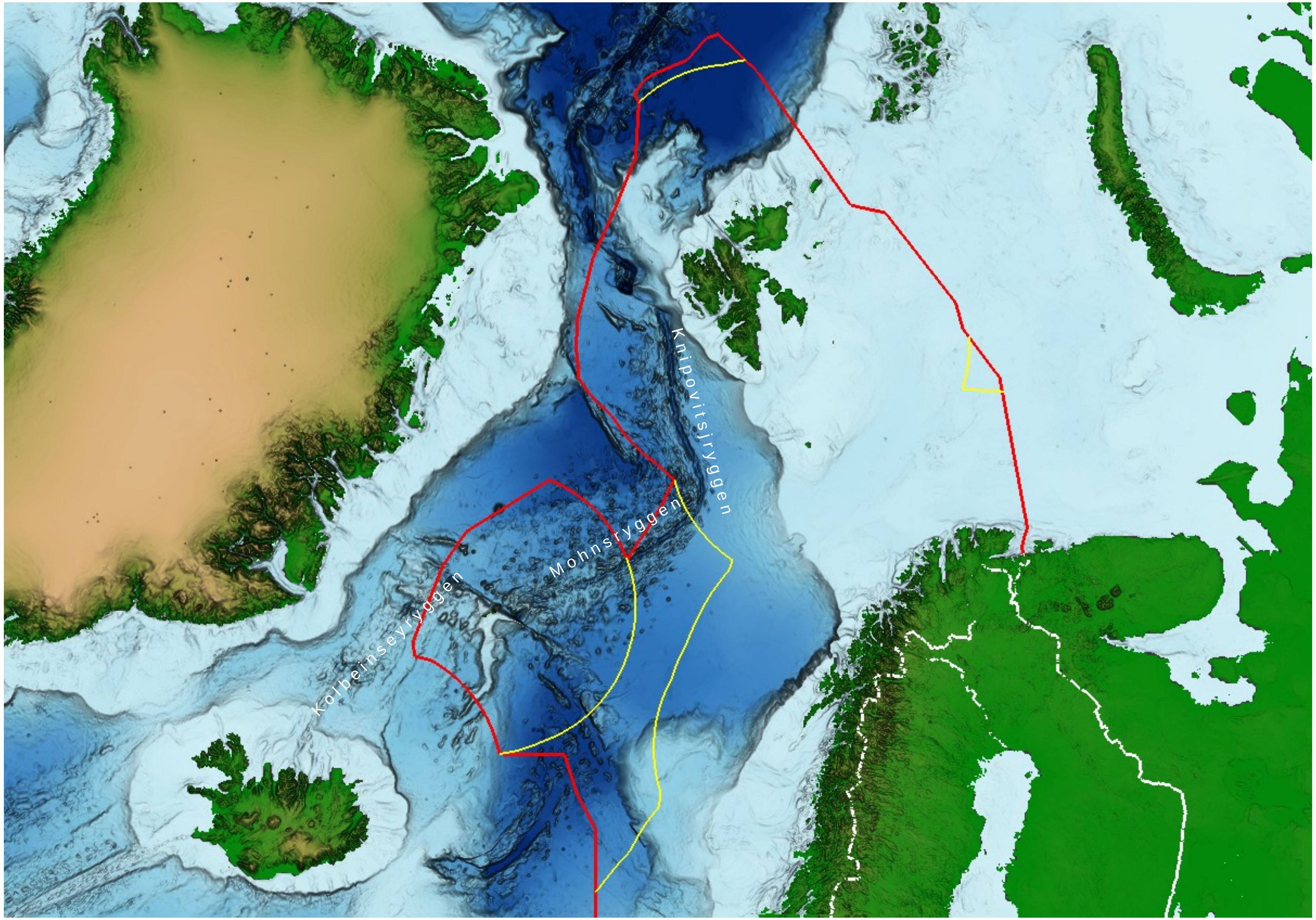
Geologiske modeller,
betydning for ressursevaluering

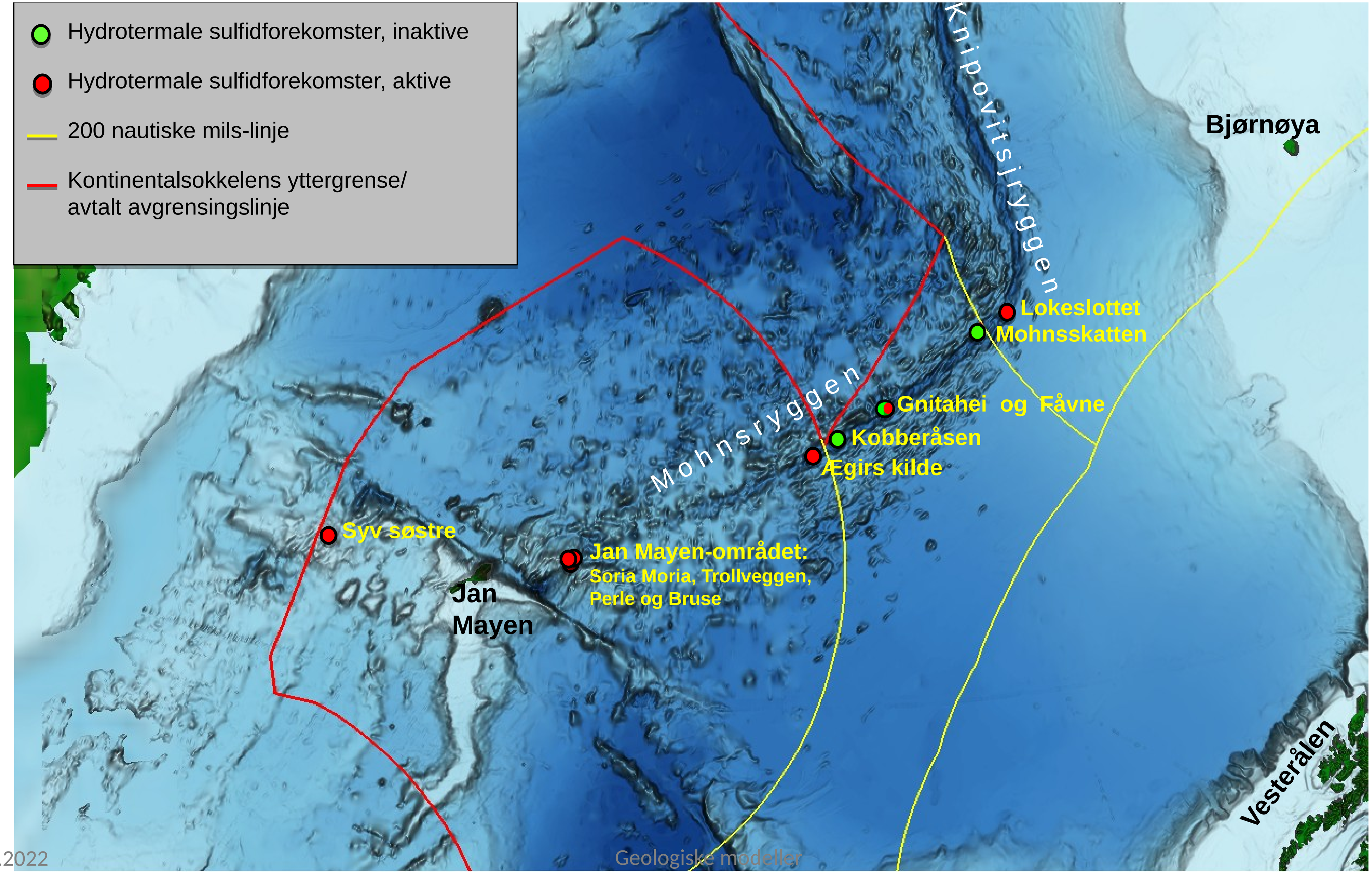
Harald Brekke, Oljedirektoratet, 2 juni 2022

OLJEDIREKTORATET
50 år

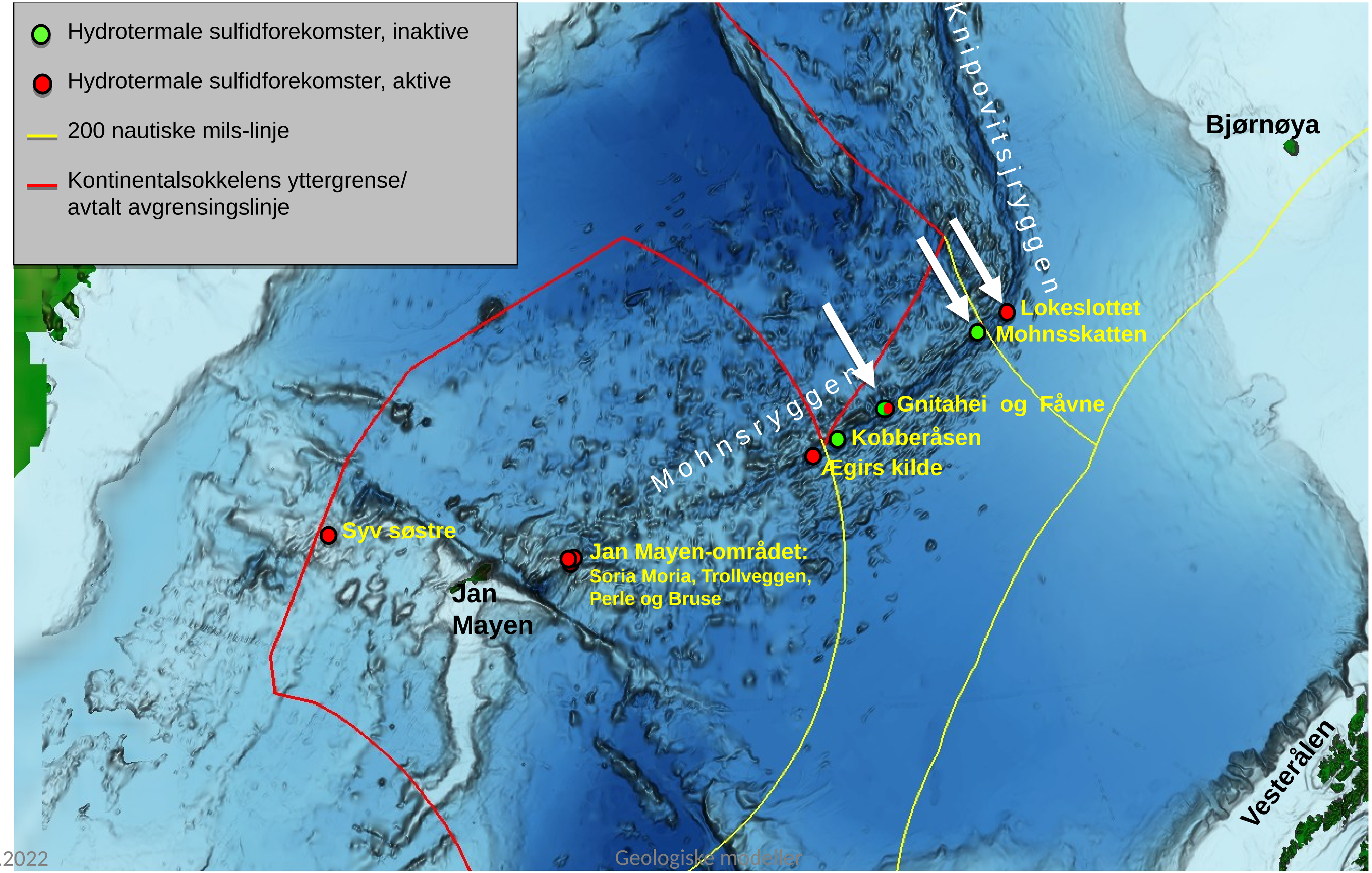
Spredningsrygger på norsk kontinentalsokkel



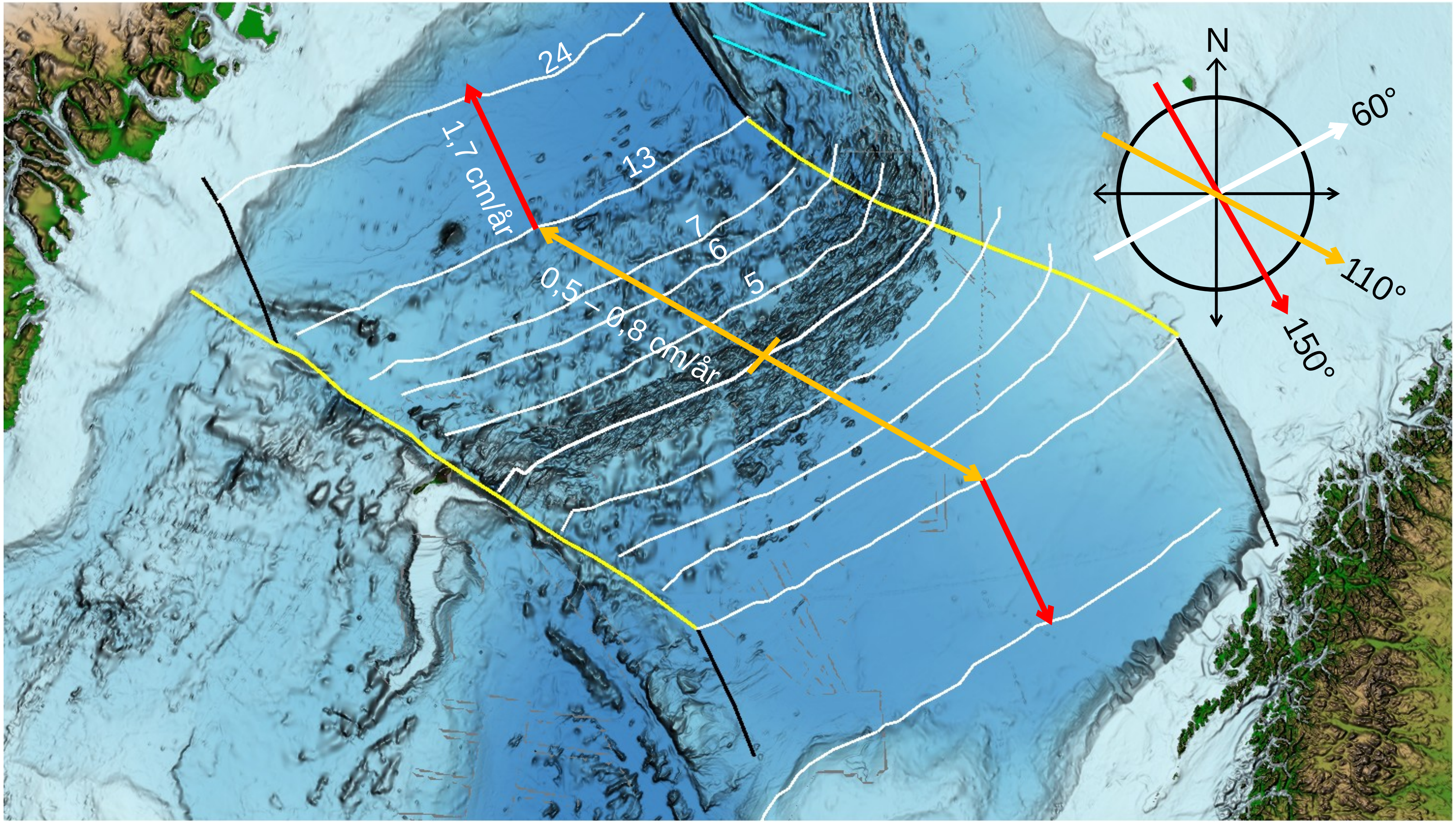
Kjente hydrotermalforekomster på norsk sokkel



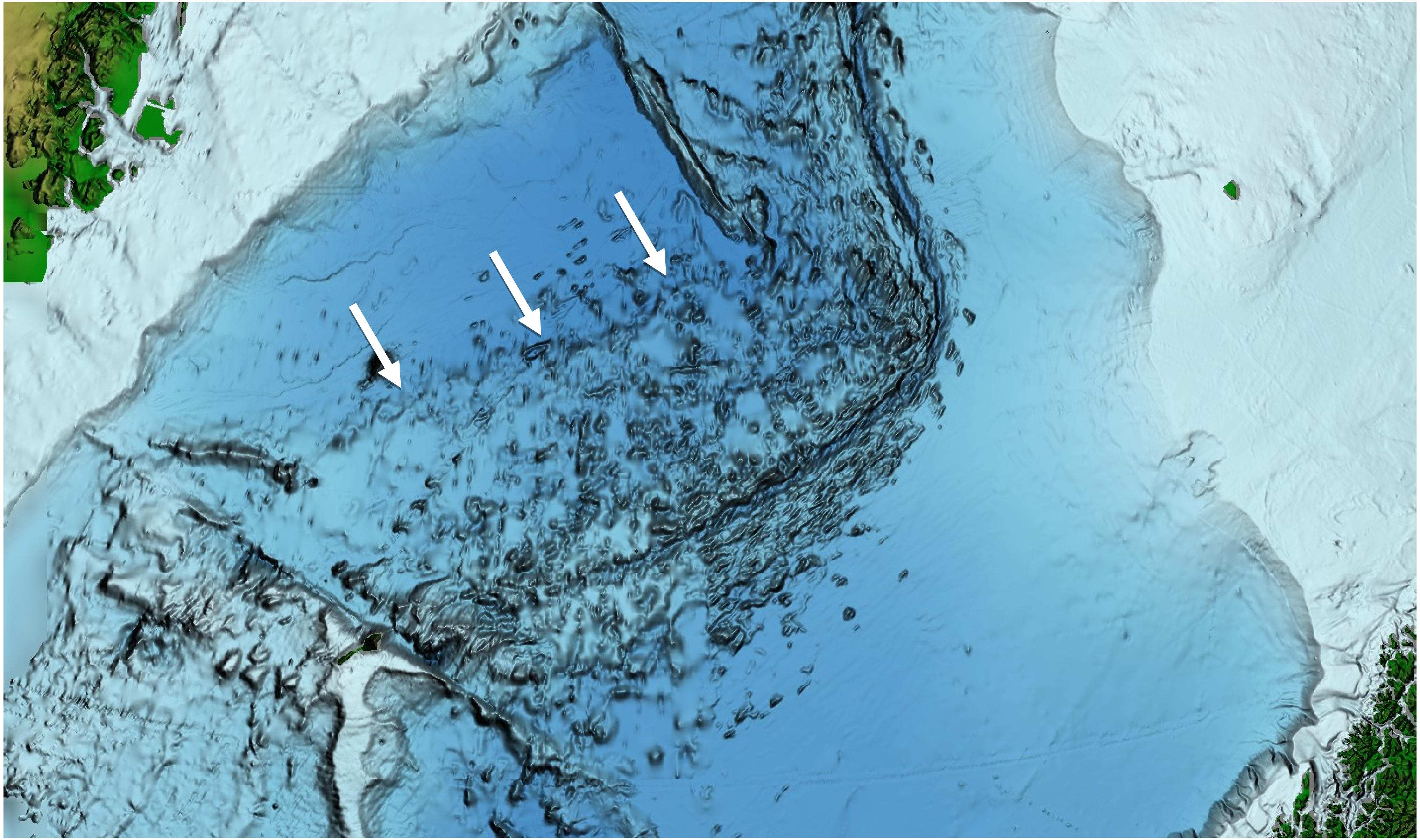
Kjente hydrotermalforekomster på norsk sokkel



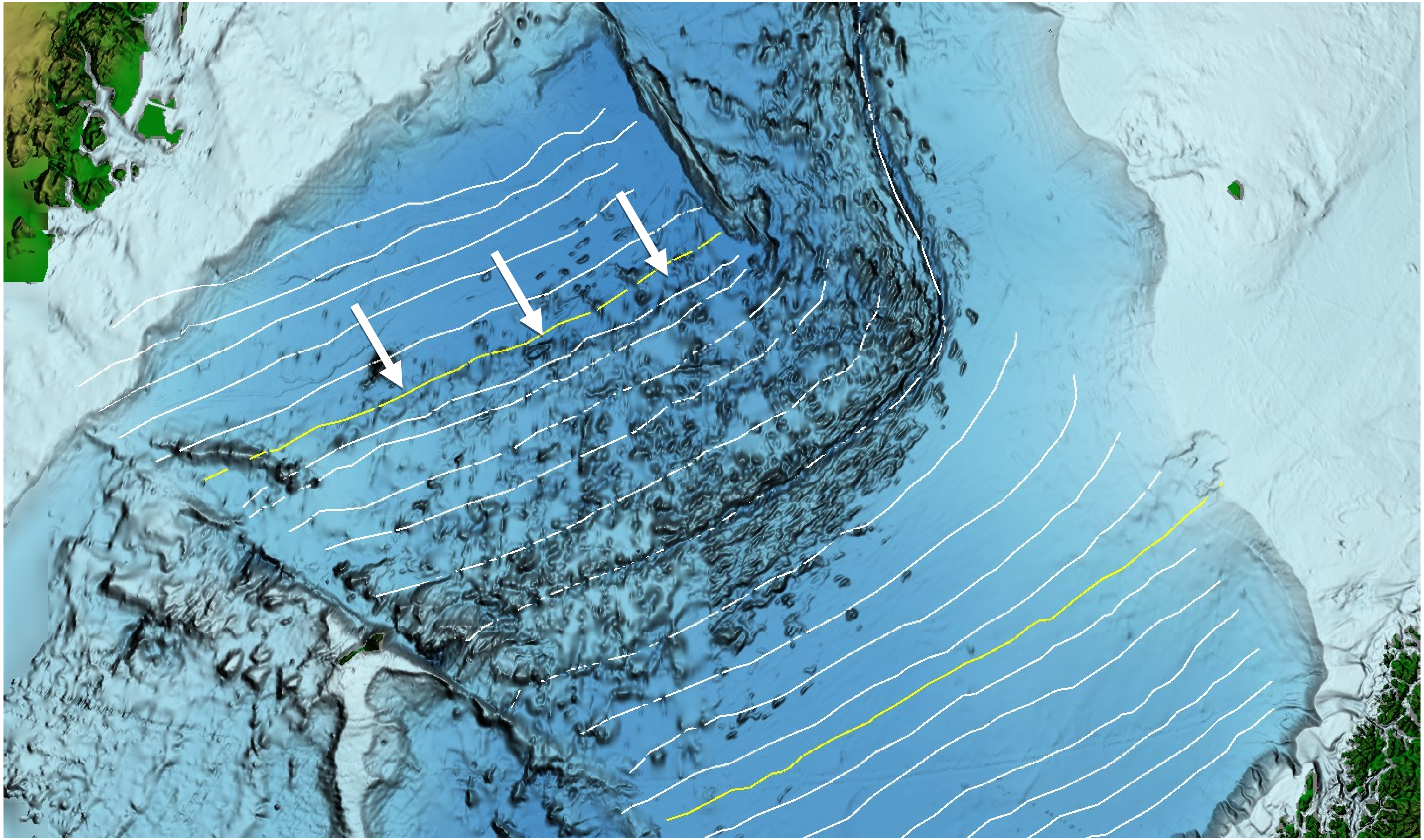
Spredningsretninger og hastigheter



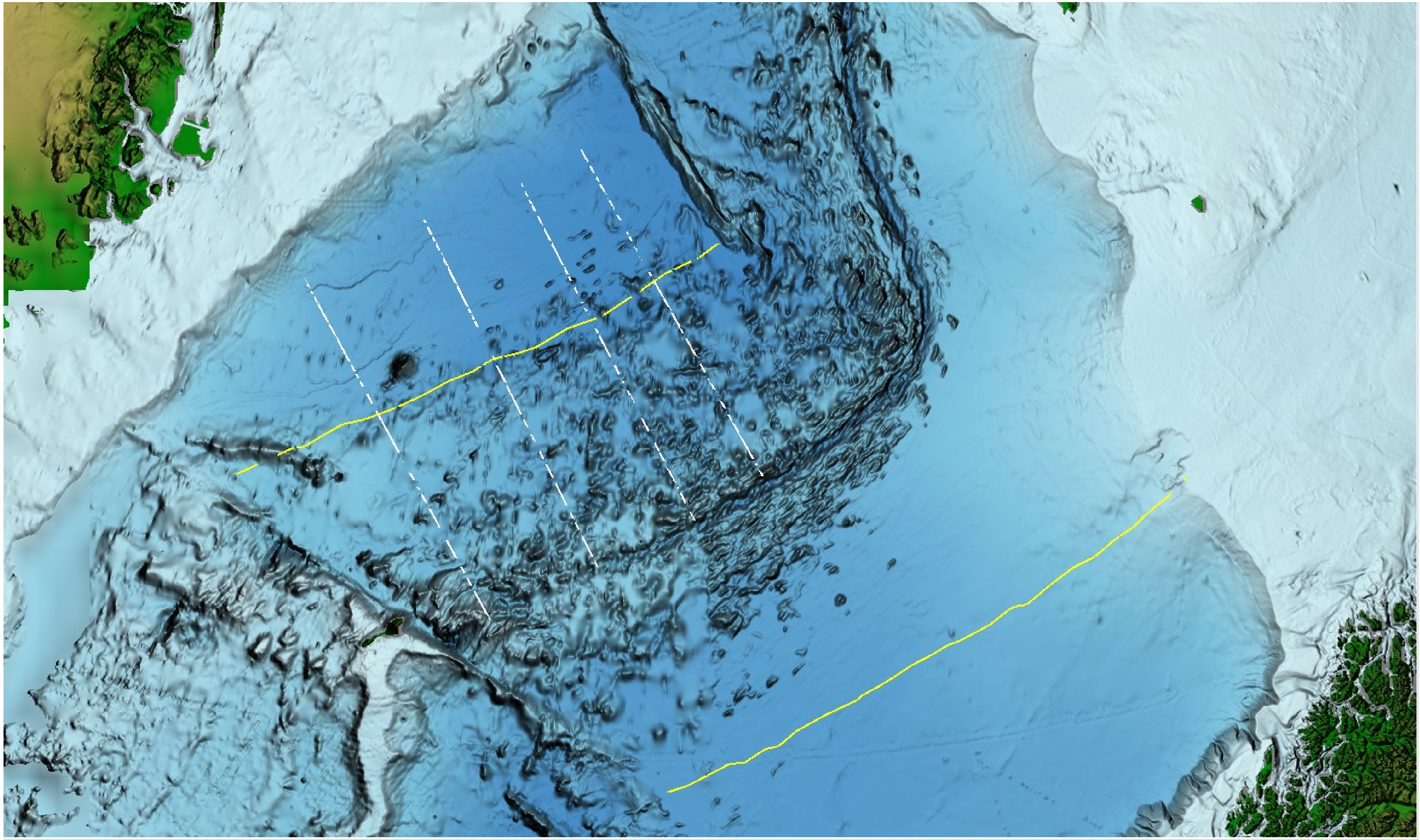
Havbunnstopografi og spredningshastighet



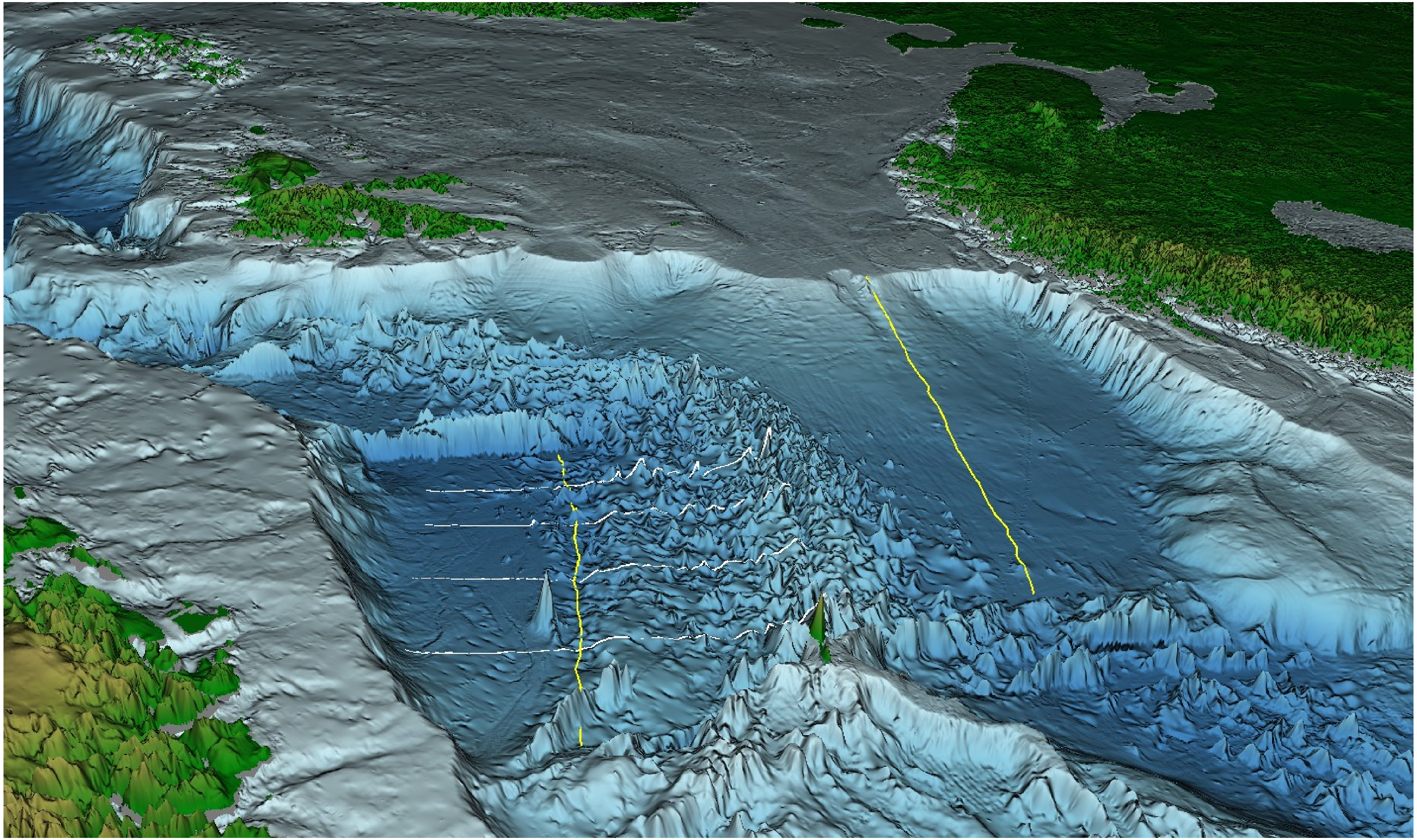
Havbunnstopografi og spredningshastighet



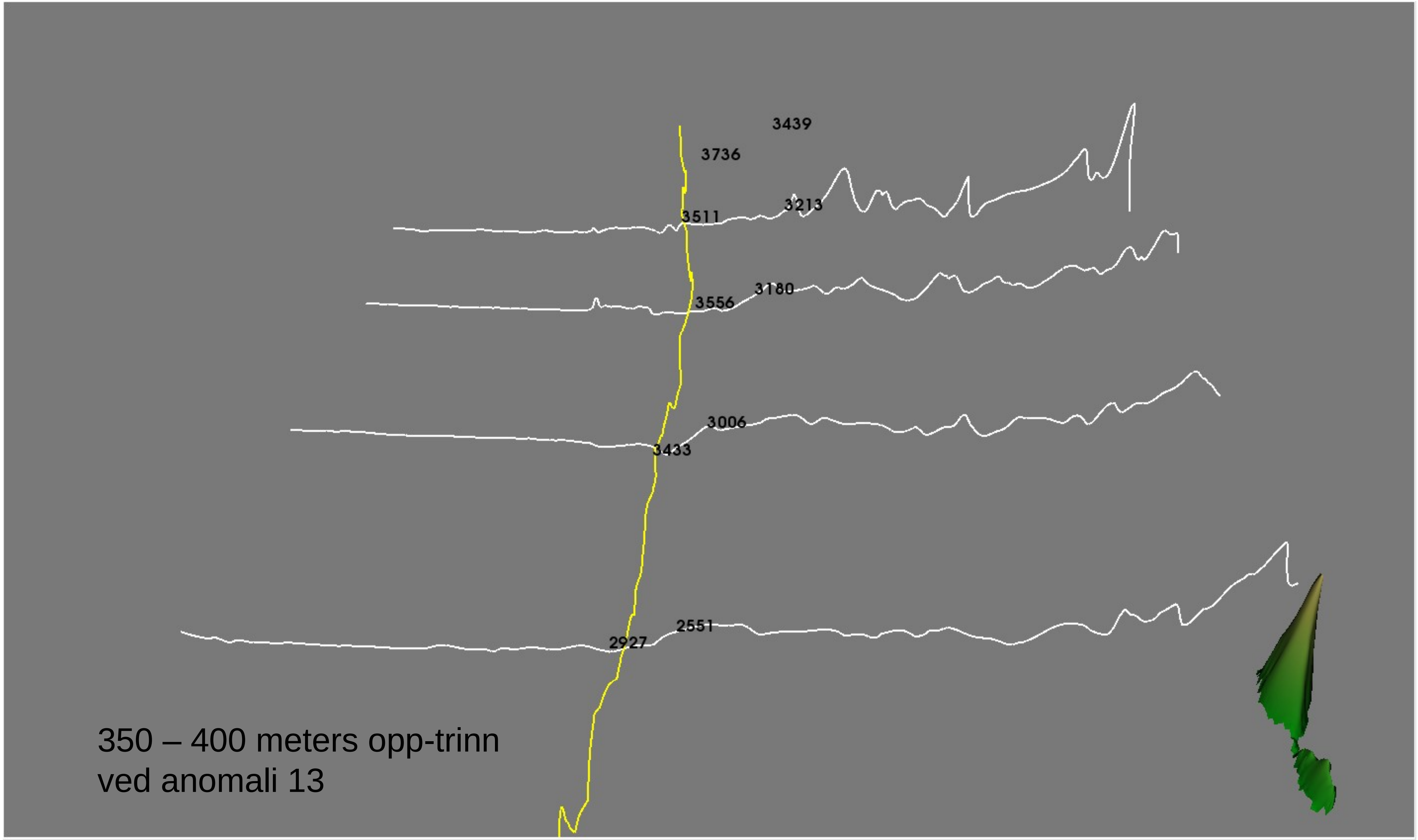
Endring av havbunnstopografi ved anomali 13



Endring av havbunnstopografi ved anomali 13



Endring av havbunnstopografi ved anomali 13



Midt-oseanske spredningshastigheter, globalt

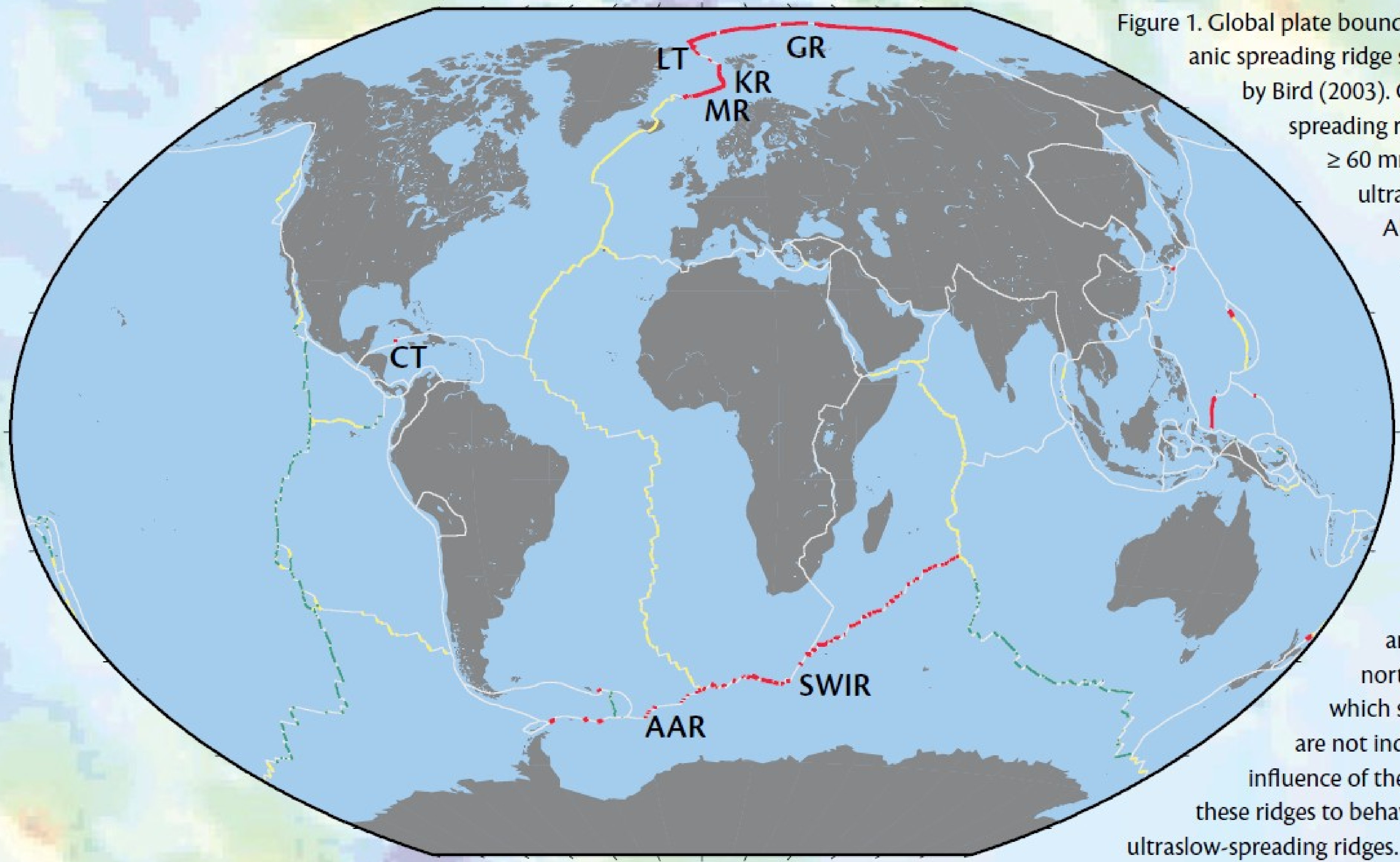
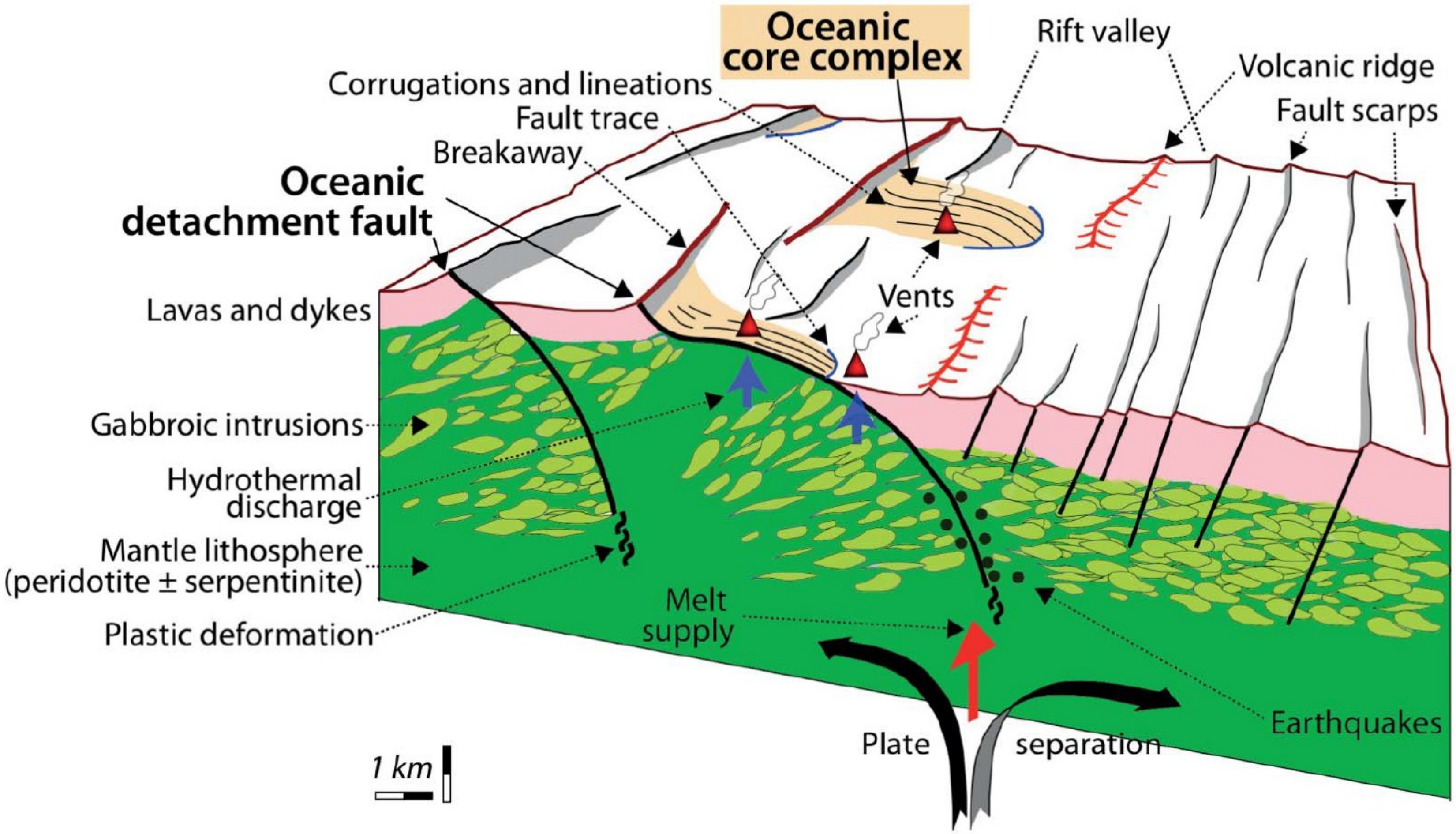


Figure 1. Global plate boundaries (gray) and oceanic spreading ridge segments as defined by Bird (2003). Green indicates fast-spreading ridges (full spreading rate ≥ 60 mm yr^{-1}). Red indicates ultraslow-spreading ridges. All other ridge segments are indicated in yellow. GR = Gakkel Ridge, LT = Lena Trough, KR = Knipovich Ridge, MR = Mohns Ridge, CT = Cayman Trough, AAR = America-Antarctic Ridge, and SWIR = Southwest Indian Ridge. Note that sections of the Kolbeinsey and Reykjanes Ridges north and south of Iceland, which spread at < 20 mm yr^{-1}, are not indicated in red because the influence of the Iceland hotspot causes these ridges to behave differently than other ultraslow-spreading ridges.

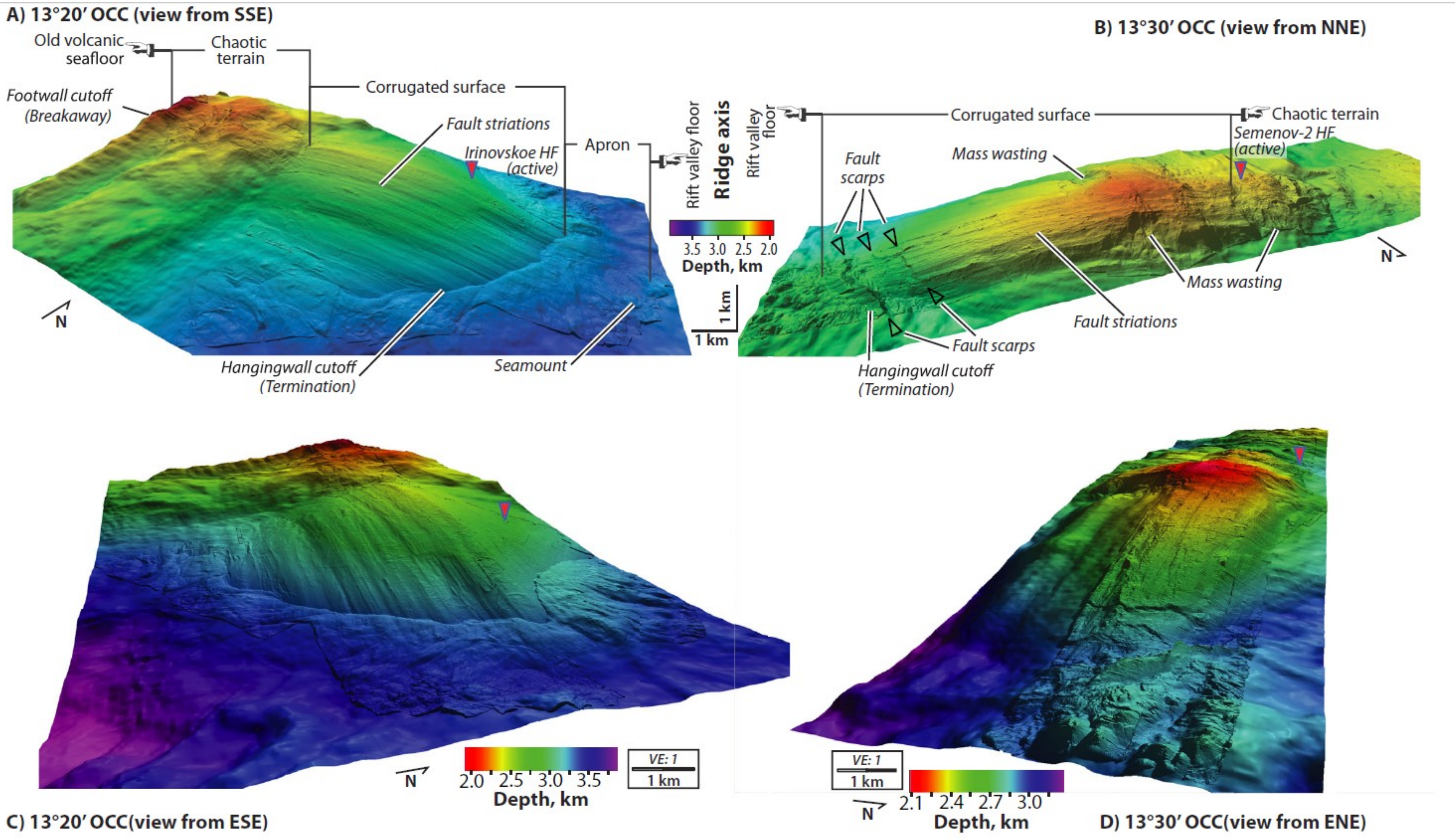
Snow & Edmonds, Oceanography 2007

Ultra-sakte plate-spredning – “Chapman Model”



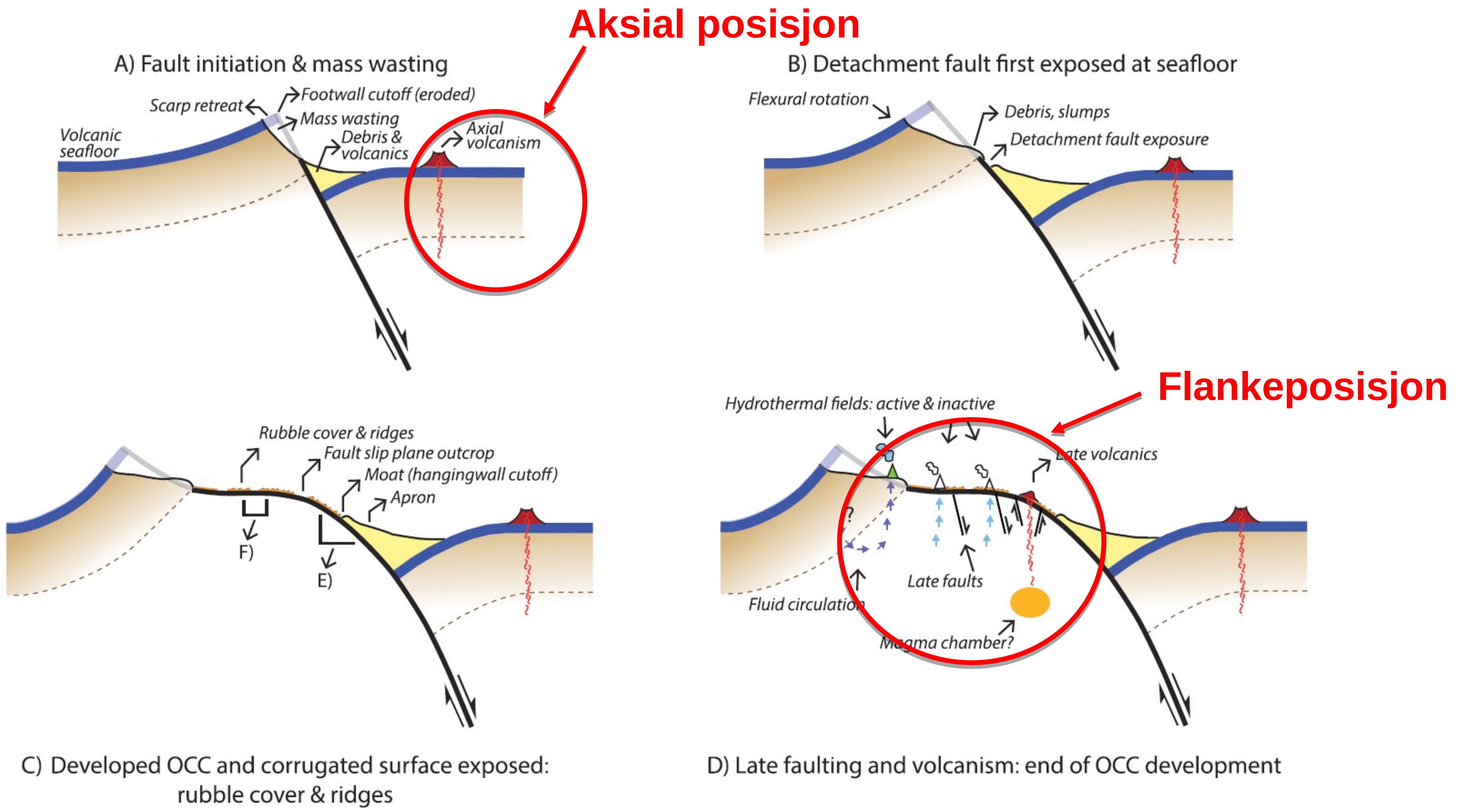
Maffione et al., 2013

Kjernekomplekser fra Den midt-atlantiske rygg



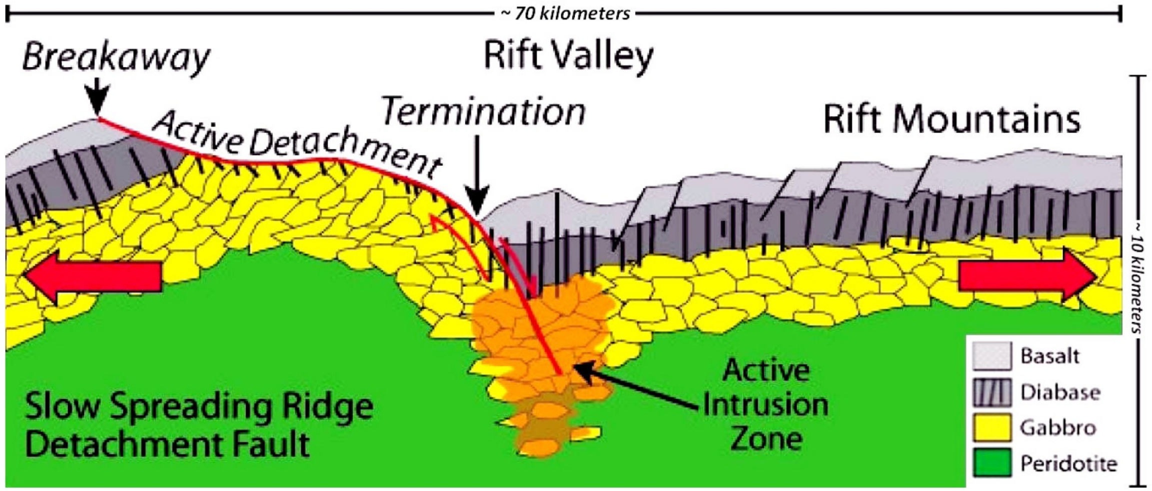
Escartin et al. 2017

Tektoniske forhold rundt hydrothermal aktivitet

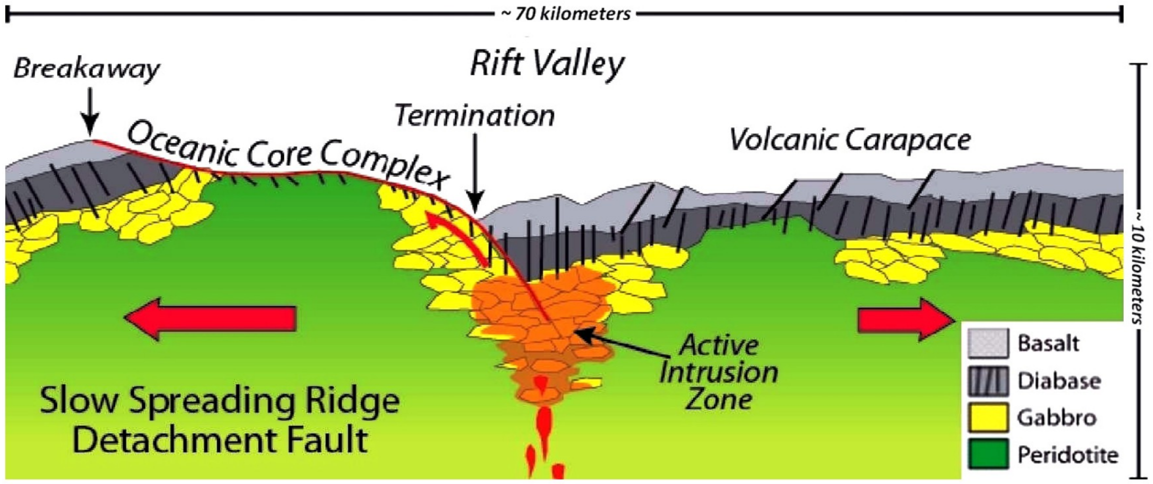


Escartin et al., 2017

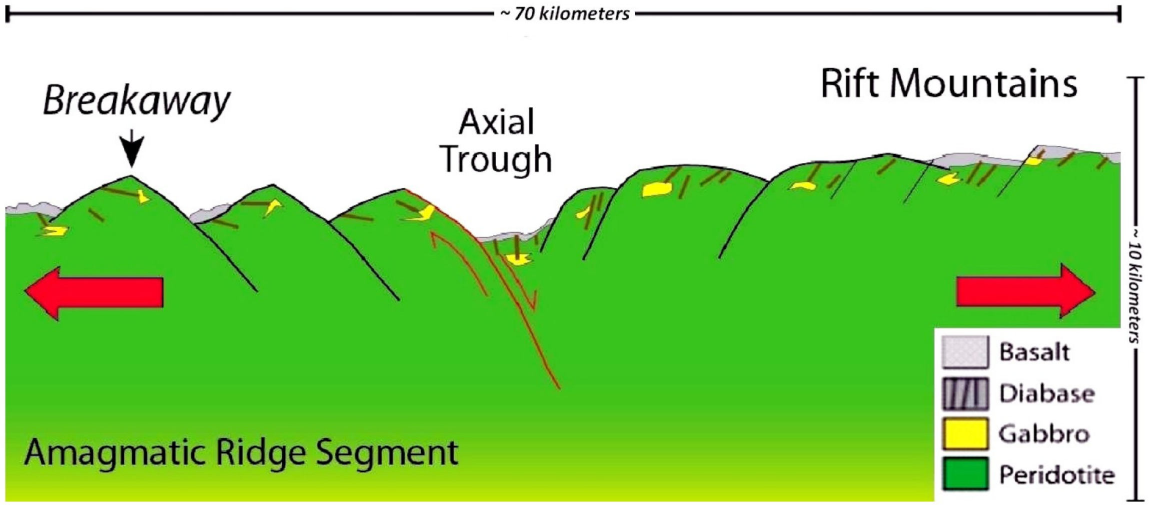
Sakte spredning og magmafluks



Høy magmafluks



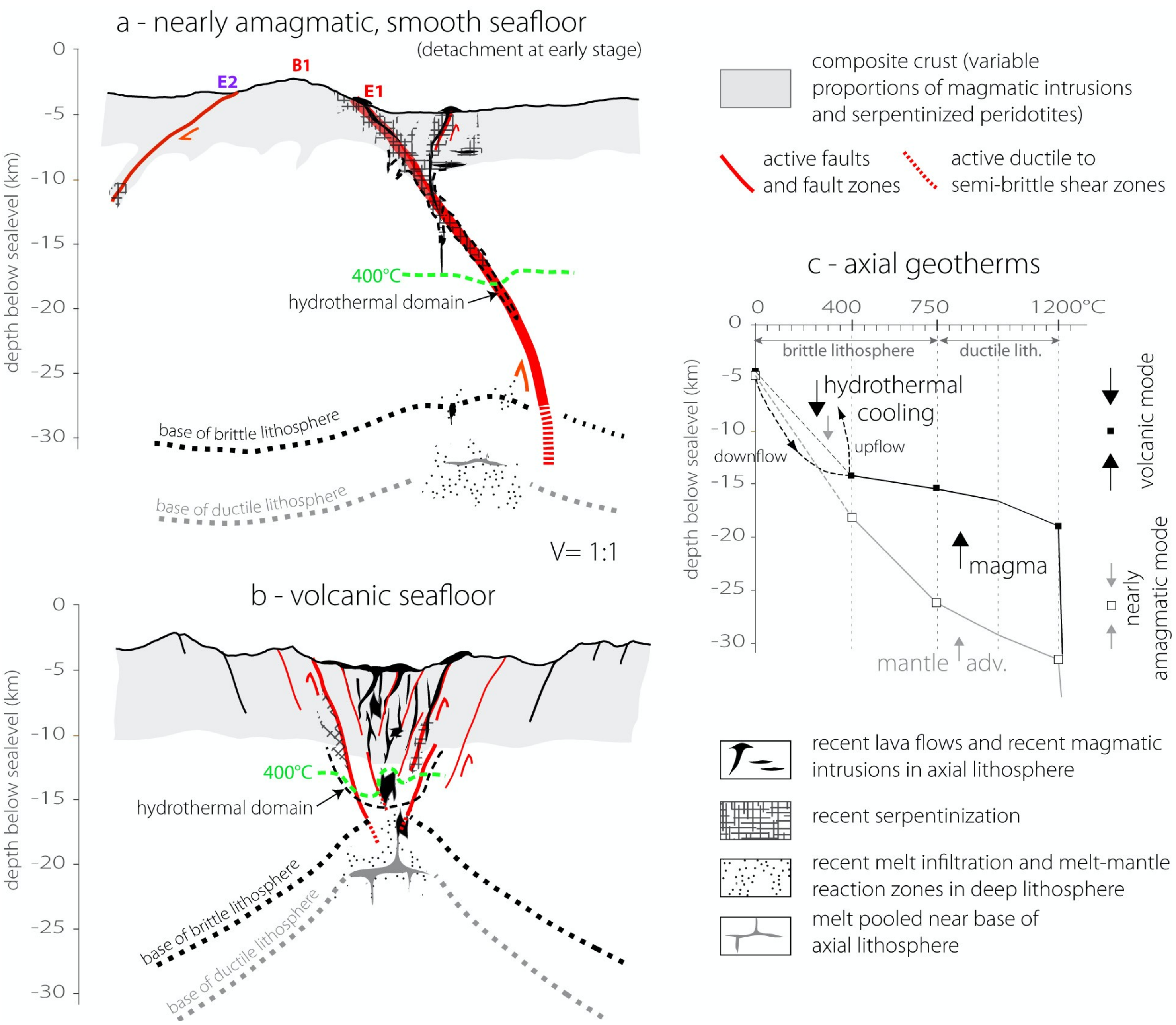
Intermediær magmafluks



Lav magmafluks

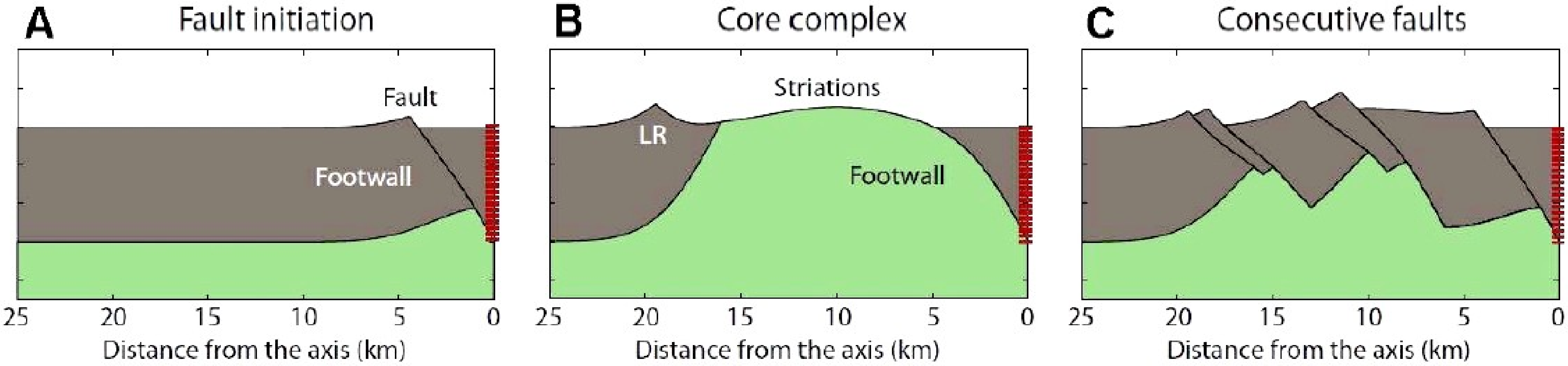
Henry J. B. Dick et al. 2019

Ultrasakte platespredning – amagmatisk vs magmatisk tektonikk



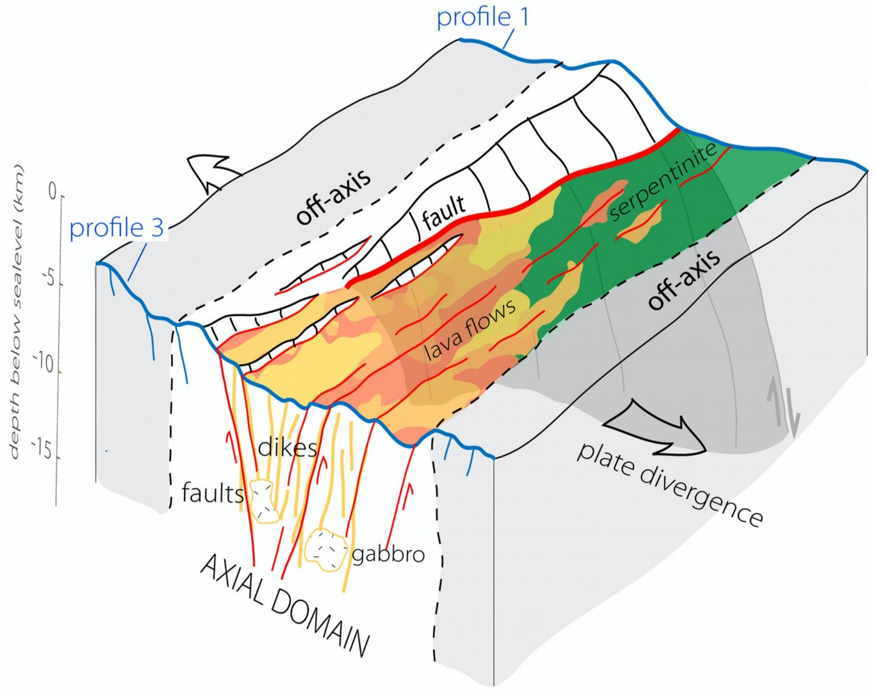
Cannat et al. 2019

Ekstensjon ved platespredning



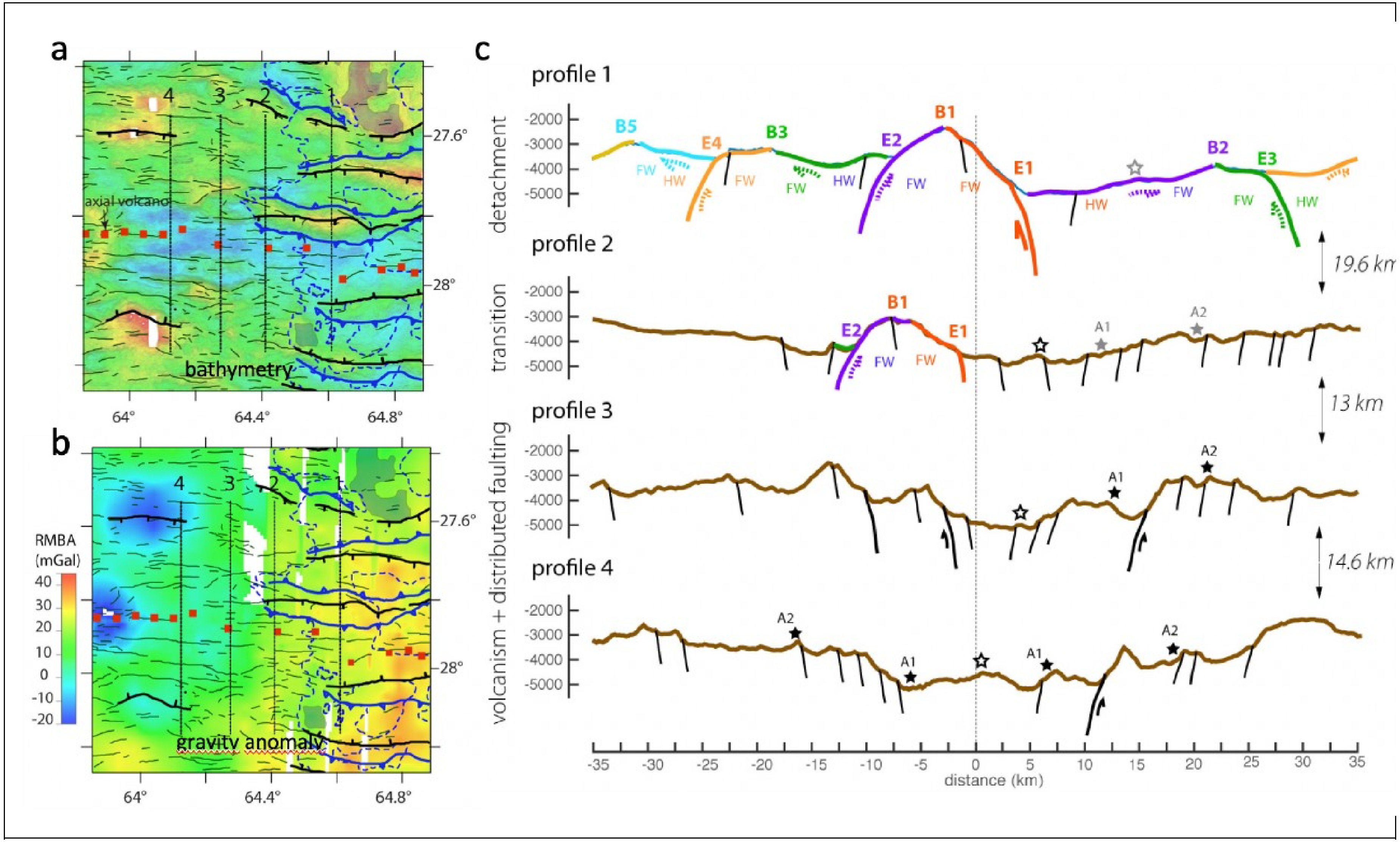
Ciazela et al, 2015

Lateral variasjon



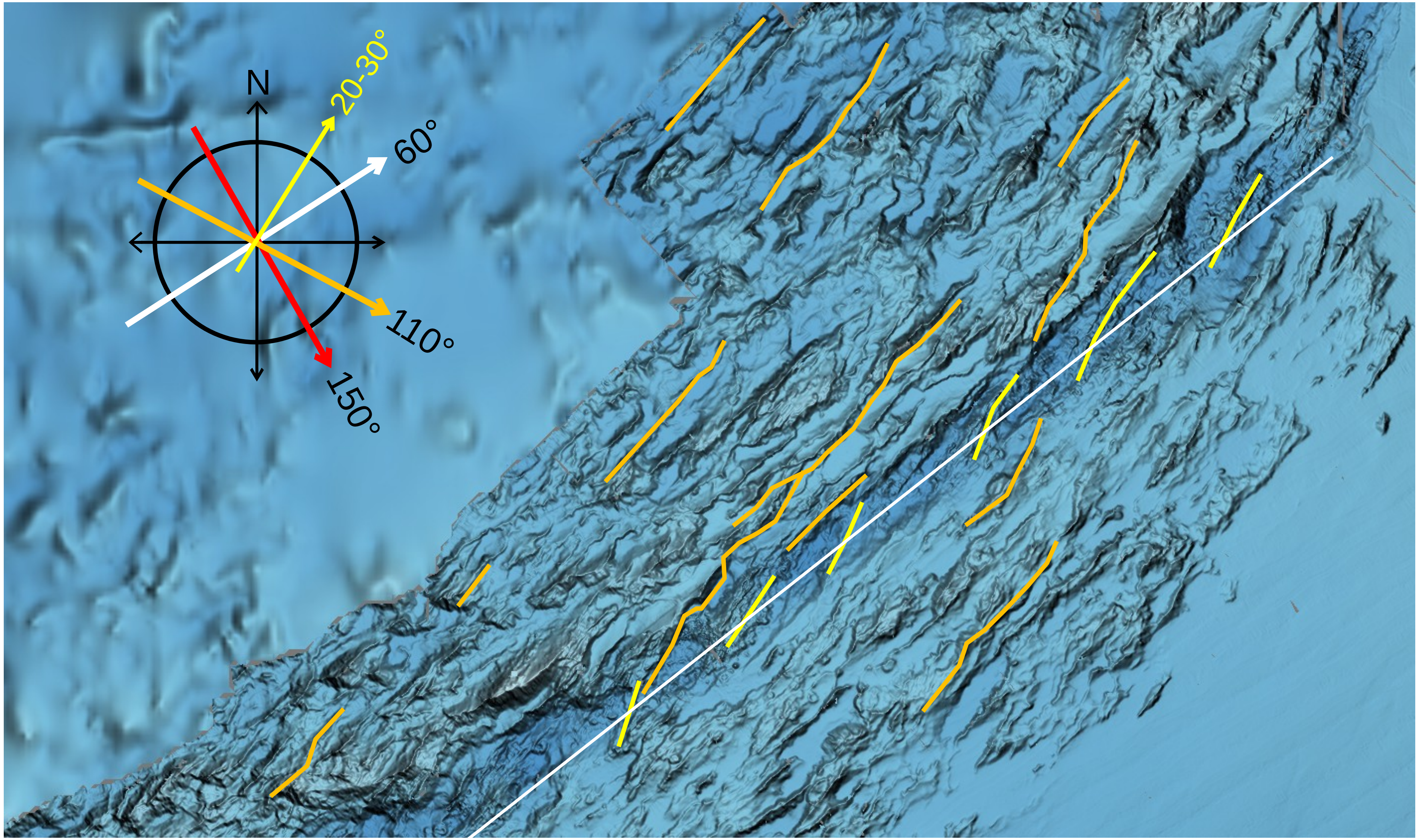
Cannat et al. 2019

Lateral variasjon (SWIR)

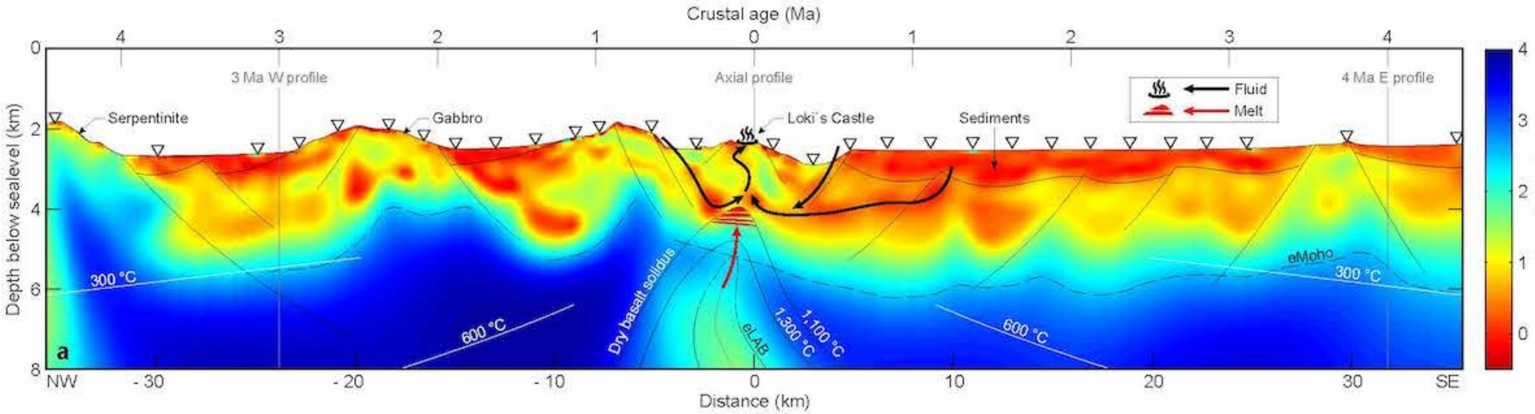


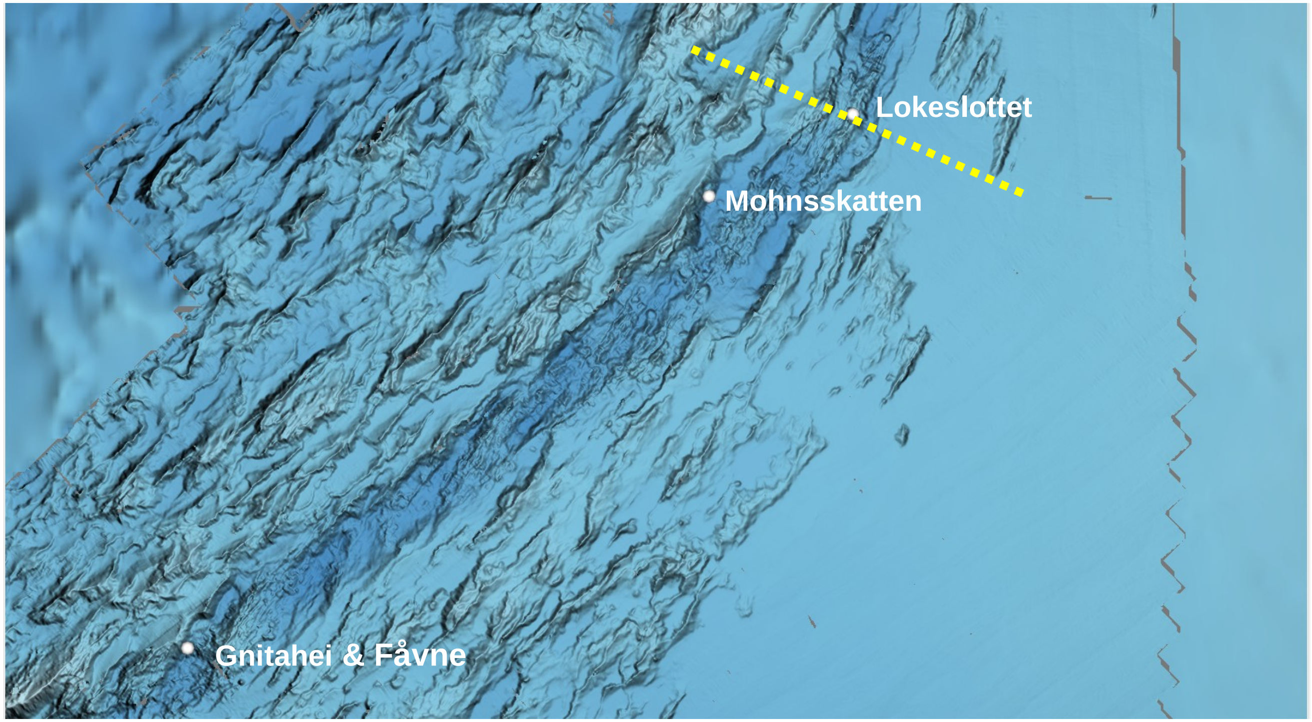
Cannat et al. 2019

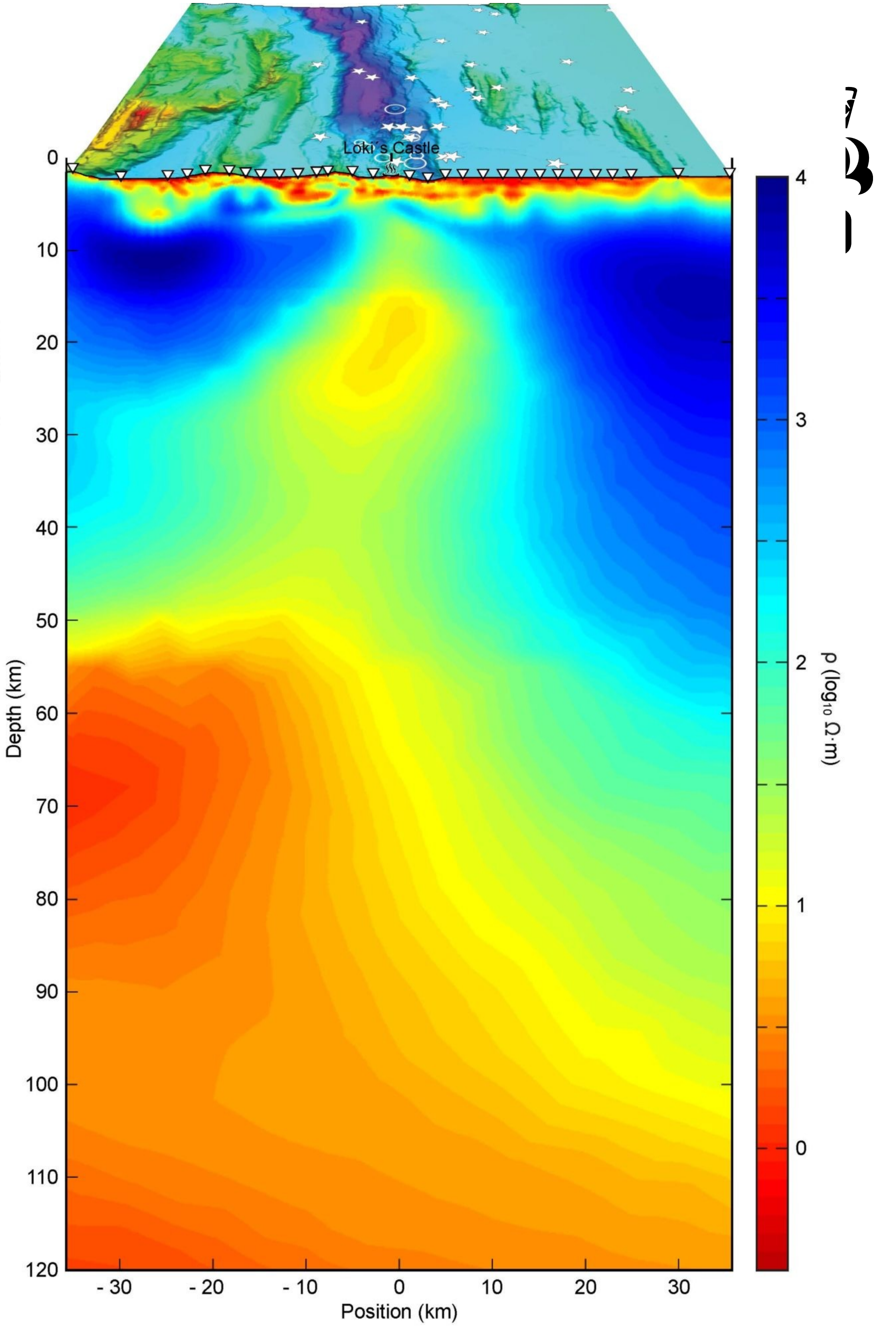
Spredning skeivt på aksedalen



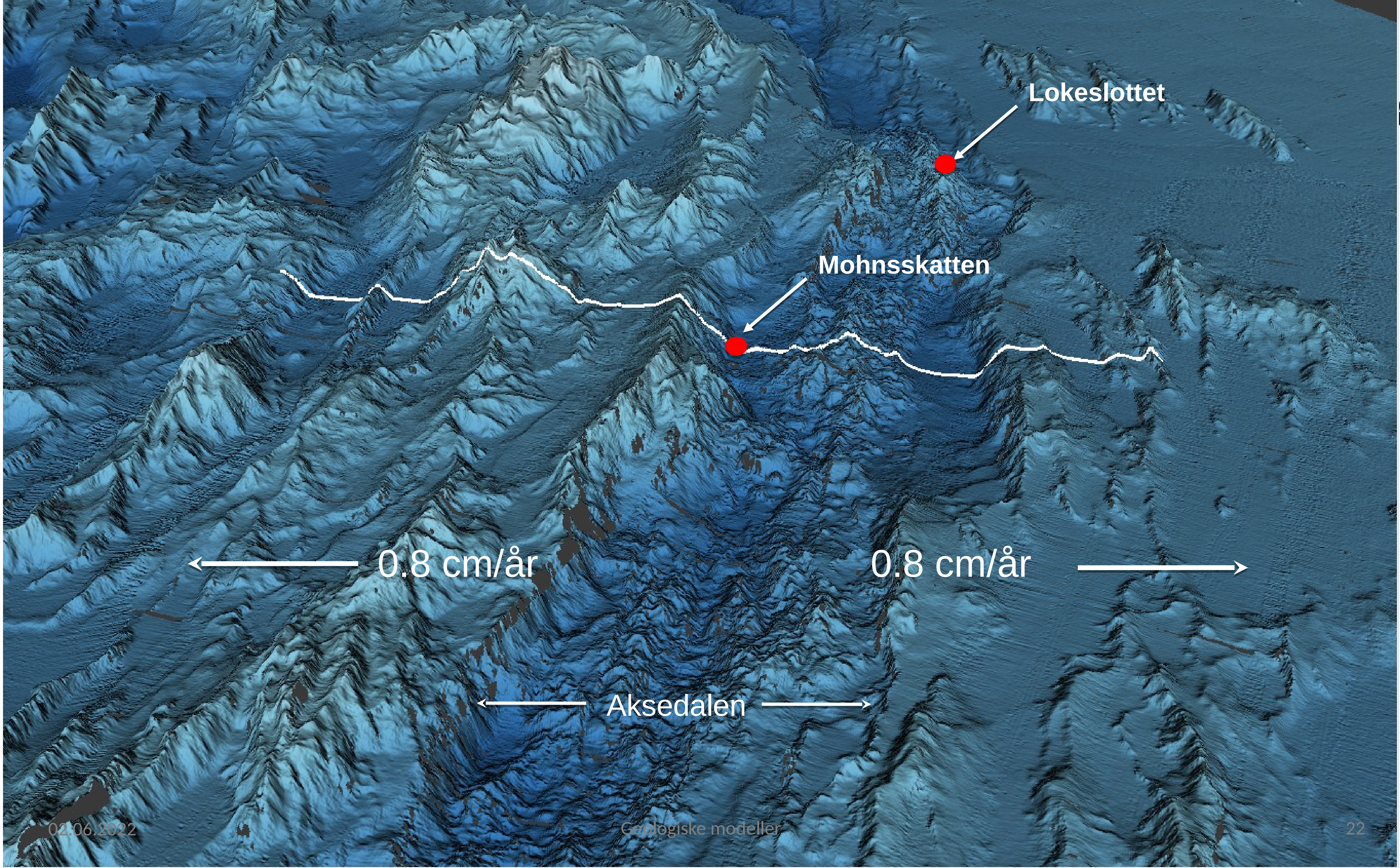
Skorpestruktur, CSEM-studie

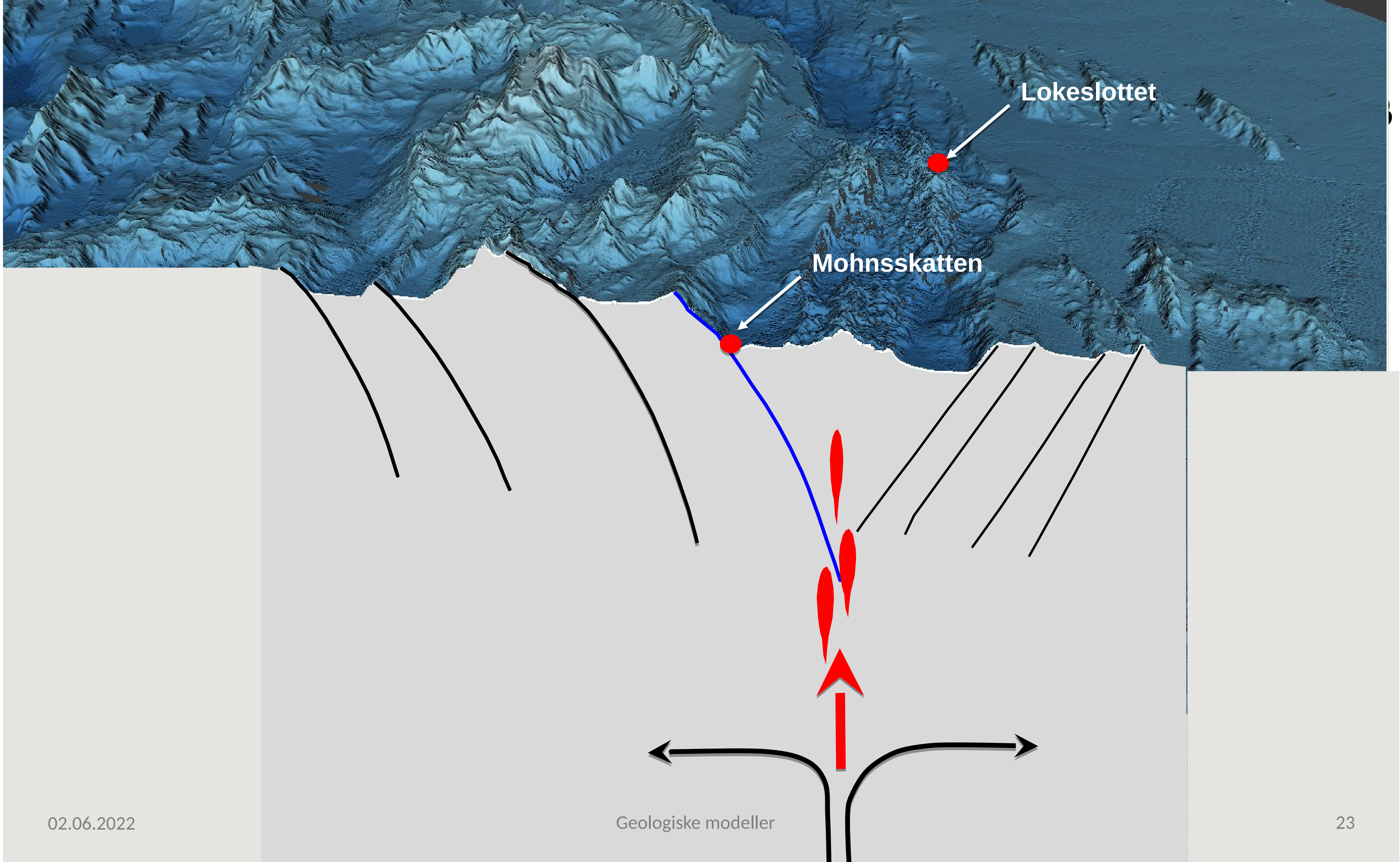


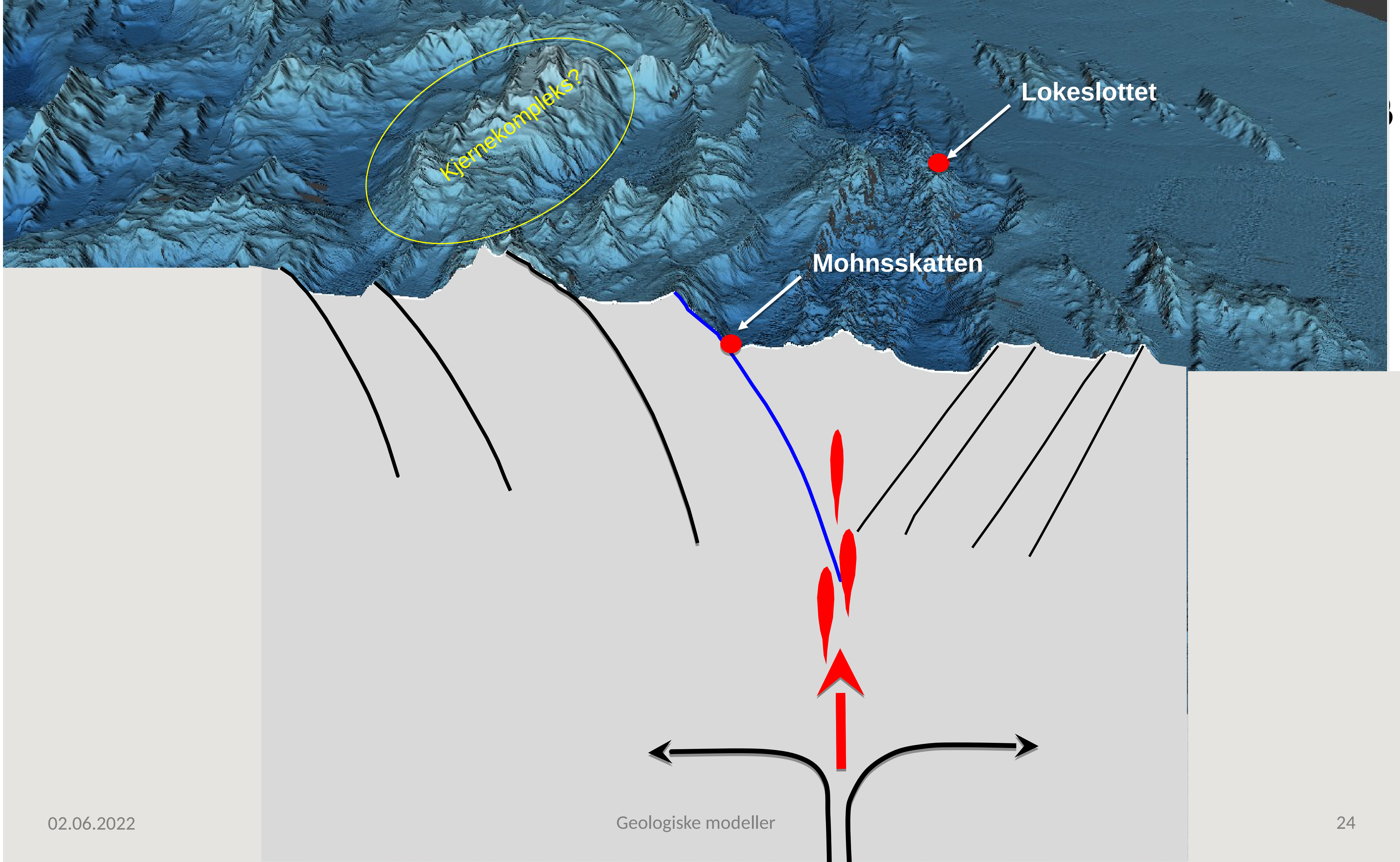




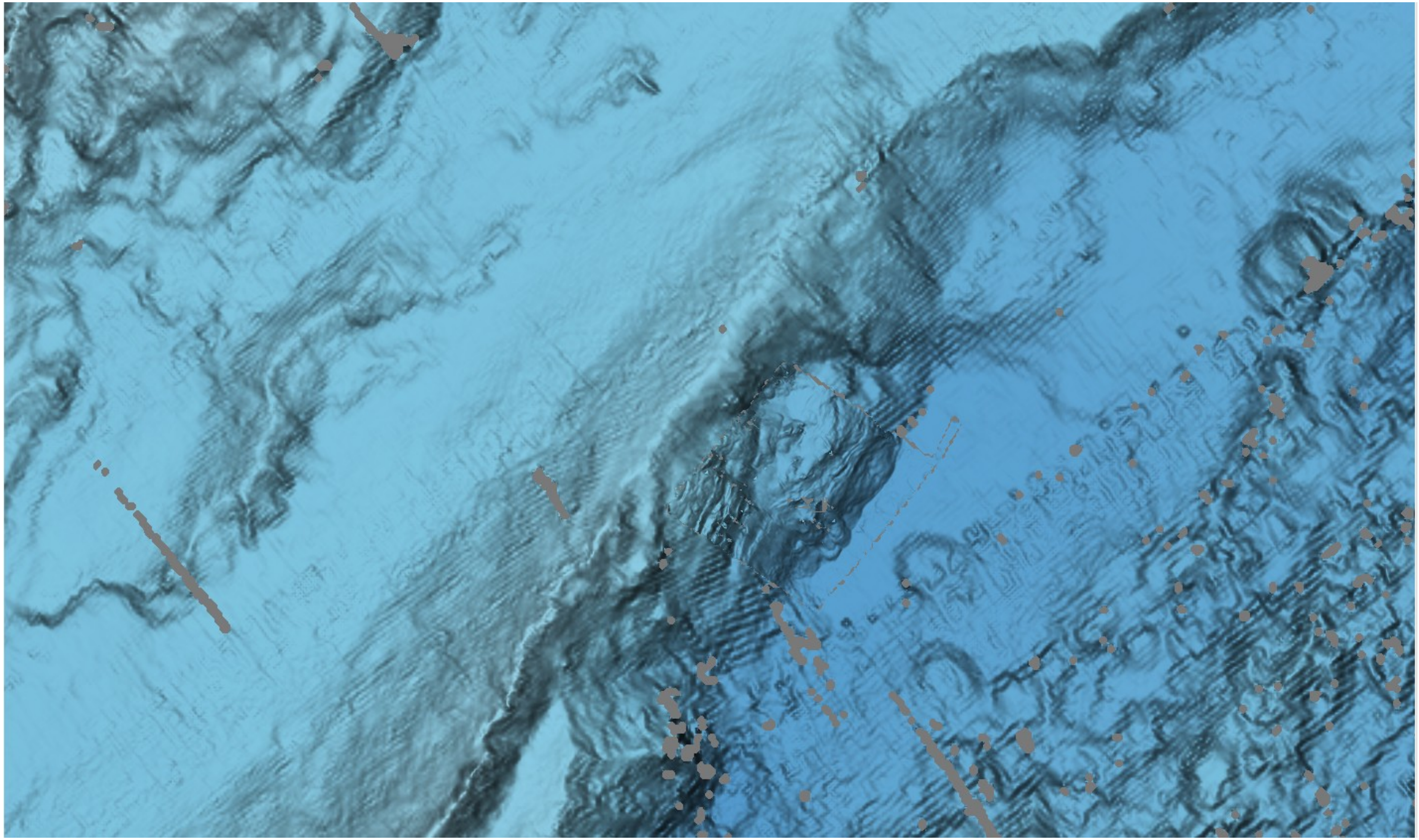
Johansen et al. 2019


Lokeslottet
Mohnsskatten
0.8 cm/år
0.8 cm/år
Aksedalen

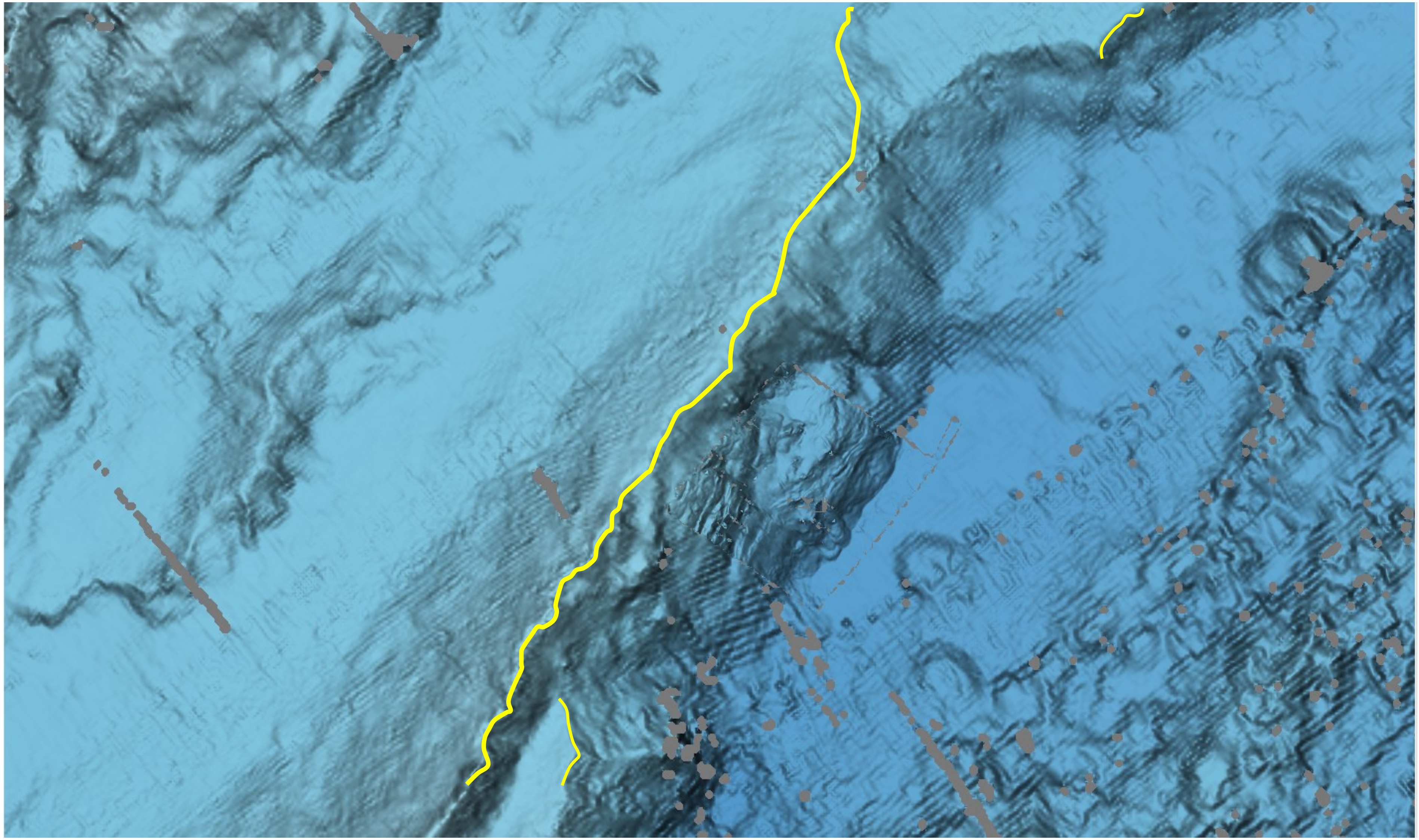

Lokeslottet
Mohnsskatten


Kjernekompleks?
Lokeslottet
Mohnsskatten

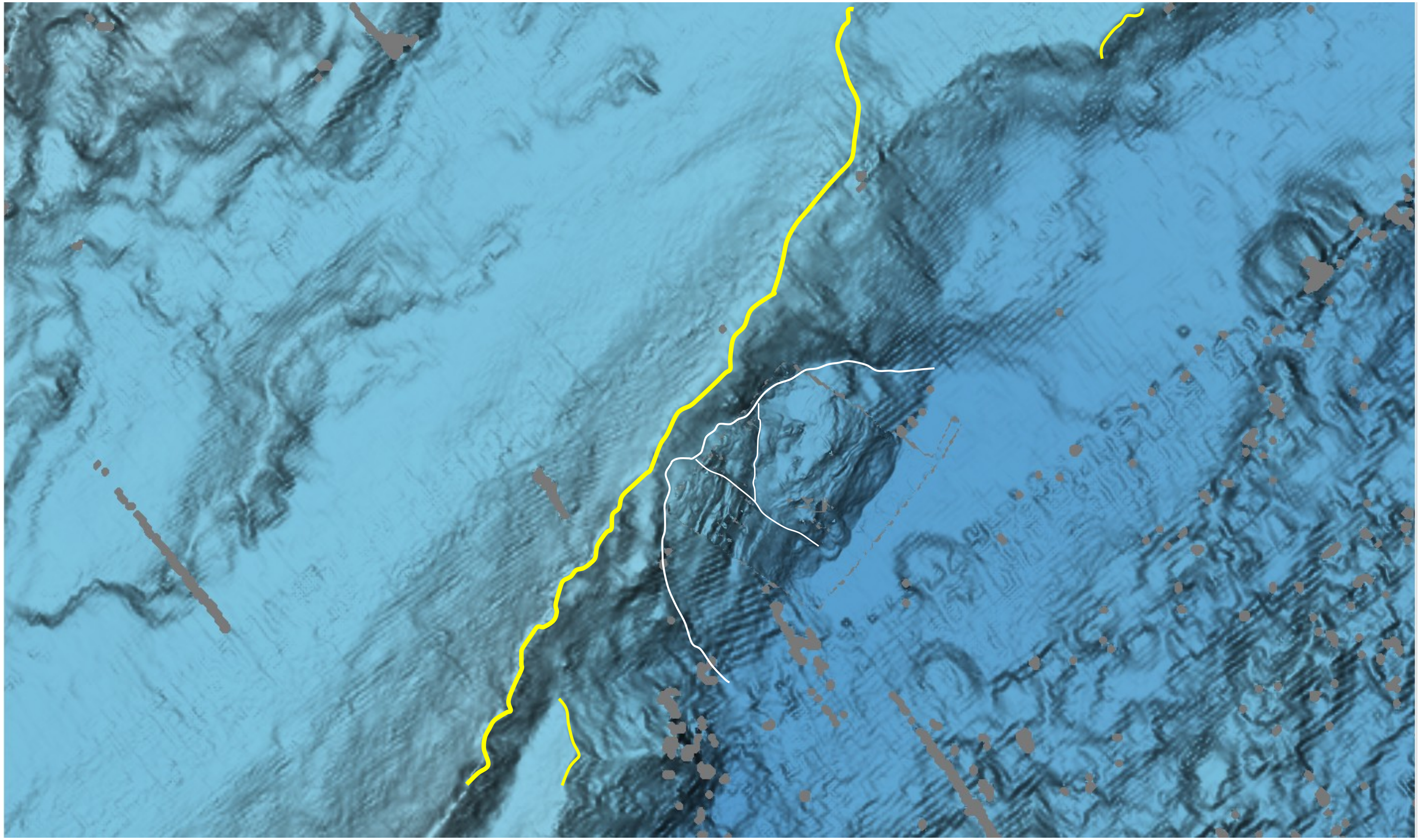
Grabenskrenten ved Mohnsskatten



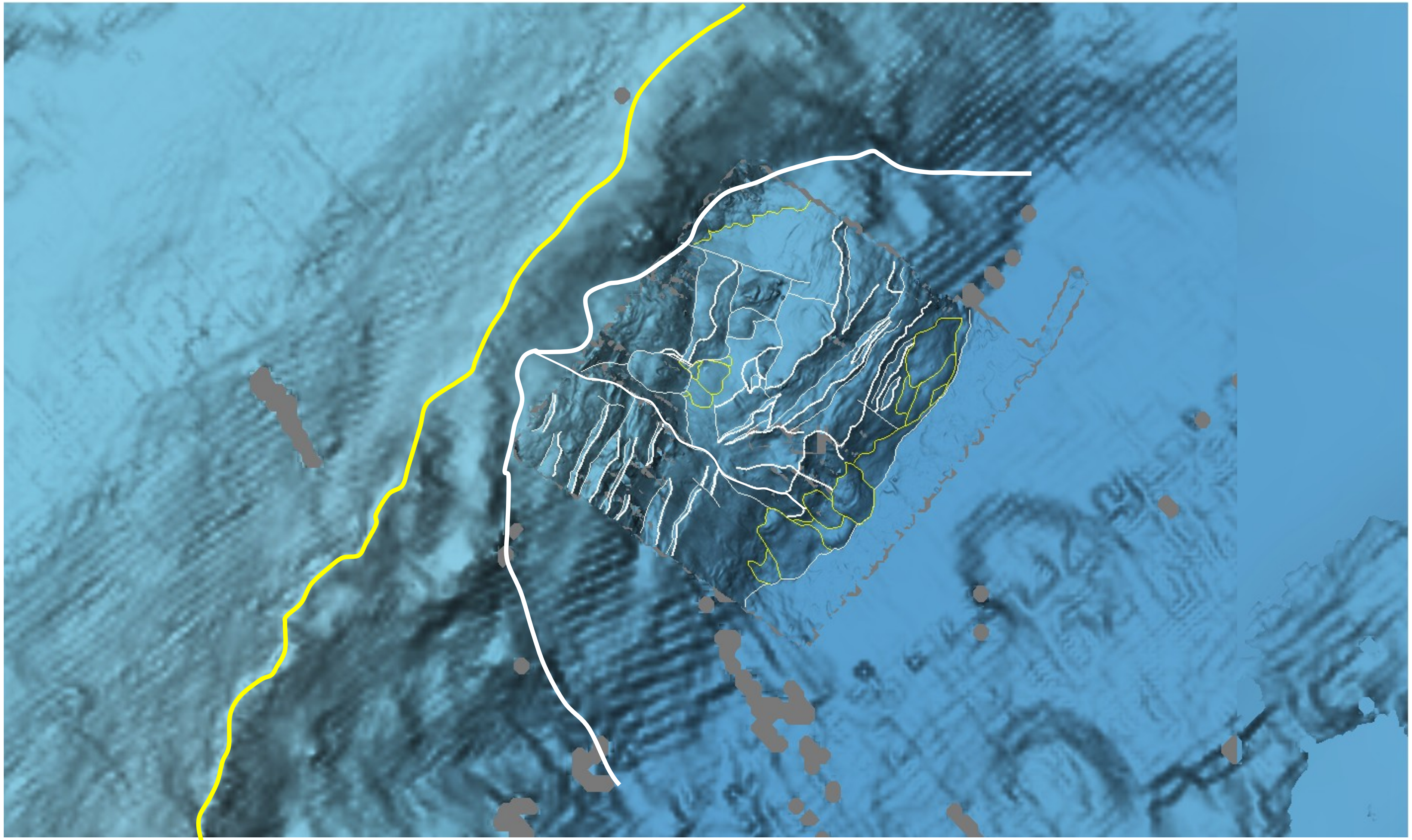
Reaktivering og modifisering av grabenskrenten



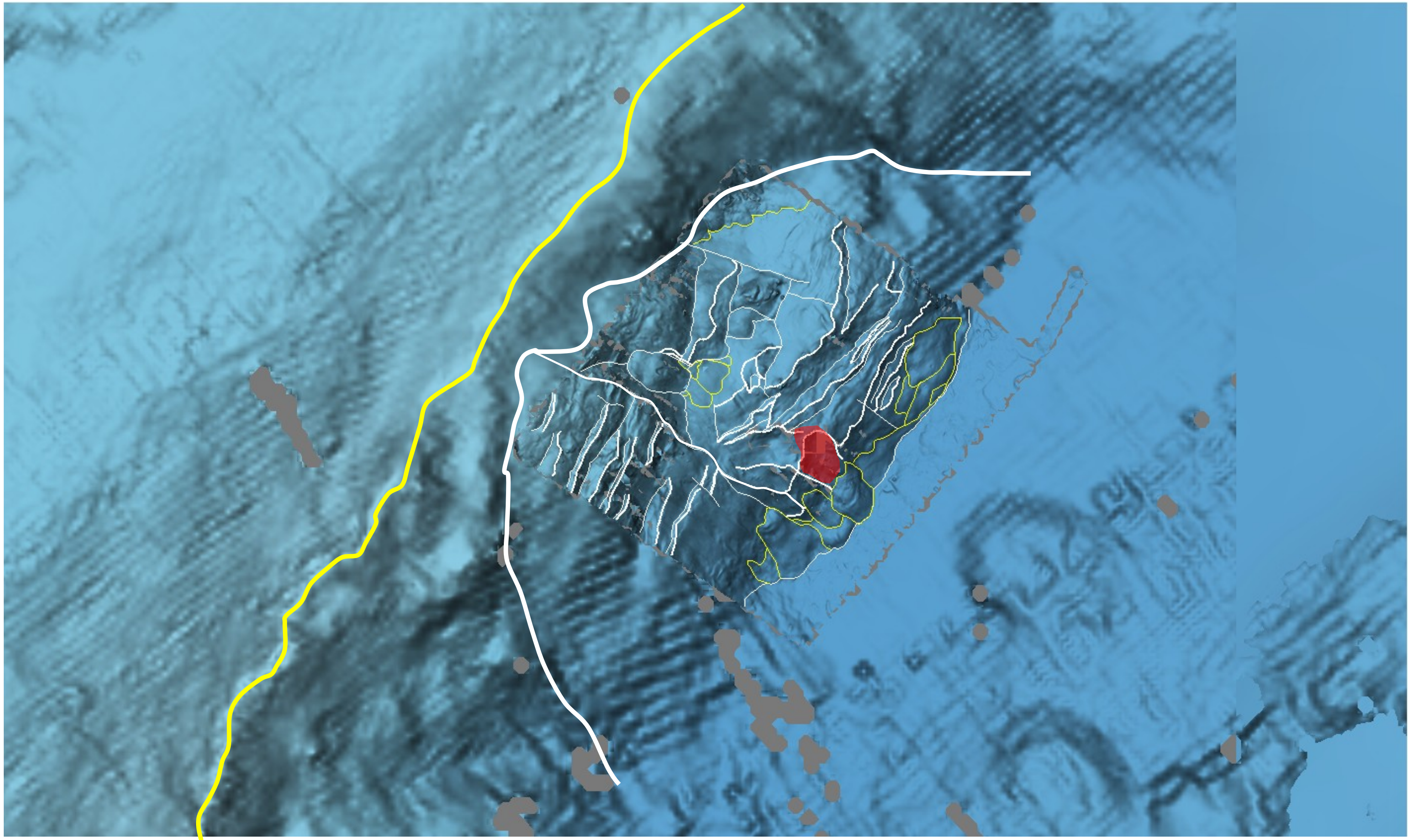
Reaktivering og modifisering av grabenskrenten

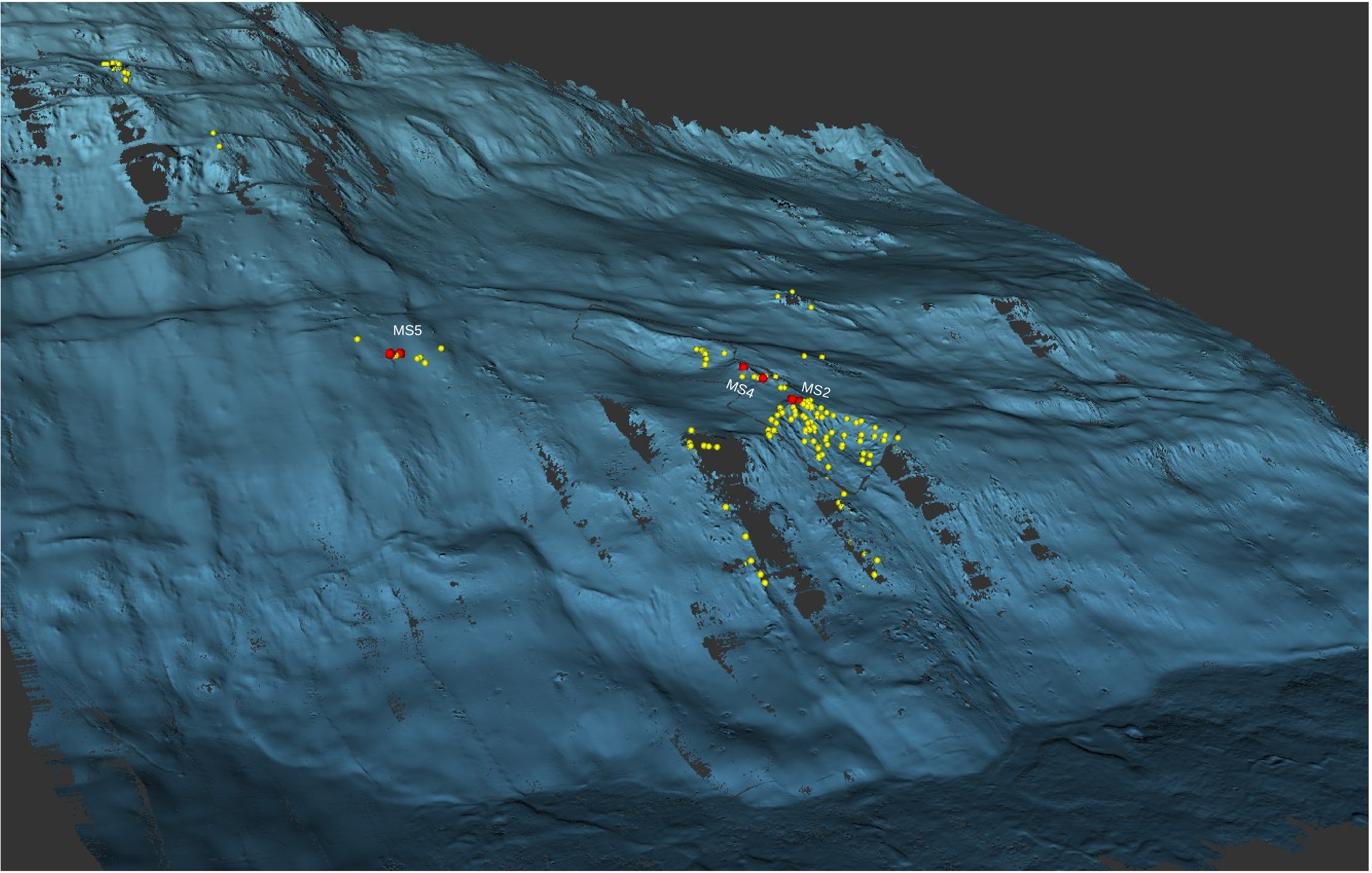


Reaktivering og modifisering av grabenskrenten, detaljer



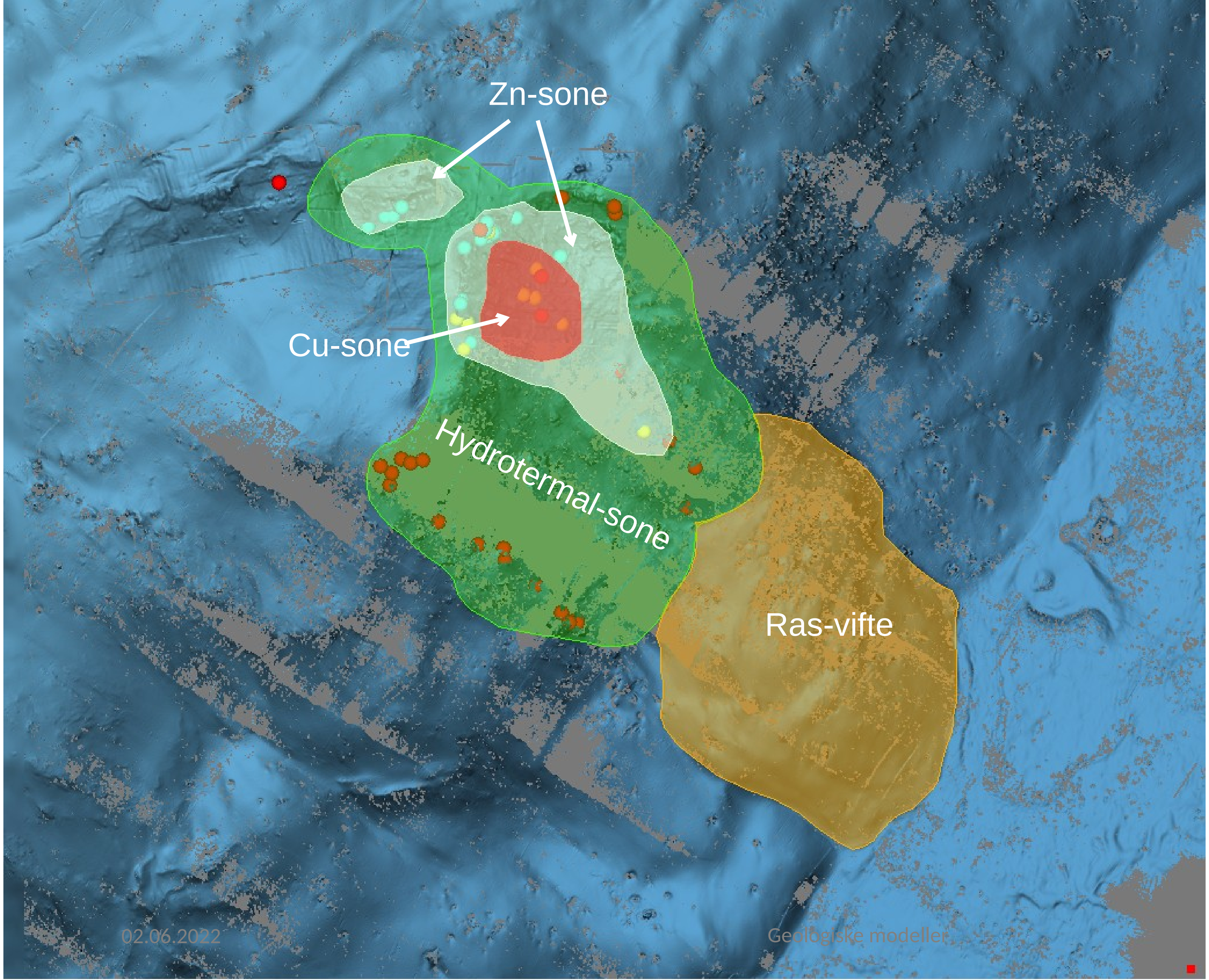
Reaktivering og modifisering av grabenskrenten, detaljer



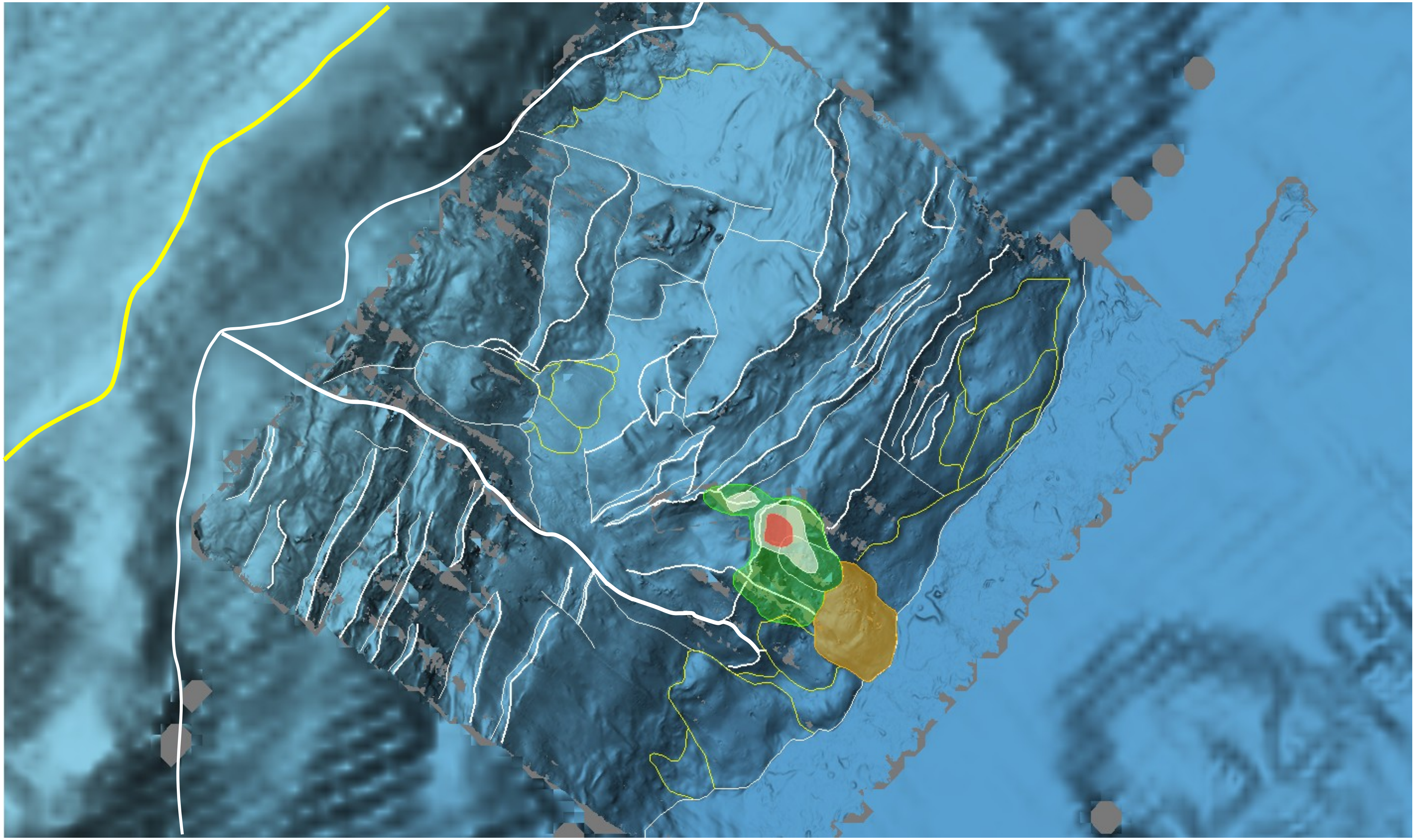


Prøvetaking på Mohnsksatten

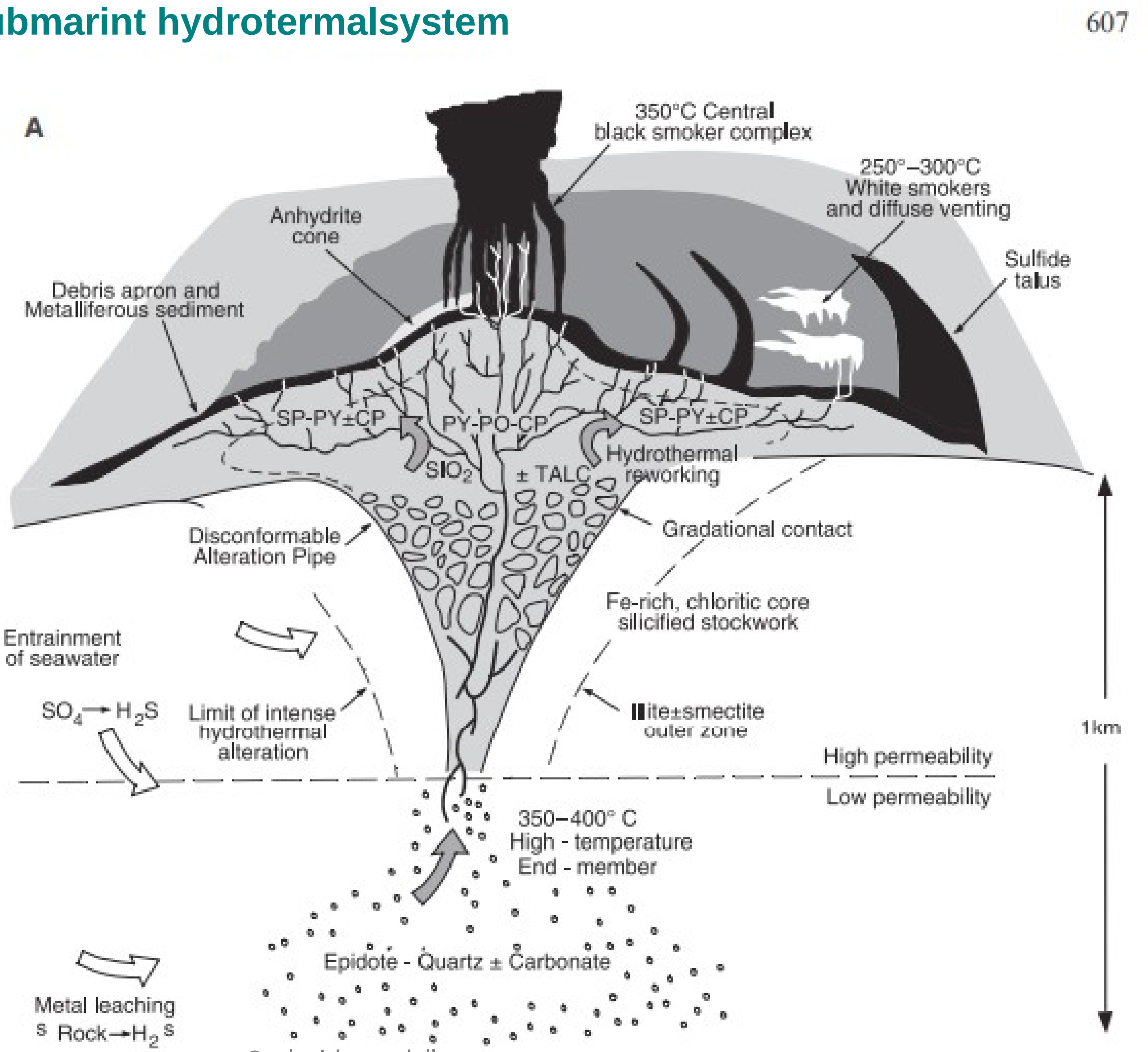
Mohnsskatten



Tektoniske forhold rundt Mohnsskatten

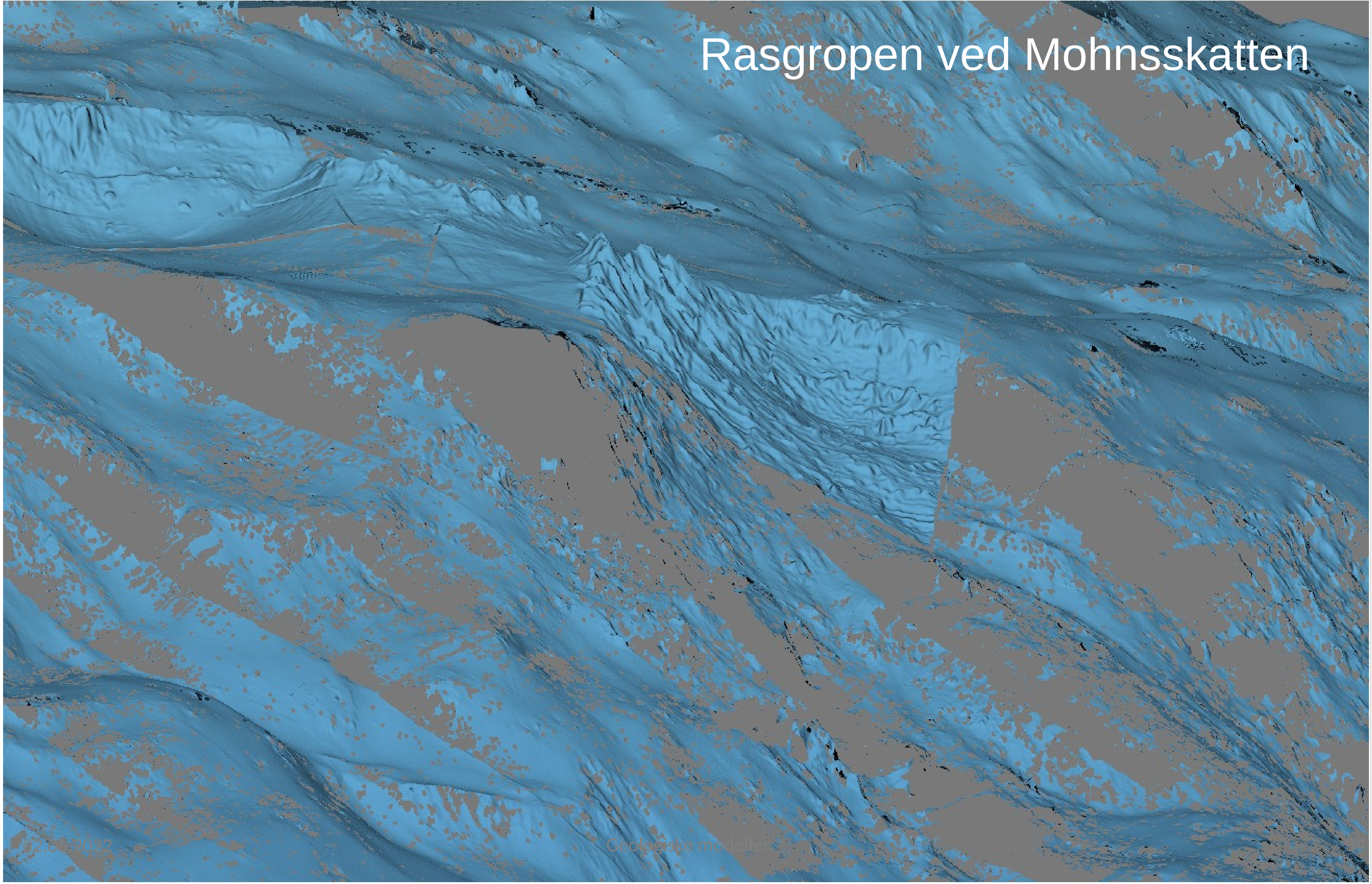


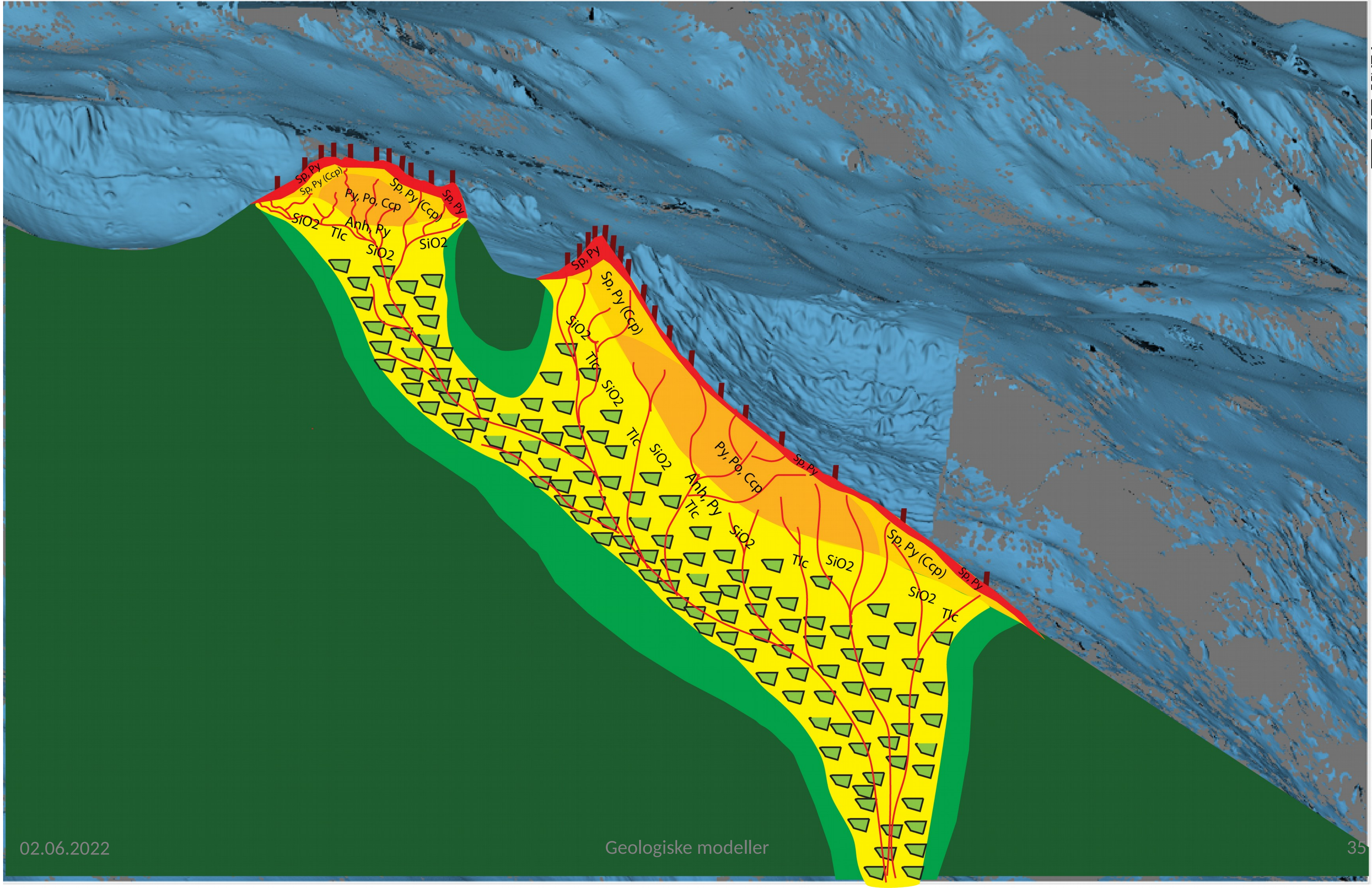
Submarint hydrotermalsystem

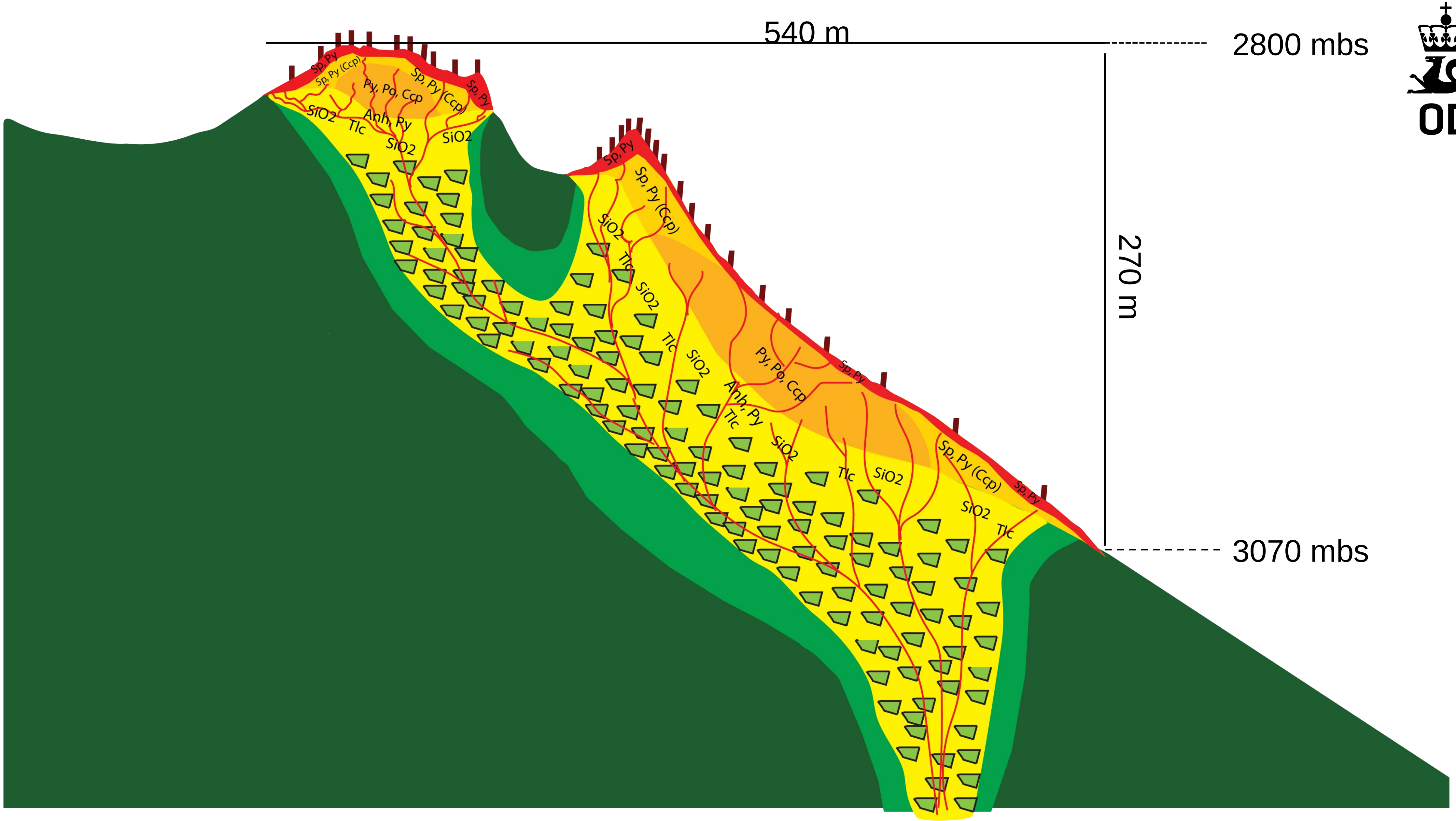


Fra Piranjo 2009, etter Hannington et al 1995

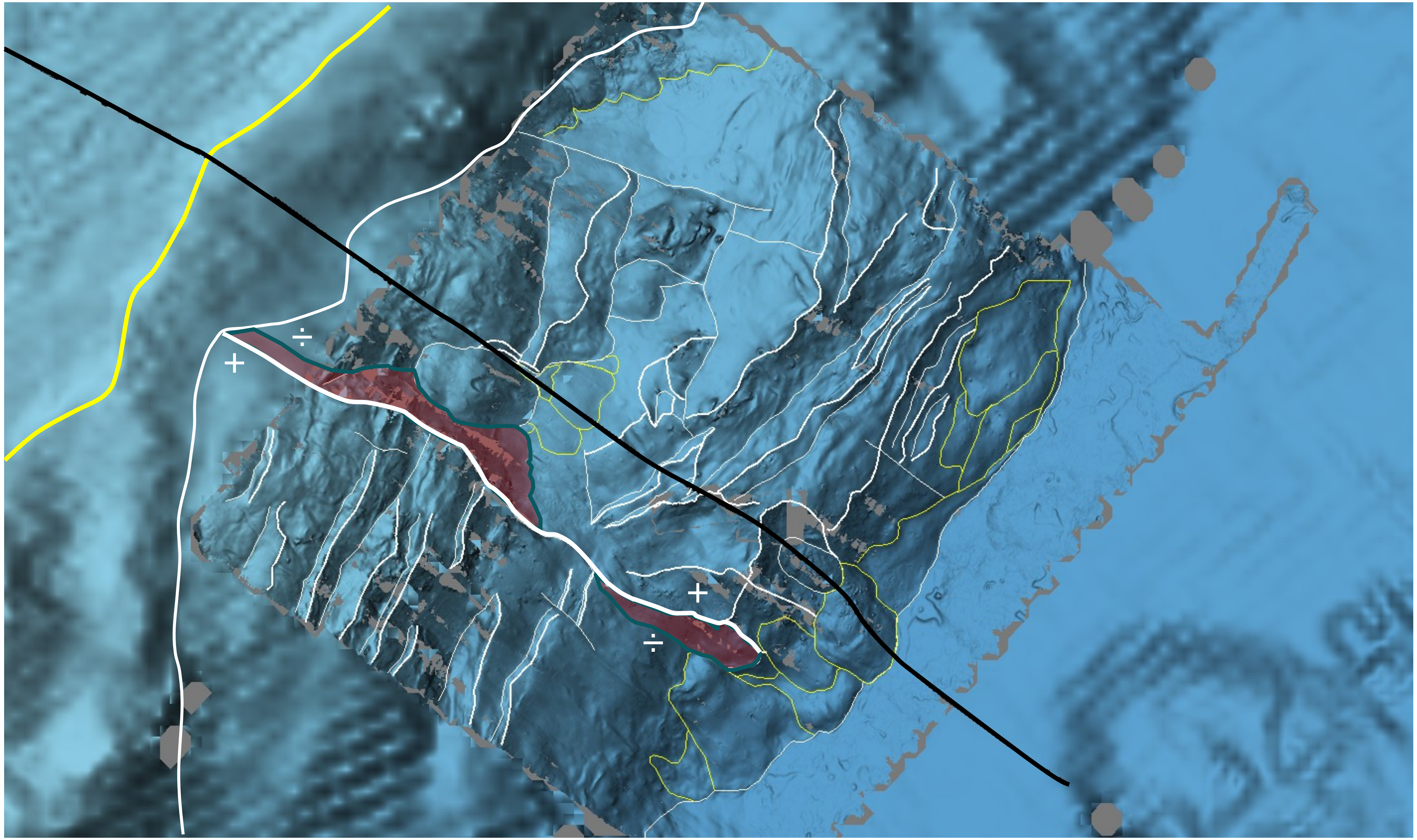
Rasgropen ved Mohnsskatten



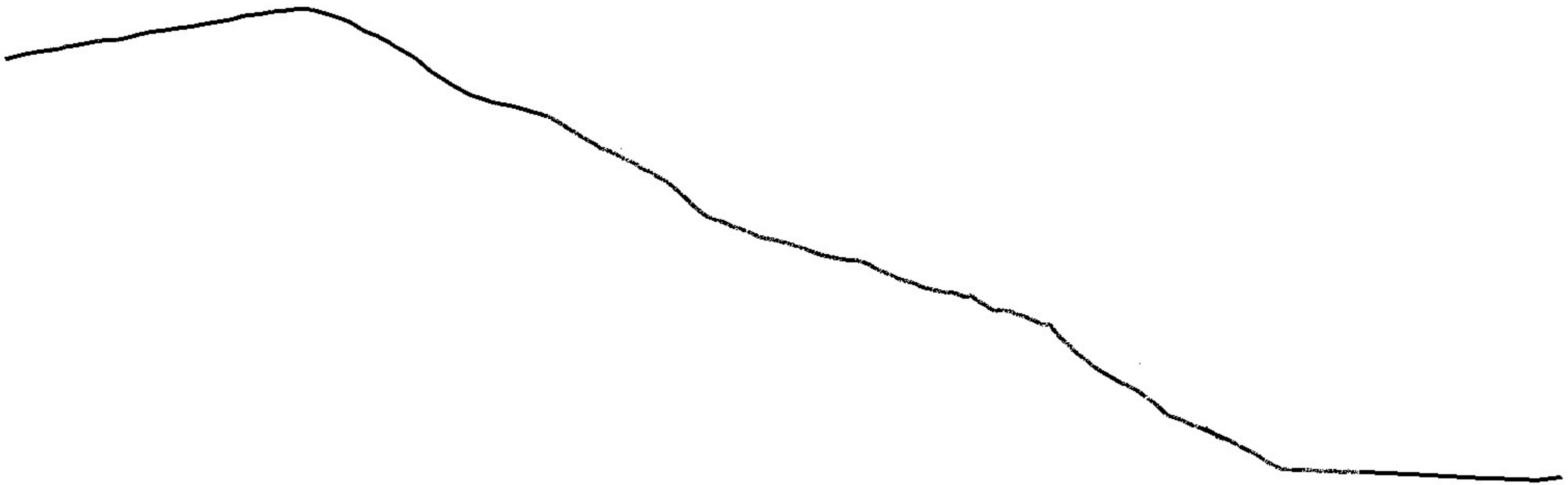

Sp, Py
Sp, Py (Ccp)
Py, Po, Ccp
Sp, Py (Ccp)
Sp, Py
SiO2
Tlc
Anh, Py
SiO2
SiO2
Sp, Py
Sp, Py (Ccp)
SiO2
Tlc
SiO2
Tlc
SiO2
Py, Po, Ccp
Sp, Py
Anh, Py
Tlc
SiO2
Tlc
SiO2
Sp, Py (Ccp)
Sp, Py
SiO2
Tlc


540 m
2800 mbs
270 m
3070 mbs
Sp, Py
Sp, Py (Ccp)
Py, Po, Ccp
Anh, Py
SiO2
Tlc
Py, Po, Ccp
Anh, Py
Sp, Py (Ccp)

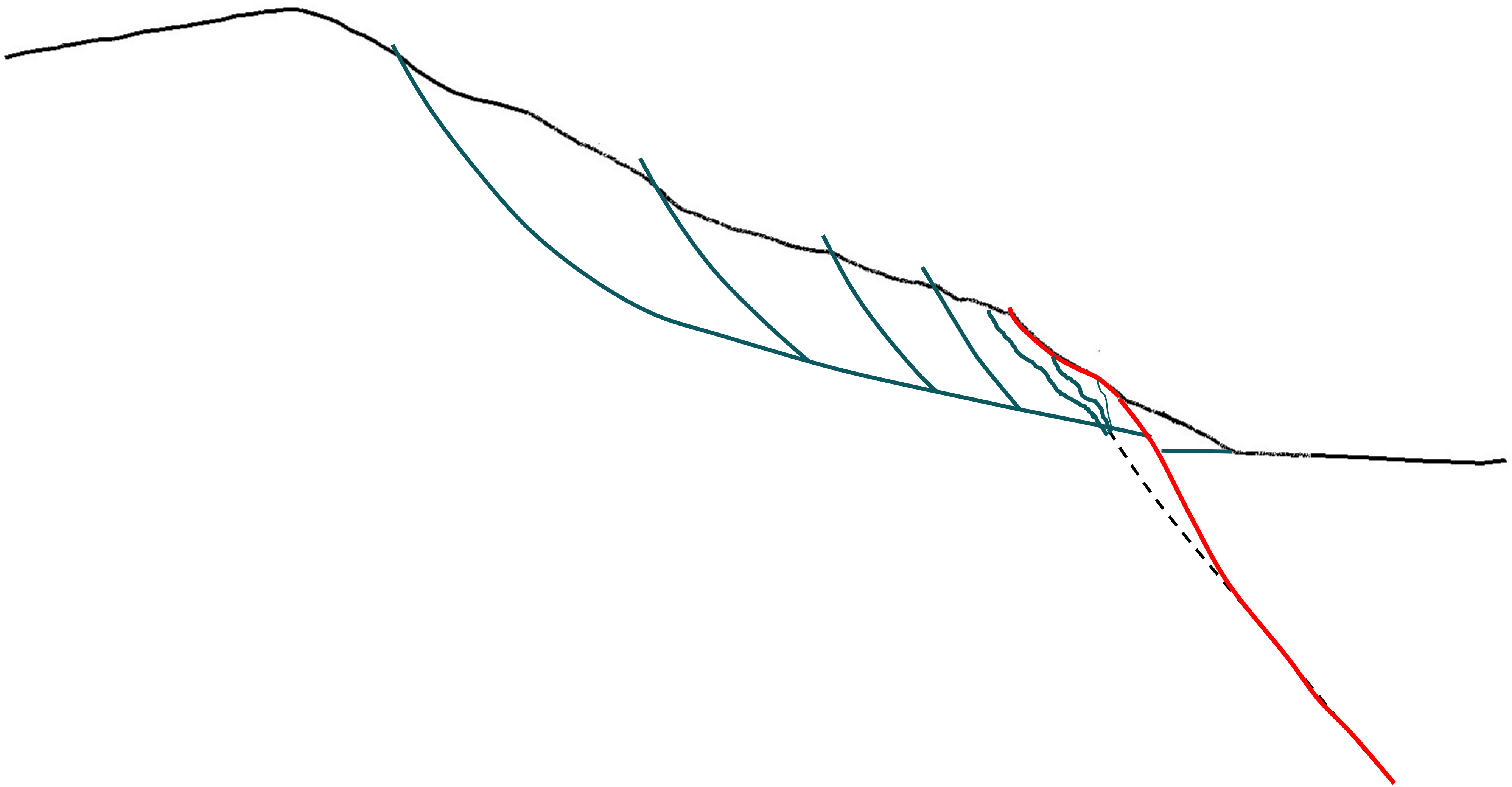
Modifisering av grabenskrenten, detaljer



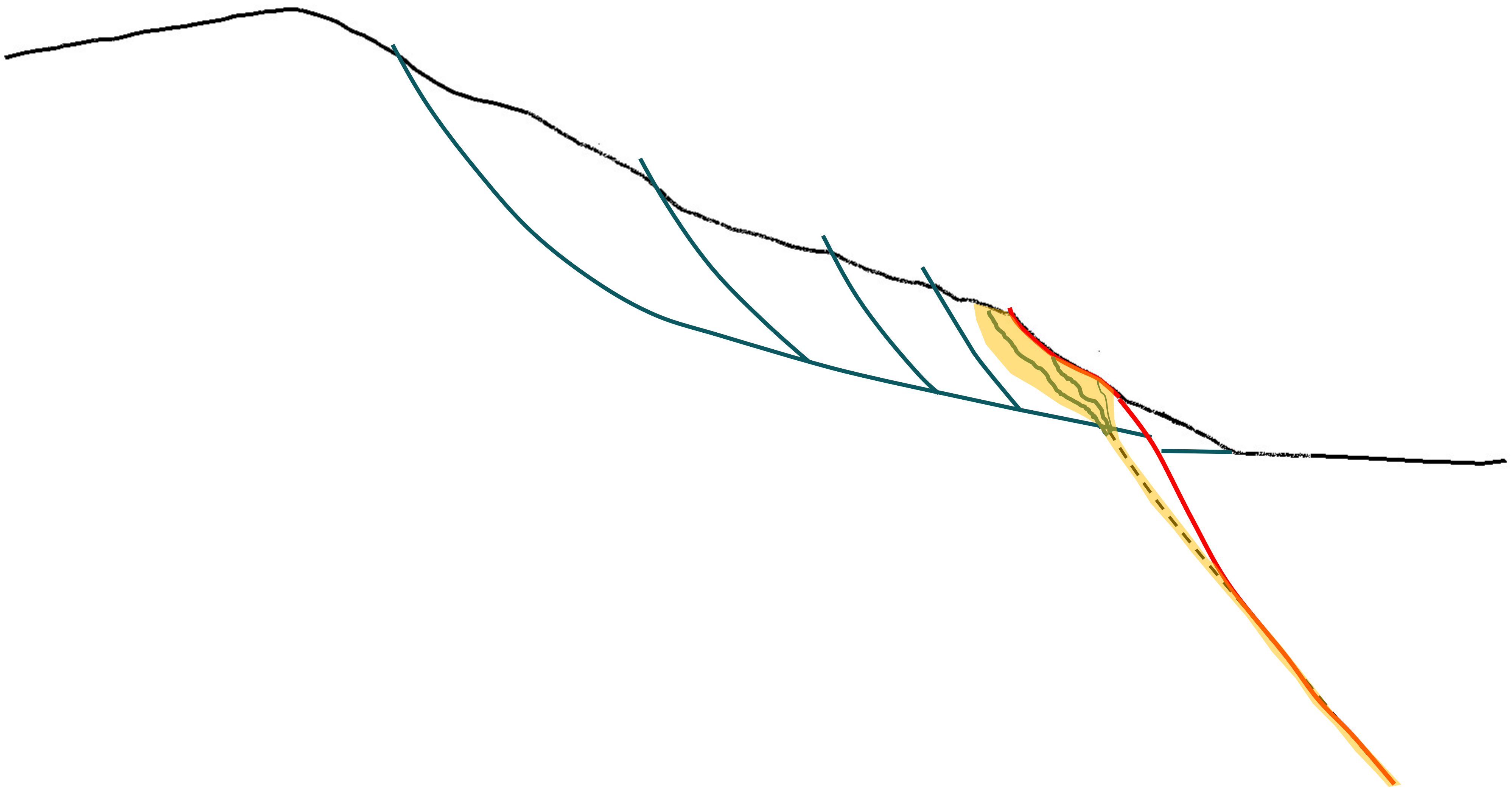
Grabenskrenten ved Mohnsskatten, batymetrisk profil



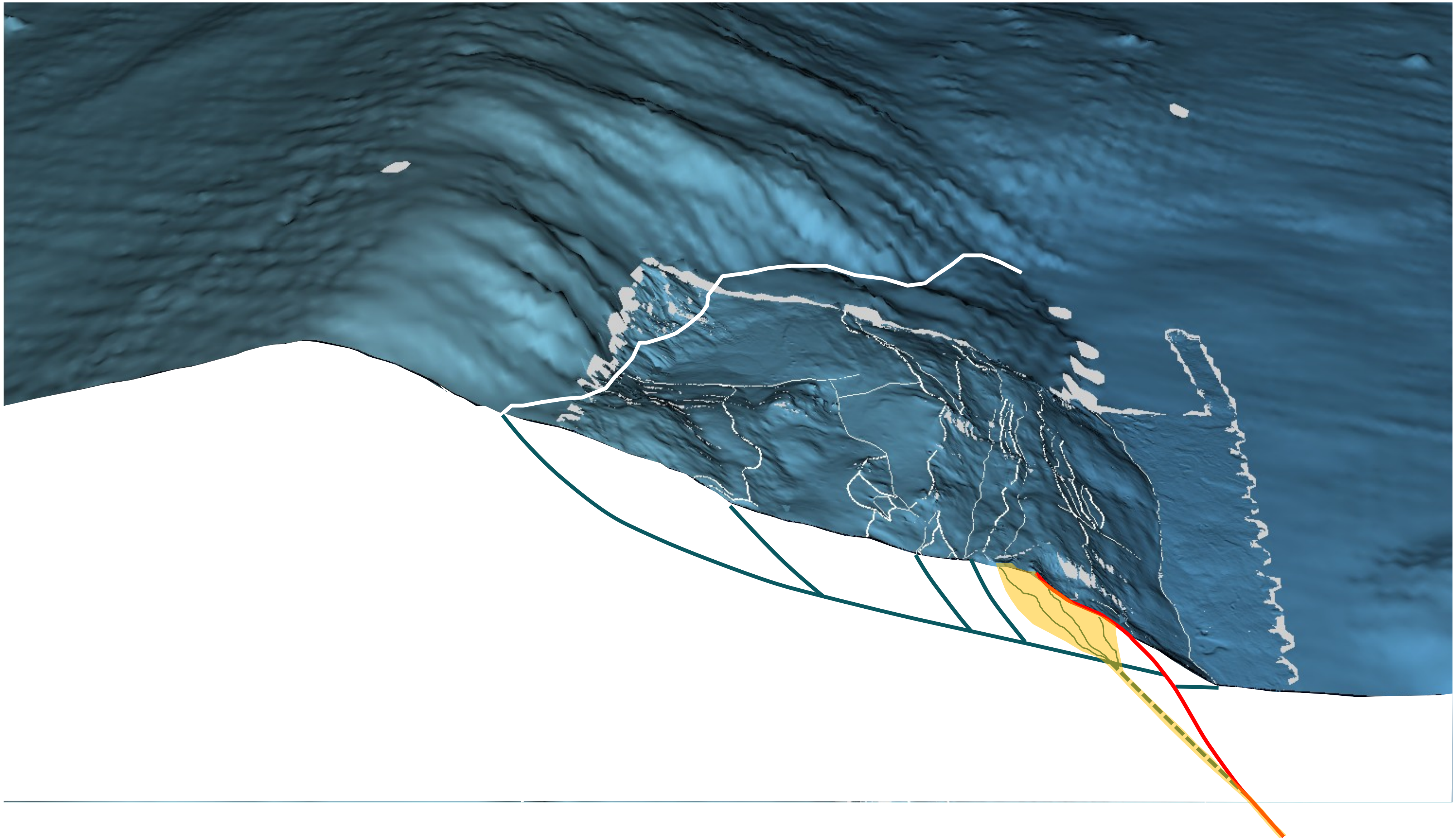
Modell for tektonisk reaktivering av skrent



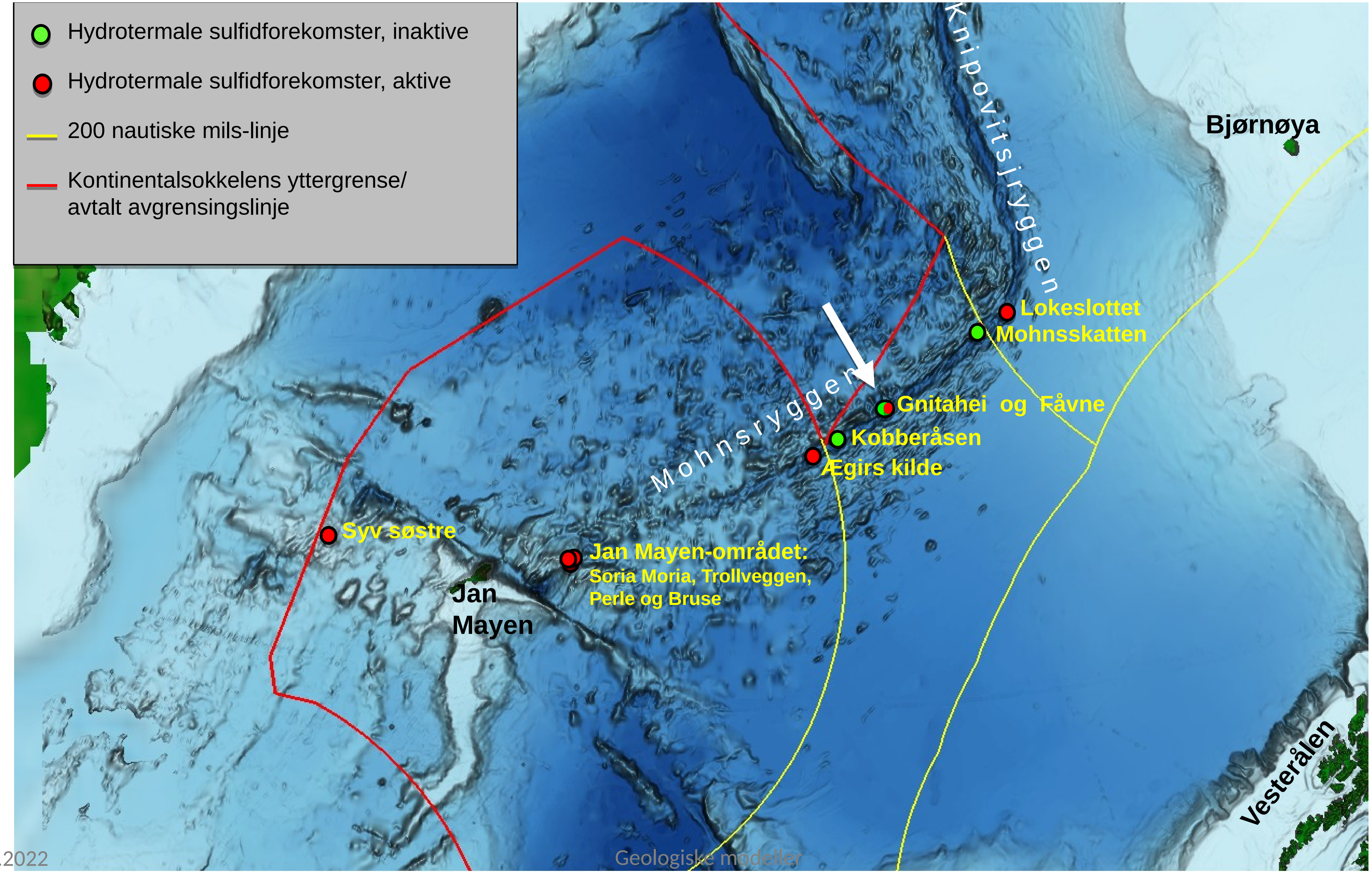
Tektonisk reaktivering og mineralisering



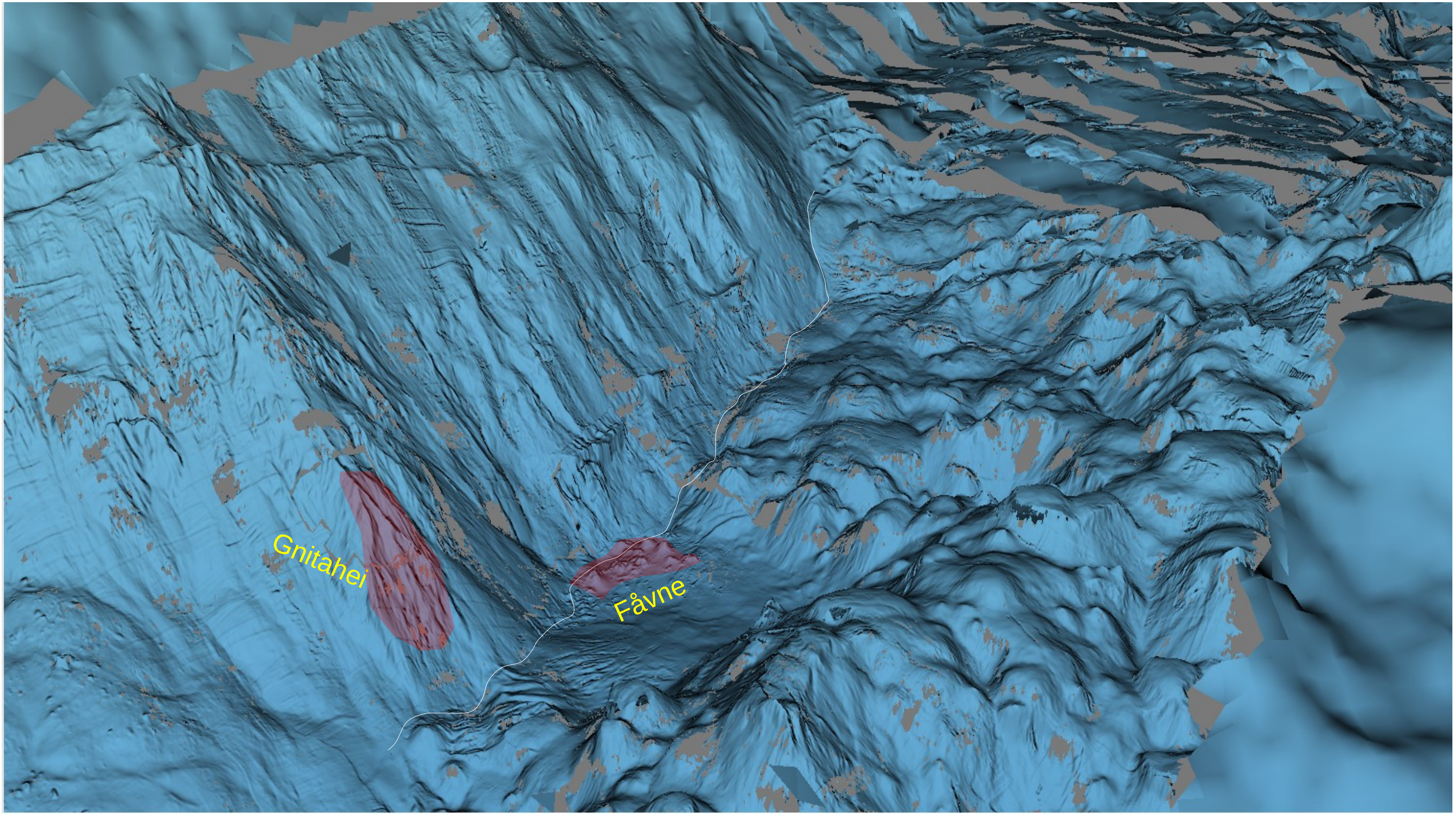
3D-framstilling

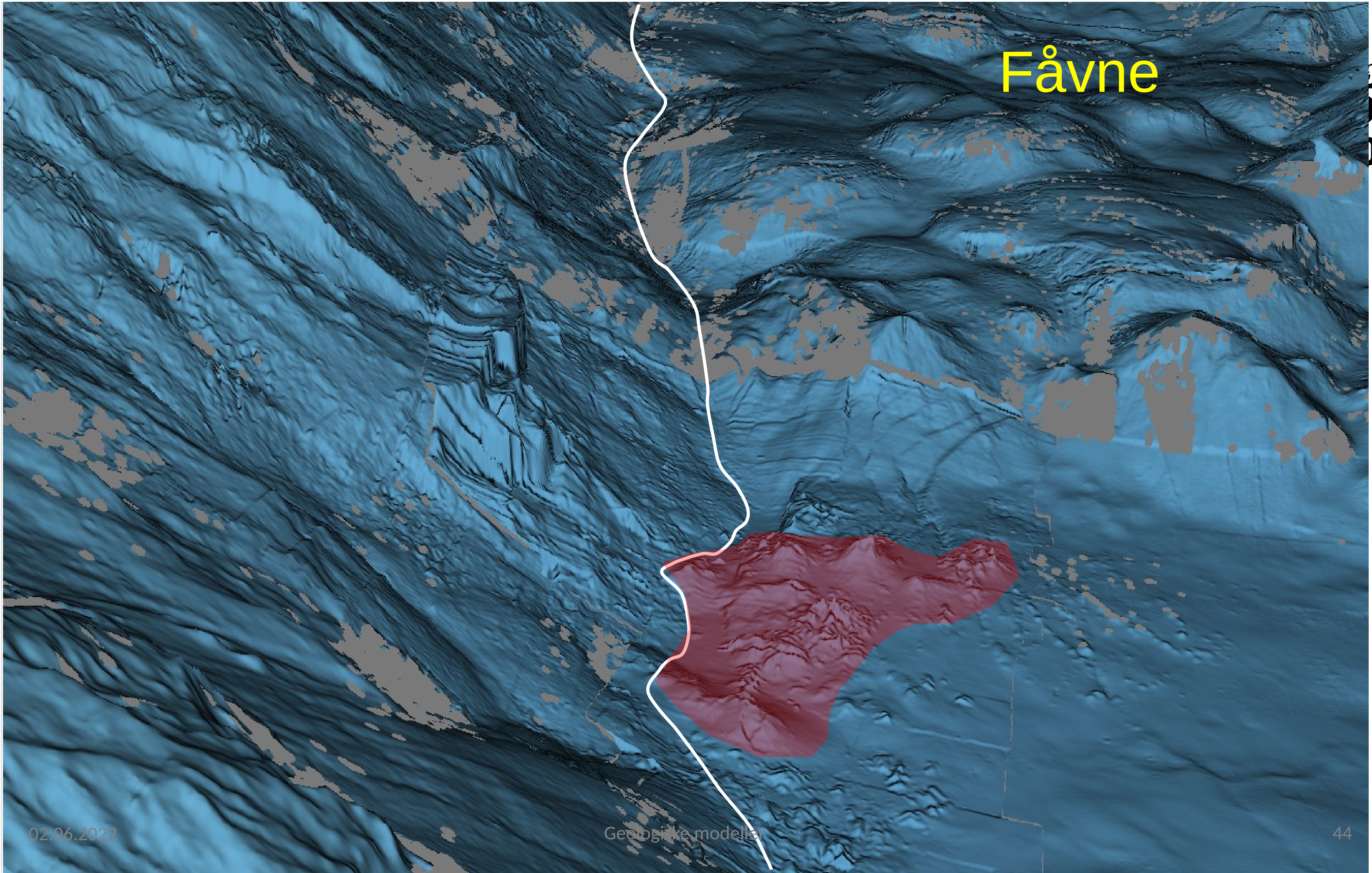


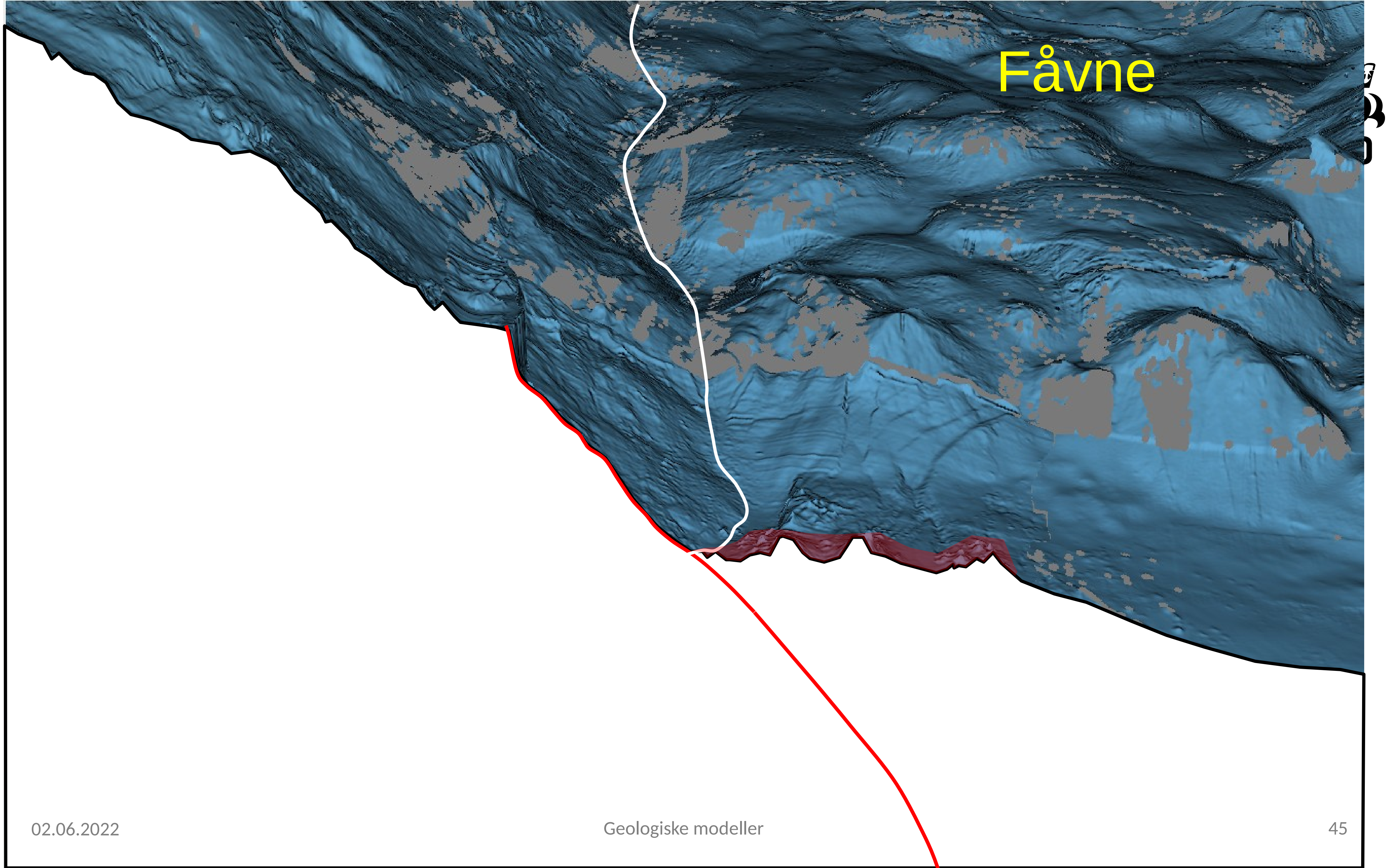
Kjente hydrotermalforekomster på norsk sokkel

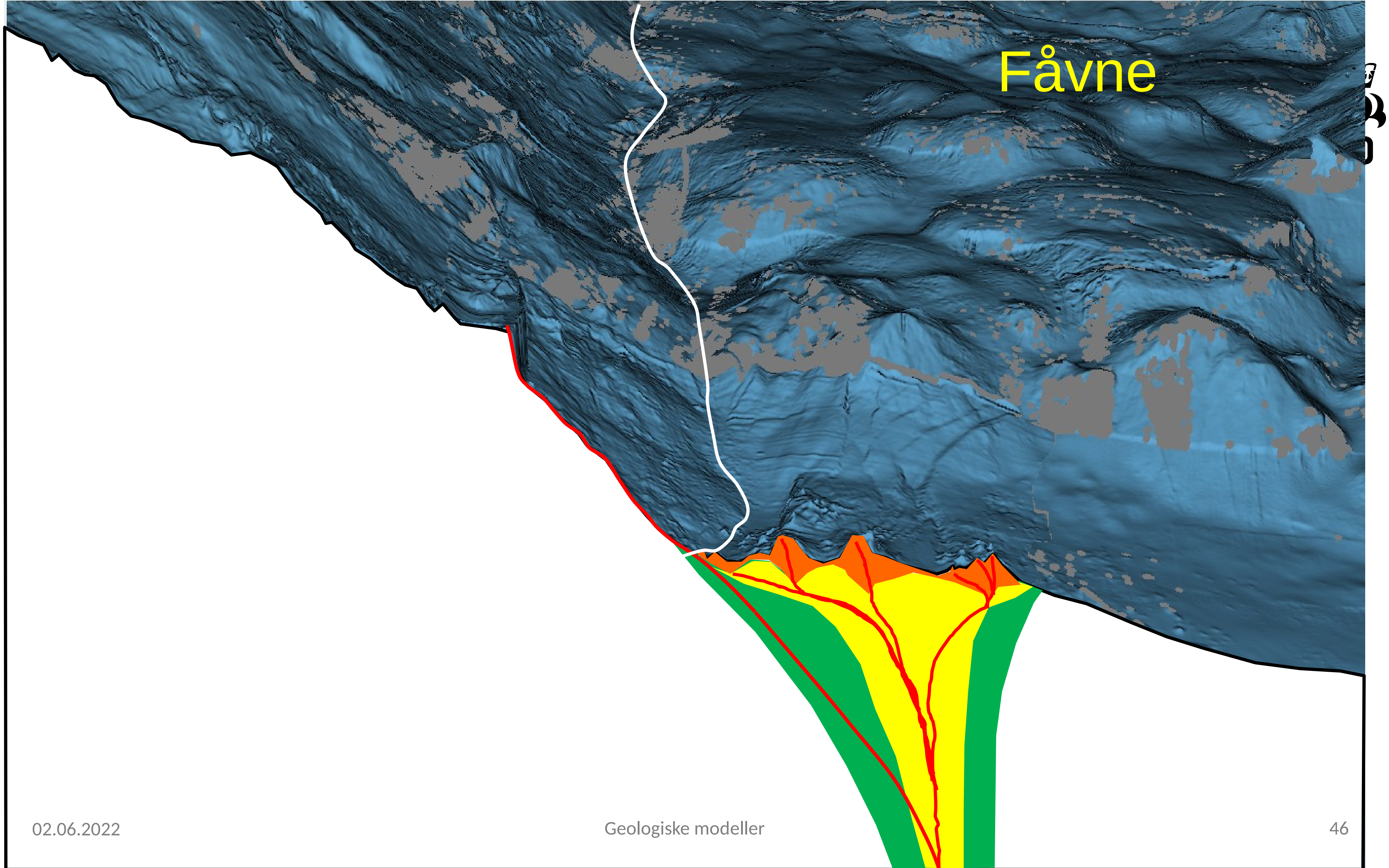


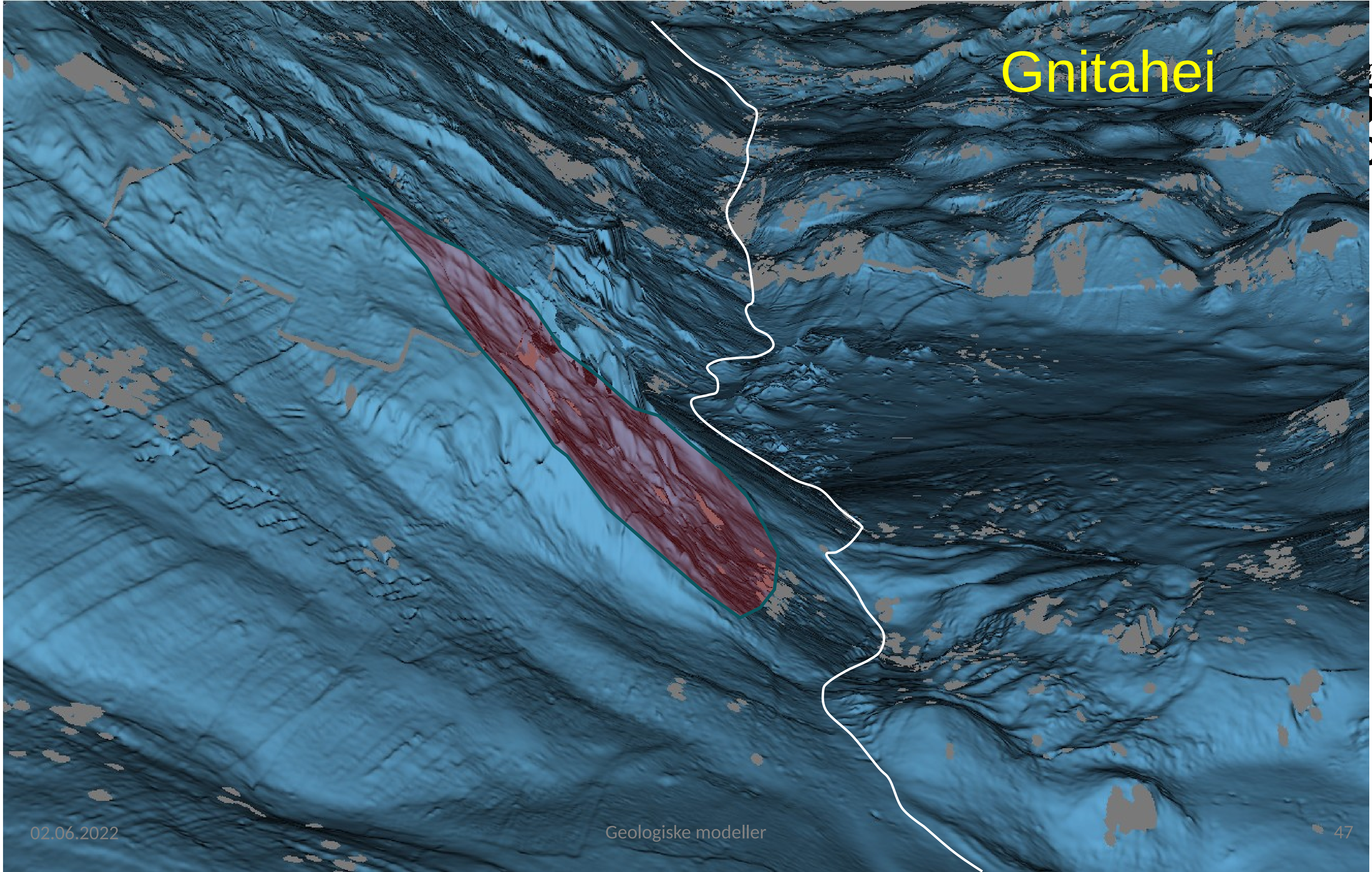
Gnitahei og Fåvne, tektonisk ramme

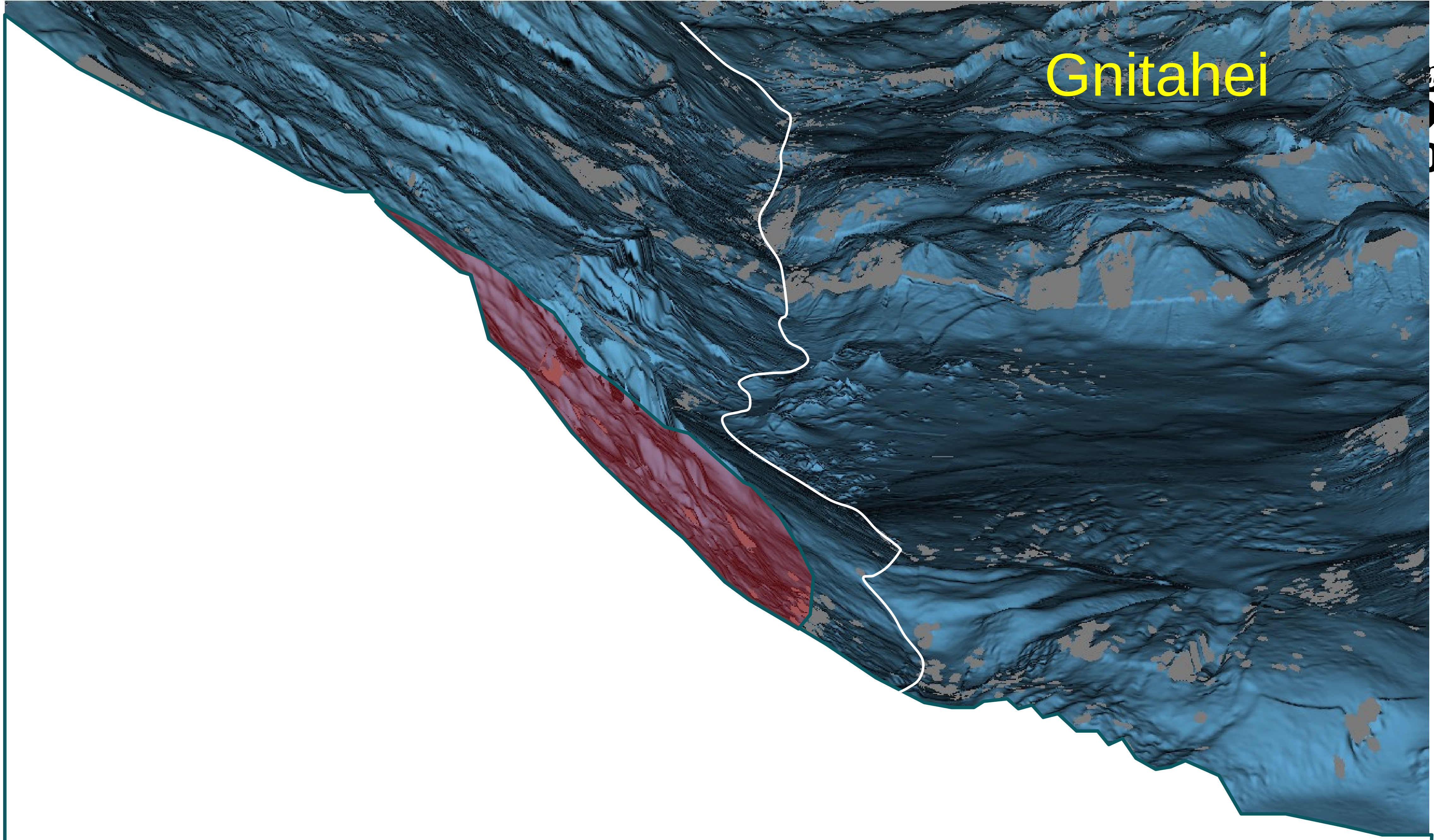


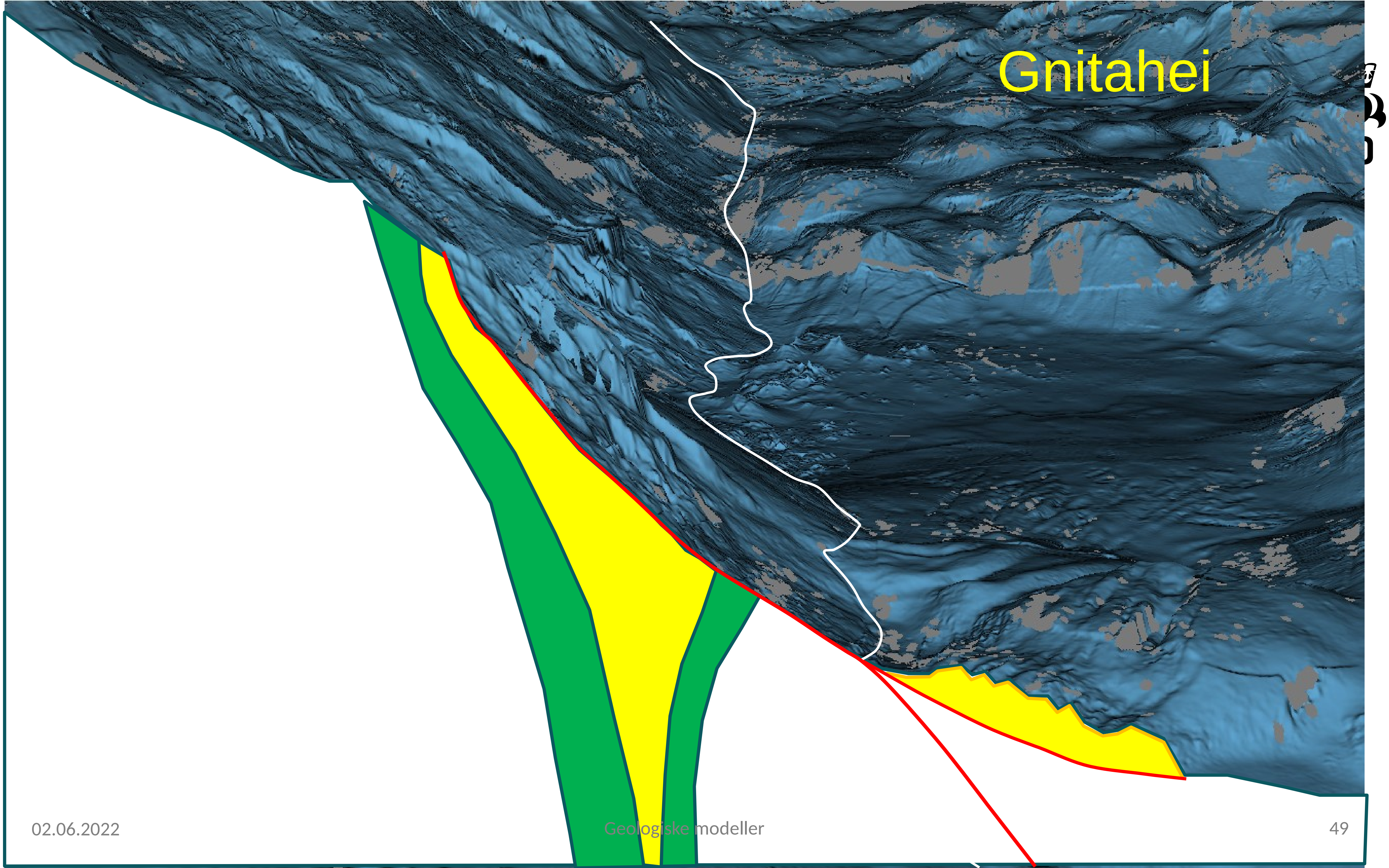

Fåvne


Fåvne

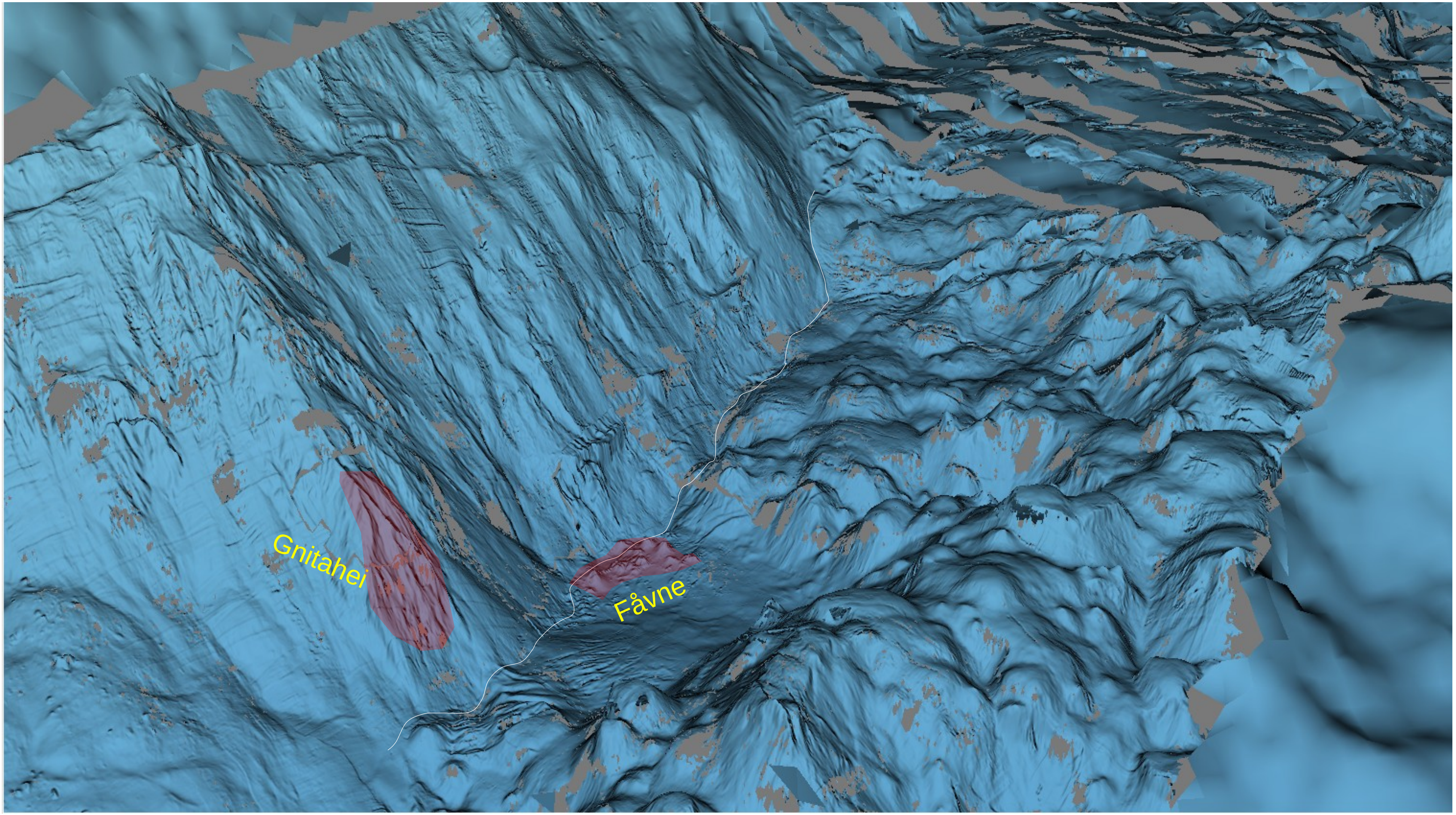

Fåvne


Gnitahei

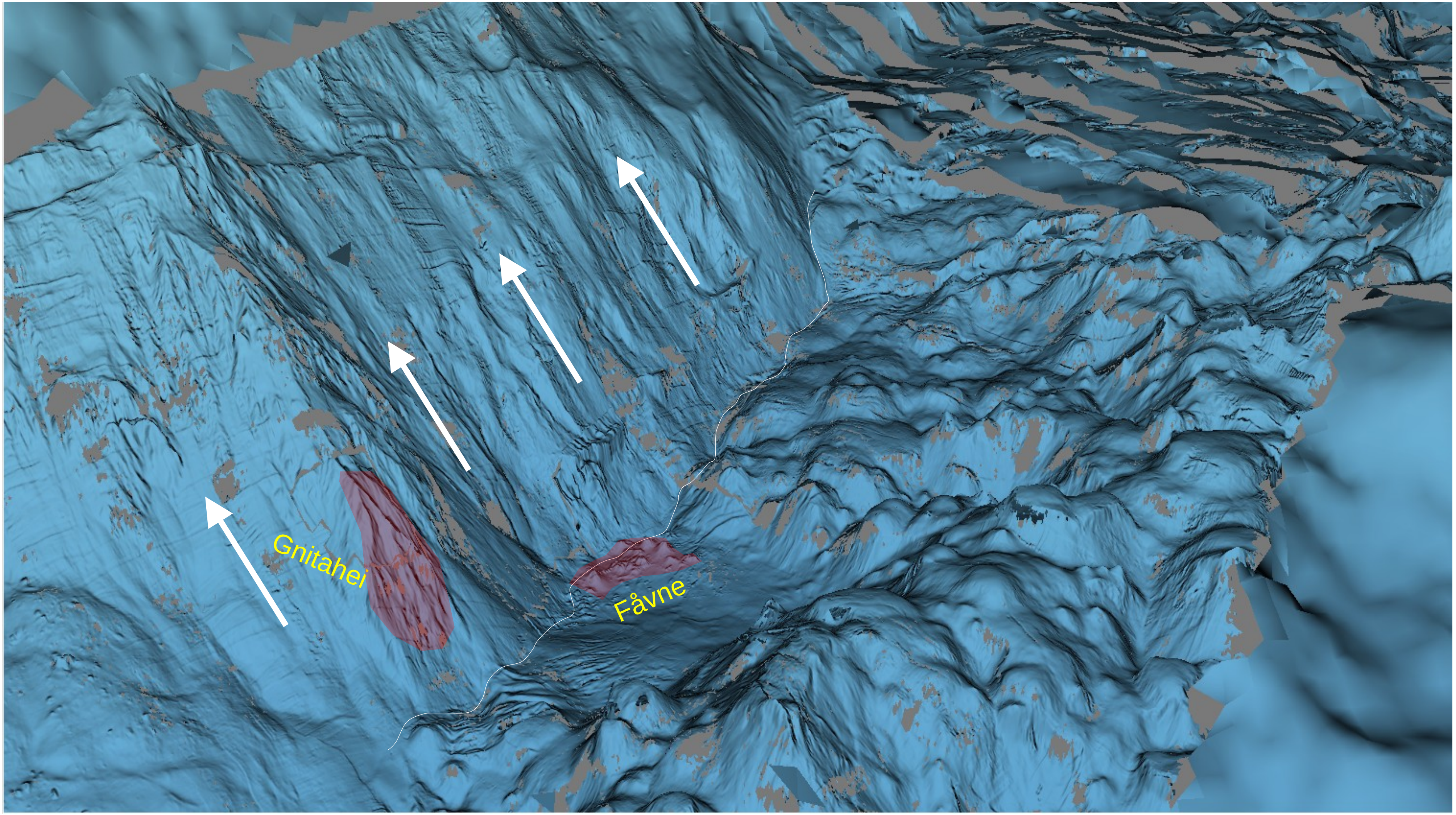

Gnitahei


Gnitahei

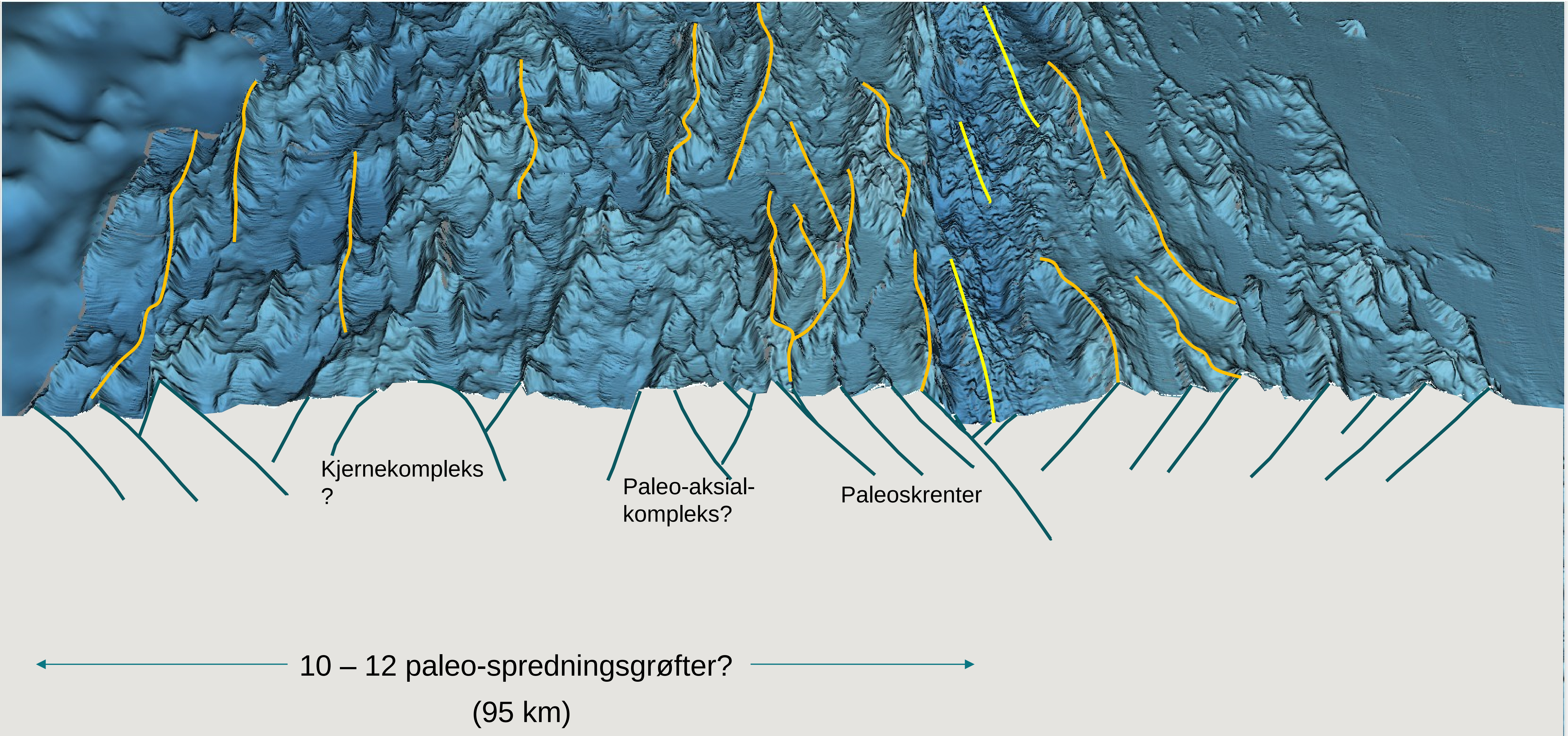
Gnitahei og Fåvne, veien videre



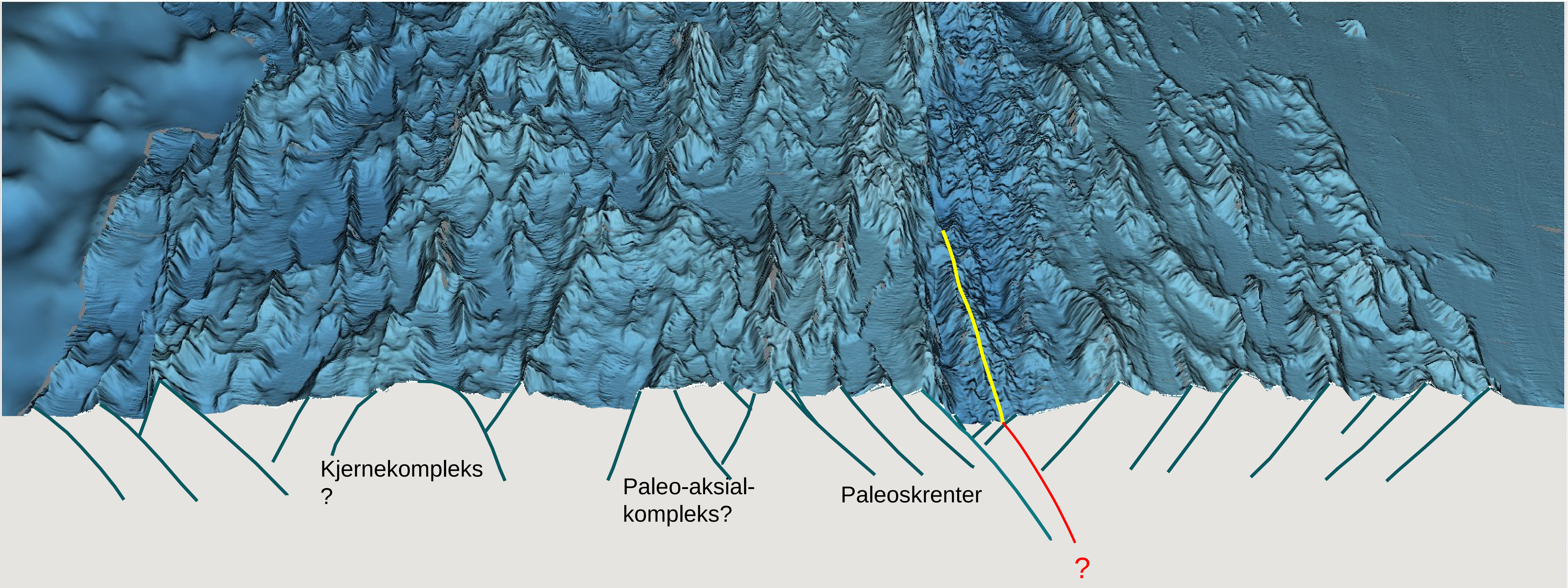
Gnitahei og Fåvne, veien videre



Nordlige Mohnsryggen, snitt



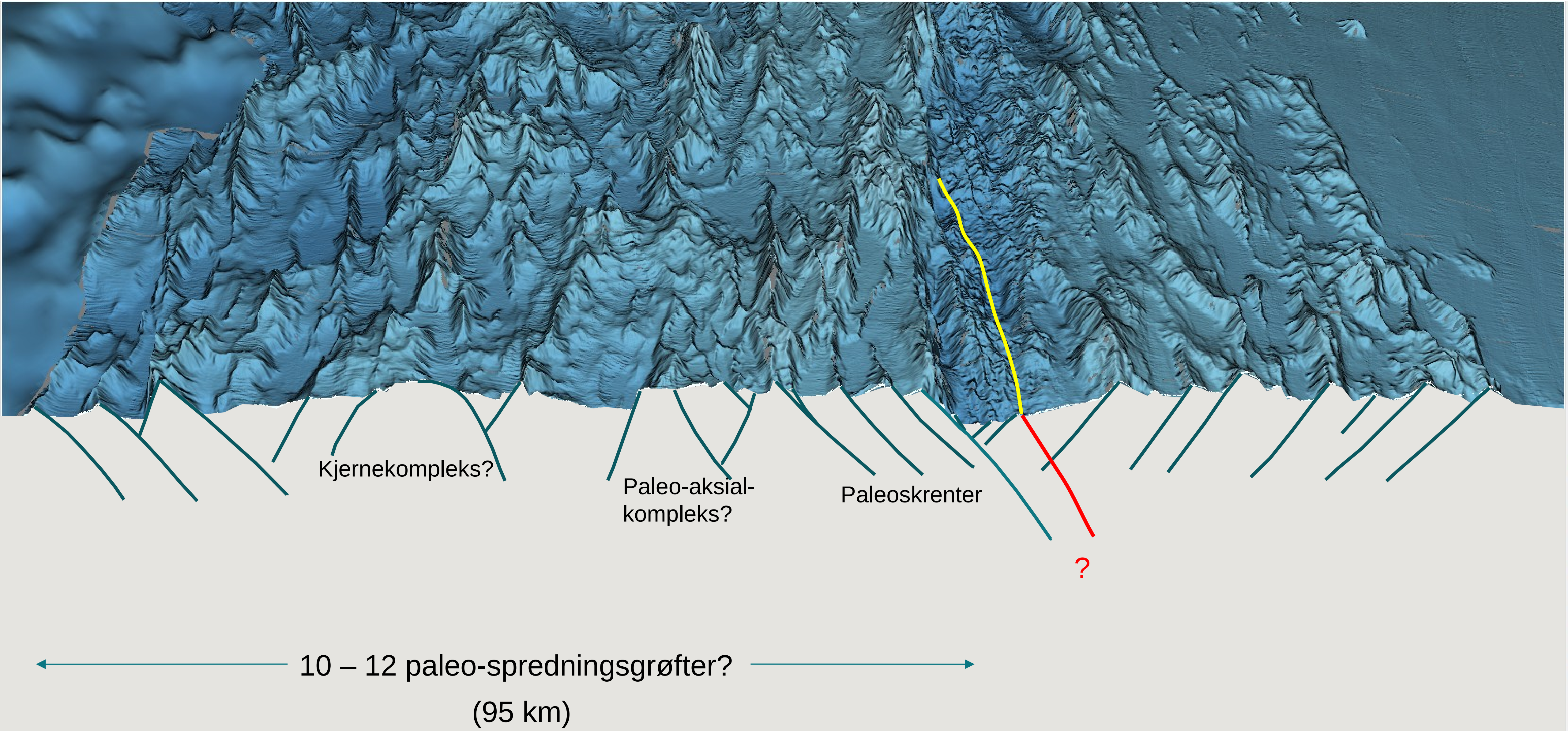
Nordlige Mohnsryggen, snitt



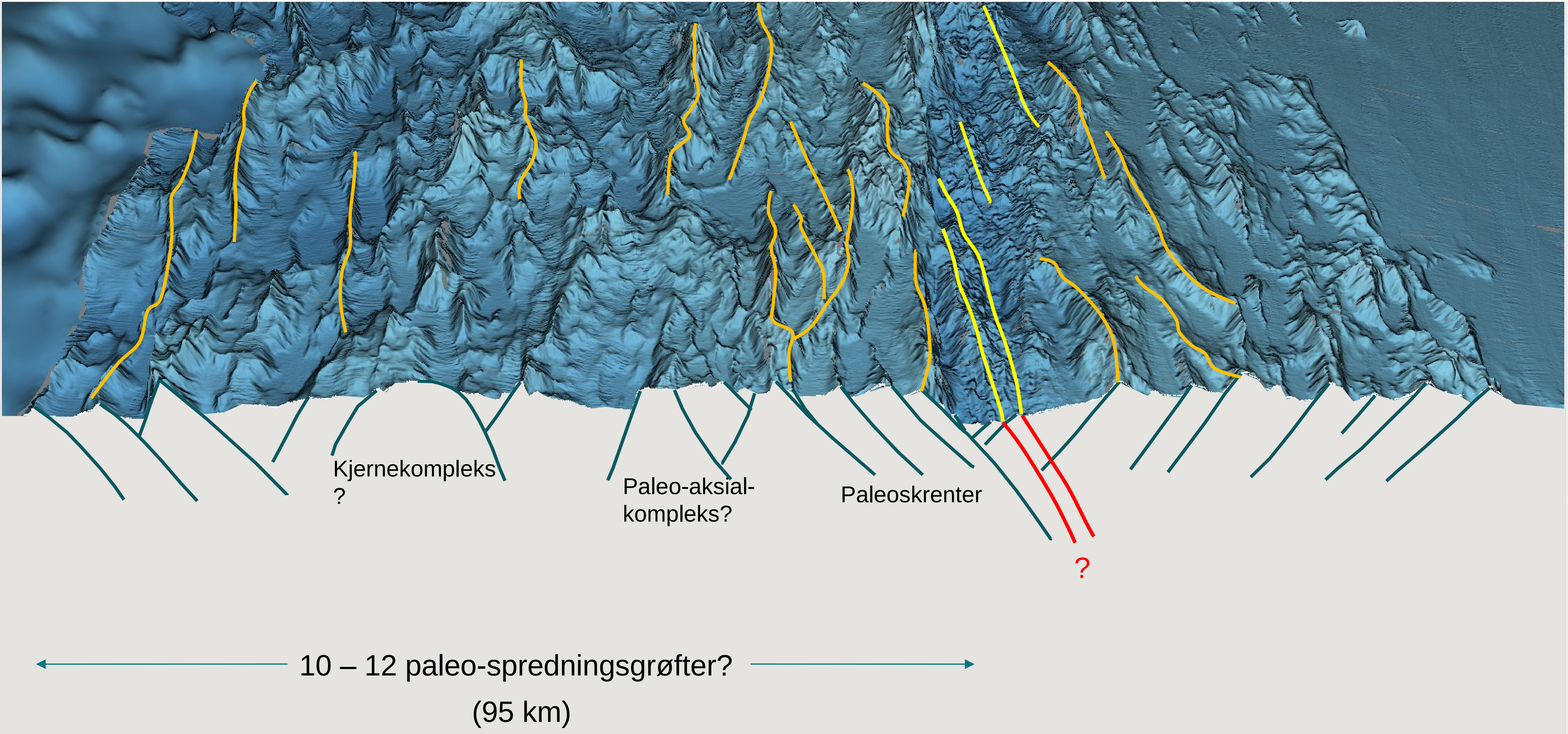
10 – 12 paleo-spredningsgrøfter?

(95 km)

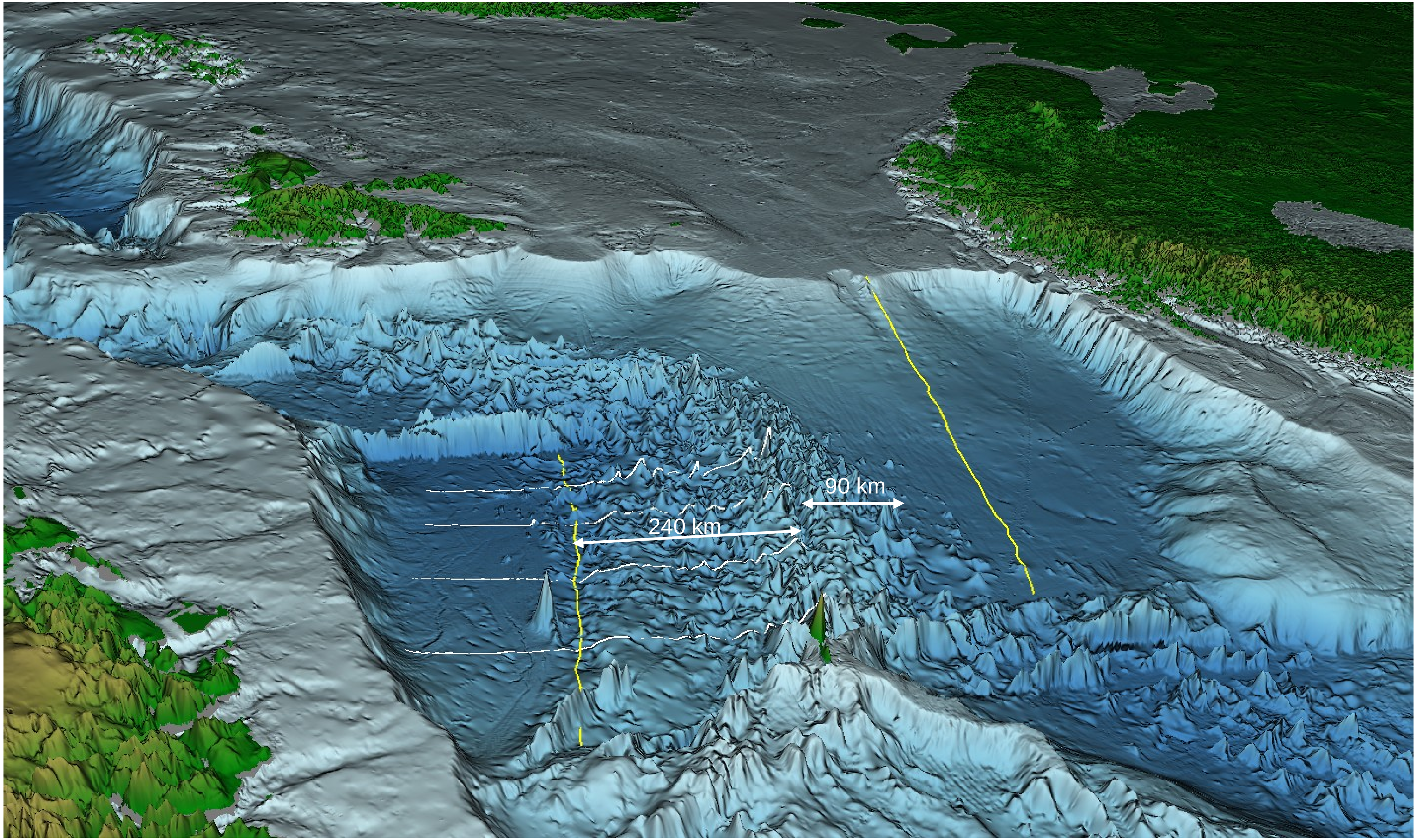
Nordlige Mohnsryggen, snitt



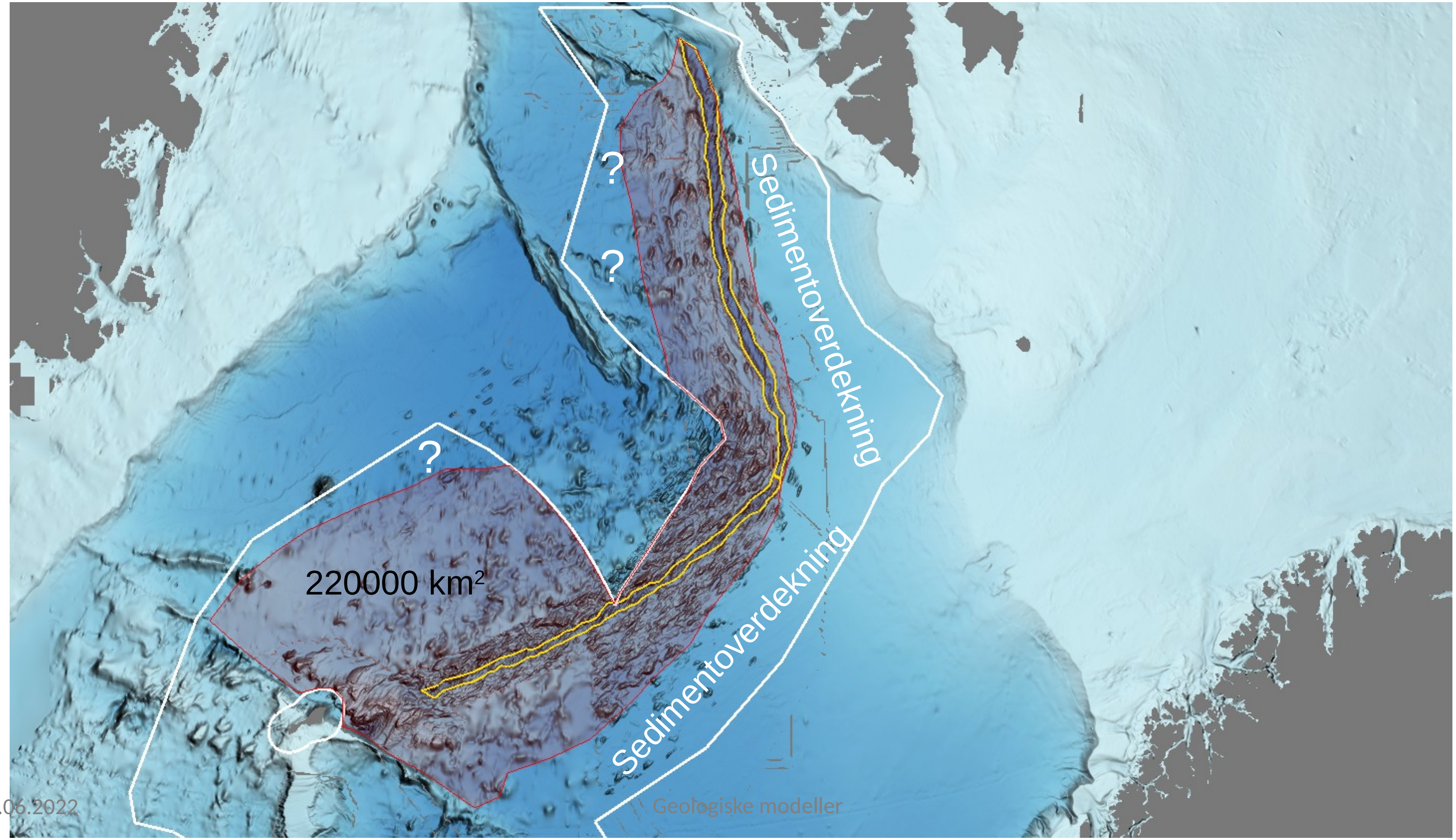
Nordlige Mohnsryggen, snitt



Havbunnstopografi og sulfidforekomster



Områder med mulige sulfidforekomster



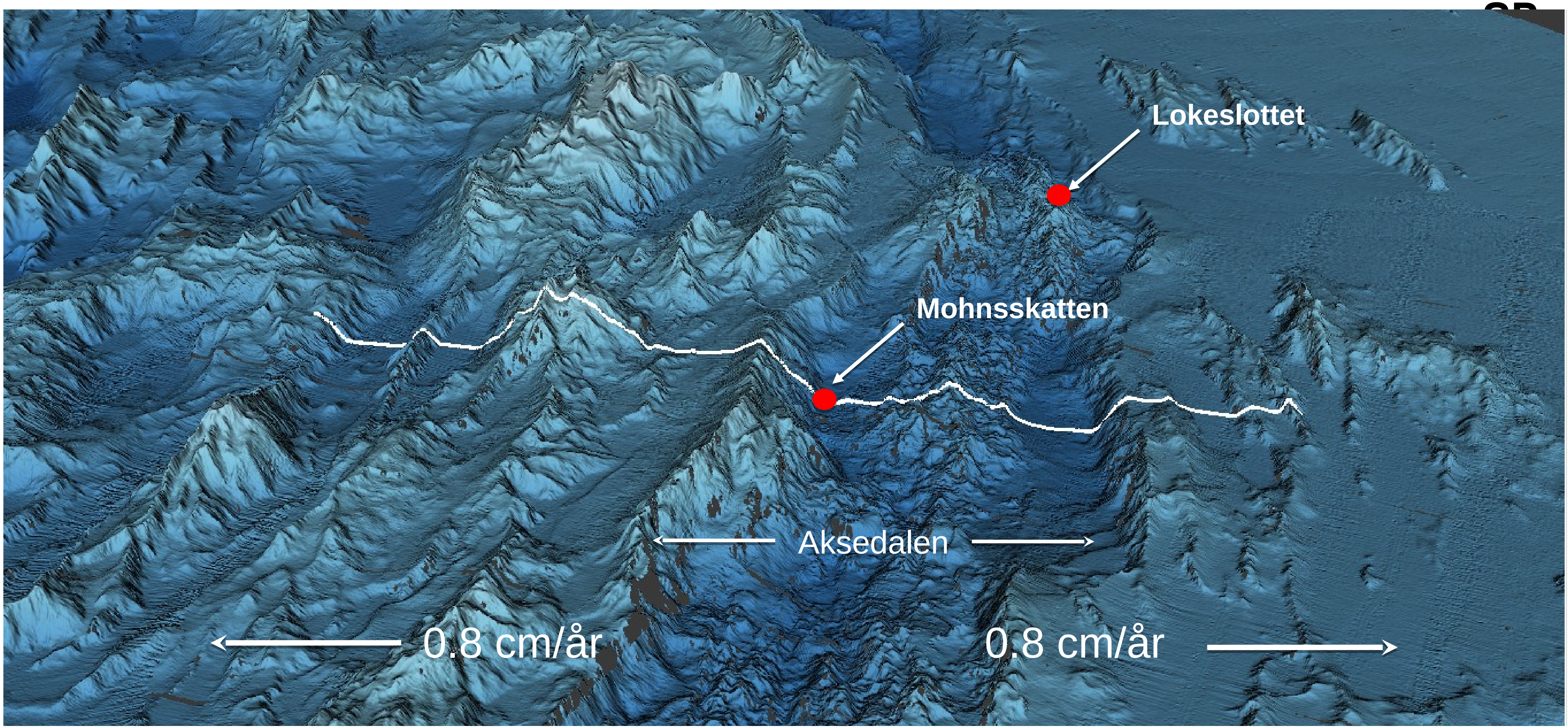
Kort oppsummering

- Mohnsryggen:
  - Går fra intermediære til ultra-sakte spredningshastigheter ved anomali 13 (33 Ma)
  - Spredningshastighet påvirker havbunnstopografi og fordeling av ressurser
  - Nedarvet spredningsakse i dypet; asymmetrisk rifting; spredning skeivt på aksen
  - Dominert av intermediær magmafluks og plane flankeforkastninger; mulige kjernekomplekser påvist
- To grupper med sulfidavsetninger ut fra tektonisk posisjon:
  - Fra hydrotermal aktivitet i aksiale vulkankomplekser
  - Fra hydrotermal aktivitet i grabenskrentene
- Grabenskrentene utsatt for reaktiveringer som kan utløse hydrotermal aktivitet
- Mesteparten av sulfidmineralressursene bevart i paleo-grabenkomplekser utover i flankeområdene
- Sulfidavsetninger i grabenskrentene har antagelig best sjanse for å bli bevart i overflaten

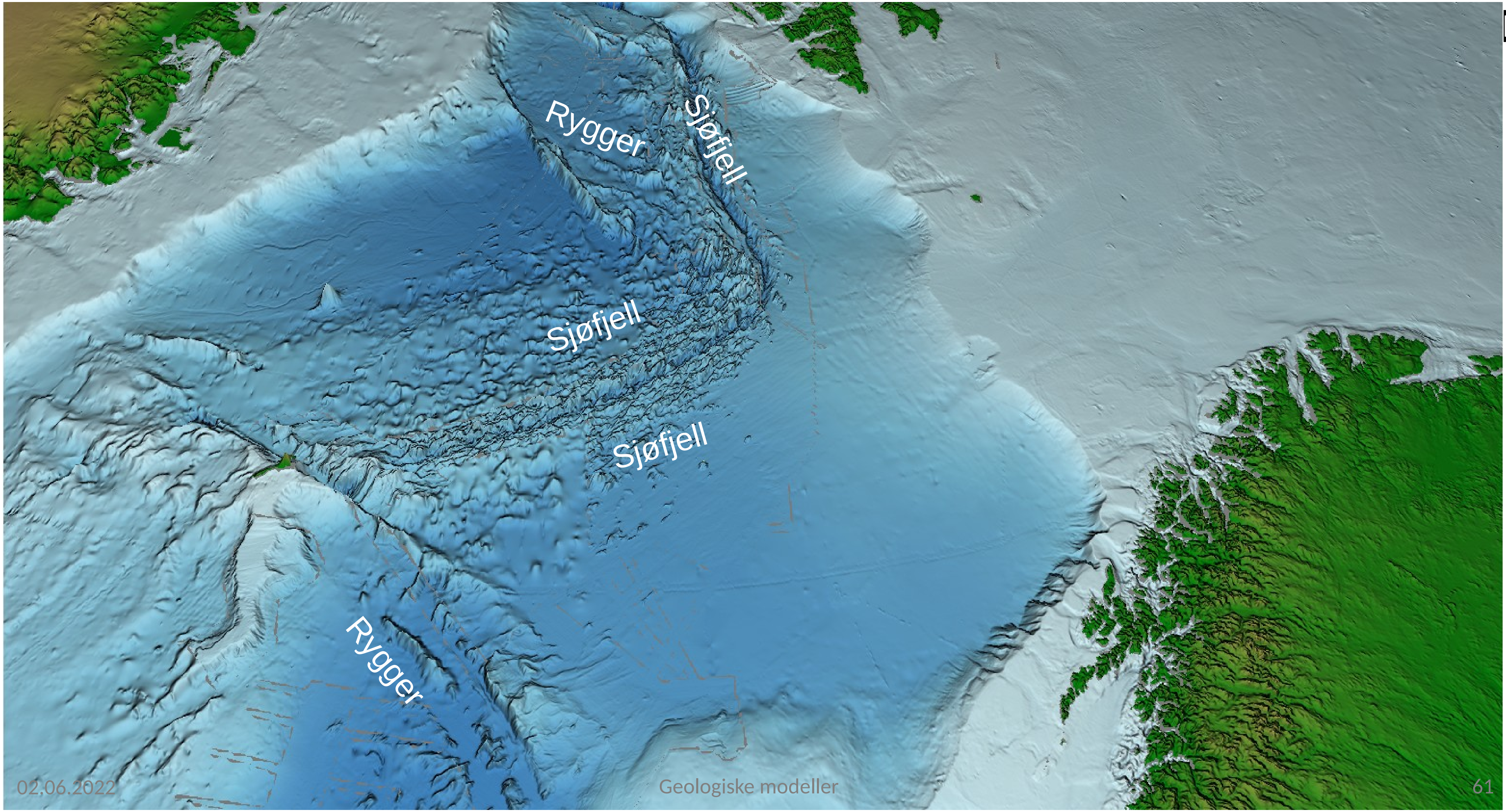
OLJEDIREKTORATET
50 år

Letemodeller og beregningsparametere

Tektonisk sammenheng - sulfidforekomster



Tektonisk sammenheng - skorpeforekomster



Klassifisering (populasjonskriterier)

- Sulfidforekomster
  - Tektonisk sammenheng (letemodell)
    1. Grabenskrent (flankeforkastning) *Gnitahei, Fåvne, Mohnsskatten, Kobberåsen*
    2. Aksialt vulkankompleks *Ægirs kilde, Lokeslottet*

- Skorpeforekomster
  - Tektonisk sammenheng (letemodell)
    1. Sjøfjell
    2. Undersjøiske rygger

Sentrale kjemiske analyser fra sulfidprøver

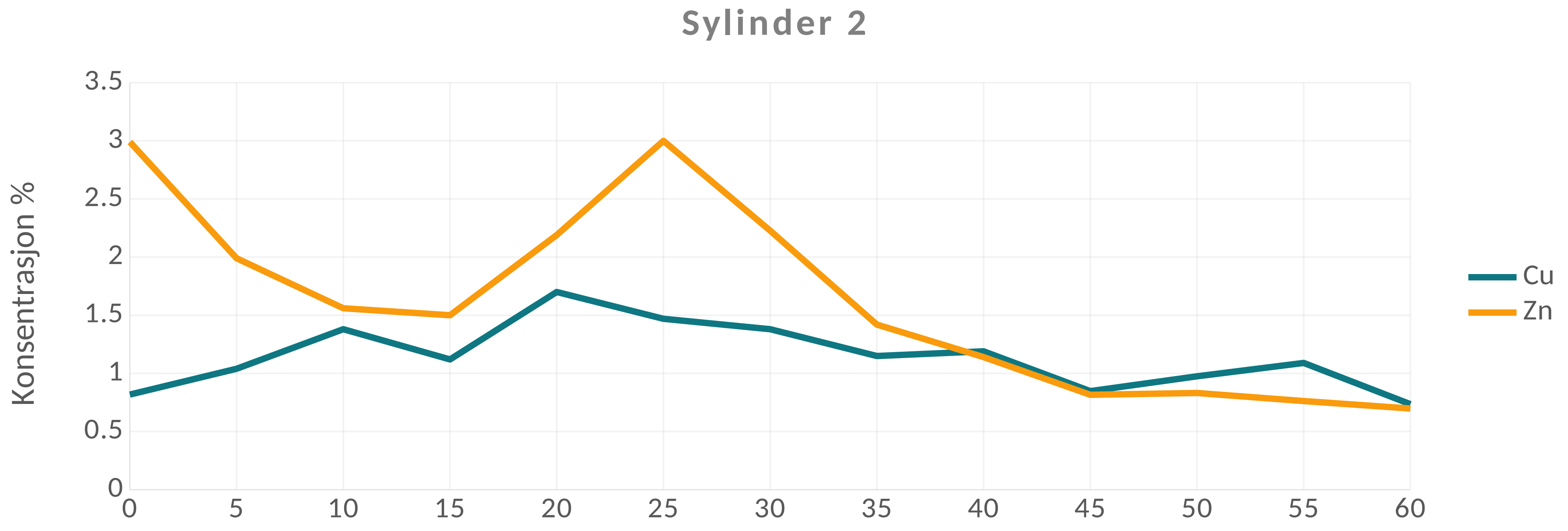
	Fåvne 2018				
Element	Average	MEDIAN	STDV	Max	N
Cu %	4,51	3,72	4,13	14,90	15
Zn %	2,13	0,26	5,50	22,40	15
Co %	0,330	0,404	0,233	0,730	15
Fe %	35,1	37,4	9,4	46,8	15
Ni ppm	5	4	4	18	15
Au ppm	0,37	0,39	0,238	0,737	15
Ag ppm	9,7	4,1	12,4	44,5	15

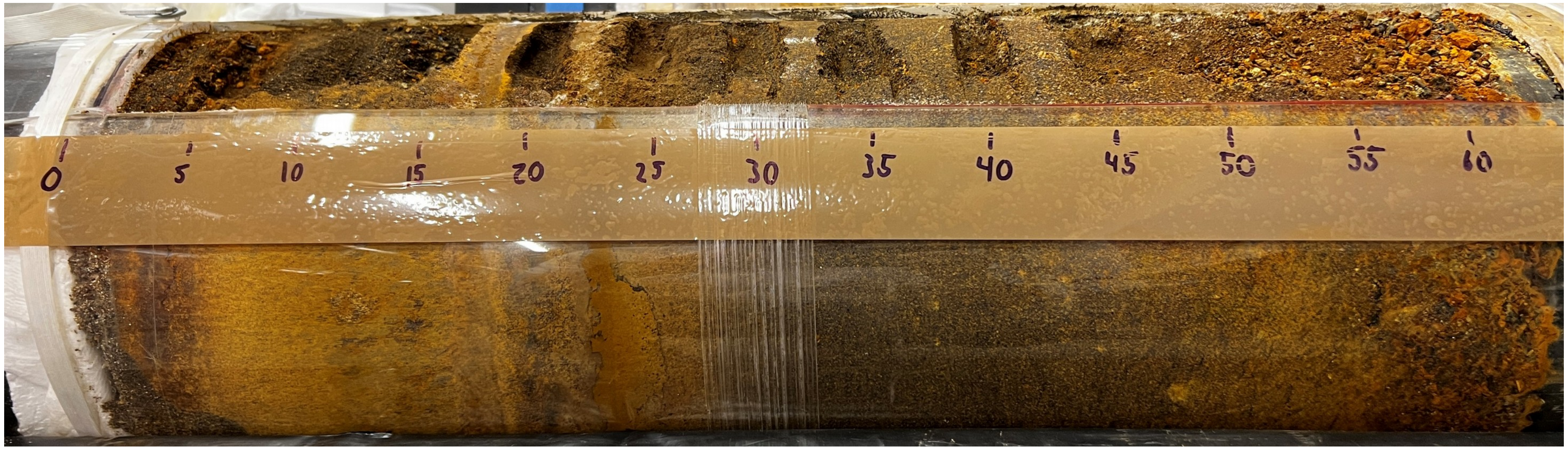
	Gnitahei 2019				
Element	Average	MEDIAN	STDV	Max	N
Cu %	0,150	0,070	0,189	0,670	16
Zn %	0,199	0,152	0,194	0,680	16
Co %	0,039	0,024	0,035	0,100	16
Fe %	35,8	42,5	13,1	54,8	16
Ni ppm	32	11	49	207	16
Au ppm	1,07	0,52	1,02	2,19	16
Ag ppm	8	2,35	14	30,6	16

	Mohnsskatten 2020				
Element	Average	MEDIAN	STDV	Max	N
Cu %	0,91	0,48	1,92	14,30	65
Zn %	2,70	0,13	5,19	24,40	65
Co %	0,014	0,005	0,031	0,140	65
Fe %	21,7	21,7	11,3	49,3	65
Ni ppm	19	9	26	141	65
Au ppm	2,58	1,16	3,62	19,2	65
Ag ppm	64,5	8,25	123,5	548	65

	Lokeslottet, Snook et al 2018				
Element	Average	MEDIAN	STDV	Max	N
Cu %	0,42	0,135	0,532	2,05	16
Zn %	0,82	0,175	1,762	7,38	16
Co %	0,0003	0,0003	0,0003	0,0012	16
Fe %	4,98	2,1	6,2	21,27	16
Ni ppm	909	1027	660	1998	16
Au ppm	2,8	2,8	1,8	6,3	12
Ag ppm	57,8	20,3	87,1	340	16

Cuttings, Fåvne 7





Sulfidforekomster - beregningsparametre

Letemodeller	Parameter	Min	Med	Max
Aksialt vulkankompleks	**Forekomst - størrelse**			
Grabenskrent (flankeforkastning)	Areal (10^6 m^2)	x	x	x
	Tykkelse (m)	x	x	x
	Volum (10^6 m^3)	x	x	x
	Tetthet malm (tonn/m^3)	x	x	x
	Total masse (10^6 tonn)	x	x	x
	Forekomst - antall			
	Totalt antall forekomster	x	x	x
	Gehalt			
	Cu (% wt)	x	x	x
	Zn (% wt)	x	x	x
	Co (% wt)	x	x	x
	Ag (ppm)	x	x	x
	Au (ppm)	x	x	x

Skorpeforekomster - beregningsparametre

Letemodeller	Parameter	Min	Med	Max
Havfjell	**Forekomst - størrelse**			
Rygger	Areal (km2)	x	x	x
	Tykkelse (m)	x	x	x
	Volum (m3)	x	x	x
	Tetthet malm (tonn/m3)	x	x	x
	Total masse (tonn)	x	x	x
	Forekomst - antall			
	Frekvens (forekomst/10000 km2)	x	x	x
	Modellareal (km2)	x	x	x
	Totalt antall forekomster	x	x	x
	Gehalt			
	Mn (% wt)	x	x	x
	Ti (% wt)	x	x	x
	Sc (ppm)	x	x	x
	V (ppm)	x	x	x
	∑REE (ppm)	x	x	x

Ressursevaluering

- Mye analogt med letemodell-metodikk for petroleumsressurser
- Foreløpig to letemodeller for sulfidforekomster og to for skorpeforekomster basert på tektoniske forhold
- Usikkert om entydig sammenheng mellom letemodeller og gehalter – må foreløpig kompenseres med spredning i verdier
- Usikker sammenheng mellom overflateareal og volum – spredning må foreløpig baseres på modeller kalibrert av egne og i stor grad publiserte data
- Data fra forekomster i ofiolitter på land vil være gi verdifull kalibrering av sulfidressursene, men krever kvalitetssikring for å unngå skeive fordelinger