

Quick clays – hydrogeological considerations

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Main points

- Salinity decrease
- Groundwater gradients and flow
- Permeability contrasts and groundwater flow
- Effective stress development during heavy rain and snowmelt
- Homogeneity/heterogeneity of clay sediments?
Weak layers
- Groundwater importance during slow QC formation versus critical factor during slide initiation and development

Reduction of pore water salinity



Quick clay formation

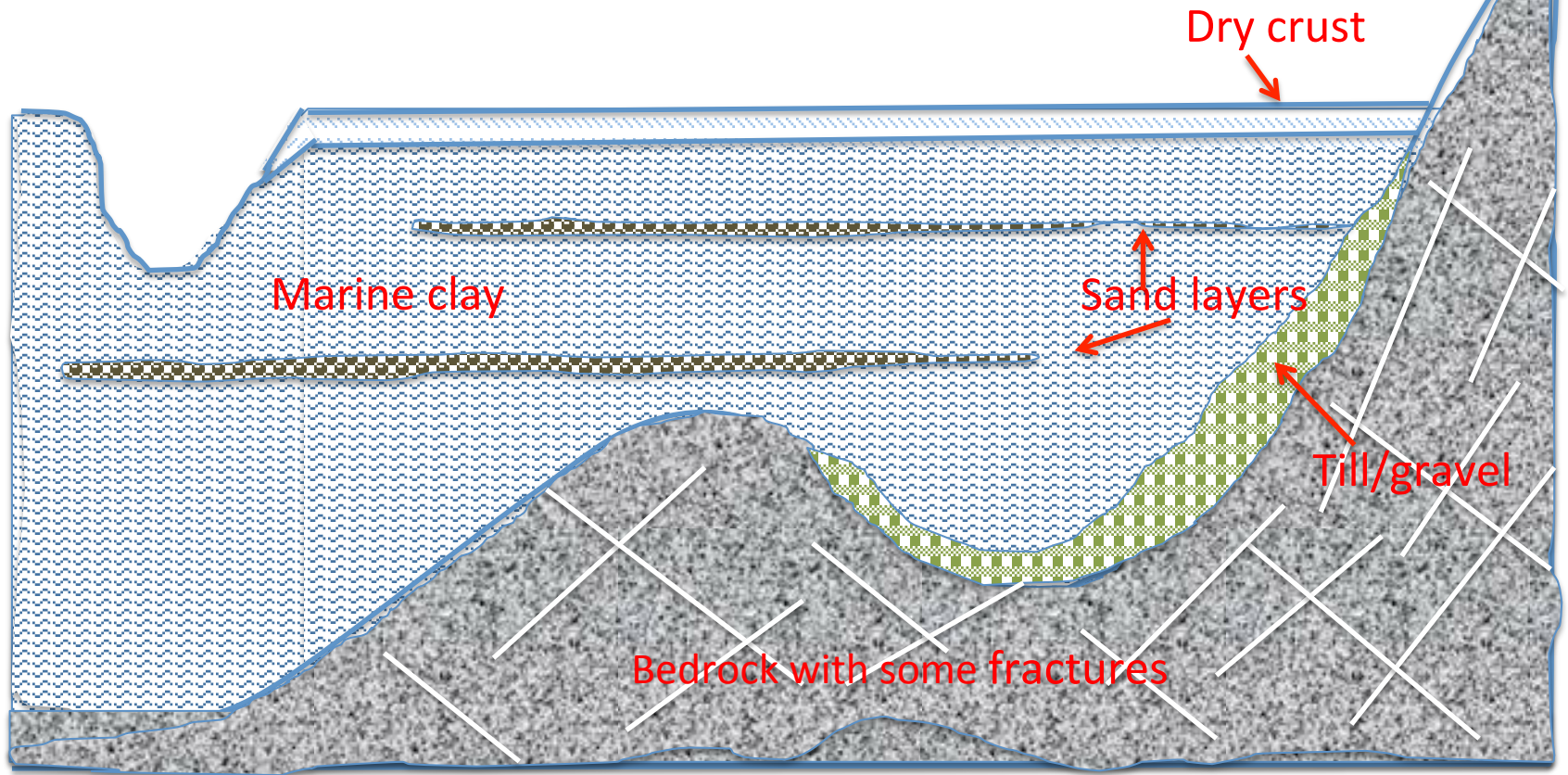
Rosenqvist (1946)

“....Etter leiravsettingens dannelse er saltinnholdet i leirgelene blitt sterkt nedsatt ved at saltes joner er difundert ut i det øvrige grunnvann i sand og gruslag. Dette kan skje ikke bare der hvor leiravsetningene heves over havnivå, men også i landnære undersjøiske sedimenter, idet det ferske grunnvann under og i en leiravsetting ikke vil bli oppblandet med havvannet selv forholdsvis langt fra land”

Requires

Combination of diffusive and advective transport

Compositional structure of glaciomarine basin infill



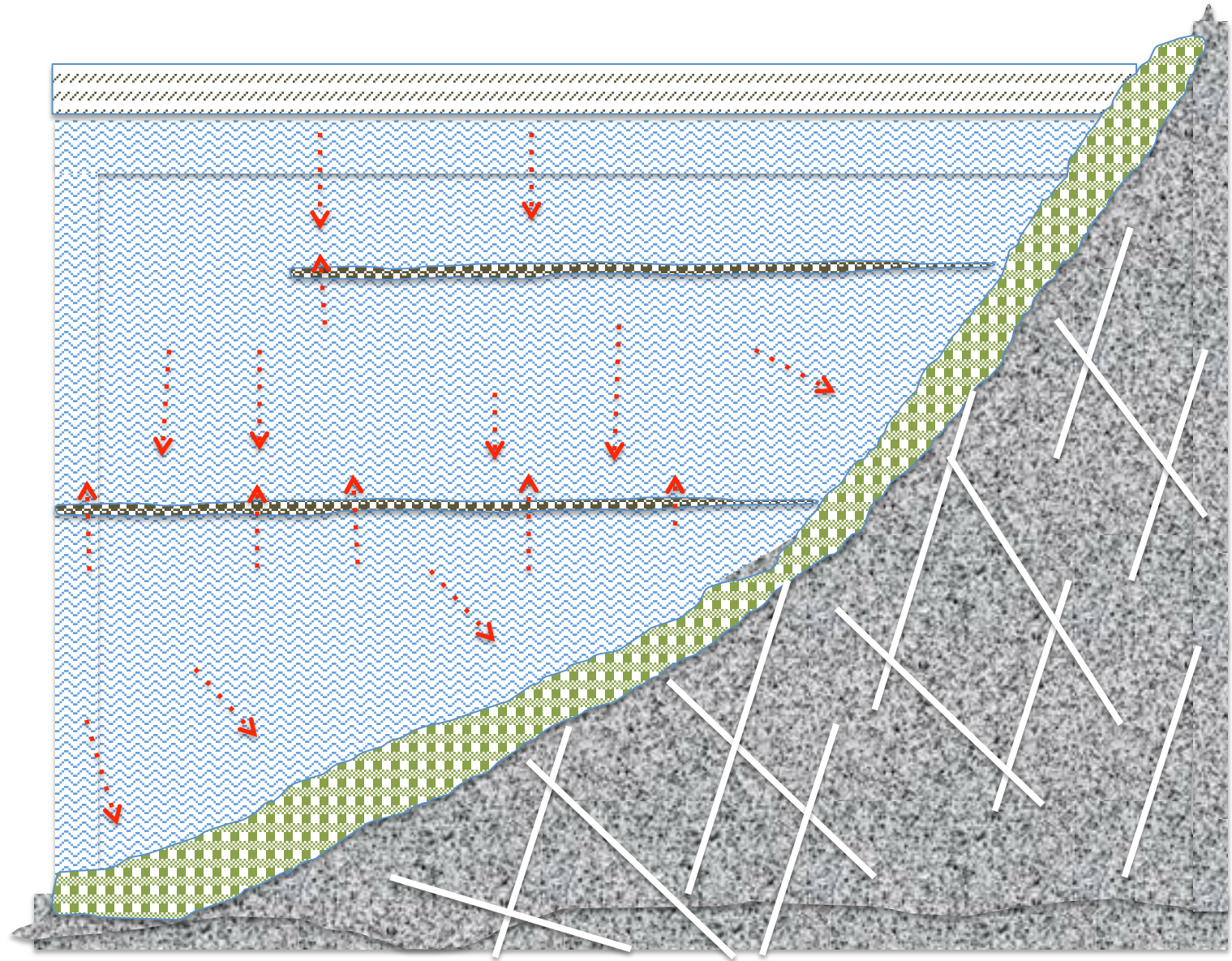
Clays with very low hydraulic conductivity ($10^{-9} - 10^{-12}$) m/s

Sand layers/coarser regions of basin infill ($10^{-2} - 10^{-6}$) m/s

Till/gravel layers on top of bedrock ($10^{-6} - 10^{-11}$) m/s / ($10^{-3} - 10^{-1}$) m/s

Underlying bedrock with a fractures network ($10^{-8} - 10^{-9}$) m/s

Salt diffusion towards regions of fresh groundwater



Constraints on salt leaching from marine clays:

- The very low hydraulic conductivity of clays means that the main ion transport out of the bulk clay is by diffusion.
- For diffusion to be effective and last, concentration gradients have to be maintained.
- This requires more permeable regions where the salt can be steadily removed by freshwater groundwater flow.
- The combined salt transport by diffusion and groundwater flow is a slow process, and may take thousands of years.

Some hydrodynamic characteristics of regions covered by marine clays.

- The large differences in hydraulic conductivity for clays and adjoining material (sand layers, till, gravel and even fractured bedrock) constrain the whole hydrodynamic system
- Can be illustrated by a few examples:
 - Artesian conditions/upward gradients in Champlain Sea clays, Eastern Canada
 - Landslides along fjords with Reisafjorden as example
 - Weak layers?

The Champlain clays in Eastern Canada (Lefebvre, 2017)

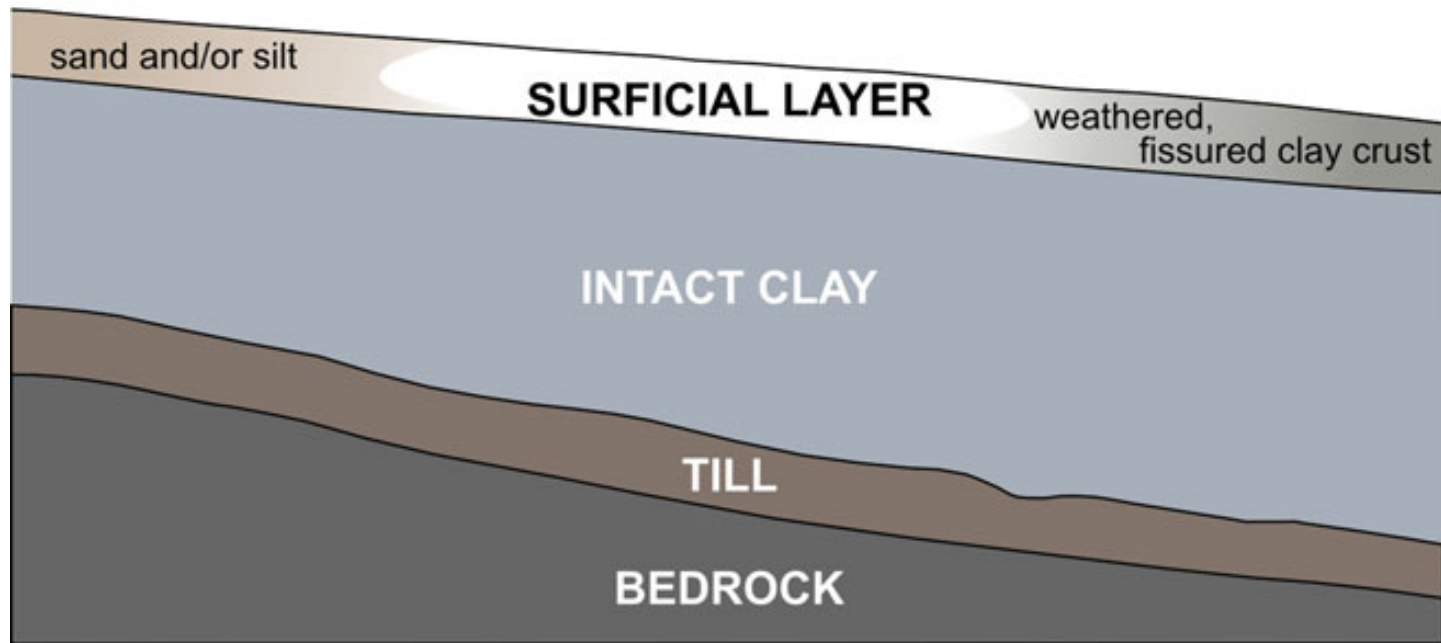
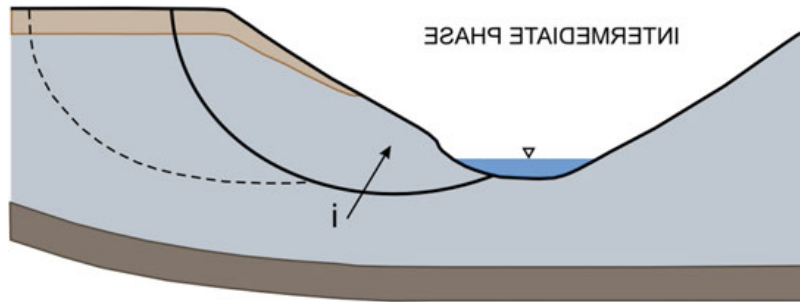


Fig. 2.2 Simplified stratigraphy of a typical marine clay deposit of Eastern Canada

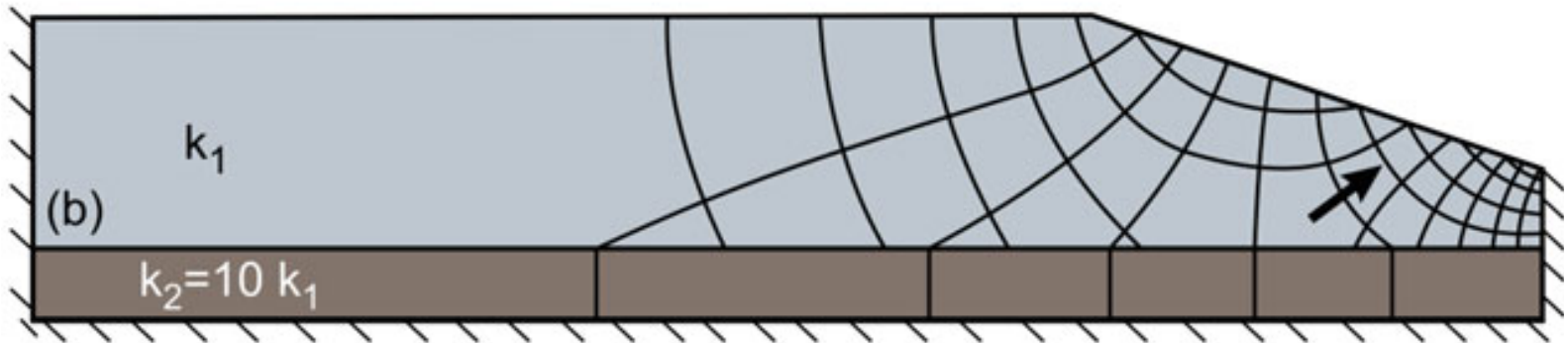
General stratigraphy of the Champlain sea basin in Eastern Canada.

The Champlain clays in Eastern Canada (Lefebvre, 2017),



Case at Intermediate stage
of river valley formation

Modeling



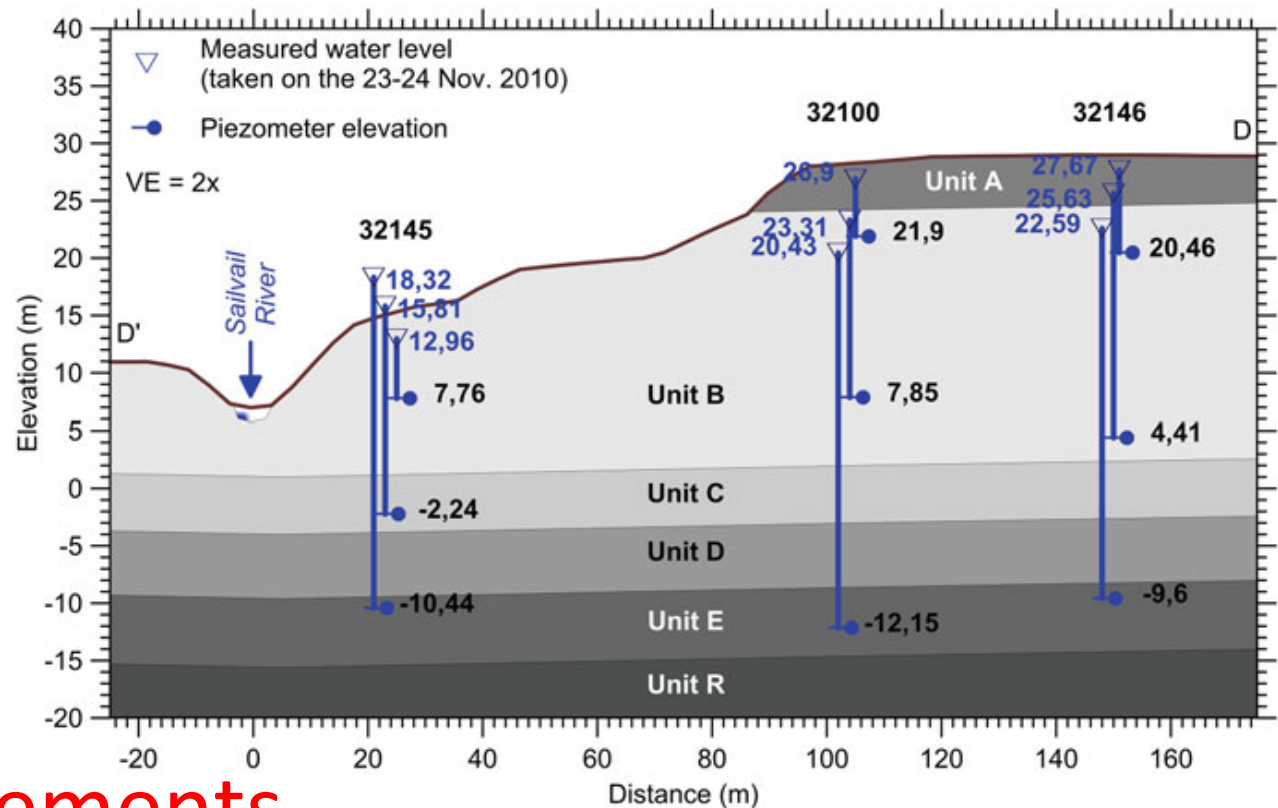
Lefebvre (2017) discussed the hydrodynamics of river valleys in the Champlain clays, by performing static hydrogeological modeling where the **till had 10 times higher permeability than the bulk clay**. He found that even with such a small conductivity contrast between clays and underlying till, one was able **to cause artesian conditions and upward hydraulic gradient**.

Saint-Jude landslide, Québec, Canada (Locat et al 2012)

Unit B,C,D:
Marine clays
Unit E: Till
Unit R:
Bedrock basement

$$K_B \approx K_C \approx K_D = K_{\text{clay}}$$

$$K_E \approx 1000 K_{\text{clay}}$$



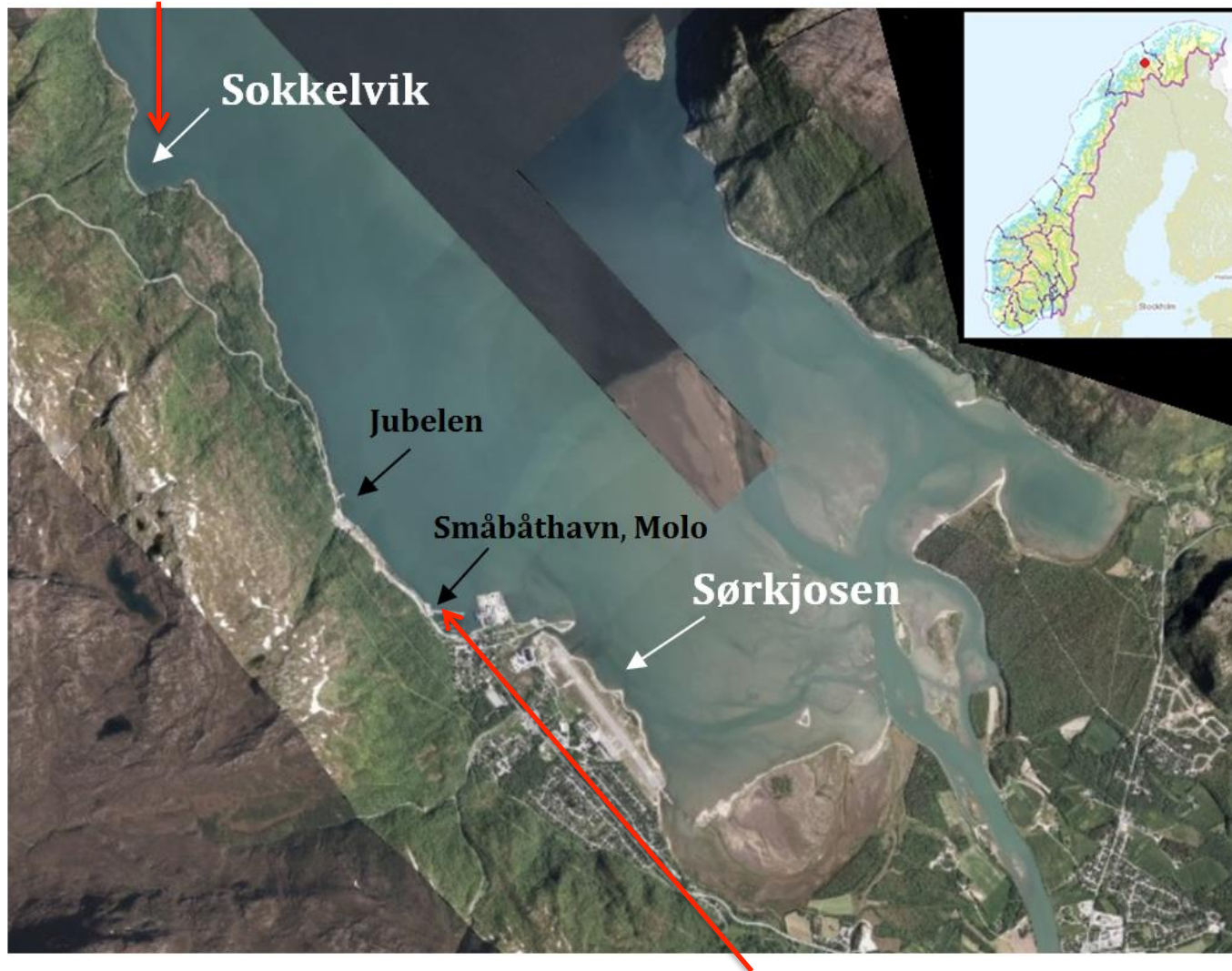
Field measurements

Fig. 2.6 Example of ground water regime for a slope in a valley at intermediate stage (Locat et al. 2012b)

Hydraulic head measurements demonstrated artesian conditions and upward gradient in the river slope at Saint-Jude

Nearshore landslides along Reisafjorden

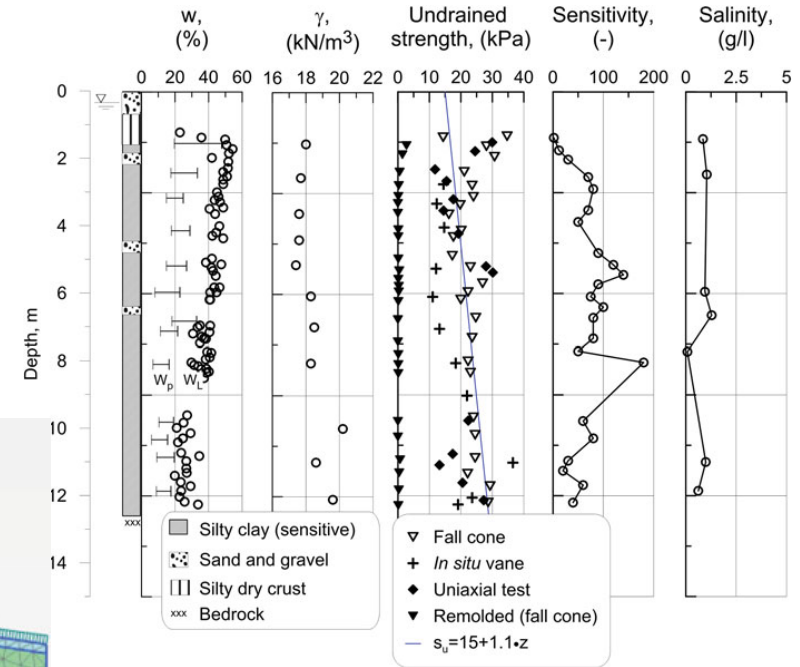
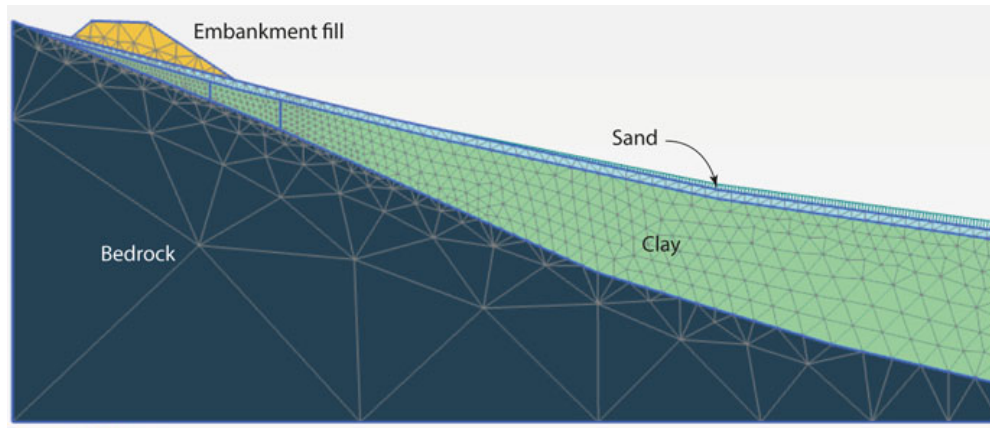
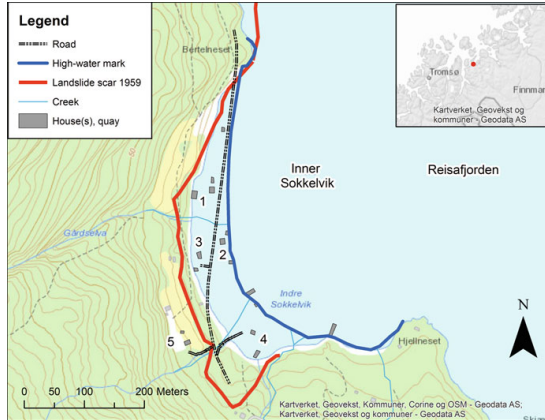
Sokkelvik slide (May 7th 1959)



Sørkjosen slide (May 10th 2015)

Sokkelvik slide (May 7th 1959)

9
deaths



35.3 Geotechnical borehole from Ytre Sokkelvik (Modified from NGI 1960)

“It is concluded that the Sokkelvik landslide compares well to many other cases of nearshore landslides triggered by **a combination human activities and intense rainfall events**. ...It is therefore vital to assess the impact of extreme intense rainfall events, snow melt and regional groundwater flow when planning construction work in nearshore areas”.

Jean-Sébastien L’Heureux, Steinar Nordal, and Synnøve W. Austefjord (2017)

Sokkelvik slide (May 7th 1959)

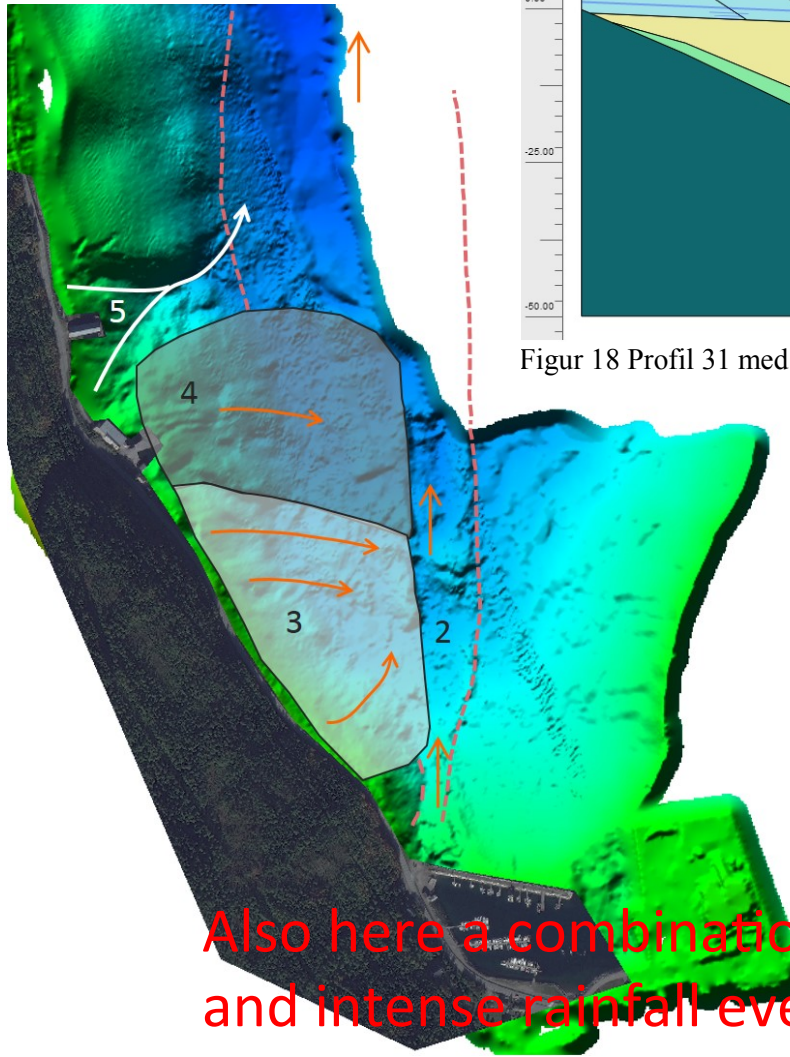
It resulted in nine casualties, in the destruction of many farms and offshore structures, and in the initiation of a tsunami wave.

NGI employes visited the site and carried out geological and geotechnical field work as soon as they could, and gave recommendation to secure the area.

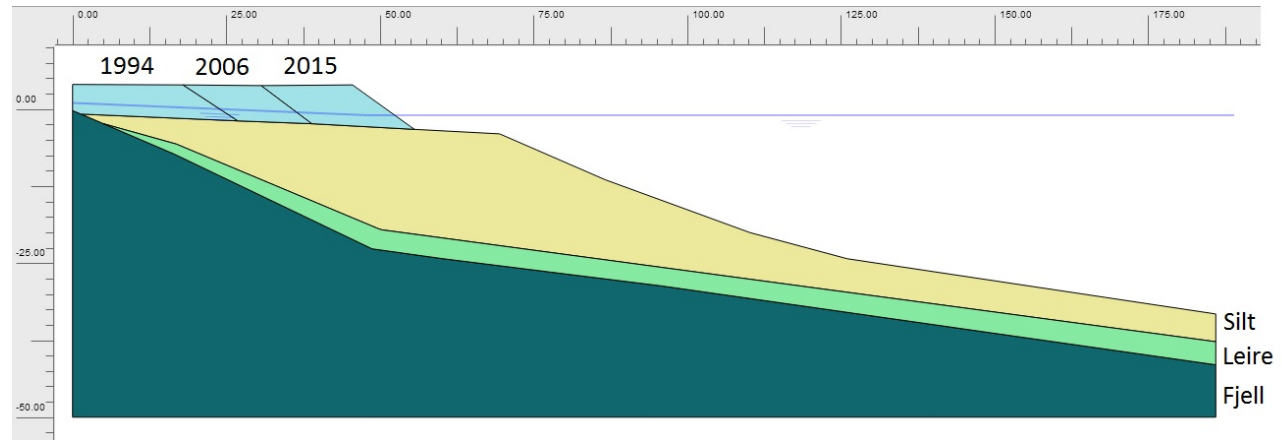
Jørstad came 2 days after the slide, so his report is important. He reported that a fishing net had moved about 3.5 km away, making the slide run-out distance more than 5 km

Rosenqvist also visited Sokkelvik one month later.

Sørkjosen (May 10th 2015)



Also here a combination of human activities and intense rainfall events.



Figur 18 Profil 31 med last og lagdeling for situasjonen i 1994, 2006 og 2015.



Precipitation and snow melts – triggering event?

- Groundwater response?
- Increased load of upper water water saturated material?
- Is there communication and a rapid increase in pore pressures in
 - => coarser layers in the clay?
 - => Fracture network in bedrock?

Sokkelvik 1959 (Nordal 2016):

“Undersøkelsesgruppa konkluderer med at den utløsende årsak til skredet i Sokkelvik den 7. mai 1959 sannsynligvis var ekstrem nedbør kombinert med snøsmelting. Dette kan ha vært nok til å øke poretrykket i de grove massene i strandsonen og i grovere lag i leira slik at stabiliteten ble ytterligere redusert og skredet utløst.”

Homogeneity/heterogeneity of clay sediments?

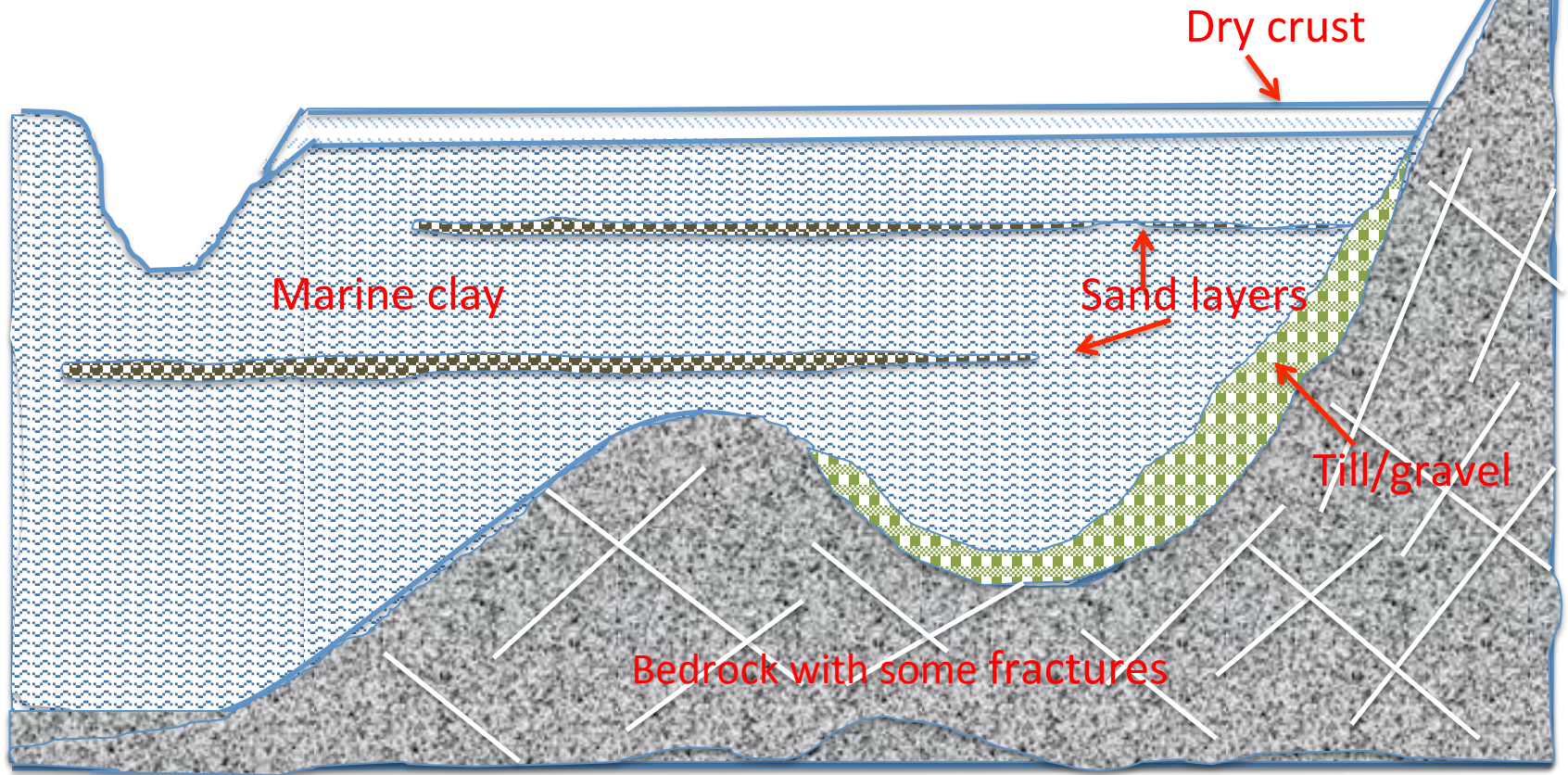
Weak layers?

- Clays are never homogeneous
- They may have coarser layers corresponding to a.o. to slides/release of unstable sediments on delta front or delta slope?
- The material could both be sand or re-sedimented clays with different structure:
- Weak layer term (Gatter et al (2021), Locat et al (2014), L'Heureux et al (2012))

Effects:

- Coarser layer will have higher hydraulic conductivity
- Clay layers more unstable structure?
- Will act as a gliding plane

Potential permeability contrasts



Clays with very low hydraulic conductivity ($10^{-9} - 10^{-12}$) m/s

Sand layers/coarser regions of basin infill ($10^{-2} - 10^{-6}$) m/s

Till/gravel layers on top of bedrock ($10^{-6} - 10^{-11}$) m/s / ($10^{-3} - 10^{-1}$) m/s

Underlying bedrock with a fractures network ($10^{-8} - 10^{-9}$) m/s

Permeability/ hydraulic conductivity

(Freeze & Cherry, 1979)

Material	Permeability m ²		Hydraulic conductivity m/s	
Gravel	10^{-7}	10^{-10}	1	10^{-3}
Sand	10^{-9}	10^{-13}	10^{-2}	10^{-6}
Silty sand	10^{-10}	10^{-14}	10^{-3}	10^{-7}
Silt/loess	10^{-12}	10^{-16}	10^{-5}	10^{-9}
Till	10^{-13}	10^{-19}	10^{-6}	10^{-12}
Clay	10^{-16}	10^{-19}	10^{-9}	10^{-12}
Schist	10^{-16}	10^{-20}	10^{-9}	10^{-13}
Metamorphites/plutonite (unfractured)	10^{-17}	10^{-20}	10^{-10}	10^{-13}
Metamorphites/plutonite (fractured)	10^{-11}	10^{-15}	10^{-4}	10^{-8}

Tor Løken proposed in 1983 how bedrock topography could lead to localized formation of quick clays.

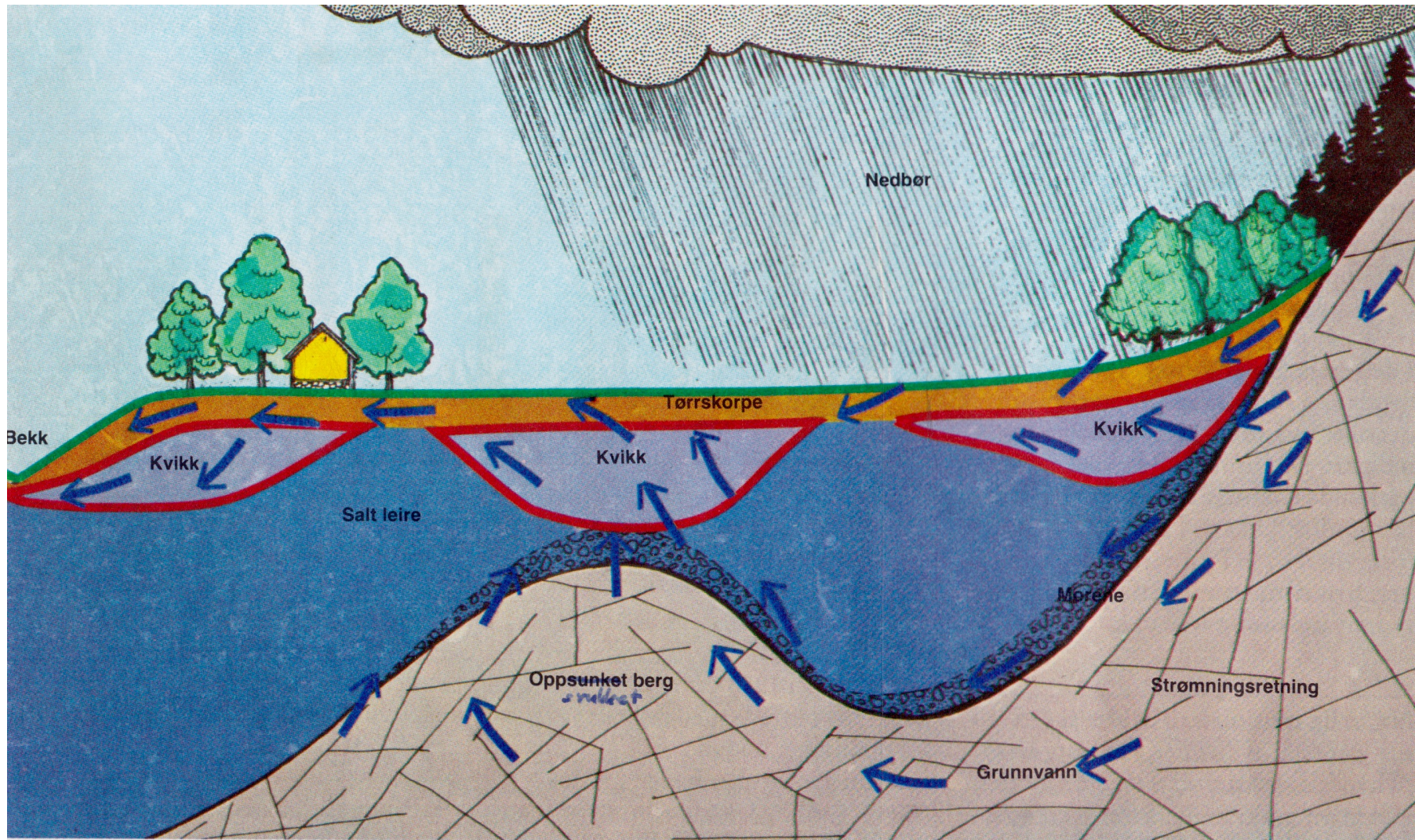
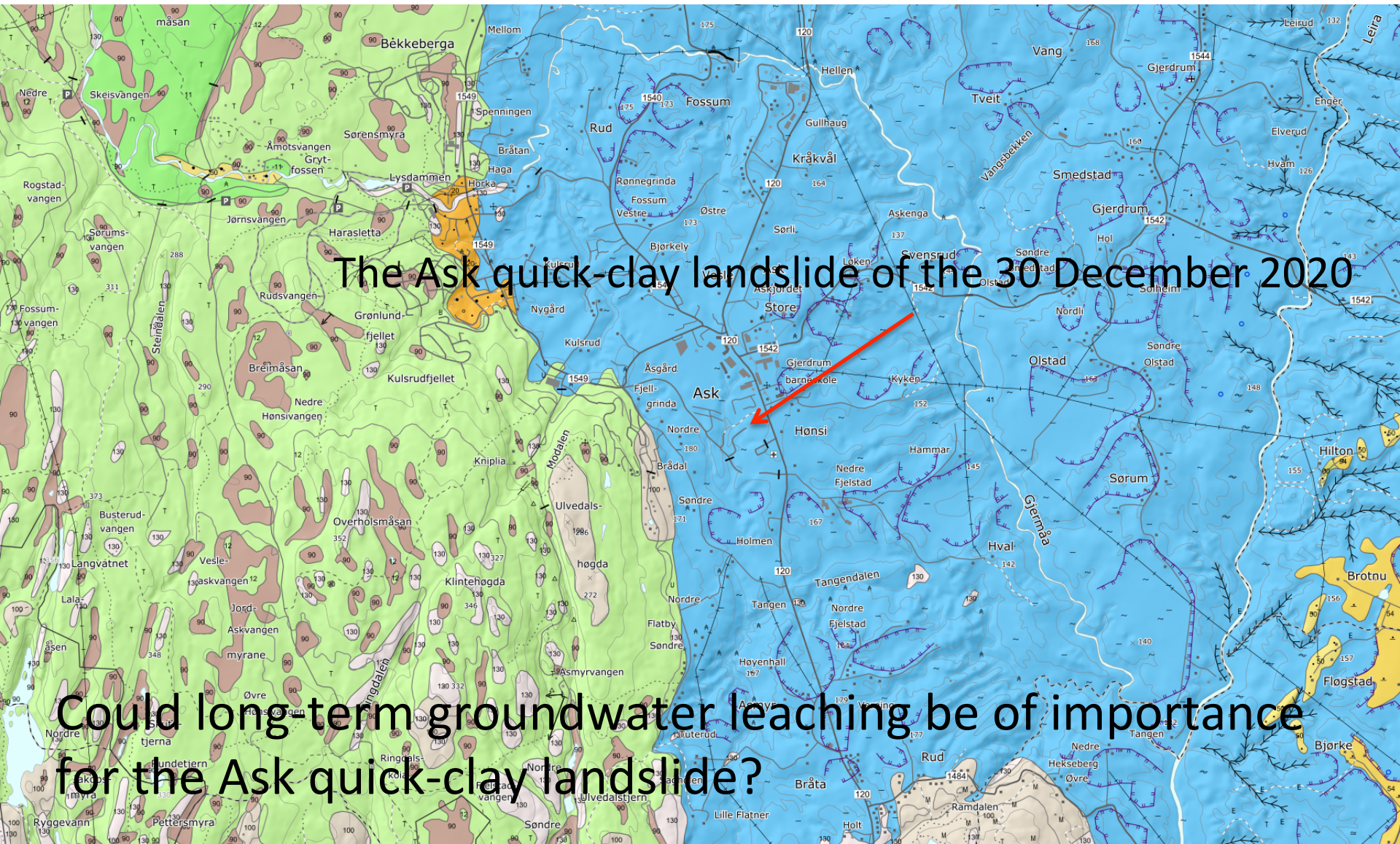


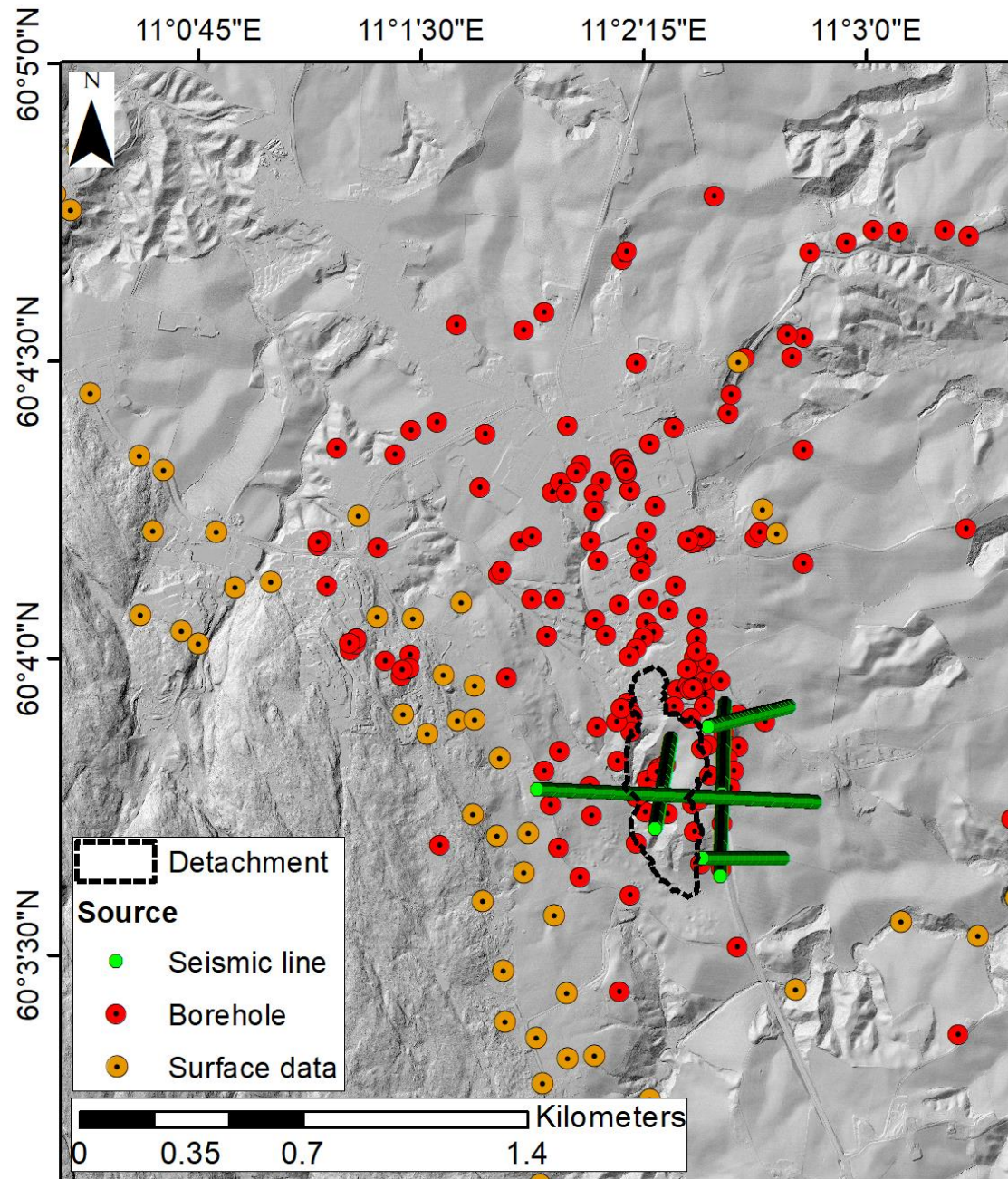
Fig. 2. Prinsippskisse som viser utvasking og kvikkleiredannelse.

Quaternary deposits in the Romerike area



Data base Bedrock topography

NGU Report
2021.023



Sediment thickness and depth to bedrock

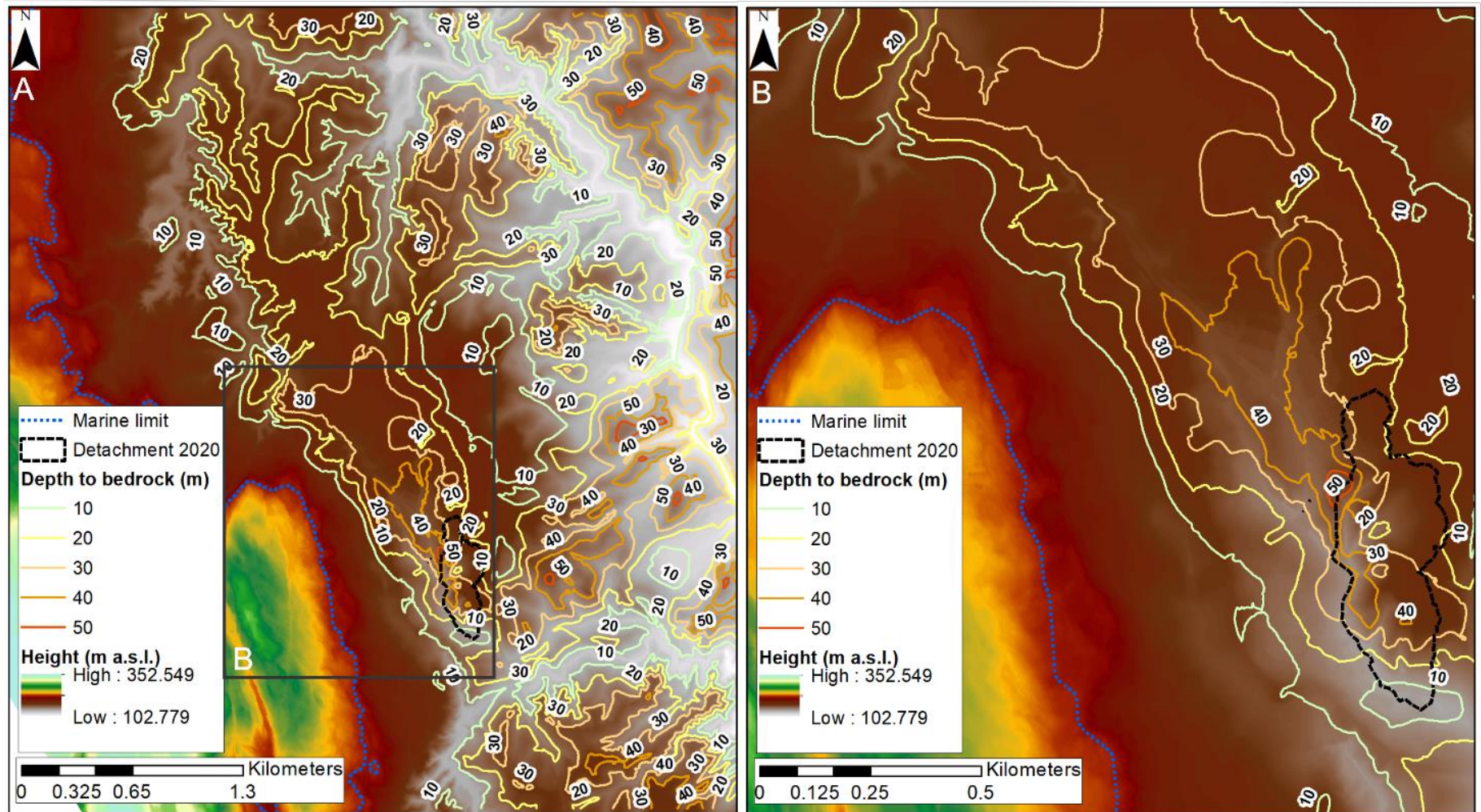


Figure 40. (A) Isopach map showing the contour lines of depth to bedrock (sediment thicknesses). (B) Isopach map with the contour lines corresponding to depth to bedrock in the area of the 2020 landslide.

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The Tømte Symposium October 24st 2022

Sediment thickness and depth to bedrock

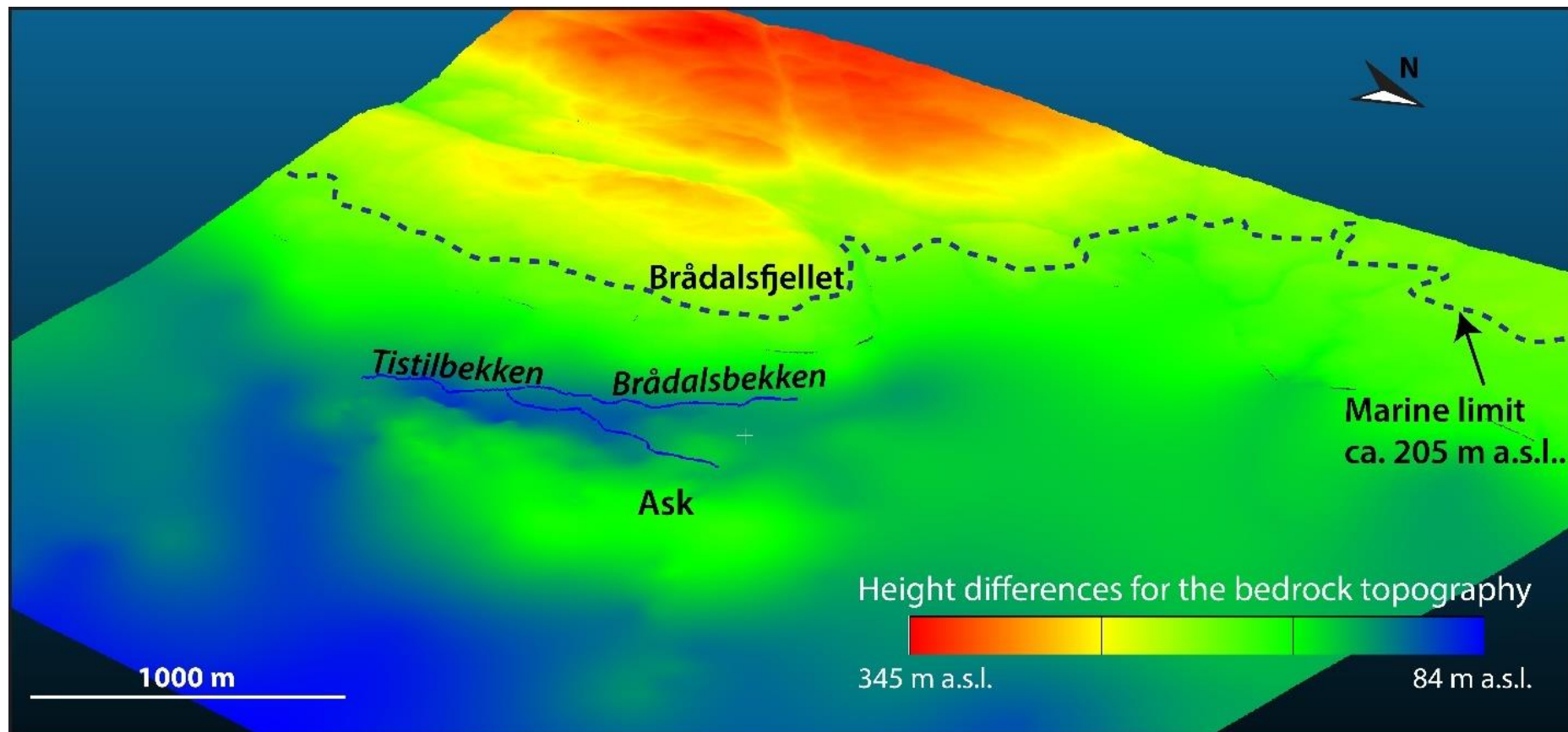


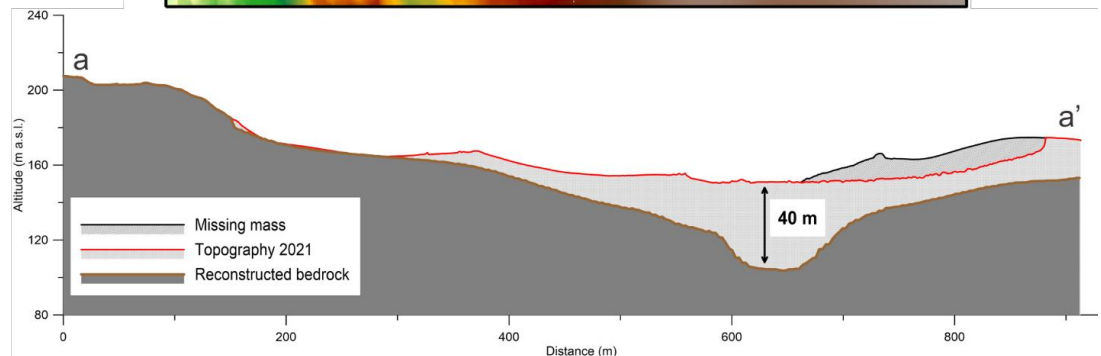
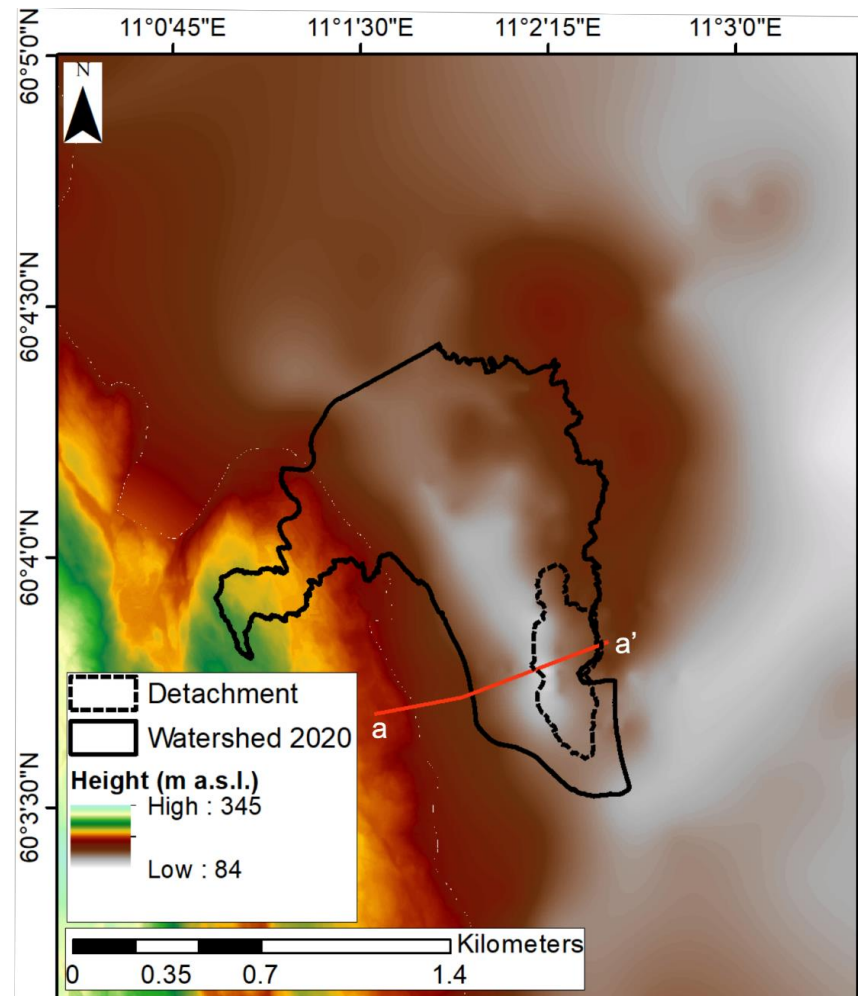
Figure 41. The Cloud Compare model of the bedrock topography. Areas below the Marine limit are covered by marine sediments.

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Cross section at Ask

“Below Ask centre
there is a north-south
lying ridge”

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Final points

- Groundwater flow combined with diffusion is needed to form quick clay
- Even small permeability contrast may be essential for long term leaching.
- Heavy rain and snowmelt may infiltrate rather fast leading to increased pore pressure and reduced stability, being critical for slide initiation.