainage in channels at the ice-bed interface and occasional basal decoupling by pressurized meltwater.

Day 2 (30 May 2026)

Site 3 (Fig. 19)

Tunnel valley at Hald Lake

In Mid-Jutland, pre-Quaternary deposits, mostly Miocene quartz sands, are covered by up to 100 m thick glacial deposits. The ground surface consists of contrasting landscapes with flat outwash plains in front of the Late Glacial Maximum (LGM) Main Stationary Line (MSL) (~23-21 ka) and heavily undulating morphology in its backfield. The site is located at the MSL corner marking the contact between the Norwegian ice advancing from the north and the Swedish ice advancing from the east. The area covered by the LGM ice sheet is characterized by a network of conspicuous tunnel valleys eroded under the ice by pressurized meltwater. Hald Lake marks a terminal part of a tunnel valley that can be traced in the up-ice direction for several tens of kilometers in the present-day morphology. The lake is 31 m deep (one of the deepest lakes in Denmark) and its surface is around 50 m below the outwash plain in front of it, which gives an adverse slope of subglacial meltwater flow of at least 81 m. Hald Lake is a spectacular example of channelized drainage under the Scandinavian Ice Sheet at its outermost extent during the Weichselian glaciation relevant to any considerations of large-scale sediment redistribution, ice sheet stability, and land-forming processes in general.

Site 4 (Figs 19 – 20)

Proglacial drainage at Hjortedal dry valley

During the ice sheet stagnation at the MSL, large volumes of meltwater delivered to the ice margin mainly through the well-developed system of numerous tunnel valleys such as the one terminating at Hald Lake drained in the westerly direction to the North Sea and created extensive outwash plains. As the Norwegian ice started to retreat a new, shorter drainage path opened to the north through the Karup valley first to Venø Bay and thereafter to Skive Fjord. This has resulted in a series of downcutting events triggered by progressively steeper gradients along the Karup valley and its tributaries such as Hjortedal. The downcutting generated several levels of erosional terraces incised in the outwash plain clearly visible as distinct topographic levels such as in the now dry Hjortedal valley.

Site 5 (Figs 21 – 31)

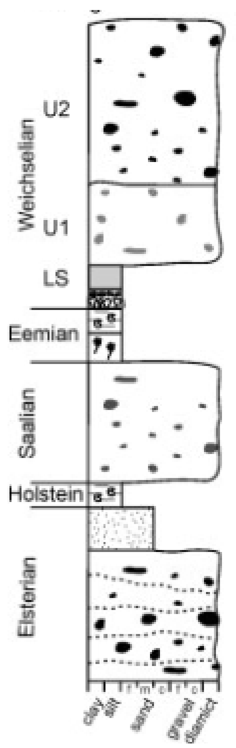
Meltwater megadunes at Mogenstrup and potholes at Flynder Lake

When the Norwegian ice started to retreat at ~21 ka and a shorter drainage passage to the north became exposed, a major meltwater flood fed by waters delivered to the MSL through tunnel valleys from the Swedish ice further to the south, took place. This flood is interpreted from a field of fluvial megadunes clearly discernible on LiDAR images. Around 50 mapped mega-dunes have crests stretching in roughly E-W direction, they reach heights of up to 2.2 m (mean 1.1 m), widths of up to 320 m (mean 138 m) and cover an area of approximately 18 km^2. Excavations, Ground Penetrating Radar surveys and luminescence dating reveal that the megadunes consist of poorly bleached parallel- and cross-bedded meltwater sand and gravel, with occasional large-scale foresets indicating palaeoflow directions from south to north, perpendicular to the dune crests. Estimates of flow conditions utilizing different empirical approaches suggest water depth of around 9 m (most likely), flow velocities between 1.5 and 14.5 m/s, and water discharges of at least 82,000 m^3/s. To the west, the megadune field is flanked by the Flynder Lake tunnel valley formed earlier by subglacial meltwater under the Norwegian ice. Along the tunnel valley, there are over 170 mapped circular potholes up to ~15 m deep likely generated by helicoidal flows of pressurized subglacial meltwater.

Site 6

Quaternary succession at Knud Strand

Knud Strand is a coastal cliff on the Salling Peninsula, forming the southern coast of Limfjorden. There is an approximately 4 km long cliff section of Quaternary sediments within the outer extent of the last glaciation (as marked by the Main Stationary Line), containing sediments relating to the Elsterian (MIS 12), Saalian (MIS 6), and Weichselian (LGM) glaciations, and the Holsteinian (MIS 11) and Eemian (MIS 5e) interglacials. The full simplified stratigraphic profile includes: (1) a sandy Elsterian till, (2) Elsterian deglacial outwash sands, (3) Holsteinian marine clay, (4) a clayey Saalian till, (5) Eemian peat (rarely visible), and (6) an upper two-part Weichselian till.



Idealised synthetic profile of Knud Strand sediments from Larsen *et al.* (2004).

All sediments underlying the upper Weichselian till have undergone significant glaciotectonic deformation from the north/northeast during the Weichselian glacial advance. The three exposed tills provide a good example of the variety in composition, structure, and geotechnical properties of subglacial tills, caused by differences in parent materials and subglacial depositional regimes.

The upper Weichselian till is a homogenous clay till with occasional boulder pavements at its lower contact. The Saalian till is also homogenous while being darker and richer in clay minerals, reflecting a greater incorporation of marine parent materials through ice-sheet advance through the Baltic Sea depression. The lower hydraulic conductivity created a dynamic subglacial environment with thin films during ice-bed separation and channelized drainage with sandy infill. The oldest till from the Elsterian is far more heterogenous than the younger tills. It is evident of less pervasive shear, through incomplete mixing of sandy and clay-rich layers. The parent material comprises pre-Quaternary (Miocene) mineralogically mature quartz and mica sands and clays; Denmark's youngest pre-Quaternary materials.

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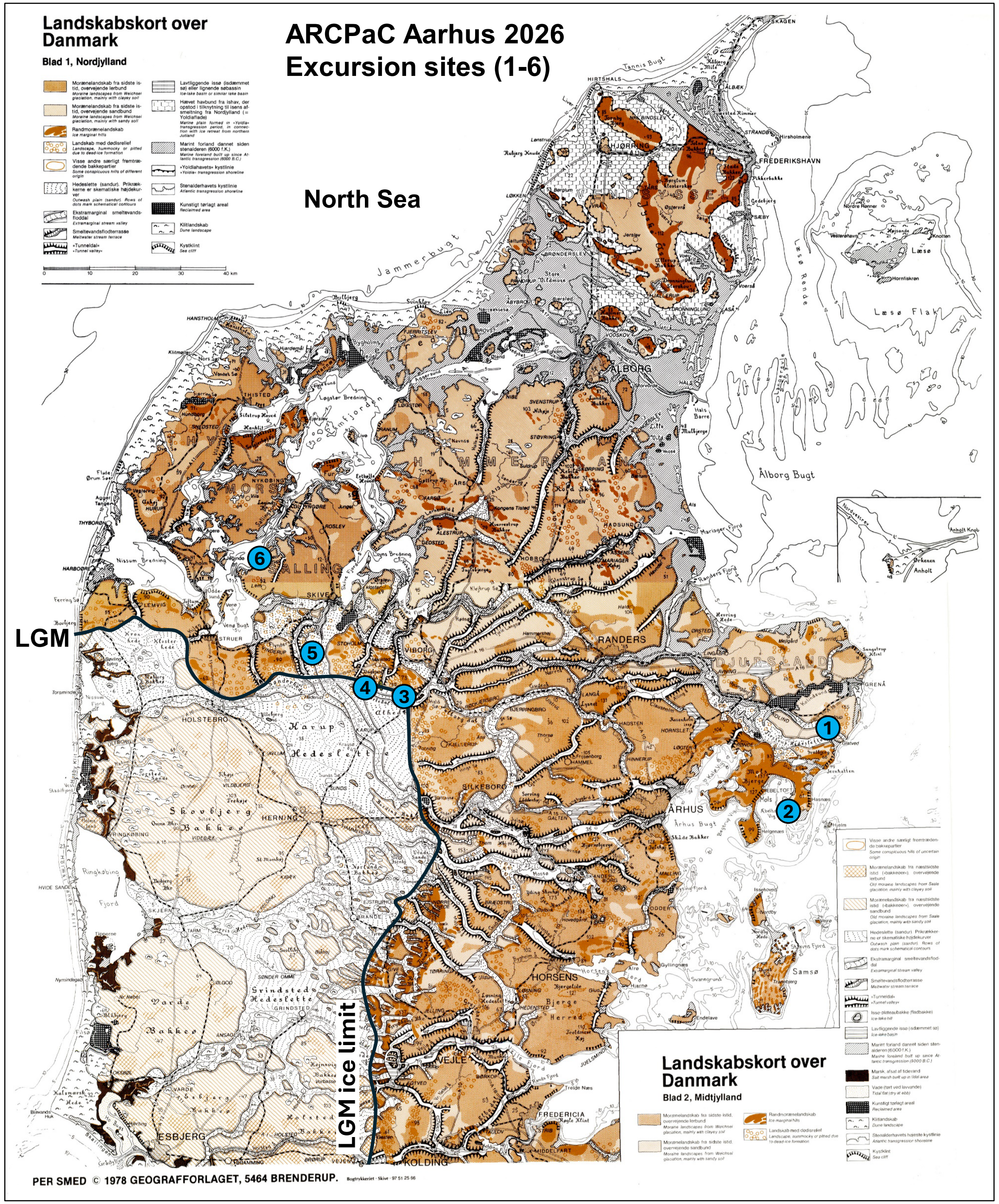


Scandinavian Ice Sheet 23-21 ka ago (Houmark-Nielsen 2005)

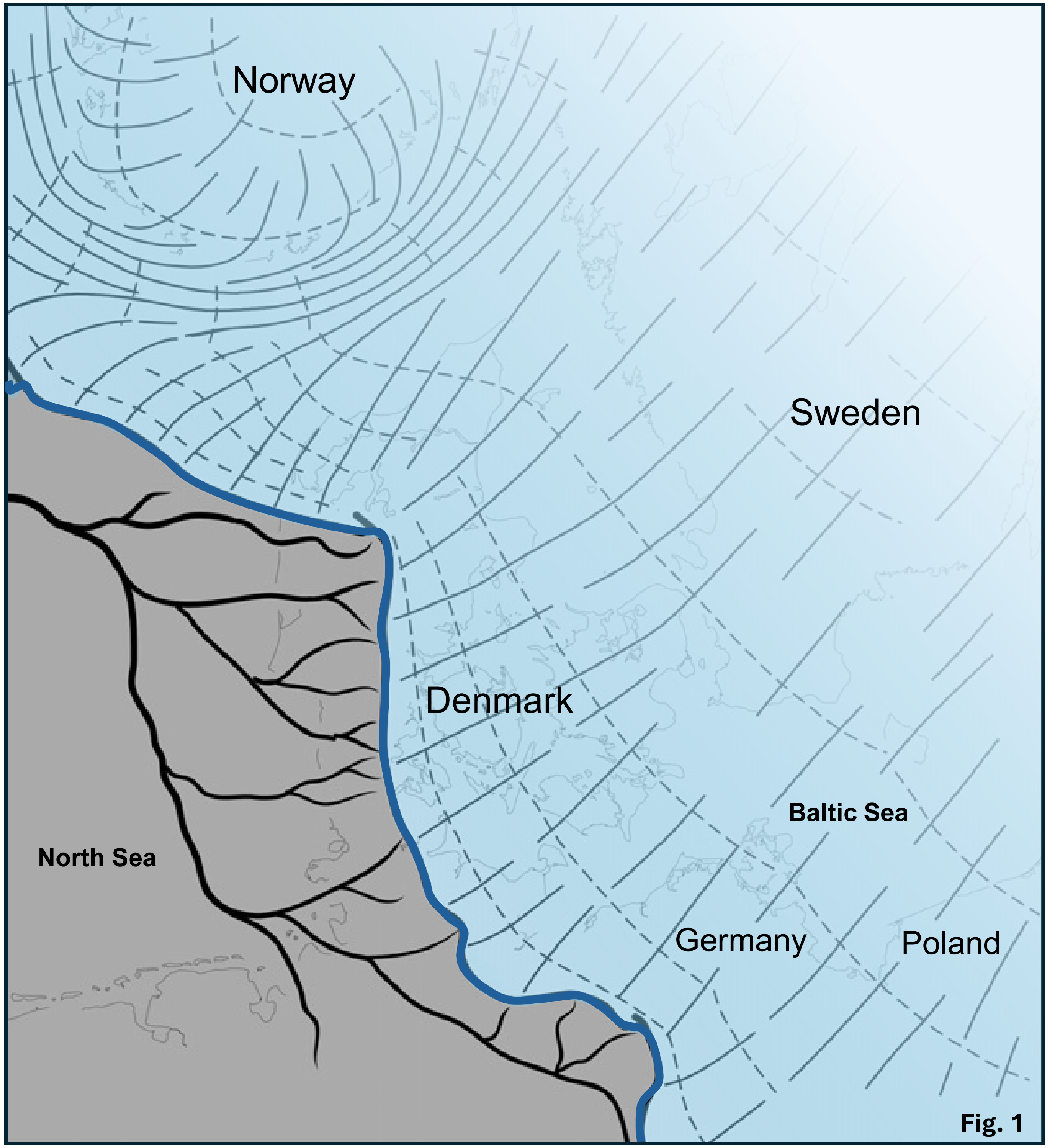
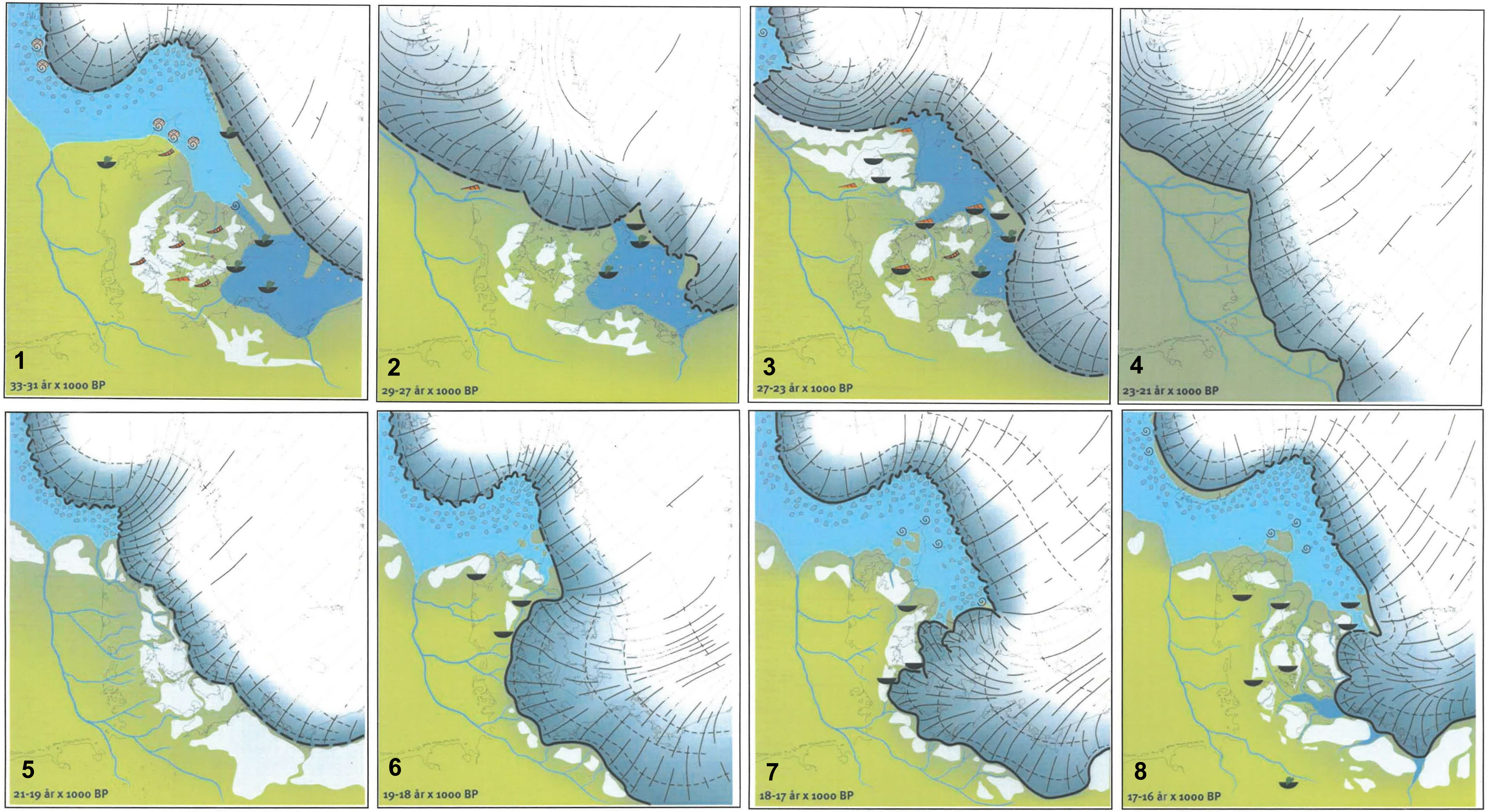
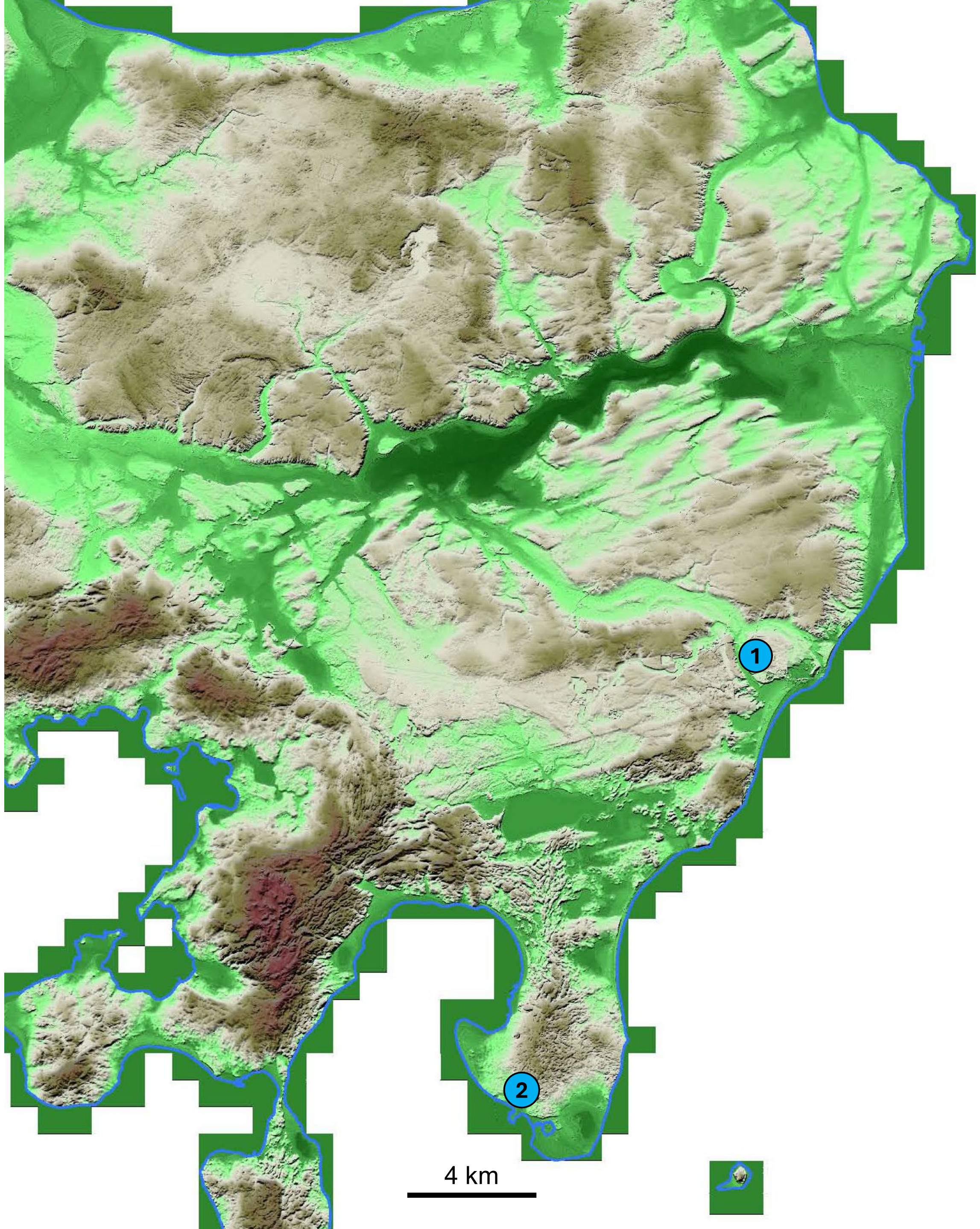


Fig. 1



Houmark-Nielsen (2025)

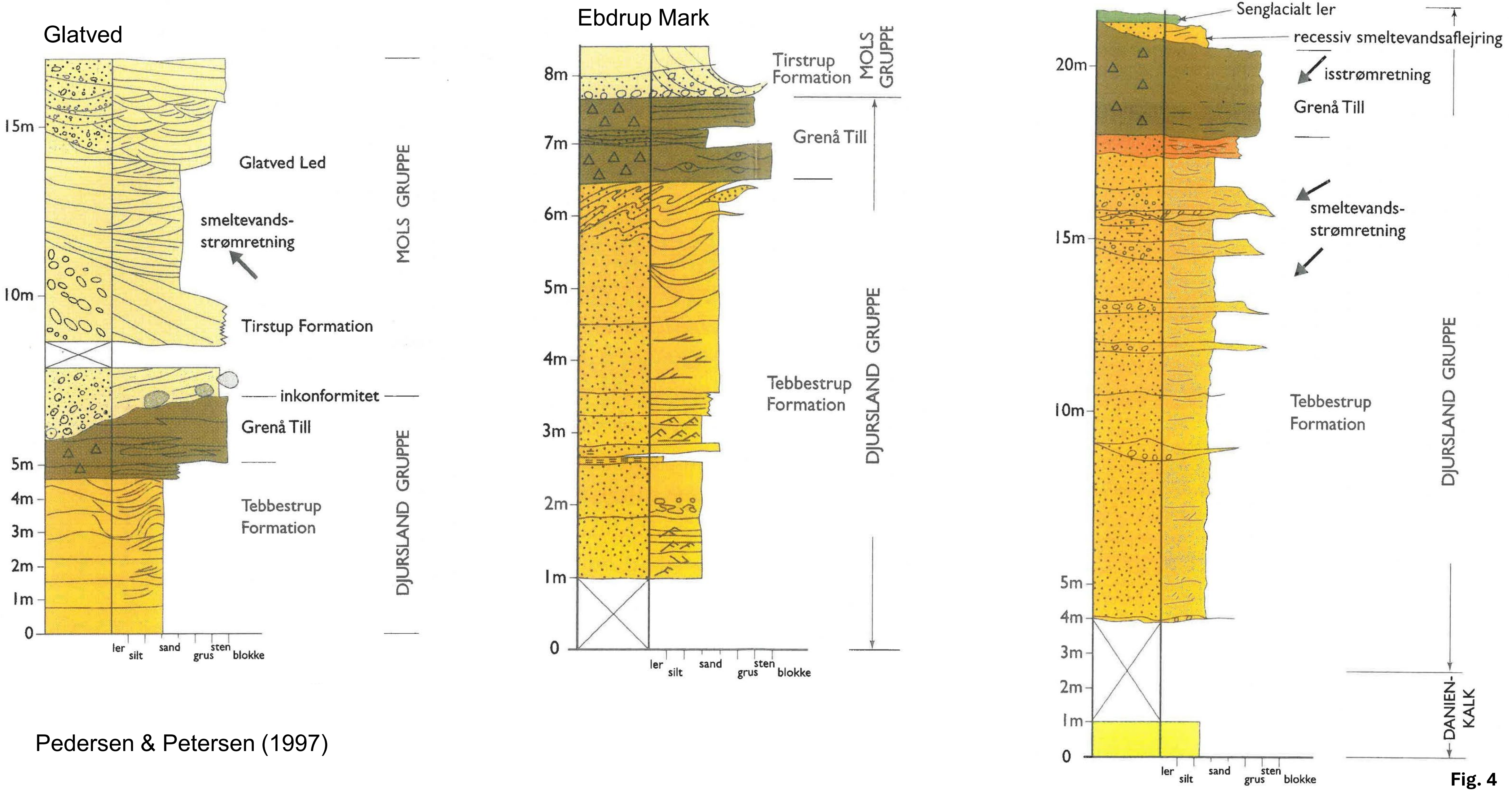
Fig. 2



Glacial relief in Djursland with mega-scale glacial lineations (MSGLs) formed by NE ice and terminal moraines of the Young Baltic ice lobes

Fig. 3

Weichselian stratigraphy in Djursland, Denmark.



Pedersen & Petersen (1997)

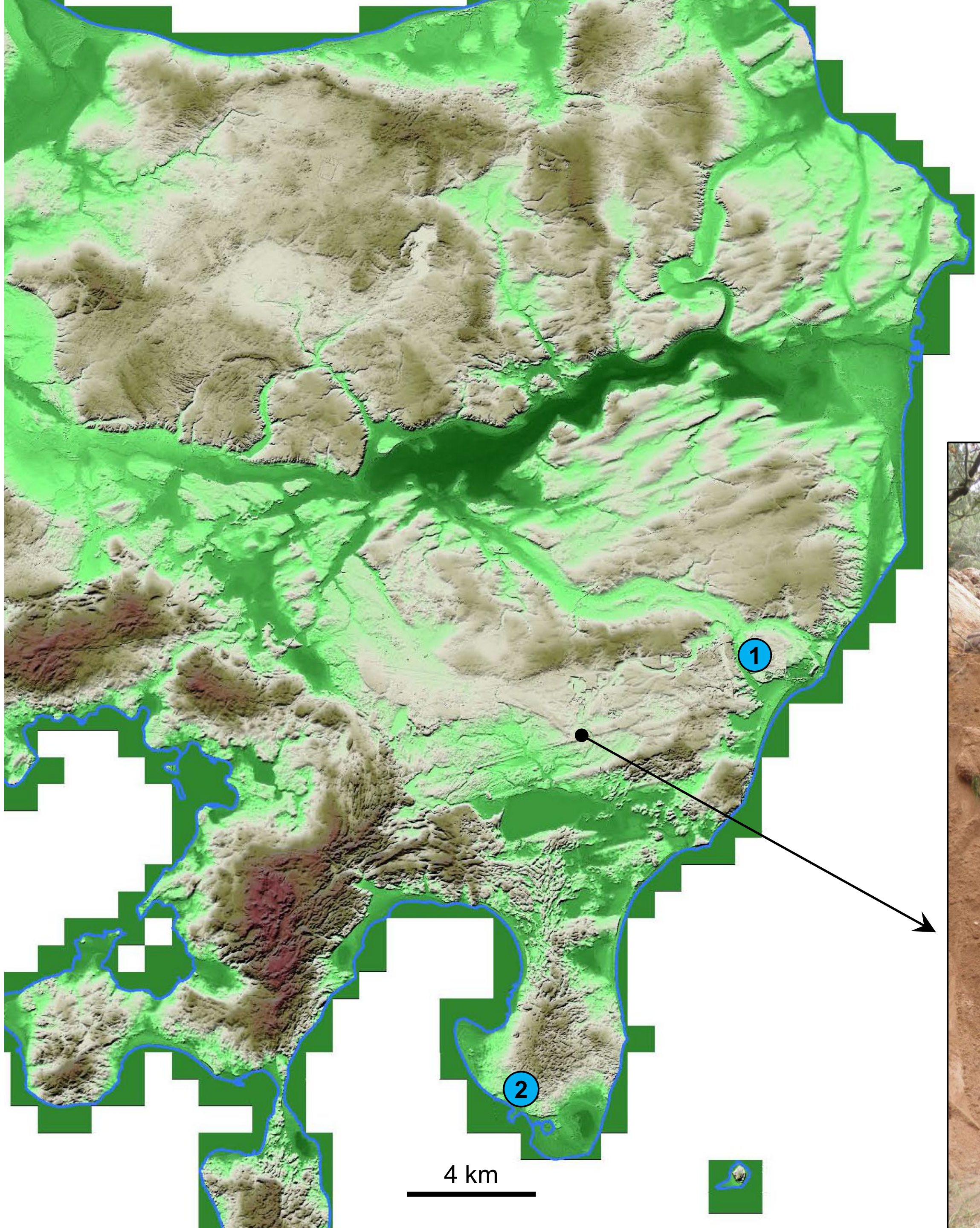
Fig. 4

Very coarse-grained, crudely stratified outwash deposit with well rounded pebbles and boulders, Mols Group at Balle, Djursland, Denmark.

Fig. 5

Outwash pebbles and boulders shattered by frost under periglacial conditions, Mols Group at Balle, Djursland, Denmark.

Fig. 6

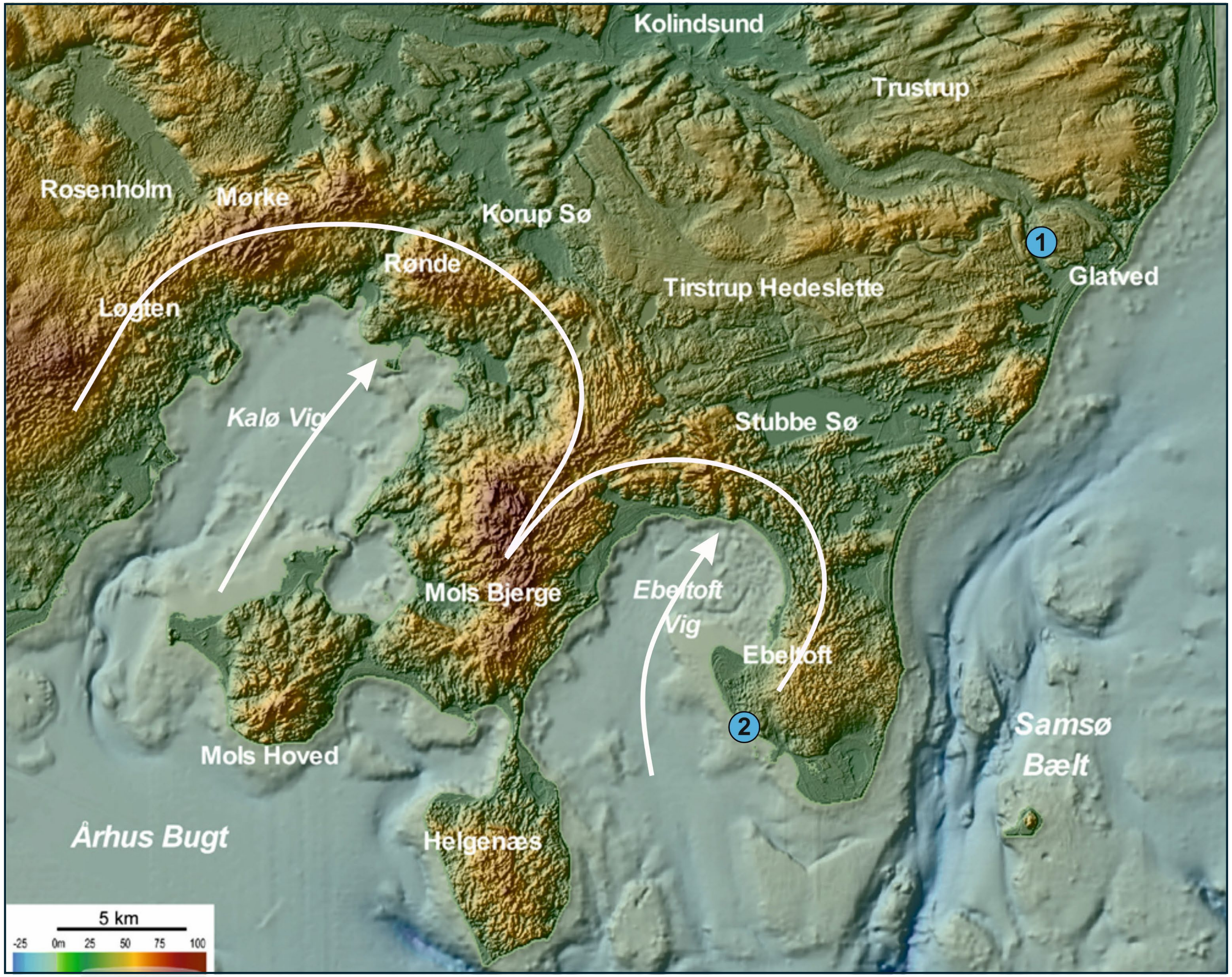


Glacial relief in Djursland with mega-scale glacial lineations (MSGLs) formed by NE ice and terminal moraines of the Young Baltic ice lobes

Fig. 7

Internal composition of a mega-scale glacial lineation (MSGL) at Gravlev, Djursland, Denmark. Note the glaciofluvial deposit and the lack of till.

Fig. 8



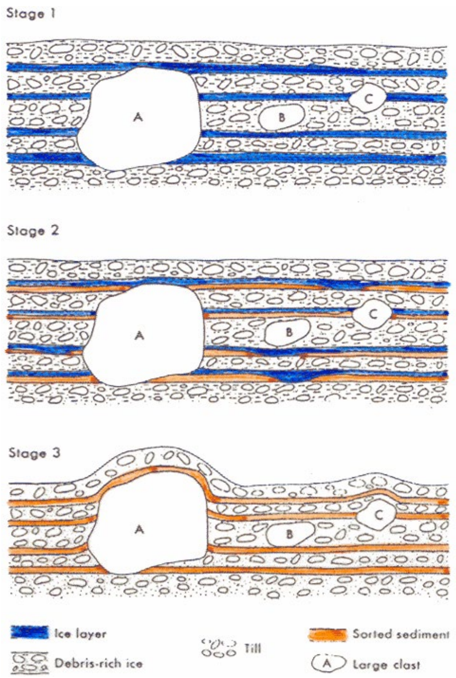
Glacial relief in Djursland with mega-scale glacial lineations (MSGLs) formed by NE ice and terminal moraines of the Young Baltic ice lobes.

Fig. 9

Ebeltoft Till in Djursland, Denmark
Based on:
Dal Bruun (2017)
Møller Just (2017)
Beck Laursen (2022)
Hachenberger Thomsen (2025)
Ottosen (2025)

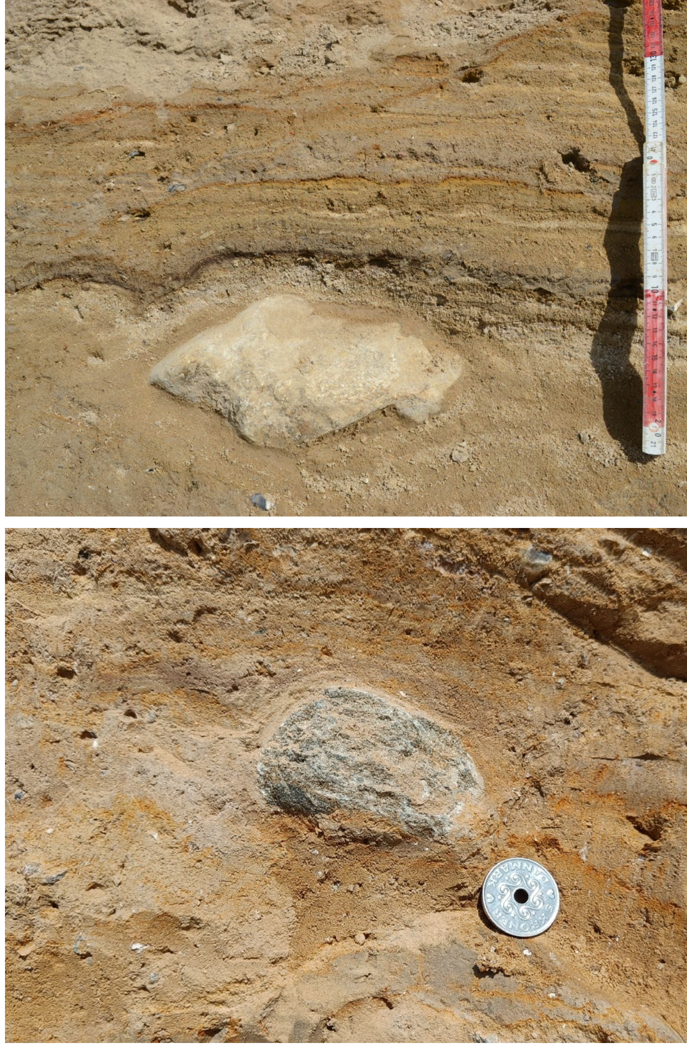
Fig. 10

Ebeltoft Till: Bedded structure with sorted-sediment coatings over pebbles



Formation model of a melt-out till after Shaw (1977).

Fig. 11



Ebeltoft Till: Bedded structure with sorted-sediment layers coating the pebbles or downwarped beneath them. A boulder (knife for scale) with flattened and striated upper surface.

Fig. 12

Till fabrics in Ebeltoft Till, E profile

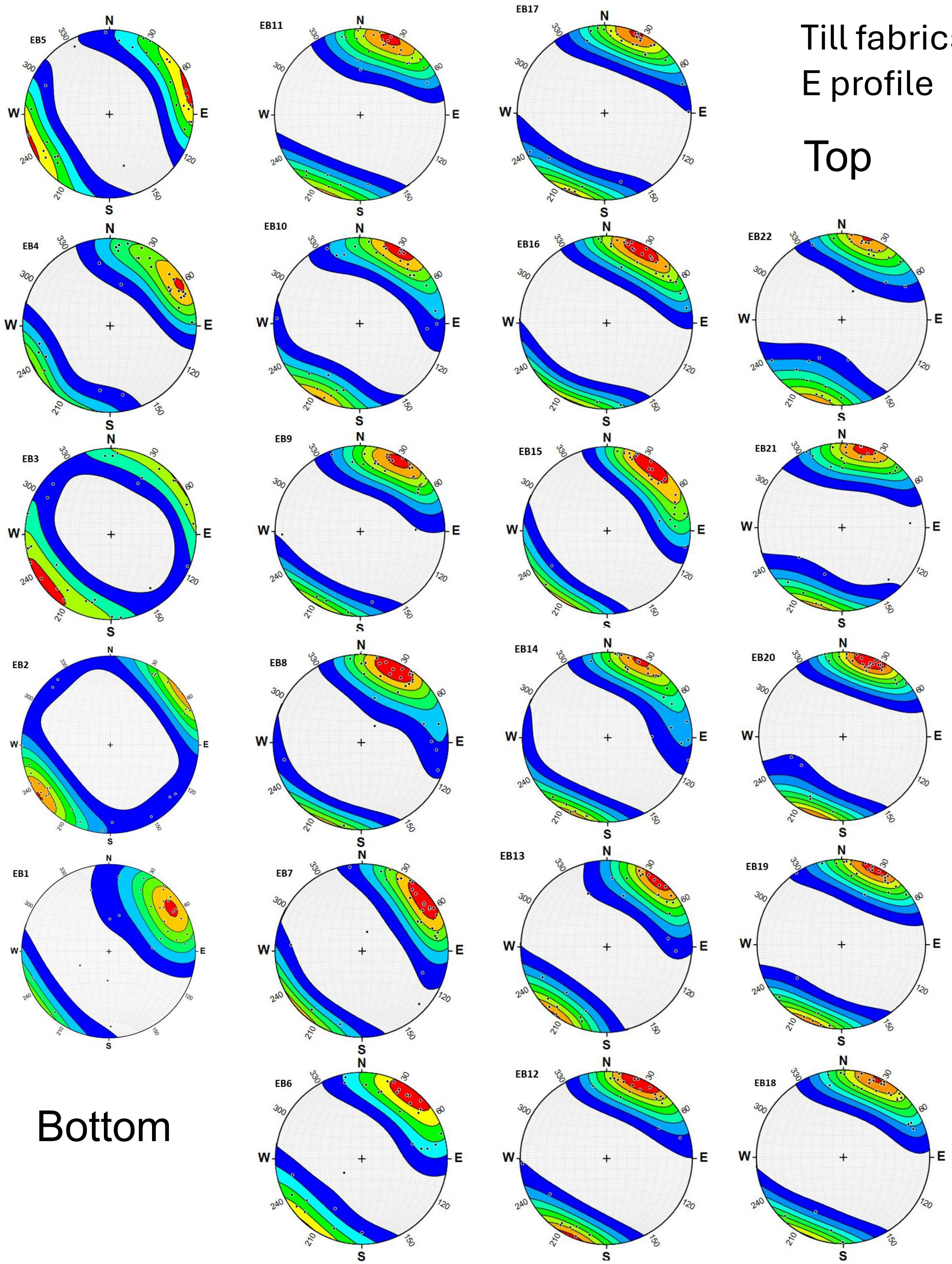
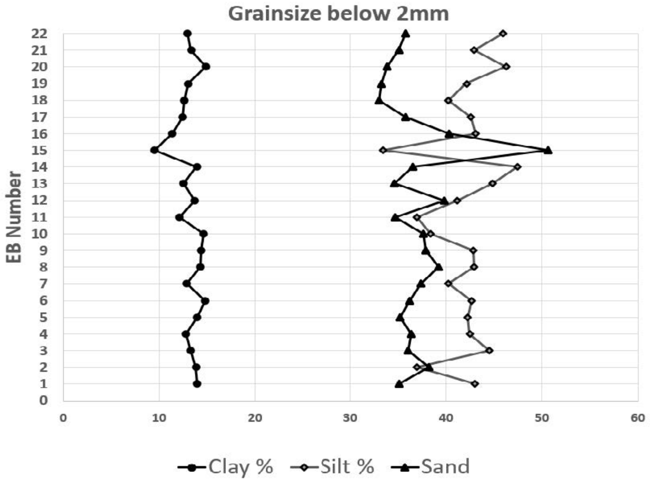
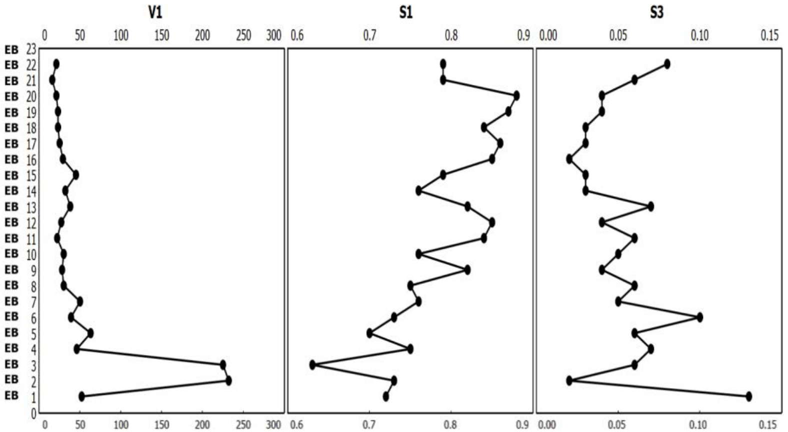
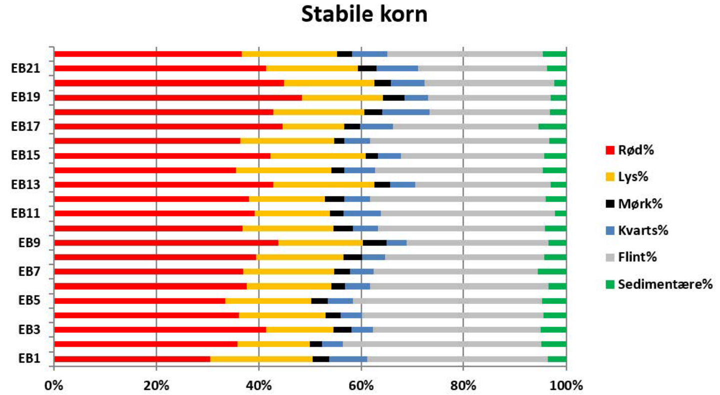
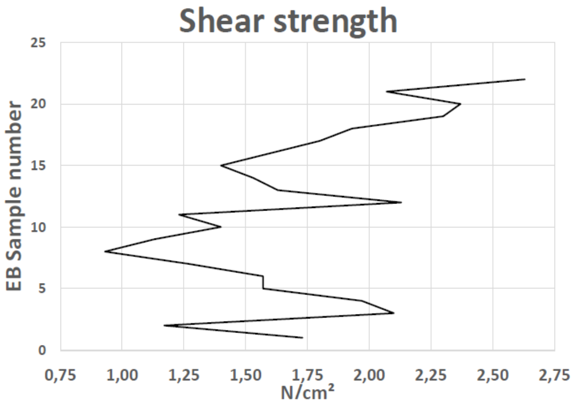


Fig. 13









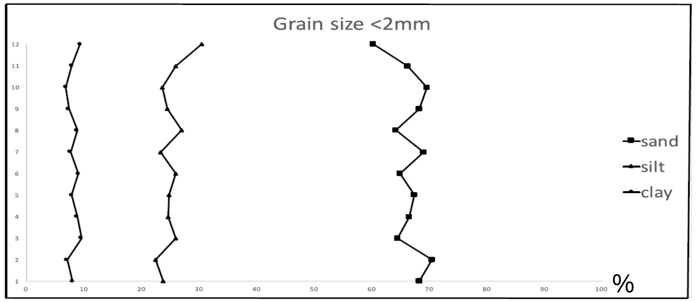
Properties of Ebeltoft Till, W profile.

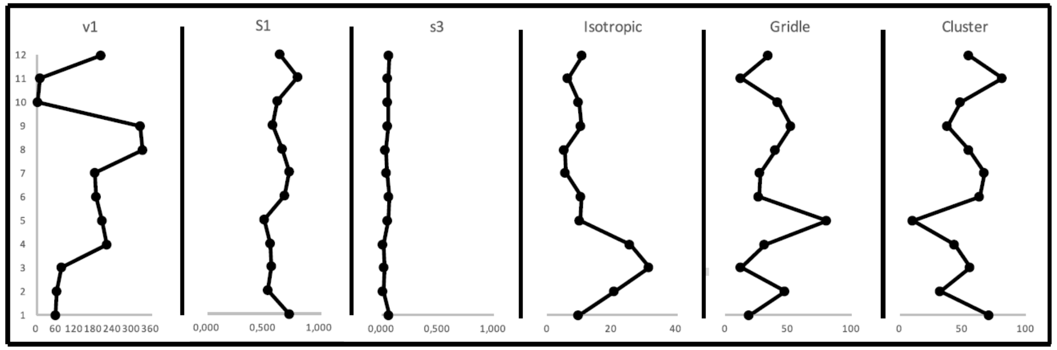
Fig. 14

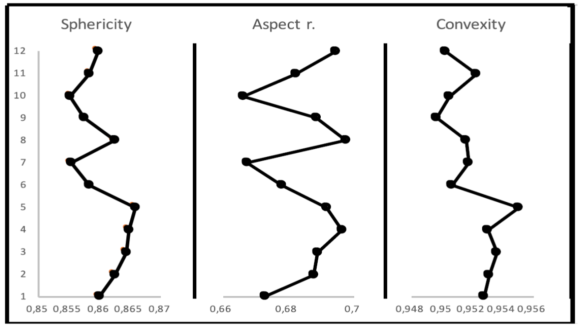
Till fabrics in Ebeltoft Till, W profile.

Fig. 15

Properties of Ebeltoft Till, W profile.







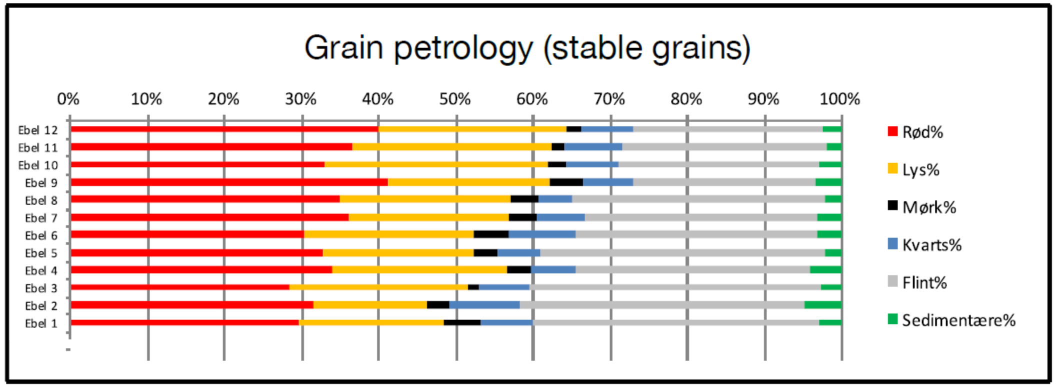


Fig. 16

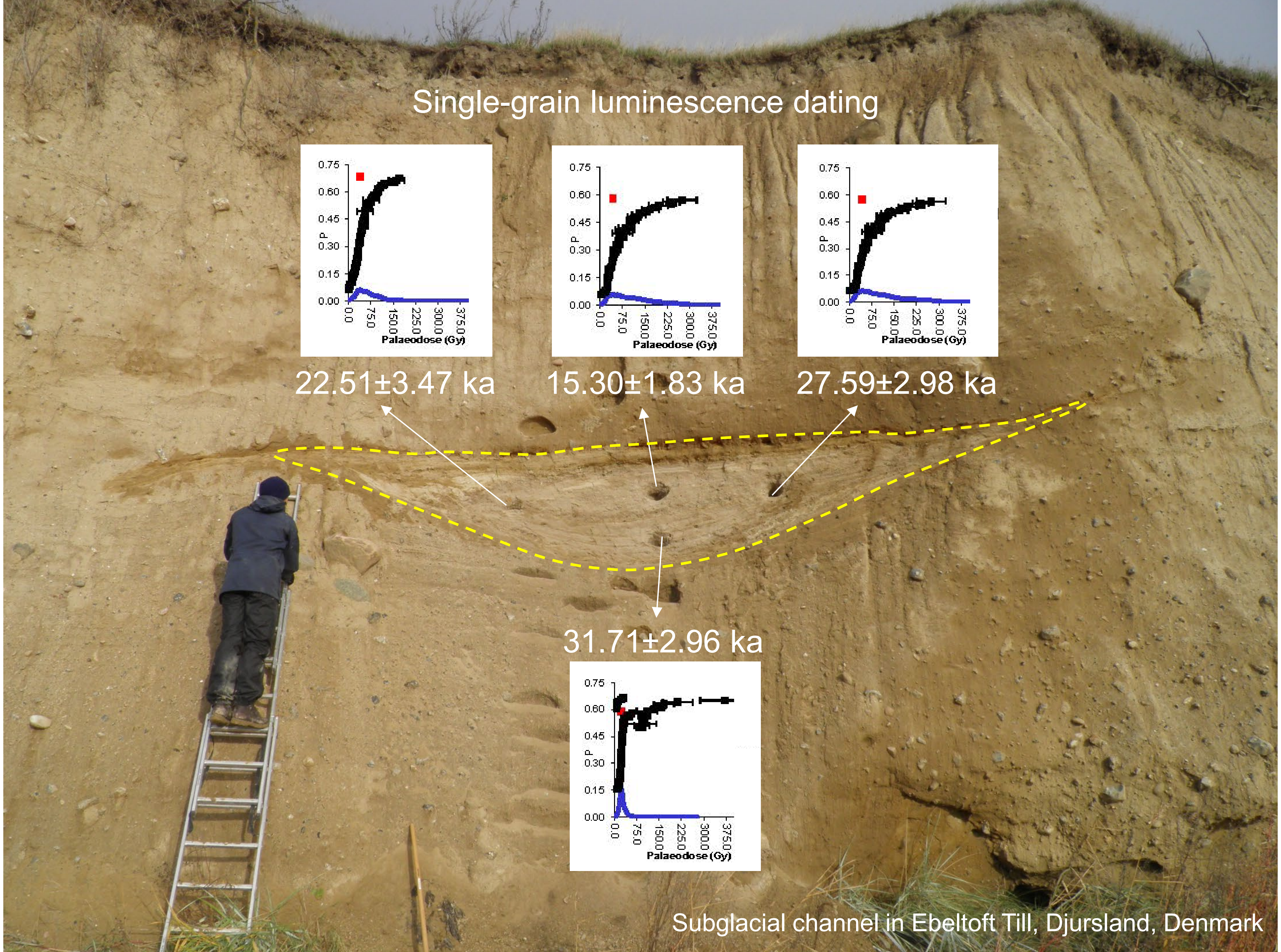
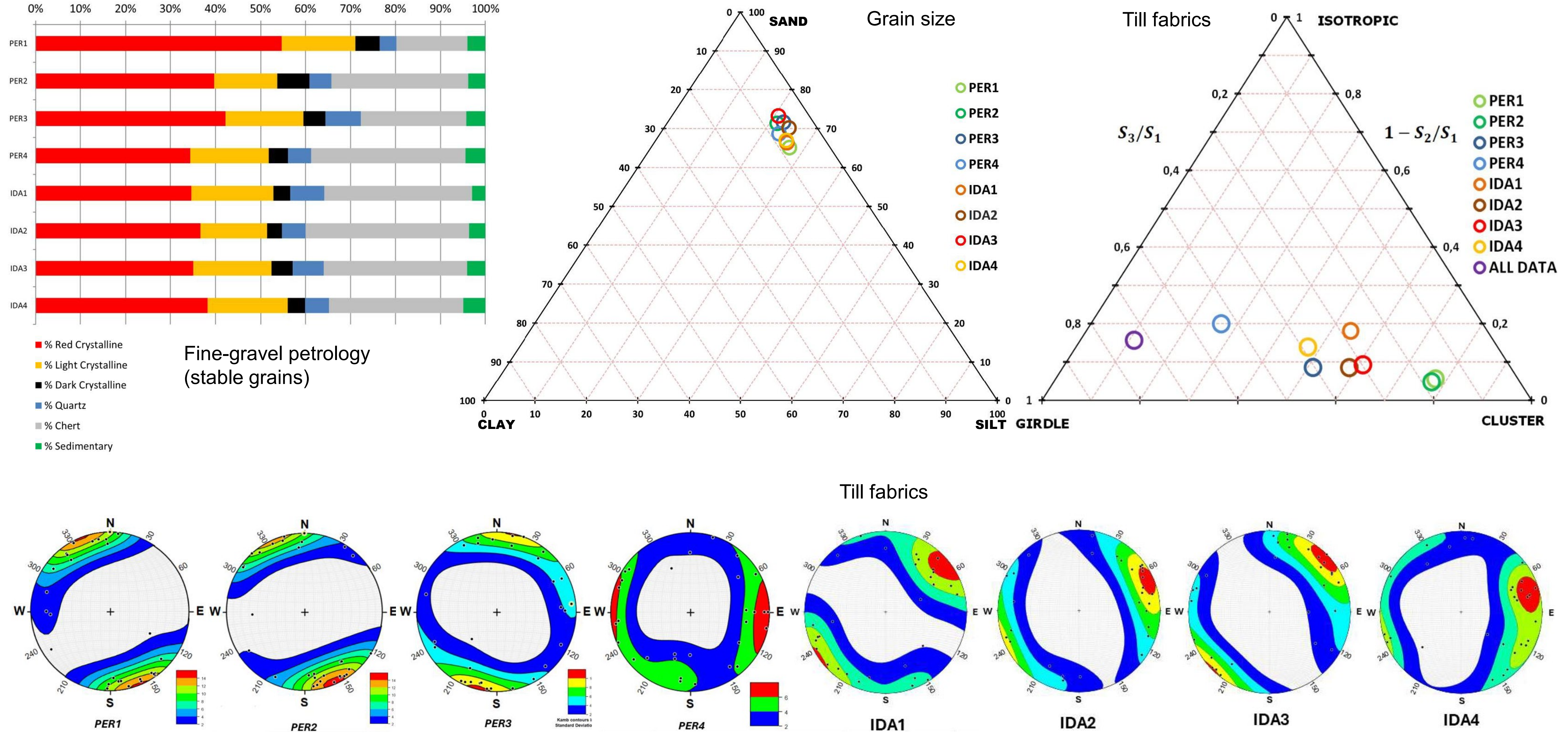
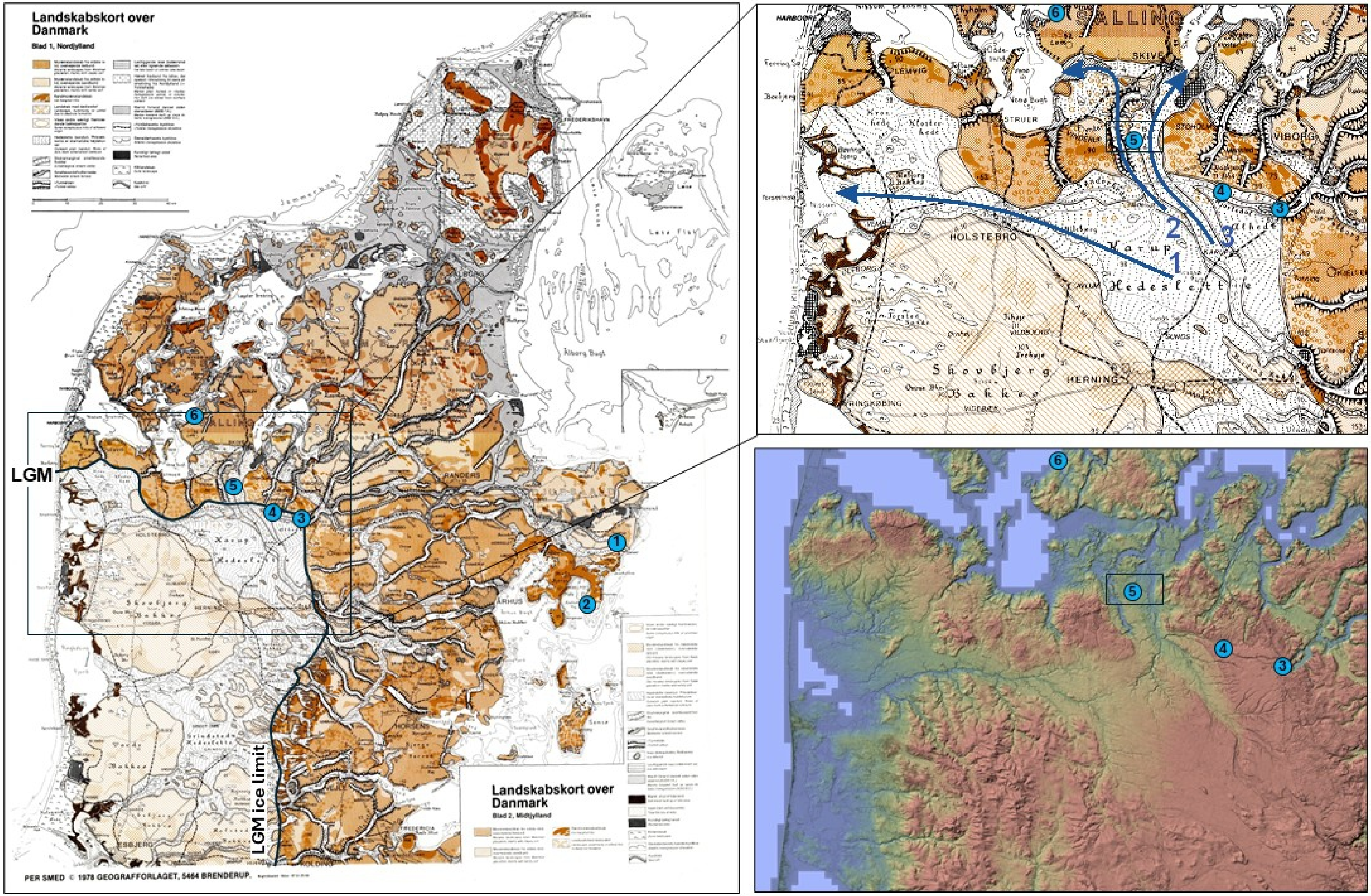

Single-grain luminescence dating
22.51±3.47 ka
15.30±1.83 ka
27.59±2.98 ka
31.71±2.96 ka
Palaeodose (Gy)
Subglacial channel in Ebeltoft Till, Djursland, Denmark

Fig. 17



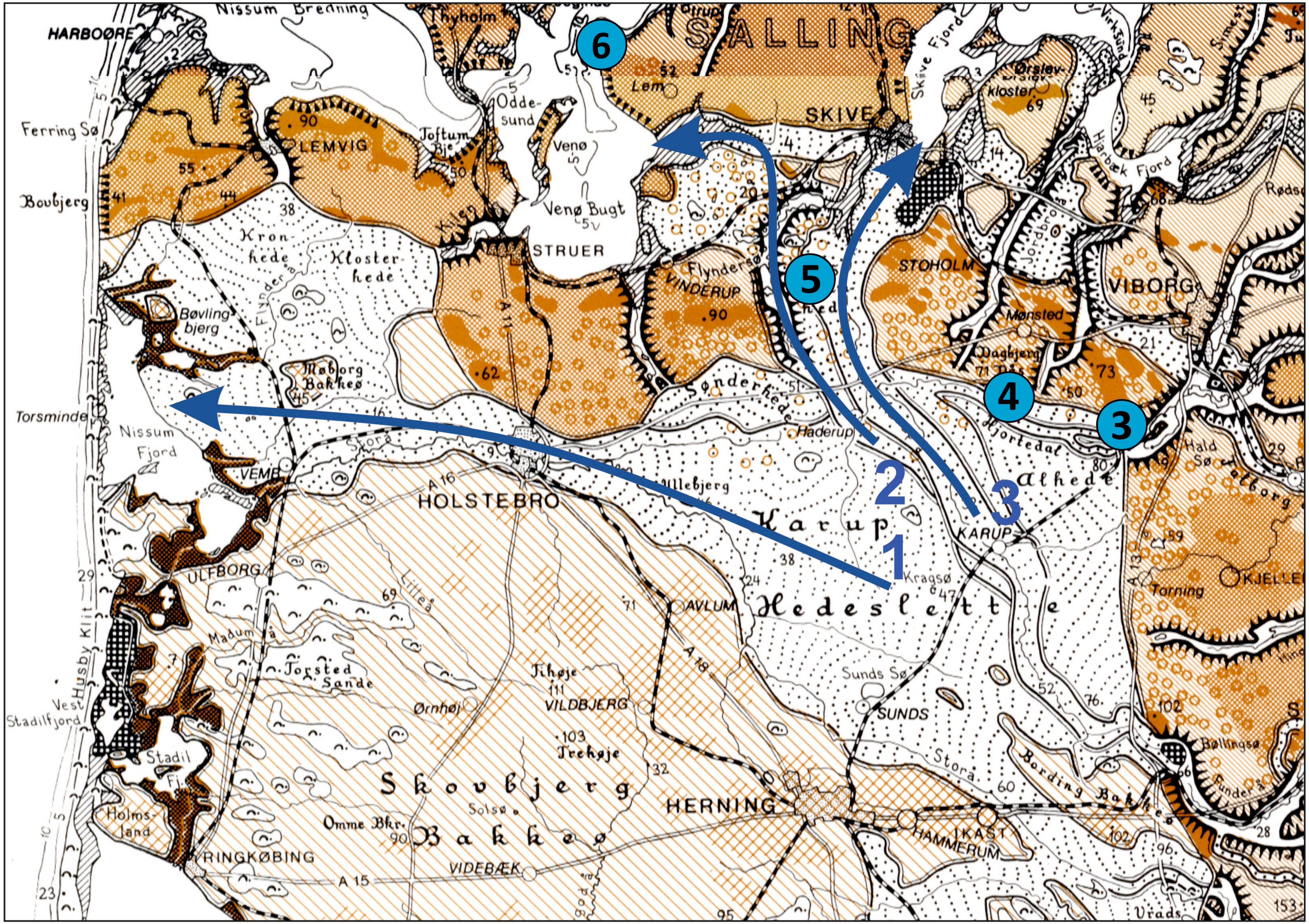
Ebeltoft Till data from a 130 m long horizontal section, bottom 1.5 m of exposure.

Fig. 18



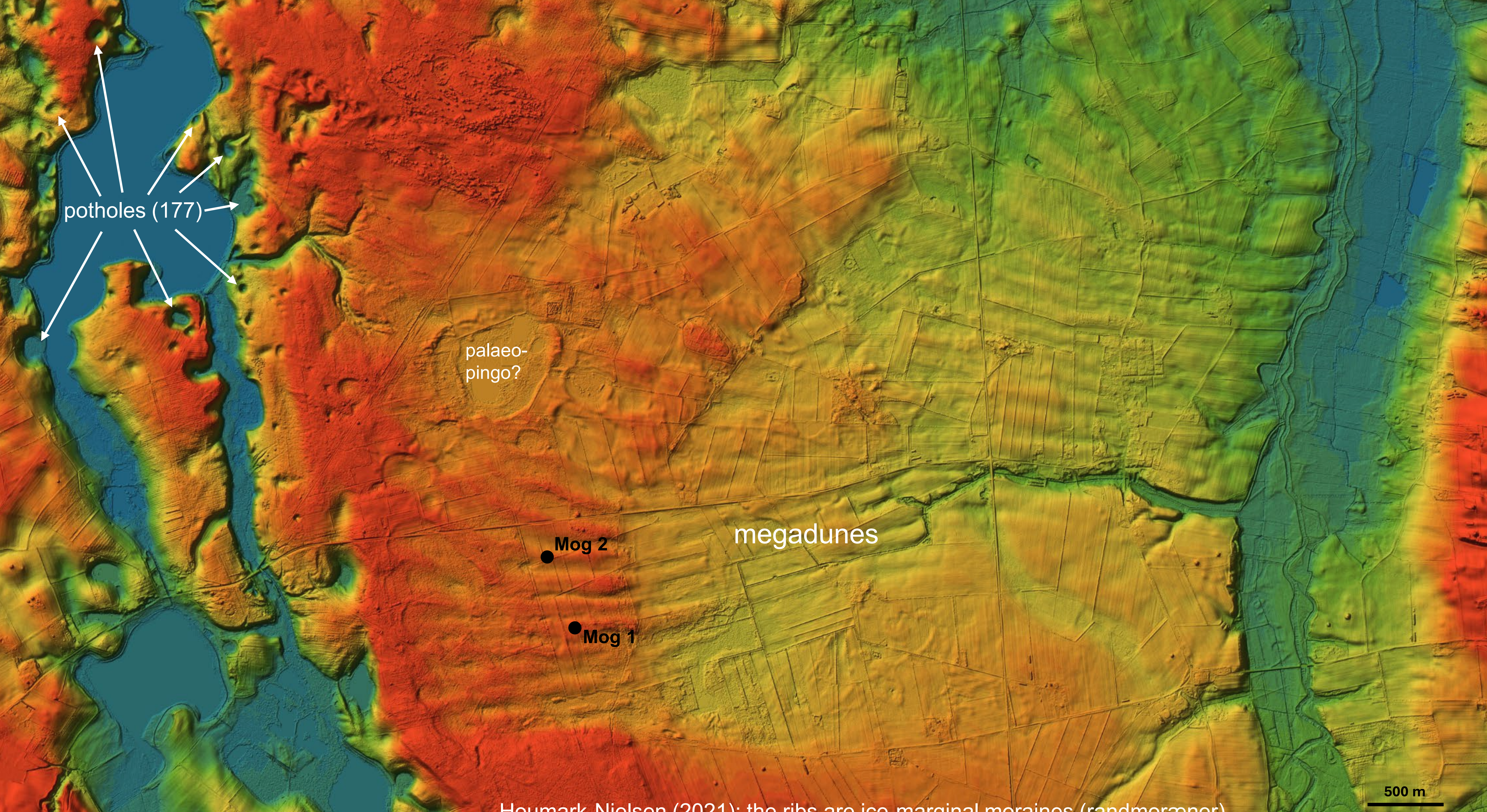
1-3 Meltwater drainage phases and progressive channel down-cutting. Meltwater fed from tunnel valleys while ice margin resting at Main Stationary Line.

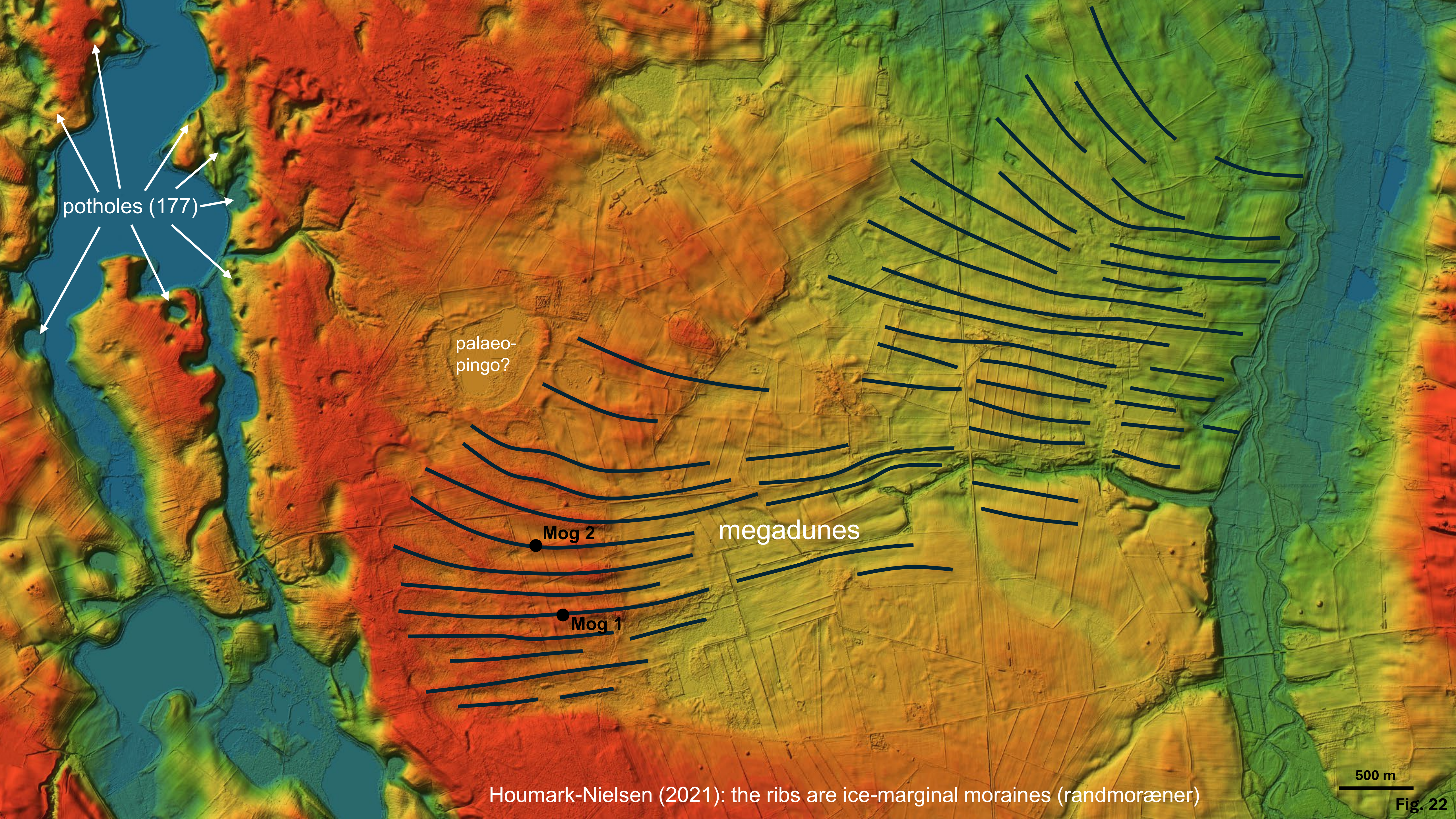
Fig. 19



1-3 Meltwater drainage phases.

Fig. 20


potholes (177)
palaeo-
pingo?
megadunes
Mog 2
Mog 1
Houmark-Nielsen (2021): the ribs are ice-marginal moraines (randmoræner)
500 m
Fig. 21


potholes (177)
palaeo-
pingo?
megadunes
Mog 2
Mog 1
500 m
Houmark-Nielsen (2021): the ribs are ice-marginal moraines (randmoræner)
Fig. 22

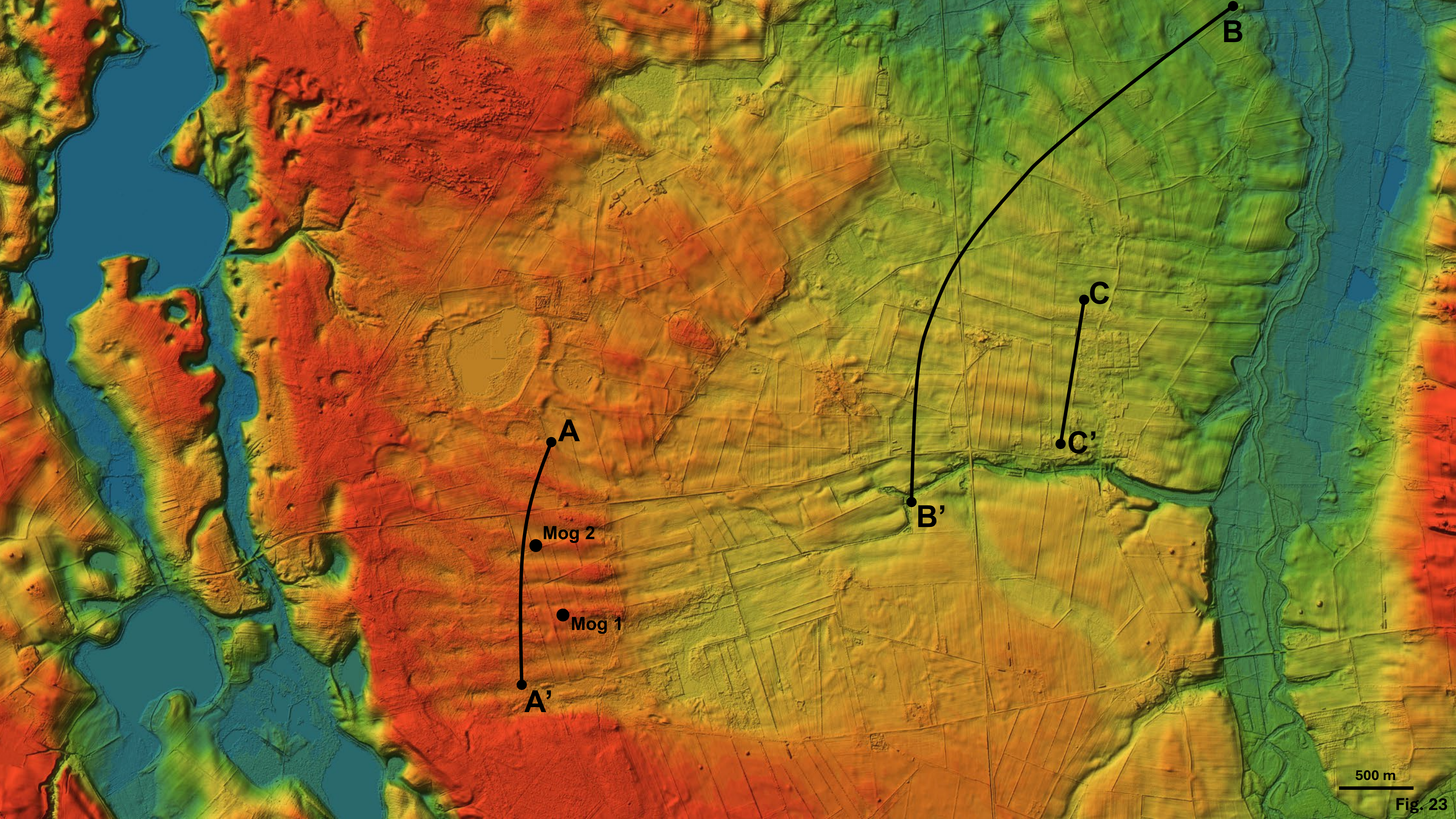


Fig. 23

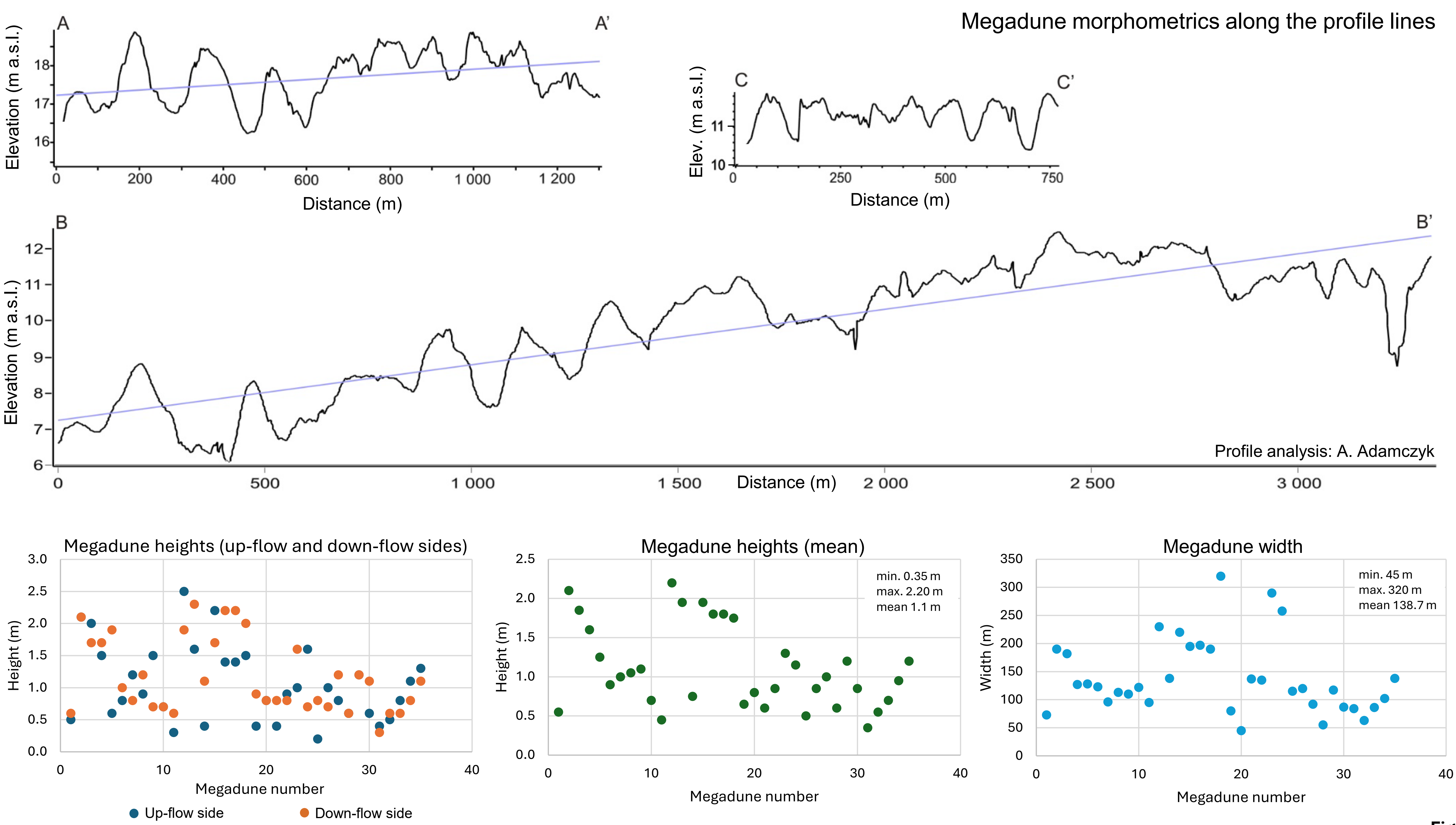
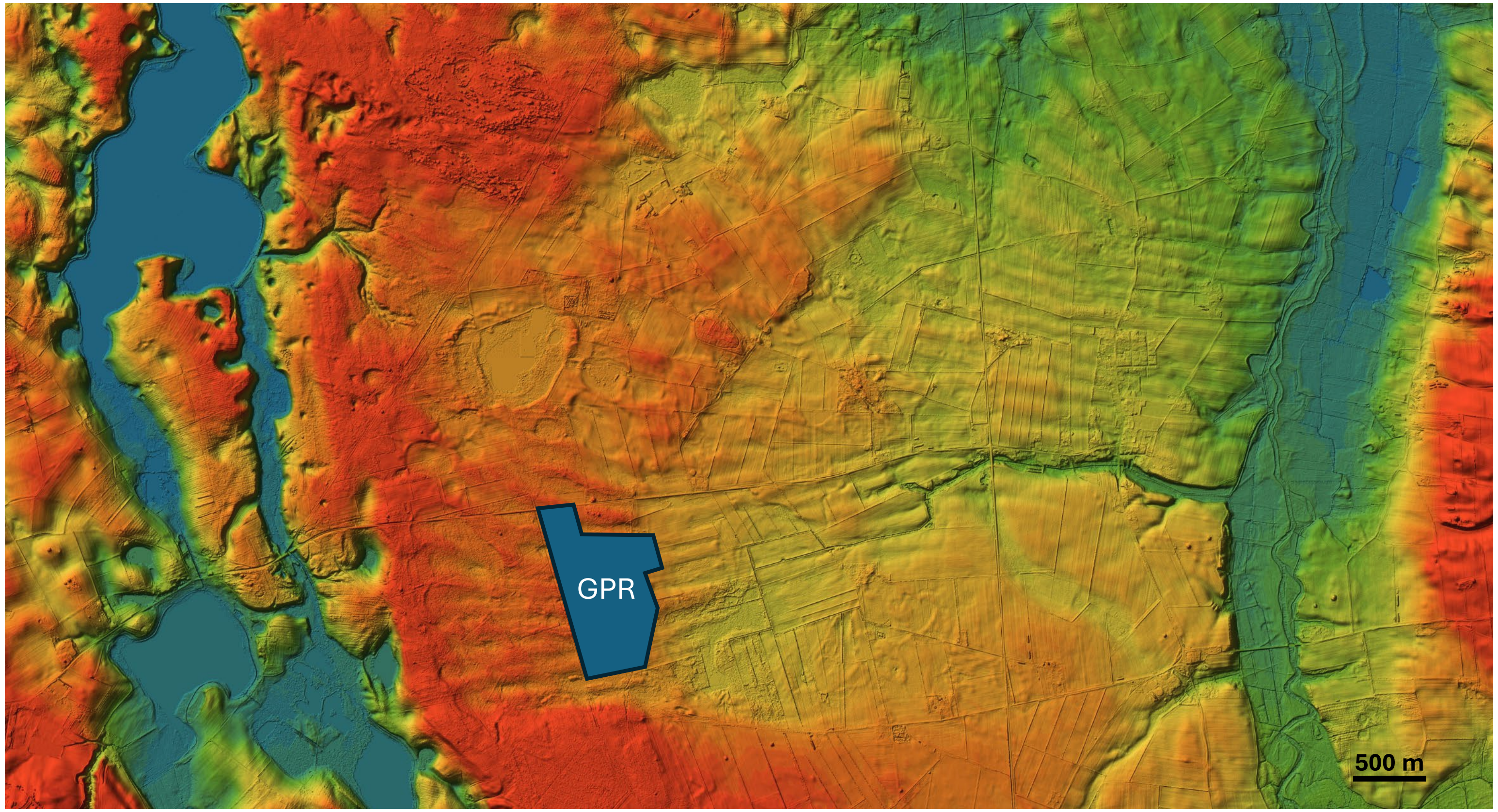

Megadune morphometrics along the profile lines
A
A'
Elevation (m a.s.l.)
Distance (m)
C
C'
Elev. (m a.s.l.)
Distance (m)
B
B'
Elevation (m a.s.l.)
Distance (m)
Profile analysis: A. Adamczyk
Megadune heights (up-flow and down-flow sides)
Height (m)
Megadune number
Up-flow side
Down-flow side
Megadune heights (mean)
min. 0.35 m
max. 2.20 m
mean 1.1 m
Height (m)
Megadune number
Megadune width
min. 45 m
max. 320 m
mean 138.7 m
Width (m)
Megadune number

Fig. 24

Mogenstrup megadunes; site Mog 1

Fig. 25

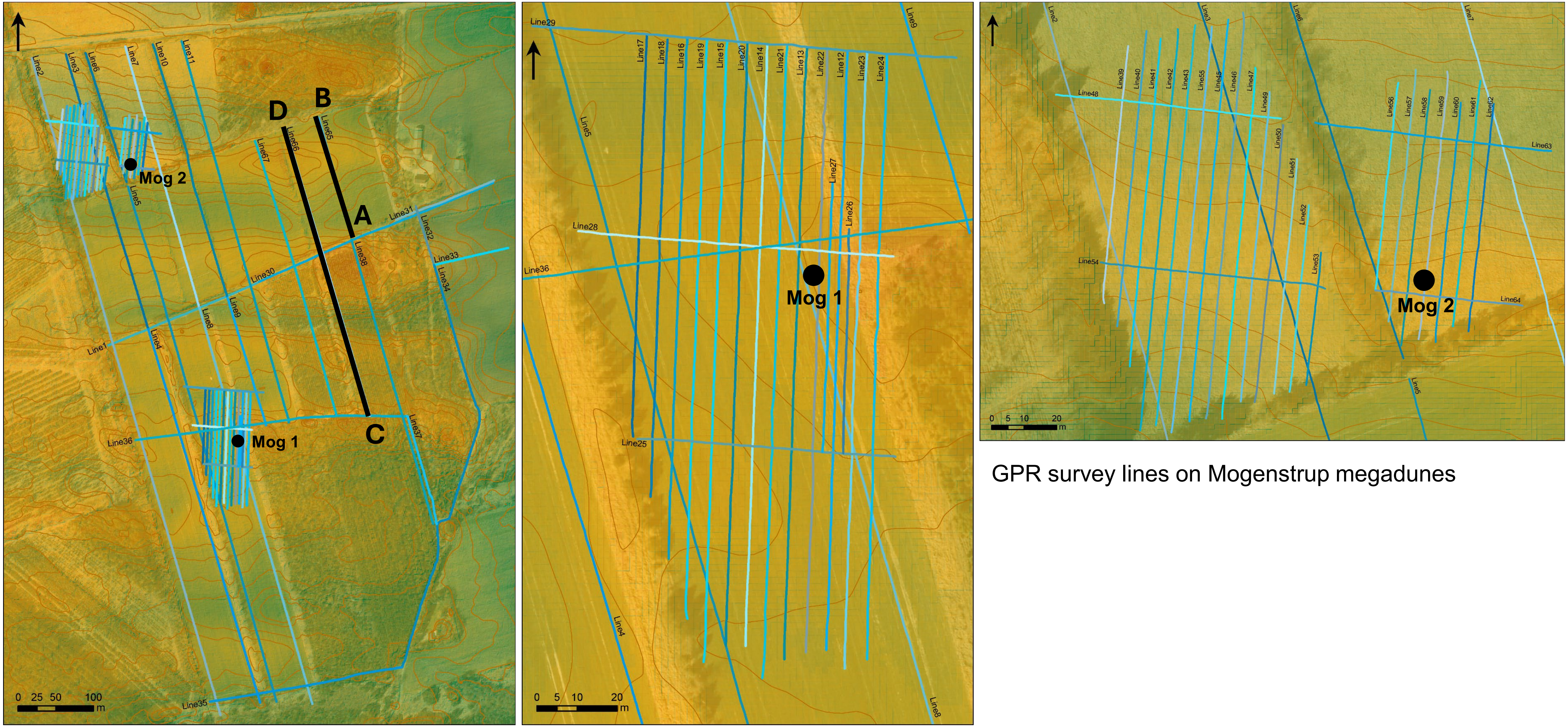
Fig. 26



GPR survey on Mogenstrup megadunes

67 lines, 12.74 km
Sensors and Software pulseEKKO pro system
Shielded antenna 250 MHz
Antenna separation 0.38 m
Step size 0.05 m
Time window 300 ns
Sampling interval 0.4 ns
Positioning with Leica system 1200 GPS
Data processing in Excel, MATLAB, EKKO View Deluxe

Fig. 27



GPR survey lines on Mogenstrup megadunes

Fig. 28

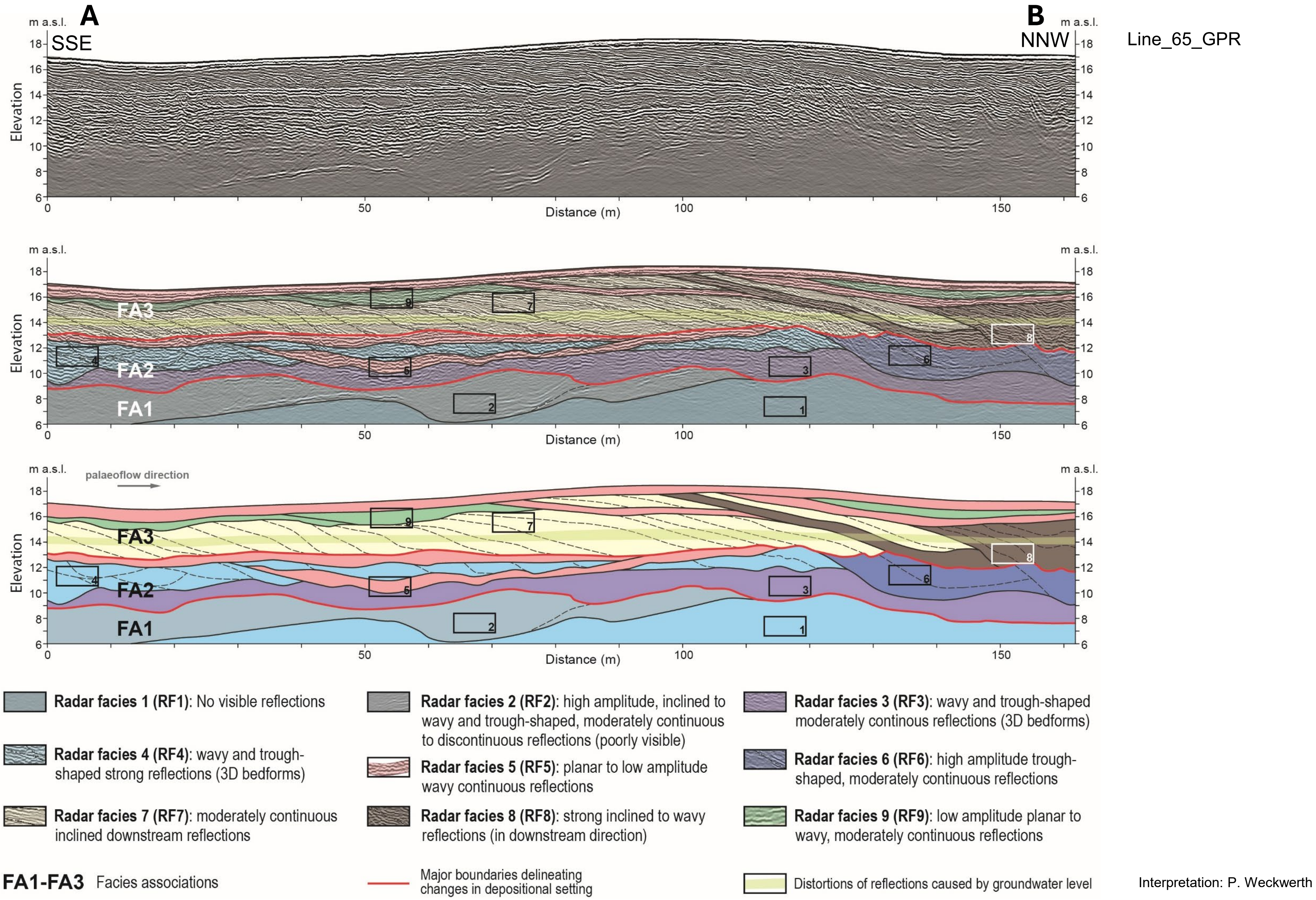
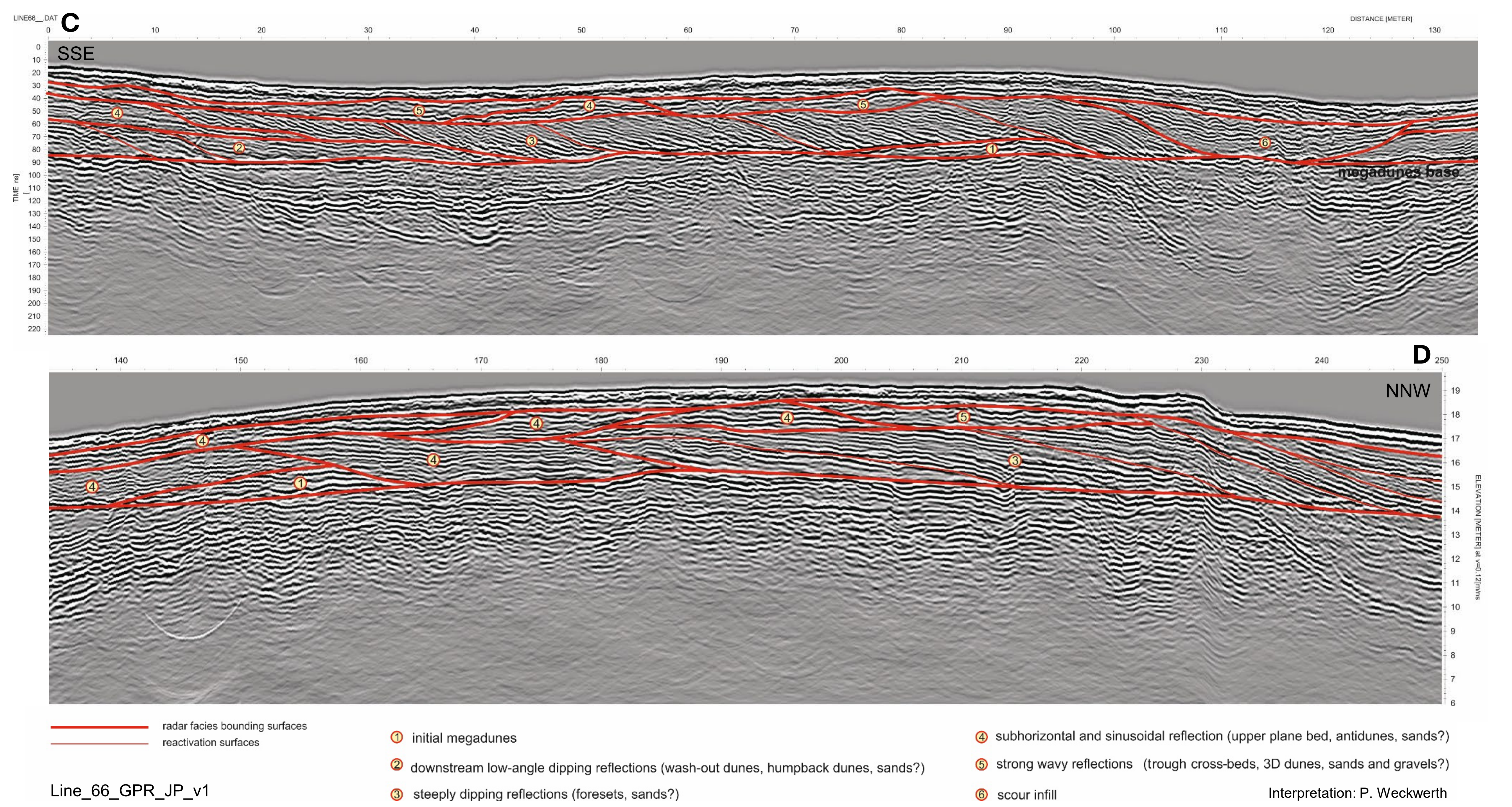

A
B
SSE
NNW
Line_65_GPR
m a.s.l.
Elevation
Distance (m)
0
50
100
150
18
16
14
12
10
8
6
FA3
FA2
FA1
palaeoflow direction
1
2
3
4
5
6
7
8
9
Radar facies 1 (RF1): No visible reflections
Radar facies 2 (RF2): high amplitude, inclined to wavy and trough-shaped, moderately continuous to discontinuous reflections (poorly visible)
Radar facies 3 (RF3): wavy and trough-shaped moderately continous reflections (3D bedforms)
Radar facies 4 (RF4): wavy and trough-shaped strong reflections (3D bedforms)
Radar facies 5 (RF5): planar to low amplitude wavy continuous reflections
Radar facies 6 (RF6): high amplitude trough-shaped, moderately continuous reflections
Radar facies 7 (RF7): moderately continuous inclined downstream reflections
Radar facies 8 (RF8): strong inclined to wavy reflections (in downstream direction)
Radar facies 9 (RF9): low amplitude planar to wavy, moderately continuous reflections
FA1-FA3 Facies associations
Major boundaries delineating changes in depositional setting
Distortions of reflections caused by groundwater level
Interpretation: P. Weckwerth

Fig. 29



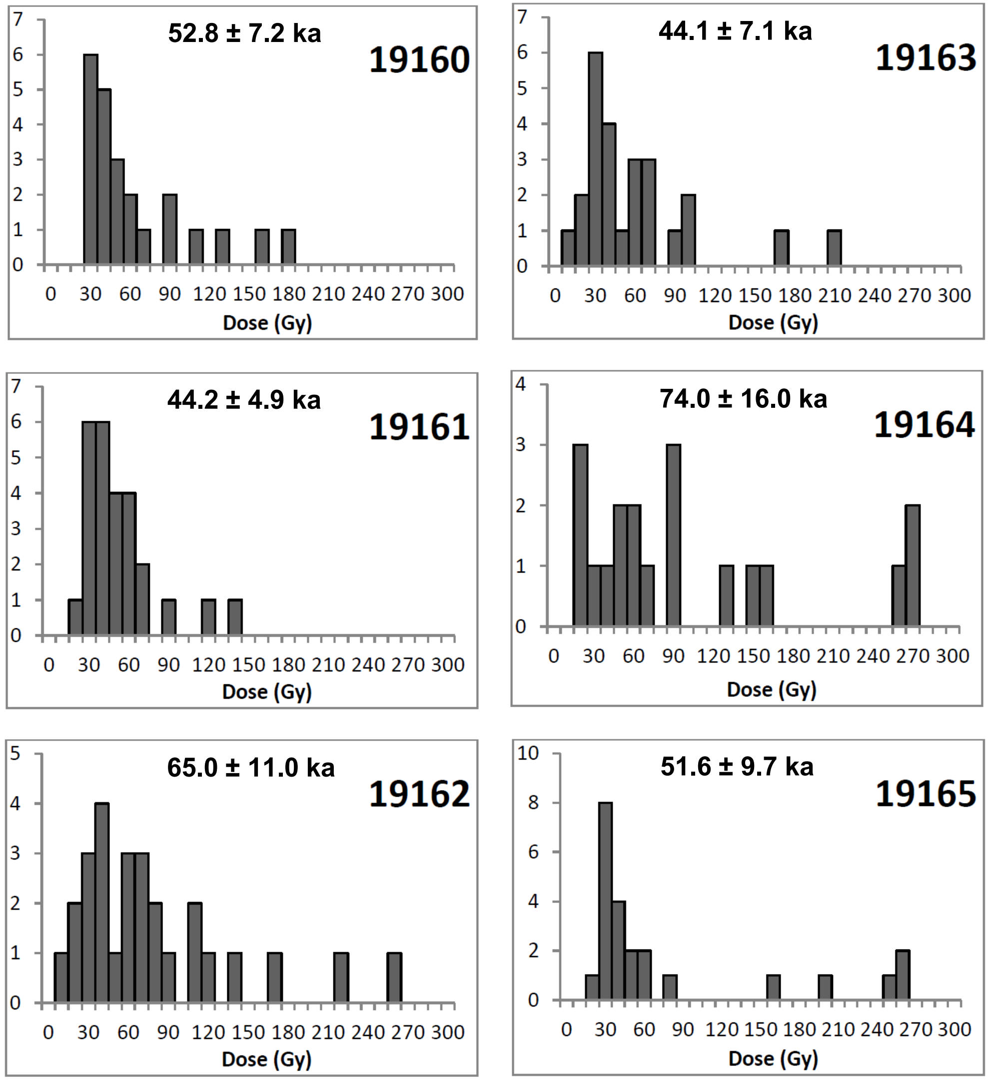
LINE66__.DAT
C
DISTANCE [METER]
SSE
TIME [ns]
megadunes base
D
NNW
ELEVATION [METER] at v=0.12 m/ns
radar facies bounding surfaces
reactivation surfaces
1 initial megadunes
2 downstream low-angle dipping reflections (wash-out dunes, humpback dunes, sands?)
3 steeply dipping reflections (foresets, sands?)
4 subhorizontal and sinusoidal reflection (upper plane bed, antidunes, sands?)
5 strong wavy reflections (trough cross-beds, 3D dunes, sands and gravels?)
6 scour infill
Line_66_GPR_JP_v1
Interpretation: P. Weckwerth

Fig. 30

OSL dating (Lund Luminescence Laboratory)

CAM (central age model; preferred over the mean age)
Small (2-mm) single aliquots of 180-250 µm quartz analyzed in Risø TL/OSL readers
Single Aliquot Regeneration (SAR) protocols used
IR-test, dose recovery and preheat plateau tests

Most samples have significantly skewed and/or broad small-aliquot dose distributions and large overdispersion (OD), which may suggest incomplete bleaching.



Histograms of D_e values for quartz

Fig. 31