



Geostatistical estimation of bedrock topography as a tool for risk assessment of sensitive clays?

The Tømte Symposium October 24th 2022

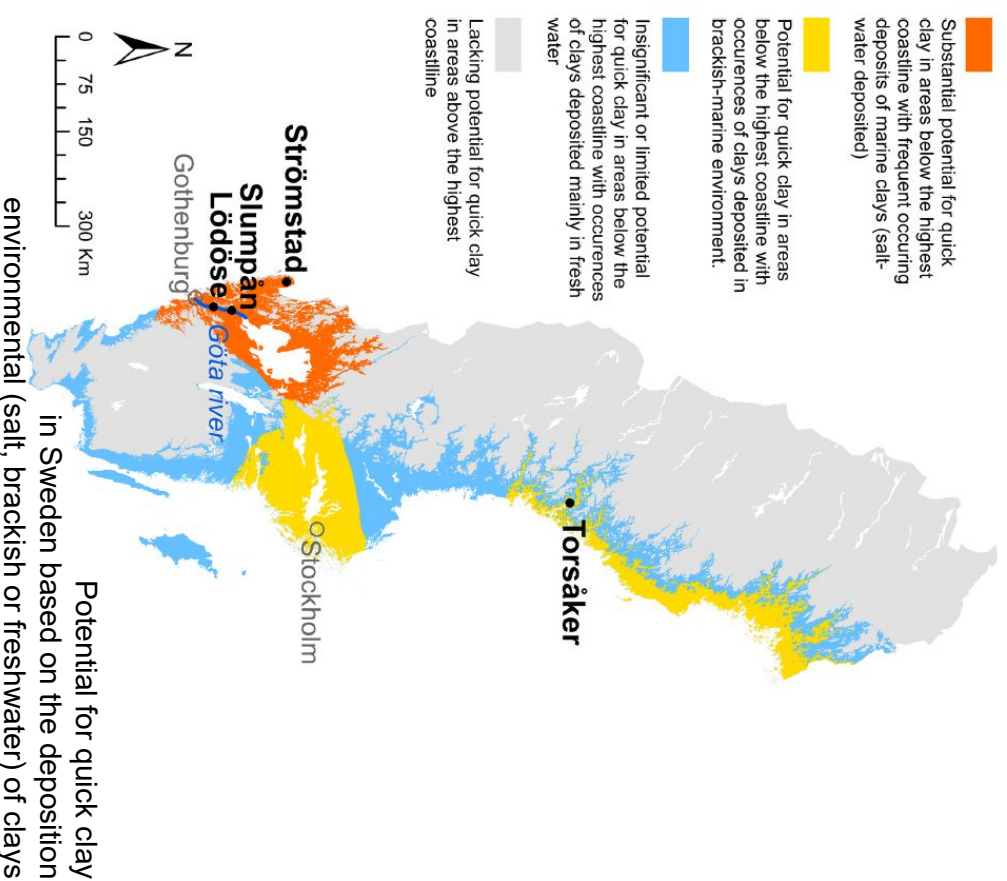
Quick clays – geological constraints and occurrences - Rosenqvist tribute

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Geo-hydrological constraints for developing sensitive clay and risk for quick clay landslides

1. Depositional environment
 - Marine/brackish/freshwater.
2. Water transport and dilution processes
 - Advection/diffusion.
3. Landslide risk.
 - Temperature and precipitation,
 - Change in land use.
 - Surface topography.
 - Bedrock topography.

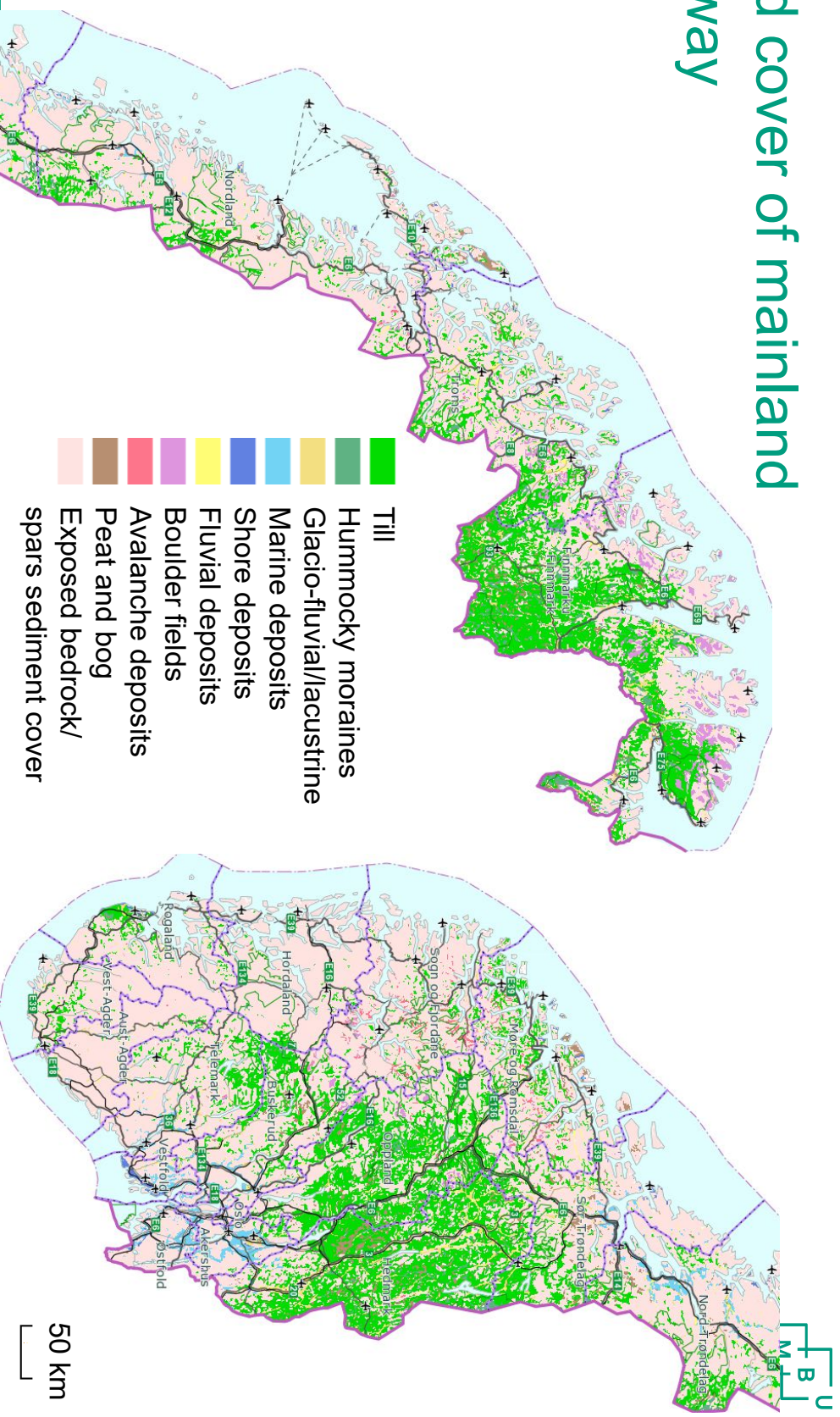


Source: With, C, Löfroth, H., Bastani, M., Persson, L., Rodhe, L., Hedfors, J., Schoning, K., 2022: A methodology for mapping of quick clay in Sweden. <https://doi.org/10.1007/s11069-022-05278-y>

Bedrock topography?

- Can estimates of bedrock topography and sediment thickness be used to **filter out potential depositional areas** with likely sedimentological conditions for development of sensitive clay?
- Can bedrock topography be associated with **focusing effects of waterflow** which is critical for transport of salt out of the clay?
- Can bedrock topography together with land surface gradients terrain be used to **screen out potential risk areas** for quick clay landslides?

Land cover of mainland Norway



geo.ngu.no/kart/losmasse/

Land cover of mainland Norway

(km ²)	Land cover	(%)
97 000	Exposed bedrock	31.59
80 719	Till material, patchy or thin cover over bedrock	26.28
65 008	Till material, continuous cover, great thickness locally	21.17
17 000	Peat and swamps (organic material)	5.54
15 600	Weathered deposits, not divided by thickness	5.08
8 829	Fluvial sediments	2.87
7 600	Marine and coastal sediments, coherent, often great thickness	1.56
7 272	Avalanche materials and landslides	2.37
2 676	Marine, beach sediments, patchy or thin cover over bedrock	0.87
1 900	Till modified by running water (ablation moraine)	0.62
1 769	Glaciofluvial sediments	0.58
1 000	Ice-marginal deposits	0.33
350	Anthropogenic deposits, unspecified	0.11
253	Glaciolacustrine and lake sediments	0.082
100	Eolian (wind) sediments	0.033
28	Scree, clay slides, rockfalls, etc.	0.0091
307 104	Sum	100.00

} ~60% → $A(u)$

} ~6% → $X(u)$

$$E[X(u) \mid A(u)]$$



Goal:

Use point observations $x(u_i)$ to estimate bedrock topography $B(u)$ and sediment thickness $D(u)$ at any location of interest:

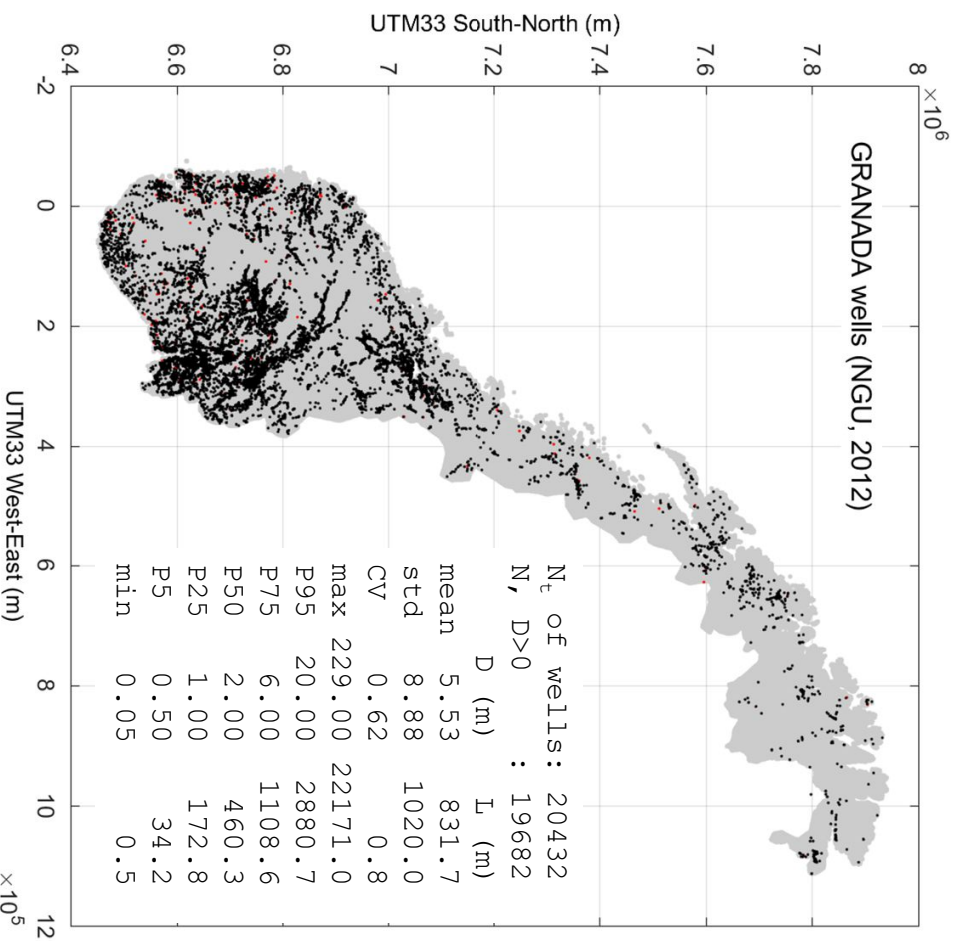
$$E[X(u) \mid x(u_i), A(u)],$$

and

$$\text{Var}[X(u) \mid x(u_i), A(u)],$$

where $i=1, \dots, N$,

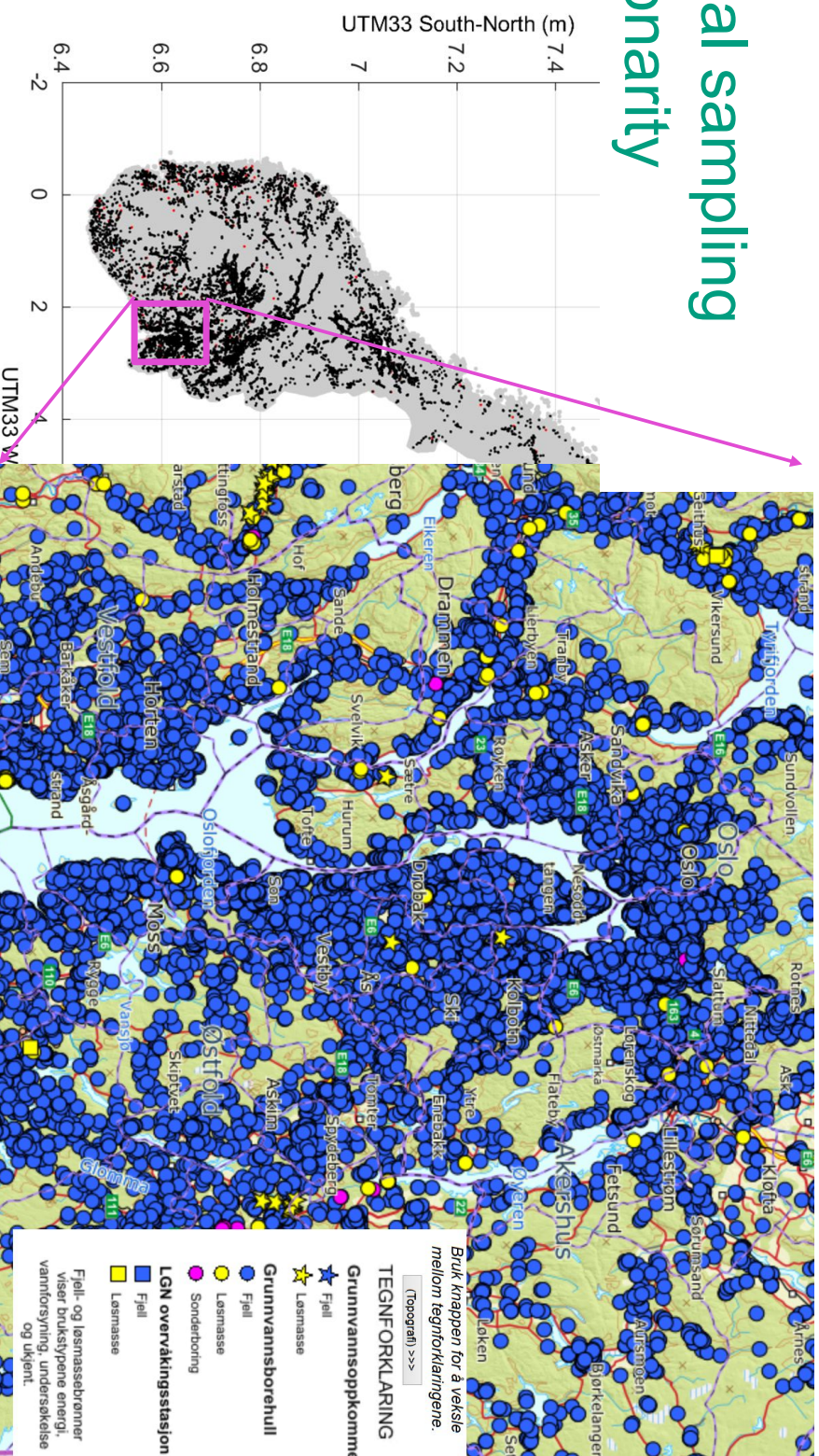
N is number of observations.



<http://geo.ngu.no/kart/granada/>

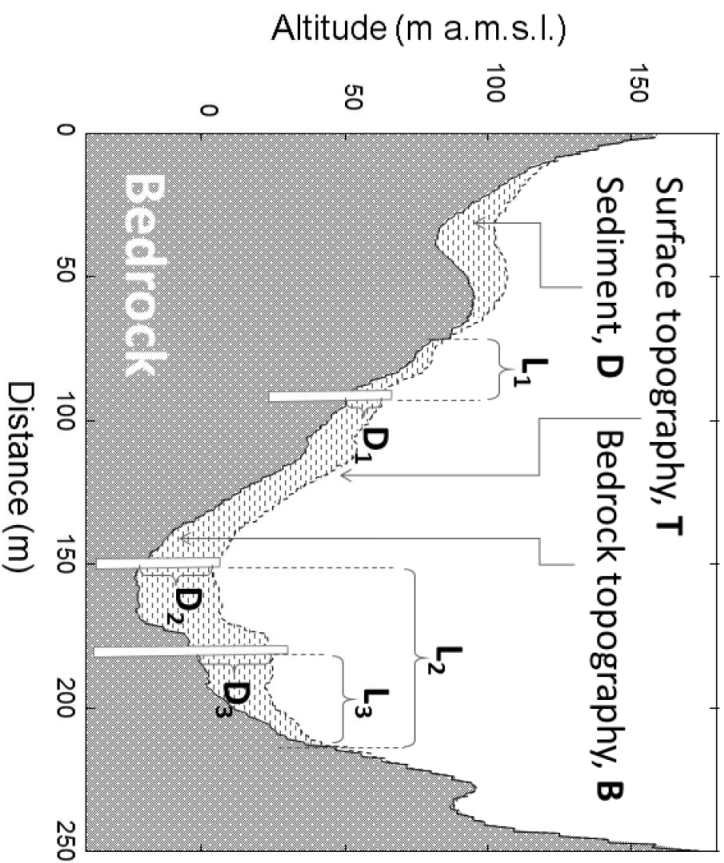
Estimation challenges:

- preferential sampling
- non-stationarity

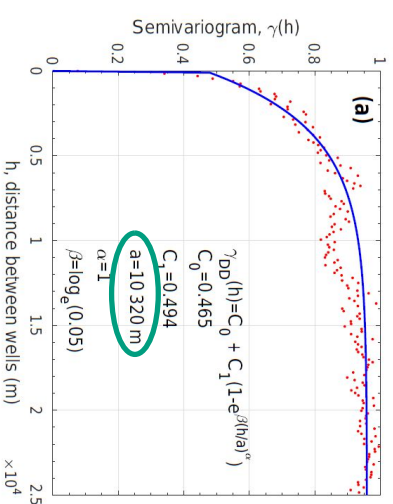




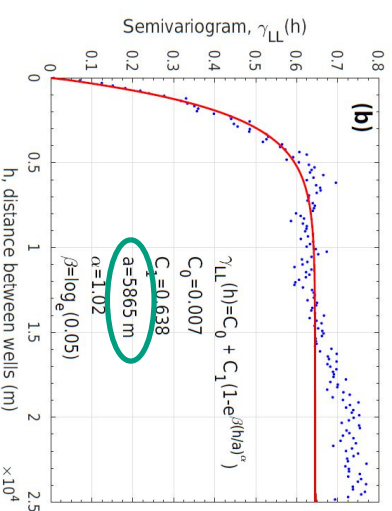
Idea:
Use $L(u)$, to reduce $\text{Var}[D(u)]$



Semi-variograms for D and L



Correlation length of
D is ~ 10 km



Correlation length of
L is ~ 6 km

Cross-validation on GRANADA observations

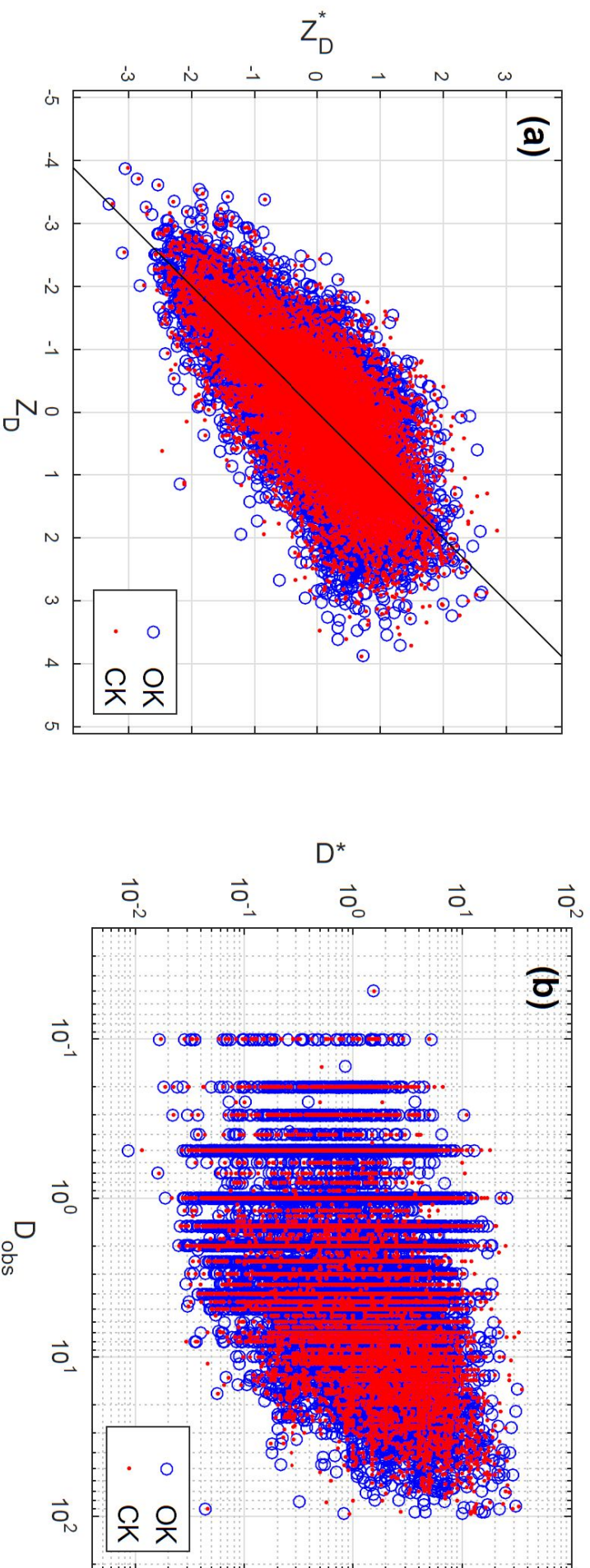


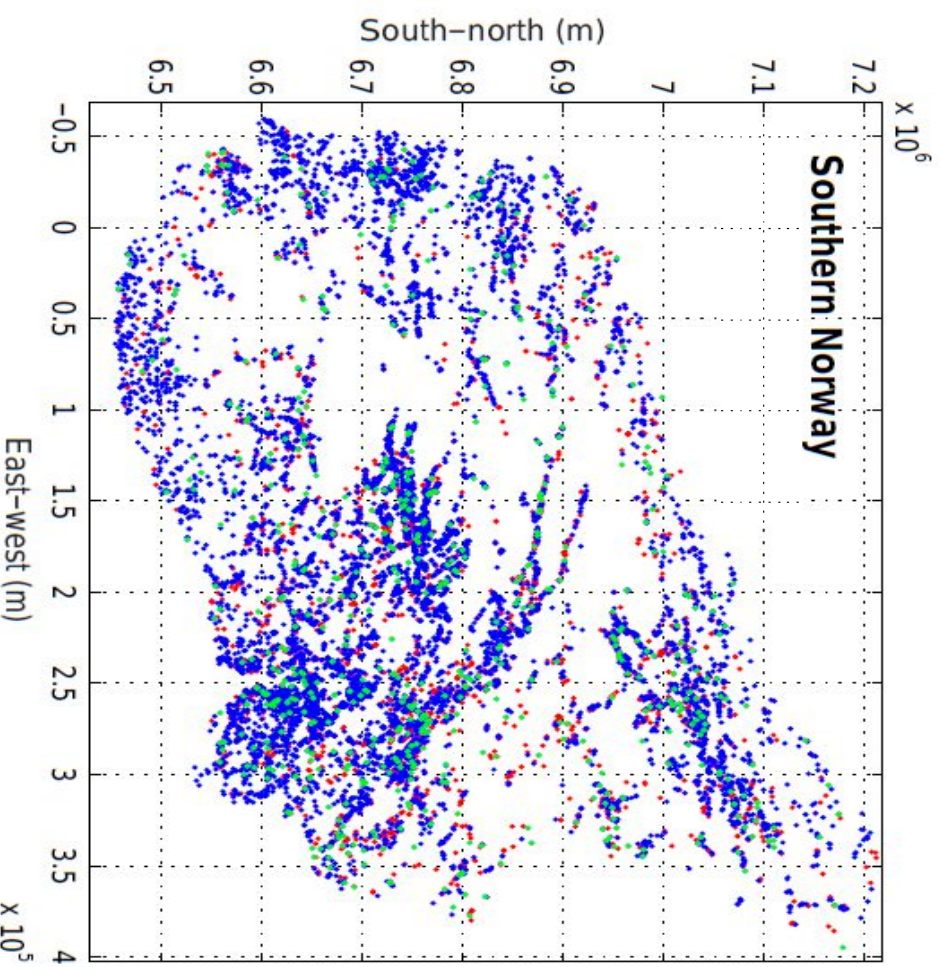
Figure 7. Cross-validation results of sediment thickness D . Normal score observations Z_D against estimates Z_D^* to the left **(a)**, and raw observations D and estimates D^* to the right **(b)**. OK denotes results from ordinary kriging, and CK from co-kriging.

Cross-validation of GRANADA observations

- **Blue: 63%** fulfilled the cross-validation test by either the Ordinary Kriging (OK) or Co-Kriging (CK).
- **Green: 3.5%** fulfilled the test by OK or CK.
- **Red: 37%** did not fulfill the test neither by OK nor OK.

Cross-validation test is defined by:

- Absolute mean error.
- Precision, and
- Accuracy.



Case study: Øvre Eiker, Drammensvassdraget.

Purpose:

Test algorithms to reduce estimation error.

What kind of mathematics?



Courtesy: Dan Hobely. Glacial valley at the head of Leh valley, Ladakh, NW India. Valley is immediately south of the pass of Khardung La. Leh valley glacier is visible at the top of the valley. Camera location: $34^{\circ} 16' 01.2''$ N, $77^{\circ} 37' 22.8''$ E, https://commons.wikimedia.org/wiki/File:U-shaped_valley_at_the_head_of_Leh_valley_Ladakh.JPG#file



Poisson's equation?

$$\nabla^2 f(x, y) = \Xi(x, y)$$

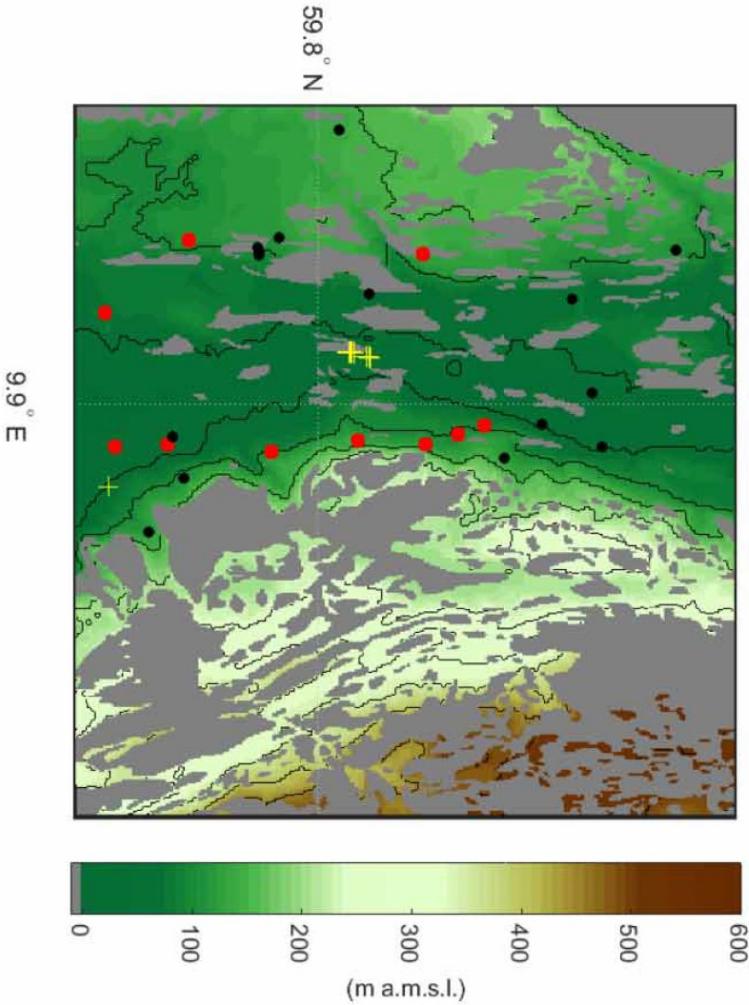
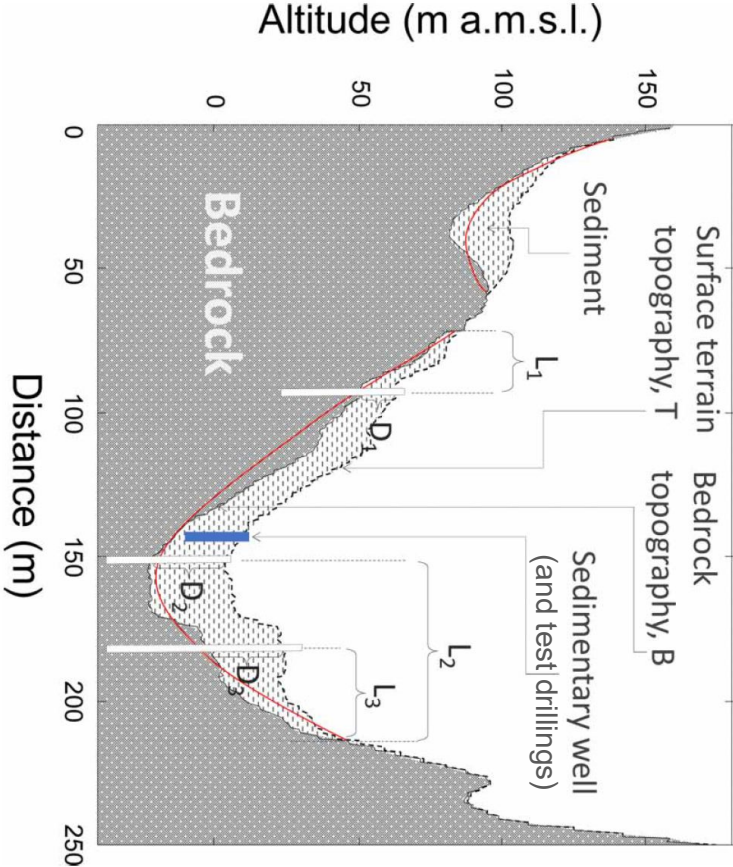
- Poisson's equation yields a parabolic function $[x, y]$ in modelling domain Ω :

$$f(x, y) = a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2.$$

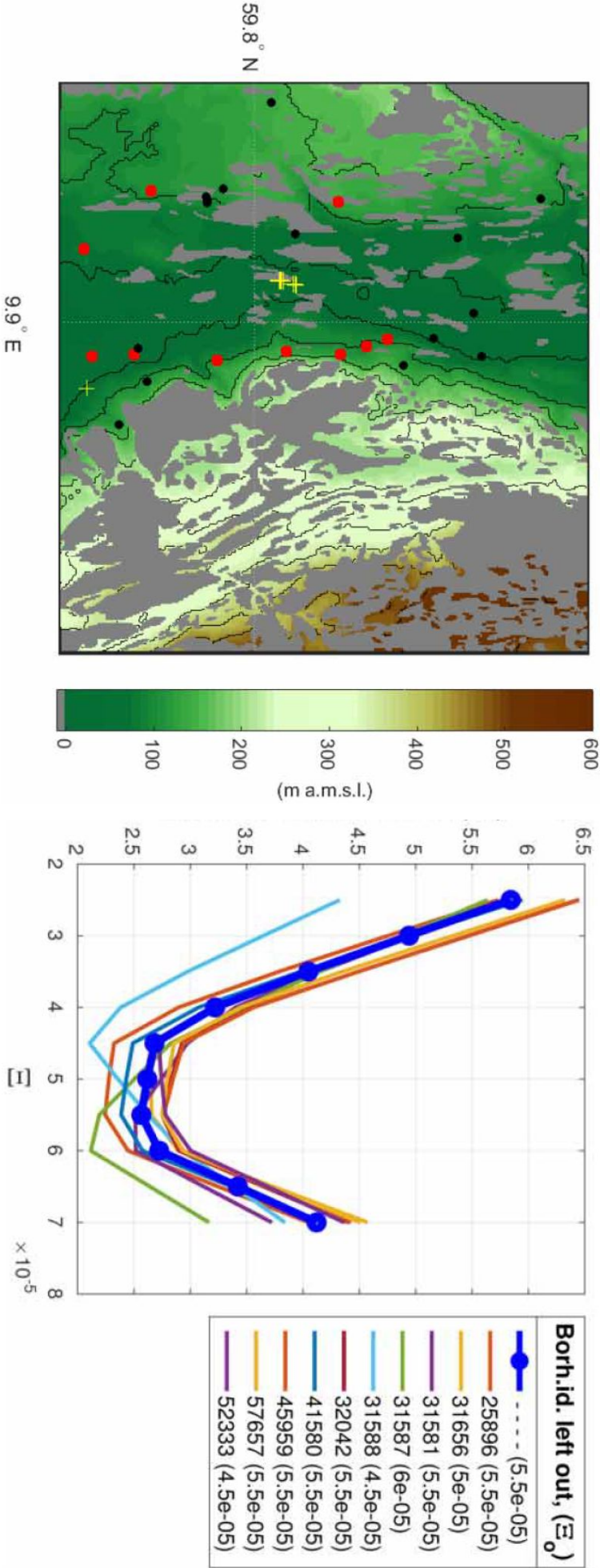
- Challenge: Poisson equation is sensitive to Dirichlet boundary conditions:

At bedrock outcrops (x_c, y_d) , $D(x_c, y_d) = 0$, or $B(x_c, y_d) = T(x_c, y_d)$.

Test: Poisson's equation + kriging on residuals

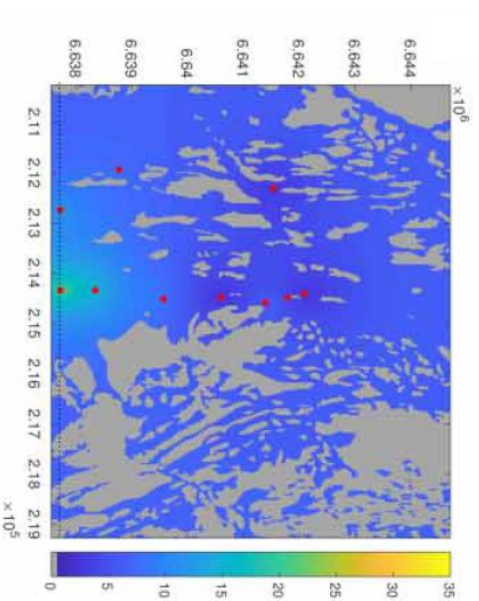


Test: Poisson's equation + kriging on residuals

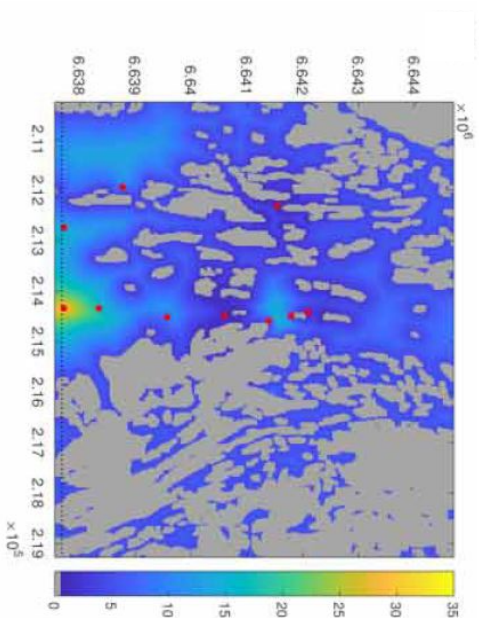


Estimation of sediment thickness, Øvre Eiker

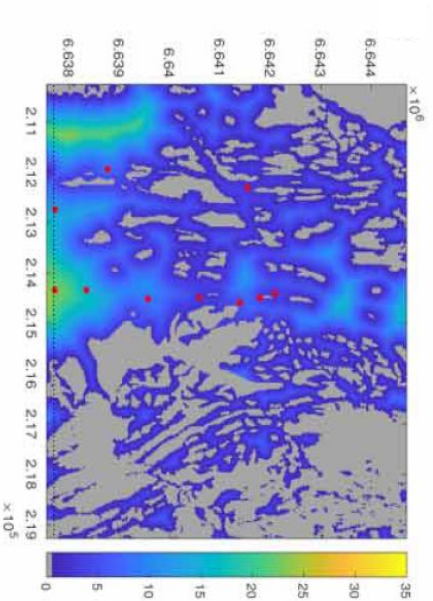
Ordinary
Kriging



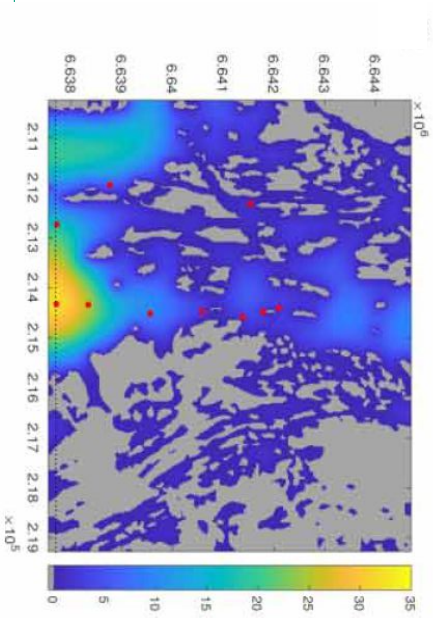
Co-
Kriging



Bedrock
Kriging



Poisson
Kriging





Case study:

Fredrikstad, InterCity connection Oslo – Halden.

Observations:

- Subsidence in central part of Fredrikstad: safety hazards for bridges, and damages on buildings.
- Leakage of artesian groundwater.
- Quick clay identification by test drilling.

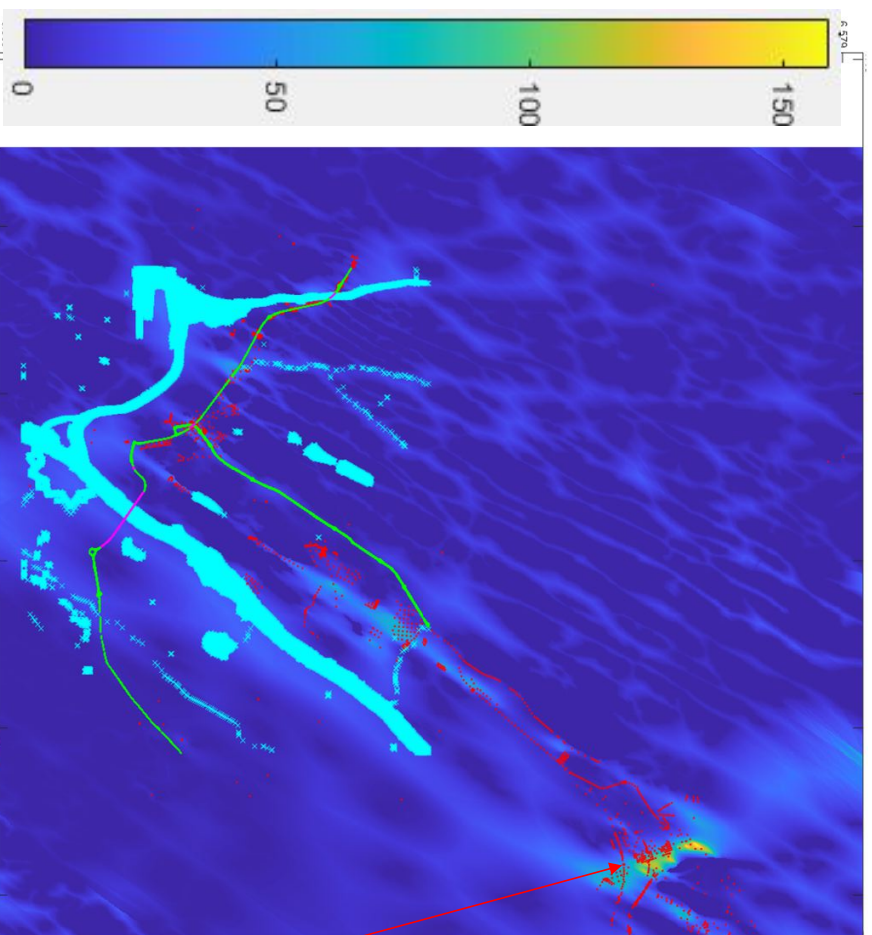
Challenges:

Constructions floating on the clay – or pillars to the bedrock?

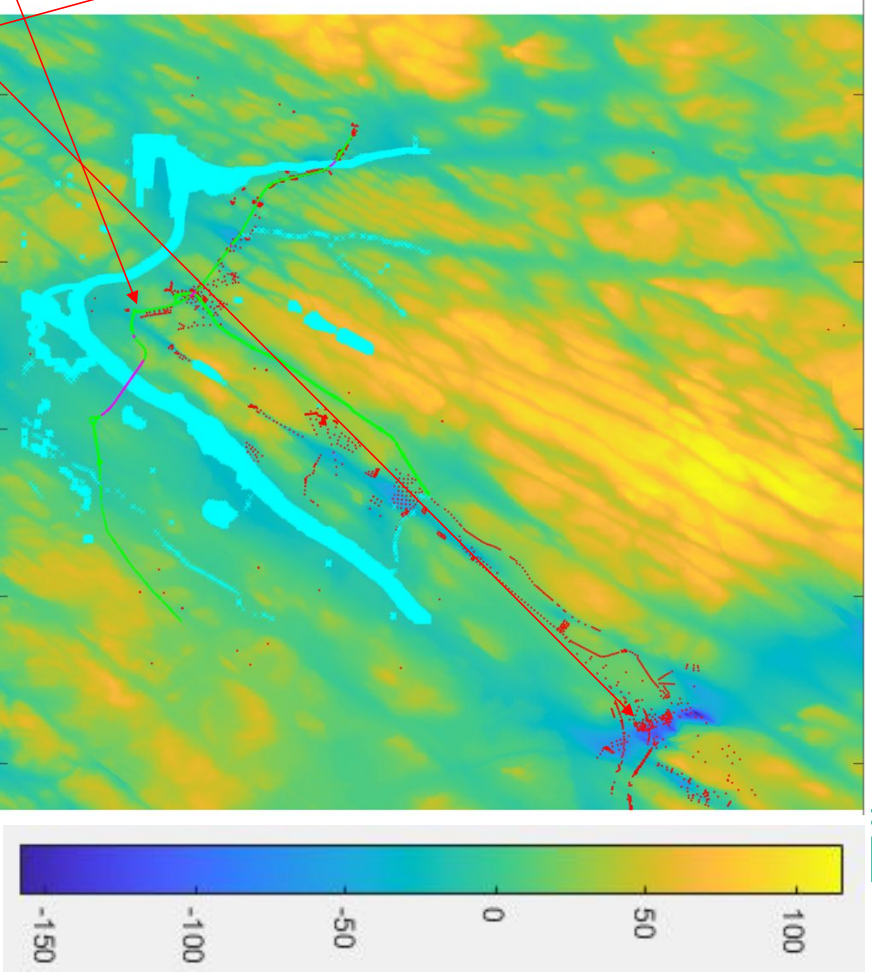
→ railways and roads?

→ new terminal building?

Sediment thickness (m below surface)

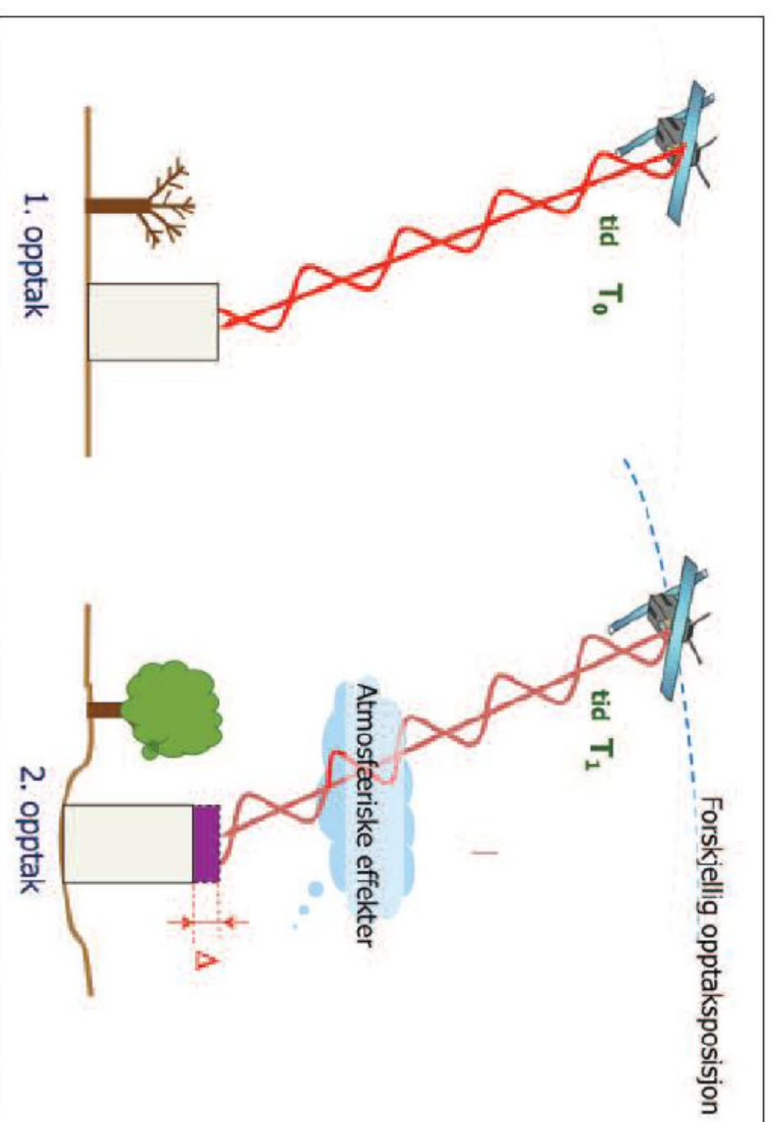


Bedrock topography (m a.m.s.l.)



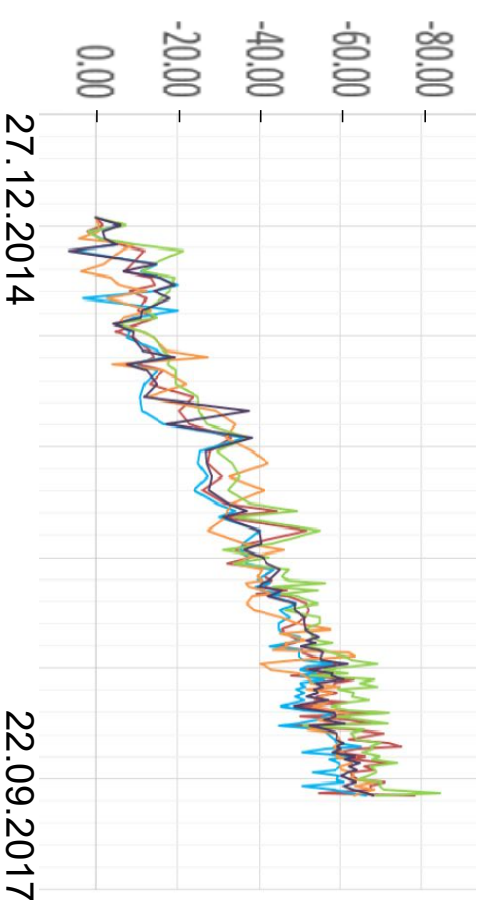
Fredrikstad – Greåker (2019 estimates)

Subsidence measurements by differential Synthetic Aperture Radar (SAR) technique



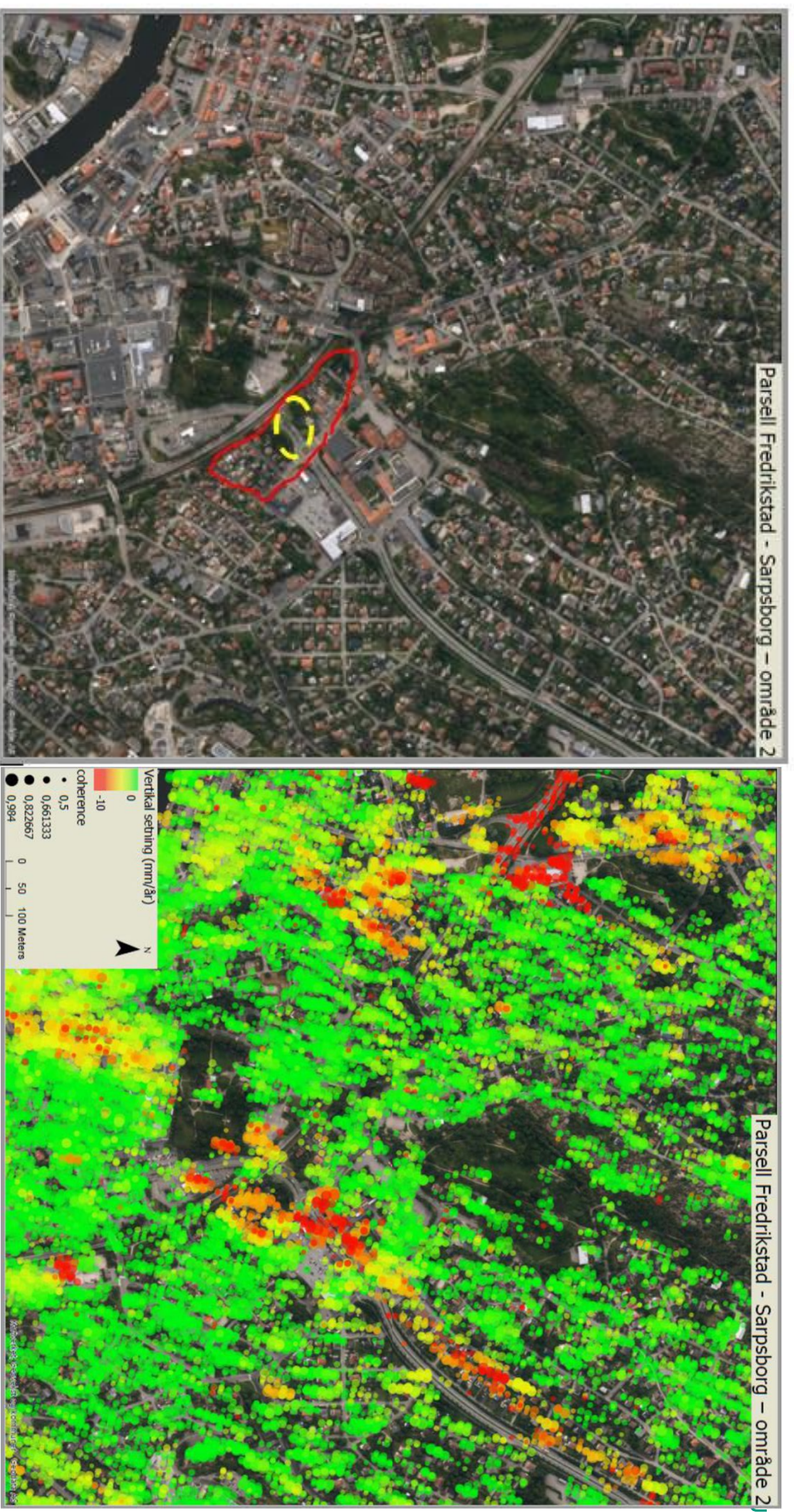
Figur 3.4. Prinsipp ved opptak med SAR-instrument. SAR-instrumentet er et aktivt instrument og sender ut pulsølger (energi) mot jorda. Når satellitten beveger seg og gjør opptak på to tidspunkt, kan det oppstå en målbart endring. Fra dette kan det avledes millimeterbevegelser i vertikaletrningen (Δ). (NGU)

Subsidence in Fredrikstad City



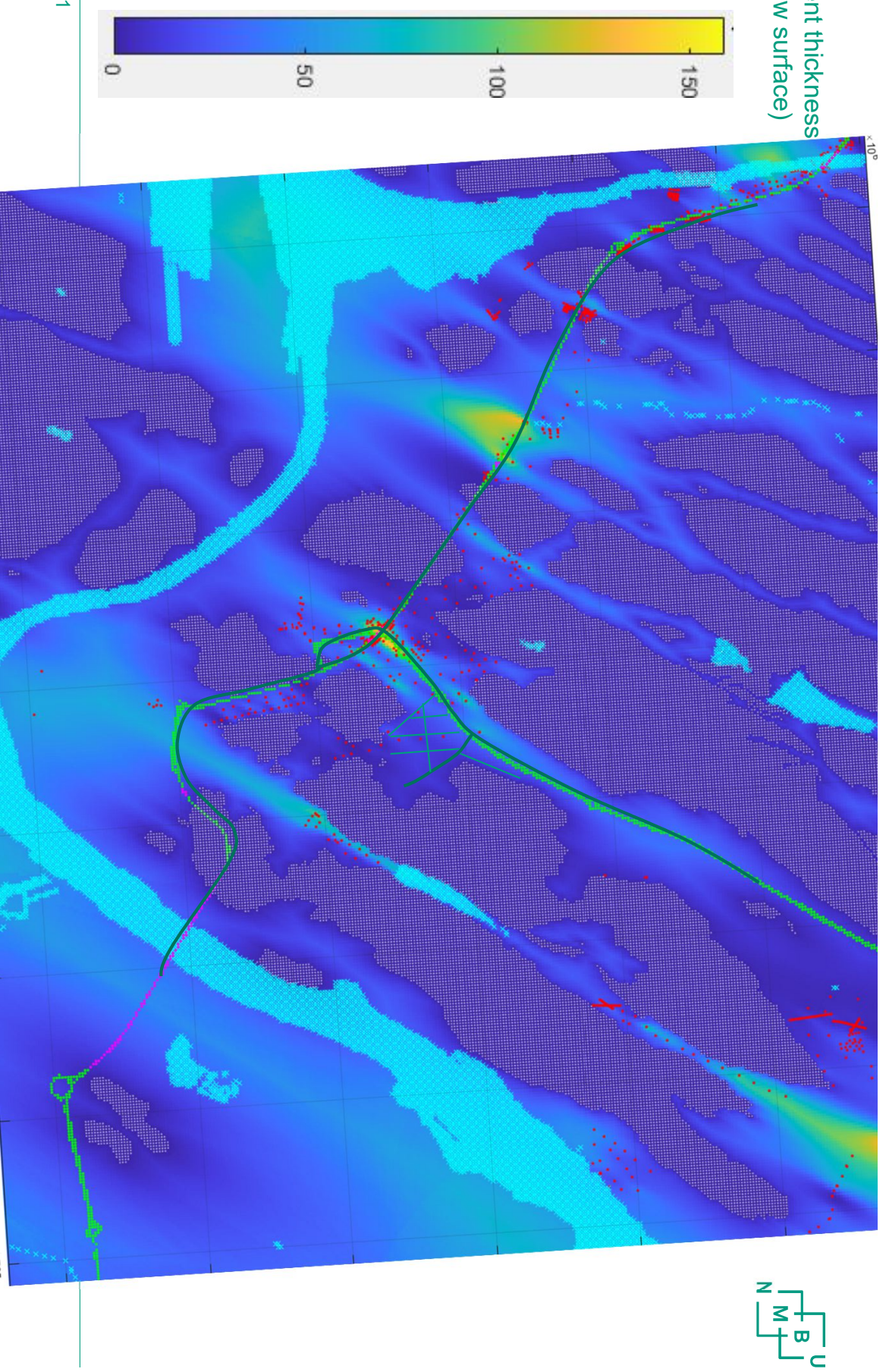
Physical level measurements

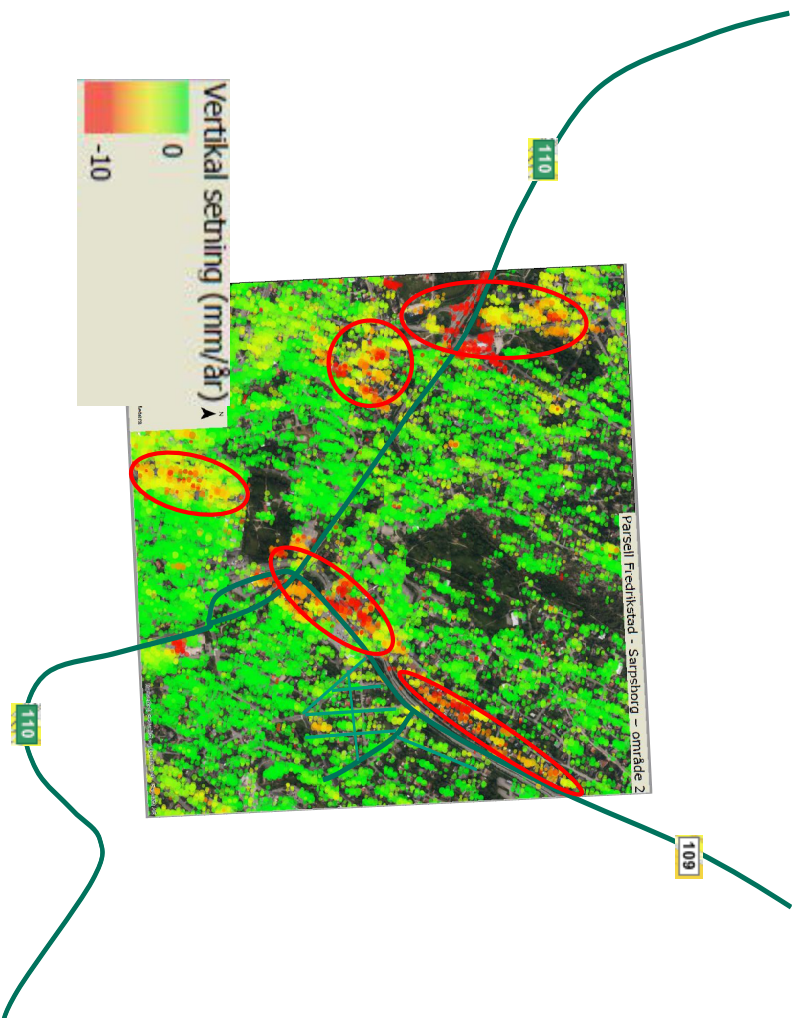
SARl measurements



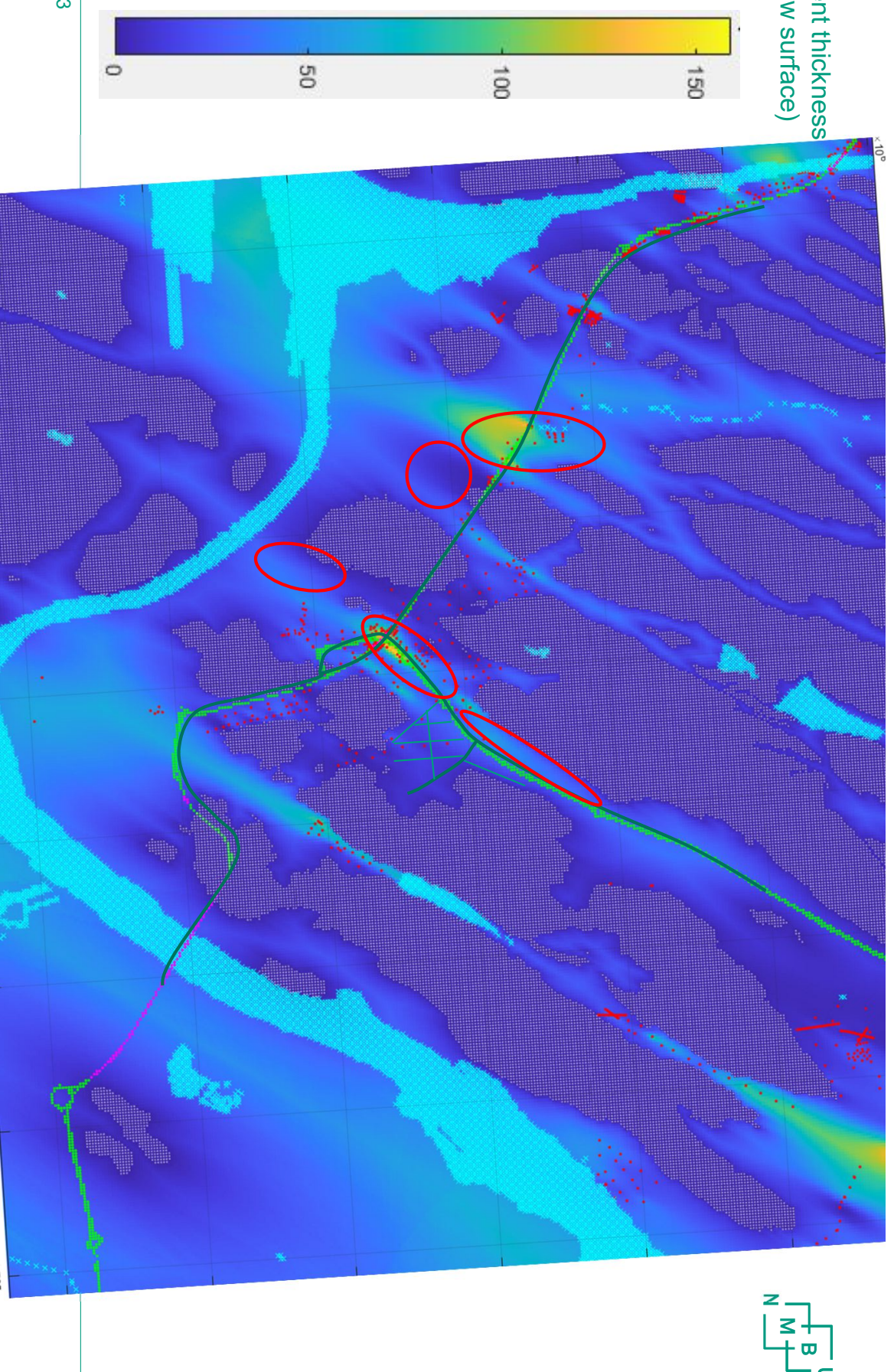
Ortofoto og vertikale setninger i stasjonsområdet (mm/år des 2012 – okt 2017)

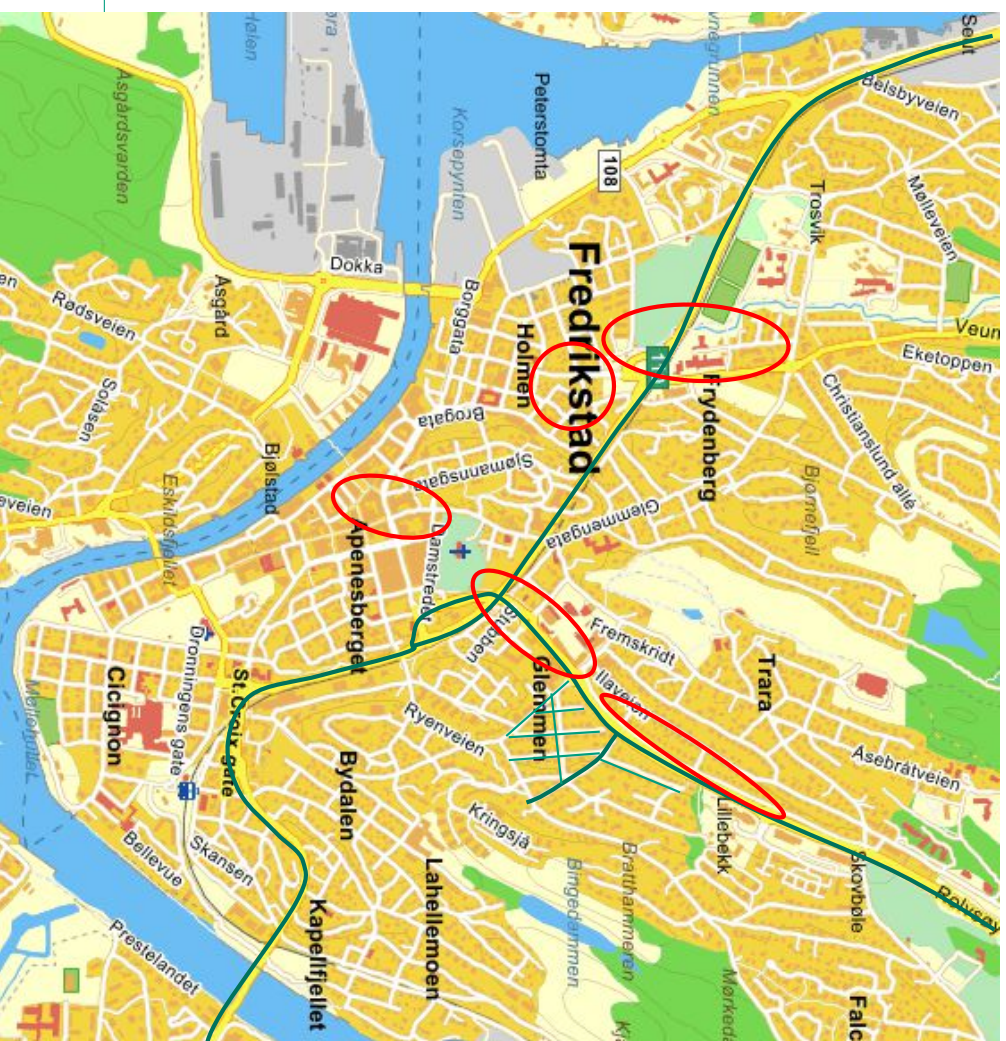
Sediment thickness
(m below surface)

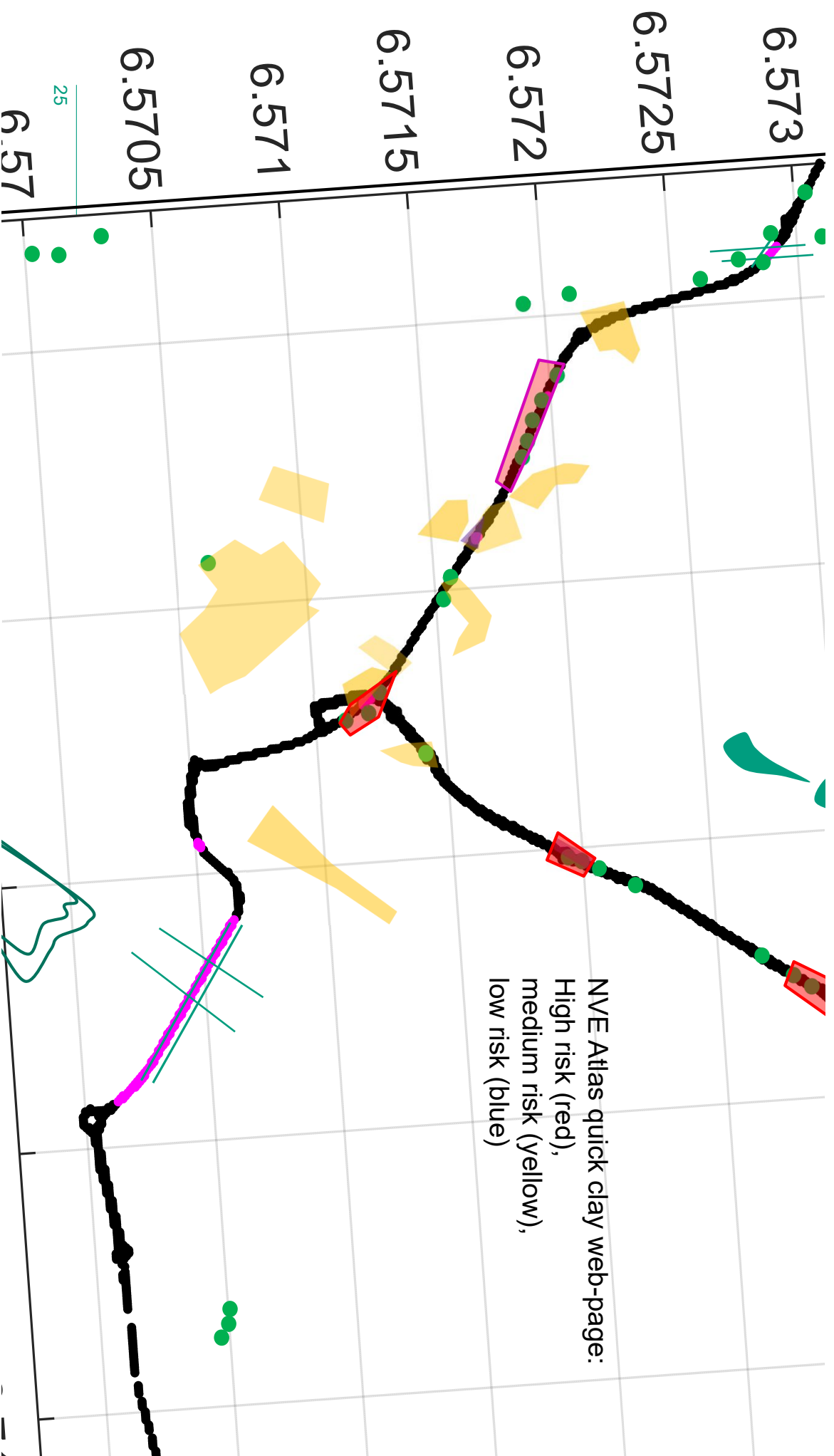




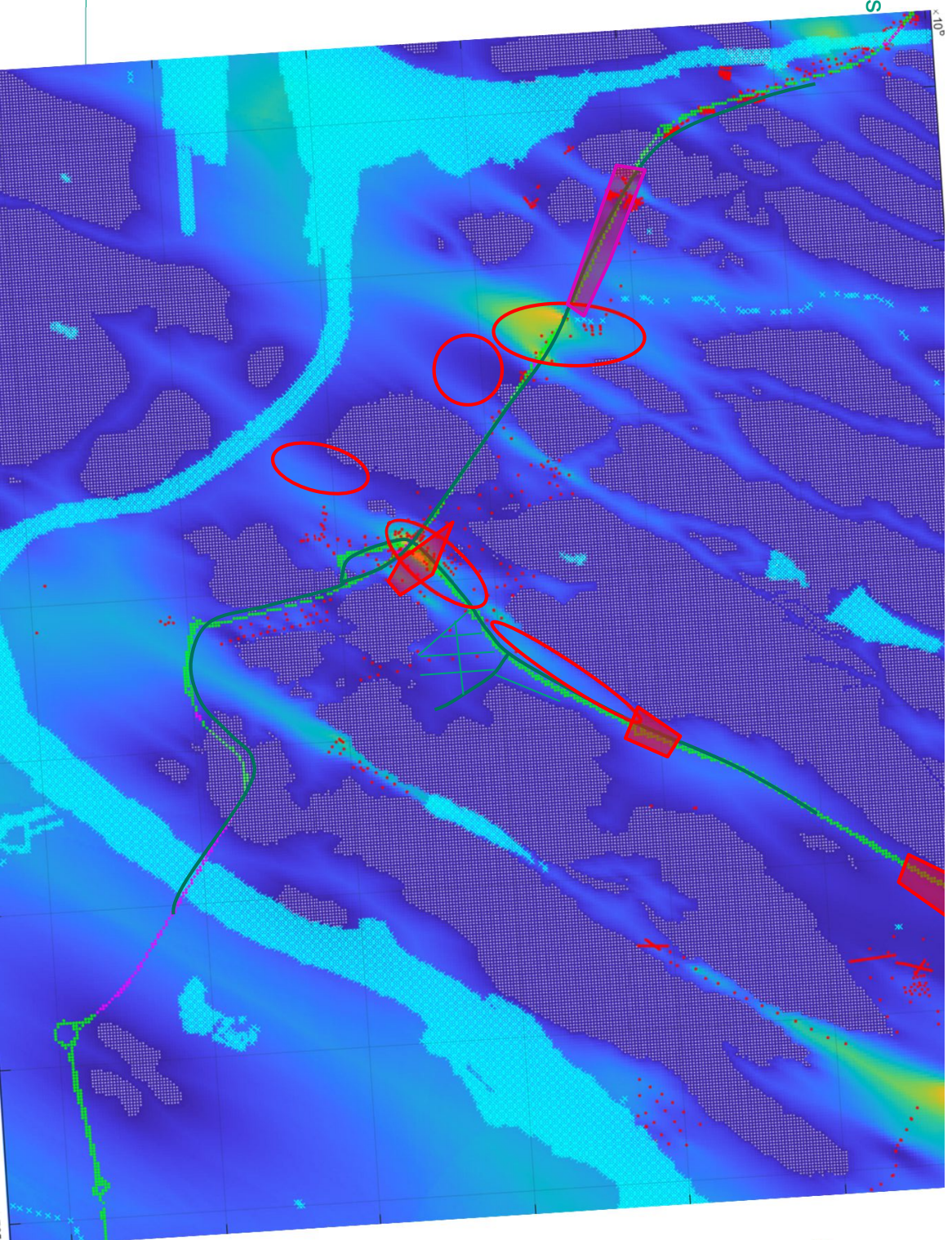
Sediment thickness
(m below surface)







Sediment thickness
(m below surface)





Conclusions so far ...

- Number of observations increase.
- Computer capacity increase.
- Bedrock topography can be estimated, but not without uncertainties.
- Further testing of algorithms are necessary (PhD and MSc projects).
- Proposals:
 - Risk for quick clay landslides should be analyzed with bedrock topography as a background variable together with other relevant variables.
 - ...

References:

- Clarke, G. K. C., Berthier, E., Schoof, C. G. & Jarosch, A. H., 2009: Neural networks applied to estimating subglacial topography and glacier volume. *Journal of Climate* 22, 2146–2160. <https://doi.org/10.1175/2008JCLI2572.1>.
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- Mey, J., Scherler, D., Zeilinger, G. & Strecker, M. R., 2015: Estimating the fill thickness and bedrock topography in intermontane valleys using artificial neural networks. *Journal of Geophysical Research: Earth Surface* 120, 1301–1320. <https://doi.org/10.1002/2014JF003270>.