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Ice-contact deltas investigation using GPR and ERT

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Rationale

What is the reason for the study?

- Ice-contact deltas provide a detailed record of processes and conditions at the ice margin of a retreating ice sheet. Understanding processes recorded in deltaic sediments can improve accuracy of palaeoglacial reconstructions and help predict the response of present day ice sheets to warming climate.

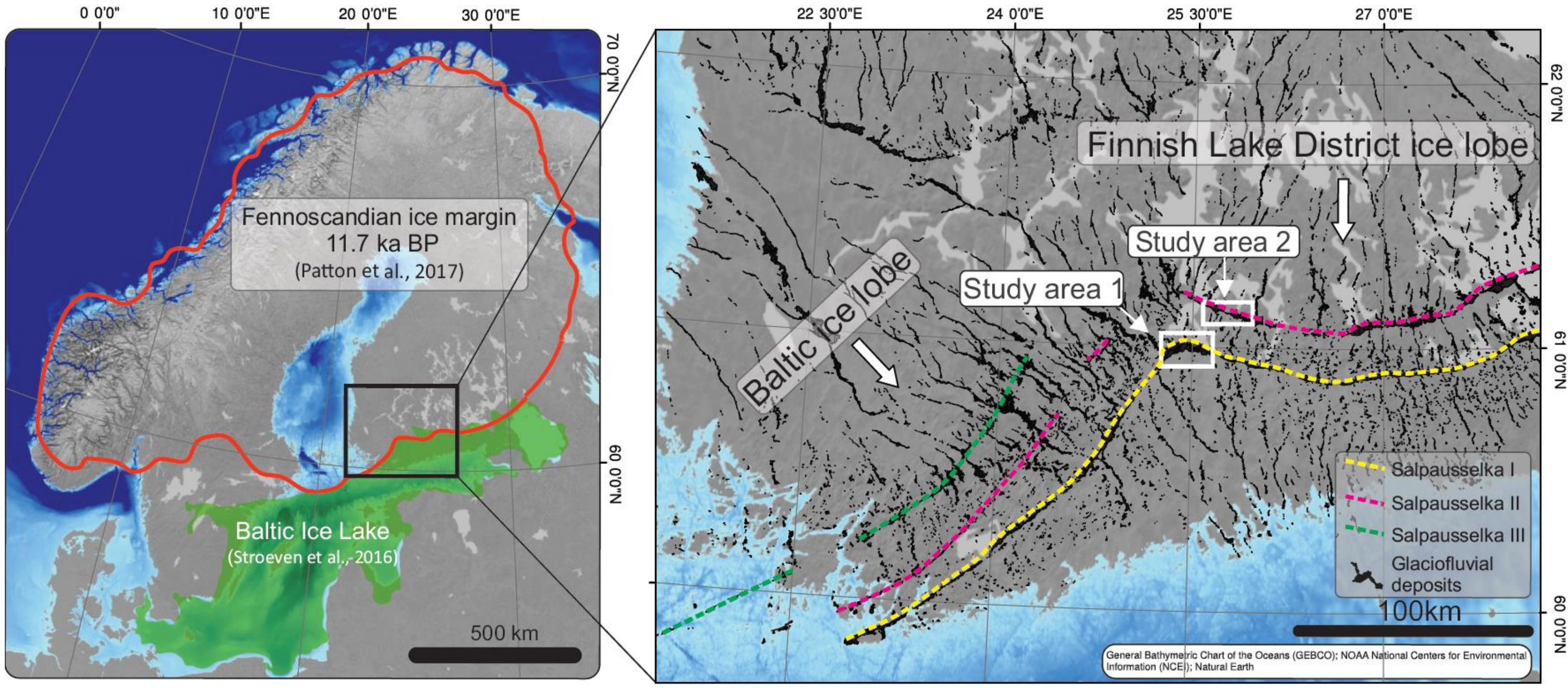
- Salpausselkas are an important aquifer in Southern Finland. Understanding sedimentary facies distribution, reservoir complexities, bedrock structure and overall thickness of sediments is essential for effective groundwater management and pollutants dispersion mitigation.

- The deltas are an important source of sand and gravel aggregate for construction industry. Understanding of the sedimentology and structure (depth to bedrock, groundwater level) of the deltas willhelp assure safe and efficient extraction of aggregates without the risk of polluting or interfering with aquifer.

- Easily accessible ice-contact deltas in Finland can be used as an analogue for similar, older sediments of glaciogenic origin in the subsurface which host important water and hydrocarbon reserves. Typically such deposits were studied either in limited 2D outcrops or using seismic data. Salpausselkas provide an unique opportunity to study such sediments in 3D using sedimentology and geomorphology together with geophysical methods thus providing a better opportunity to decipher structure of the reservoir.

Study area

- Salpausselka I and II ice-marginal ridges near Lahti, Finland
- Deposited by Fennoscandian Ice Sheet during Younger Dryas ~12.5 -11.5 ka BP
- Prominent ridges delineate re-advance or stillstand of the ice margin
- The ridges extends for over 600 km W-E and changes direction around the city of Lahti
- Ice margin at that time was grounded in a large proglacial lake – Baltic Ice Lake
- Majority of sediments were supplied to the ice margin by meltwater
- As a result, a series of amalgamated ice-contact deltas, fans and narrow ridges were deposited
- Following ice retreat and drainage of the Baltic Ice Lake Salpausselka ridges were cut off from sediment supply and emerged above the water

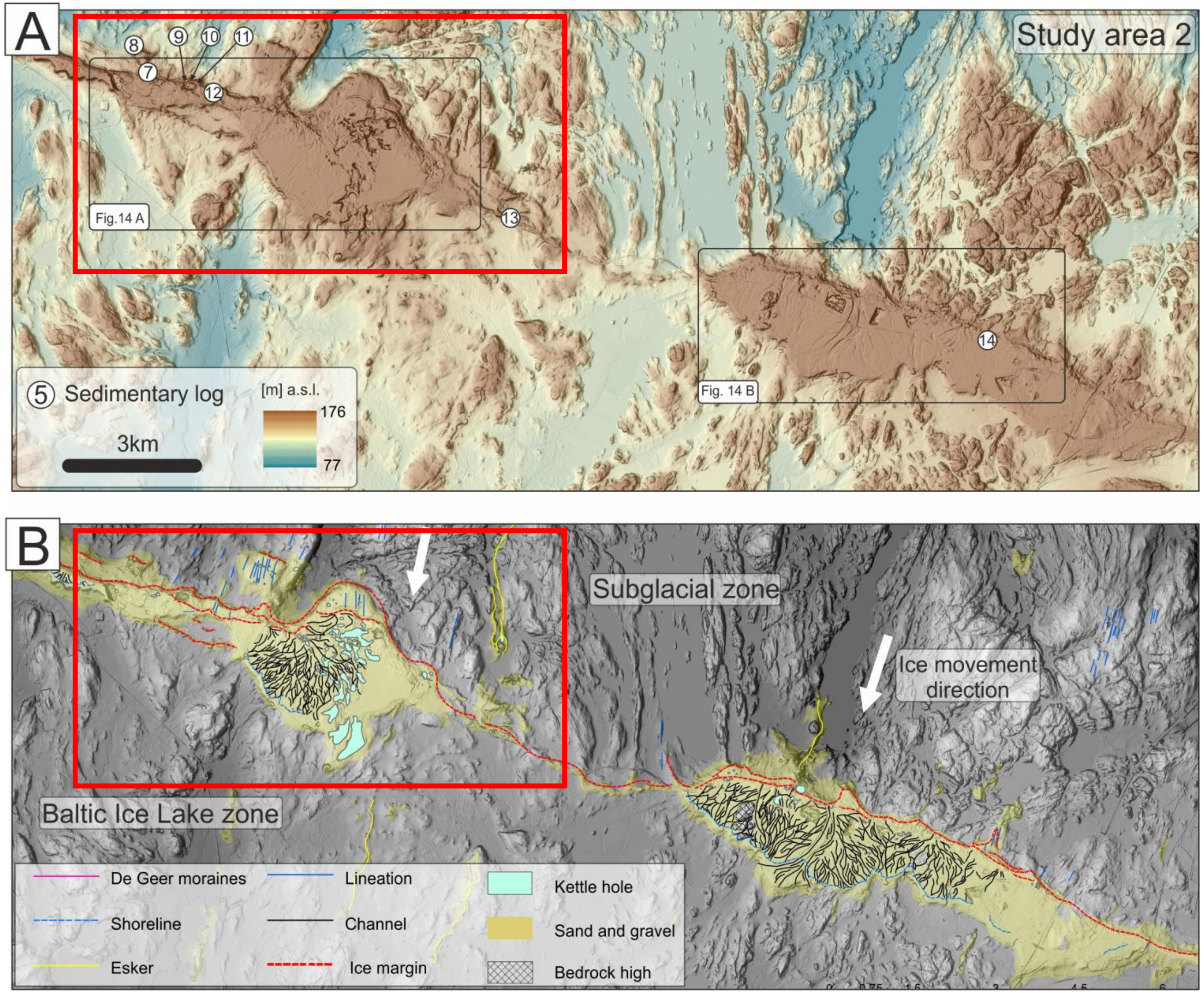


Aggregate sand and gravel (maa aines epsg3067) modified data © Geological Survey of Finland *2018*

Study area

For the purpose of this presentation only a part of Study Area 2 will be discussed:

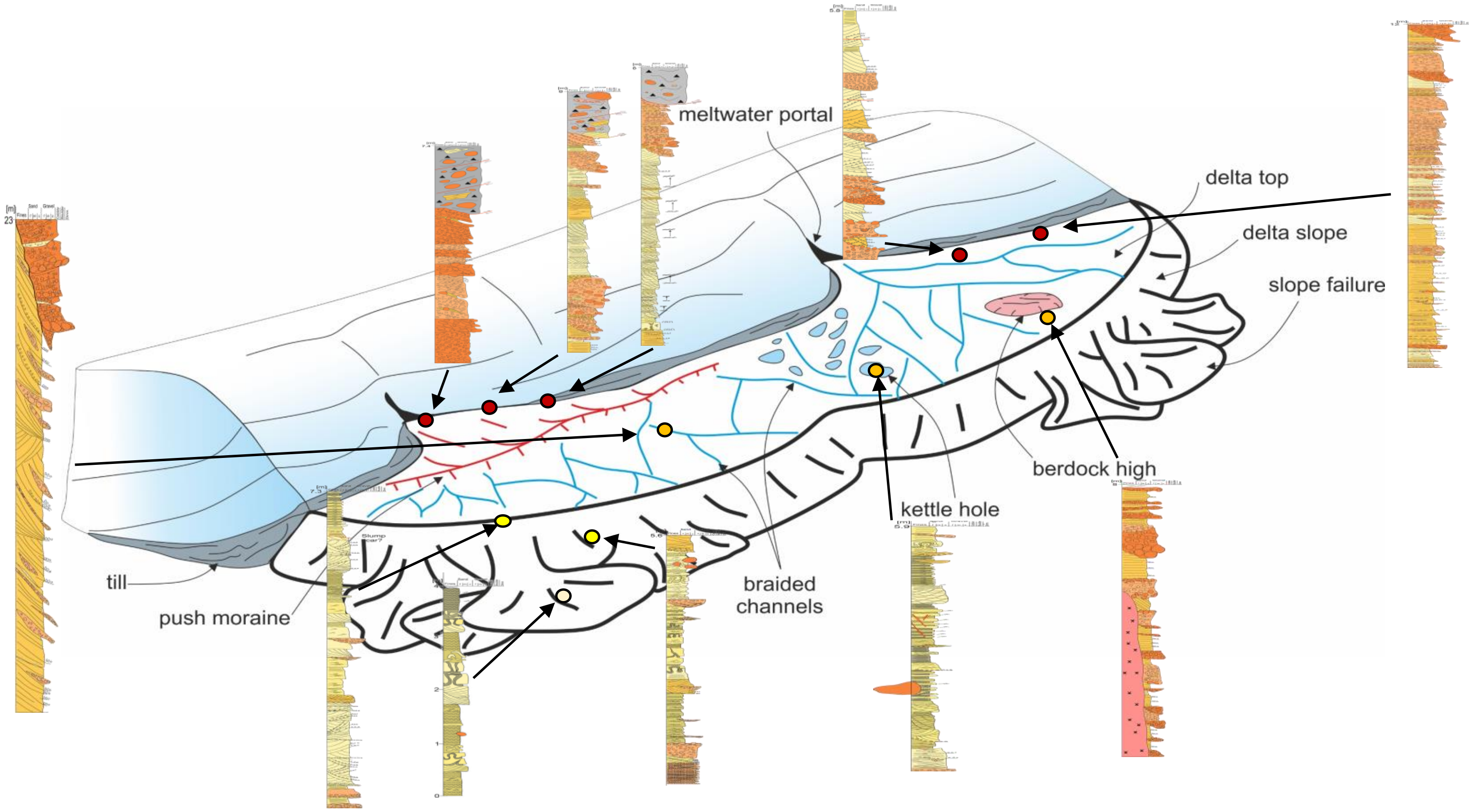
- Location name: Vesivehmaankangas
- A large, lobate ice-contact delta deposited from N to S. Sediments were supplied by meltwater most likely subglacially/englacially (eskers)
- Several smaller ridges and lineations testify to a complex history of syn-depositional ice margin oscillations
- A network of braided distributary channels is preserved on delta top
- Irregular depressions in the delta body are interpreted as kettle holes formed after buried ice blocks melted out



Sedimentology

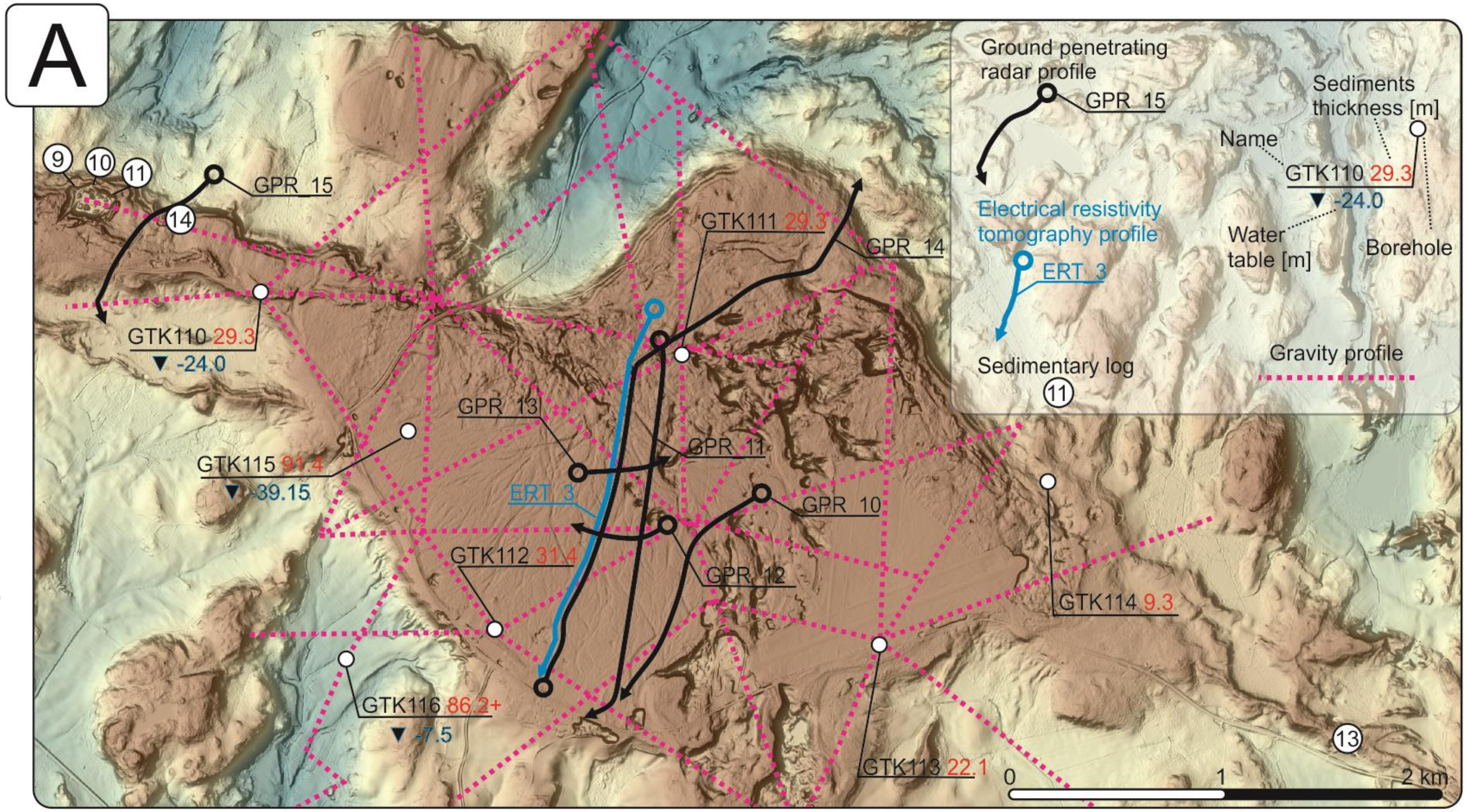
There are no good quality outcrops in the delta itself but from other locations in the vicinity it is possible to reconstruct distribution of sediments within a schematic ice contact delta.

- Cobbles and gravels dominate the proximal part – ice contact fan facies
- Sandy and gravely subglacial diamicton is present where ice had overridden part of the delta
- Central part of the delta is dominated by steeply-dipping, well sorted sands and subordinate gravels – deltaic foresets of a Gilbert-type delta
- Cobbly and gravely topsets are overlying the foresets. The topset facies represent deposition from braided streams on delta top
- Finer fractions and abundant soft sediment deformations are intertwined with sand and gravels in the distal part of the delta and delta slop
- **Take home message: Sediments are generally well sorted within individual packages but distal and proximal sections exhibit larger variety of grainsizes than the medial part**



Data

- Gravity data has been acquired previously by the Geological Survey of Finland (GTK)
- There are several observation boreholes drilled into the delta of which two (GTK111 & GTK112) are in the vicinity of the GPR and ERT profiles.
- Five ground penetrating radar (GPR) and one electrical resistivity tomography (ERT) profiles have been acquired for the purpose of this study



Gravity and borehole data

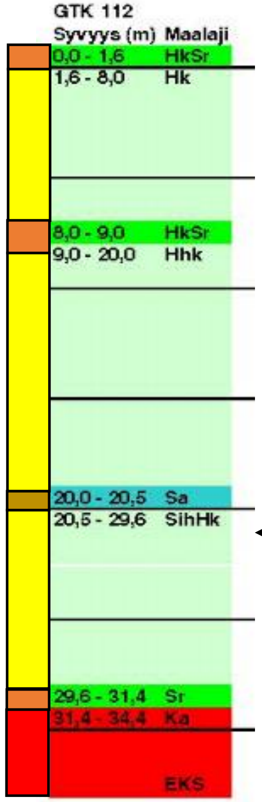
Here is a quick wrap-up of the boreholes if you aren't, like myself, fluent in Finnish ☺

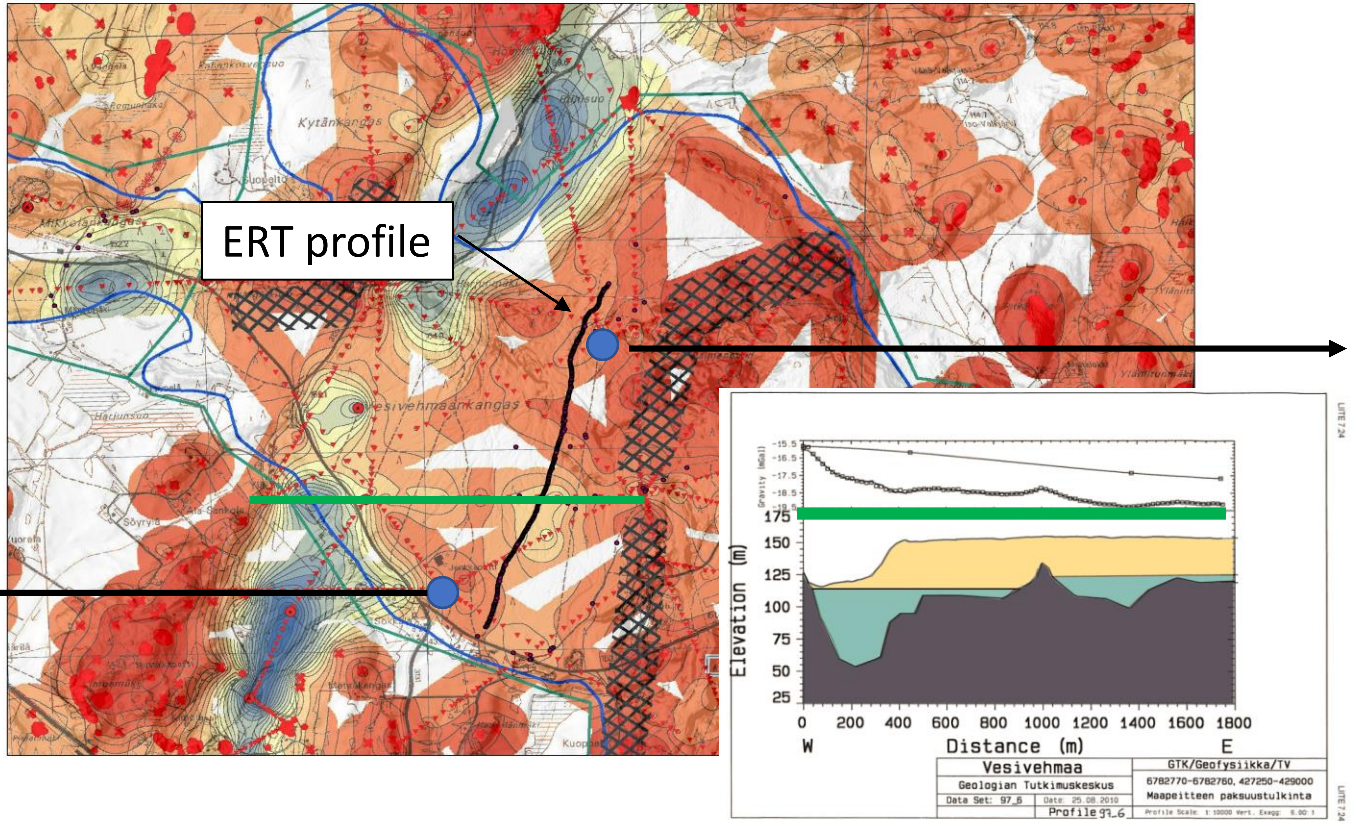
gravel

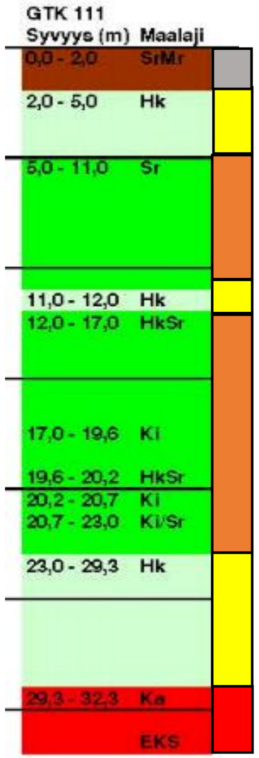
sand

silt/clay

bedrock







diamicton

sand

gravel

bedrock

Gravity data: red indicates bedrock close to surface, blue - thick sediments. Isoline cut every 5 m

One of the inverted gravity profiles.
Note that the model consists of three layers:

- bedrock
- unsaturated sediments
- saturated sediments

Methods - technical details

GPR:

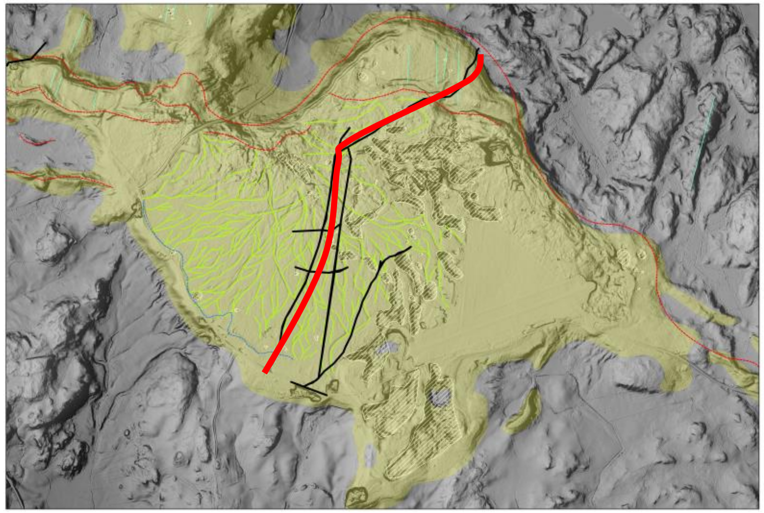
- AB Geoscanners GEKKO 80
- Centre frequency: 80 MHz
- Bistatic mode
- Range: 450 ns
- Processing: GPRsoftPRO
- Average RDP: 6.2
- Depth range(10-25 m) typically ~ 15m

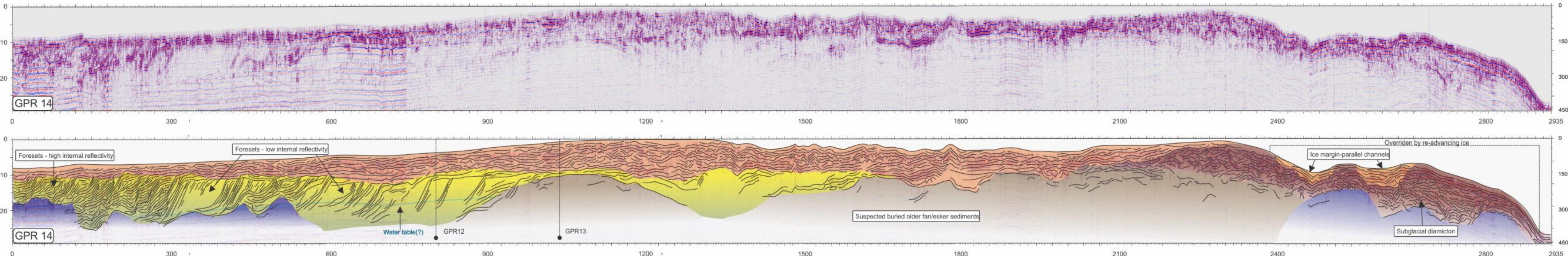
ERT:

- SyscalPro
- 72 electrodes - 5m spacing
- Dipole-Dipole & Multi gradient +IP
- Processing: Prosys II & Res2Dinv x64
- 3 profiles - 3.7 km total length

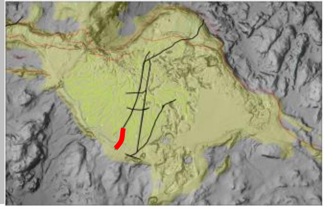
Ground penetrating radar results: profile GPR14

- The profile is almost 3km long and spans from ice distal (left) to ice-contact (right) part of the delta
- 2/3 of the profile are colinear with the electrical resistivity tomography profile 3 (ERT3)
- In the next couple of slides we will go through the profile in more detail

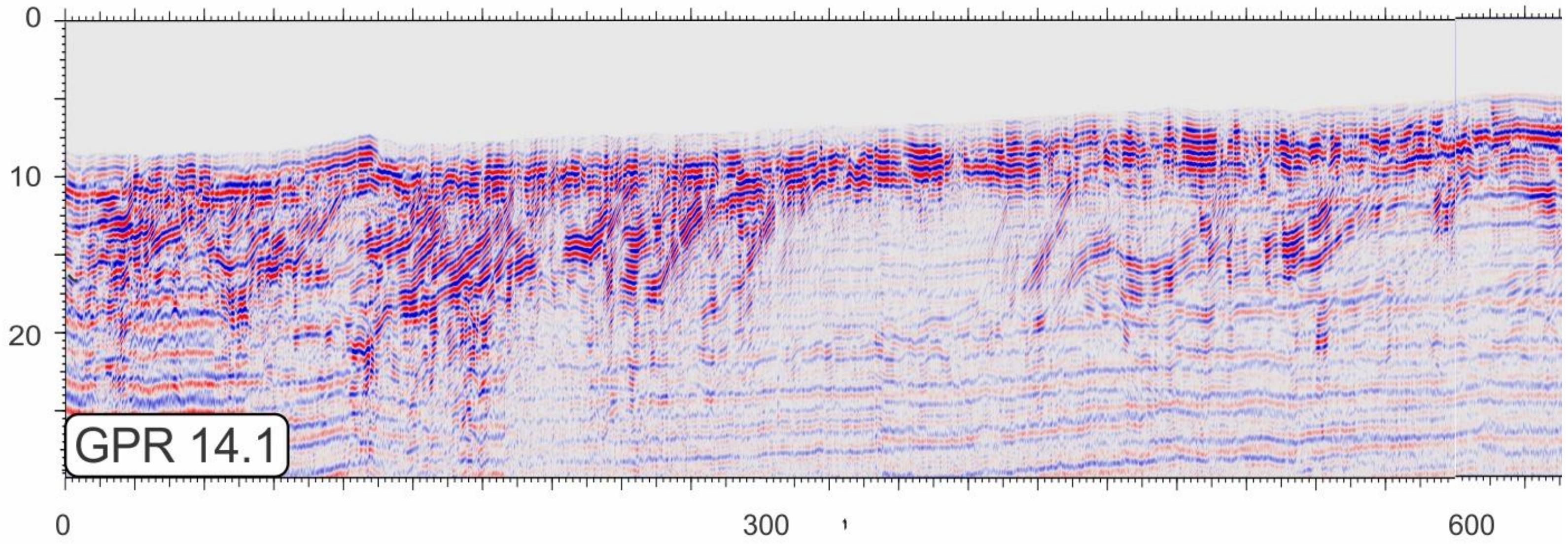


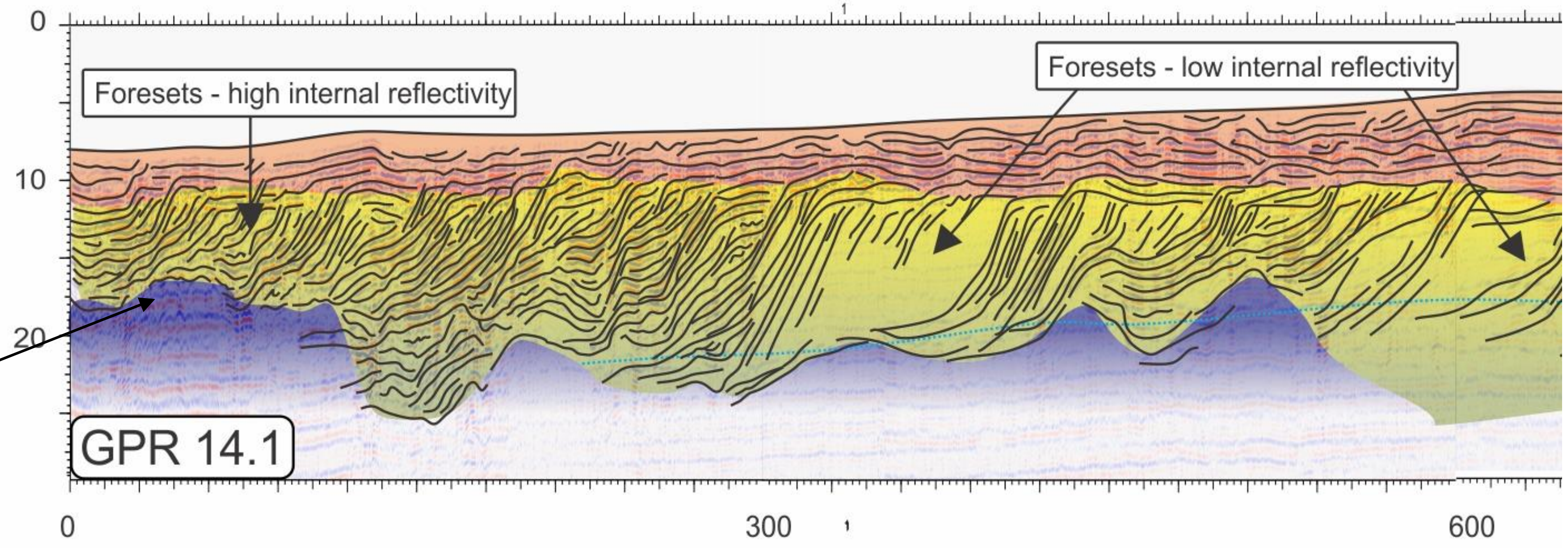


Ground penetrating radar results: distal delta

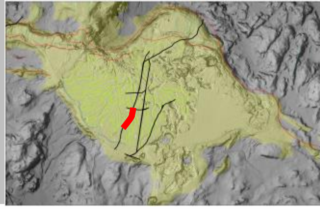


- High reflectivity and steeply dipping reflections dominate in the distal part of the delta
- The section is interpreted as distal delta foresets
- Flat, semi-continuous reflections in the top part of the profile are interpreted as topset facies – deposits of braided streams
- High reflectivity is most likely caused by changes in water saturation between finer an coarser grained packages
- Onlap/draping of some of the reflections in bedrock highs is visible (probably similar to the one in picture below)

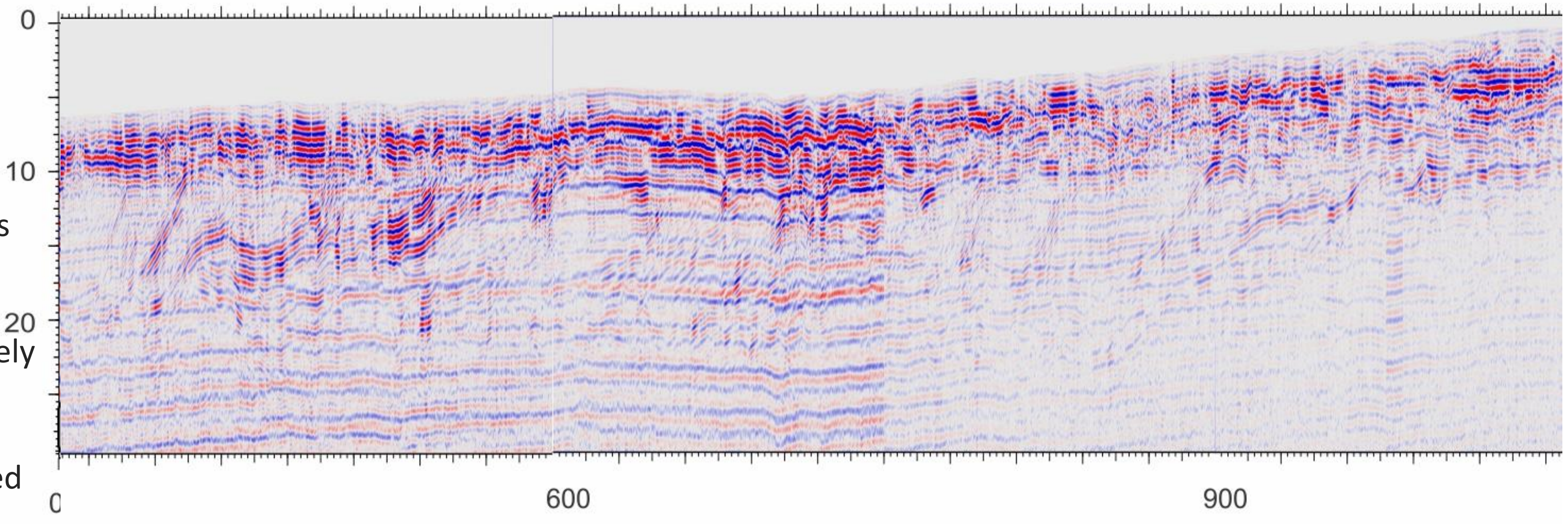


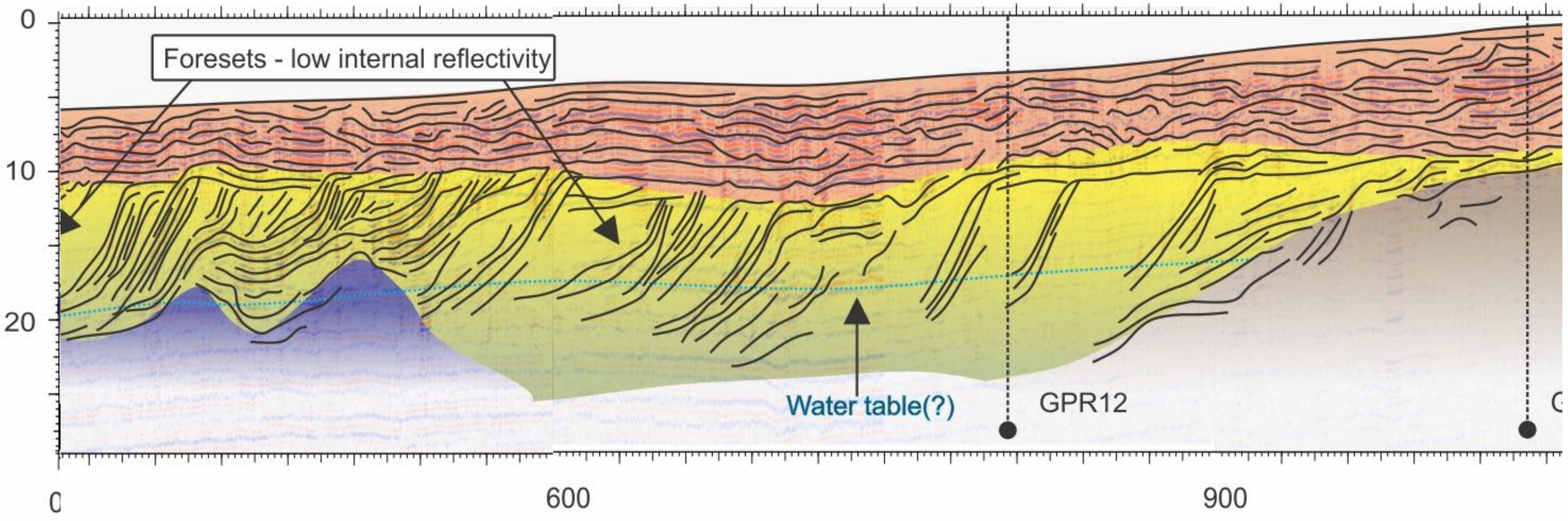


Ground penetrating radar results: medial delta



- Low internal reflectivity within steeply dipping foresets is attributed to more uniform grainsize distribution – a sustained flow energy (?)
- The above is supported by observations in outcrops located in medial parts of the delta
- A possible water table can be observed as a relatively flat zone of increased reflectivity
- Picture below shows steeply dipping and well sorted sediments in outcrop (outcrop height ~12m)

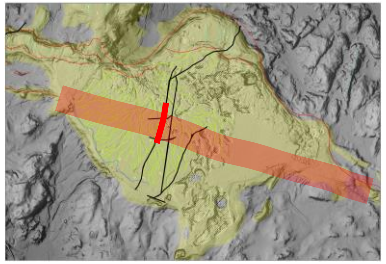


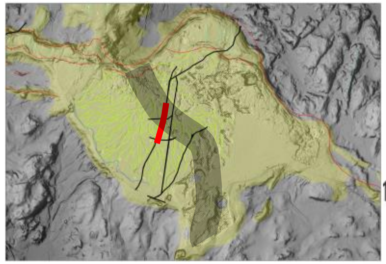


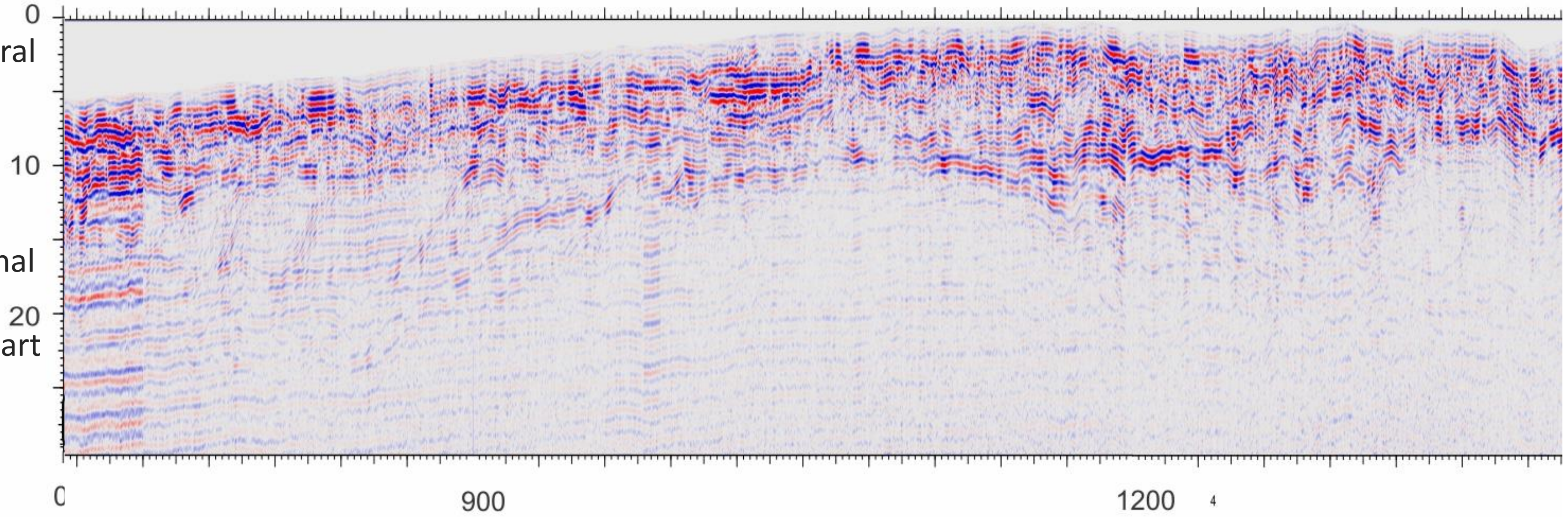
Ground penetrating radar results: bedrock high or older buried delta/esker ?

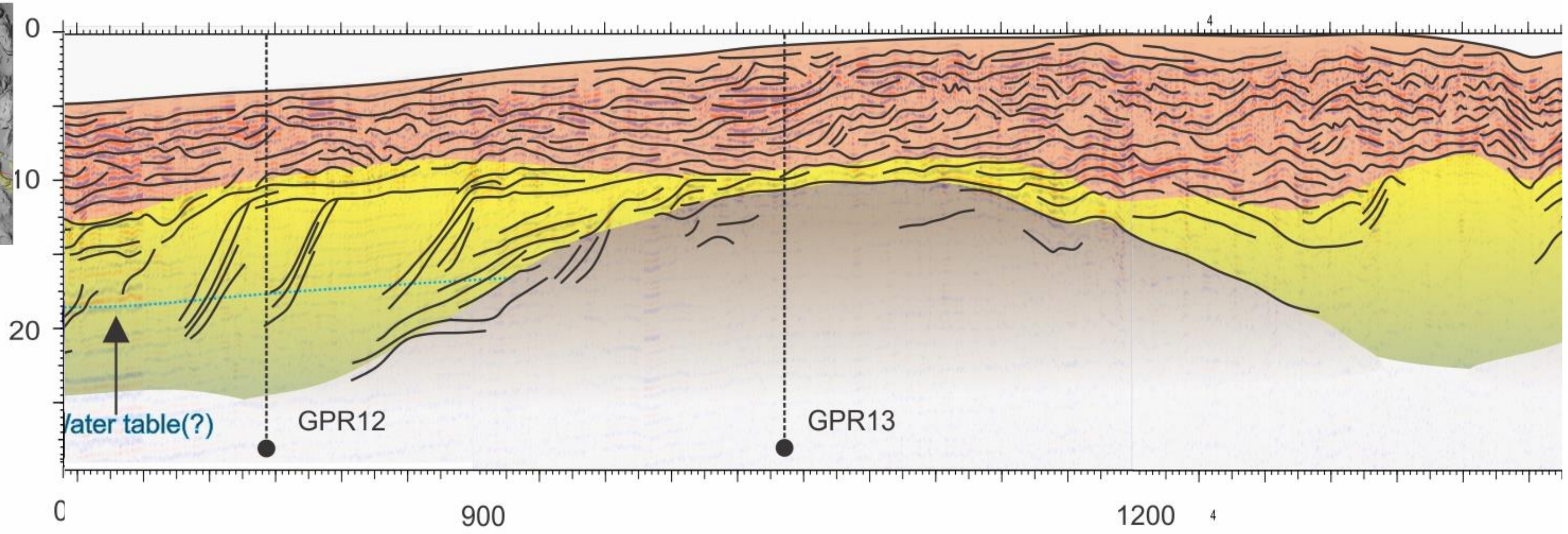
- A prominent structure can be observed in the central part of the delta. It is covered by topset facies

- The structure can be interpreted either as:
  - A bedrock high
  - Buried older delta/fan delineating ice marginal position
  - A pre-existing, buried esker deposited as a part of subglacial drainage



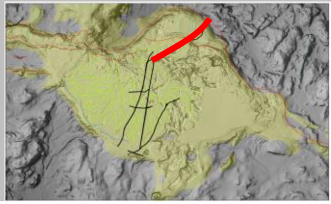


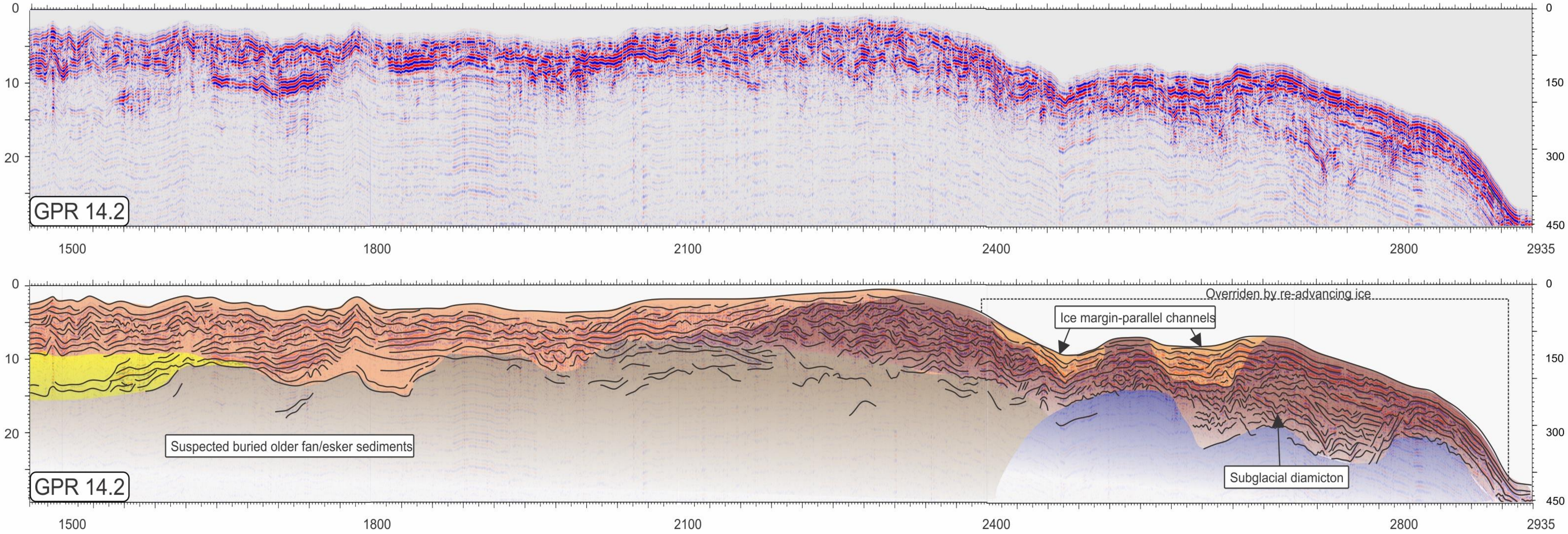




- GPR profile alone is not allowing for a confident interpretation

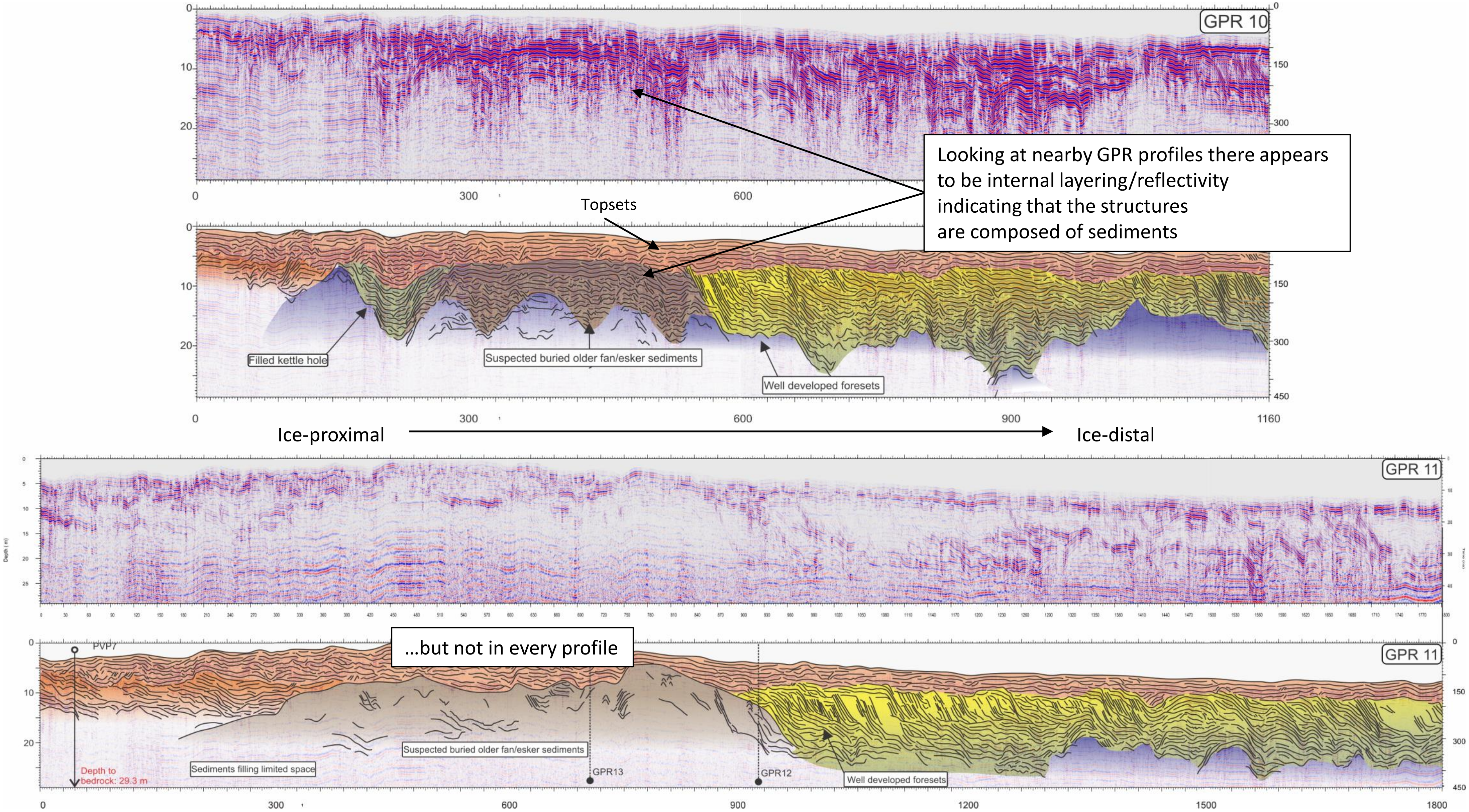
Ground penetrating radar results: Ice-proximal and ice-contact part





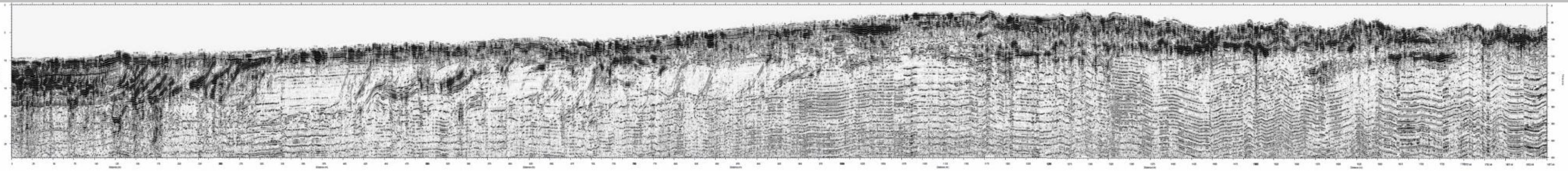
- More chaotic, discontinuous reflections
- Lower penetration depth of the GPR – higher clay content (?)
- Contorted, discontinuous reflections corelate well with the area overridden by the ice and are interpreted to represent subglacial diamicton and/ or reworked and glacitectonised deltaic sediments

Ground penetrating radar results: nearby GPR profiles

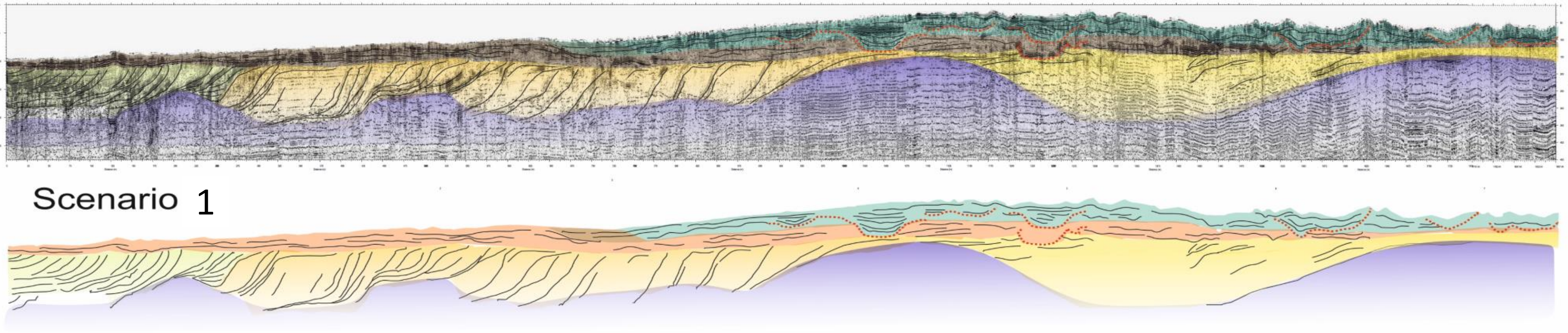


Question: what is lurking below?

Is it:



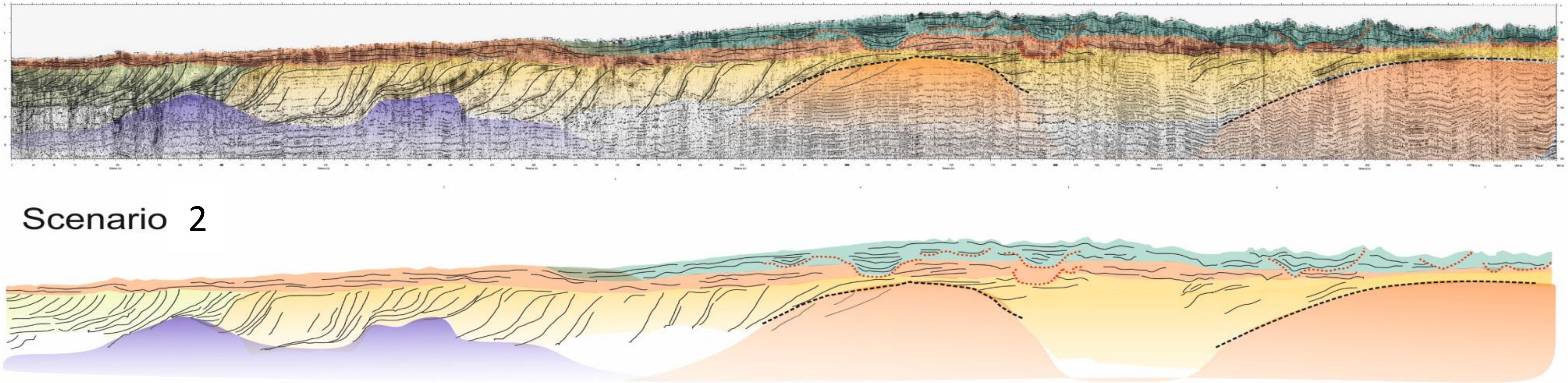
Bedrock



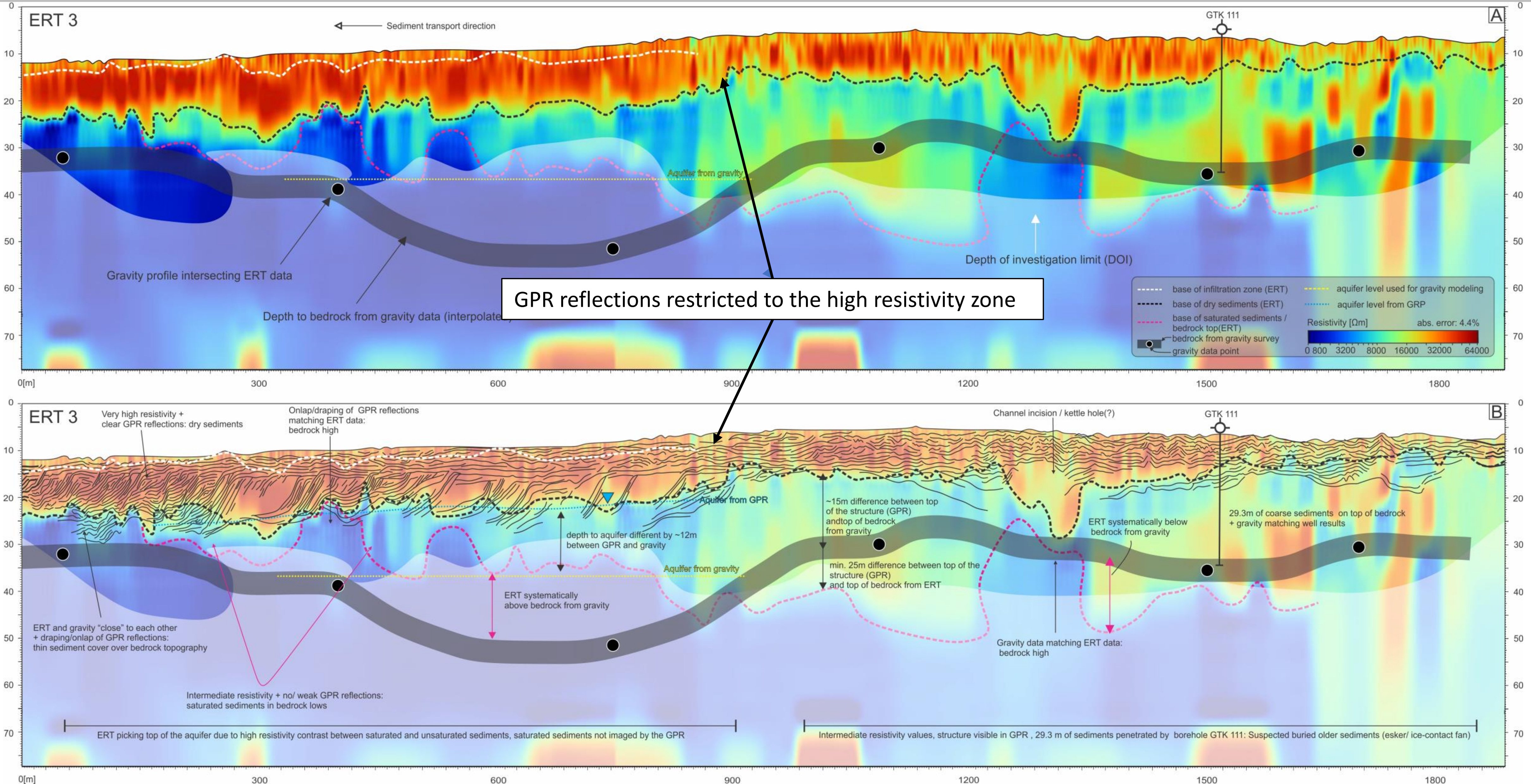
or:

To answer that question another geophysical method has to be used

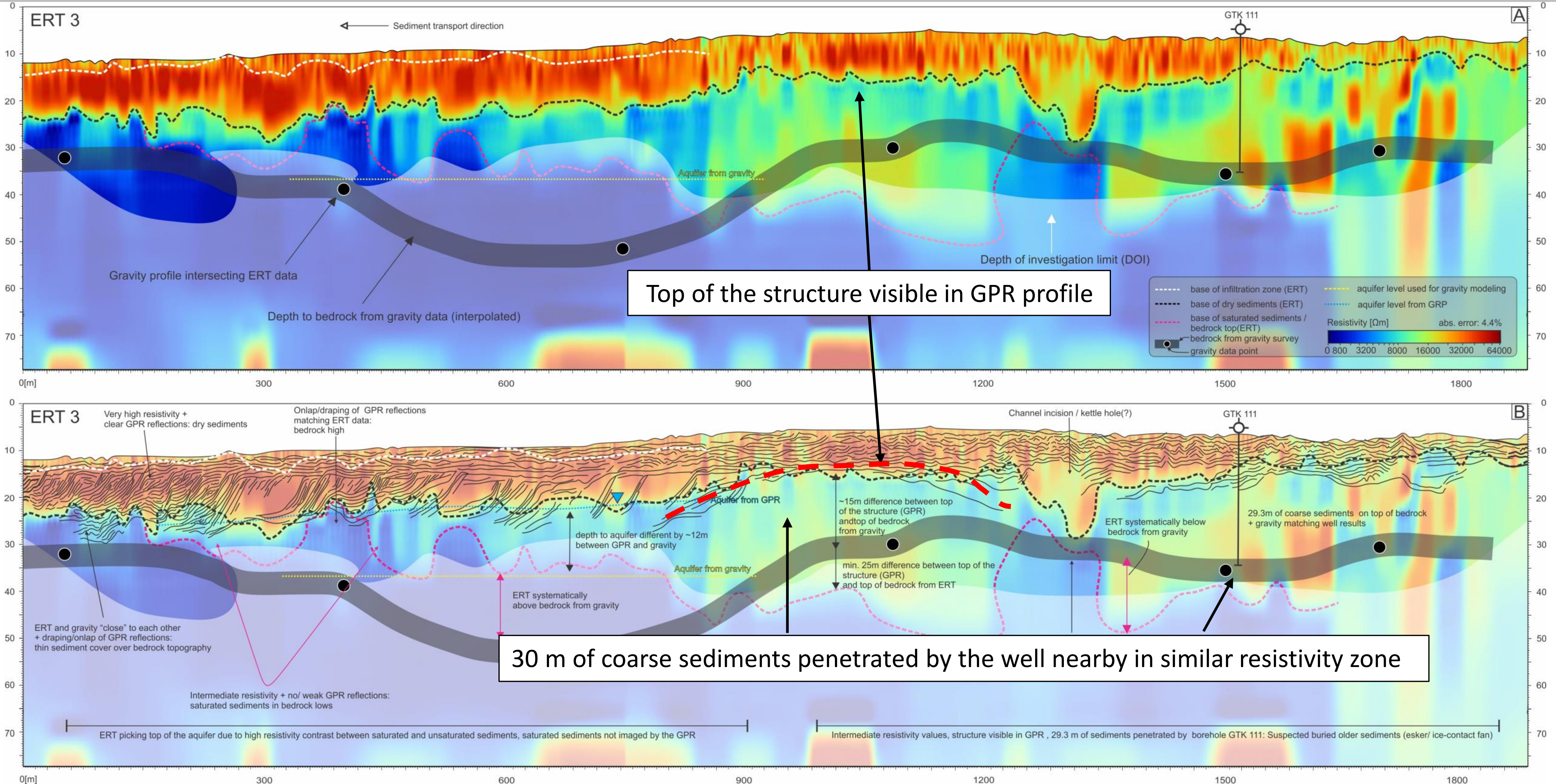
Sediments



ERT, GPR and gravity data combined



ERT, GPR and gravity data combined

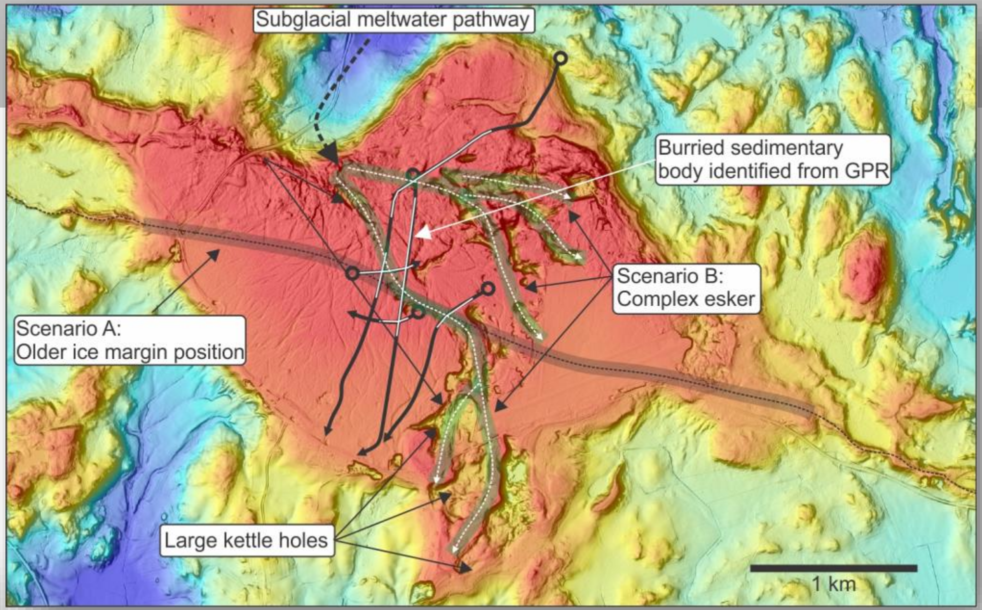


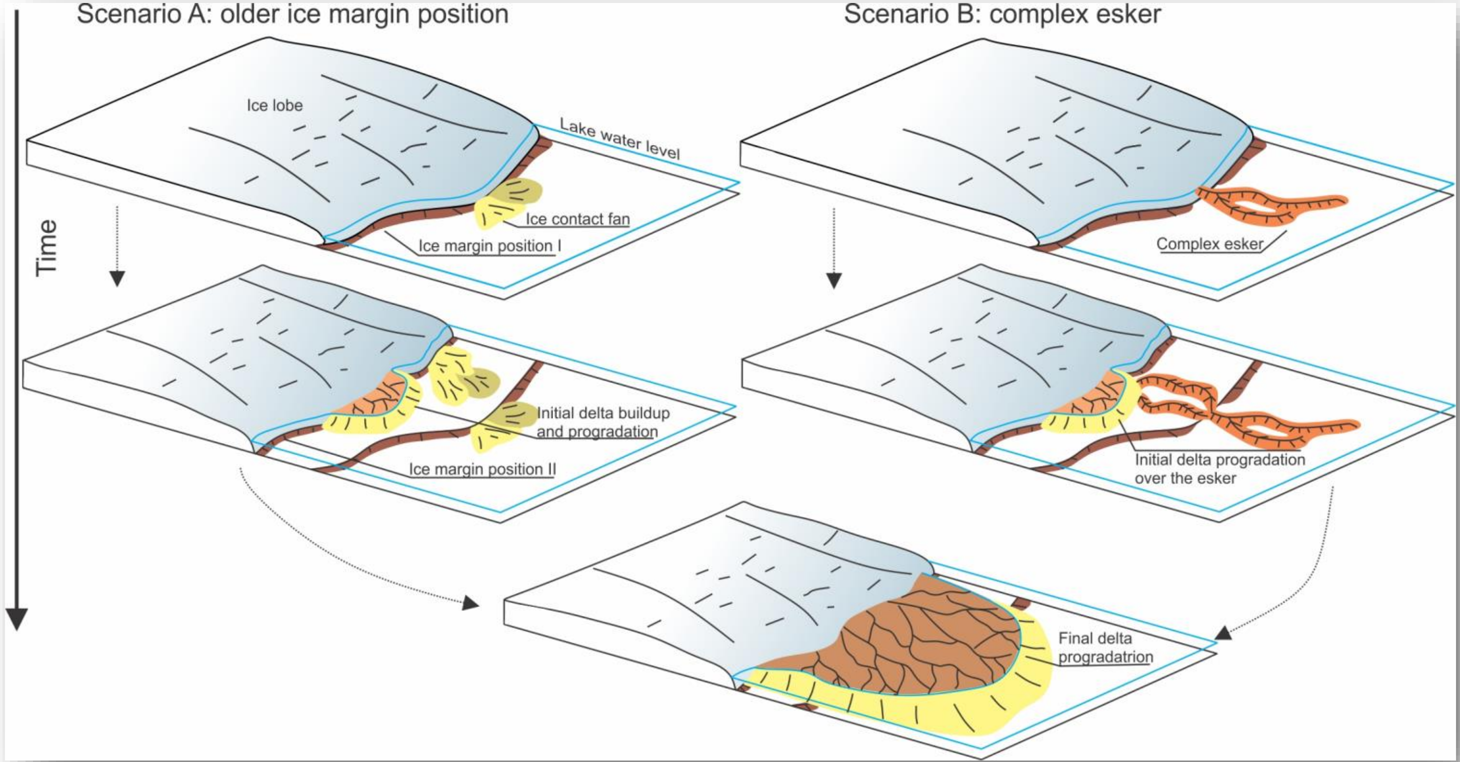
Verdict?

Hopefully this convinces you that Scenario 2 (older sediments) is more likely. However, the question remains whether the buried sedimentary body is in fact:

A: An older Ice marginal position

B: A complex, pre-existing esker deposited as a part of subglacial drainage network

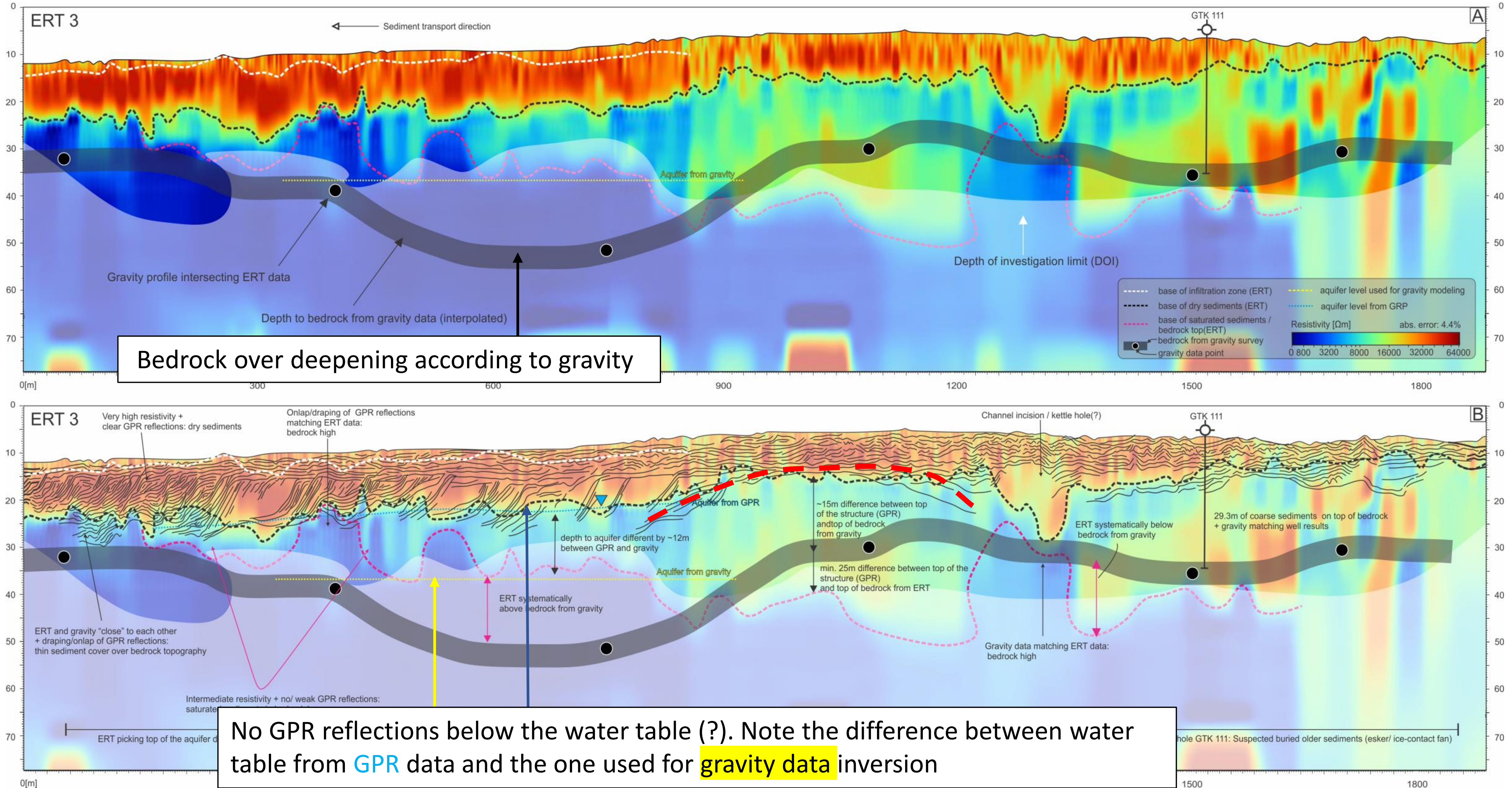




?

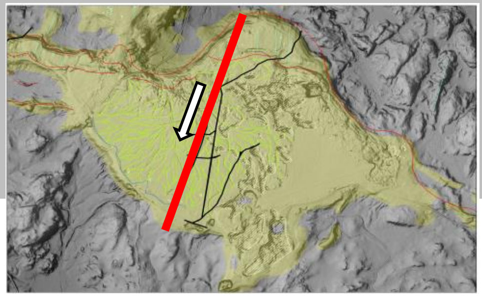
Each will affect the reservoir/aquifer performance in different ways!

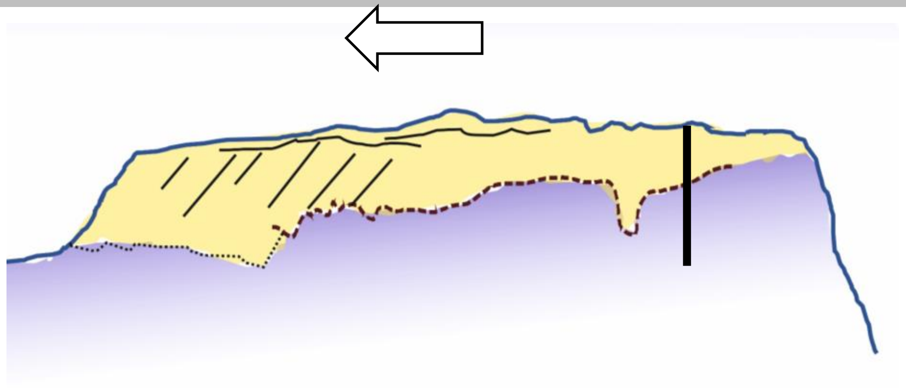
But that is not all. Where is the aquifer?



No GPR reflections below the water table (?). Note the difference between water table from GPR data and the one used for gravity data inversion

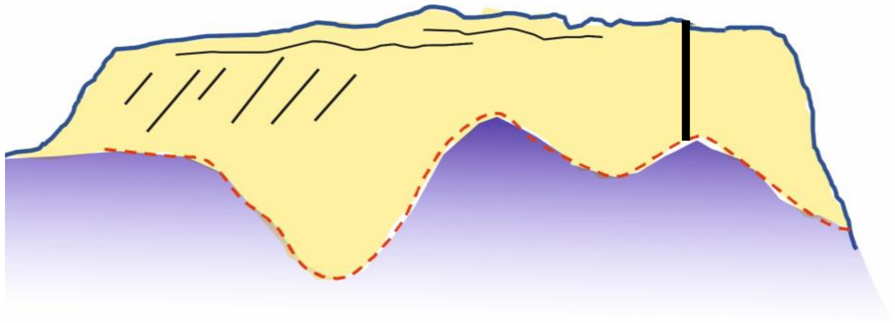
Comparison of the methods





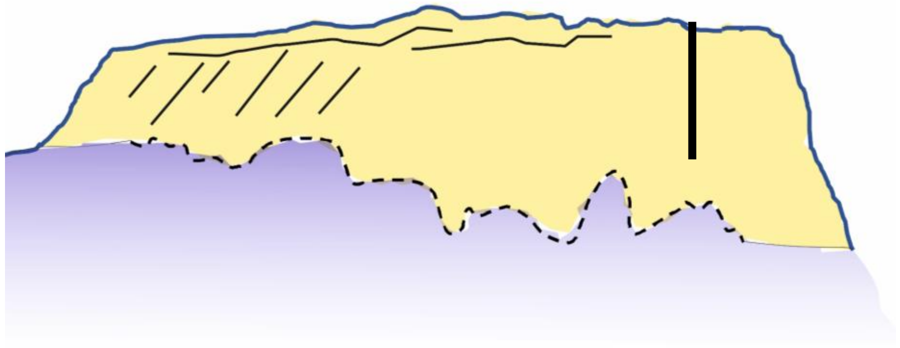
GPR

- Problems with imaging saturated sediments = underestimated thickness
- Good image of internal sedimentary structures
- Can show shallow bedrock topography in detail but may lead to overinterpretation of other structures as bedrock
- ~50% lower cross sectional area of sediments when compared to ERT/Gravity if interpretation is based solely on GPR
- Relatively quick acquisition



Gravity

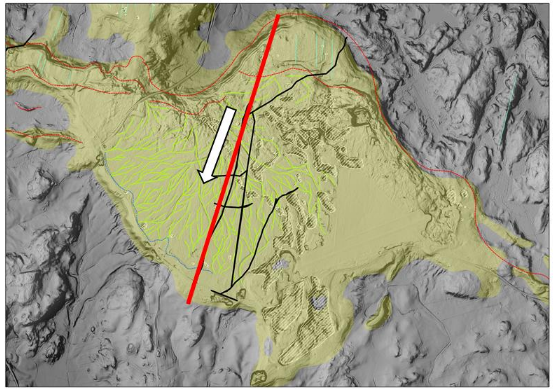
- Accuracy dependent on data density
- Results dependent on inversion parameters (density) and number of units/layers used for inversion – empirical data crucial!
- Resulting bedrock surface smoothed with respect to real bedrock topography.
- Cannot image internal structures of sediments

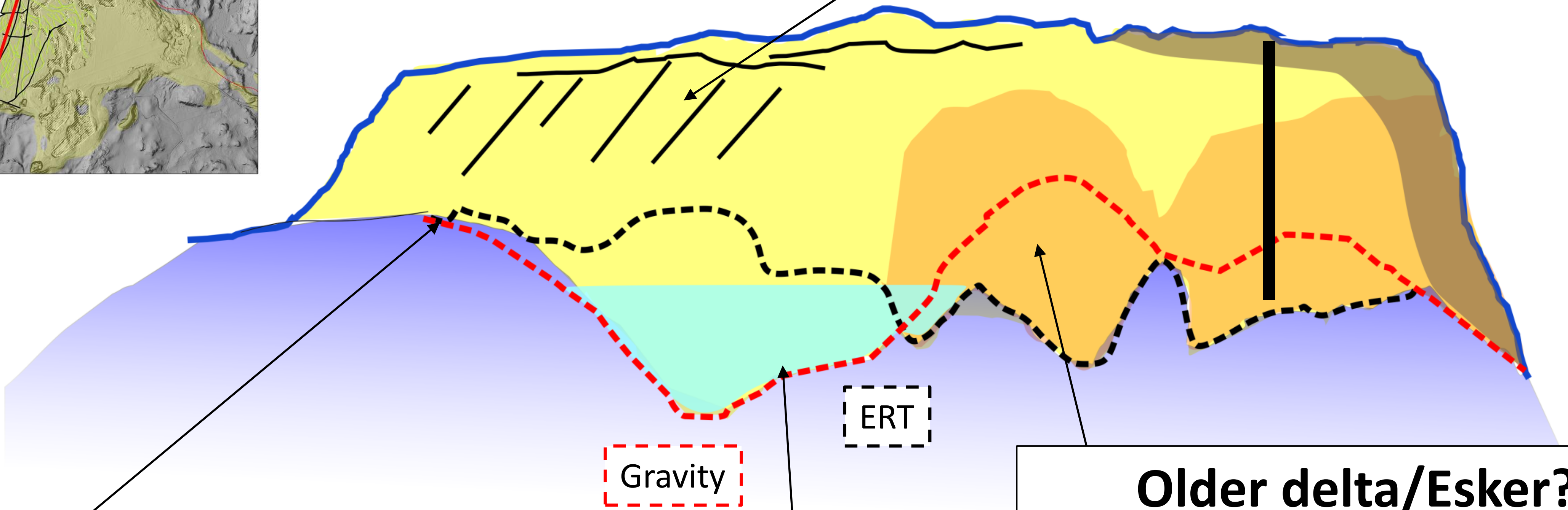


ERT

- Deeper penetration depth than GPR
- Time and effort consuming acquisition
- Can delineate saturated vs unsaturated zone
- No sedimentary structures can be imaged
- Similar cross sectional area to gravity but main thickness in different part of the delta
- Top of the aquifer rather than top of the bedrock imaged in the distal part of the delta due to extremely high contrast in resistivity
- Intermediate resistivity zone in the proximal part reinforces the interpretation of buried sedimentary body

Solution: use the best of all worlds





"Dry" sands and gravel

- Very high resistivity values
- Prograding foresets, topsets and detailed sedimentary structures visible in GPR
- GPR correlates with high resistivity zone from ERT
- Typical Gilbert-type delta
- Unsaturated zone

Bedrock

- ERT and Gravity match
- Sedimentation responding to bedrock topography (GPR)

Aquifer?

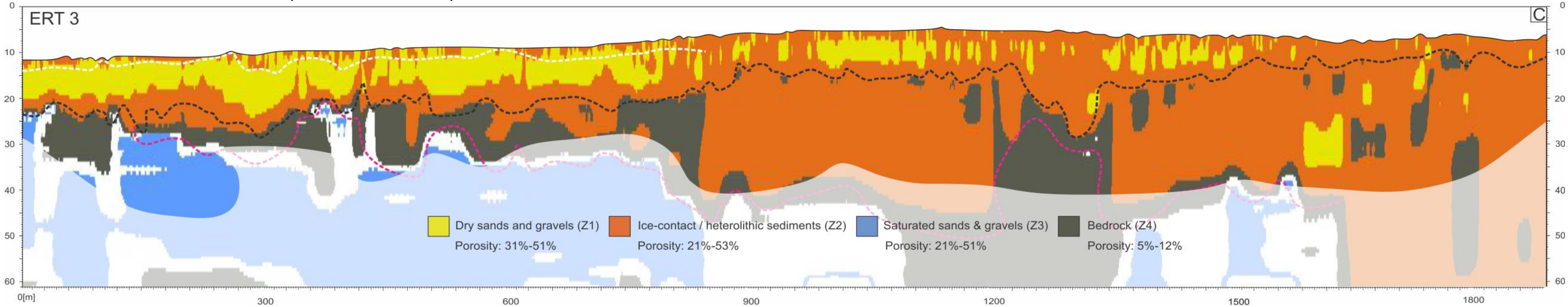
- Low resistivity
- ERT picking high contrast between saturated and unsaturated sediments
- Gravity below ERT

Older delta/Esker?

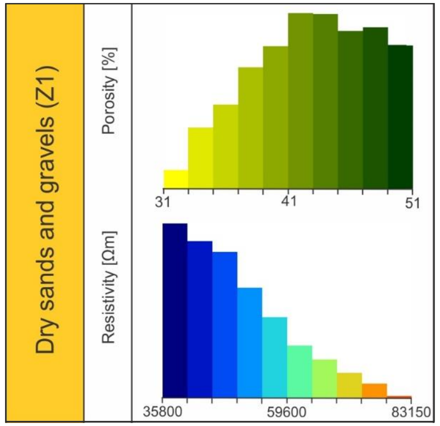
- "Intermediate" resistivity
- Gravity above ERT
- Sediments confirmed by drilling
- Only top of the structure visible at shallow level (GPR)
- Changes in sediment density not accounted for in gravity inversion (hence the mismatch)?

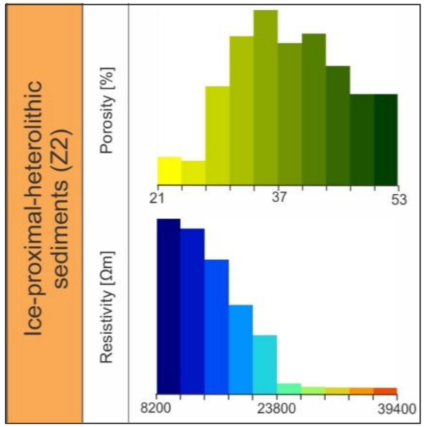
We can do more: porosity from resistivity

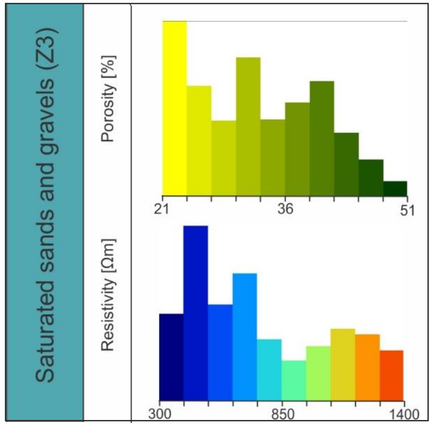
- After combining all the methods to achieve a consistent interpretation we recalculated the ERT section using Archie's equation to estimate porosities
- Four sets of input parameters used (1 set for each zone)
- Boundary condition 1: saturated and unsaturated sediments should have similar porosity = water saturation is the main reason for the difference in the ERT response
- Boundary condition 2: unsaturated sediments restricted to the high resistivity/GPR reflectivity zone
- Boundary condition 3: bedrock has low porosity and saturation close to 100%
- Non unique solutions: the same resistivity values can be achieved due to changes in porosity, water saturation and cementation factor – results need to be cross checked with GPR to best represent sedimentary structures

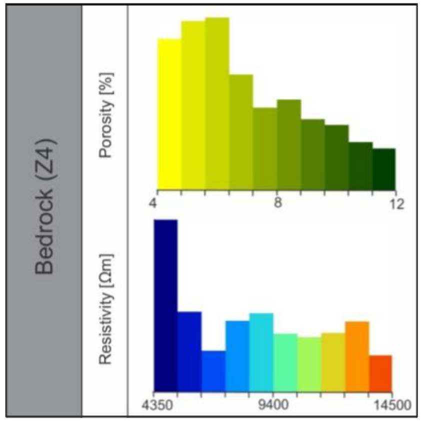


Results:









Conclusions

- Ice contact deltas often have complex depositional histories affected by abrupt changes of ice margin position and sediment input points
- As a result, simple proximal-distal grainsize distribution model may not be sufficient when considering reservoir properties of ice-contact deltas
- Understanding the interplay between ice margin position, glacially-sculped bedrock topography and sediment distribution is crucial to evaluate reservoir performance
- Use of a single geophysical method may lead to inaccurate results
- Best results where min. 2 (preferably 3) geophysical methods are combined with sedimentological observations
- Both GPR and ERT methods are working at their very limits due to high contrast in electrical properties and thickness of the sediments of the deltas
- For future investigation, it would be beneficial to acquire at least one gravity profile along an accessible road so that colinear ERT and GPR profiles can be acquired. This will allow for combined ERT-gravity data inversion which should improve depth to basement estimation.
- ERT data can be used to establish large scale porosity distribution away from boreholes.
- GPR Reflections can be observed in sands and gravels with average water saturation < 20 % (max 45% if reflectivity contrasts are high)
- Bedrock reflection in GPR data is rarely clear. Bedrock highs can be inferred from the response/shape (onlap and draping) of delta sediments

Thank you!

Special thanks to Dr Jukka-Pekka Palmu, Rachel Oien, Mariusz Miskowicz, Markus Valkama and Aleksi Tuunainen!

Patton, H., Hubbard, A., Andreassen, K., Auriac, A., Whitehouse, P.L., Stroeven, A.P., Shackleton, C., Winsborrow, M., Heyman, J., Hall, A.M., 2017. Deglaciation of the Eurasian ice sheet complex. Quat. Sci. Rev. 169, 148–172. https://doi.org/10.1016/J.QUASCIREV.2017.05.019

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