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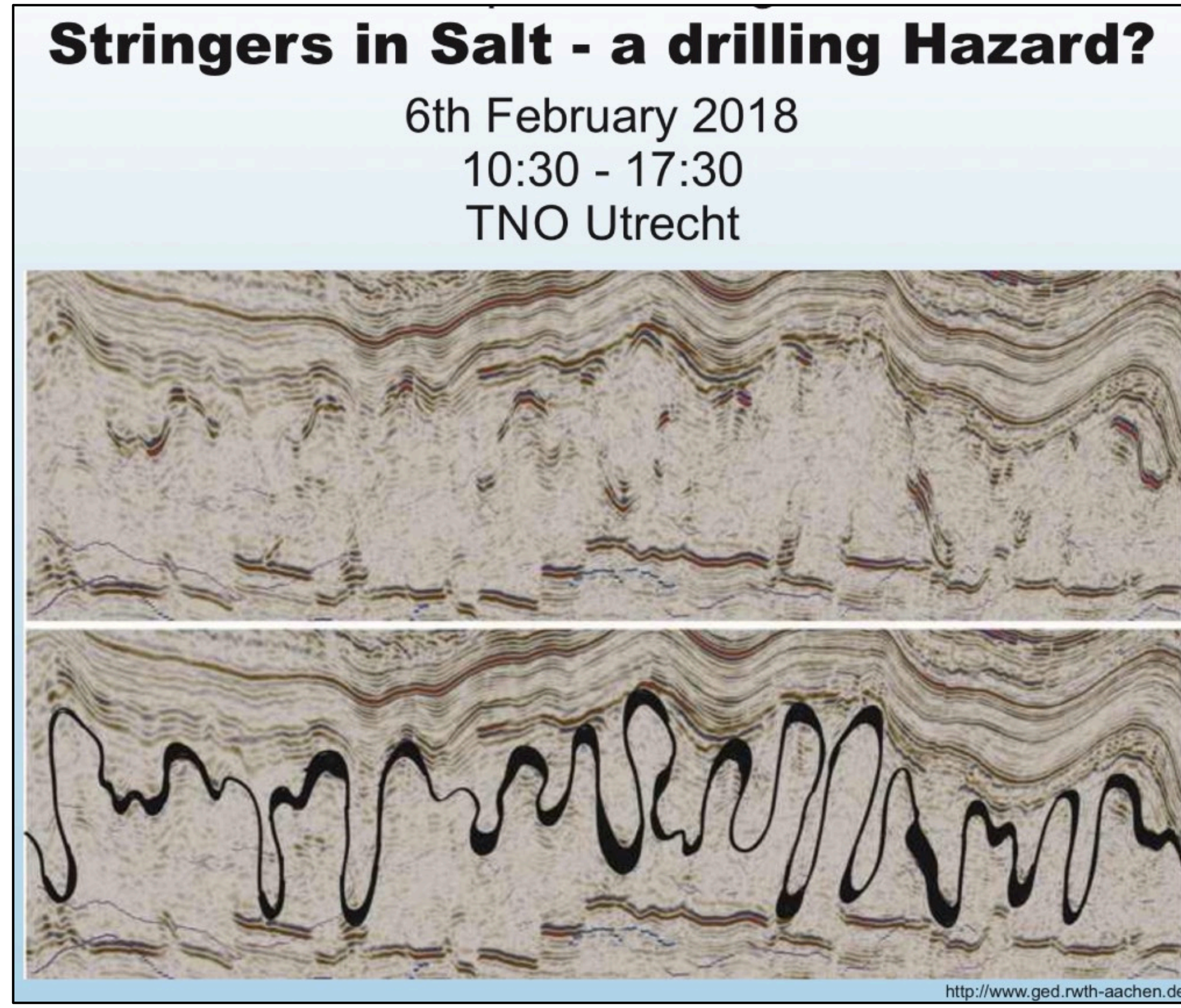
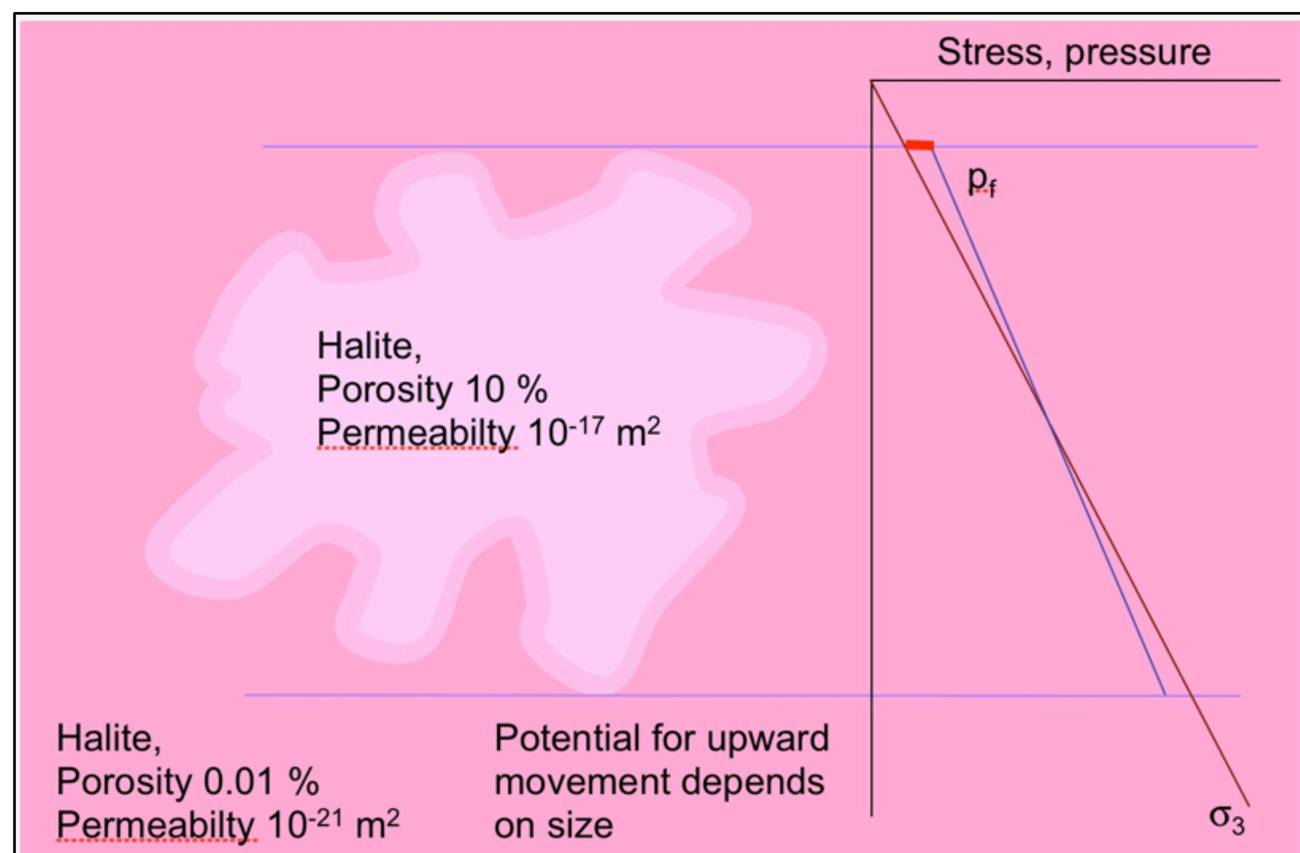
EMR Energy & Mineral Resources Group

Deutsche Forschungsgemeinschaft DFG

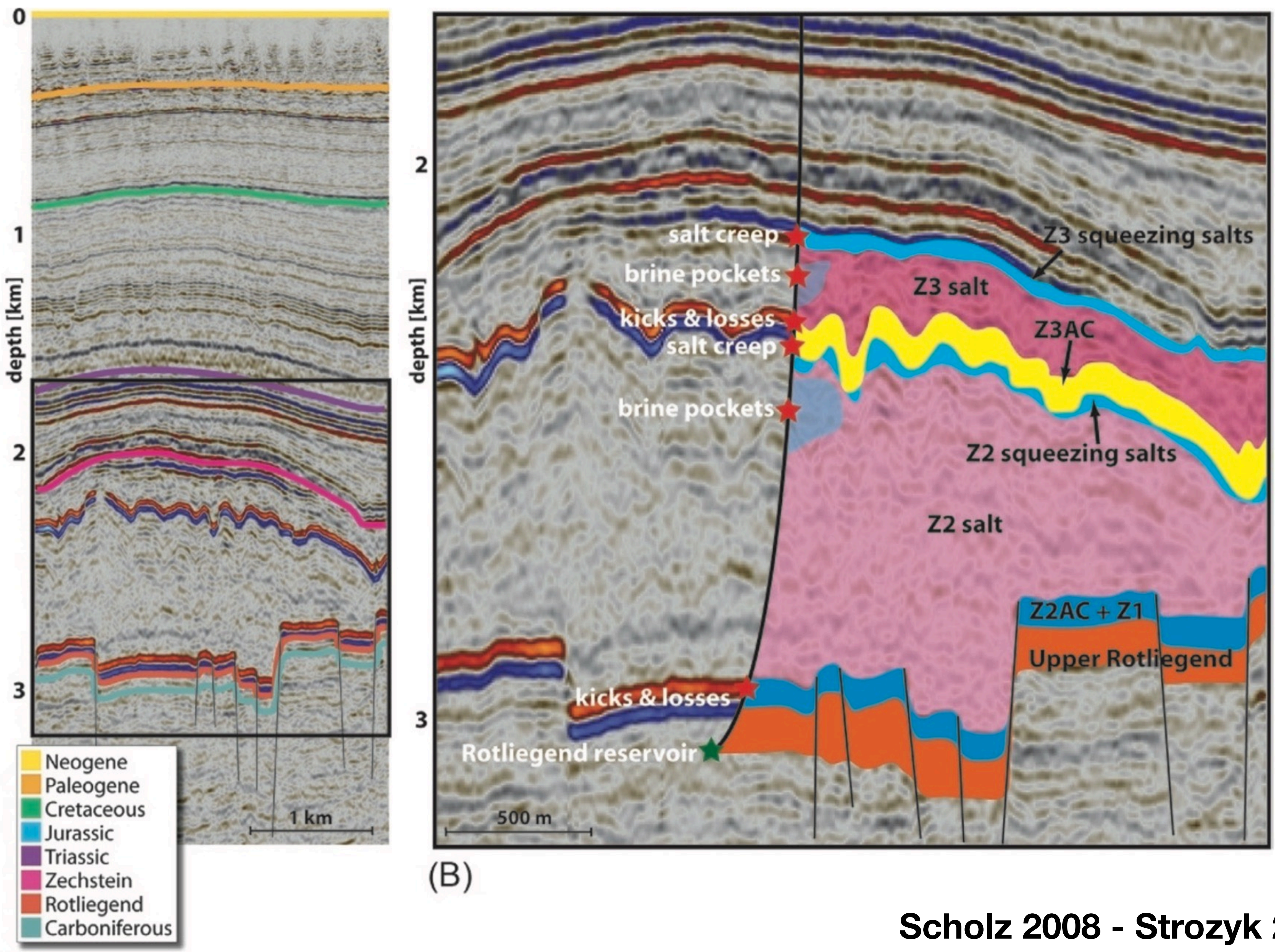




Stringers in salt - agenda

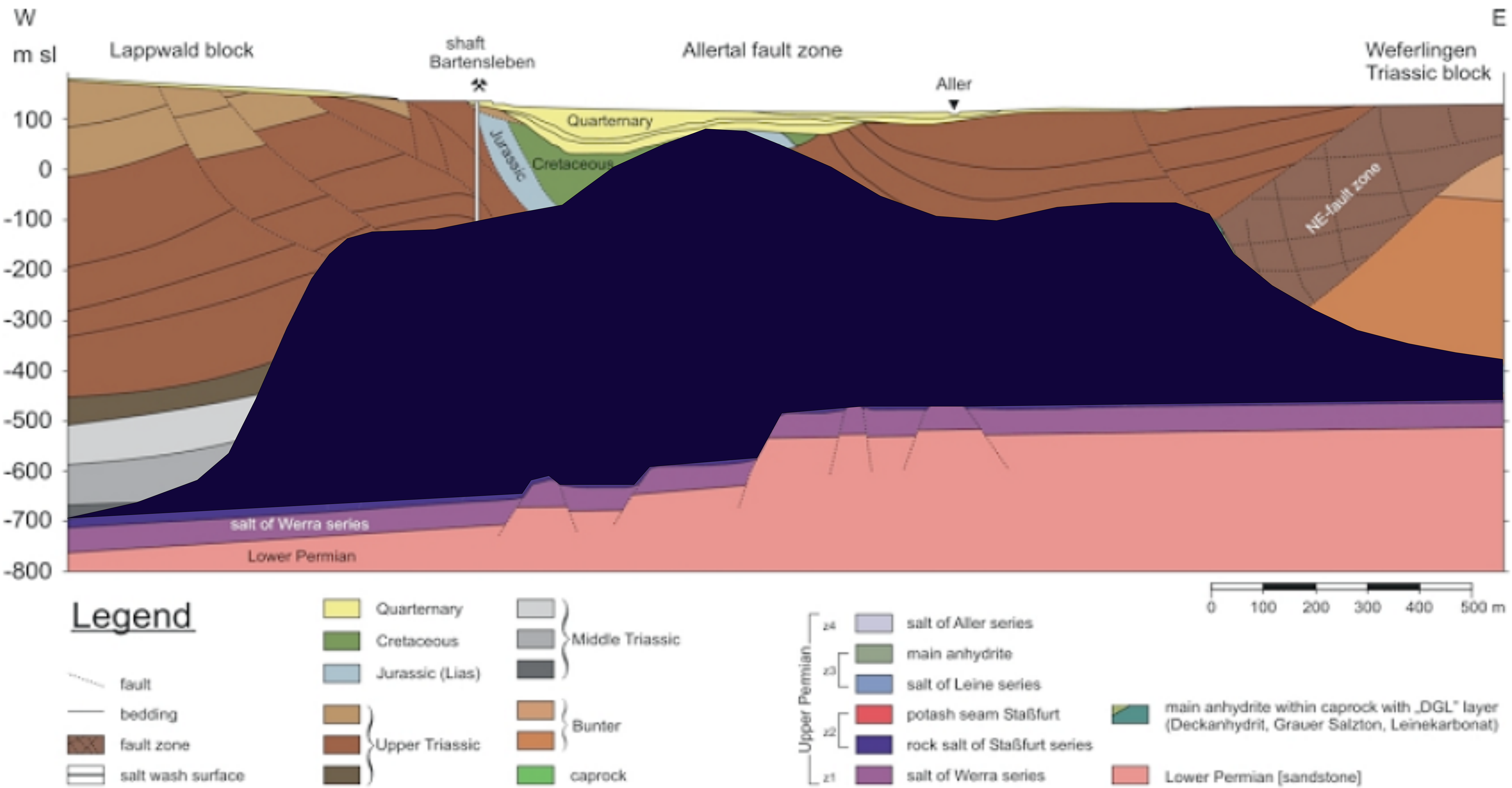
- Composition and Tectonics
- Properties of surrounding salt
- Fluid migration - pore pressure
- Drilling problems?
- Seismicity and stringers?
- Discussion and Outlook

Potential Drilling problems



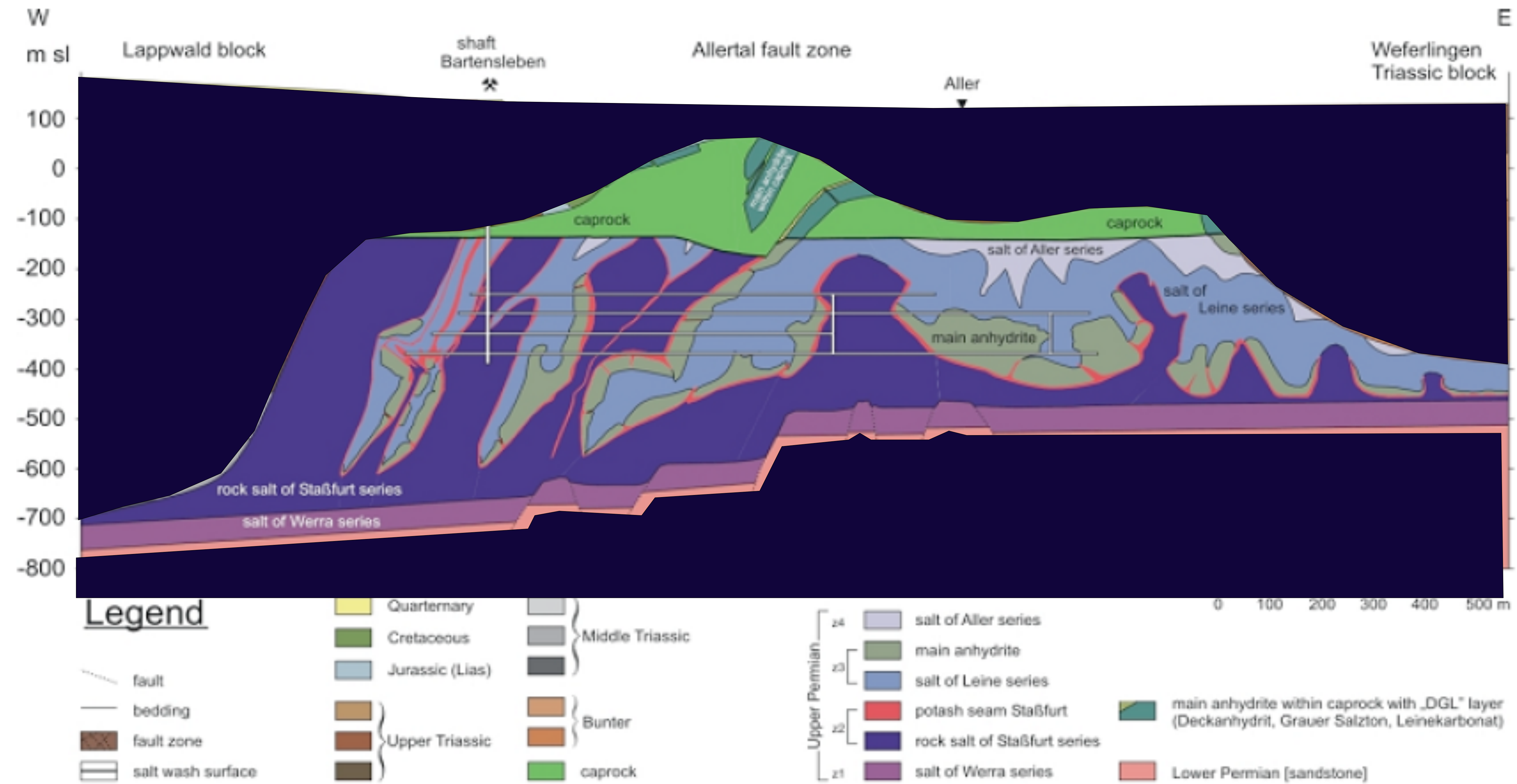
Scholz 2008 - Strozyk 2017

The Oilman's view



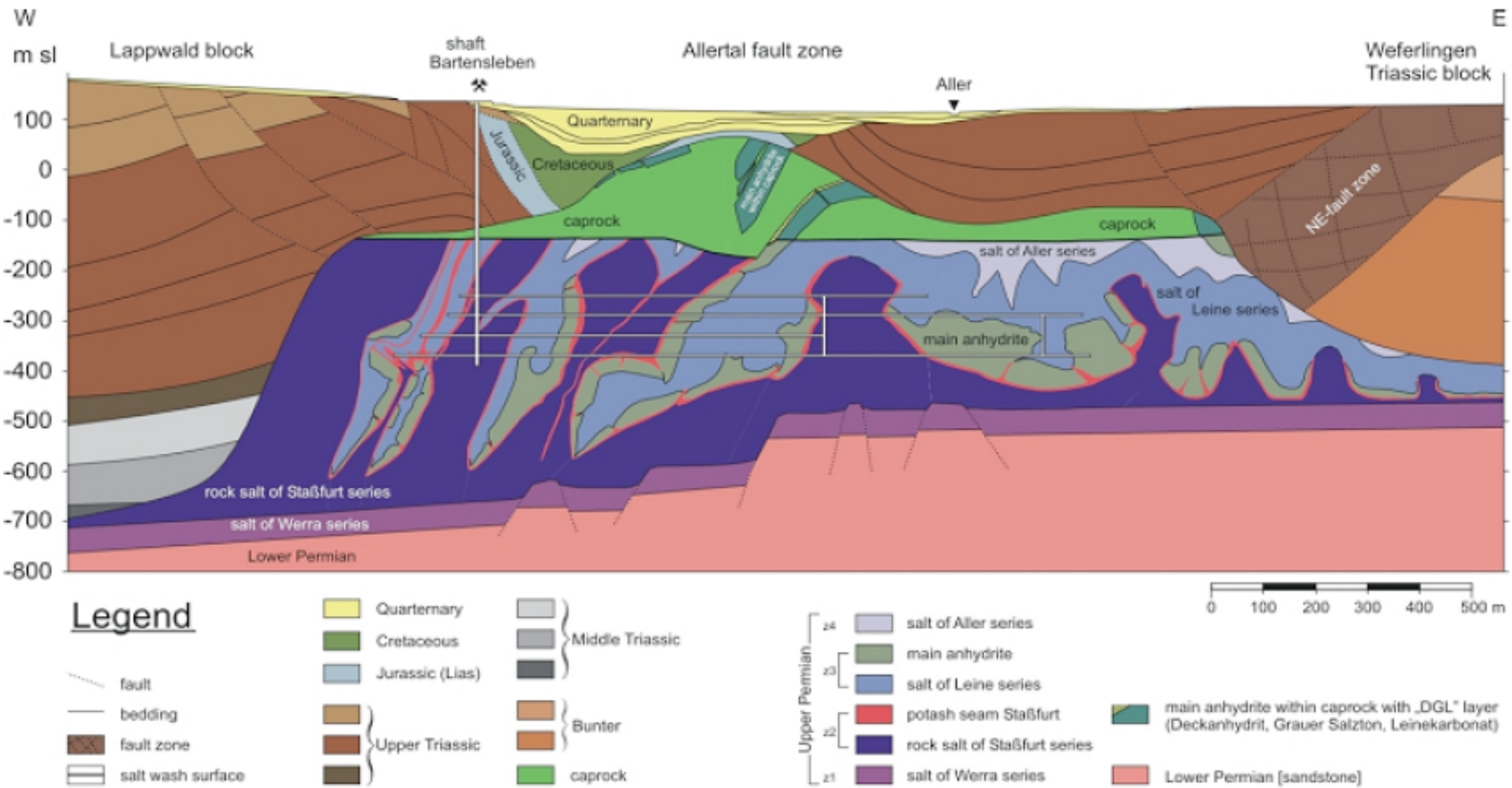
Morsleben salt dome (Bundesanstalt für Strahlenschutz)

The salt miner's view



Morsleben salt dome (Bundesanstalt für Strahlenschutz)

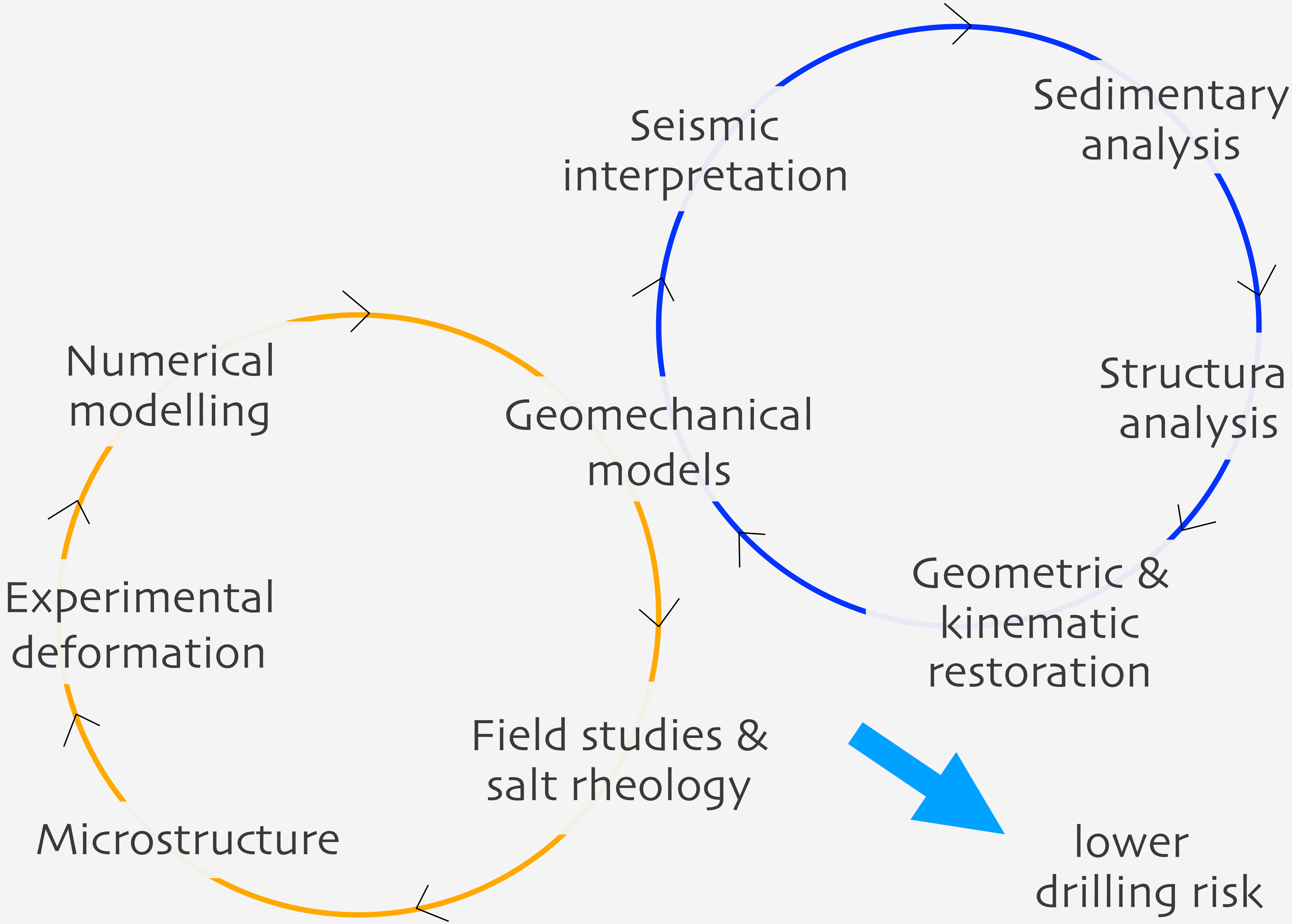
Integrated view



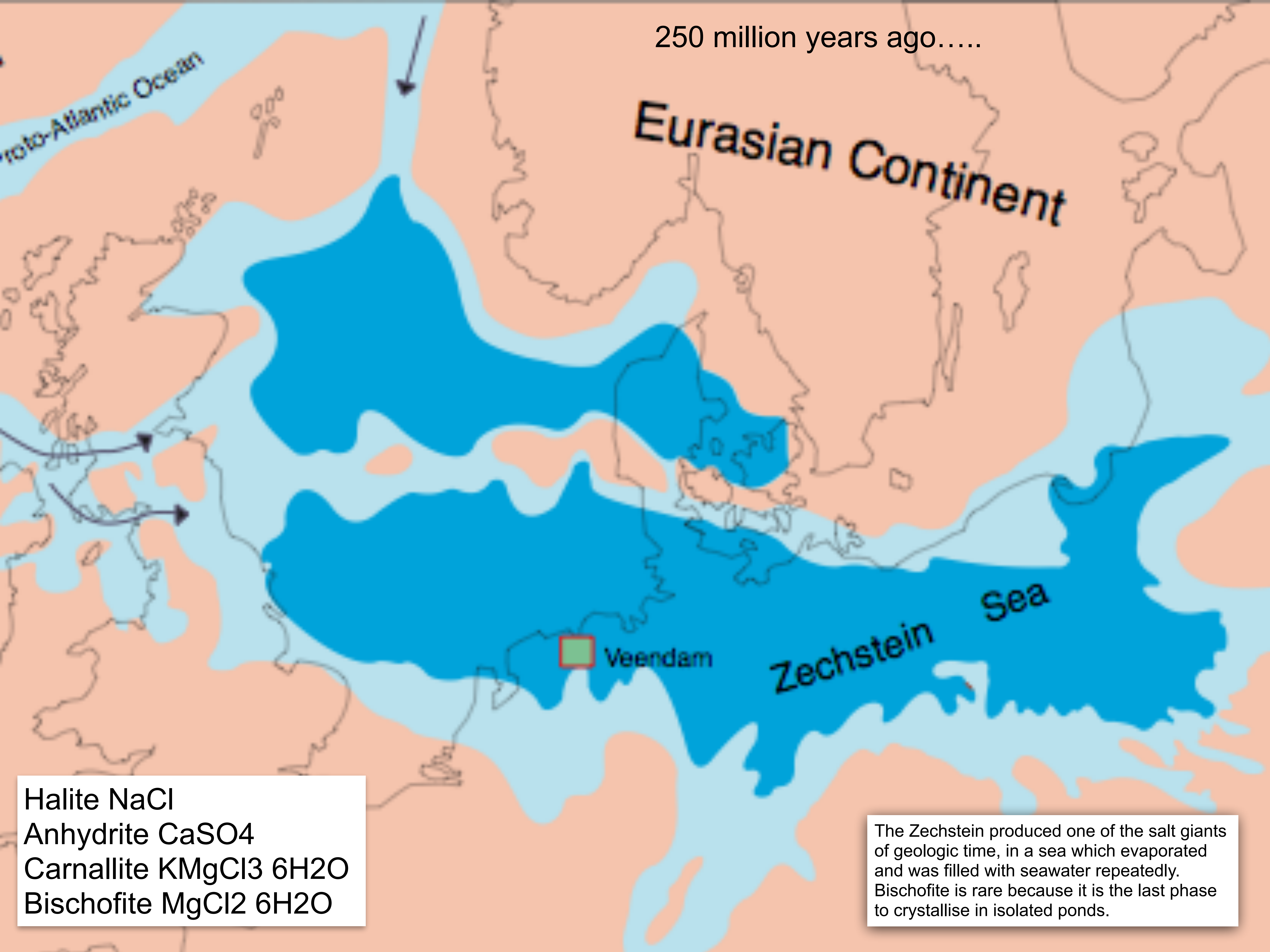
Topseal strength, Stringer exploration, Subtle tectonics,
Drilling problems, Storage caverns, Salt mining

Morsleben salt dome (Bundesanstalt für Strahlenschutz)

Integrated, multi-scale salt projects



250 million years ago…..



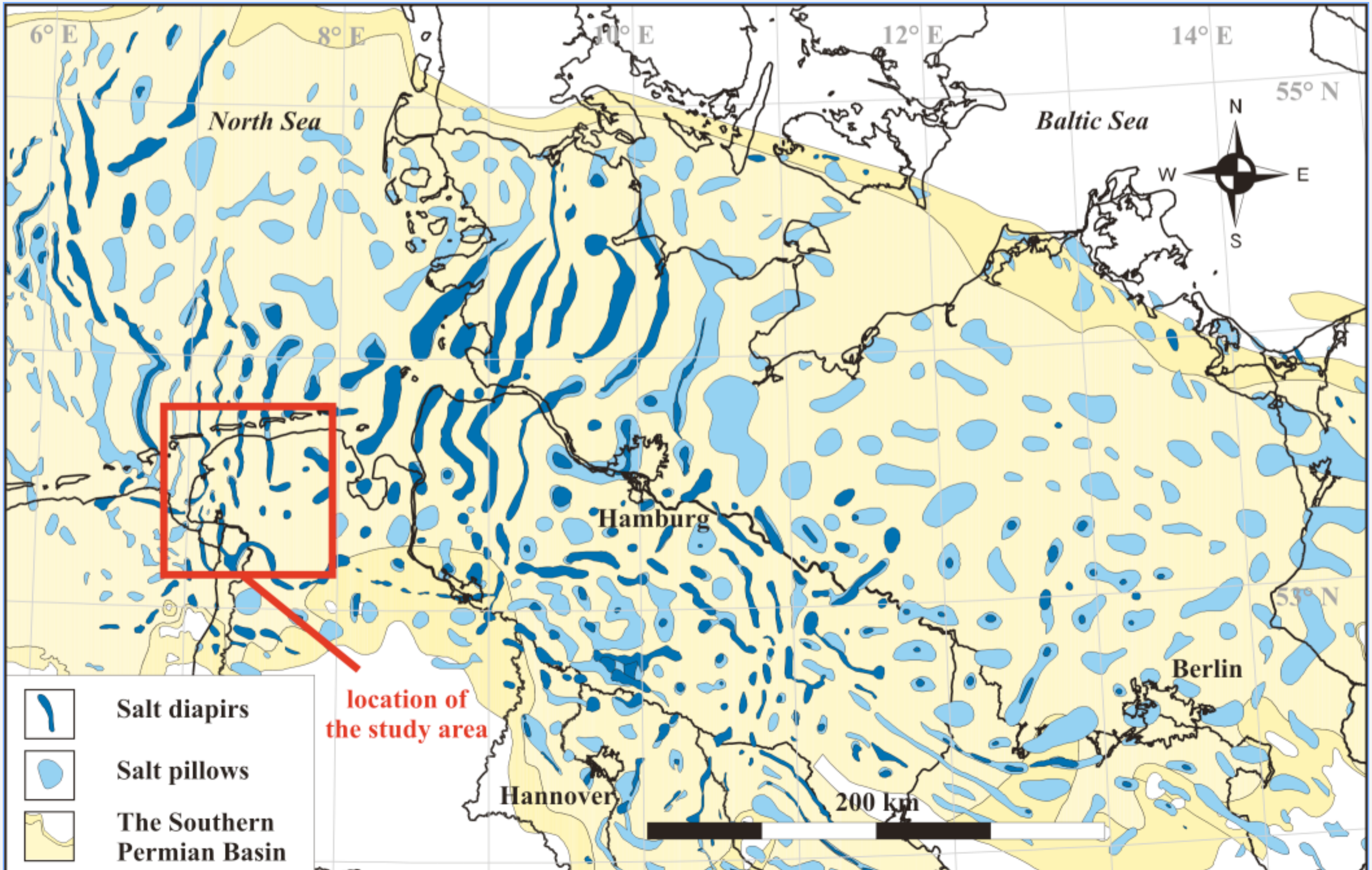
Halite NaCl
Anhydrite $CaSO_4$
Carnallite $KMgCl_3 \cdot 6H_2O$
Bischofite $MgCl_2 \cdot 6H_2O$

The Zechstein produced one of the salt giants of geologic time, in a sea which evaporated and was filled with seawater repeatedly. Bischofite is rare because it is the last phase to crystallise in isolated ponds.


http://www.scarletthooftgraafland.nl

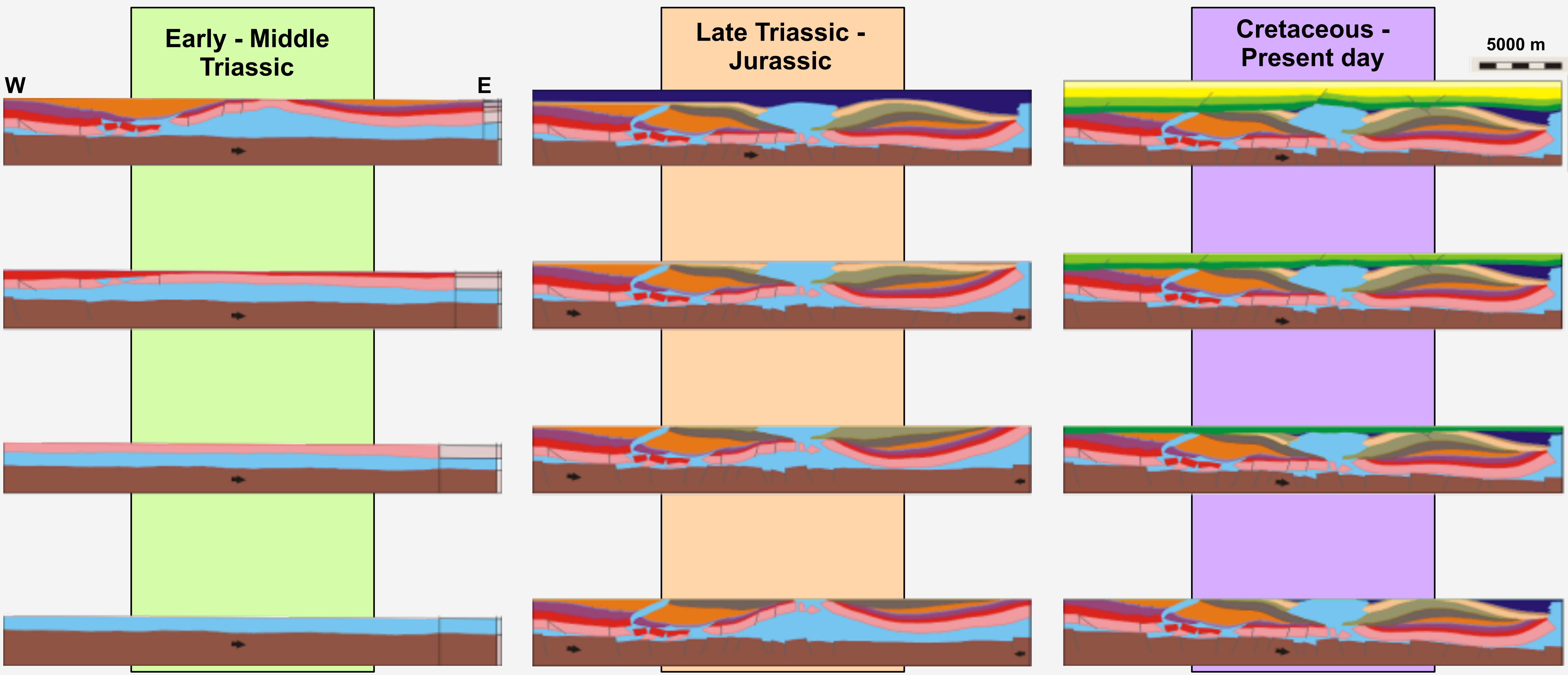
Zechstein zout tektoniek

(after Lockhorst, 1999)



Salt tectonic evolution – structural balancing

1st phase | 2nd phase | 3rd phase



1st phase

- thin-skinned extension & rafting
- lateral salt movement & growth of a salt pillow

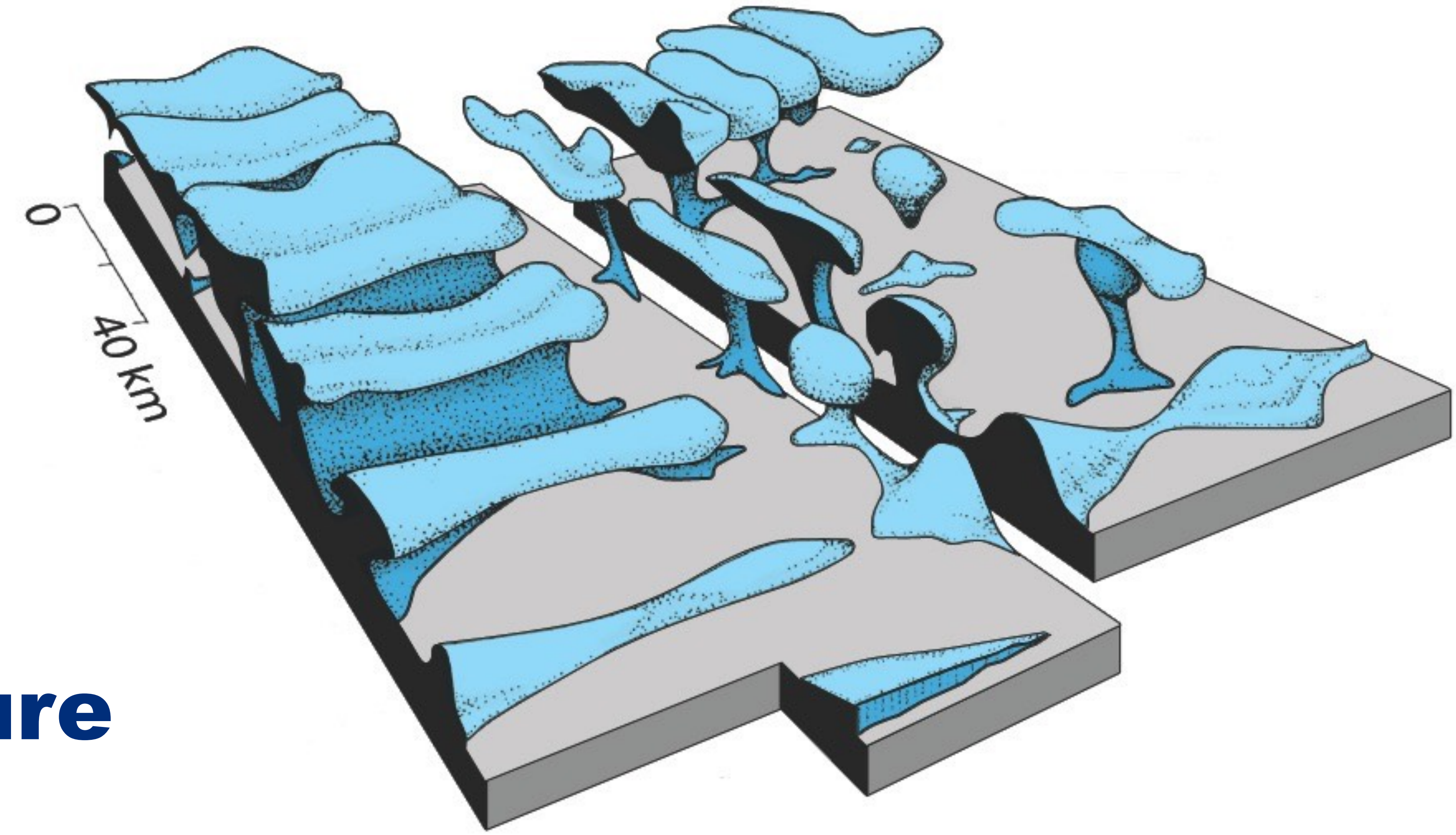
2nd phase

- extension triggered diapirism
- sedimentary downbuilding and periods of diapir emergence

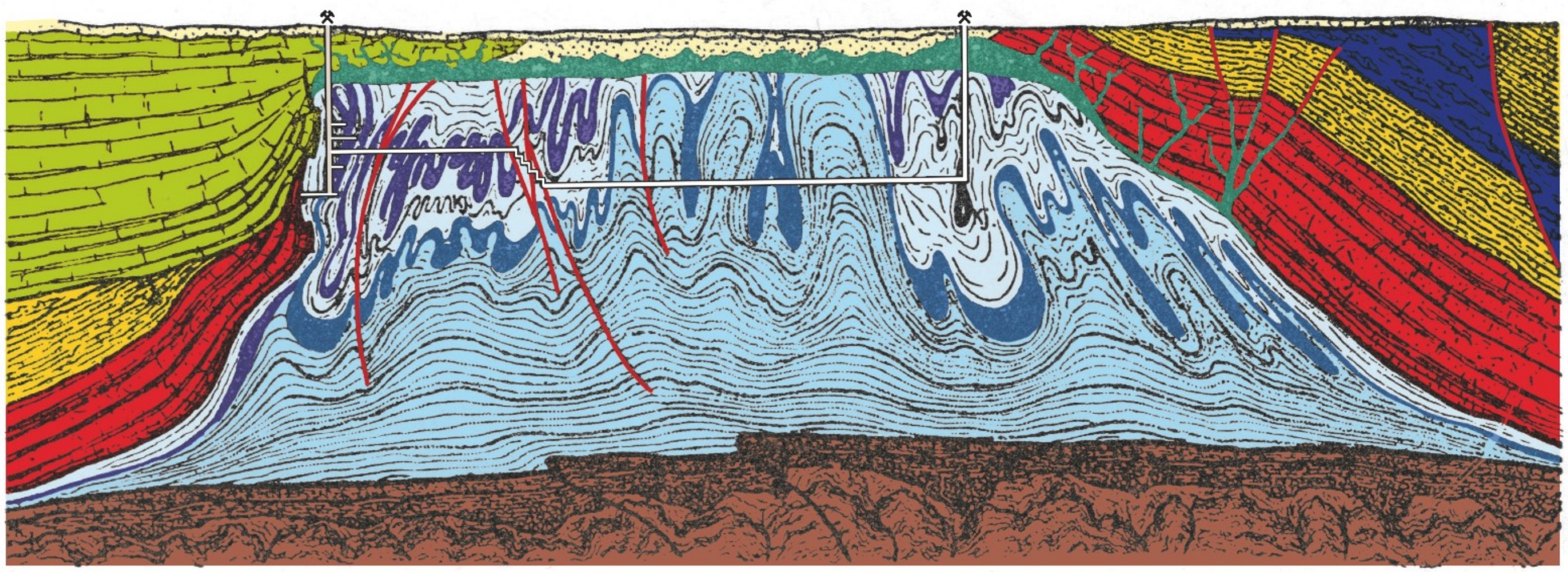
3rd phase

- compression triggered diapirism
- growth of a buried salt structure

Mohr - Kukla - Urai

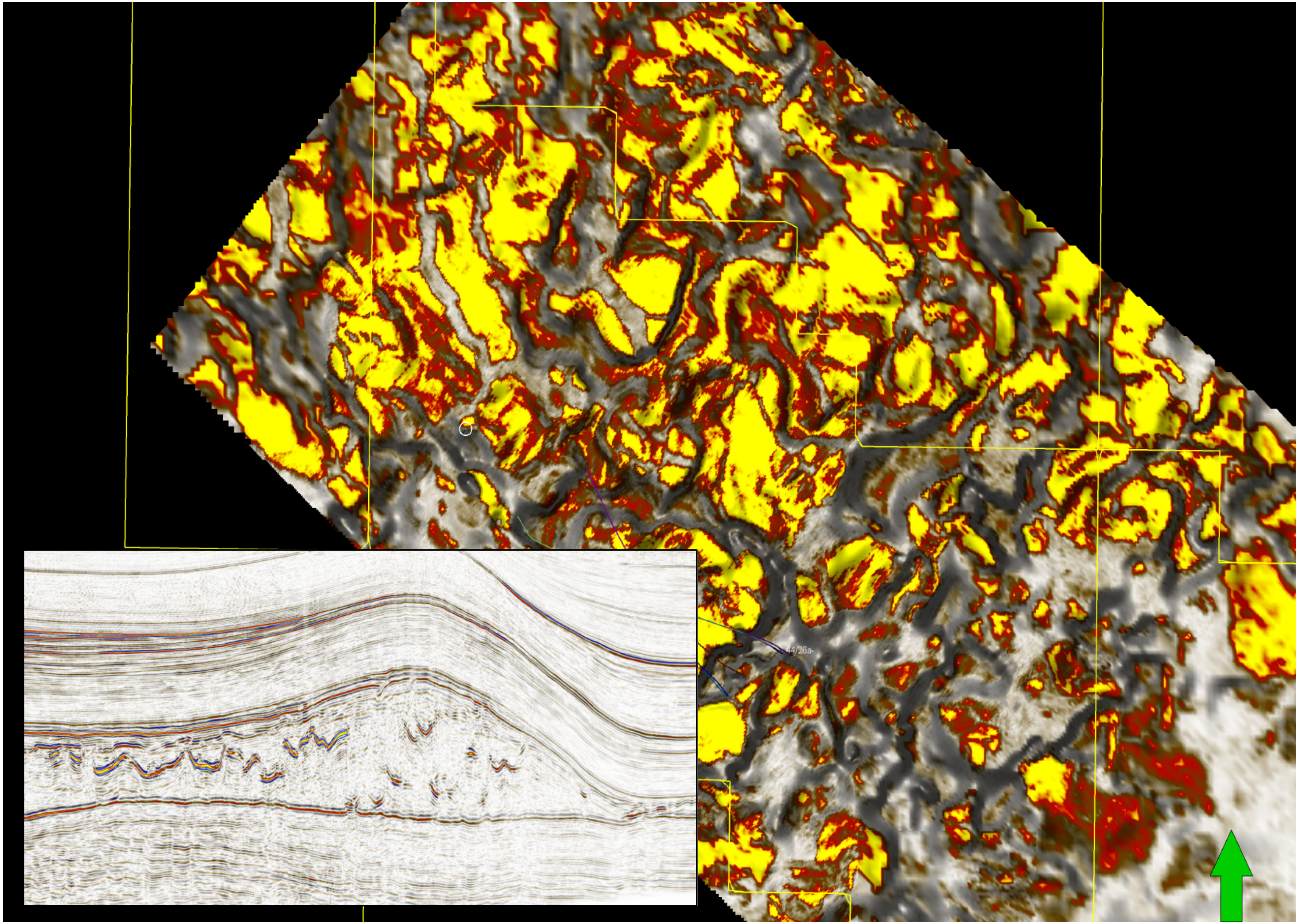


Salt Structure



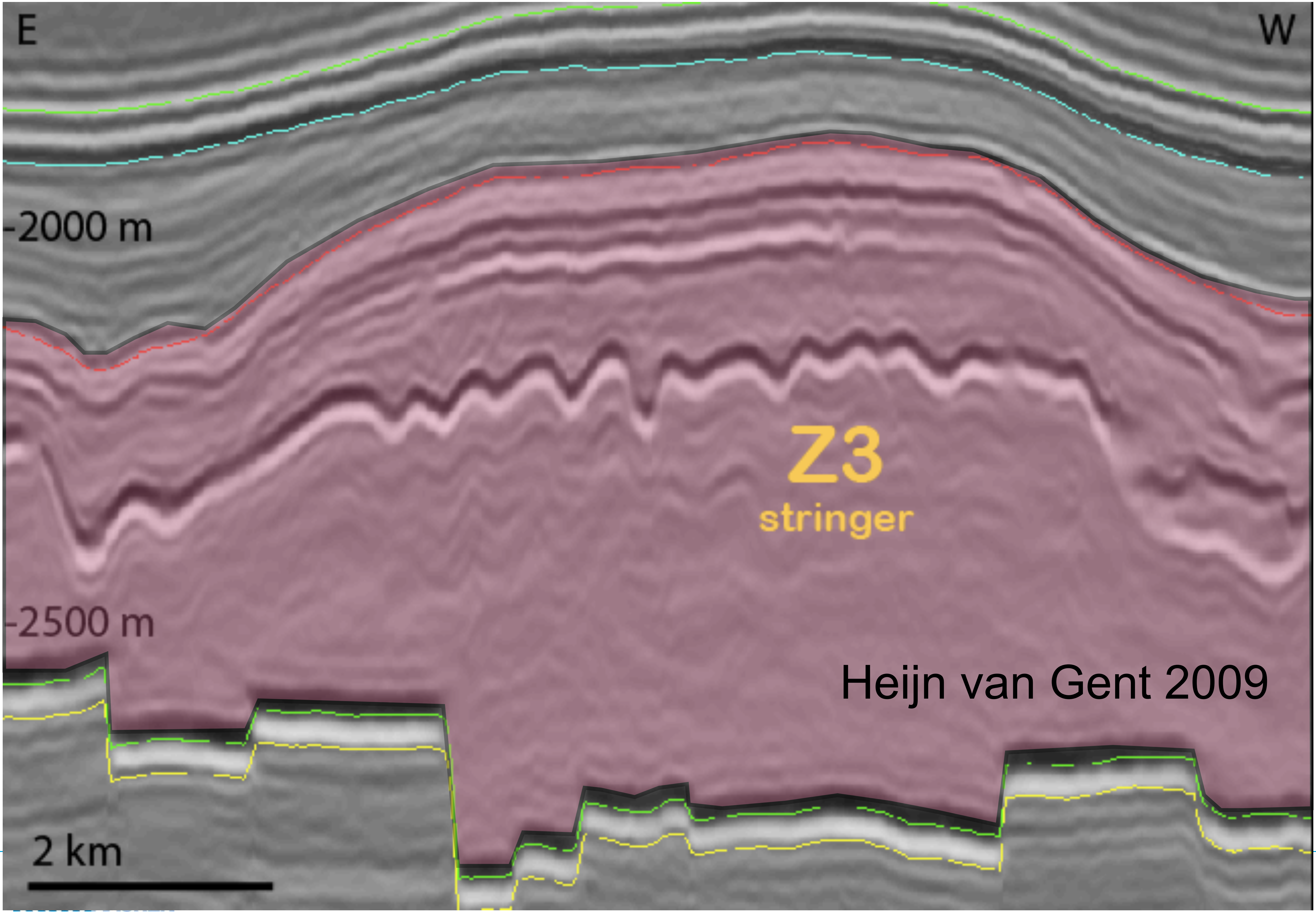
Salt Glaciers

Zechstein stringer boudinage, S-North sea (2006)

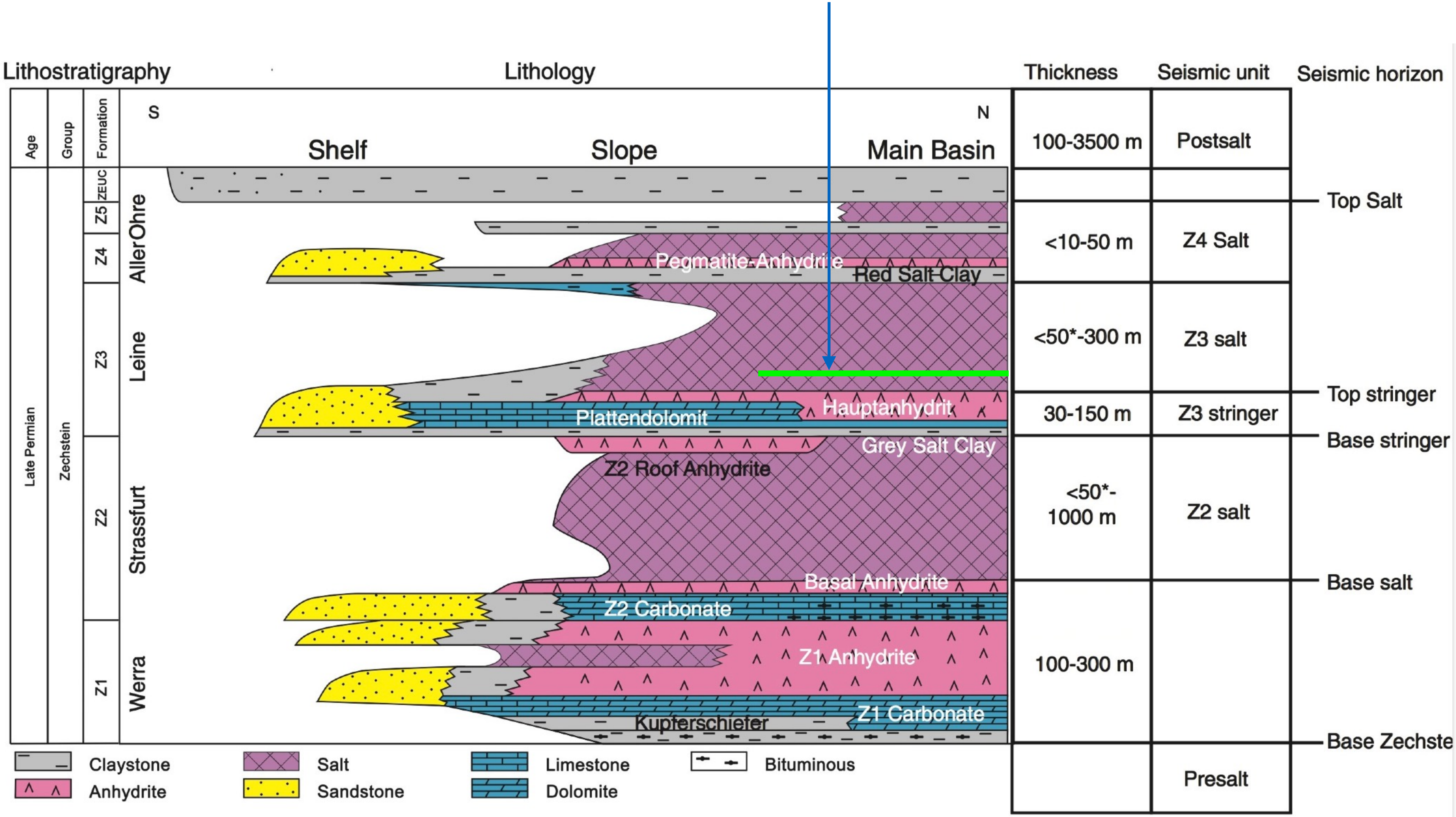


Seismic Amplitude at Platten Dolomit Horizon courtesy Tullow oil

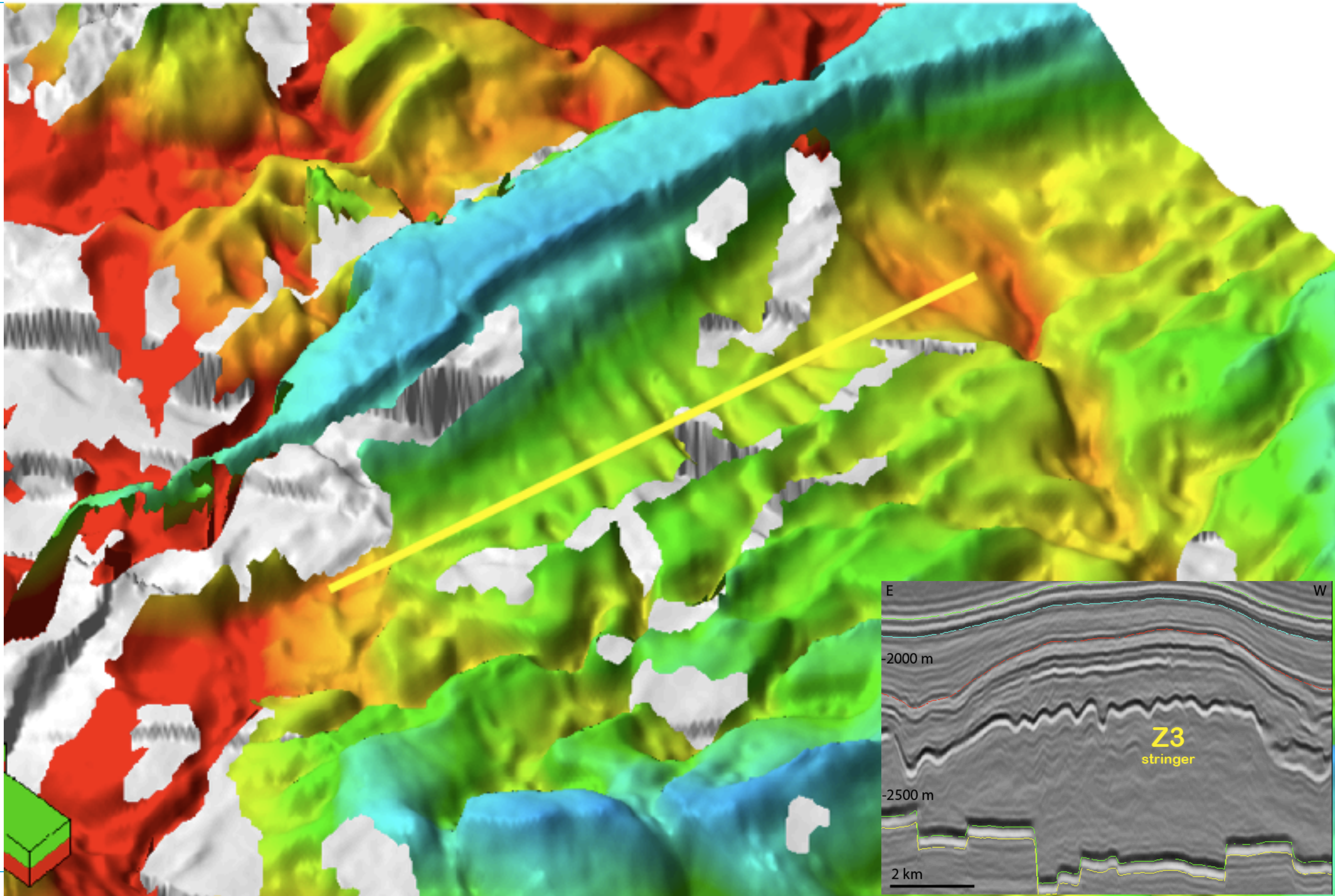
Z3 stringers in 3D seismic, Groningen



Magnesium zout



Z3 surface in Groningen area



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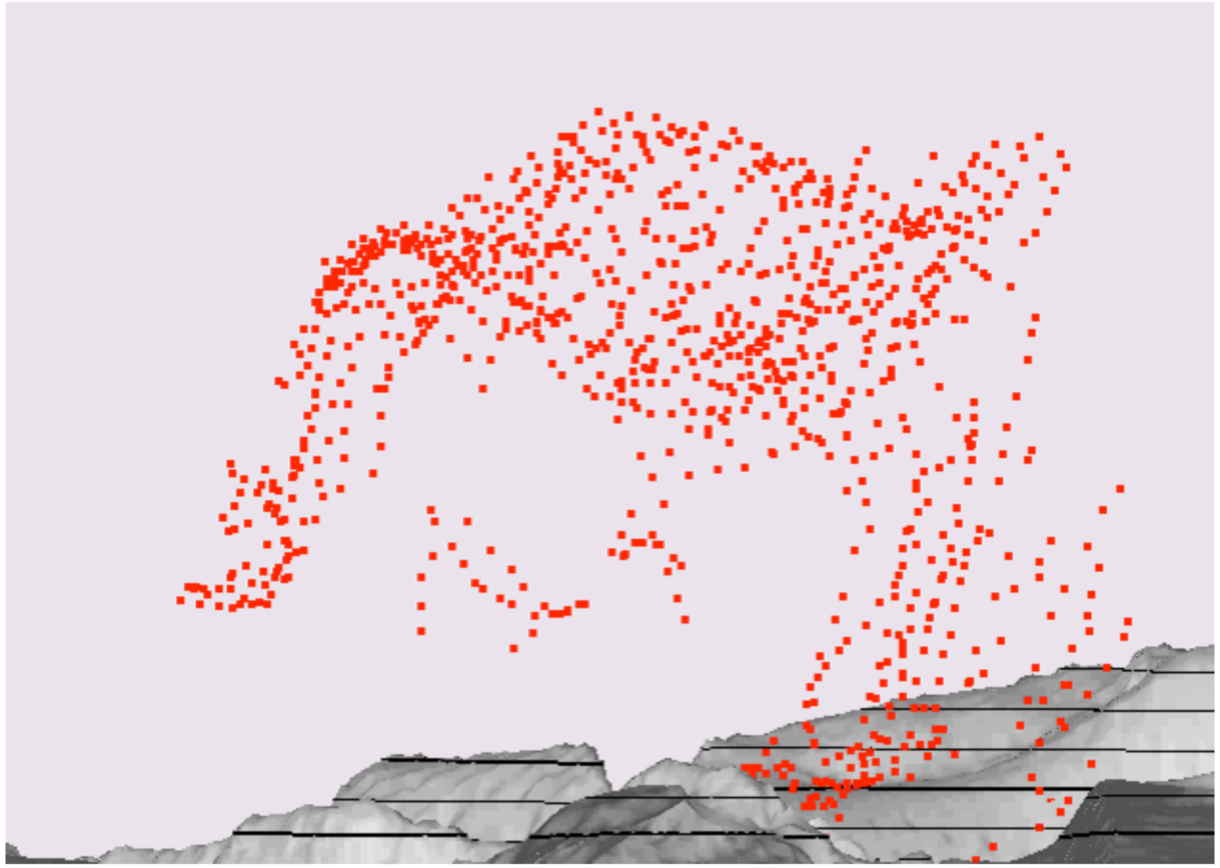
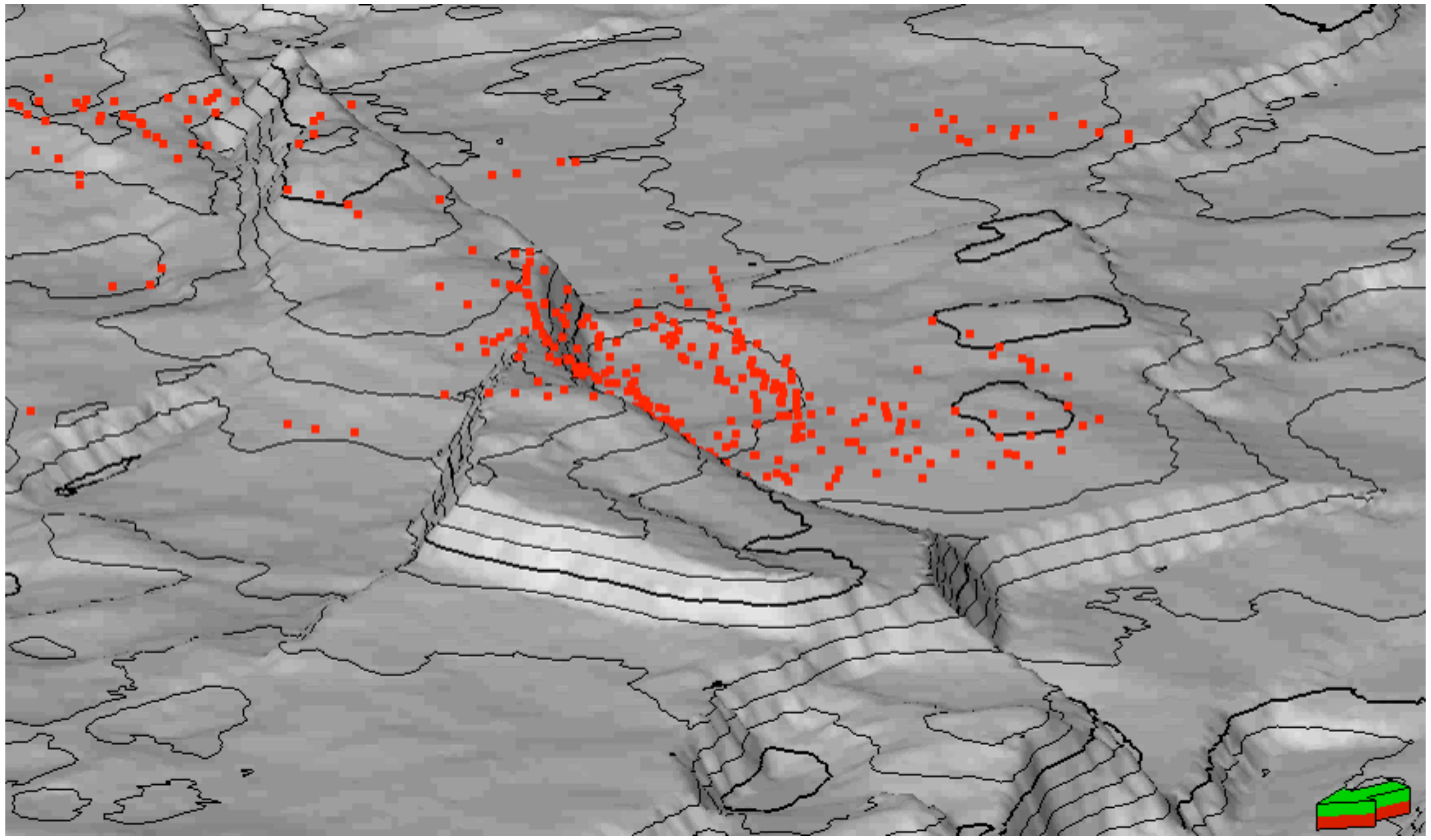
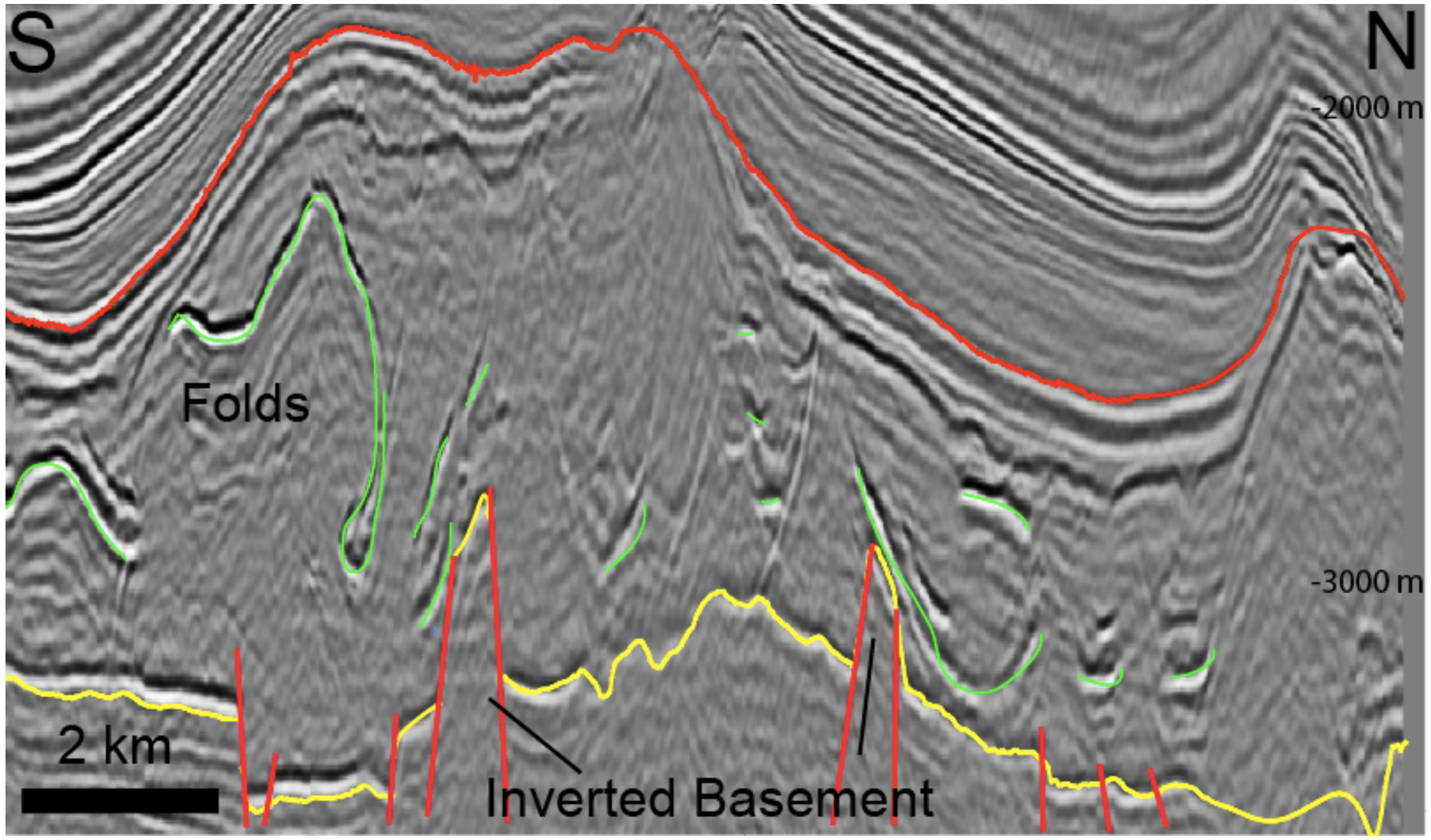
Heijn van Gent 2009

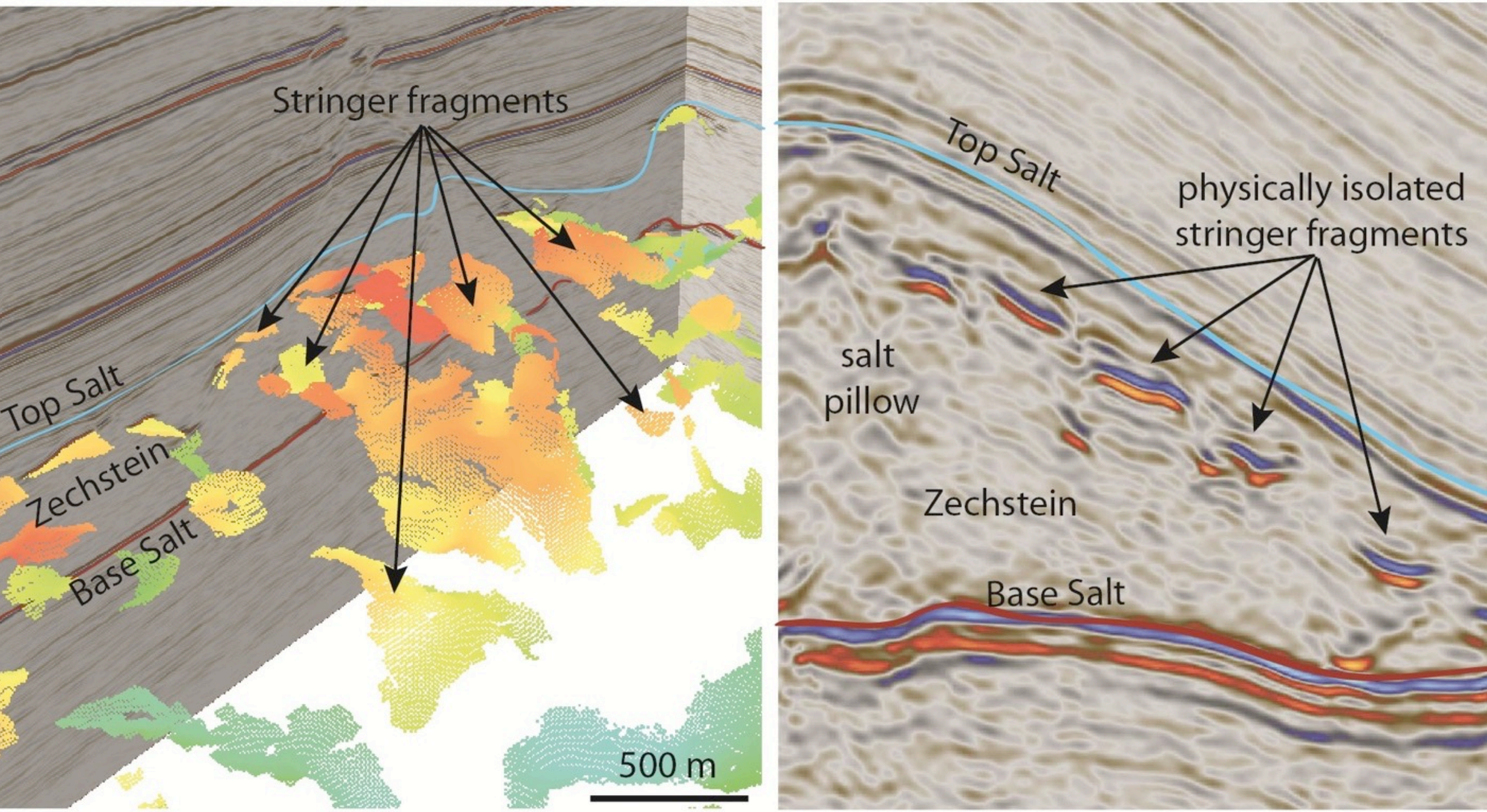
W-offshore stringer structure



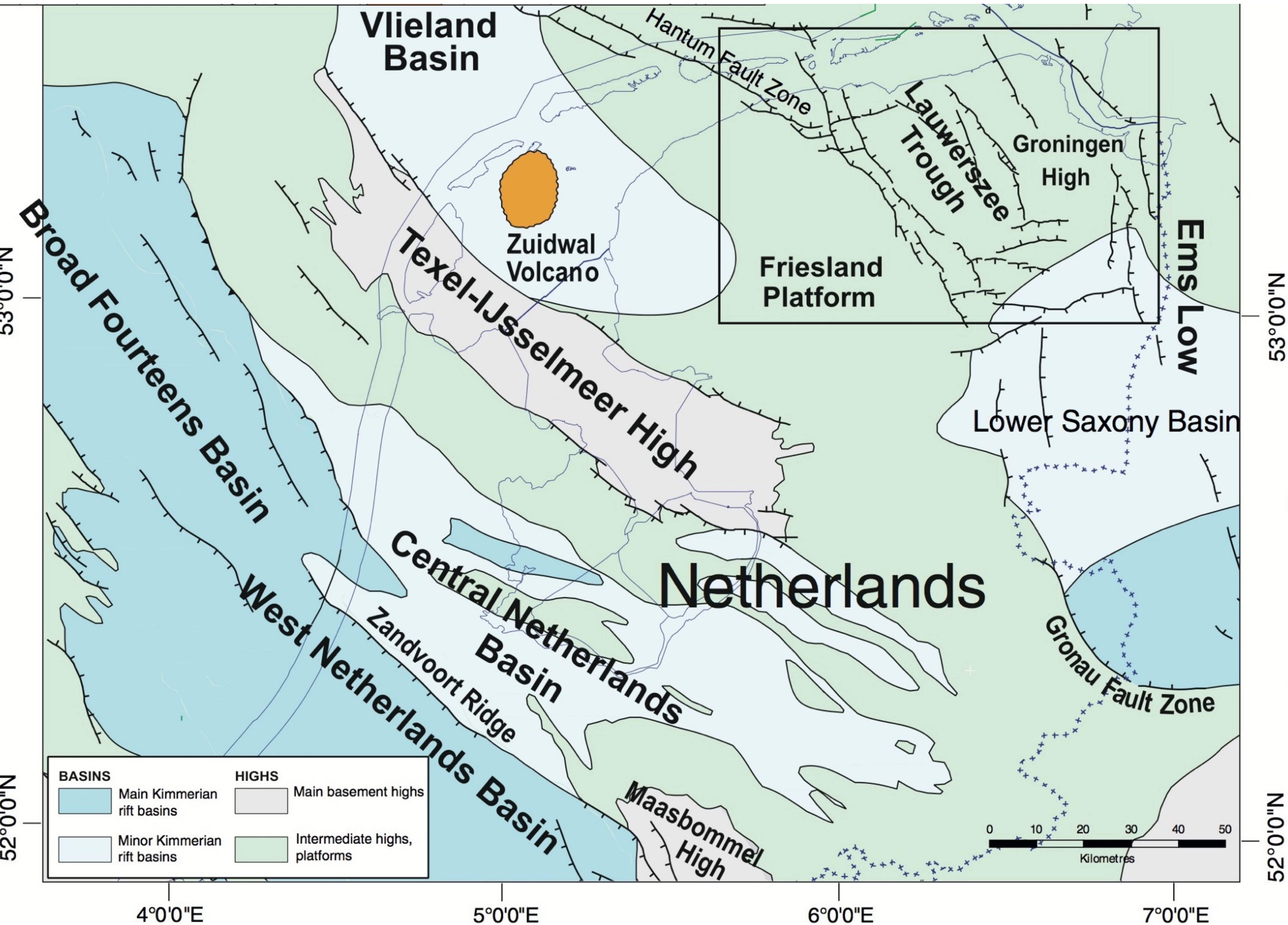




Stringers do not sink!

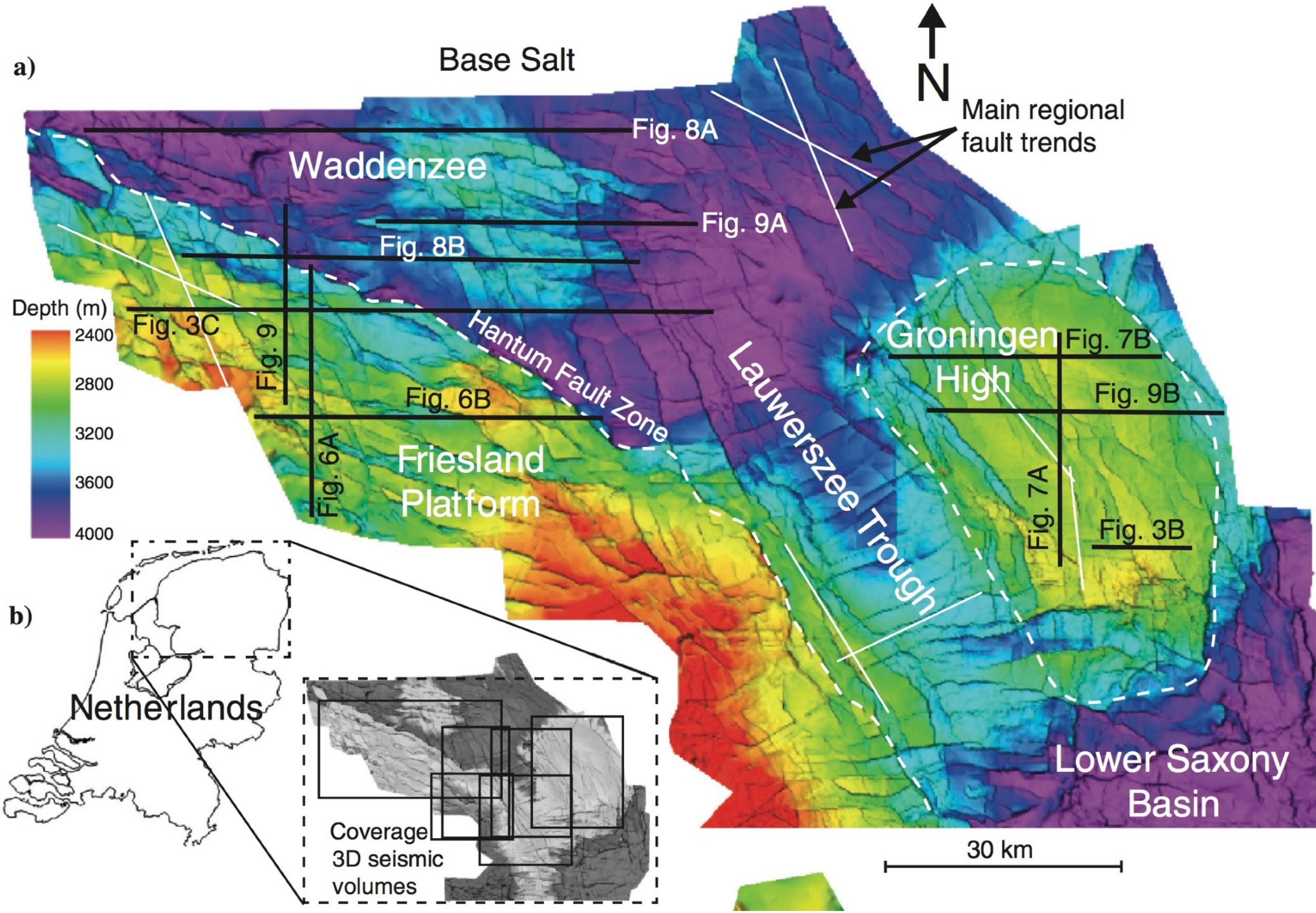


Densities: Salt = 2200, Stringer = 2900 kg/m^3

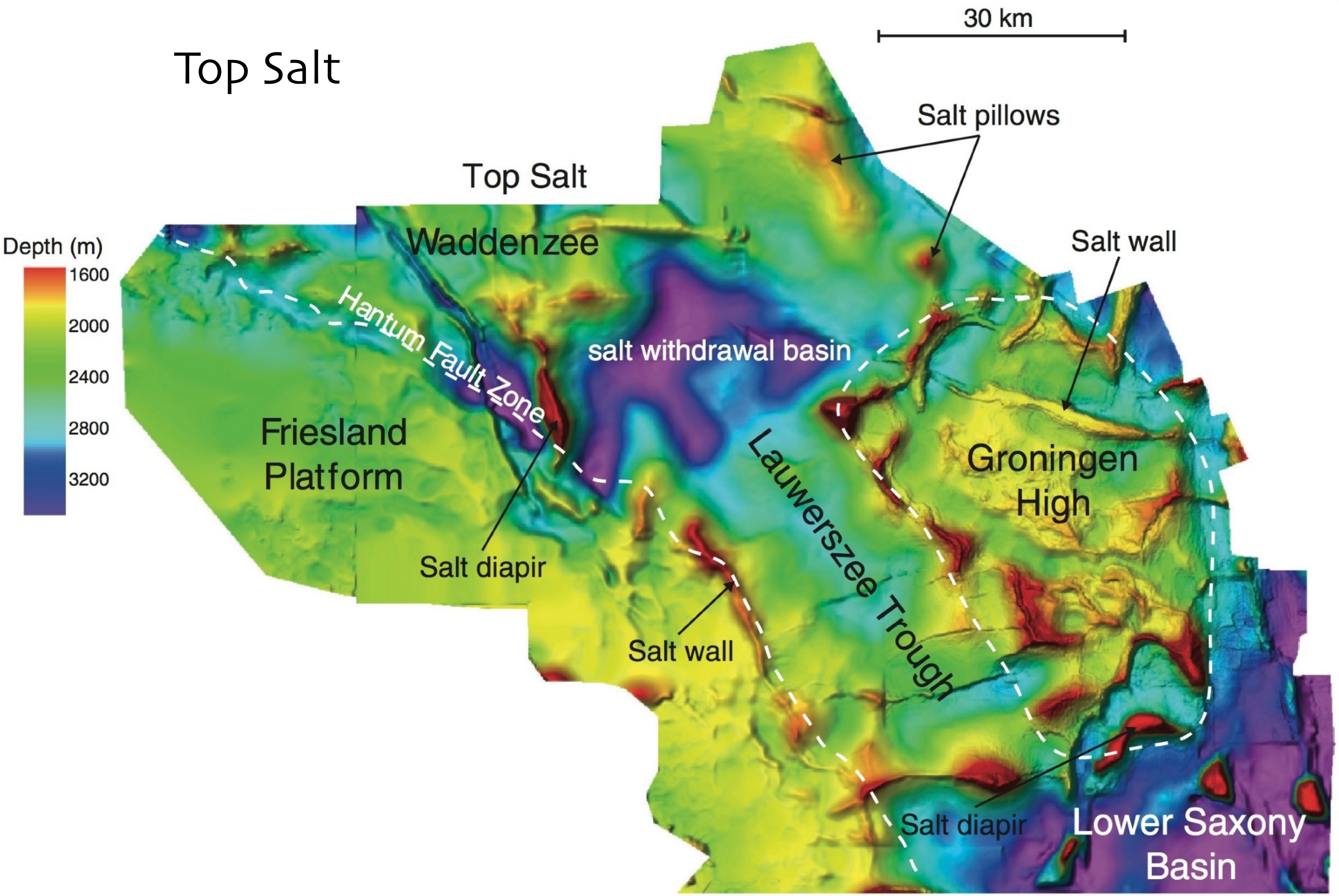


Vlieland Basin
Hantum Fault Zone
Lauwerszee Trough
Groningen High
Friesland Platform
Ems Low
Zuidwal Volcano
Texel-IJsselmeer High
Broad Fourteens Basin
Lower Saxony Basin
Netherlands
Central Netherlands Basin
West Netherlands Basin
Zandvoort Ridge
Gronau Fault Zone
Maasbommel High
BASINS
Main Kimmerian rift basins
Minor Kimmerian rift basins
HIGHS
Main basement highs
Intermediate highs, platforms
0 10 20 30 40 50
Kilometres
53°0'0"N
52°0'0"N
4°0'0"E
5°0'0"E
6°0'0"E
7°0'0"E

Regional variations in the structure of the Permian Zechstein 3 intrasalt stringer in the northern Netherlands: 3D seismic interpretation and implications for salt tectonic evolution - F Strozyk, JL Urai, H van Gent, M de Keijzer, PA Kukla — Interpretation 2 (4), SM101-SM117



Top Salt



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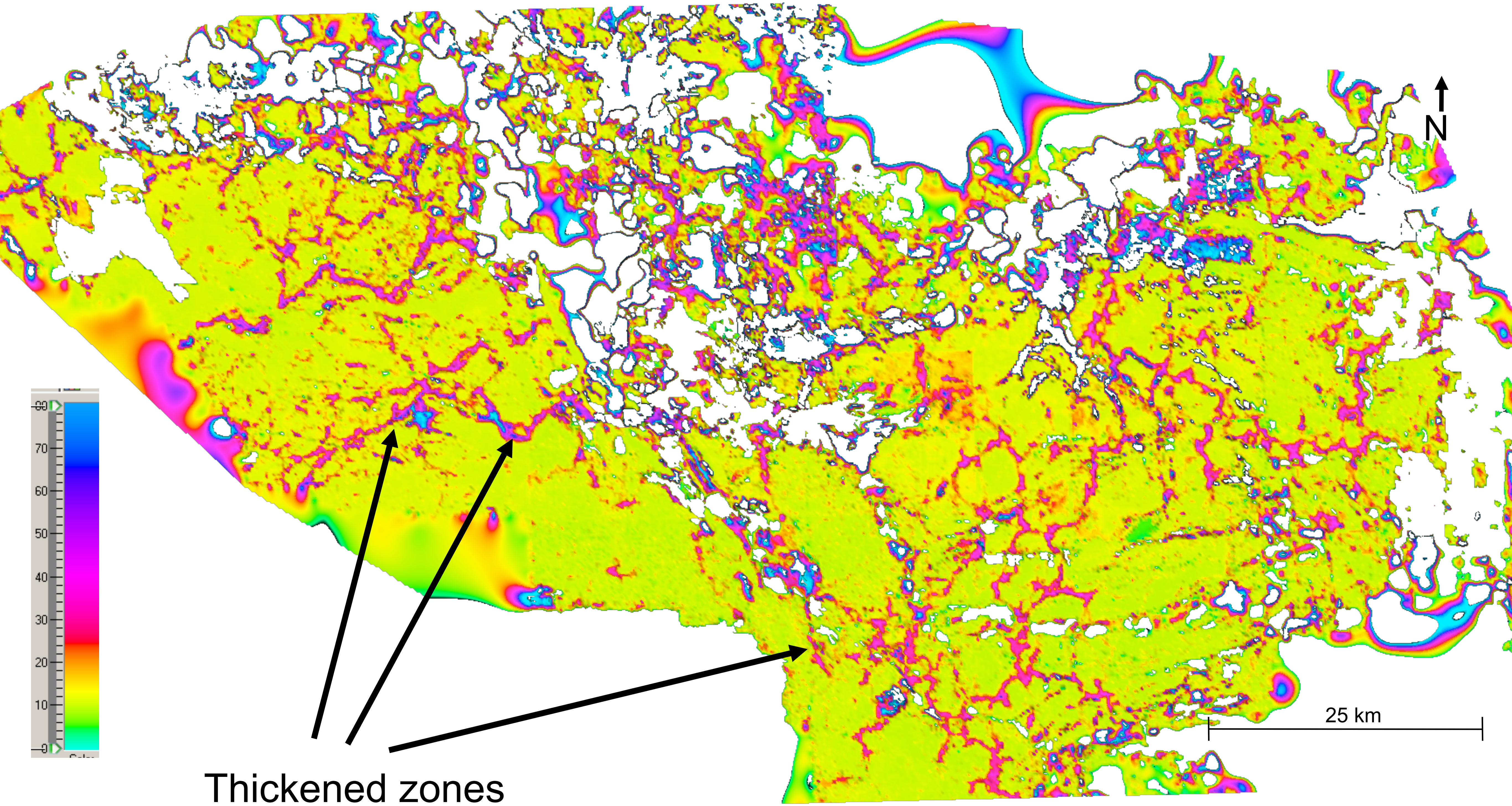
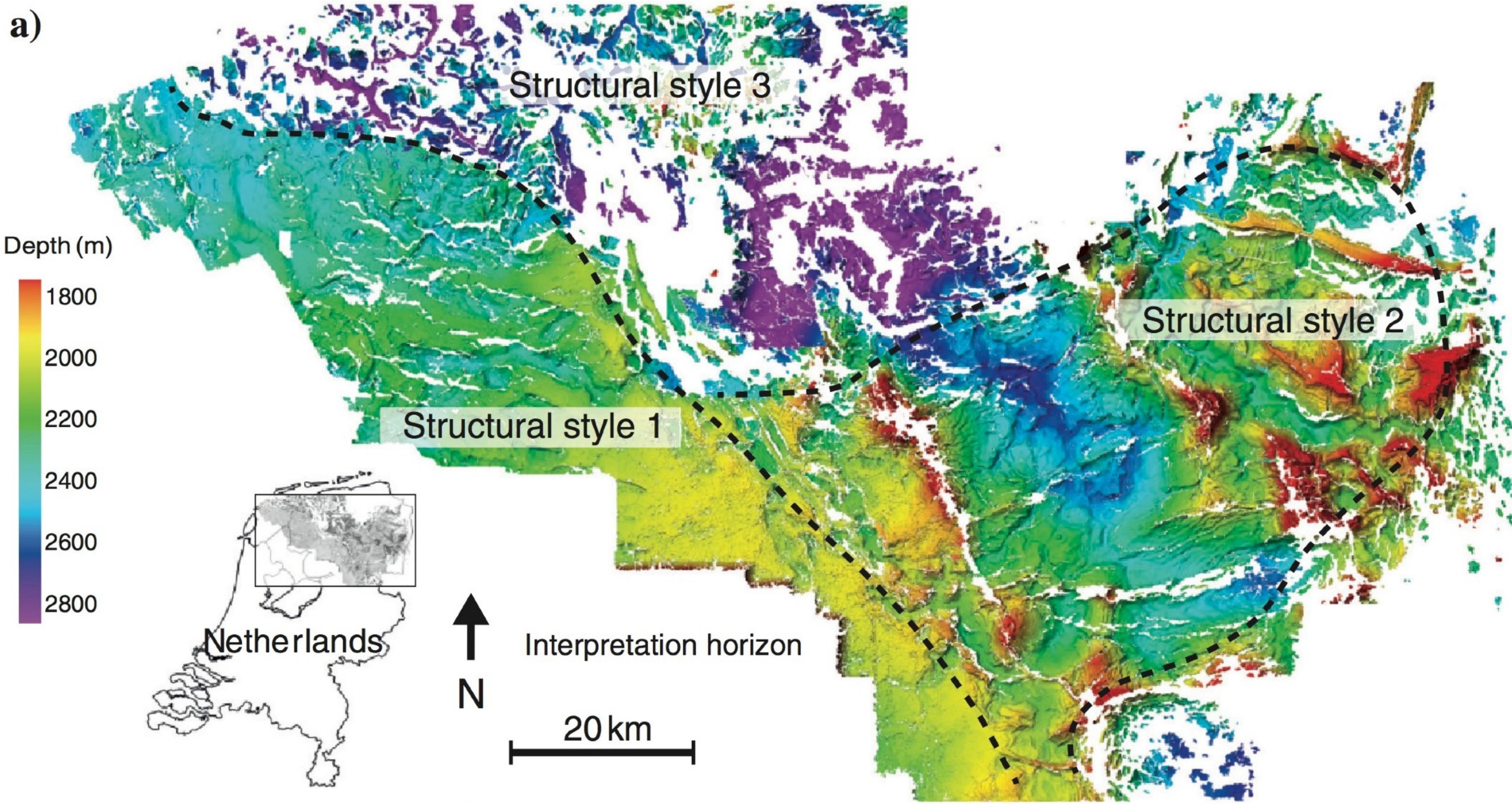
Stringer thickness

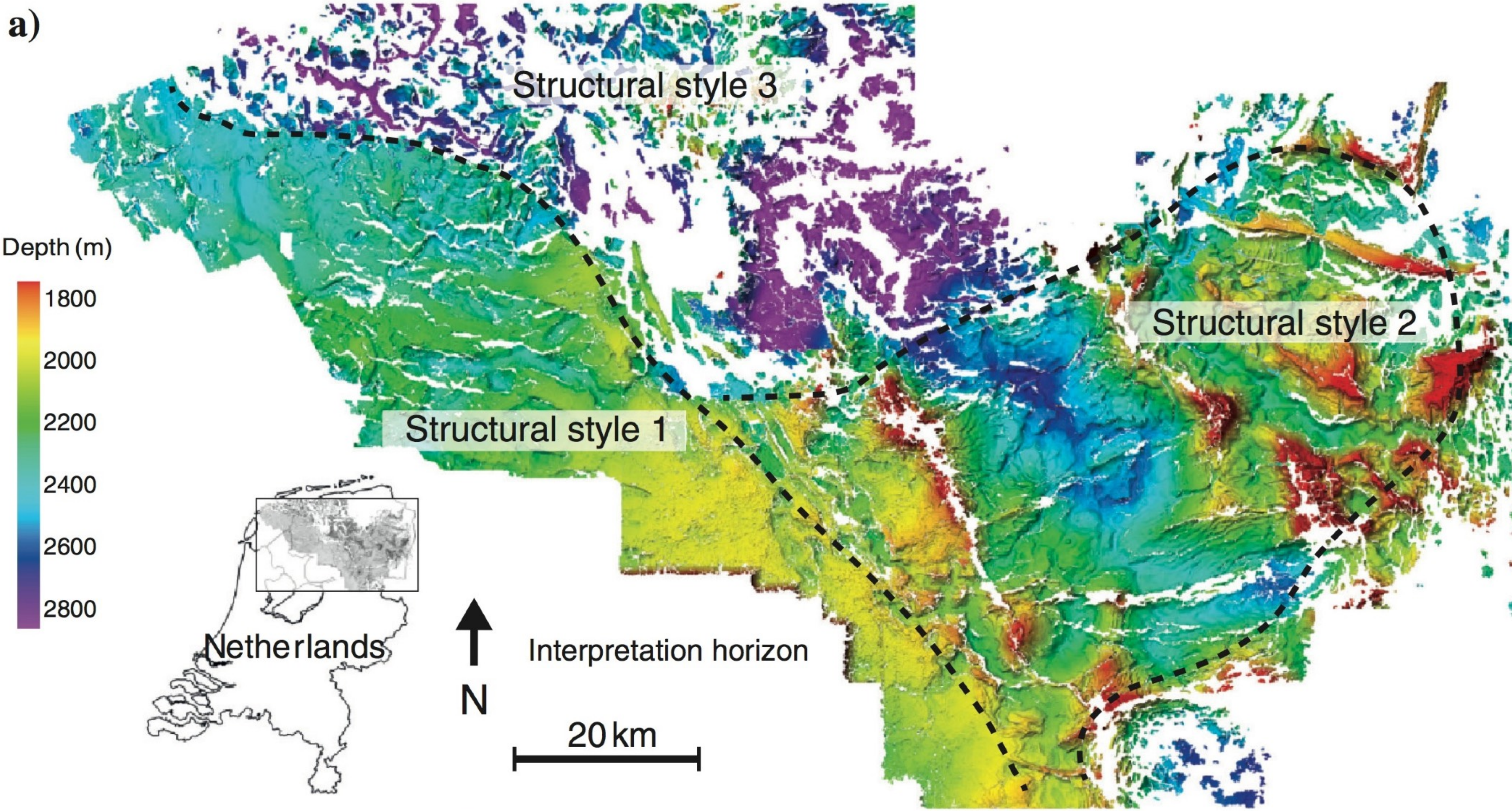
Anhydrite thickness (Top ZEZ3C toTop ZEZ3C)

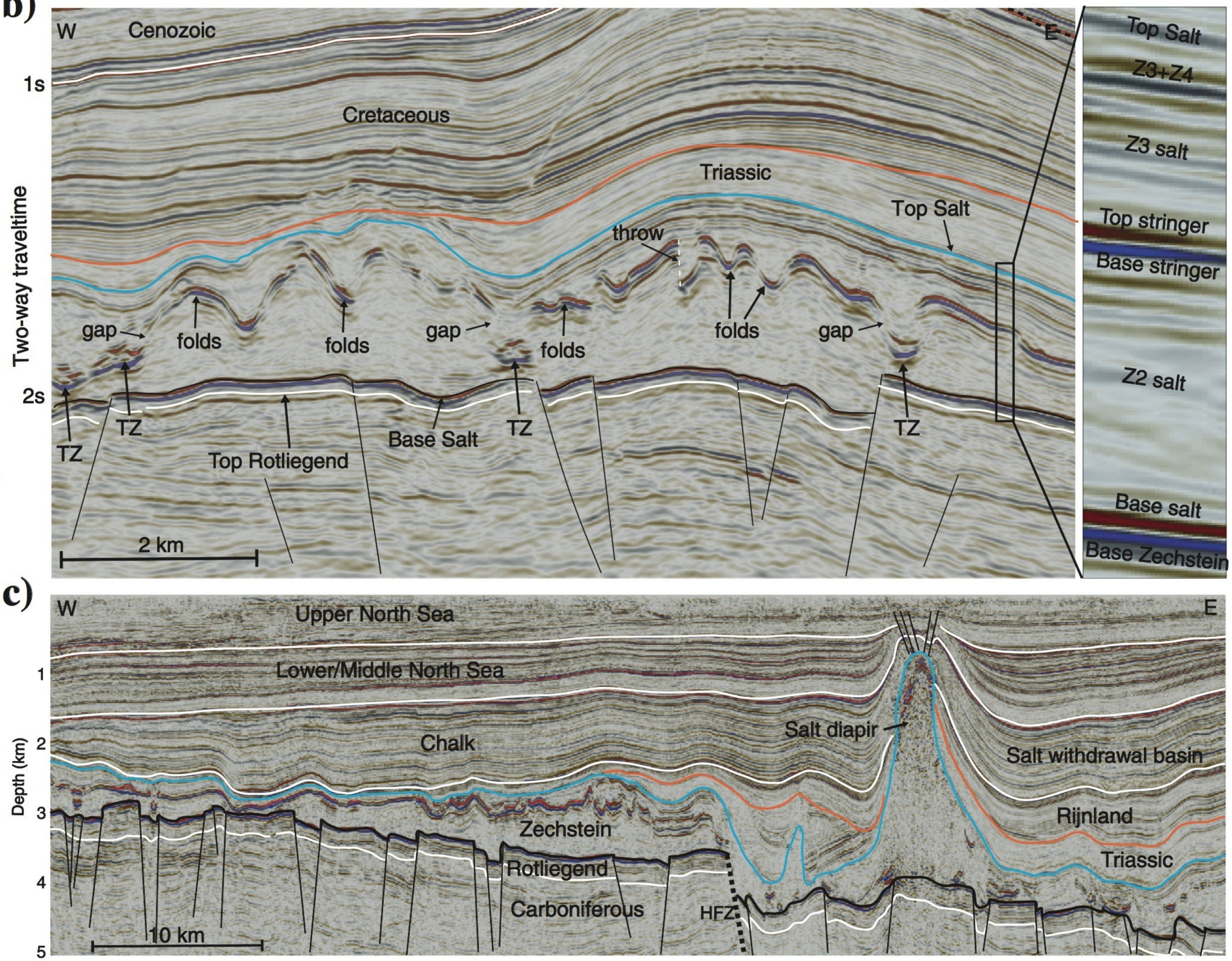



a)
Structural style 3
Structural style 2
Structural style 1
Depth (m)
1800
2000
2200
2400
2600
2800
Netherlands
N
Interpretation horizon
20 km


The Early life of salt giants
Alexander Raith, Marc Geluk, Janos Urai

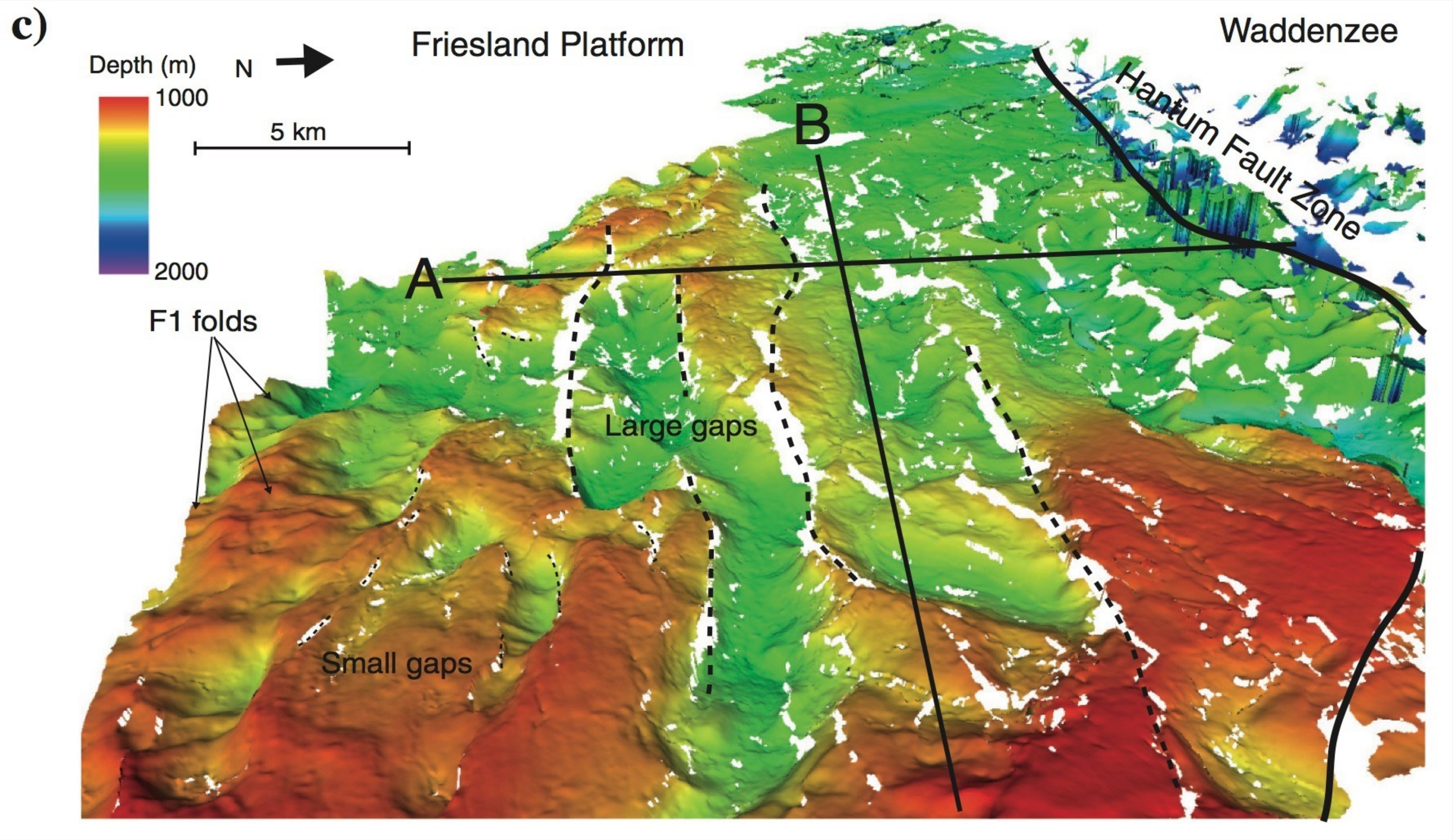
Regional variations in the structure of the Permian Zechstein 3 intrasalt stringer in the northern Netherlands: 3D seismic interpretation and implications for salt tectonic evolution - F Strozyk, JL Urai, H van Gent, M de Keijzer, PA Kukla — Interpretation 2 (4), SM101-SM117





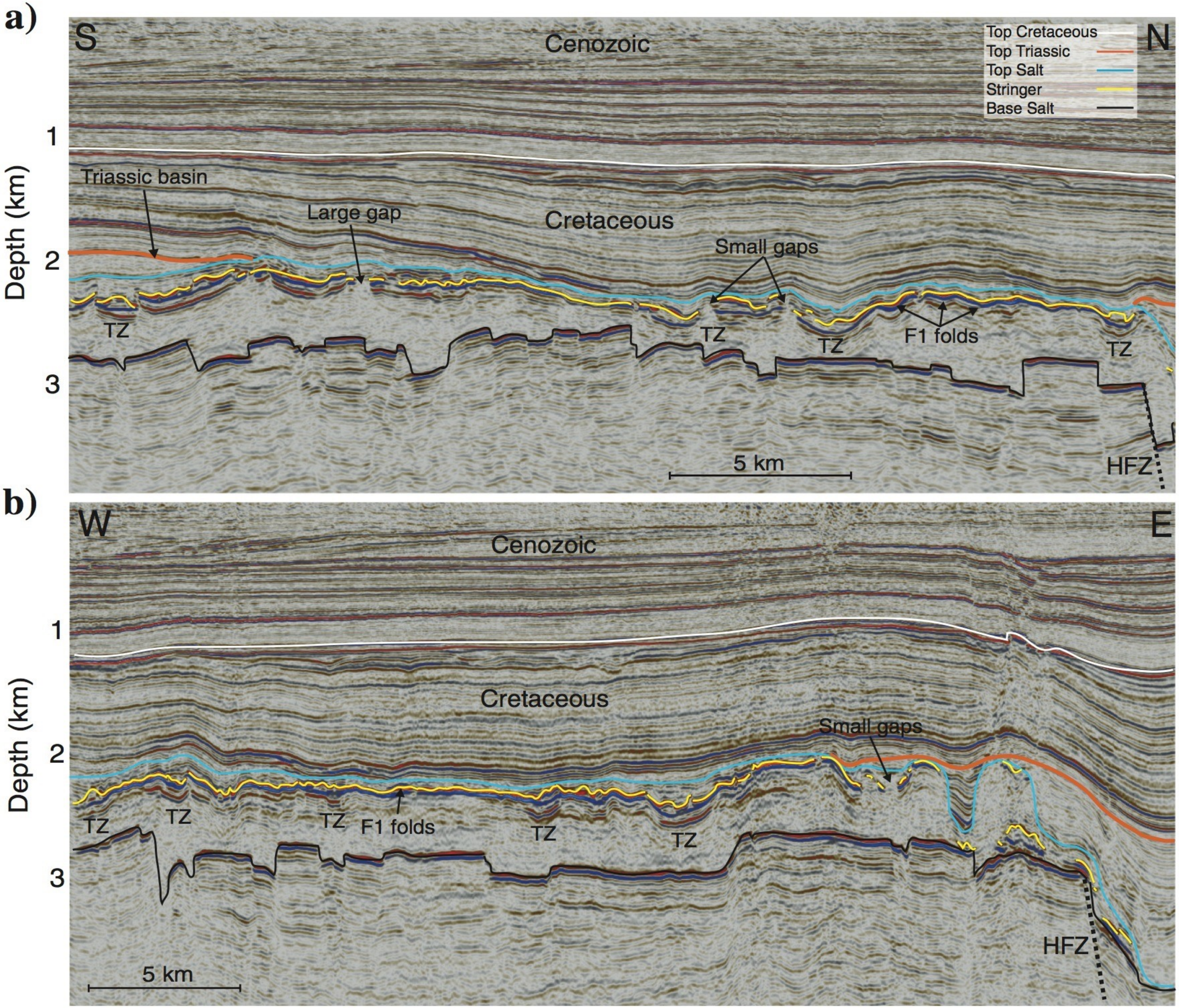
b)
W
E
Cenozoic
1s
Cretaceous
Triassic
Two-way traveltime
Top Salt
throw
gap
folds
folds
gap
folds
folds
gap
2s
TZ
TZ
TZ
TZ
Base Salt
Top Rotliegend
2 km
Top Salt
Z3+Z4
Z3 salt
Top stringer
Base stringer
Z2 salt
Base salt
Base Zechstein
c)
W
E
Upper North Sea
Lower/Middle North Sea
Salt diapir
Chalk
Salt withdrawal basin
Depth (km)
1
2
3
4
5
Zechstein
Rijnland
Triassic
Rotliegend
Carboniferous
HFZ
10 km

Low strain structural style

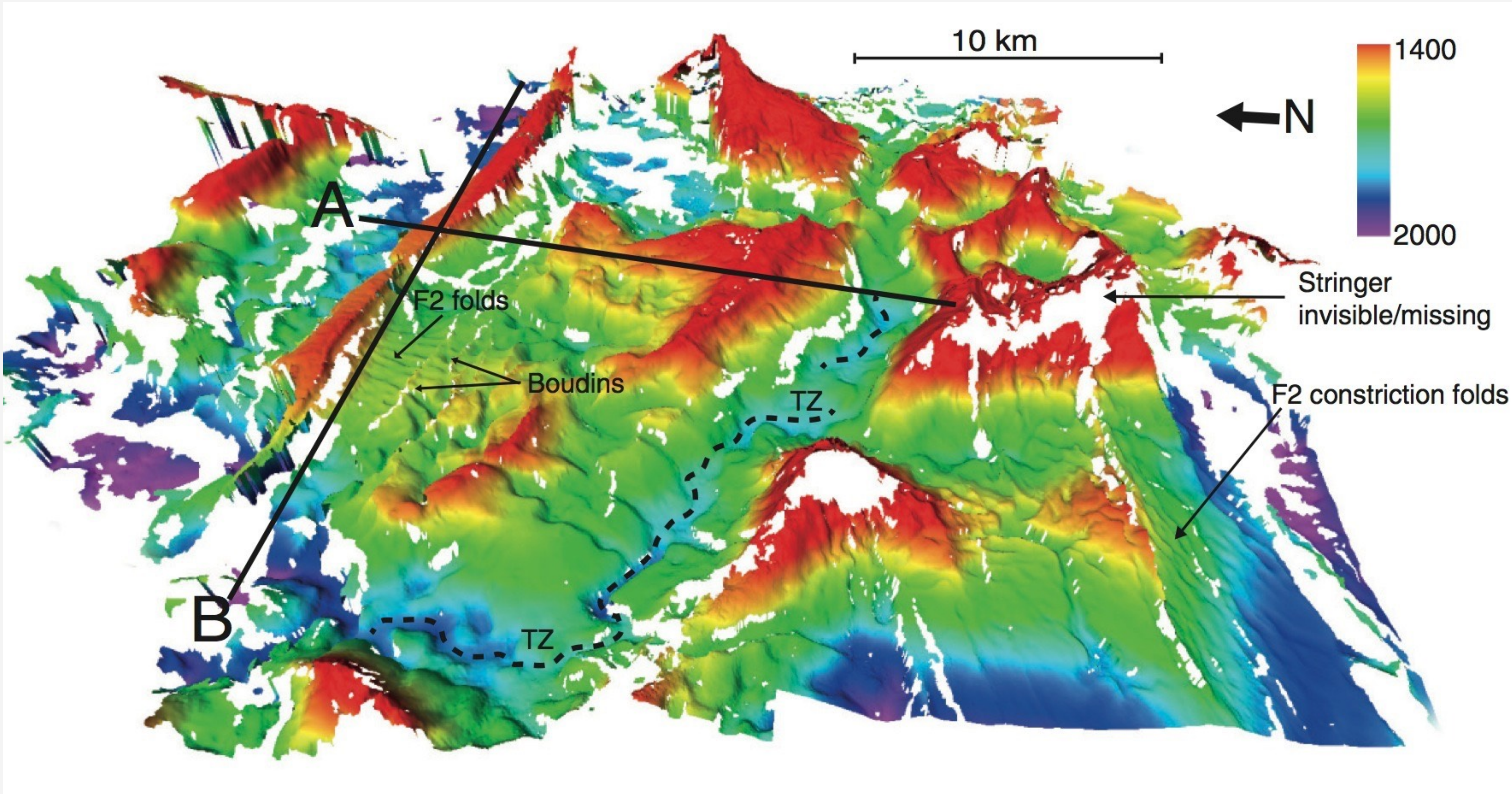


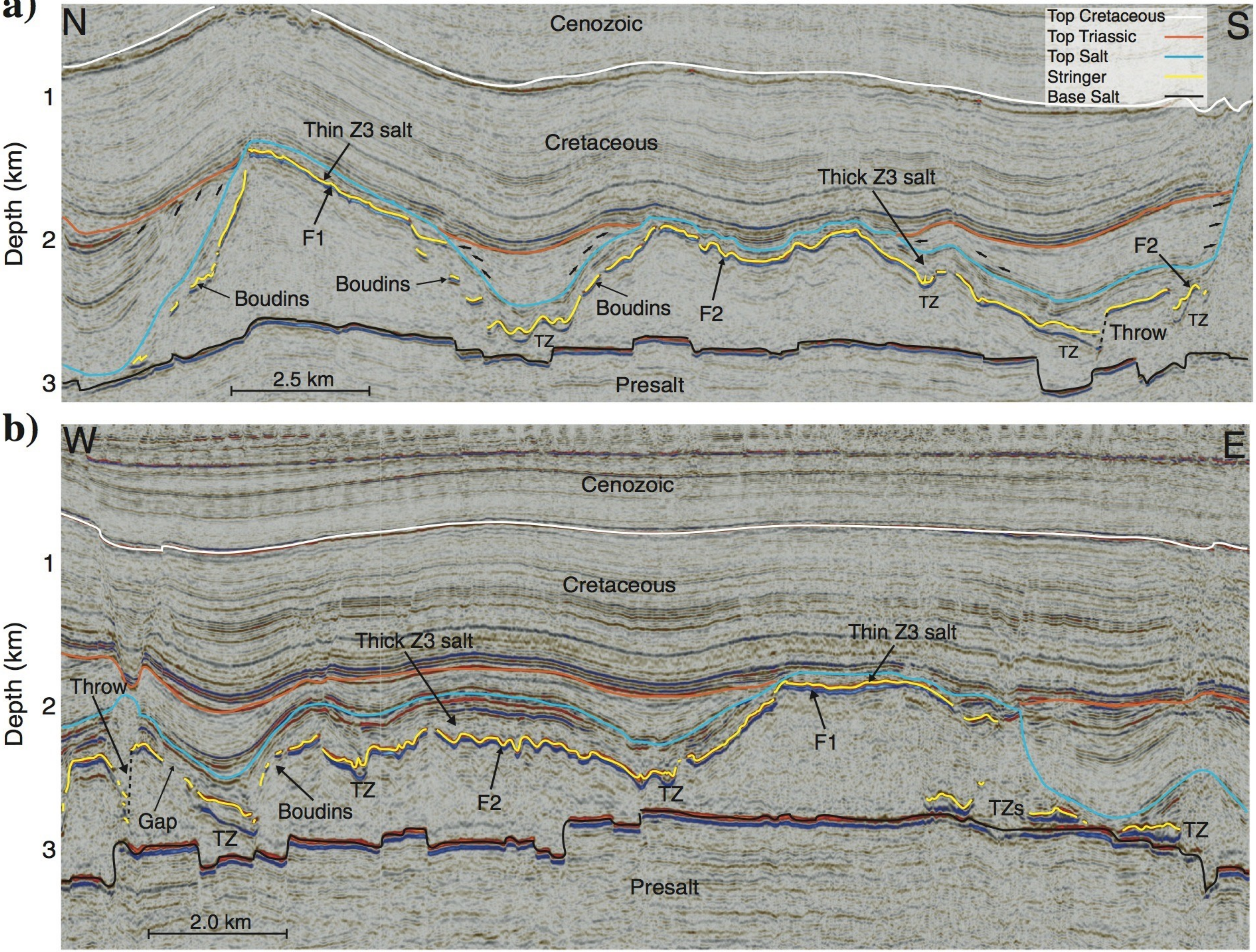
a)

b)


S
N
Cenozoic
Top Cretaceous
Top Triassic
Top Salt
Stringer
Base Salt
1
2
3
Depth (km)
Triassic basin
Large gap
Cretaceous
Small gaps
TZ
TZ
TZ
F1 folds
TZ
HFZ
5 km
W
E
Cenozoic
1
2
3
Depth (km)
Cretaceous
Small gaps
TZ
TZ
TZ
F1 folds
TZ
TZ
HFZ
5 km

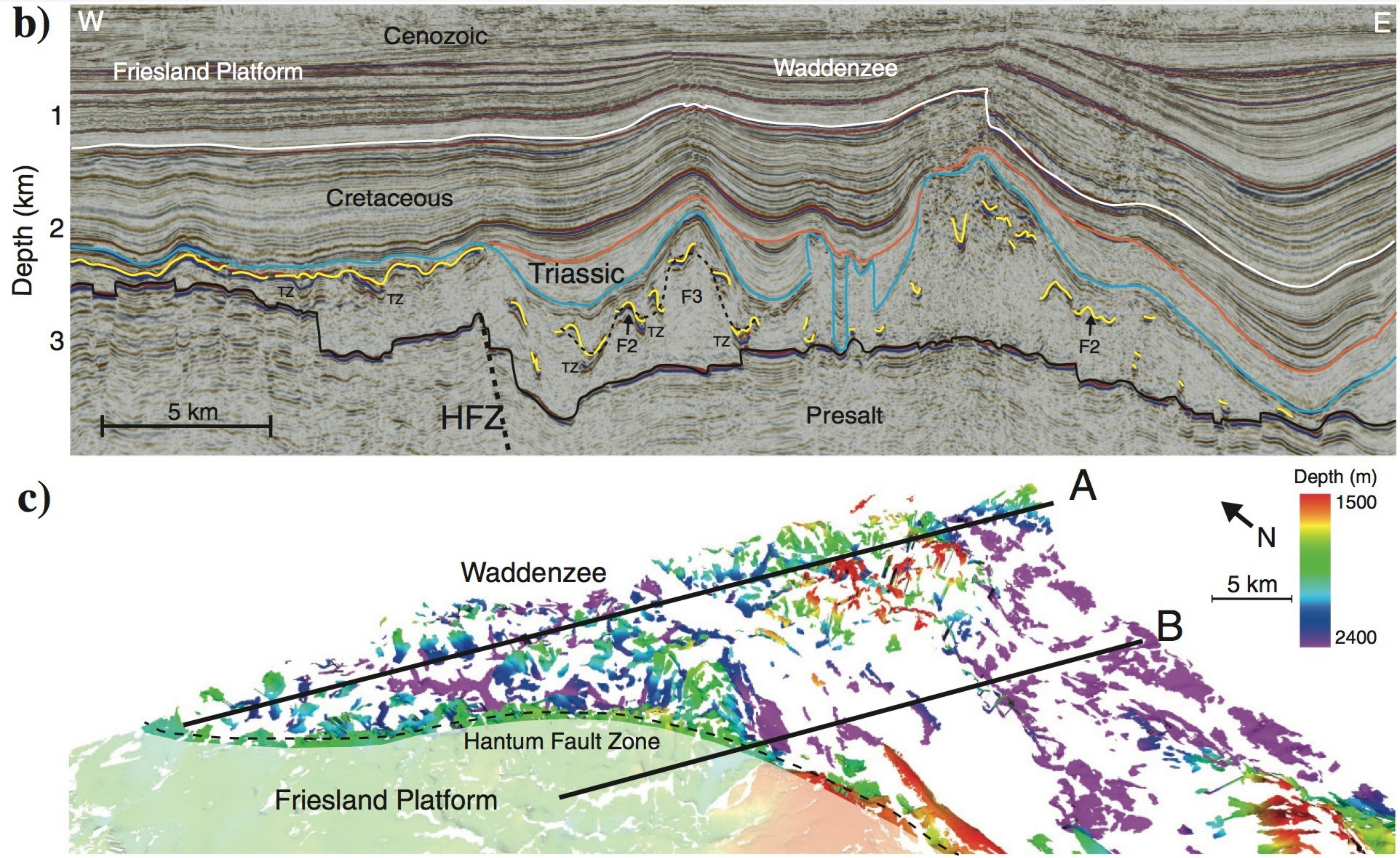
Salt dome Structural style

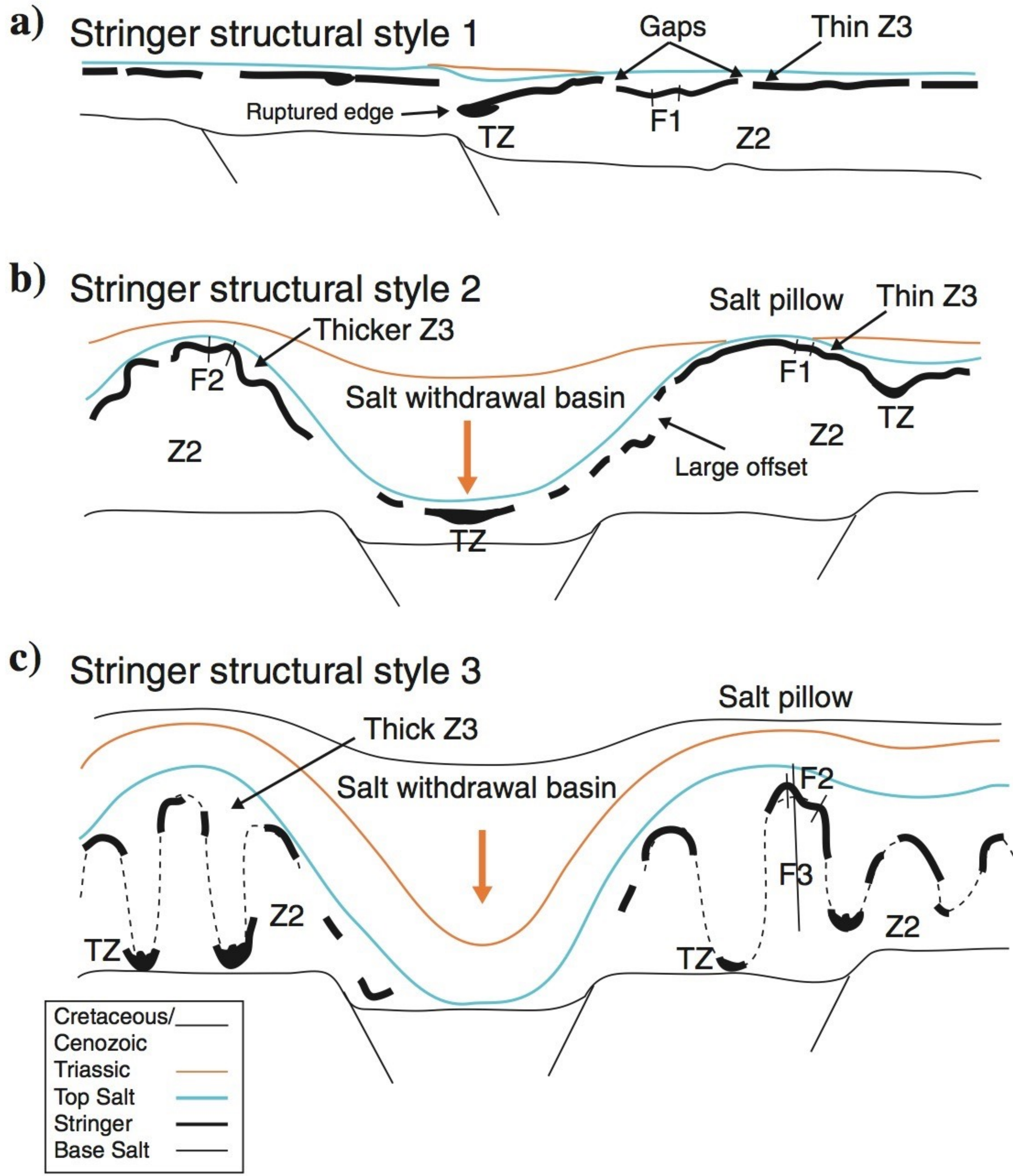




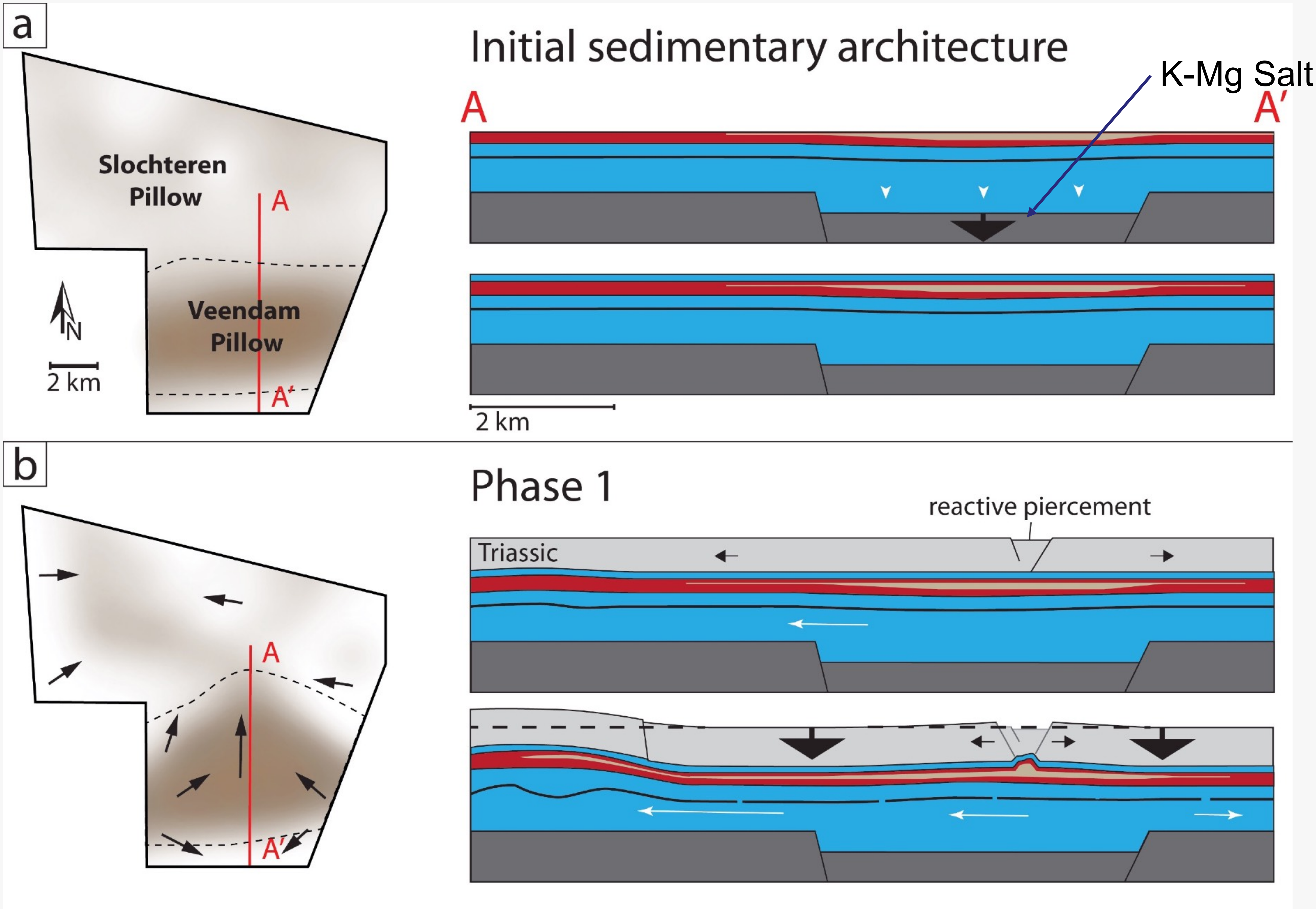
a)
N
S
Cenozoic
Top Cretaceous
Top Triassic
Top Salt
Stringer
Base Salt
1
2
3
Depth (km)
Cretaceous
Thin Z3 salt
F1
Thick Z3 salt
F2
Boudins
TZ
Throw
2.5 km
Presalt
b)
W
E
Cenozoic
1
2
3
Depth (km)
Cretaceous
Thick Z3 salt
Thin Z3 salt
Throw
F1
F2
Gap
Boudins
TZ
TZs
2.0 km
Presalt

Large strain structural style




a)
Stringer structural style 1
Gaps
Thin Z3
Ruptured edge
TZ
F1
Z2
b)
Stringer structural style 2
Salt pillow
Thin Z3
Thicker Z3
F2
F1
Salt withdrawal basin
TZ
Z2
Large offset
Z2
TZ
c)
Stringer structural style 3
Salt pillow
Thick Z3
Salt withdrawal basin
F2
F3
Z2
TZ
TZ
Z2
Cretaceous/
Cenozoic
Triassic
Top Salt
Stringer
Base Salt

Geologic Evolution of the Veendam Pillow (12)



Geologic Evolution of the Veendam Pillow (12)

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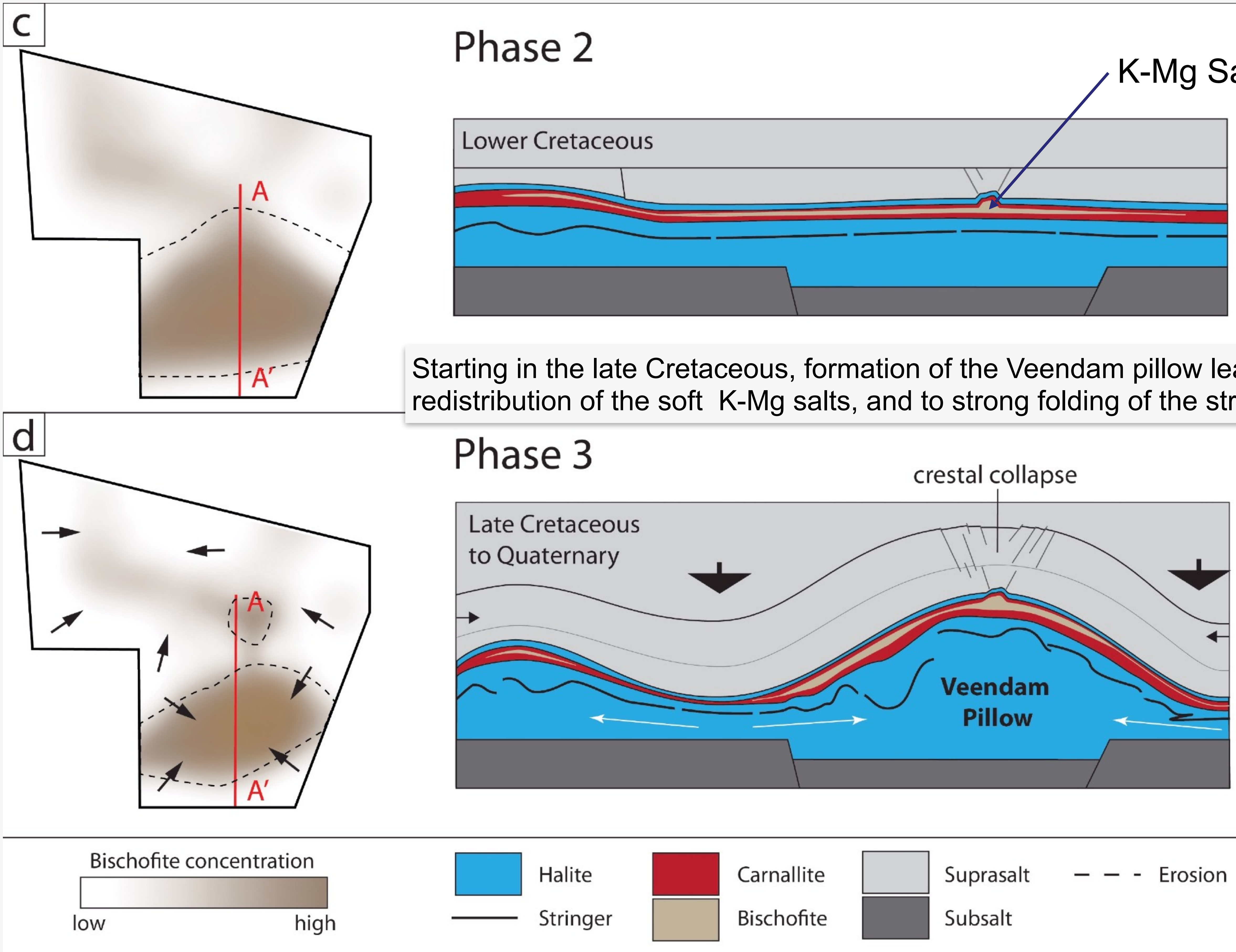
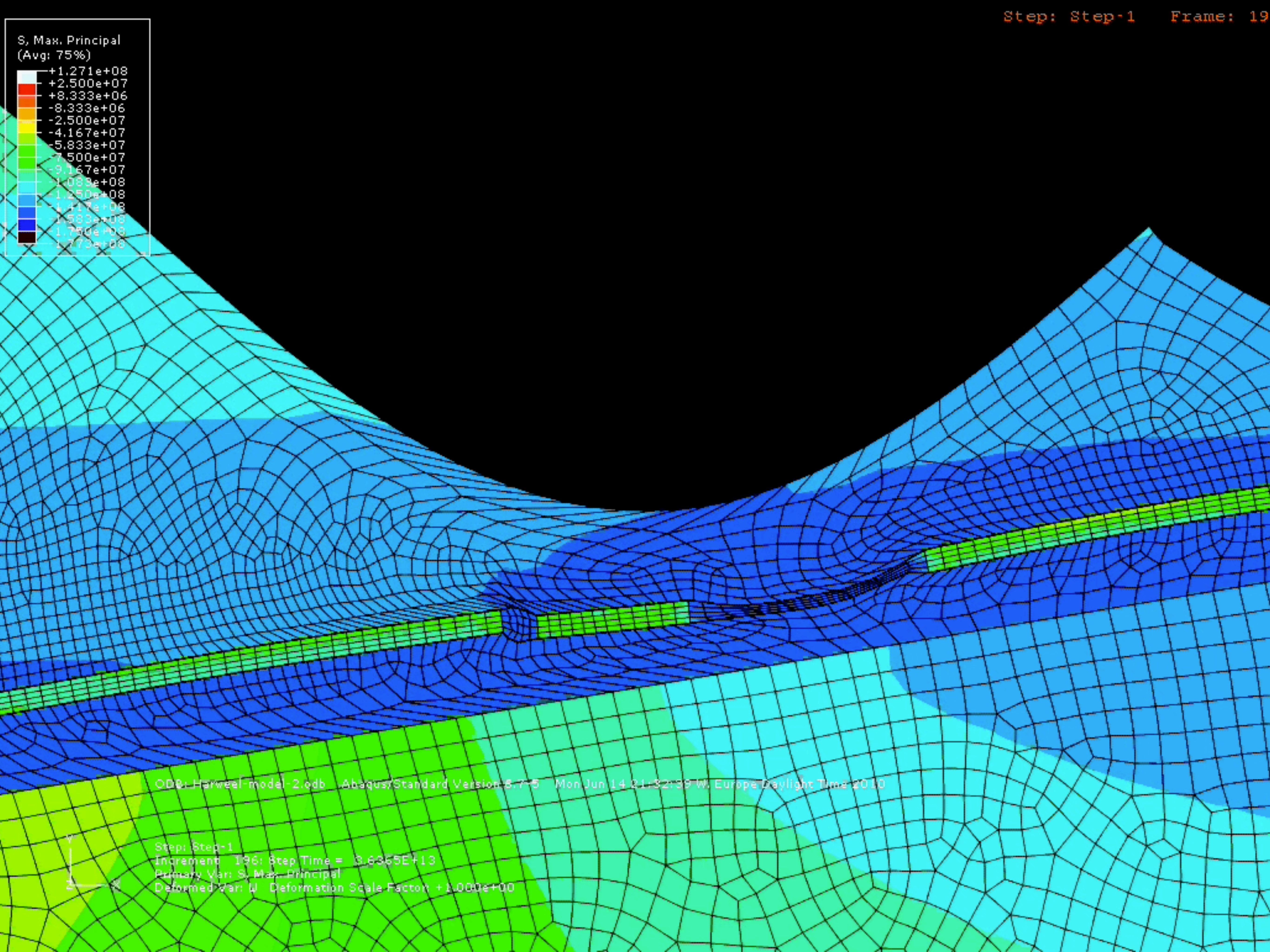
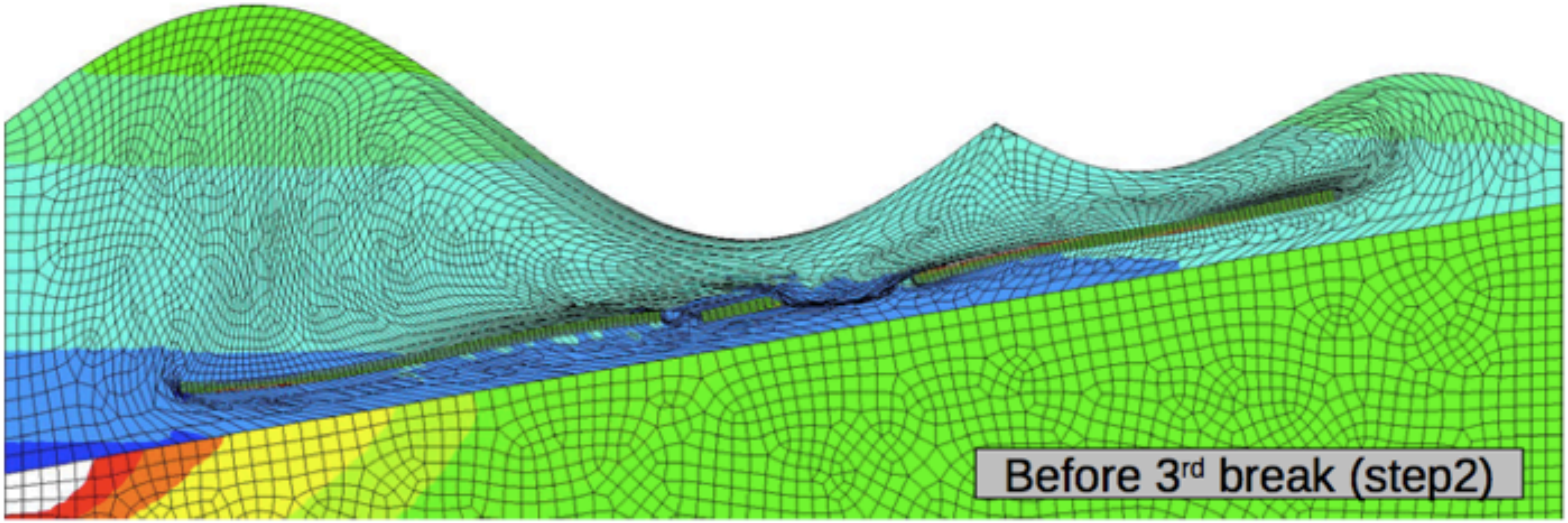


Starting in the late Cretaceous, formation of the Veendam pillow leads to redistribution of the soft K-Mg salts, and to strong folding of the stringers.

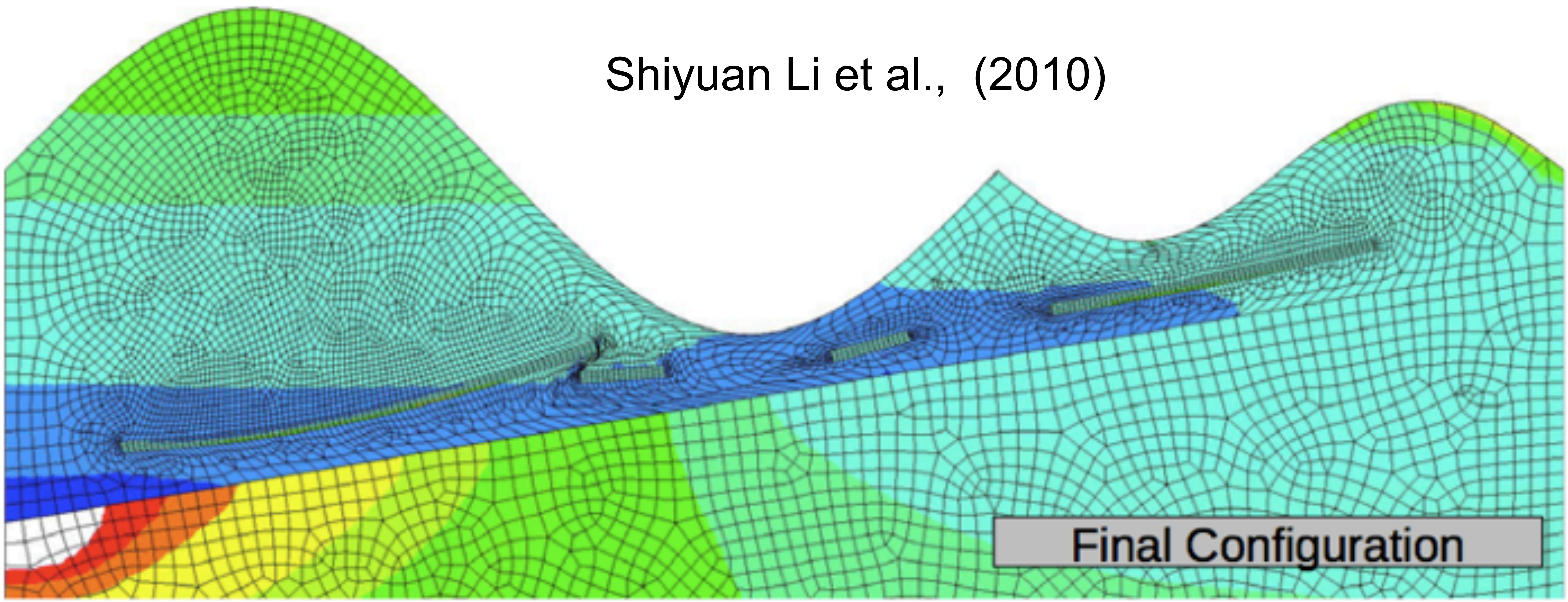


S, Max. Principal
(Avg: 75%)
+1.271e+08
+2.500e+07
+8.333e+06
-8.333e+06
-2.500e+07
-4.167e+07
-5.833e+07
-7.500e+07
-9.167e+07
-1.083e+08
-1.250e+08
-1.417e+08
-1.583e+08
-1.750e+08
-1.773e+08
Step: Step-1   Frame: 19
ODB: Harweel-model-2.odb   Abaqus/Standard Version 6.7-5   Mon Jun 14 21:32:39 W. Europe Daylight Time 2010
Step: Step-1
Increment   196: Step Time =   3.6365E+13
Primary Var: S, Max. Principal
Deformed Var: U   Deformation Scale Factor: +1.000e+00

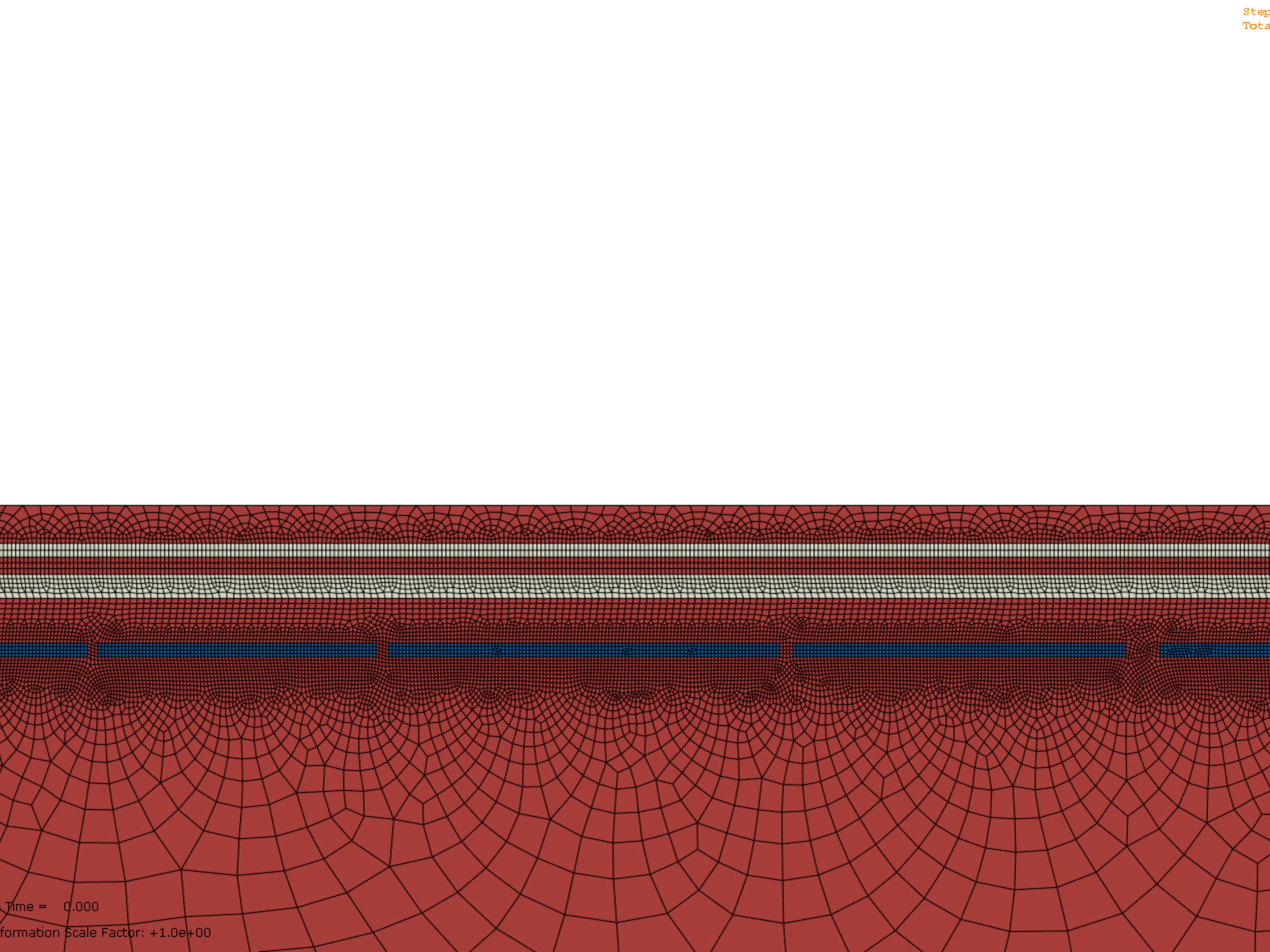
Finite element modeling of salt tectonics



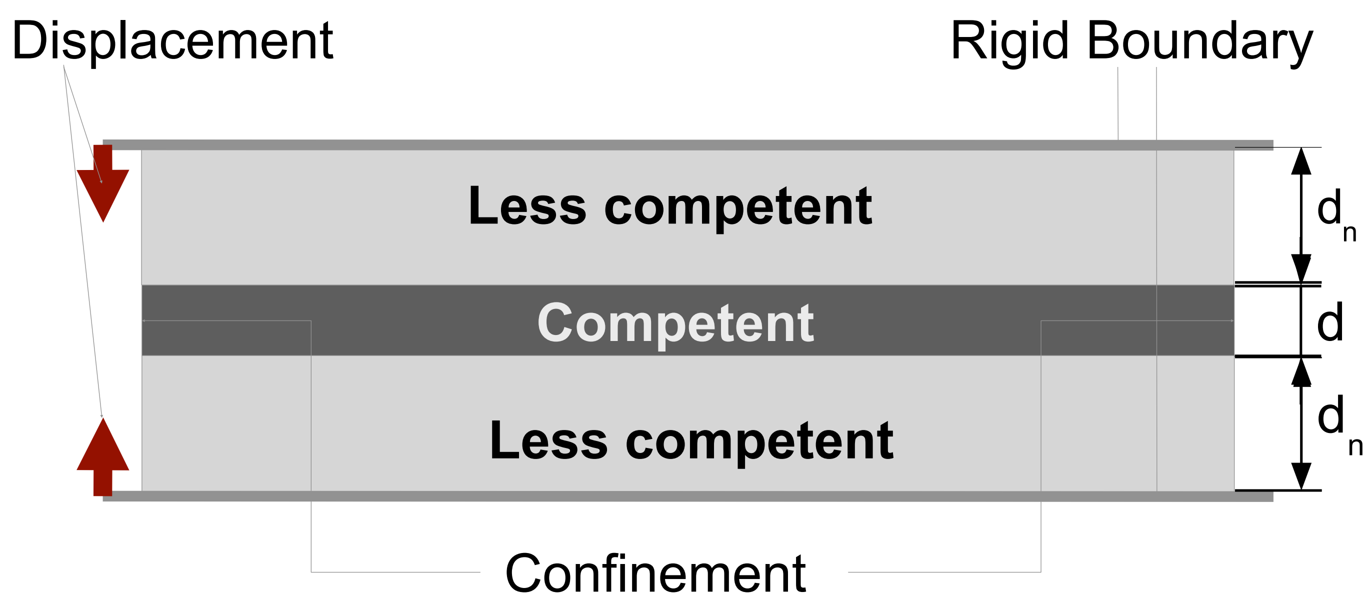
Shiyuan Li et al., (2010)



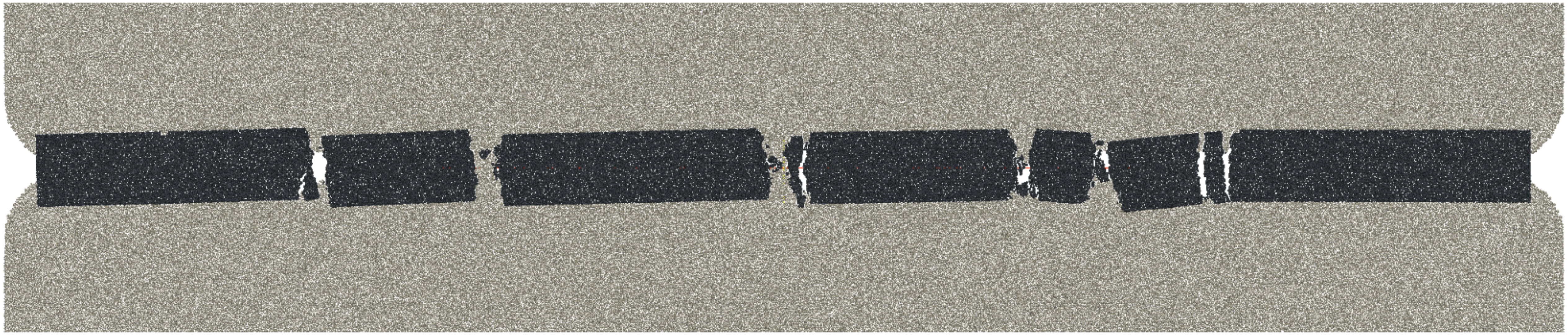
Geological Society, London, Special Publications 2012, v.363

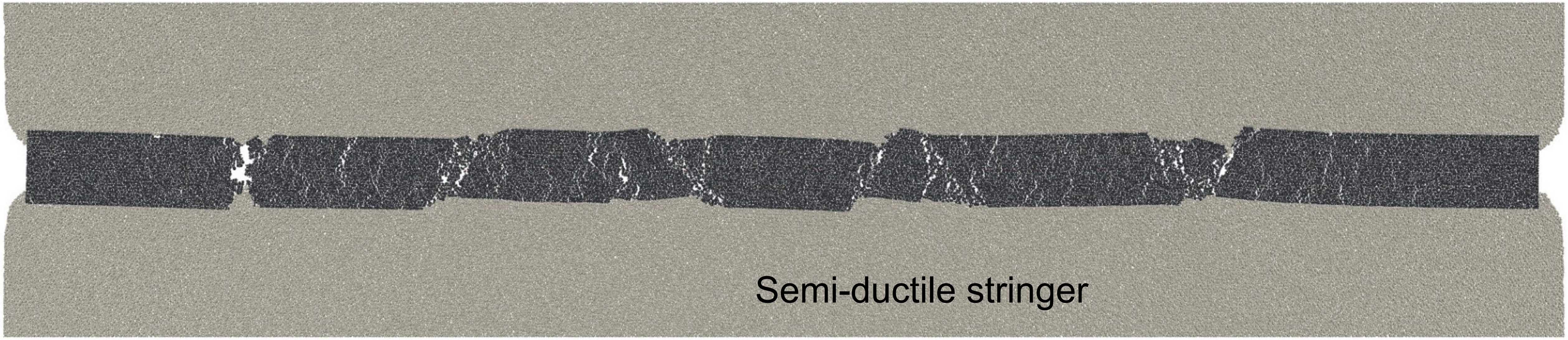

Step
Tota
Time = 0.000
formation Scale Factor: +1.0e+00

2D DEM Model
- extension



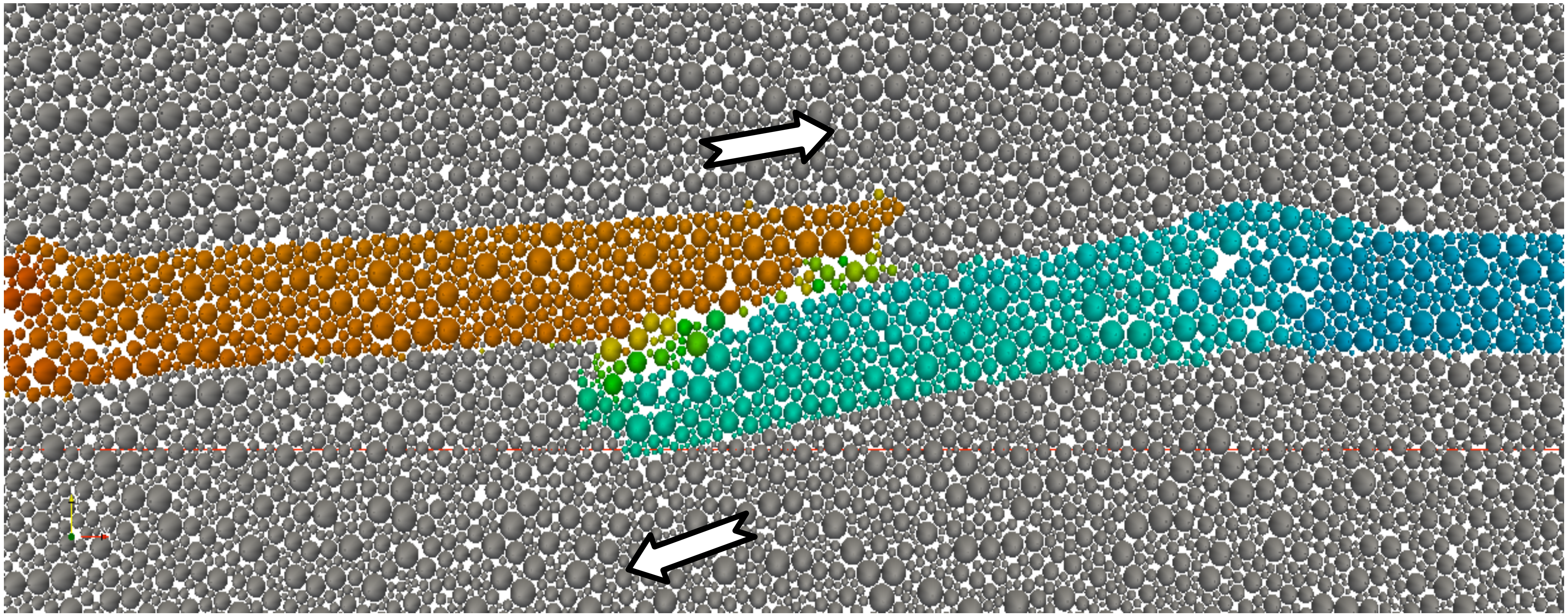
Fully brittle stringer

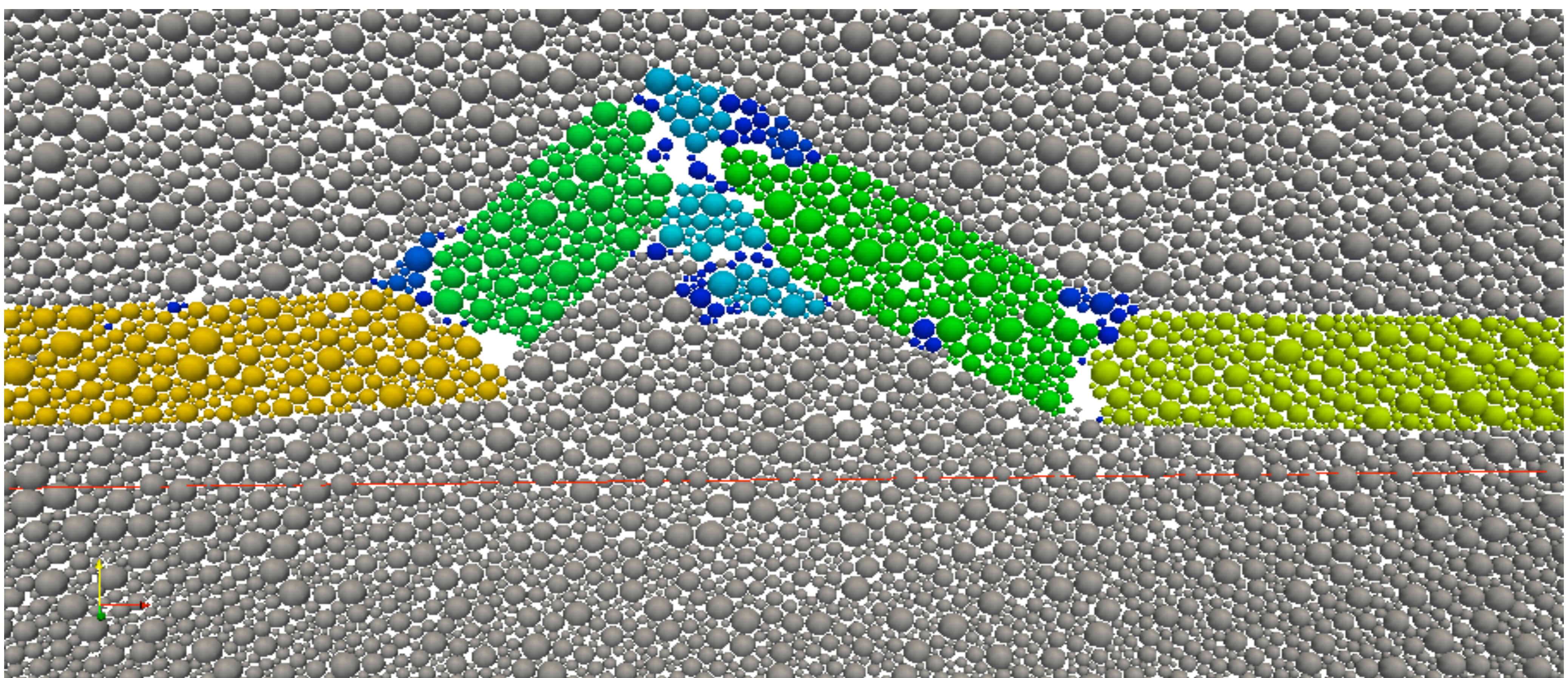




2D DEM Models- shortening

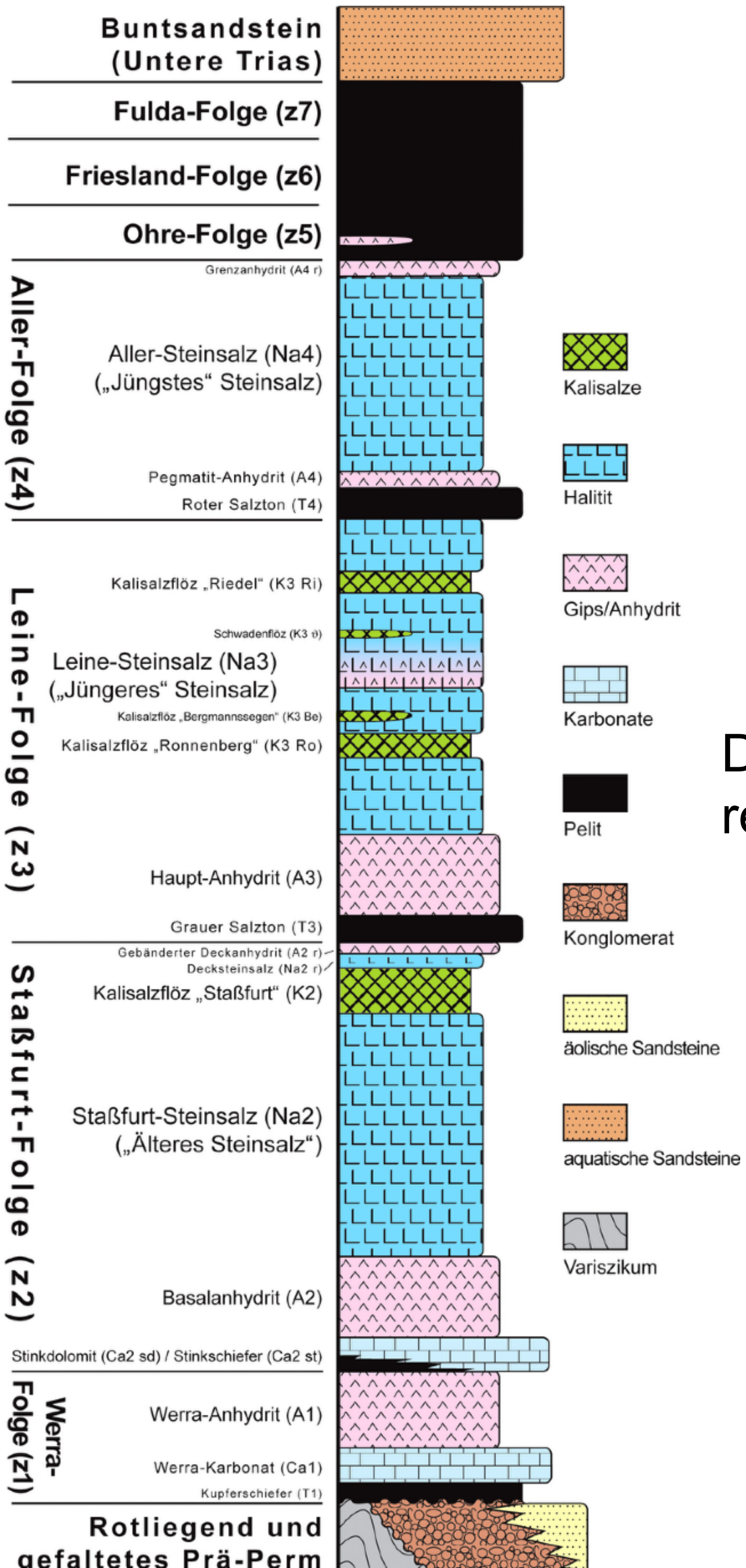
Thrusting

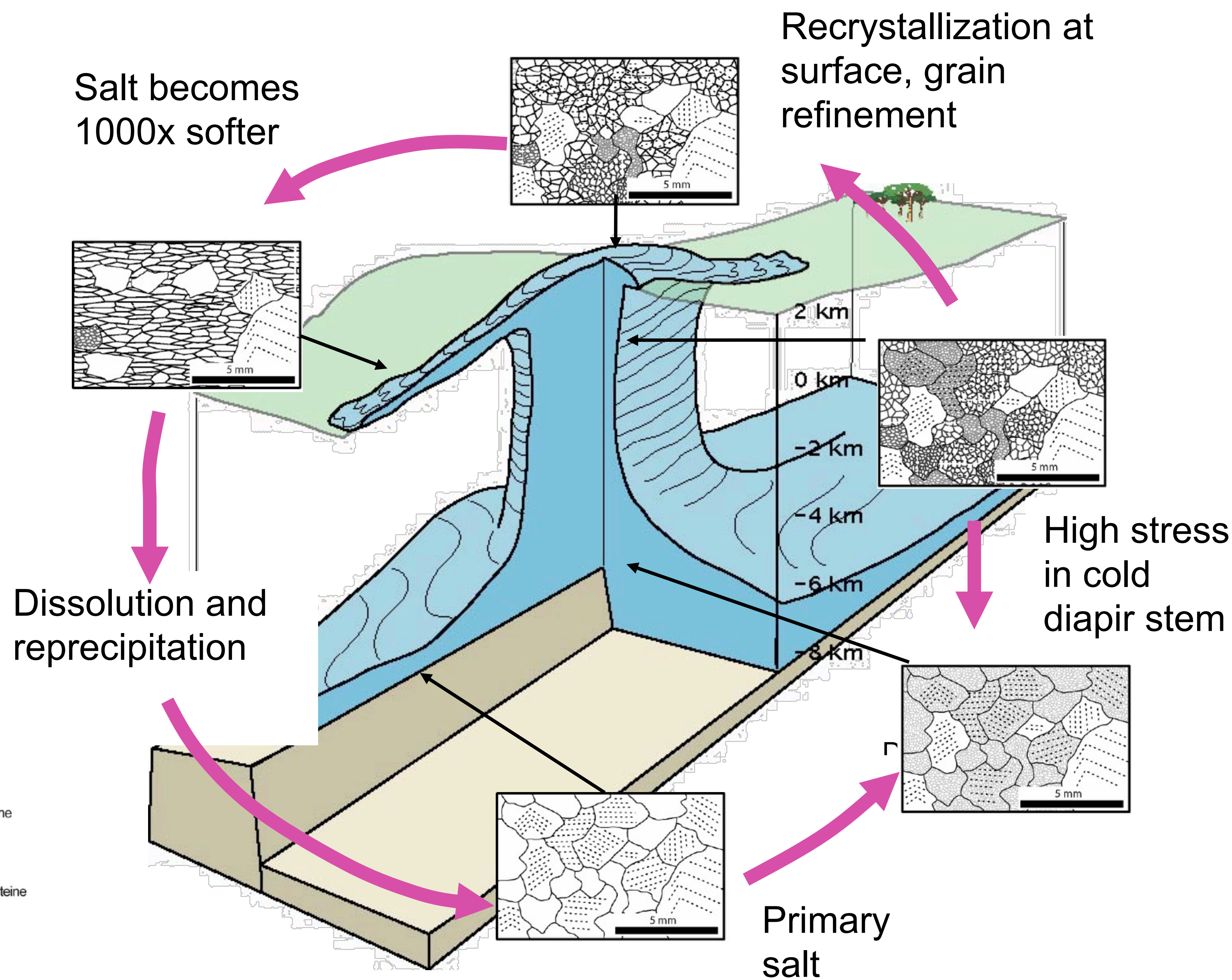




Bending

The salt - stringer universe

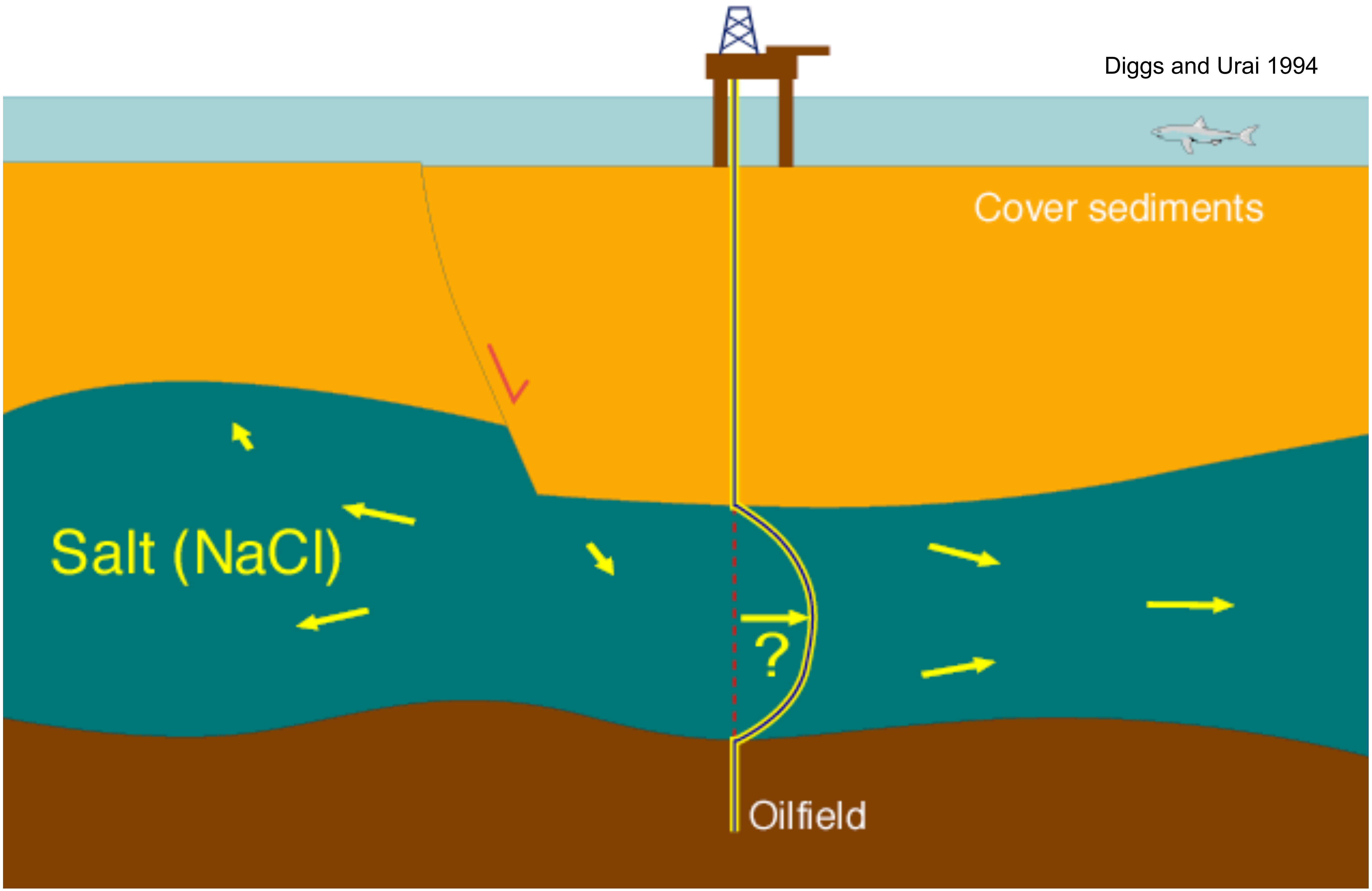




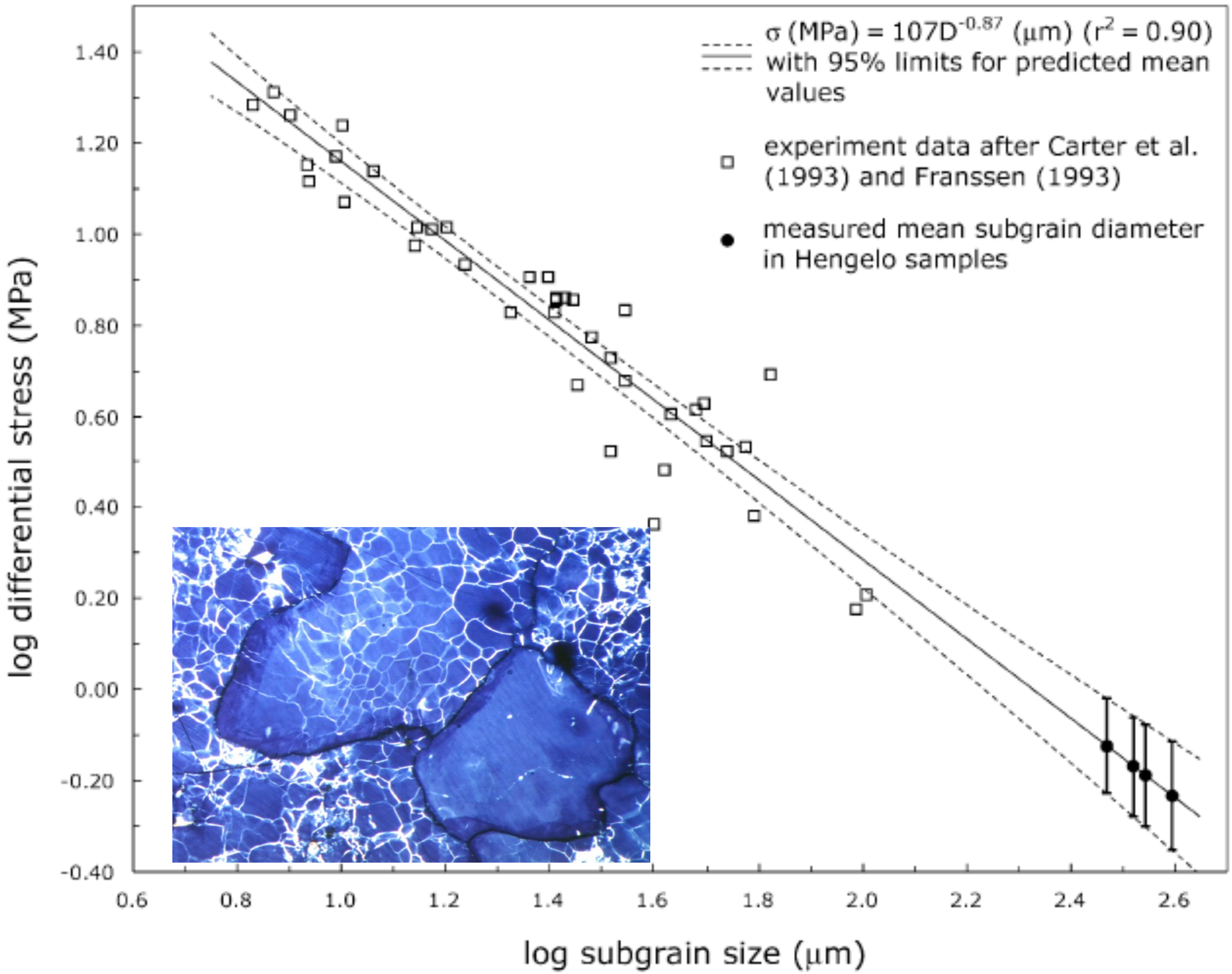
https://de.wikipedia.org/wiki/Zechsteinmeer

Salt flow and casing stability

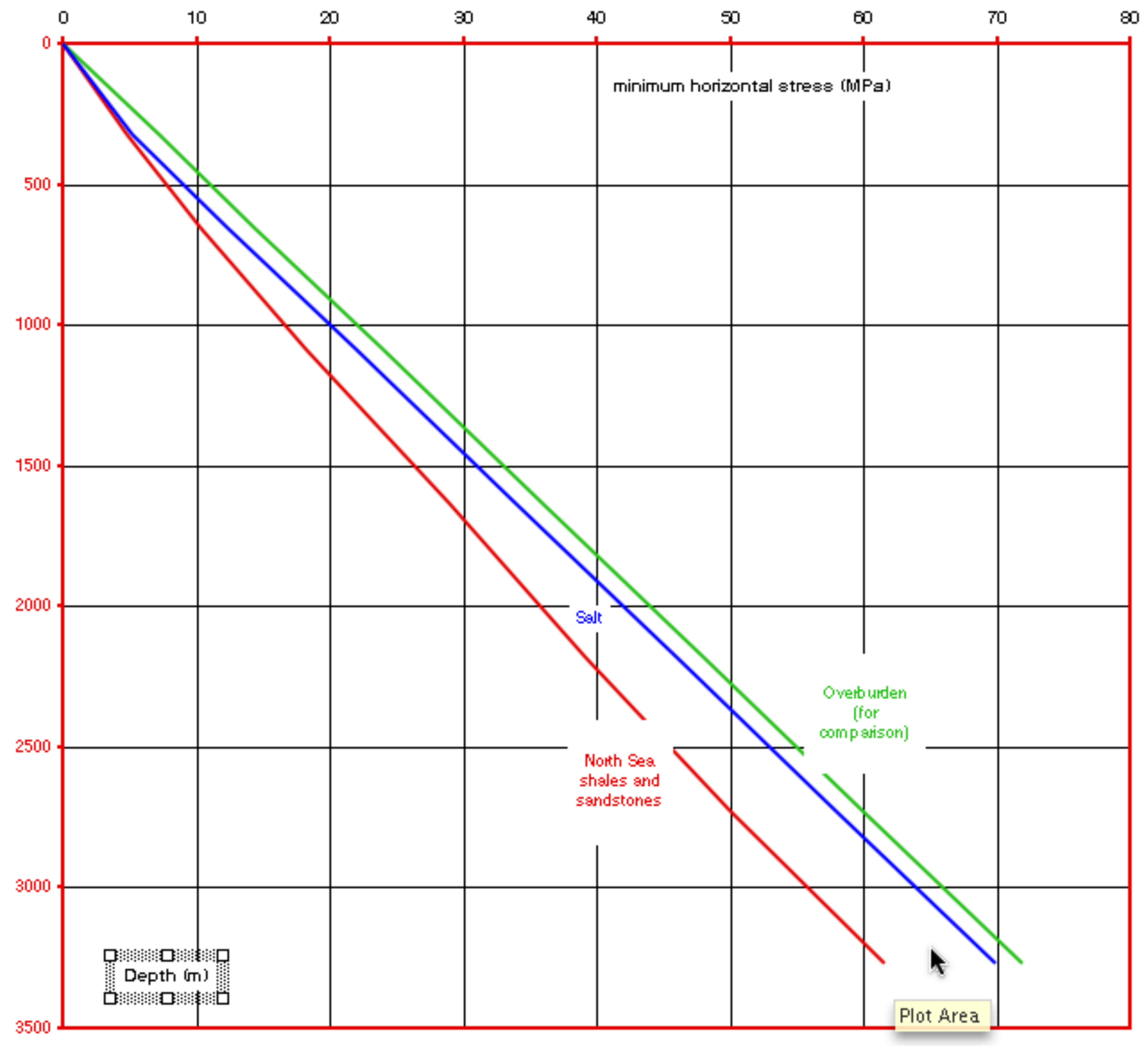
Active Halite salt flow GOM - not in North Sea - maybe recent movements in K/Mg salts

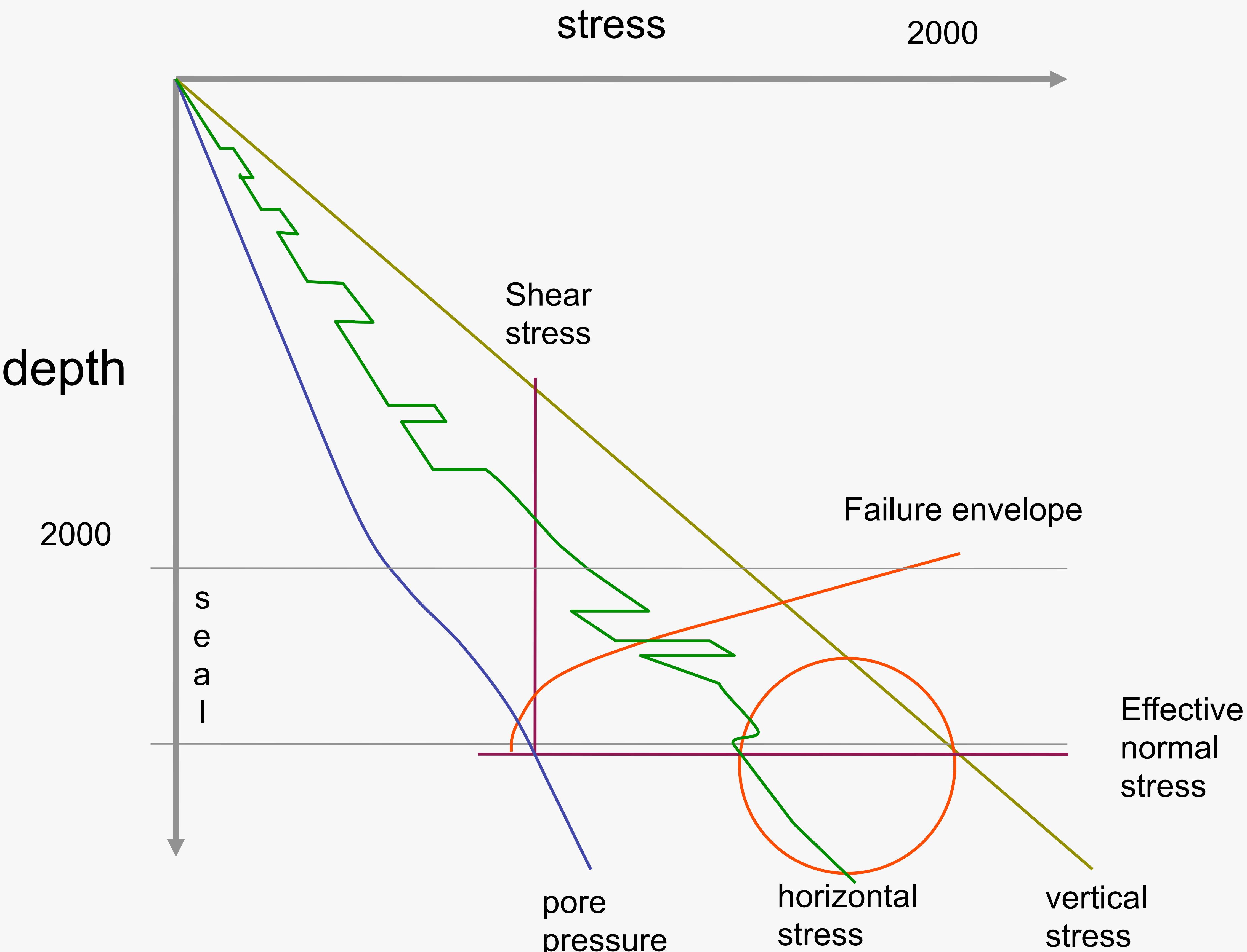


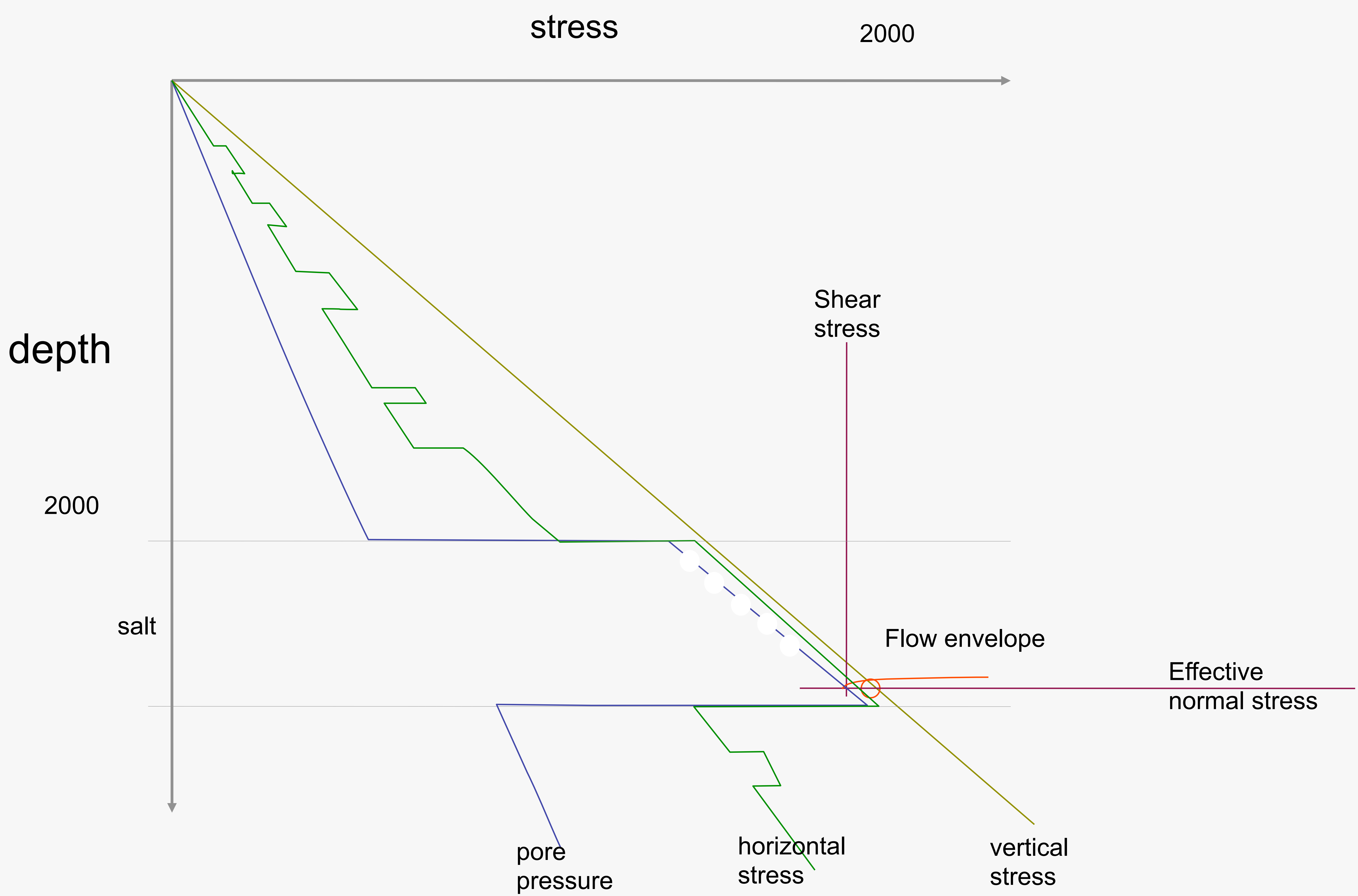
In-situ stress in salt from core measurement



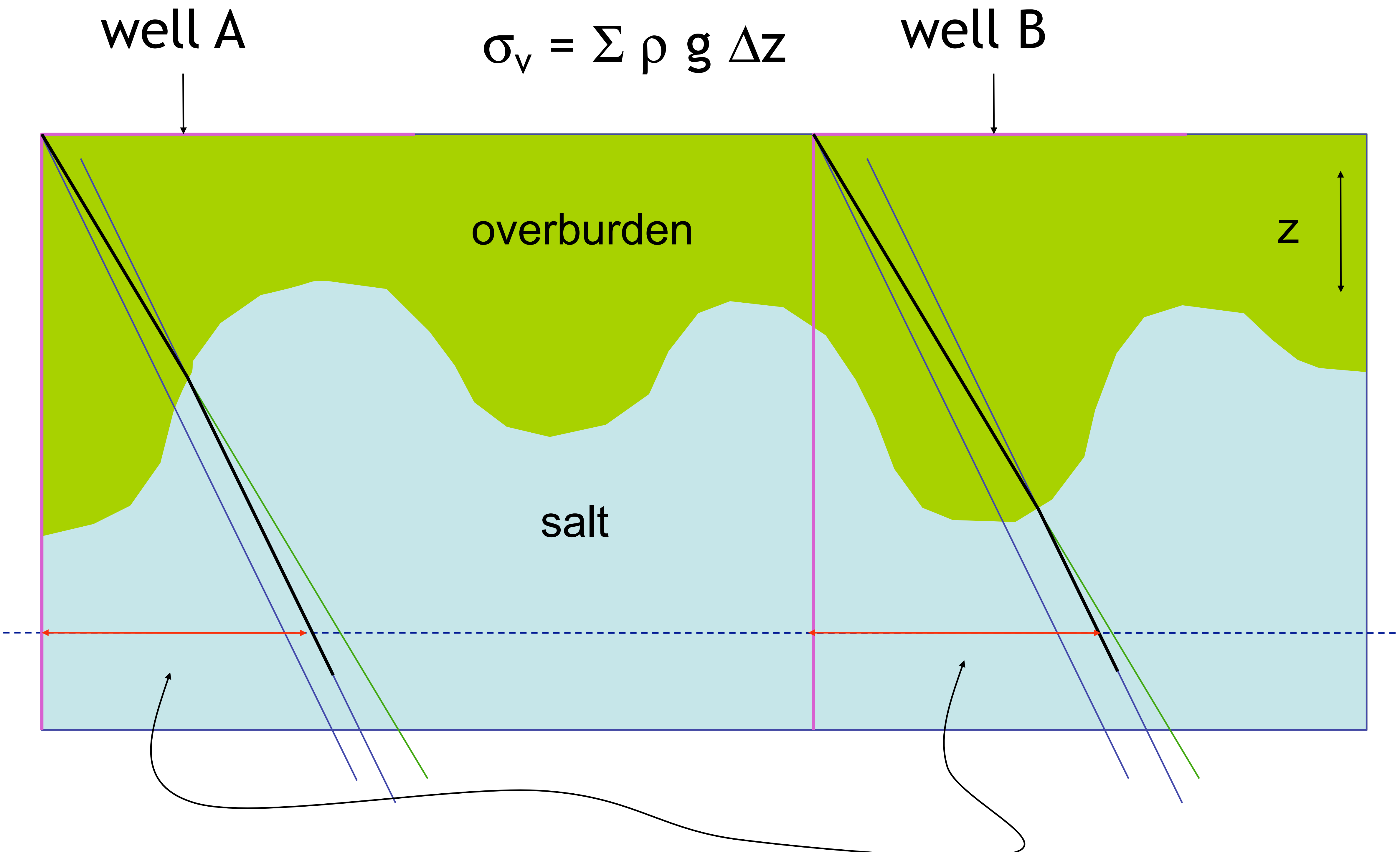
In-situ stress




stress
2000
depth
2000
s
e
a
l
Shear
stress
Failure envelope
Effective
normal
stress
pore
pressure
horizontal
stress
vertical
stress


stress
2000
depth
2000
salt
Shear
stress
Flow envelope
Effective
normal stress
pore
pressure
horizontal
stress
vertical
stress

Stress in salt basins

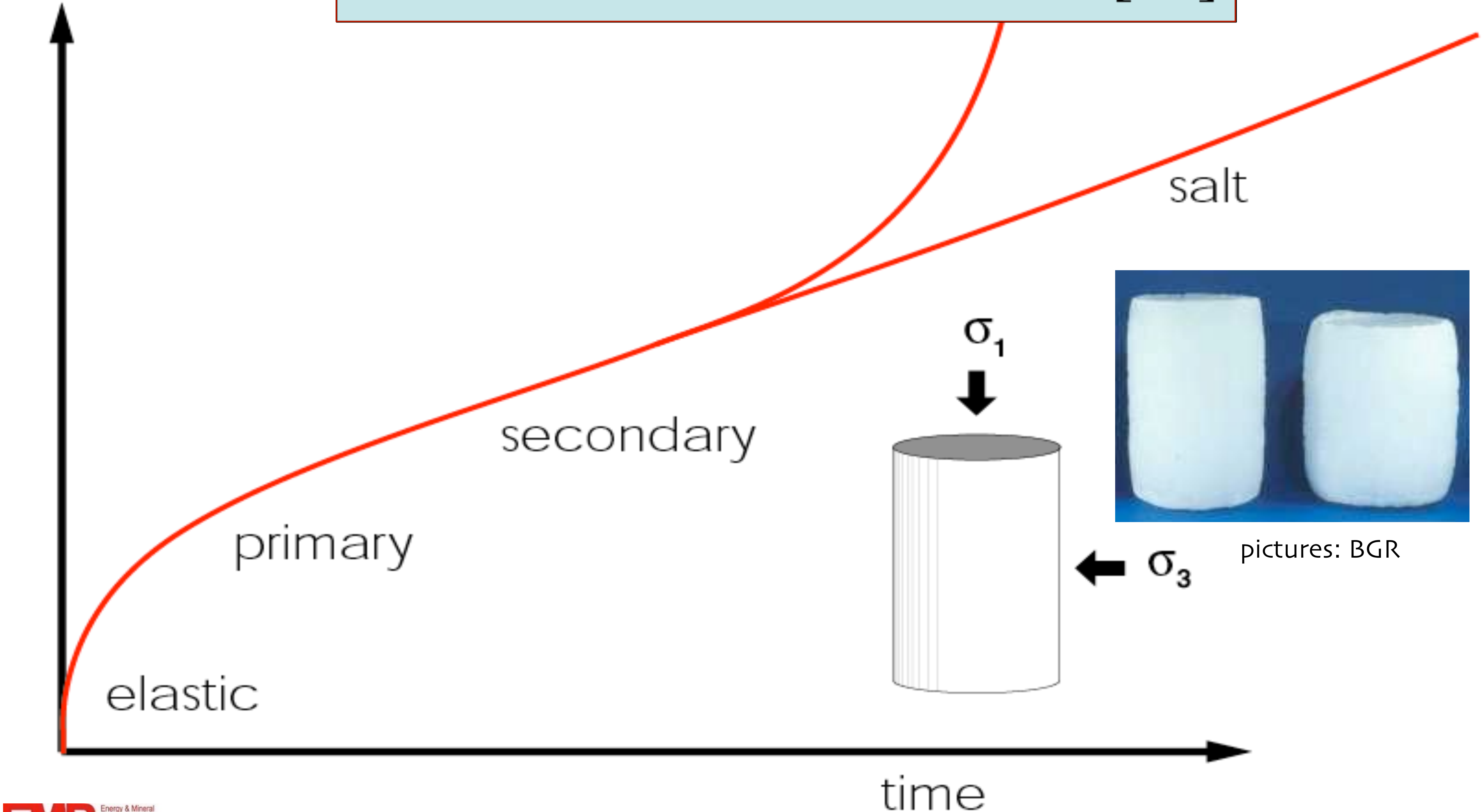


these two stresses should be equal!

Better understanding of stress in a salt basin
Equilibrium and short term geological effects

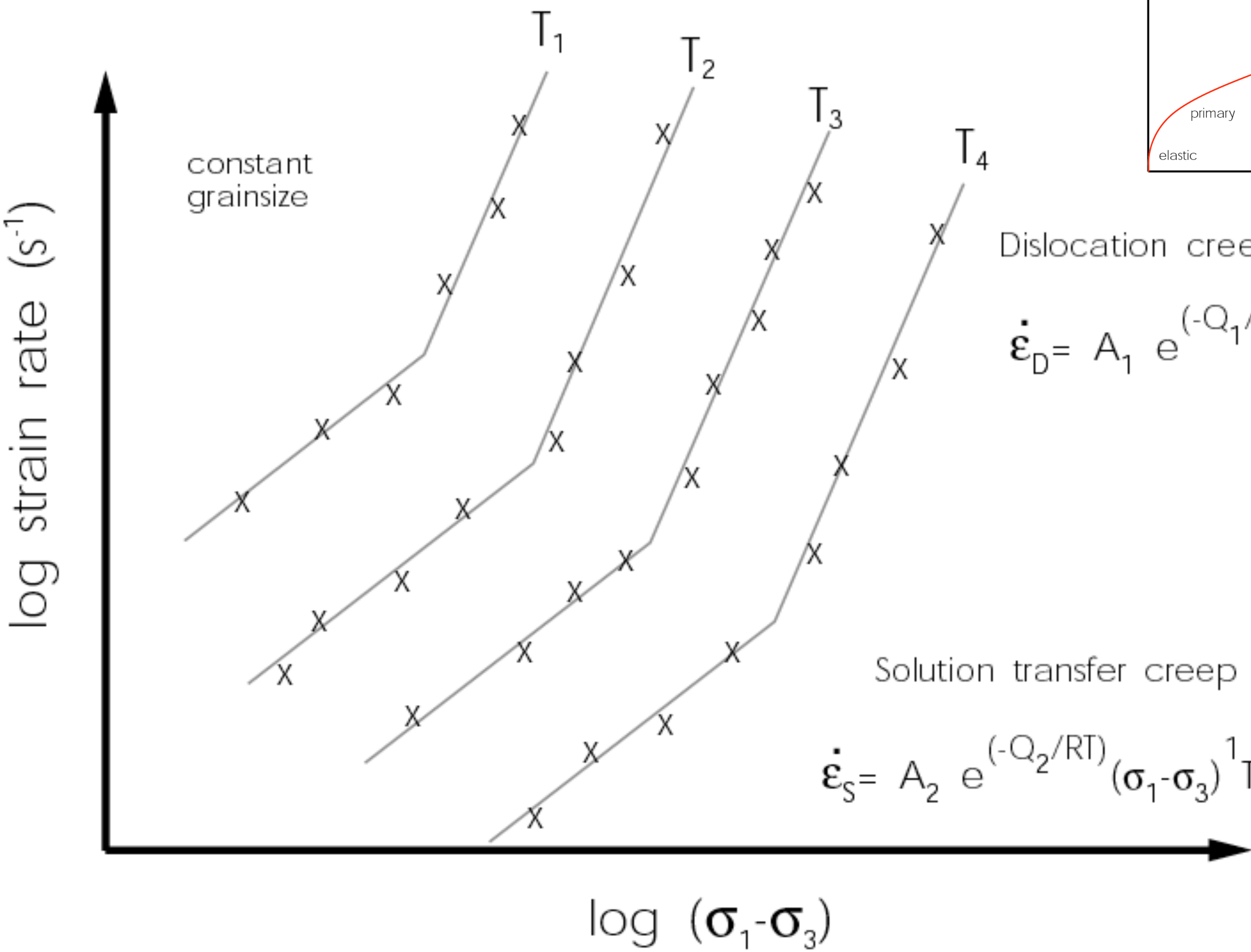
Ductile deformation of salt - constant stress

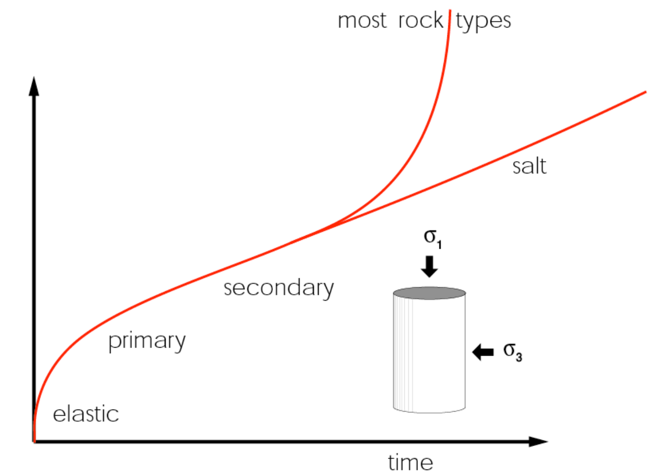
$$\text{viscosity [Pa s]} = \frac{\text{stress [Pa]}}{\text{strain rate [s}^{-1}\text{]}}$$



pictures: BGR

Power law creep





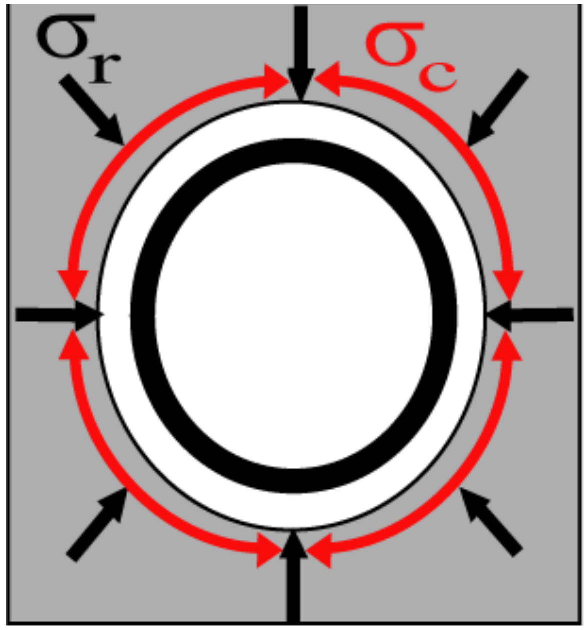
Dislocation creep

$$\dot{\varepsilon}_D = A_1 \; e^{(-Q_1/RT)} (\sigma_1 - \sigma_3)^n$$

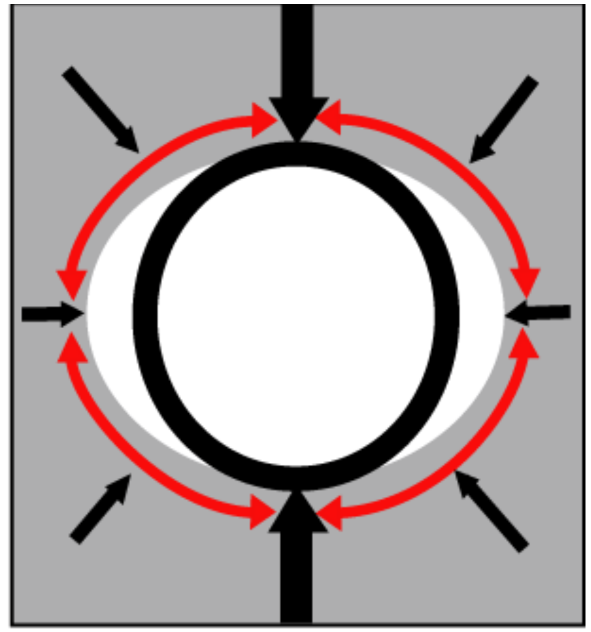
Solution transfer creep

$$\dot{\varepsilon}_S = A_2 \; e^{(-Q_2/RT)} (\sigma_1 - \sigma_3)^1 T^{-1} d^{-3}$$

Load on casing



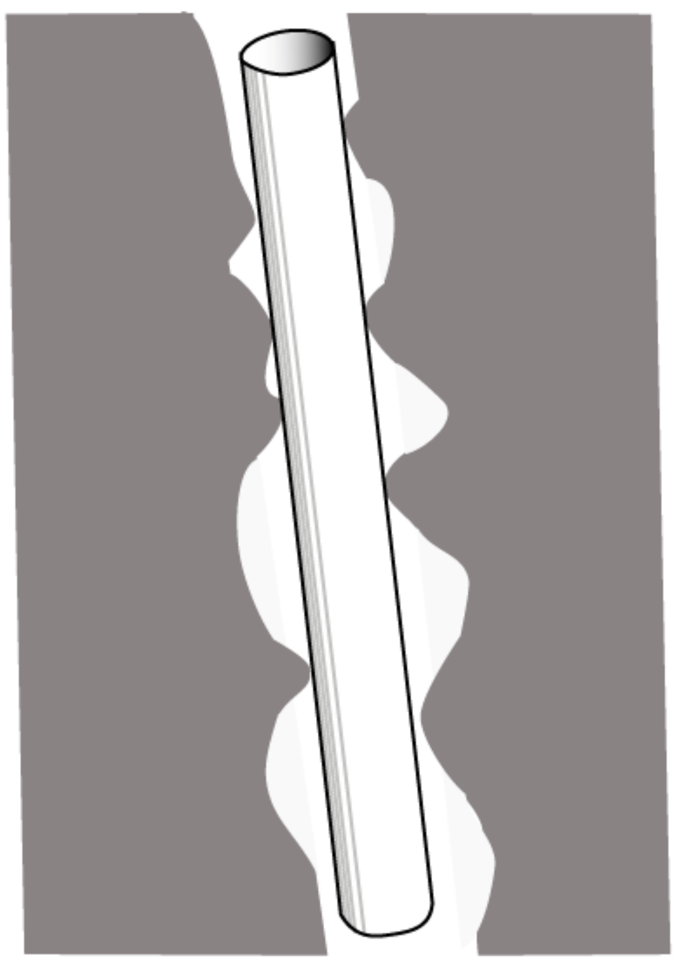
Uniform loading



Point loading

Symptoms

- Washouts
- Non uniform cement
- Rapid closure of hole

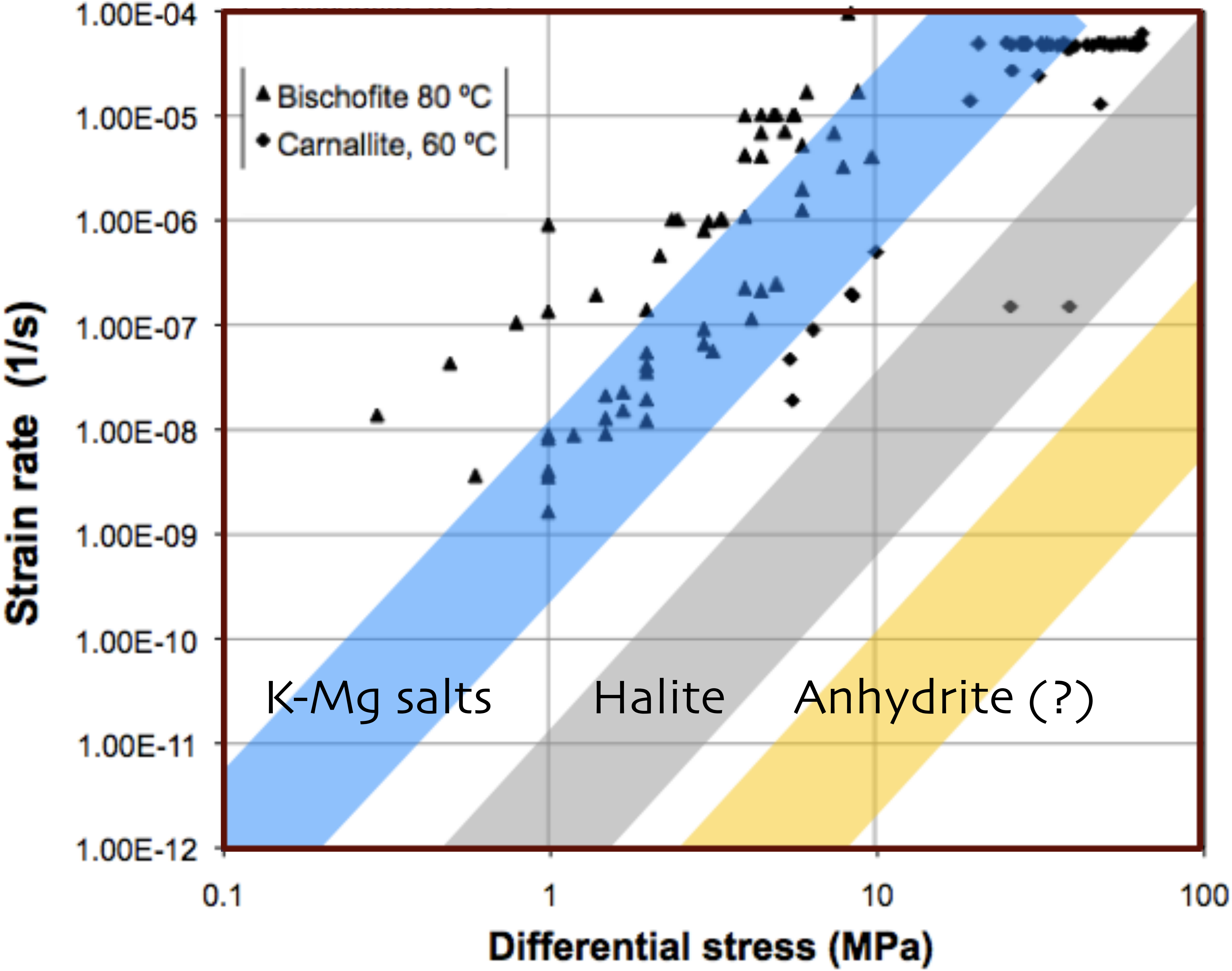


Squeezing salts "grab" the casing

Since the use of the VCM oil-based mud, washouts in K/Mg salts nearly disappeared. Creep closure of the K/Mg sections still occurs causing high torque and overpulls.

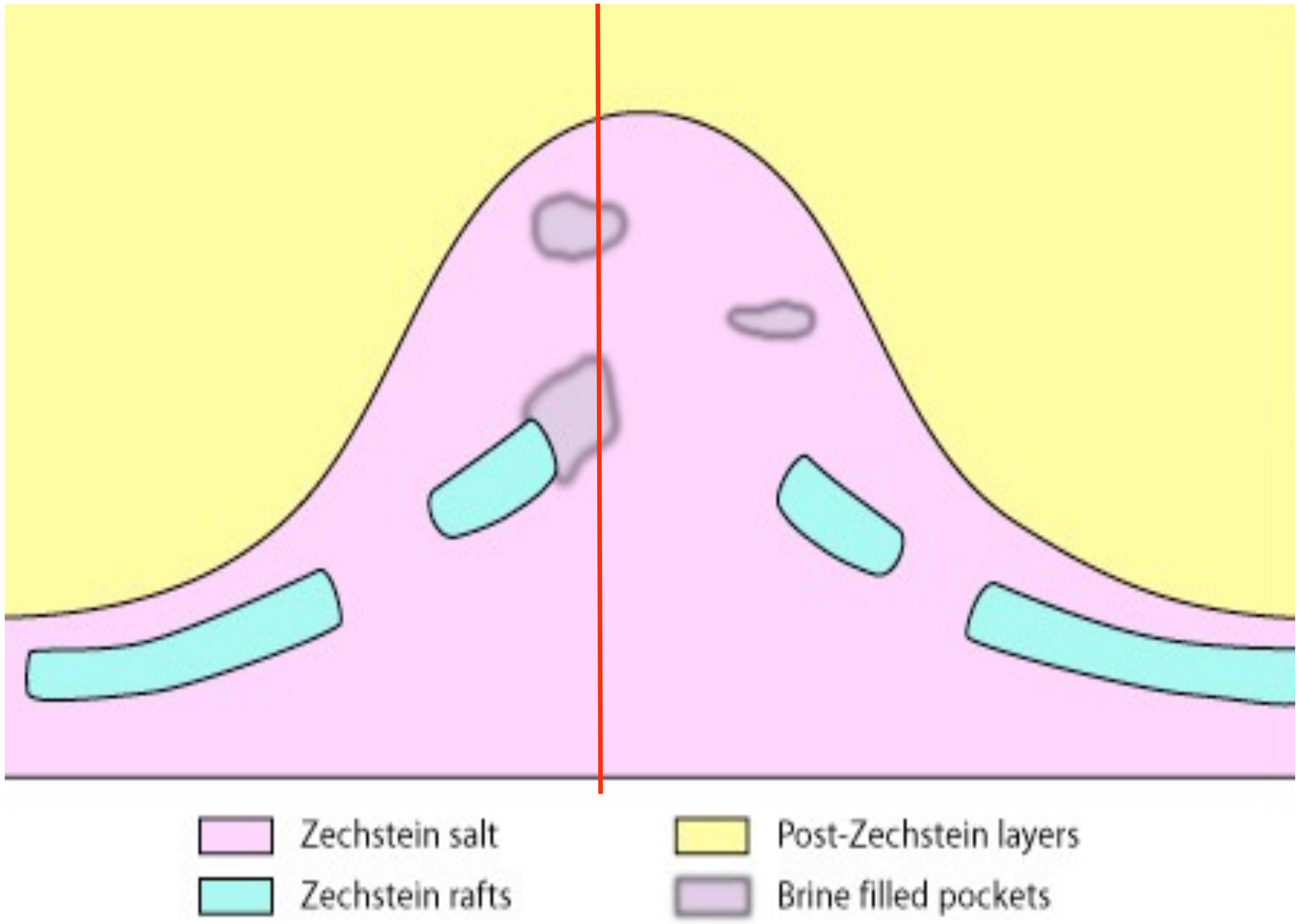
Rheology of different evaporites

Mechanical layering folding, boudinage,

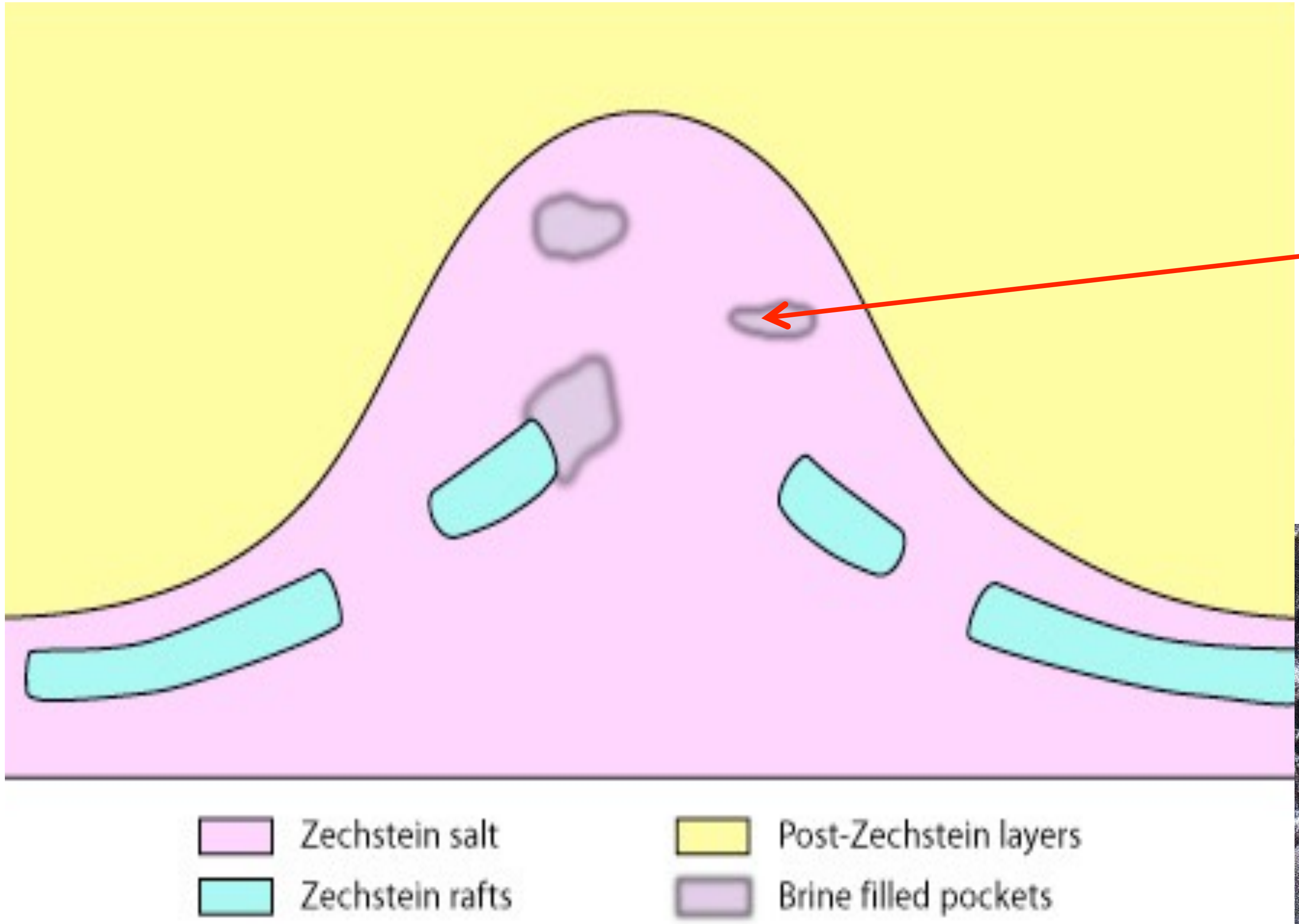


Brine pockets: symptoms

- Well starts flowing brine (+gas) while drilling through halite
- No drop of drill bit into open cavity
- Very high mudweight may reduce flow rate but usually does not completely stop it
- If flow is operationally acceptable, drilling is continued and well cased



Brine pockets are NOT salt caves



Salt with brine (+gas) filled porosity

= **brine pockets**

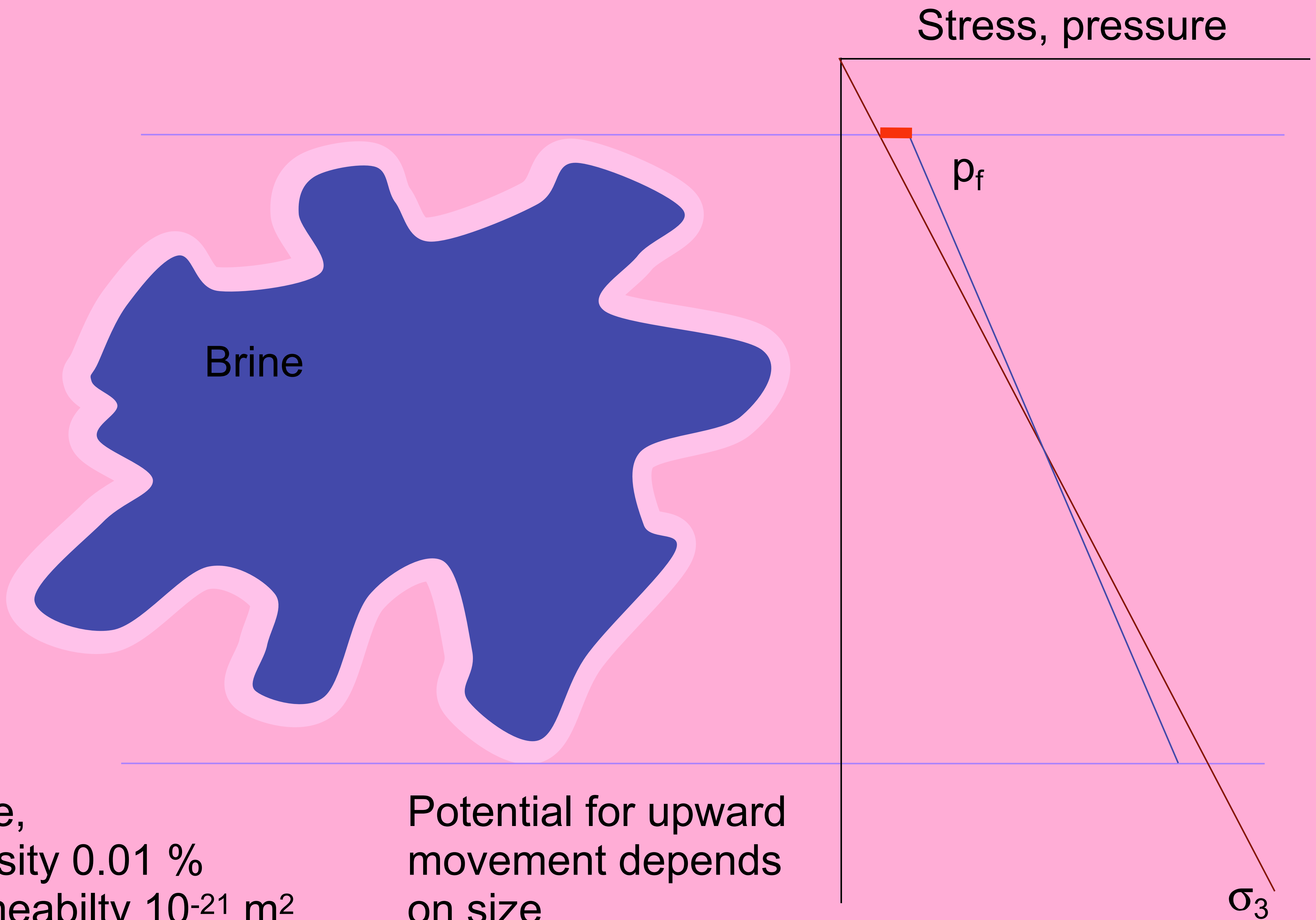
Open cavities with giant crystals on the walls filled with brine and gas

= **salt caves**

Brine pockets: literature study

- Brine pockets and Salt caves found in salt mines
- Majority of brine in mines is man-made
- Salt caves occur in positions close to the surface
- Brine pockets occur at all levels.
- The volumes vary between 1000 ml and 1000 m^3.
- Usually the brine pockets are found close to anhydrites and carbonates from which the fluids probably originate but also in association with K-Mg-salts.
- The composition of the brines is $MgCl_2$-rich (290-440 g/l).

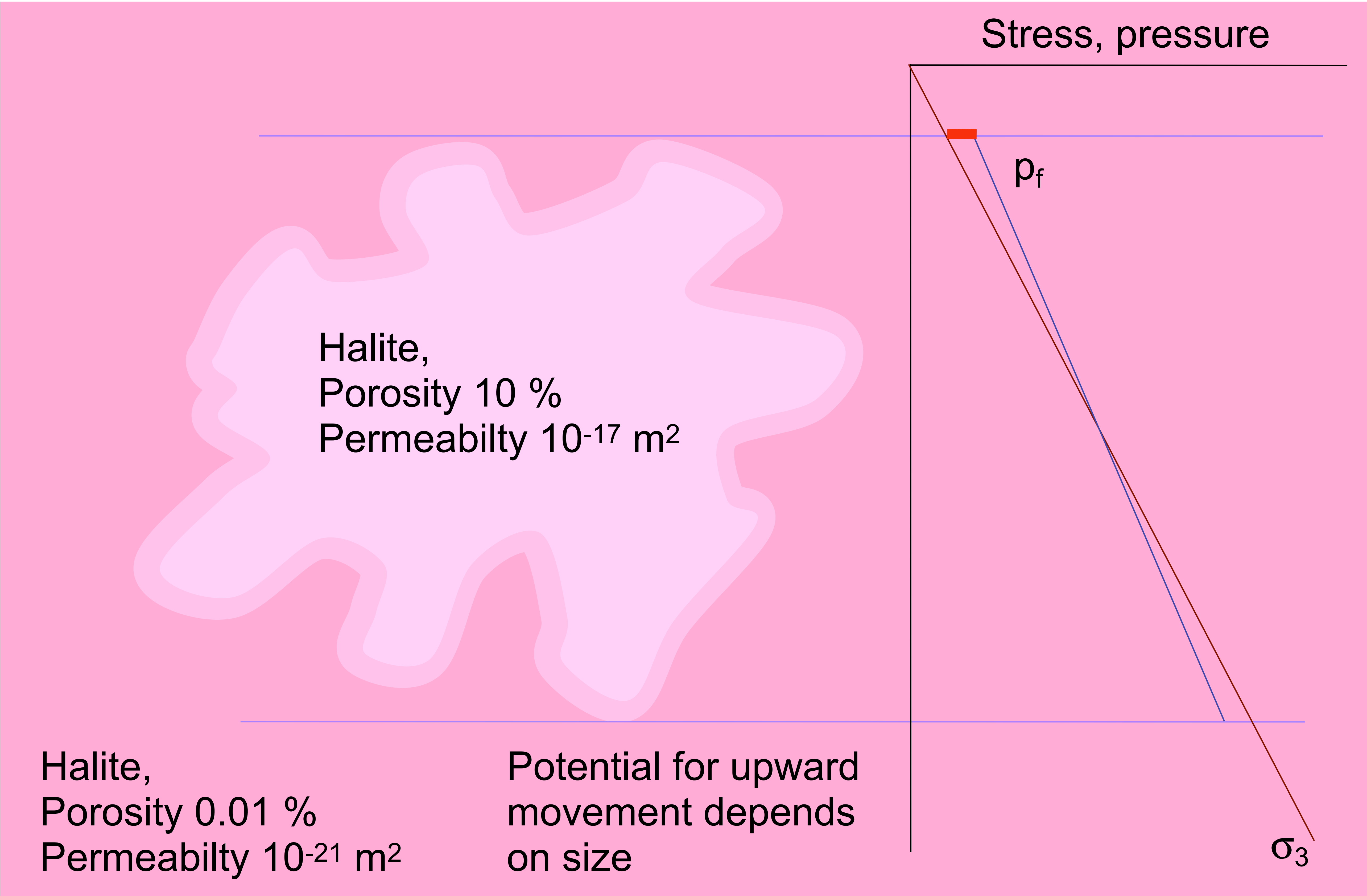
A salt cavern



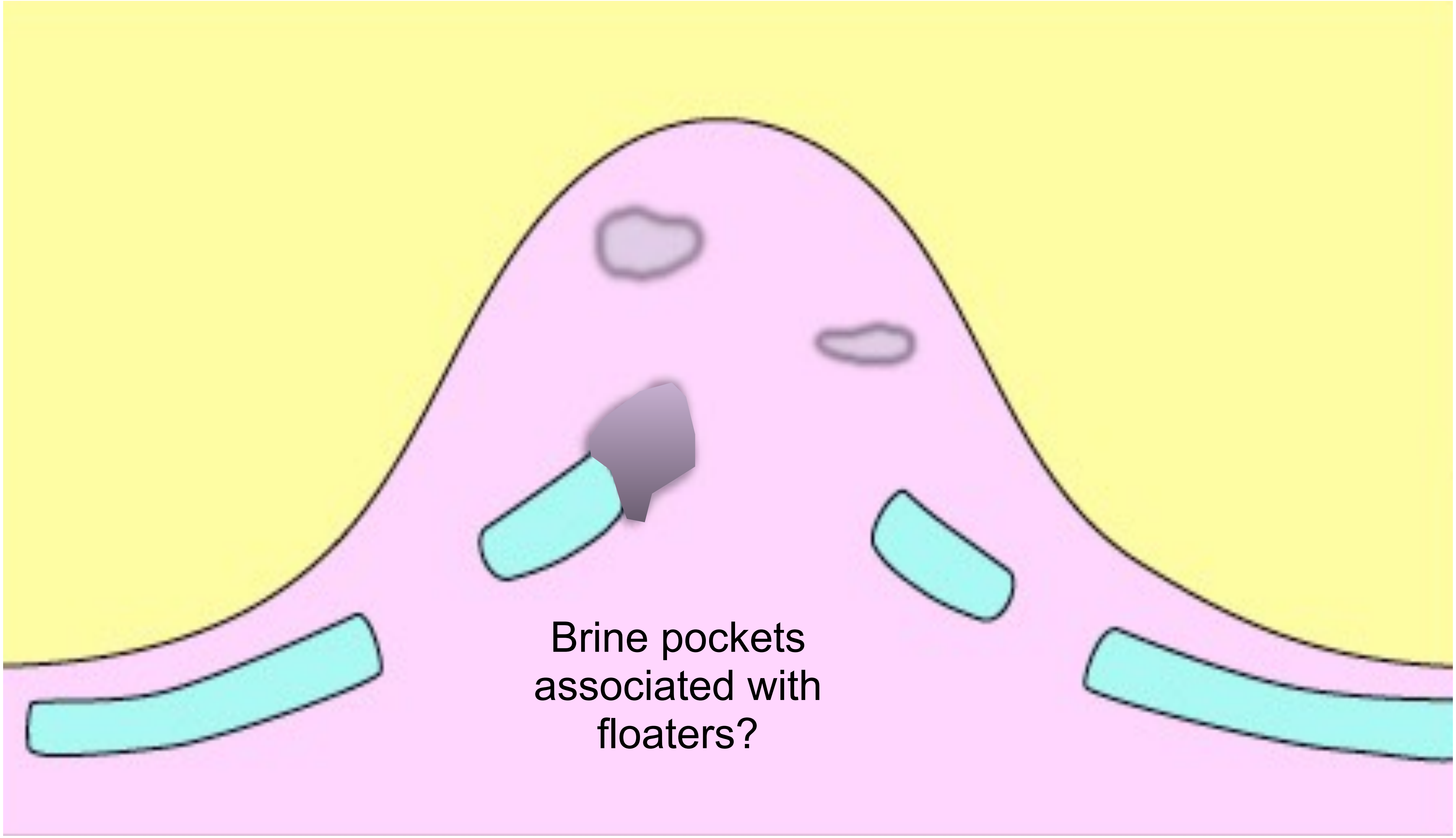
Halite,
Porosity 0.01 %
Permeabilty 10^{-21} m^2

Potential for upward movement depends on size

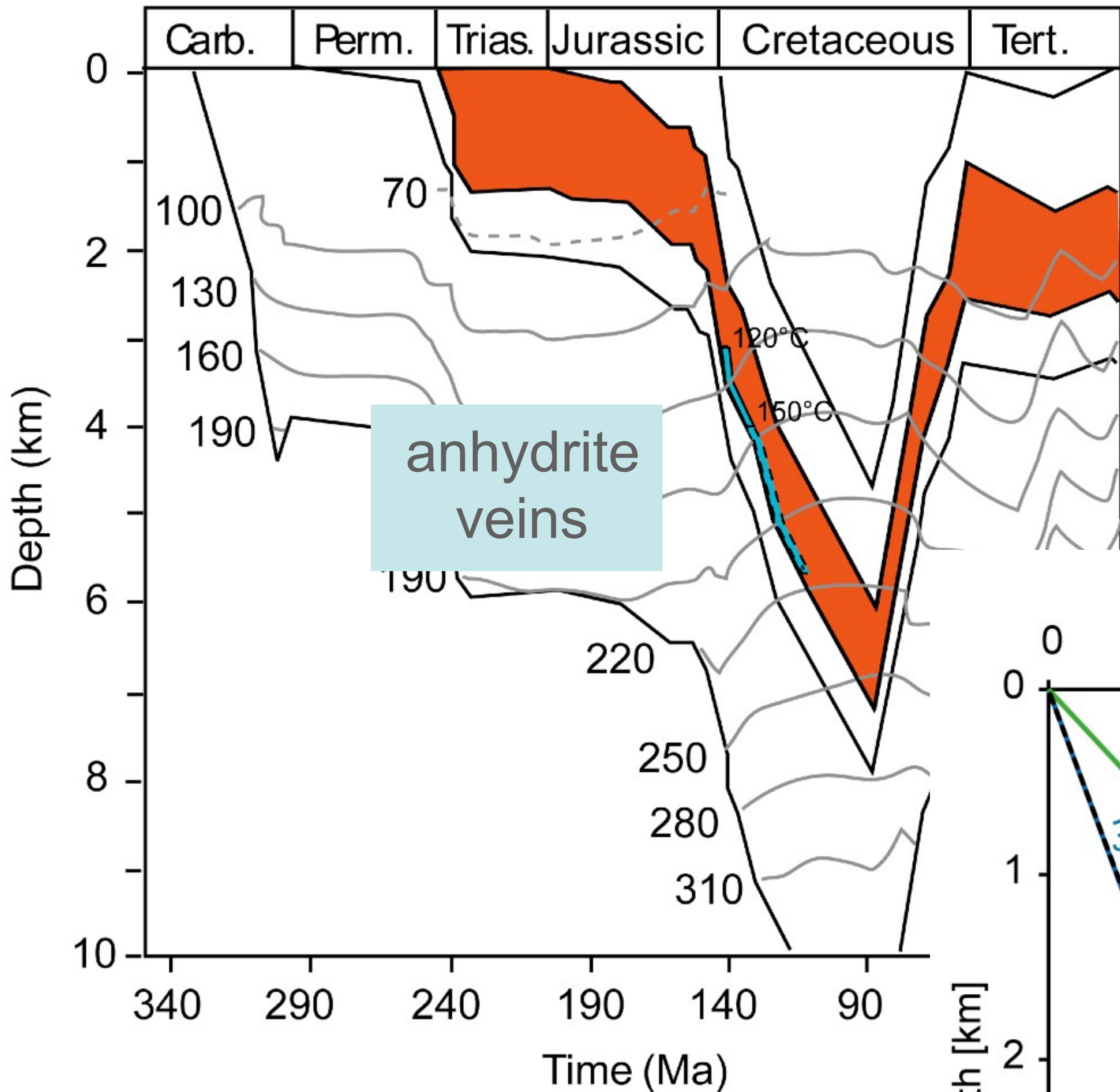
A “brine pocket”



Slow upward migration of brine pockets



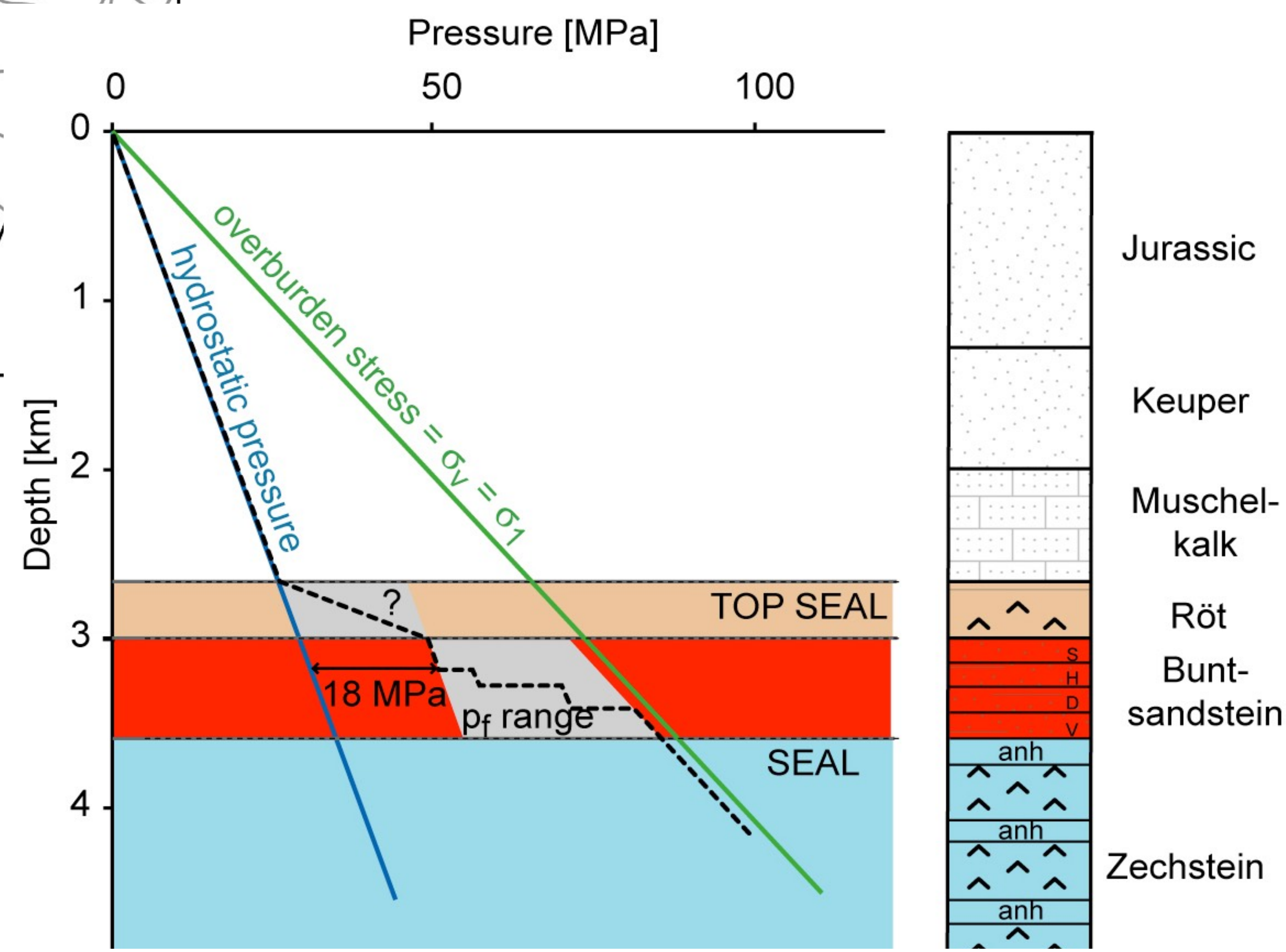
Zechstein-fluids - hard overpressure



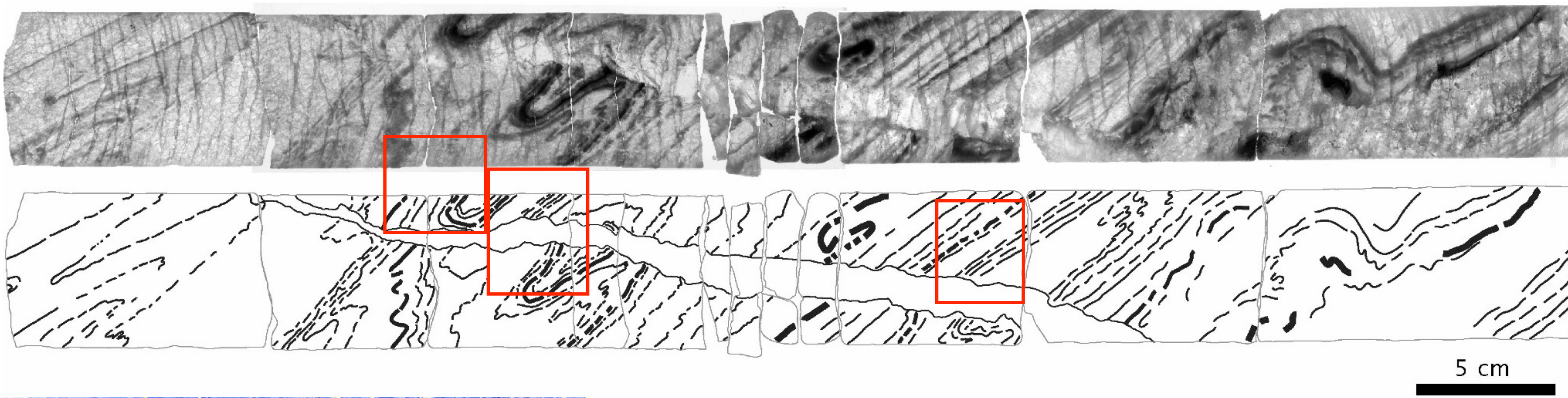
subsidence curve from Petmecky et al. (1998)

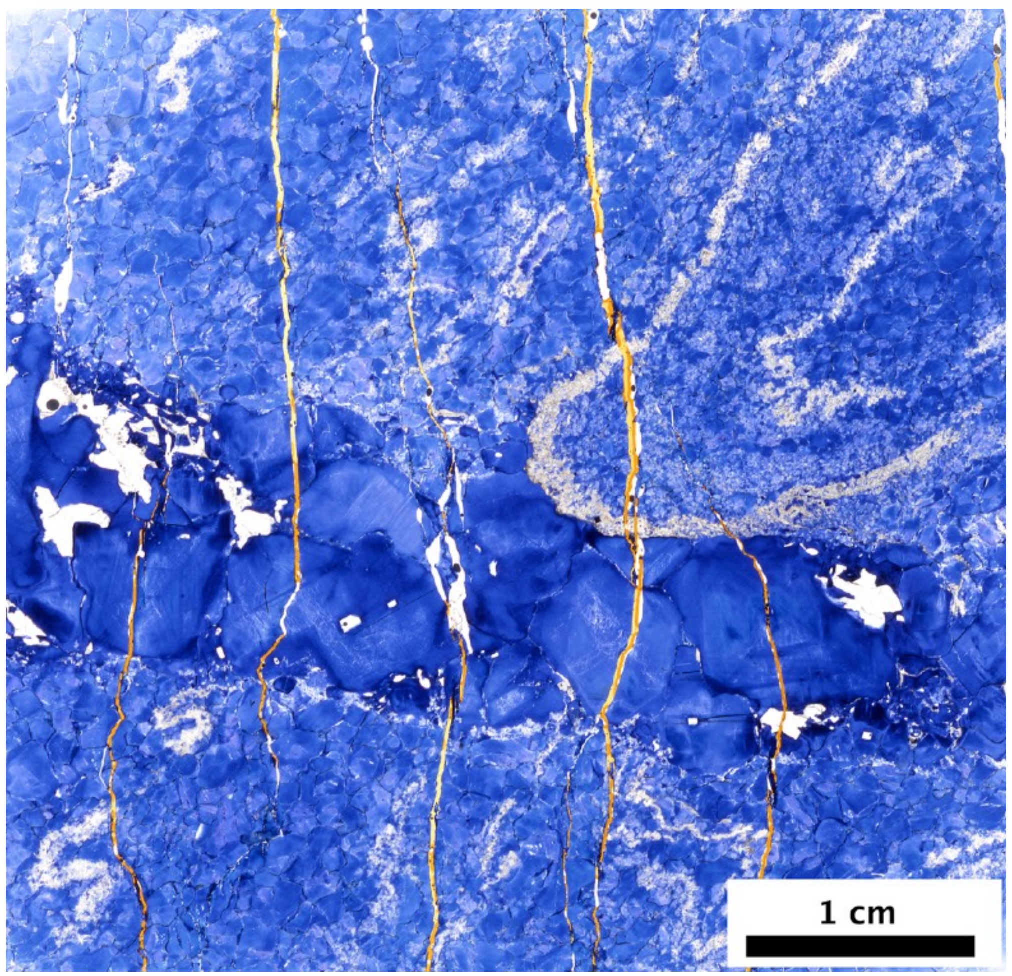
Buntsandstein in CEB, Nollet et al. (2005)

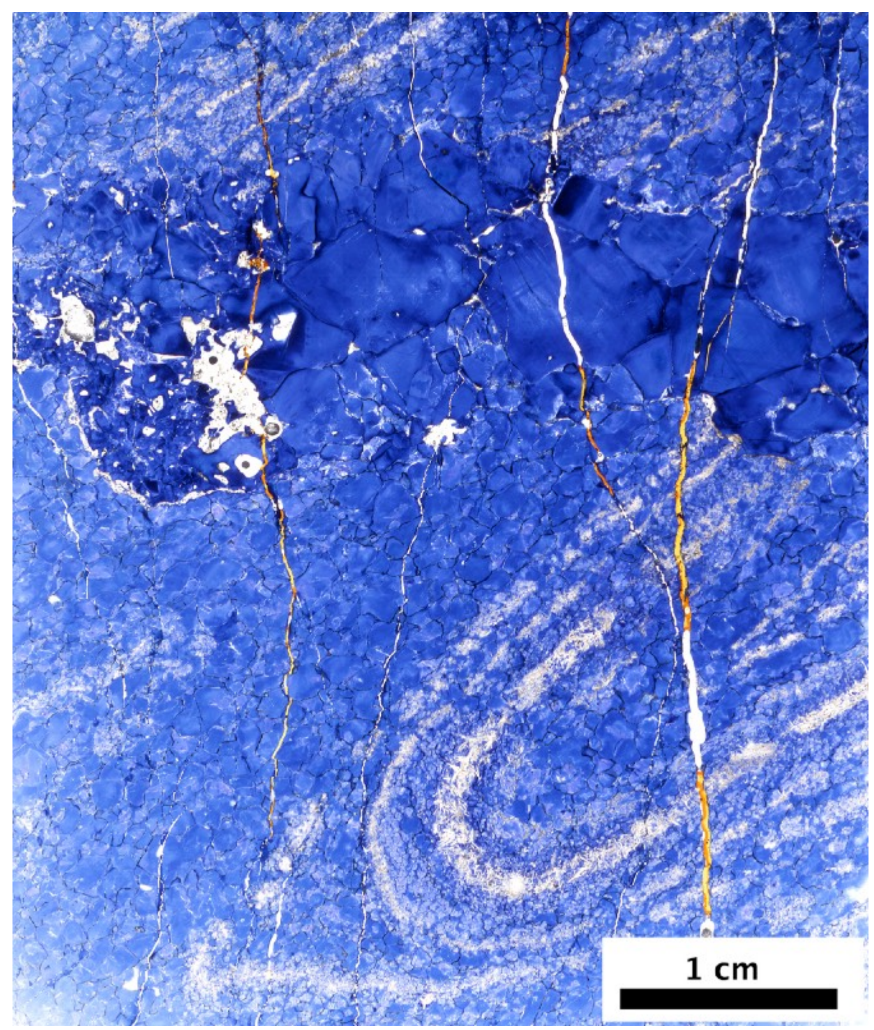
Fluids derived from Zechstein
Near-lithostatic fluid pressures in Salt



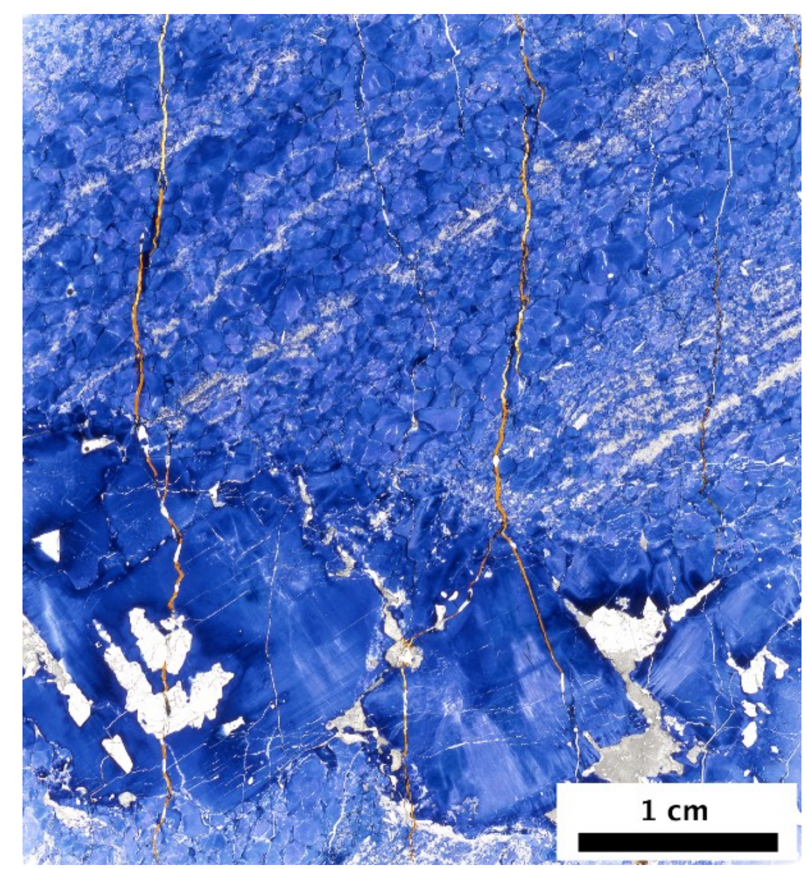
Fractures vs diffuse dilatancy



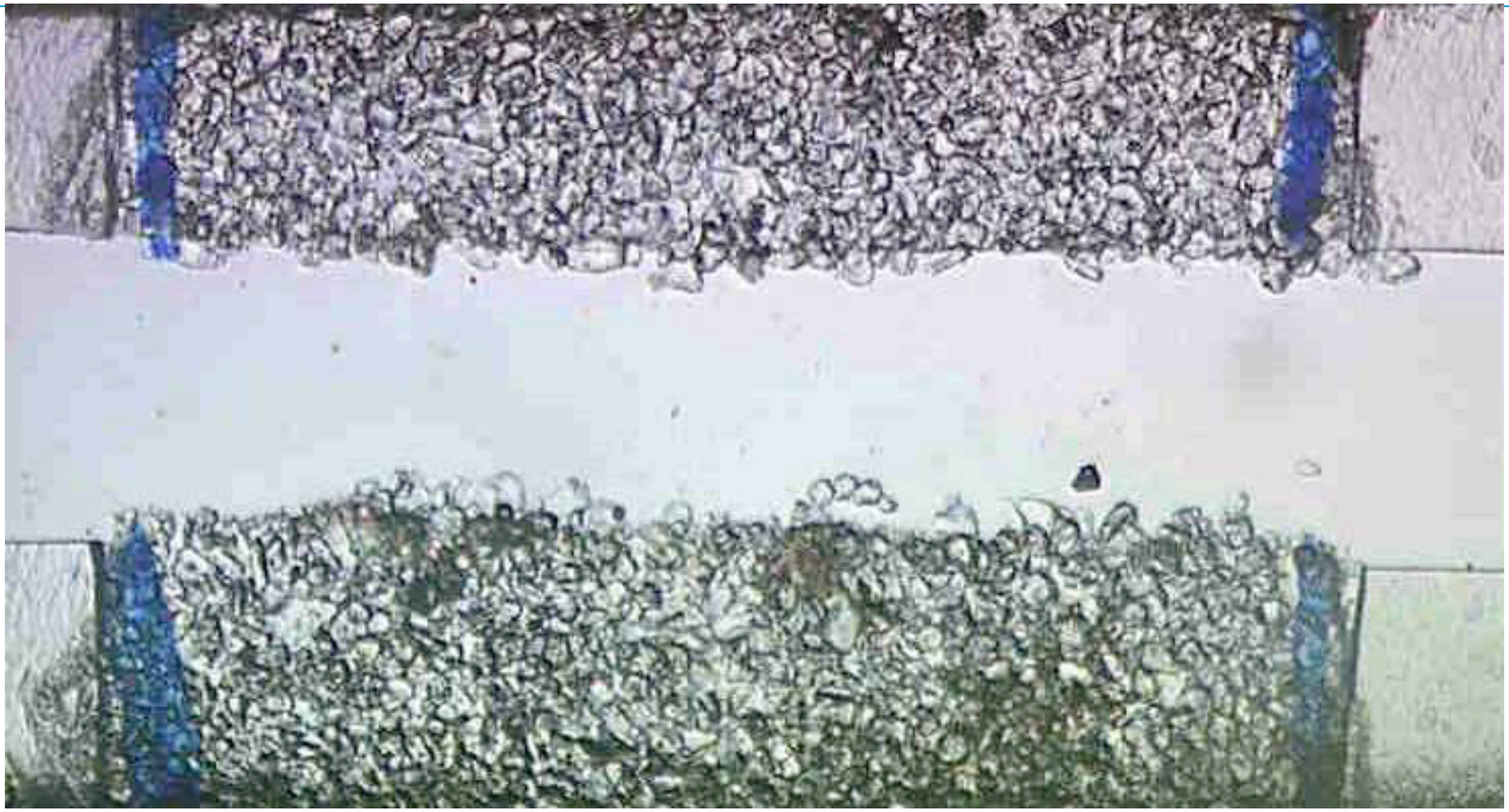


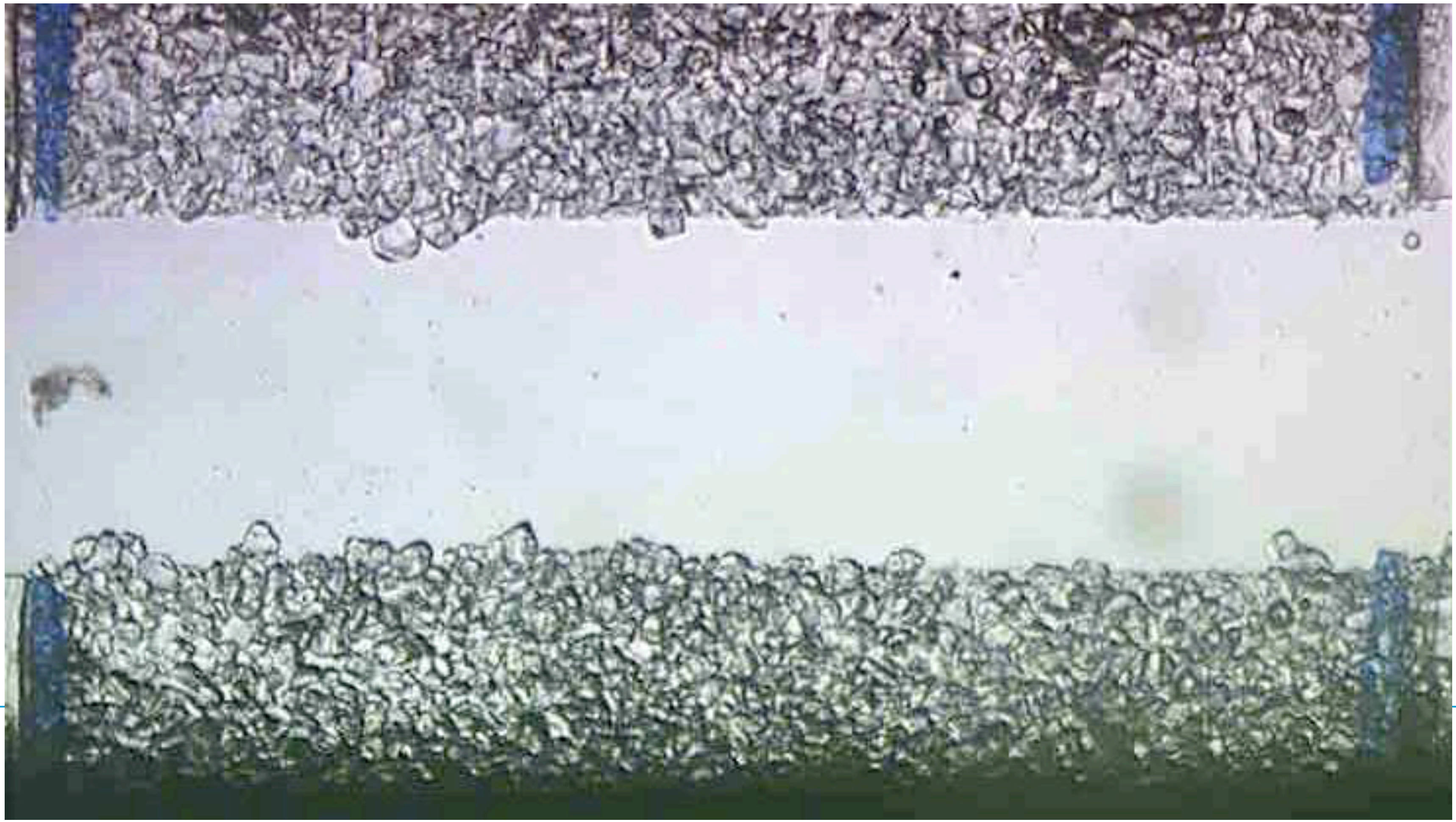


Fluid flow after main phase of deformation.



Experimental sealing of fractures in salts



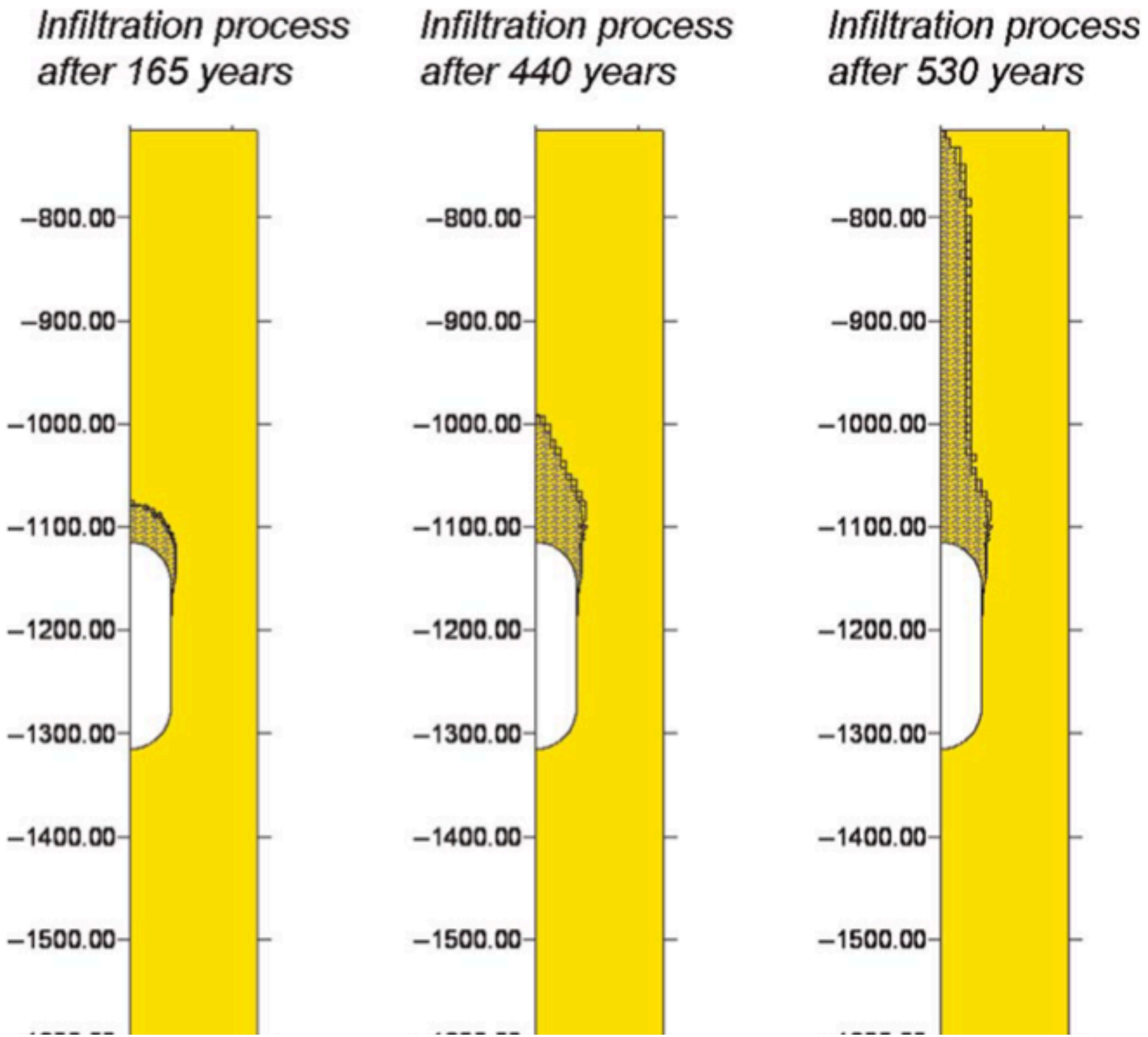


C. Hilgers

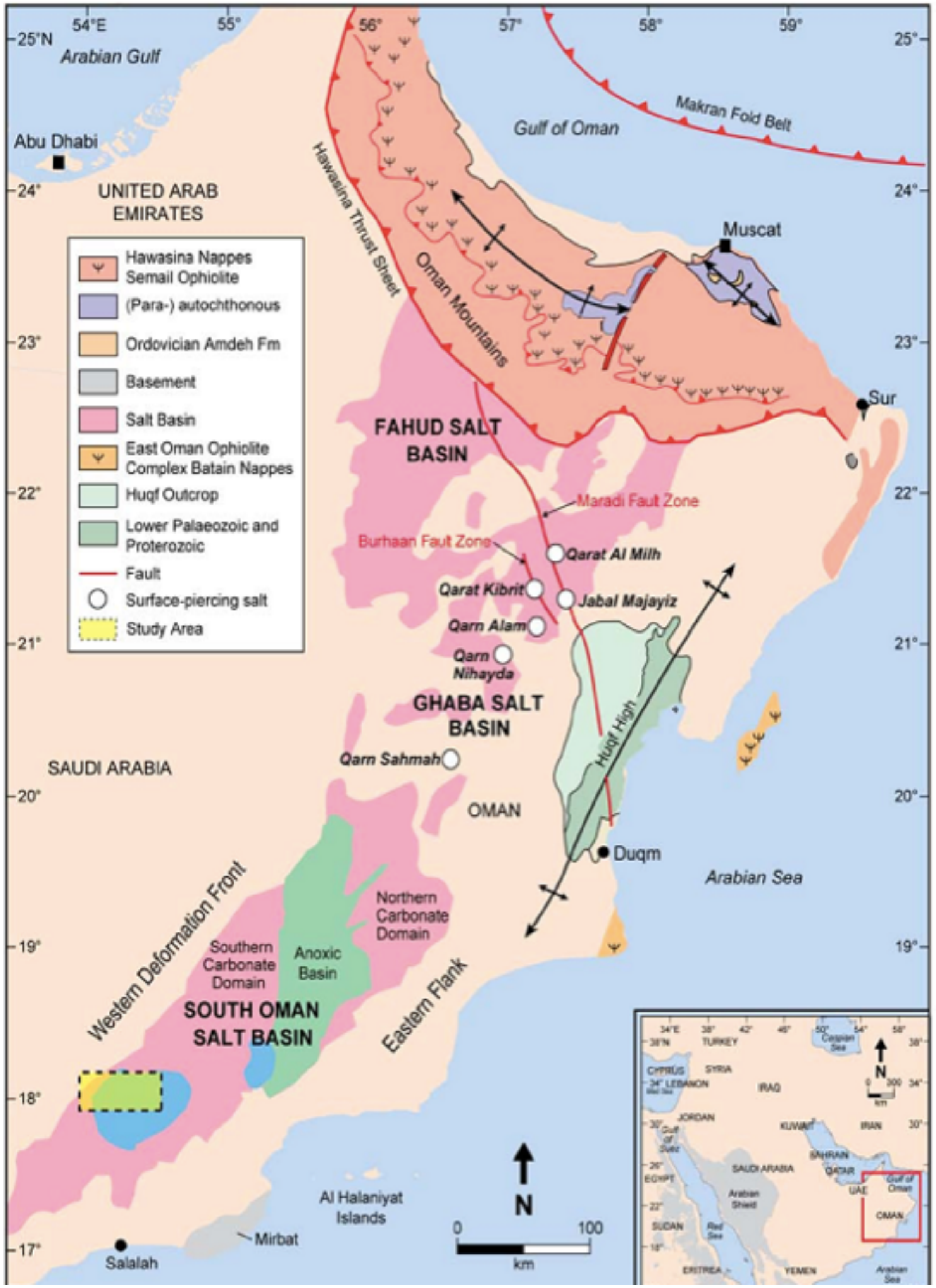
Guidelines: brine pockets

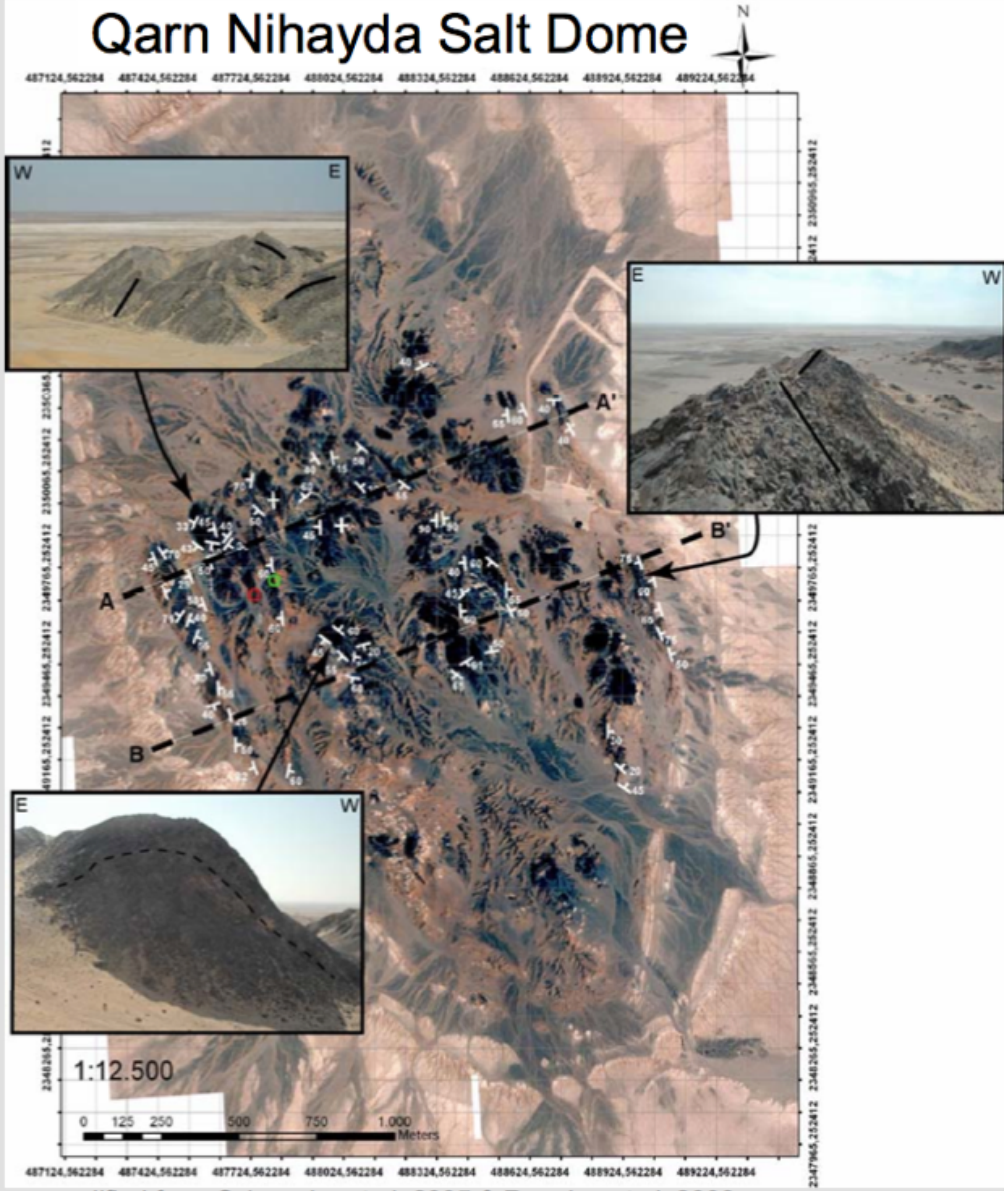
- Salt converges around brine pockets until fluid pressure becomes = minimum stress in salt. Brine density is less than salt density
- Salt can not support fluid pressures over lithostatic (like a balloon) – it becomes permeable, either by diffuse dilatancy or hydrofracturing.
- This results in upward migration of brine pockets over geologic time
- If a brine pocket is drilled the volume of flow is controlled by the volume of the pocket - very large ones are geologically unstable.
- Fluid pressure in brine pockets is lithostatic. If fluid flow is operationally acceptable, continue drilling
- Near-lithostatic mud pressure is needed to stop flow high mud pressure
- An accurate knowledge of the actual stress in the salt would be useful

Lux 2009 cavern abandonment



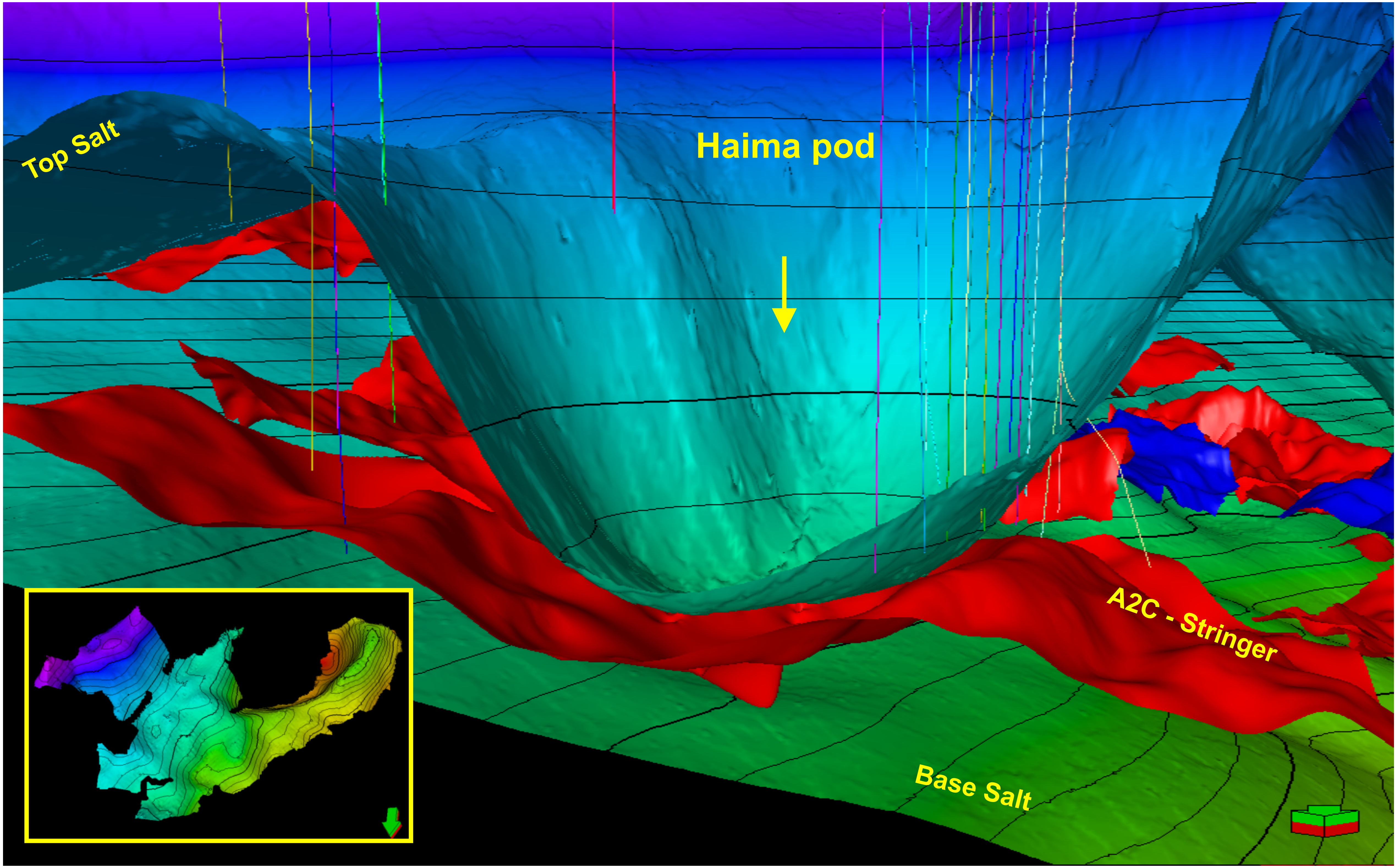
Omani Salt Basins



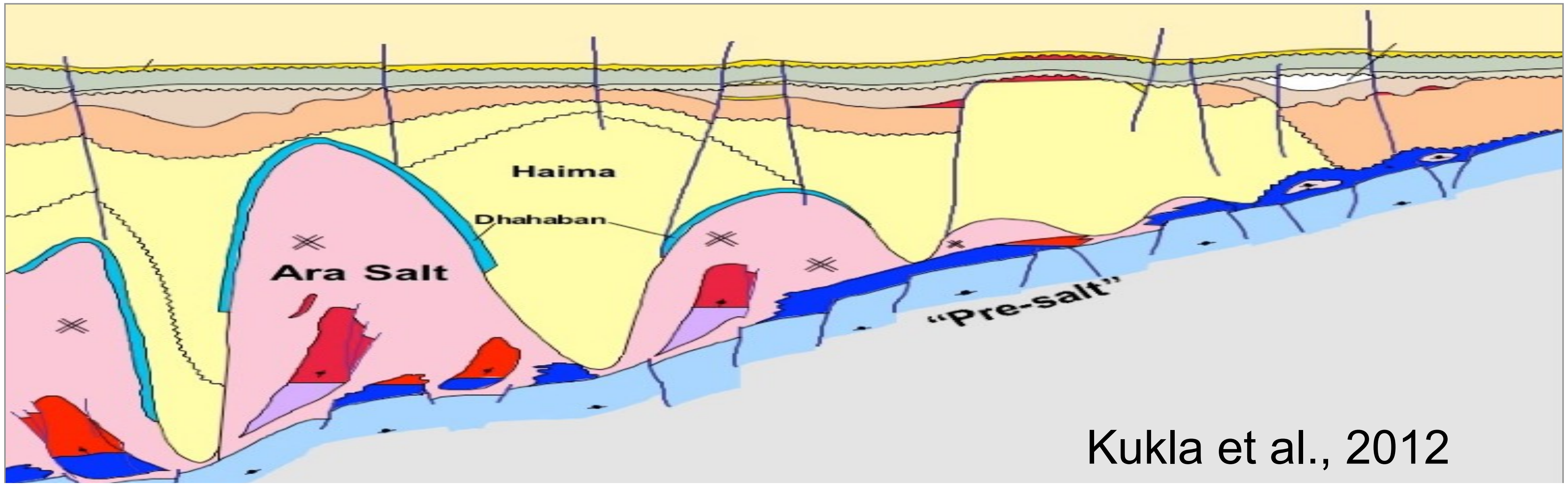


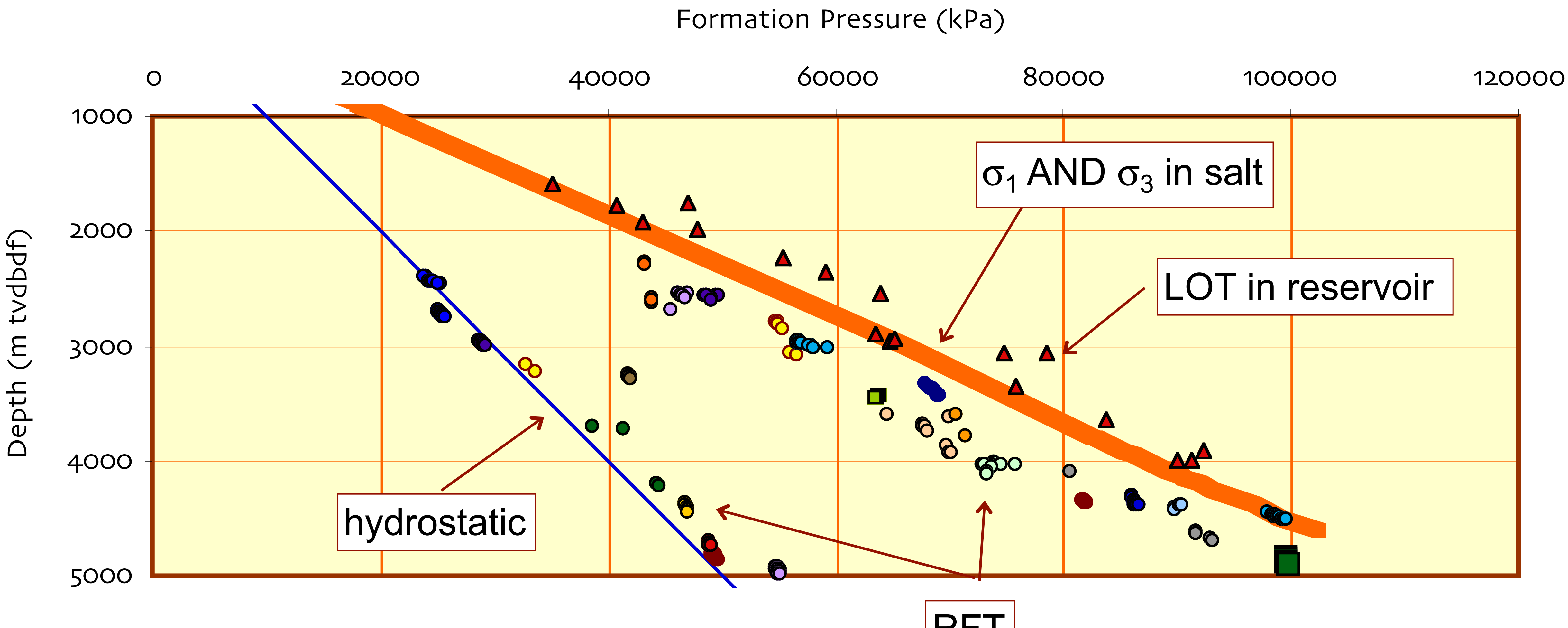
modified from Schroeder et al. 2005 & Reuning et al. 2009

Internal structures of salt, South Oman



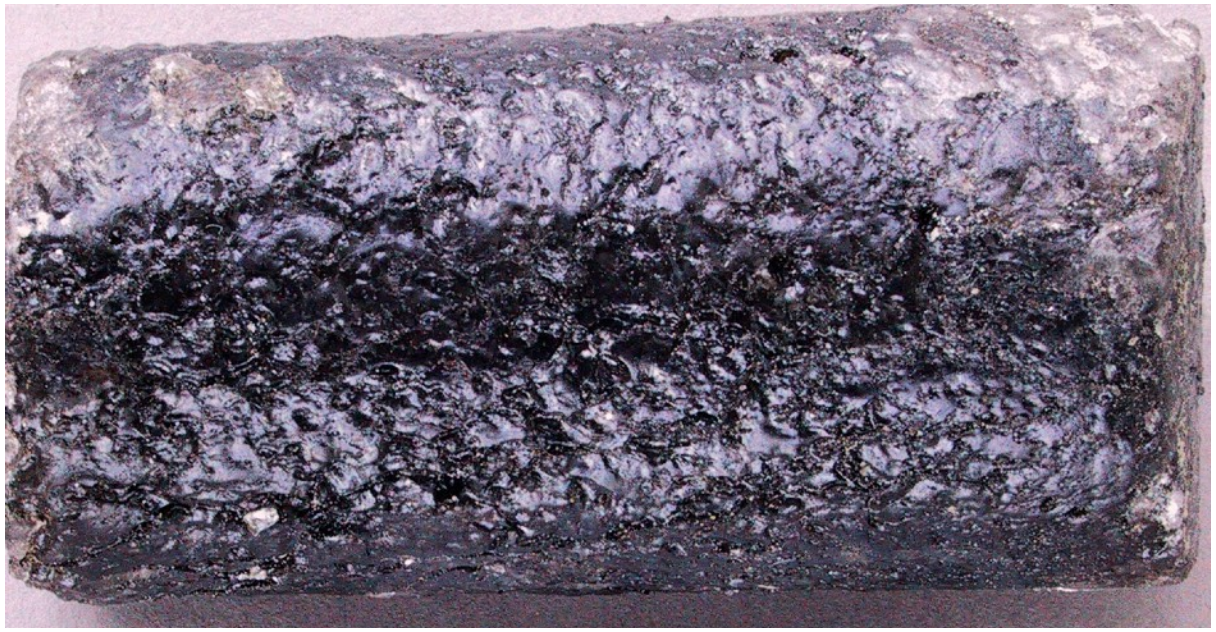
In- situ stress and fluid pressure in Ara salt

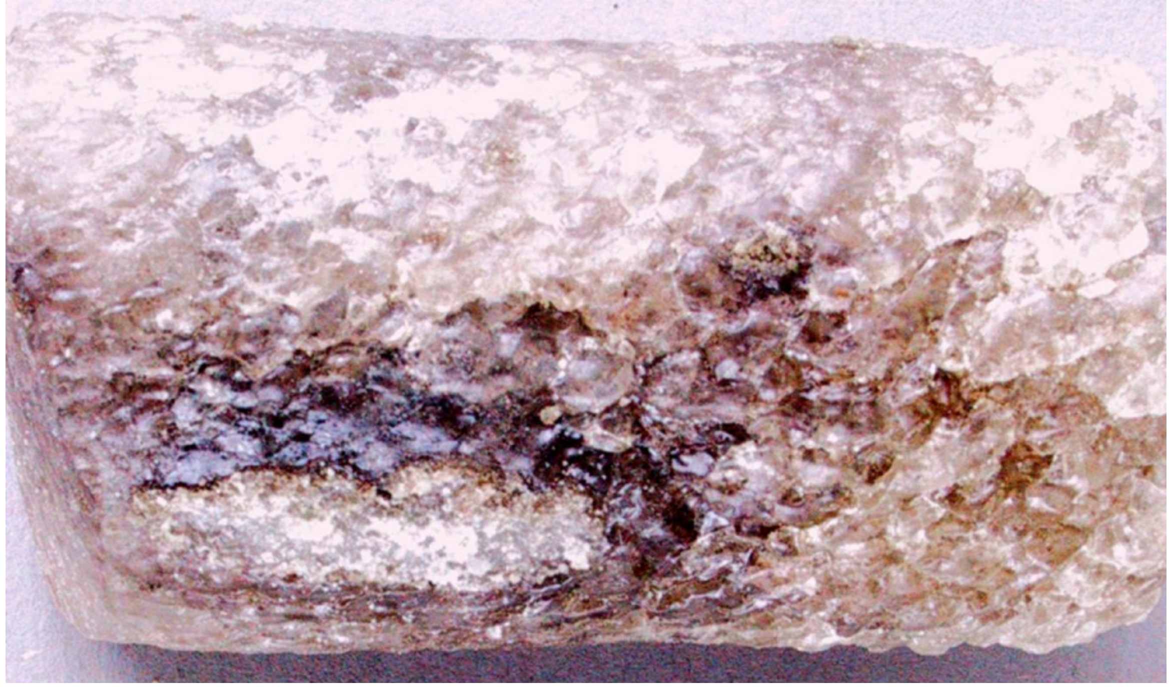




Peter A. Kukla, Lars Reuning, Stephan Becker, Janos Urai, Johannes Schoenherr Distribution and mechanisms of overpressure generation and deflation in the late Neoproterozoic to early Cambrian South Oman Salt Basin. Geofluids 11(4): 349-361. (2011)

Core plugs of bitumen-impregated Halite





2 cm

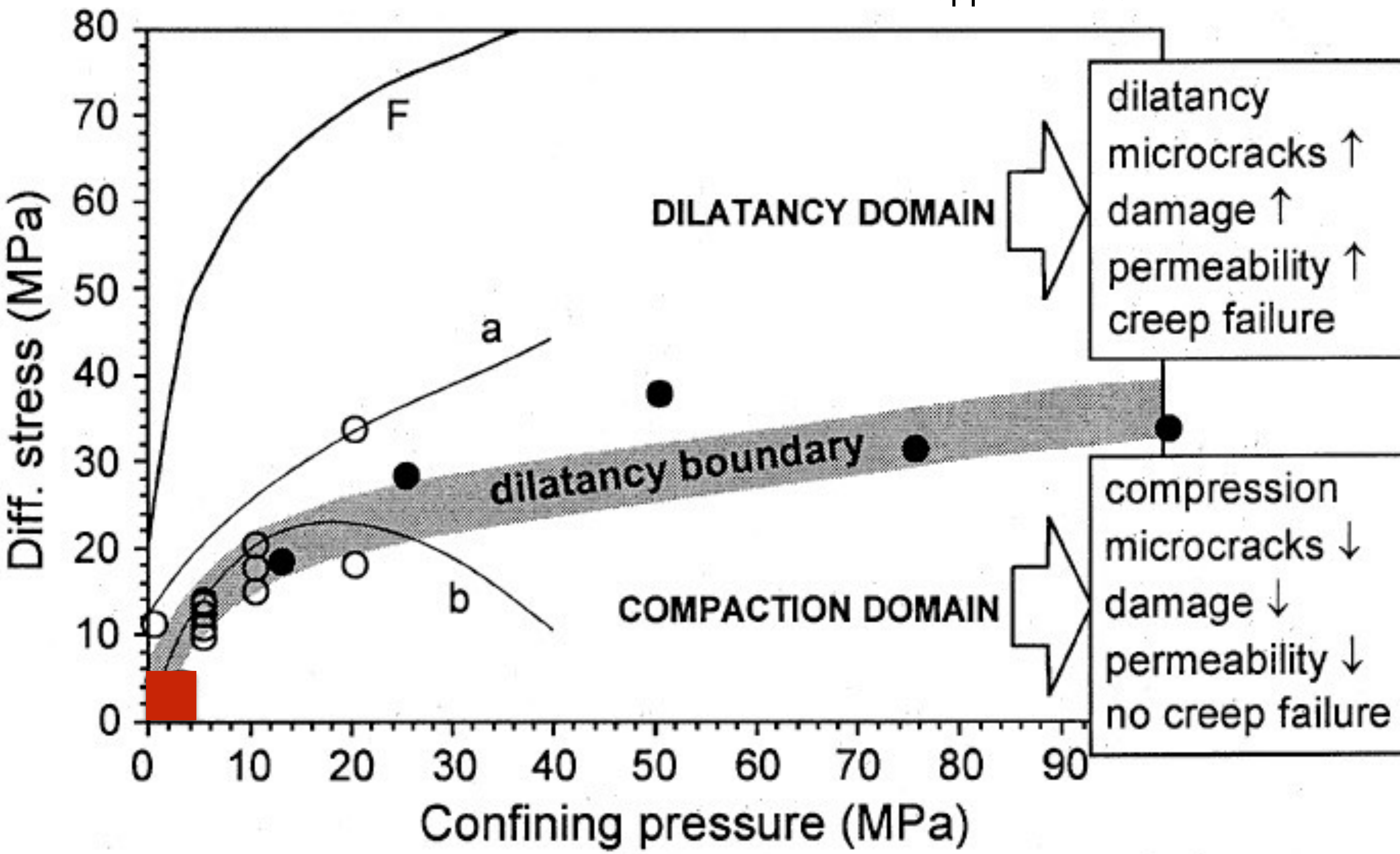
thin section

1 cm

Schoenherr et al. 2007, AAPG Bulletin 92

Dilatancy boundary for salt

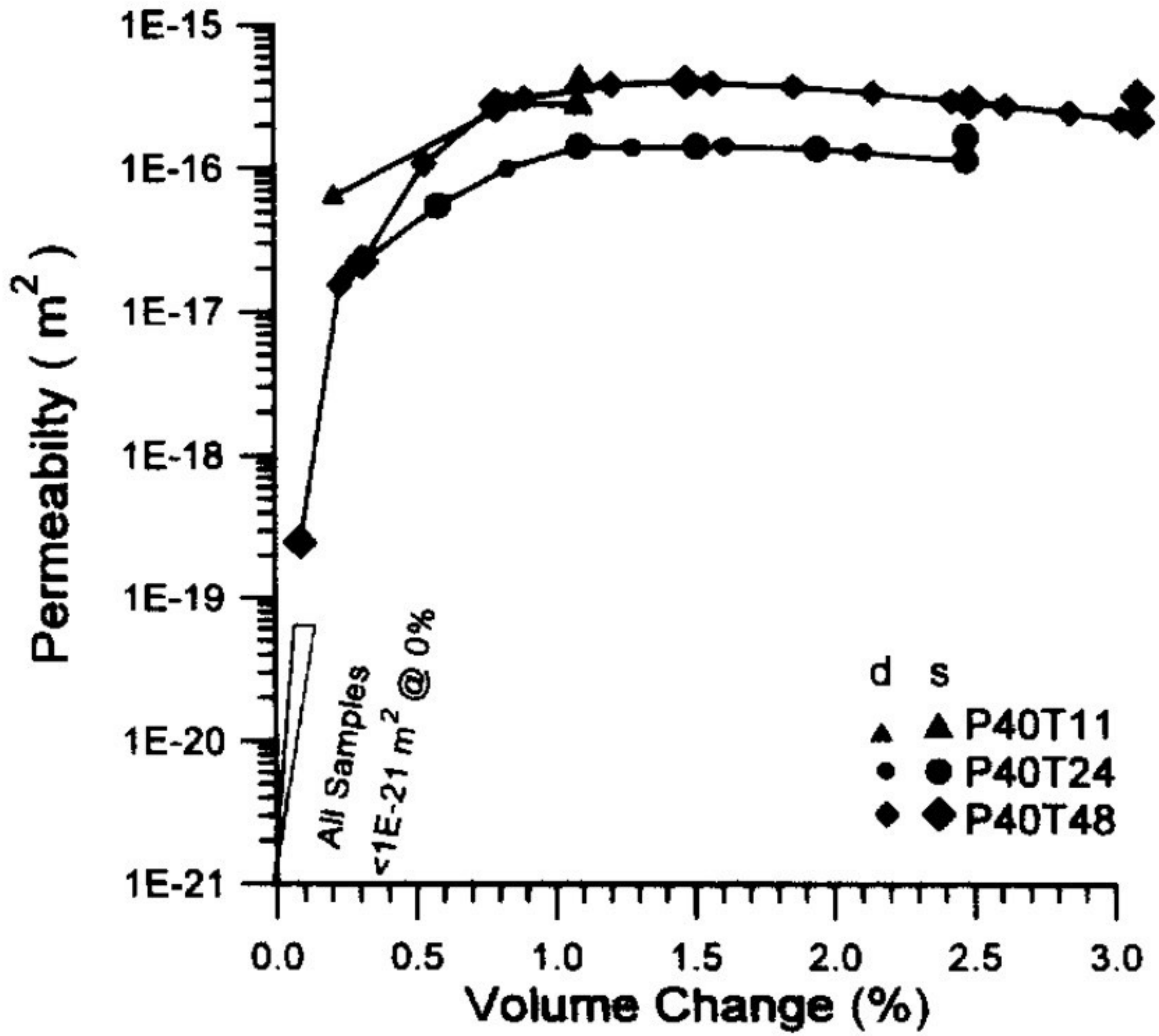
Popp et al 2001



dilatancy under low stress, high fluid pressure, is poorly known.

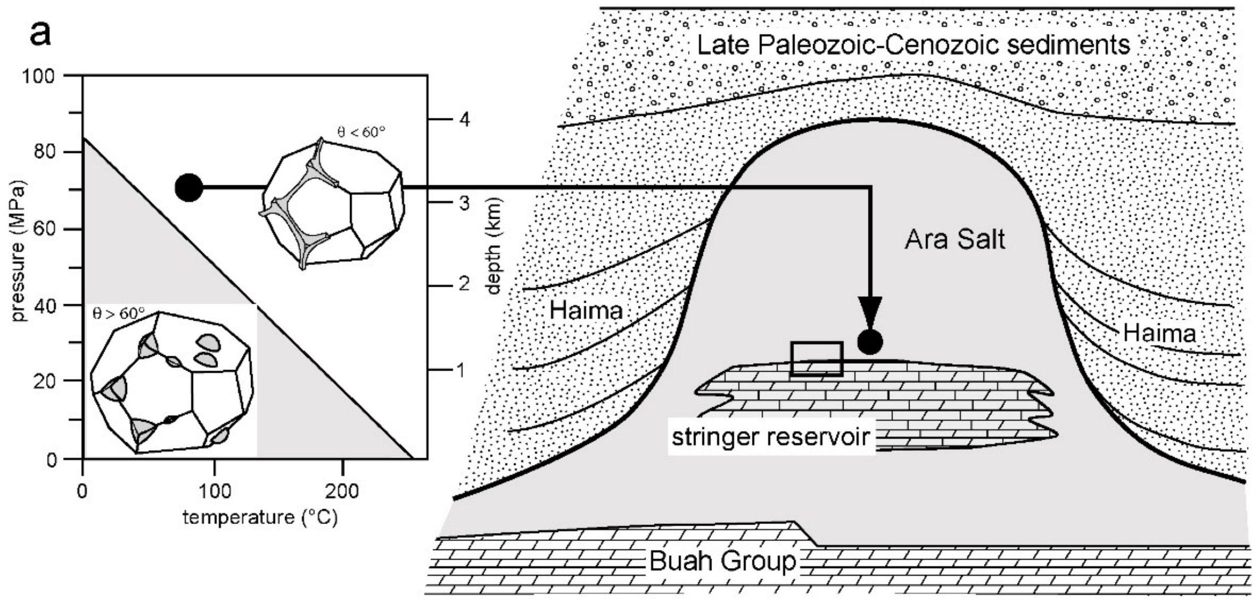
Schoenherr et al. 2007, AAPG Bulletin 92

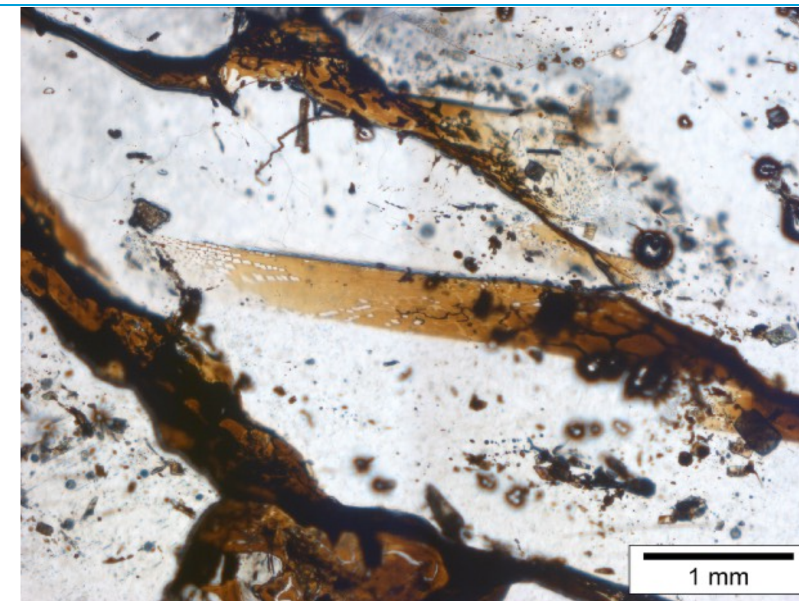
Dilatancy and Permeability evolution in salt @ 23 ºC



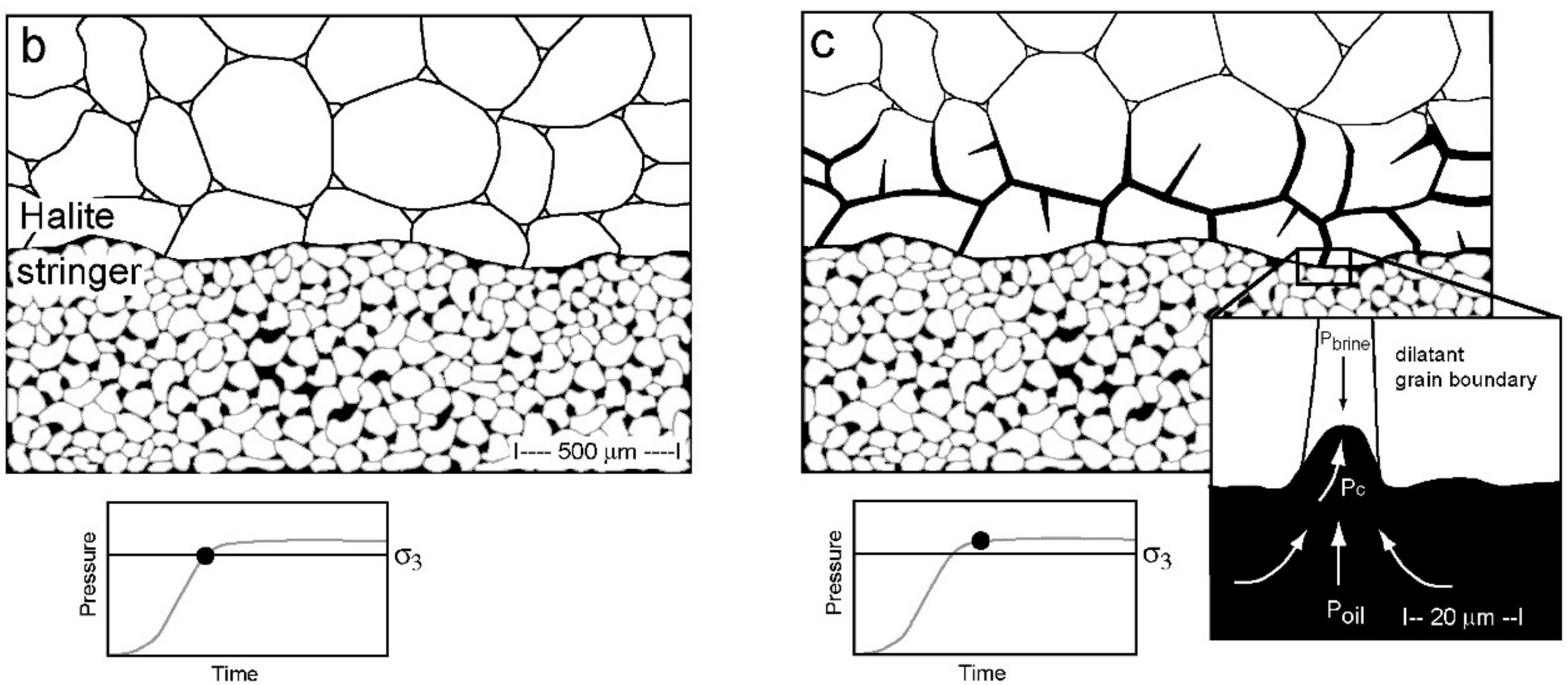
Peach and Spiers - Tectonophysics 256:101-128 1996

conditions for oil flow through salt





AAPG Bull.

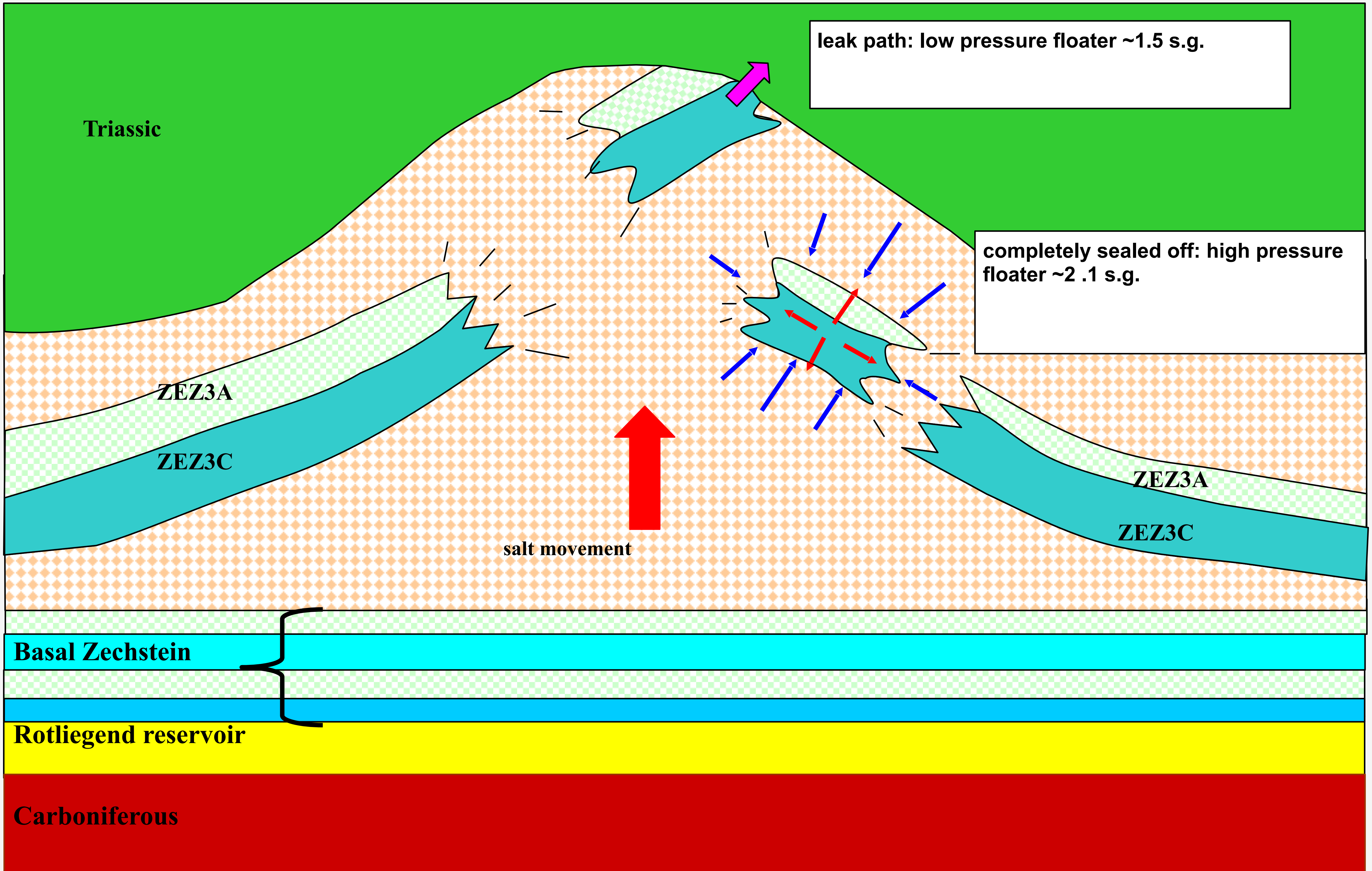


$P_{brine} \approx \sigma_3$, $P_{oil} > \sigma_3$

if $P_{oil} > \sigma_3 + P_c$ $\rightarrow$ salt starts to leak

salt remains permeable until $P_{oil} < \sigma_3$

ZEZ3 carbonate and anhydrite rafts



from Reemst 2004

Unified model for Zechstein?

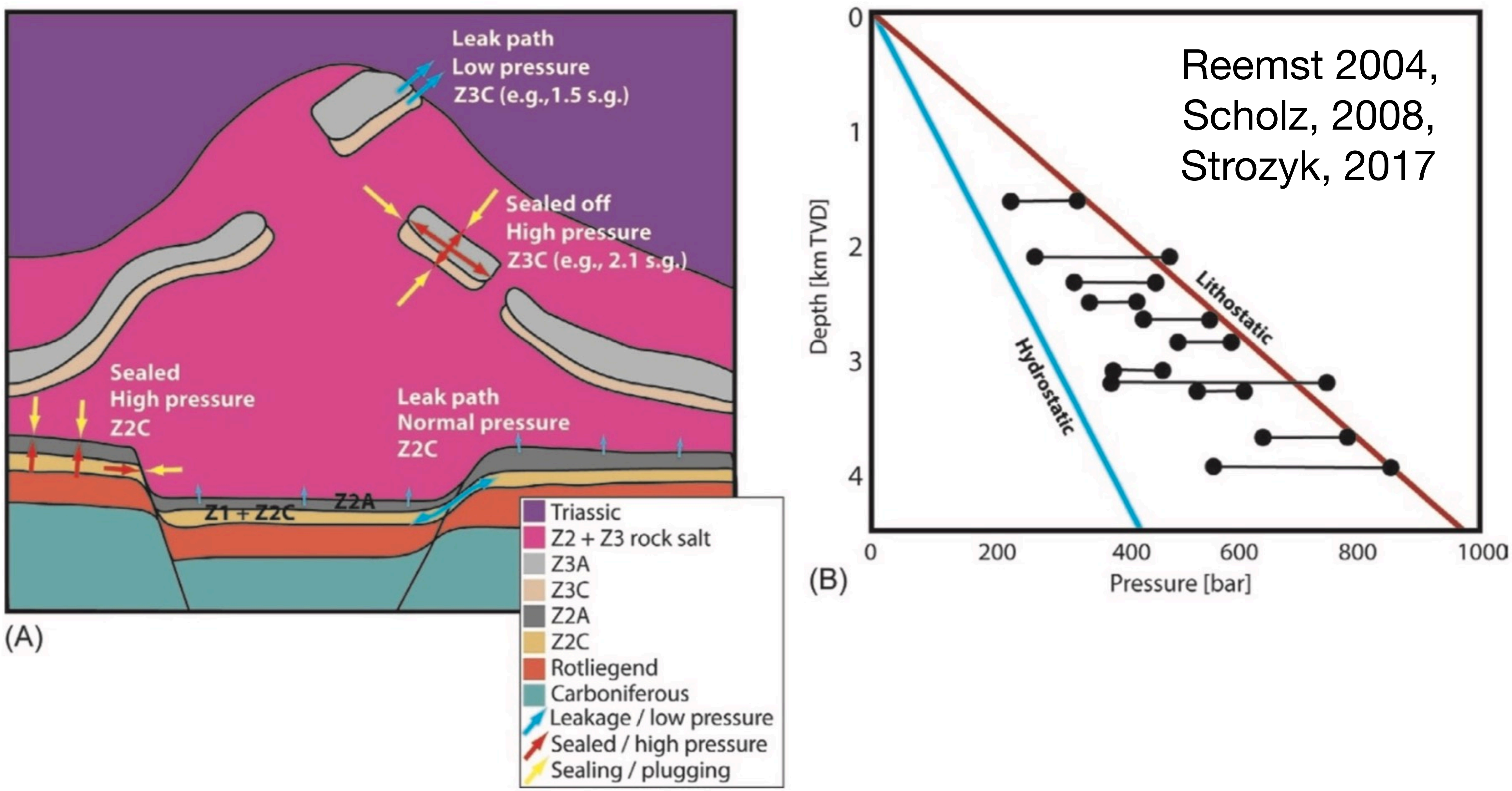
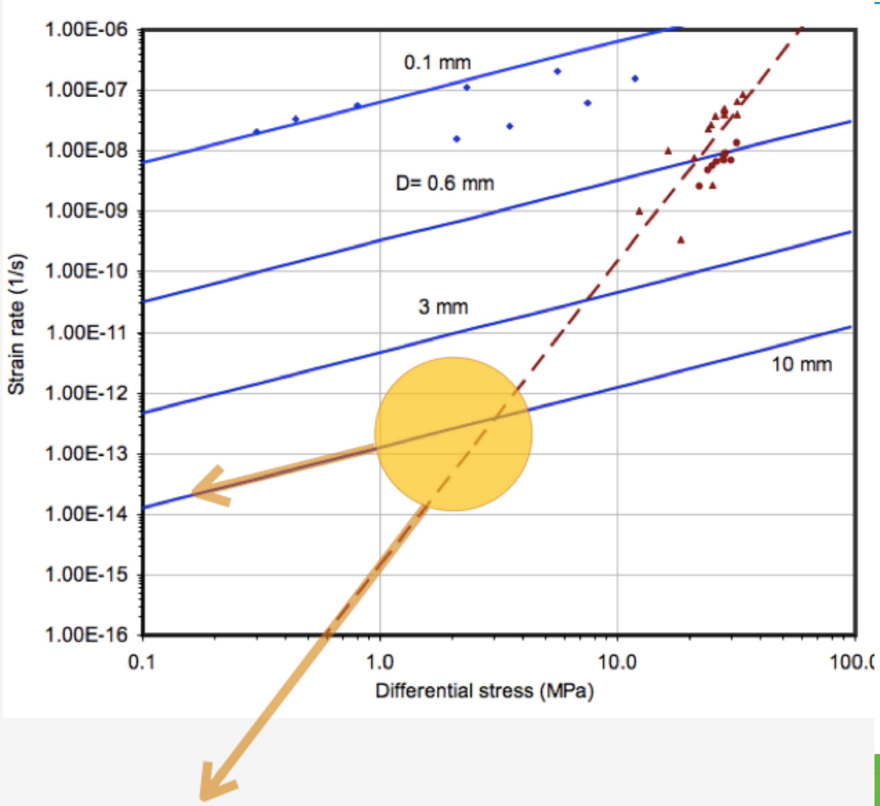
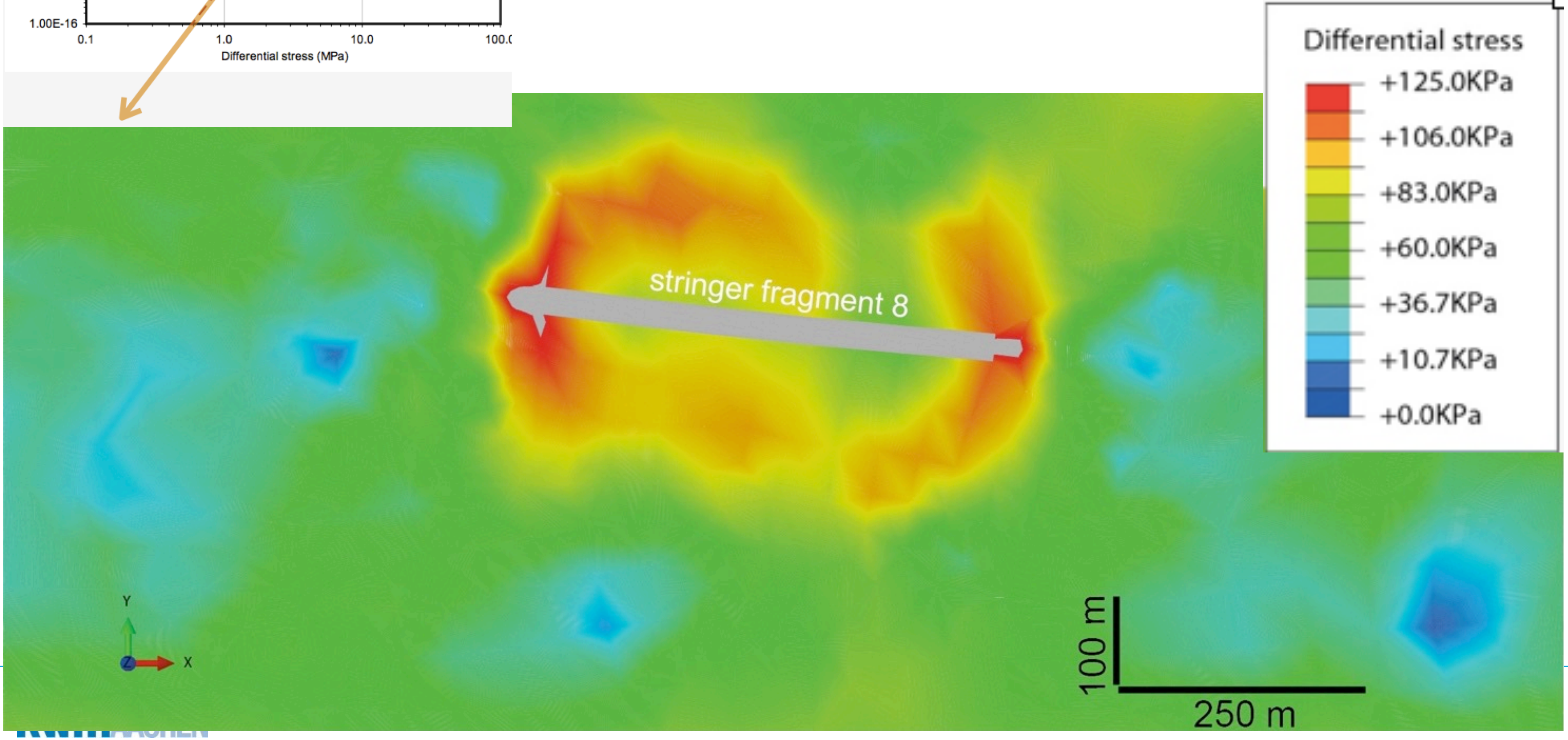


FIG. 7 (A) Conceptual sketch (not to scale; modified from Scholz, K. (2005). *Drilling problems in the Zechstein*. Diploma thesis, RWTH Aachen University, 75 p) exemplarily illustrating (i) a low-pressure Z3AC fragment (i.e., pressure is much lower than expected) inside a salt pillow, which lost fluids during contact and leakage with the sedimentary overburden and may cause losses when drilled, (ii) a high- to overpressured Z3AC fragment fully encased in salt and sealed, which may cause kicks when drilled, (iii) a high-pressure Z1 and Z2AC block, sealed by closed faults and by the rock salt and anhydrite (Z2A), and (iv) a "normal pressure" Z1 and Z2AC block, not fully sealed with fluid pathways across faults to neighboring blocks as well as into the salt above. (B) Pressure vs. depth plot (using total vertical depth, TVD) of some encountered high-pressure kicks in Z3C fragments in the Dutch on- and offshore (data from NAM). Pressures were calculated based on mud weight gradients in specific gravity (s.g.) and they are an estimate for the formation pressure. The *black dots* give the initial mud weight on the left (i.e., right before encountering the Z3C) and the final mud weight (i.e., when drilled into the Z3C) on the right along the horizontal line. Some of the mud weights applied to overcome a kick actually exceed the lithostatic pressure of the salt (represented by the *red line* (2.1 bar/10 m)), which might have caused fractures in the salt and additional losses. The *blue line* represents 1.0 bar/10 m (hydrostatic pressure), which represents a normal depth-pressure relationship.

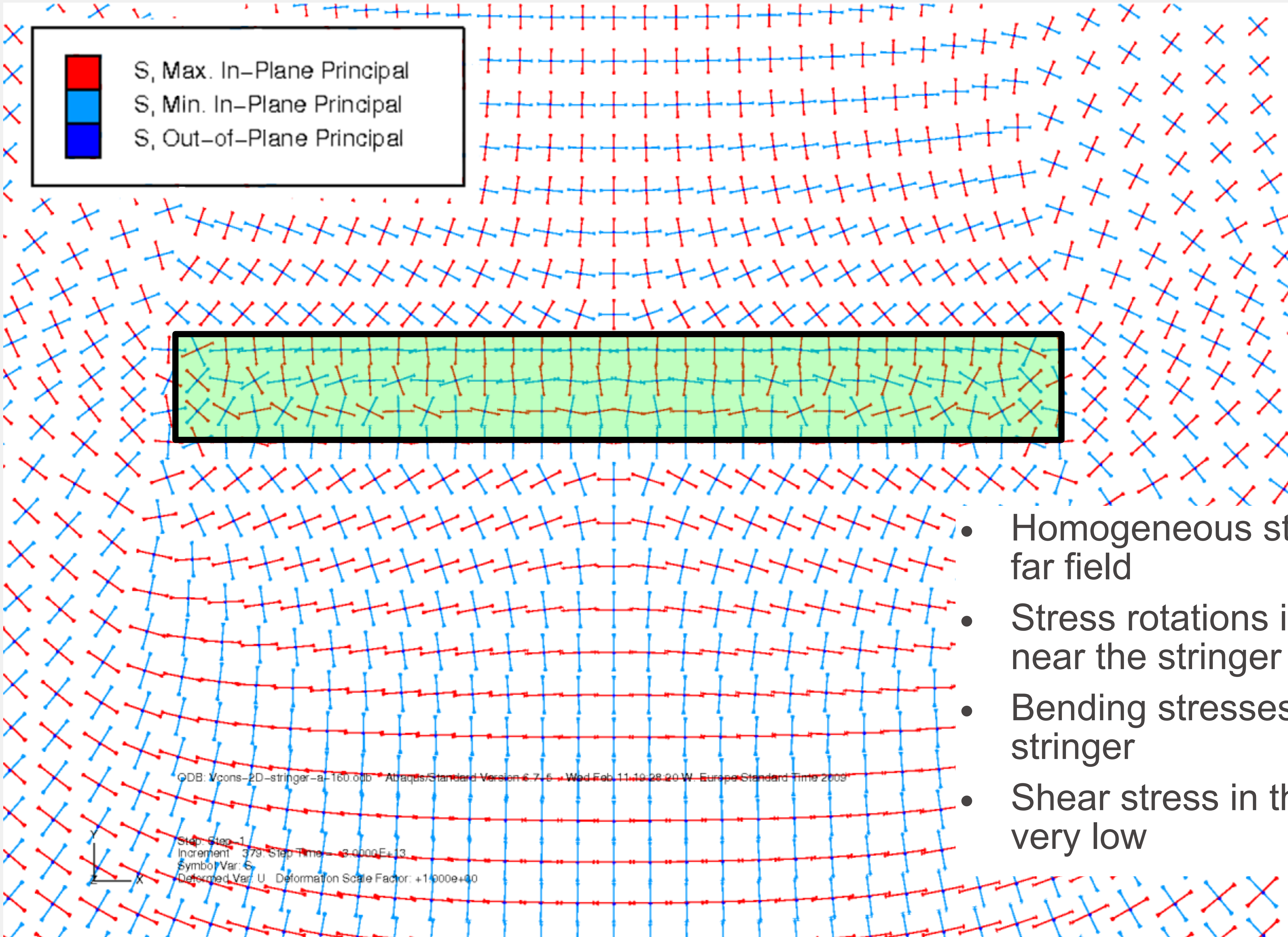
gravitational stresses around stringers



(after tectonic stresses are relaxed)



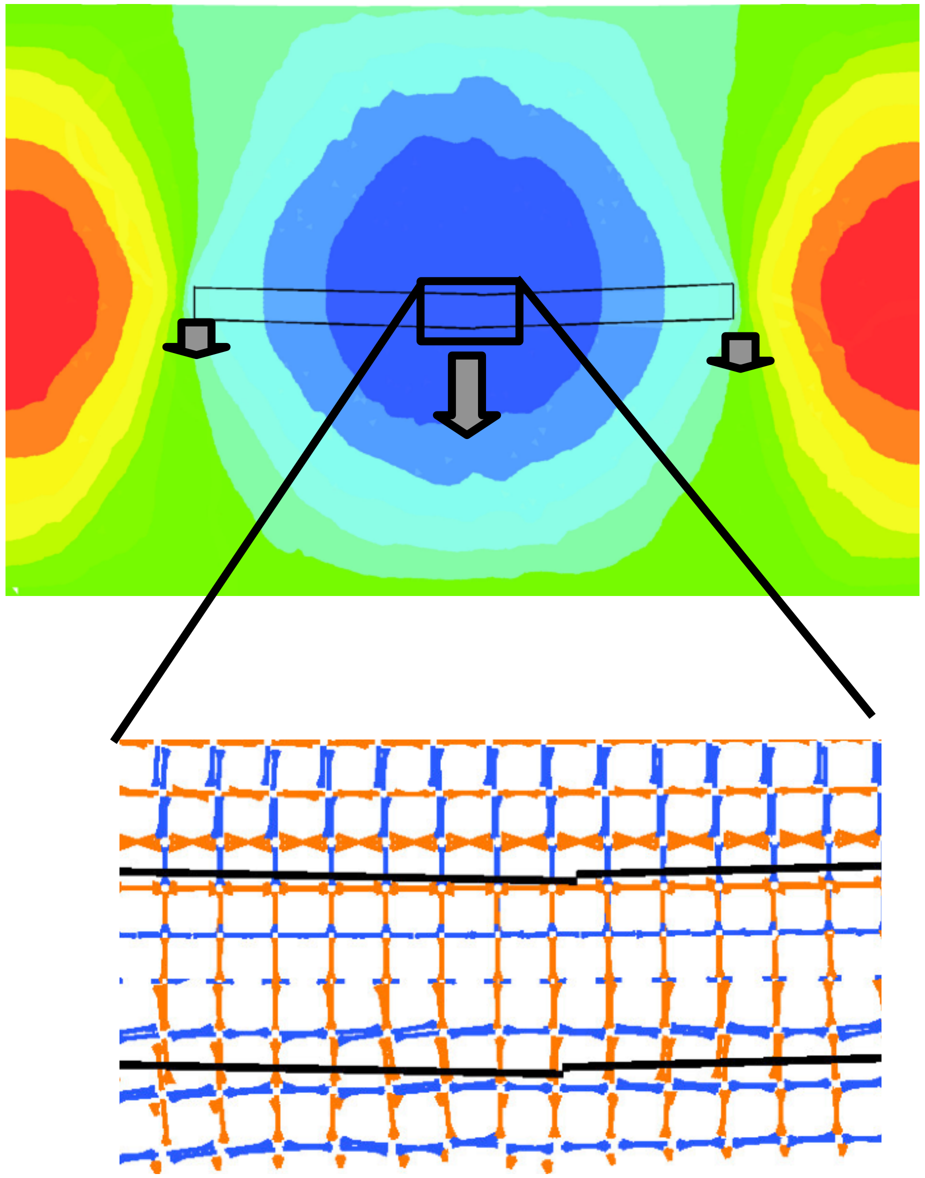
Typical Flow Stress Orientations



- Homogeneous stress in the far field
- Stress rotations in the salt near the stringer
- Bending stresses in the stringer
- Shear stress in the salt is very low

Present day production scale Stresses in Sinking Stringers

- Different distribution of horizontal stresses in sinking stringer depending on position
- Changing sign of the difference between horizontal and vertical stress between top and bottom parts of a stringer
- Mainly central section of the stringer affected



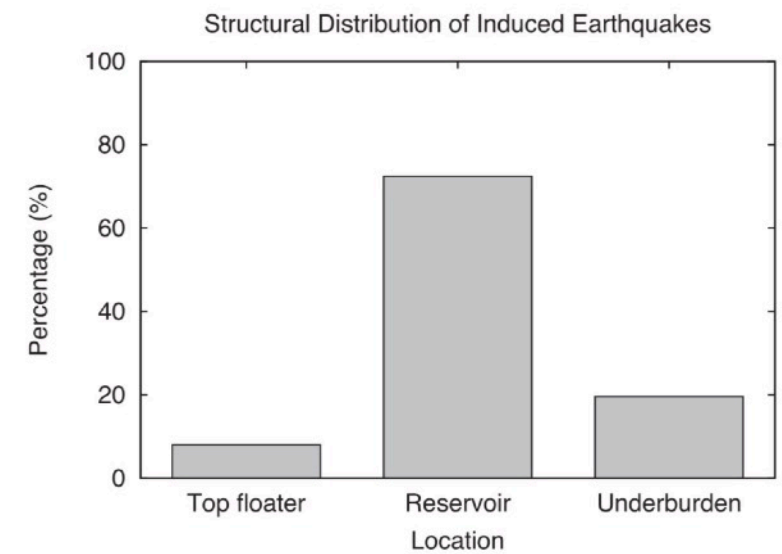
Min. compressive stress

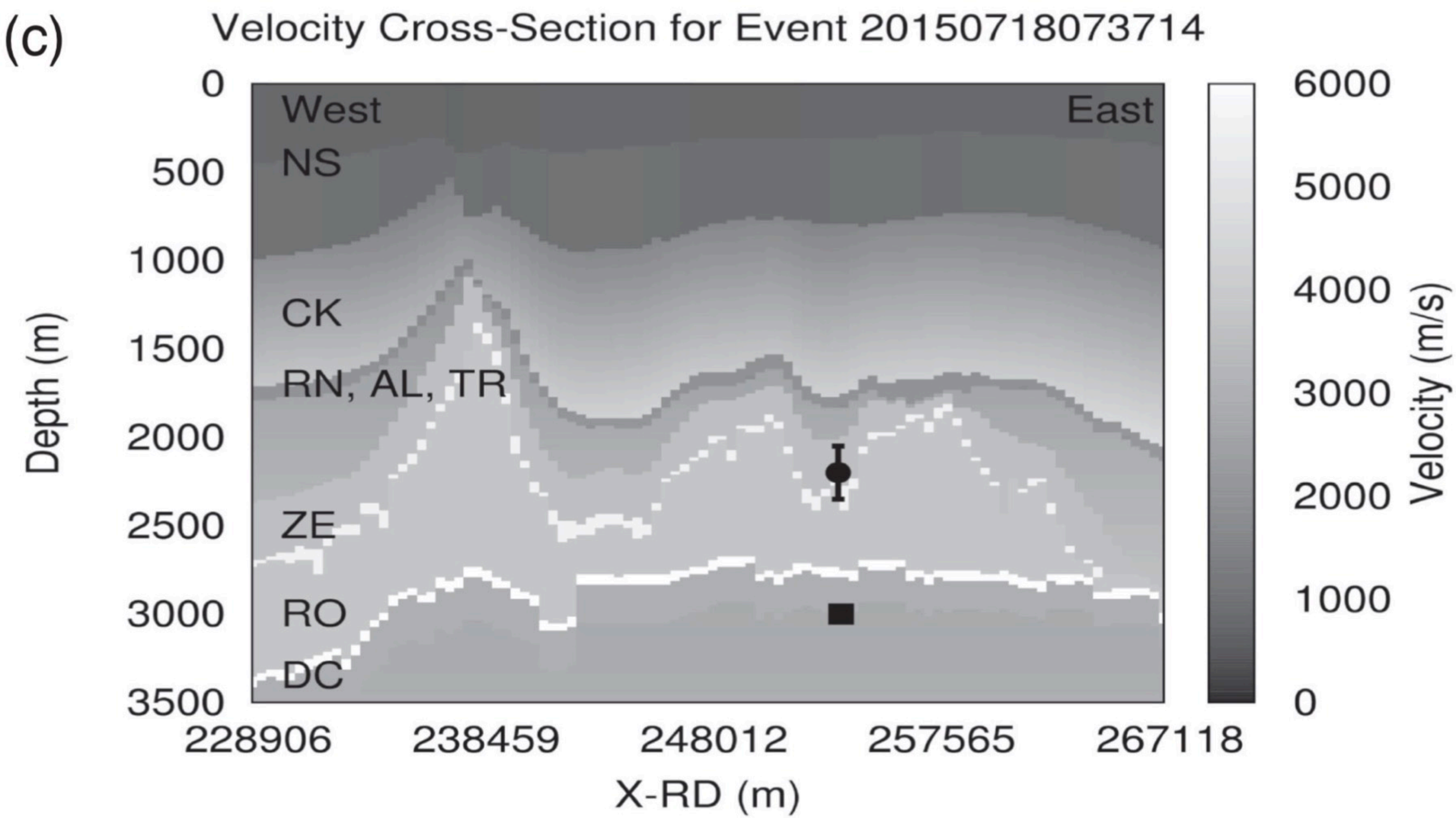
Max. compressive stress

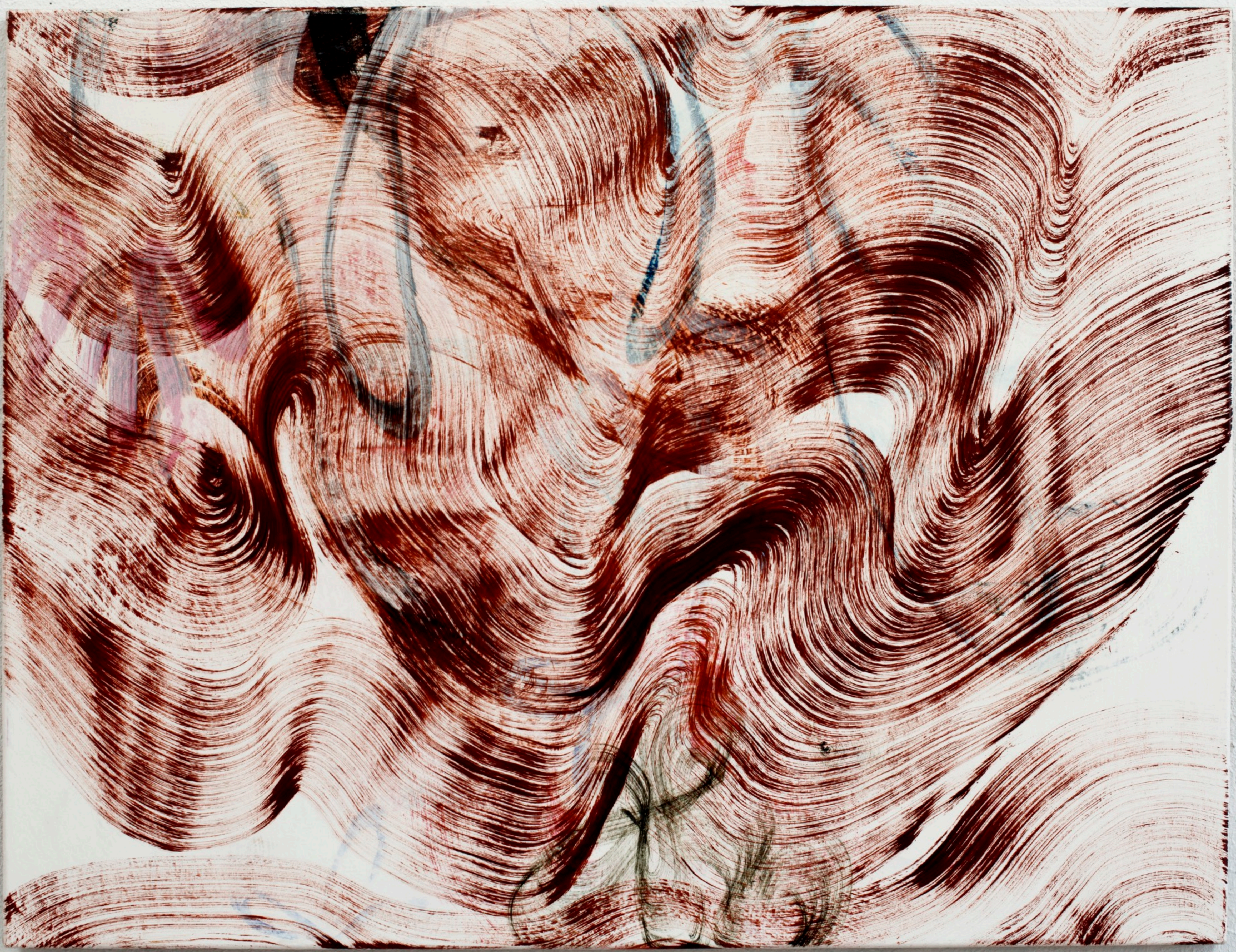
Geophys. J. Int. (2017) **209,** 453–465
Advance Access publication 2017 January 20
GJI Seismology

Hypocentre estimation of induced earthquakes in Groningen

Jesper Spetzler[1,2] and Bernard Dost[1]







Dagmar Baumann - Tectonic Synthesis

Conclusions

- stringer geometry -

- salt creep - brine pockets - kick & loss, unexpected stringers