An Integrated, Multi-scale Approach to Salt Dynamics and Internal Dynamics of Salt Structures*

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Abstract

Basins containing salt frequently display a complex geodynamic evolution characterized by several phases of halokinesis and associated sedimentation. Our approach to salt basins combines seismic, structural and sedimentary studies with analysis of rheological properties and geomechanic modelling. We illustrate these concepts with case studies from Permian Salt Basins in Europe and Precambrian to Paleozoic Salt Basins from the Middle East. One classic area of salt tectonics is the Central European Basin System (CEBS). Here, the mobile Permian Zechstein salt formed a large number of salt structures such as anticlines, diapirs, pillows, sheets, stocks, and walls during an extended period of salt tectonic activity in Mesozoic and Cenozoic times. Salt-influenced sedimentary responses to renewed phases of tectonism can be clearly discerned from detailed sequence analysis based on seismic and log data combined with retrodeformation modelling studies. Late Paleozoic sedimentation in the CEBS deposited Upper Rotliegend sediments in a series of fluvial, eolian, playa lake and sabkha settings in an extensional regime. About 800 m of bedded sulfate and halite were deposited in the study area during the hydrographic isolation and drawdown of the Late Permian Zechstein evaporite basin. High quality 3-D seismic data integrated with structural modelling improves the definition of salt structure and associated sediment architecture in salt-controlled sequences. Paleo-cap rocks inside the diapirs point to long phases of dissolution. Salt wedges formed by extrusion and lateral flow of salt glaciers during periods of diapir emergence and reduced sediment accumulation can be accurately modelled. Although salt is widely regarded as a perfect seal, it can become permeable for one- or

two-phase fluids under certain conditions of fluid pressure, temperature and deviatoric stress. The fluid pathways can be either along zones of diffuse grain-boundary dilatancy, or along open fractures, depending on the fluid overpressure and deviatoric stress. The fluid can form halite veins or networks of brine-filled grain boundaries which conduct fluid from primary inclusions during recrystallization. The main criterion for this to occur is the presence of near-lithostatic fluid pressures.

In the second part of our study, we focus on the large-scale internal geometry of salt structures. These are often represented in two strikingly different ways. In studies using 3D seismic and well data that focus on the sub-or suprasalt sediments, the evaporites are shown as homogeneous bodies. On the other hand, studies of the internal structure of salt show the extremely complex internal geometry with much less attention to the structure of the surrounding sediments. Numerical models of salt tectonics also tend to assume relatively homogeneous rheological models and, consequently, produce relatively simple internal structures. New developments in microstructure analysis, combined with 3D seismic study of complex internal structures in salt form the basis of integrating these two. A review and synthesis of the mechanical and transport properties and their extrapolation to relevant strain rates must be based on an understanding of the microscale deformation mechanisms in natural laboratories and measurement of salt flow in-situ. Dislocation creep and grain boundary dissolution-precipitation processes, such as solution-precipitation creep and dynamic recrystallisation, play a significant role. The switch between these processes can cause major changes in rheology, at time-scales both relevant to geologic evolution and subsurface operations. New methods of microstructure analysis based on microstructure decoration, orientation analysis and trace-element geochemistry, combined with paleorheology indicators based on structures observed in natural laboratories, allows an integration of these data and the development of a unified model for salt creep and prediction of regions where high fluid pressures led to a dramatic increase in permeability, strongly reducing sealing capacity. Many evaporite deposits contain brittle-ductile claystone, carbonate and/ or anhydrite layers enclosed in salt. Although these stringers can be reservoirs for hydrocarbons and can pose serious operational challenges, little is known about the early evolution and deformation history of these layers. 3D seismic study of these, combined with well data and core analysis of diagenetic evolution, shows highly complex structures caused by both brittle and ductile deformation, in good agreement with observations in salt mines, and forms the basis of a new generation of mechanical models to investigate the complex coupling between the internal deformation of the salt and the evolution of the surrounding sediments.

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Adapted from two oral presentations at GSL-SEPM Conference - Salt Tectonics, Sedimentation, and Prospectivity.
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PART I: AN INTEGRATED, MULTI-SCALE APPROACH TO SALT DYNAMICS

Integrated, multi-scale salt projects - Introduction

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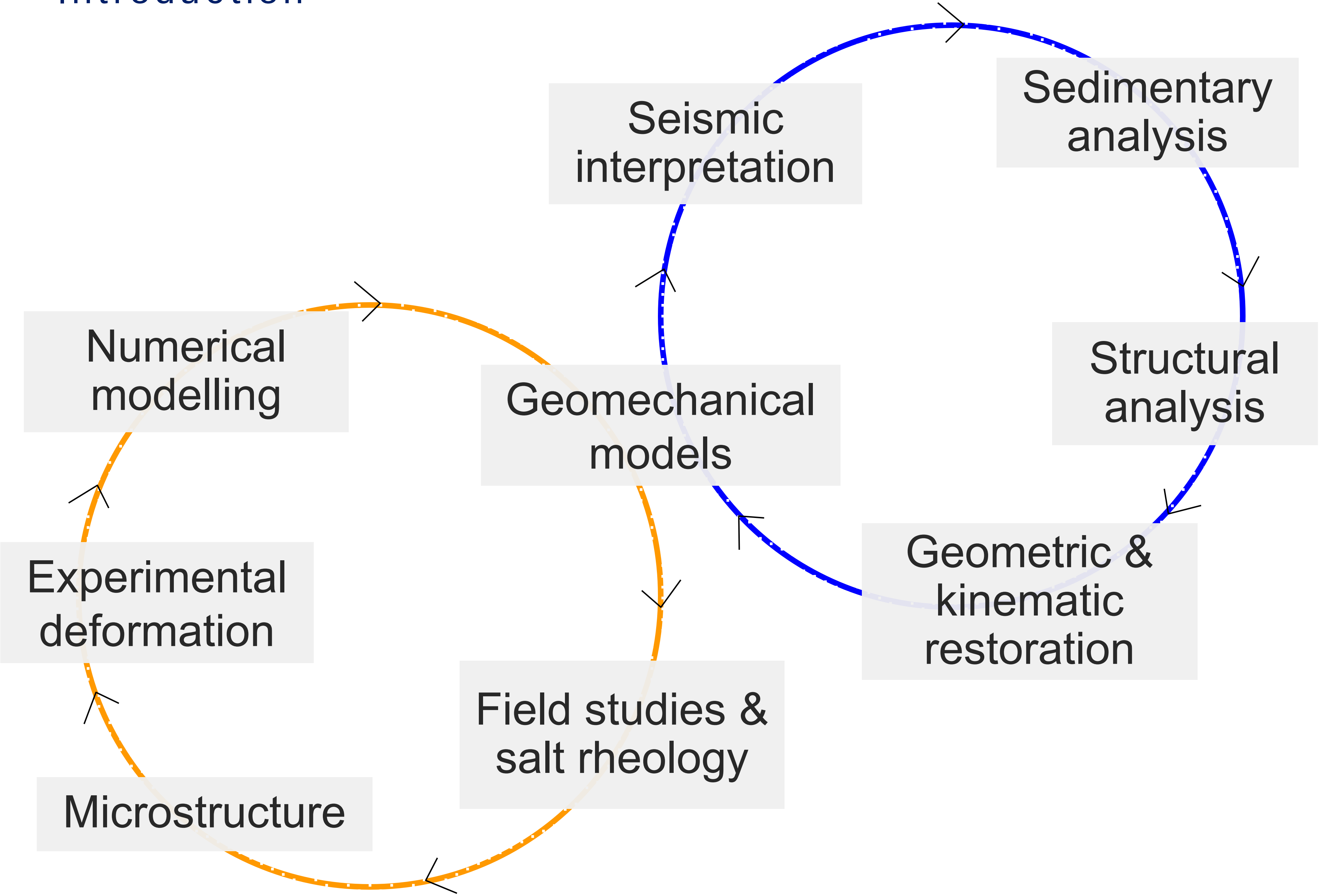


Seismic interpretation

Sedimentary analysis

Structural analysis

Geometric & kinematic restoration

Geomechanical models

Numerical modelling

Experimental deformation

Microstructure

Field studies & salt rheology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes:

Salt terranes are complex; some are more complex than others. From an economic point of view, they constitute plays which cannot be simply put into one pigeonhole (structural, stratigraphic etc.).

From studying salt terranes over the last decade, we think that both macro- and micro-scale studies are needed to handle the complexities associated with salt terrains.

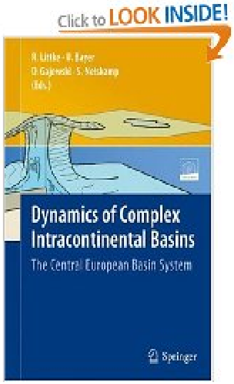
The first part of this article (presentation by Peter Kukla) covers the blue circle - the macroscale aspects, such as Seismic Interpretation.

The second part of this article (presentation by Janos Urai) presents our approach to studying the internal deformation of salt, covering aspects seen along the orange circle.

Two studies intended to demonstrate the importance of an integrated macro-scale analysis are presented. It is especially the geometric and kinematic restoration, together with other information, which provides the input for micro-scale analysis and numerical modelling of internal deformation.

Salt tectonics in mixed terranes

Permian Zechstein in the Central European Basin



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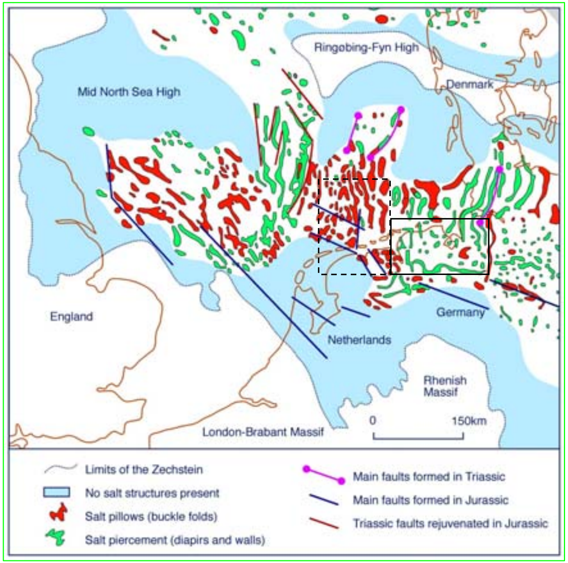
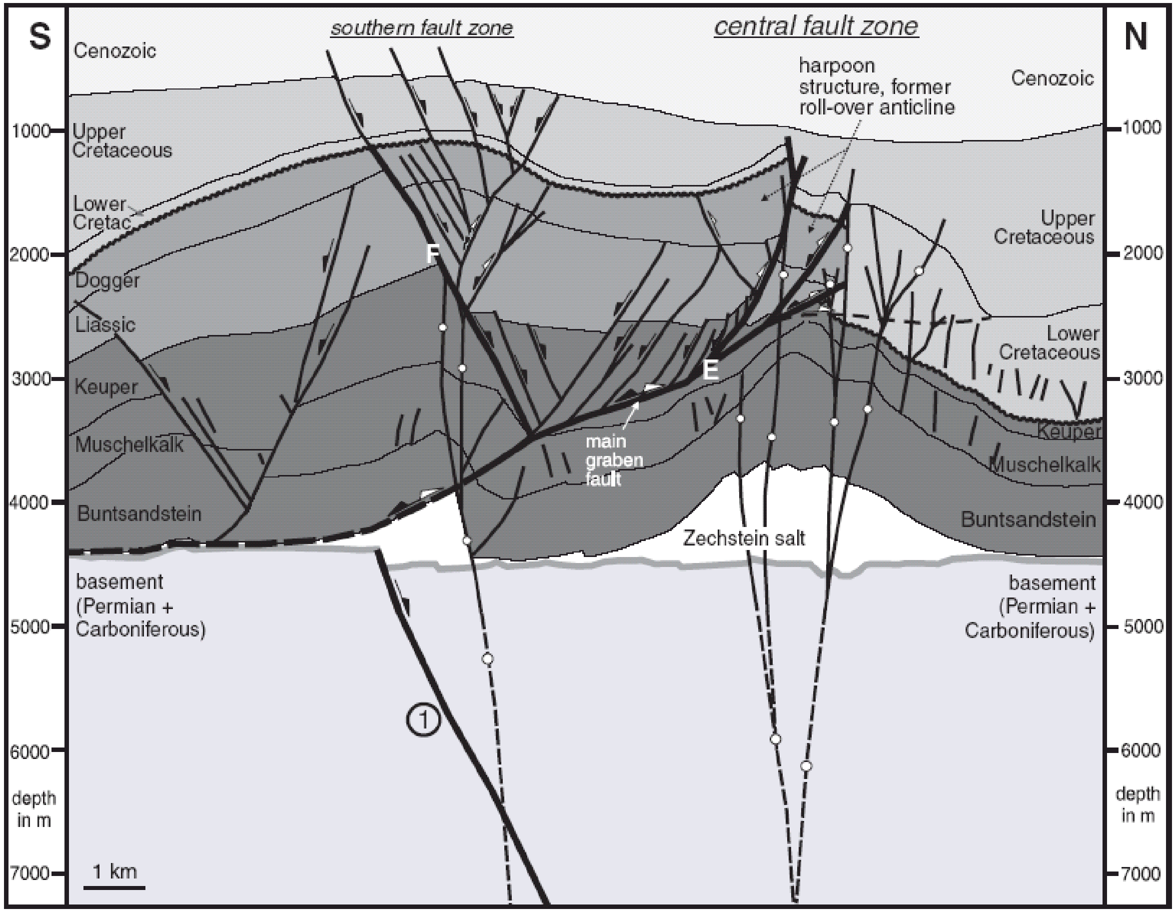


Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes: From a salt tectonics point of view we know that salt structures are commonplace in **extensional terranes (rifts, passive margins - -GOM type) and compressional terranes (e.g., Zagros Namakiers)**
A third type are **mixed terranes**, and one of the classic ones we can see here is the Permian in the CEB.
I illustrate our approach and key findings in such a complex terrane in the following slides.

Changing stress fields and strain partitioning

Click to view Presenter's Notes



Lohr et al., 2007; Basin Research

- Pre-existing faults and salt dynamics control deformation styles through time
- Decoupling (post-salt deformation) and coupling (pre- and post-salt deformation)
- Stress perturbations and local strain partitioning responsible for different stress regimes between basement and cover

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter’s Notes:

The availability of high-resolution 3D seismic surveys in recent years has greatly improved our understanding of the onshore Permian Zechstein basin.

One example from an area separating the Lower Saxony Basin and the Pompeckj High along one of the major NW-trending lineaments extending into the North Sea Basin, is shown here from our study group involving Potsdam/Aachen/Hannover. Tina Lohr has been able to show the relations given above.

In **decoupled** areas deformation occurred only within post-salt units, leading to different deformation styles in the same area (as shown in the Central Fault Zone); the most prominent normal fault detached along a Middle Keuper salt layer, and soled out into the Zechstein salt (**E**). The main graben fault proceeds into several **imbricate listric normal faults**, building a **roll-over anticline and tilted blocks**.

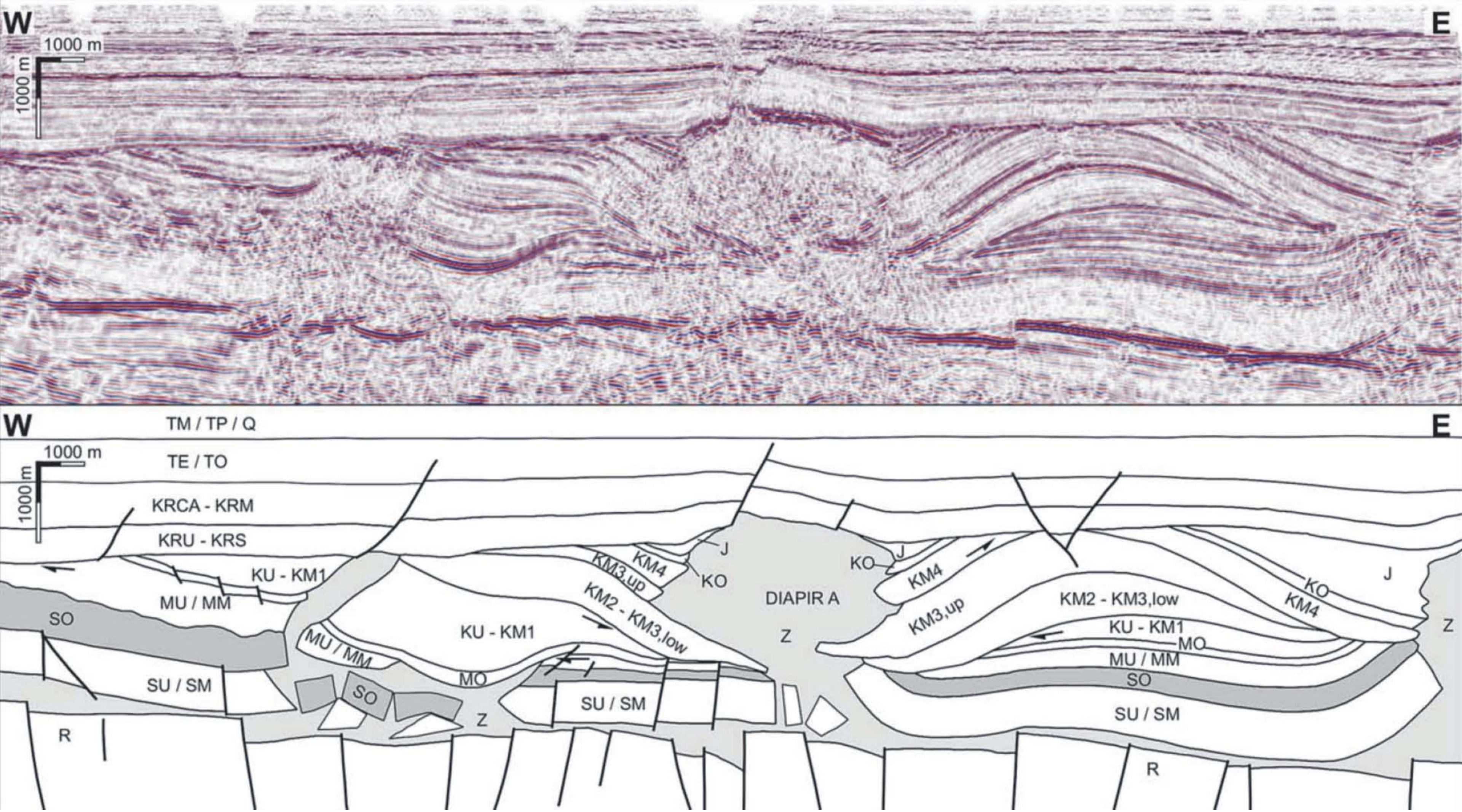
In **coupled** areas deformation occurred in both post- and pre-salt units, and is characterized by strike-slip faulting (white circles).

Thrusting of Mesozoic sediments (**imbricate thrusts**) occurred contemporaneously with the **oblique thrusting** (positive flower structure) of Upper Permian sediments during the Late Cretaceous.

The heterogeneity in distribution and timing of deformation is controlled by different reactivation of pre-existing faults depending on their orientation, and by salt distribution. These factors led to stress perturbations and therefore local strain partitioning; areas with greater salt thickness triggered a decoupling of the stress field between pre- and post- salt units.

Salt tectonics in changing regional stress fields

Click to view Presenter's Notes



Mohr et al., 2005; Int. J. Earth Sci.

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes:

A little farther to the south in the Emsland area at the SW-margin of the CEB, a regional study aimed at deciphering the geometry and the kinematics of a section east of the Groningen block in NL.

The regional section includes a salt diapir, salt walls, salt sheets, rafted blocks and mainly decoupled basement as well as a partly faulted overburden (at top of diapir A).

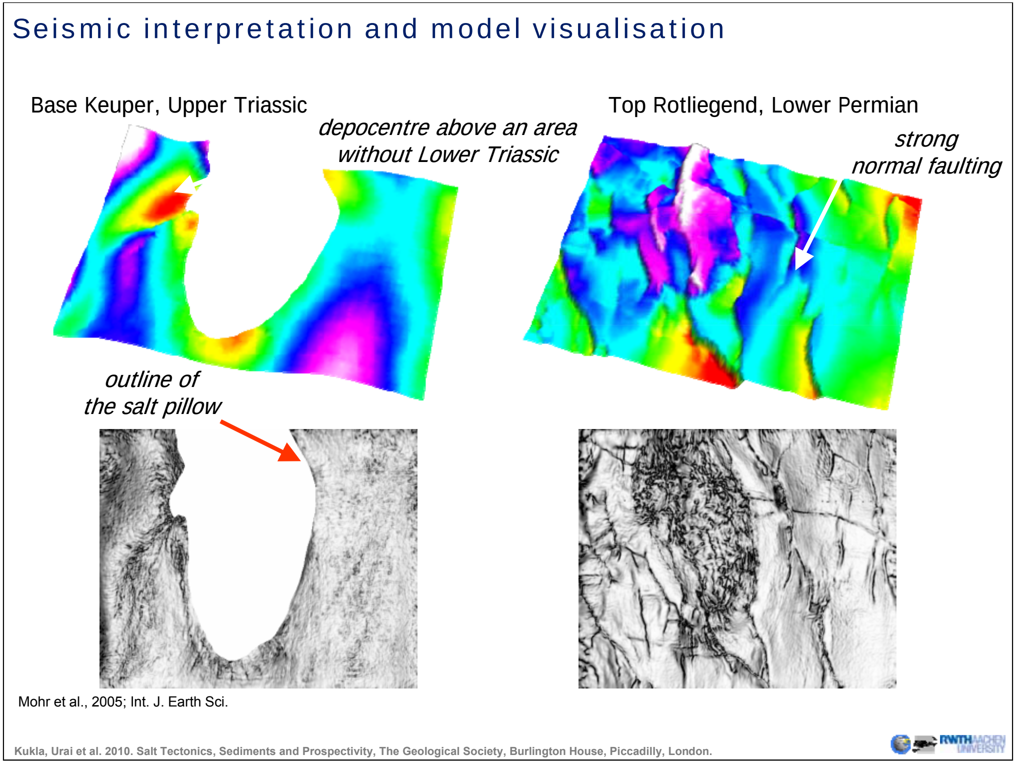
In the course of this project, detailed interpretation, facies analysis, well data analysis and retrodeformation modelling occurred.

Database:

10 x 13 km 3D seismic cube

Network of 28 depth-migrated 2D sections

11 deep exploration wells - log data



Seismic interpretation and model visualisation

Base Keuper, Upper Triassic

depocentre above an area without Lower Triassic

Top Rotliegend, Lower Permian

strong normal faulting

outline of the salt pillow

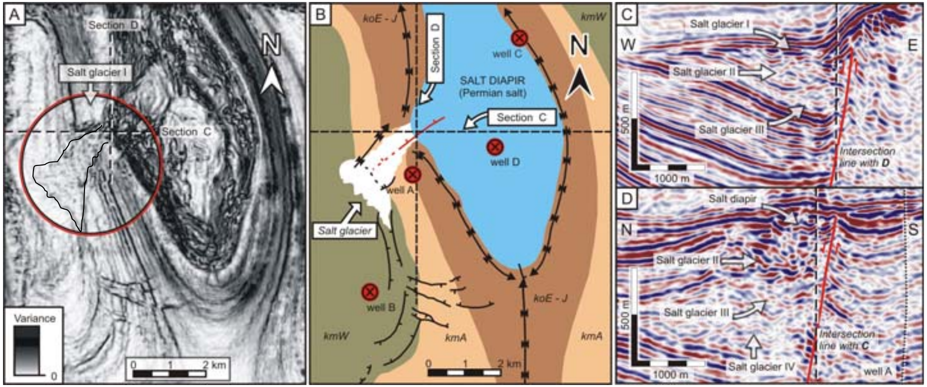
Mohr et al., 2005; Int. J. Earth Sci.

Presenter's Notes: Attribute volumes (coherency (variance) maps here) from the 3D surveys were calculated and subsequently interpreted for structure, salt geometries and depocentre evolution and migration through time.

At this stage I show just one slide with the deformation of the pre-salt at top Rotliegend and the evolution of a depocentre in the Middle Triassic Keuper, with more images to follow.

Late Triassic salt glaciers

coherency map **Geological interpretation** **3D seismic**



50 m below Base Cretaceous

Mohr et al., 2007; Geology

Presenter's Notes: A further feature observed from careful screening of the 3D survey was a Late Triassic (Keuper) salt glacier, the first of its kind reported from the German subsurface.

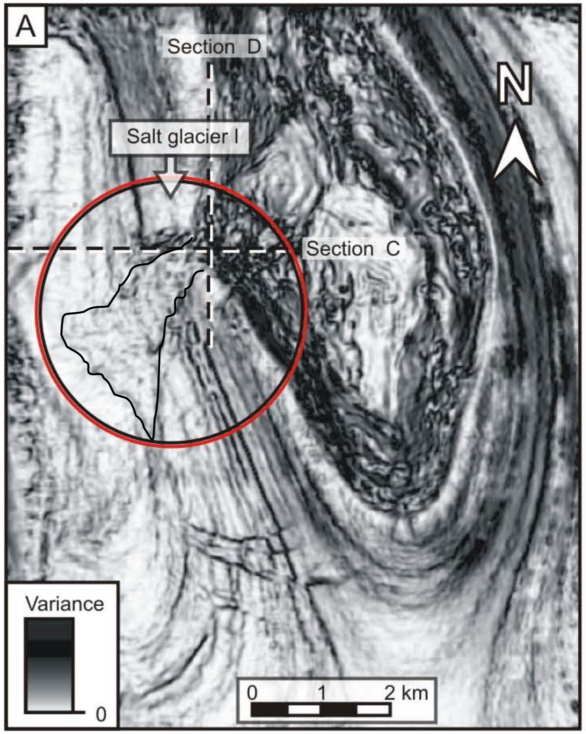
This confirms active salt dynamics during tectonism in the basin.

Late Triassic salt glaciers

coherency map

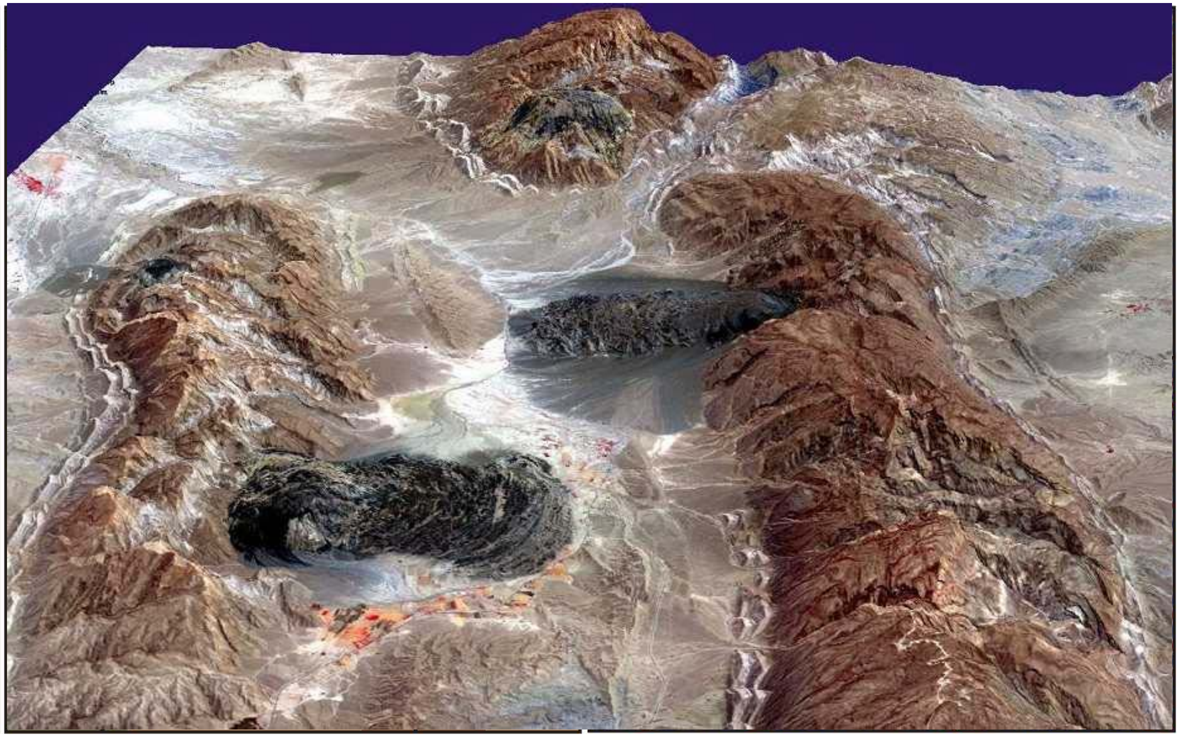
Geological interpretation

3D seismic



50 m below Base Cretaceous

Mohr et al., 2007; Geology



(U.S./Japan ASTER Science Team;
see http://asterweb.jpl.nasa.gov/gallery)

Sequence analysis – salt/sediment interface

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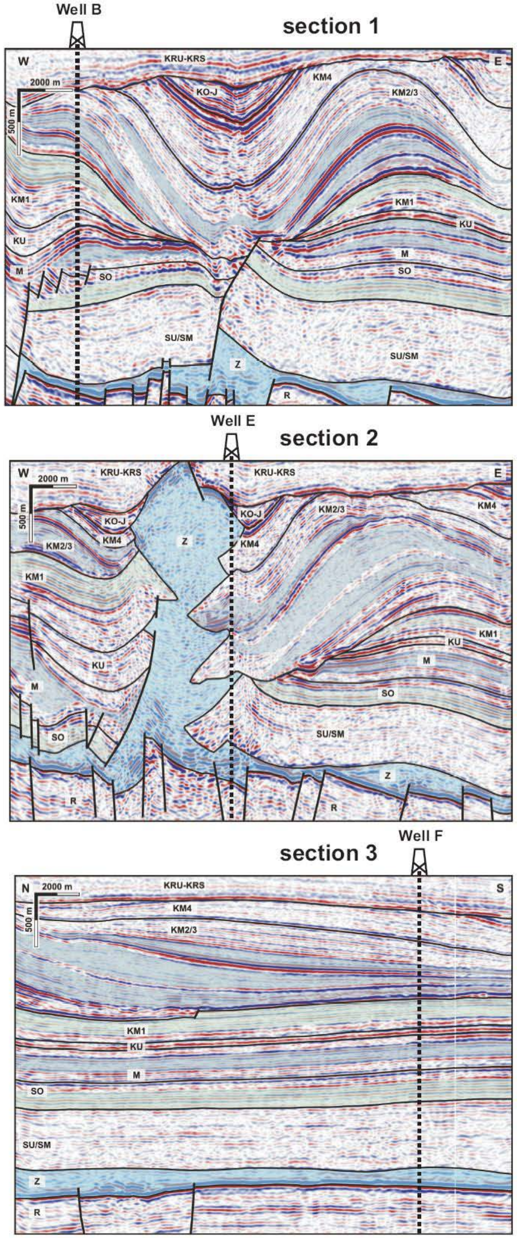
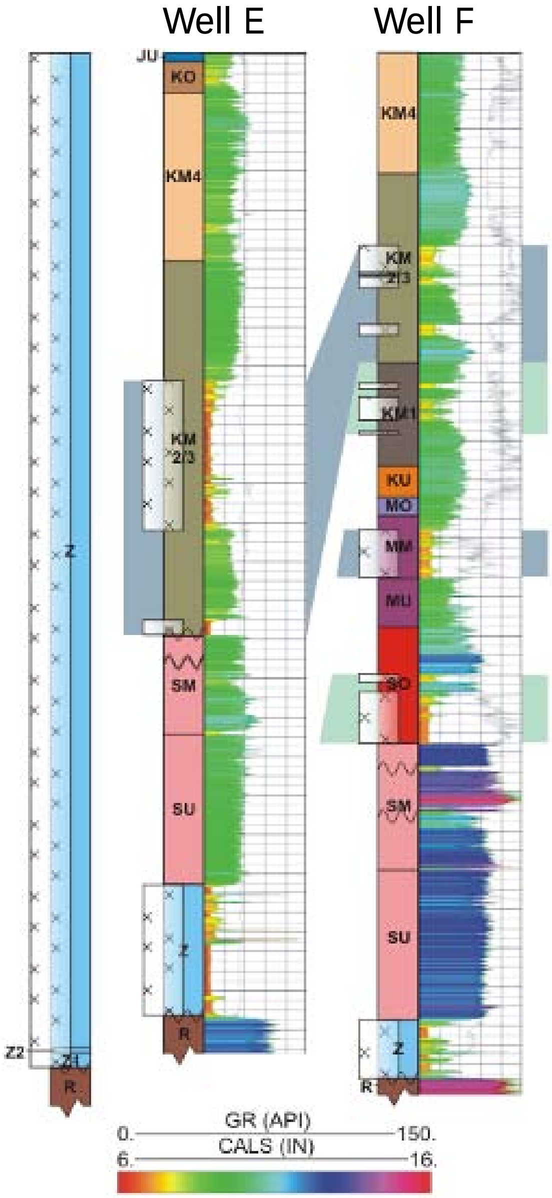




- Up to 800 m thick primary salt deposits in the rim-syncline

- Thickness of the bedded salt units corresponds to rim-syncline evolution

- Buckle folds cored by thick Triassic evaporites

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes:

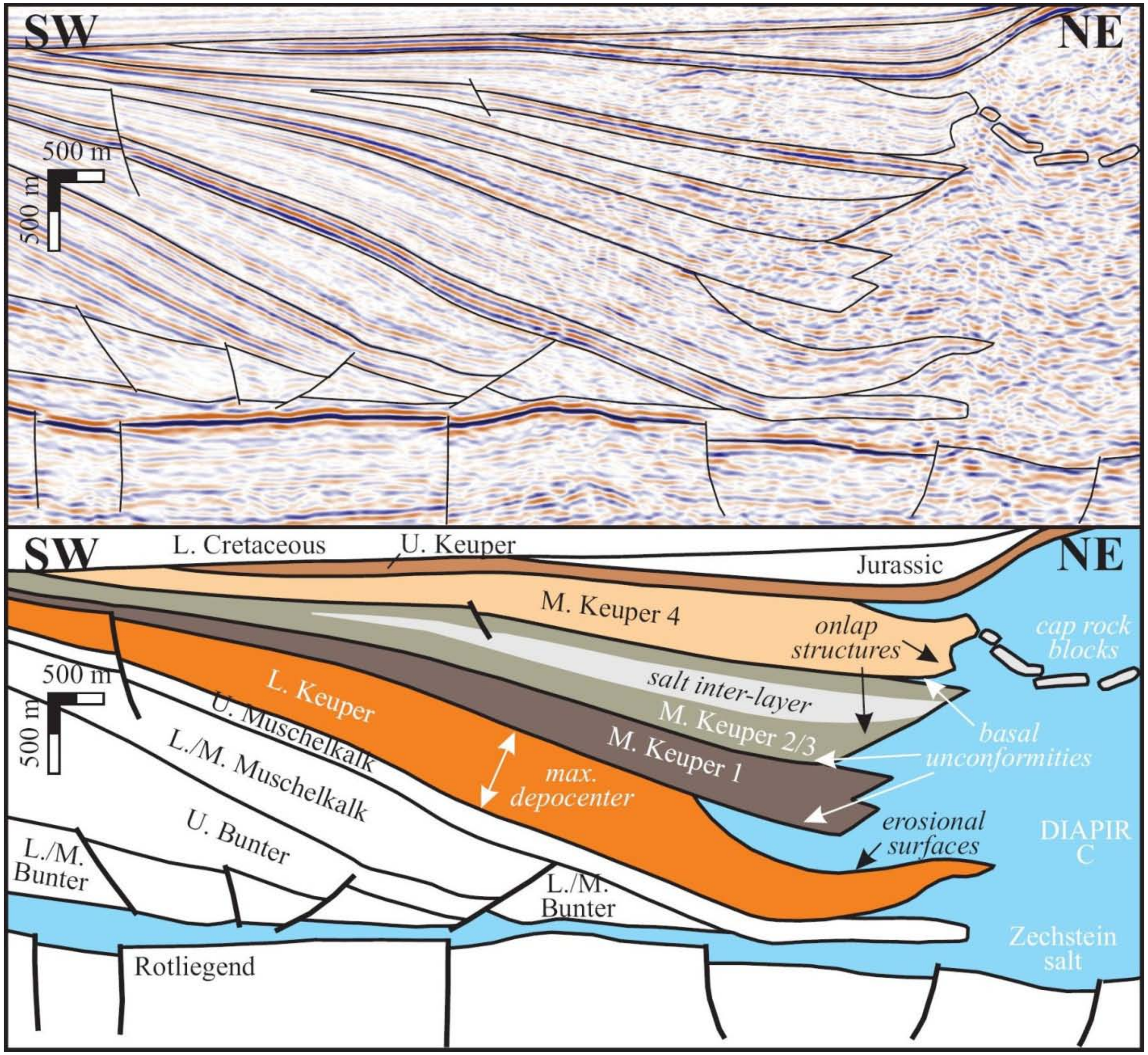
Selected 3D seismic sections with geological interpretation highlighting (in blue) the Permian and Triassic salt units in the CEB.

- The Mesozoic of the area has thick inter-layered salt sequences. Especially in the Late Triassic we observed up to 800-m-thick primary salt deposits (in the rim-synclines from seismic and borehole data). Their role to date has not been considered strongly for salt dynamics purposes.
- **The thickness of the bedded salt units corresponds well to the structural rim-syncline evolution of the diapirs**.
- We suggest that salt dissolution from the diapir and brine supply to the landscape enabled accumulation of high salt volumes in the rim-synclines.

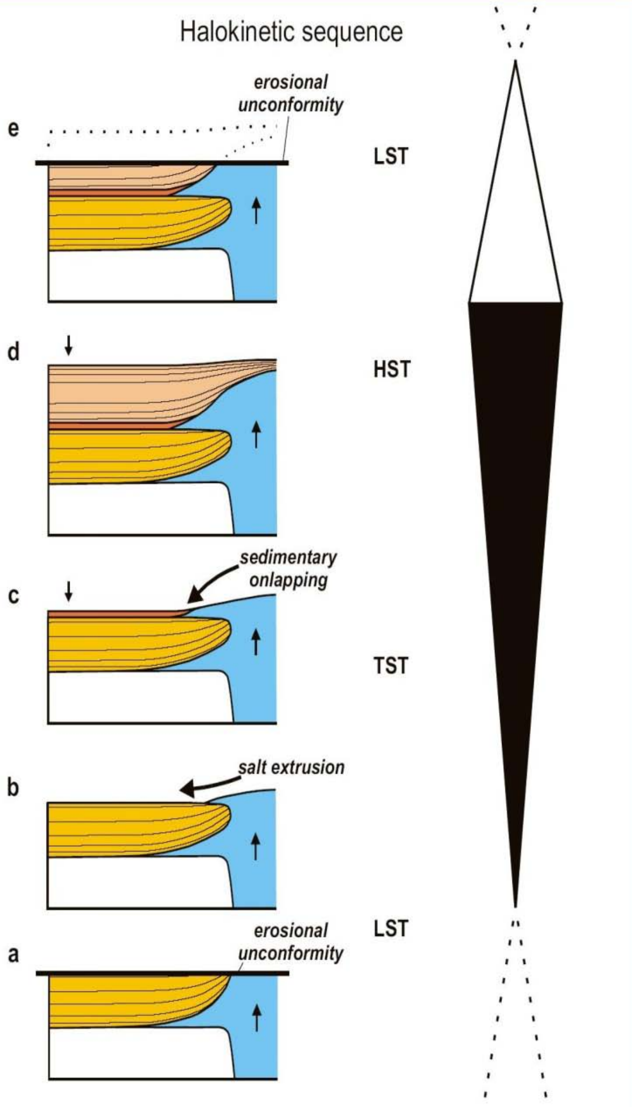
Tectono-sedimentary analysis of diapir flanks

Click to view Presenter's Notes

Sedimentation controls the plan form of passive diapirs



Kukla et al., 2008



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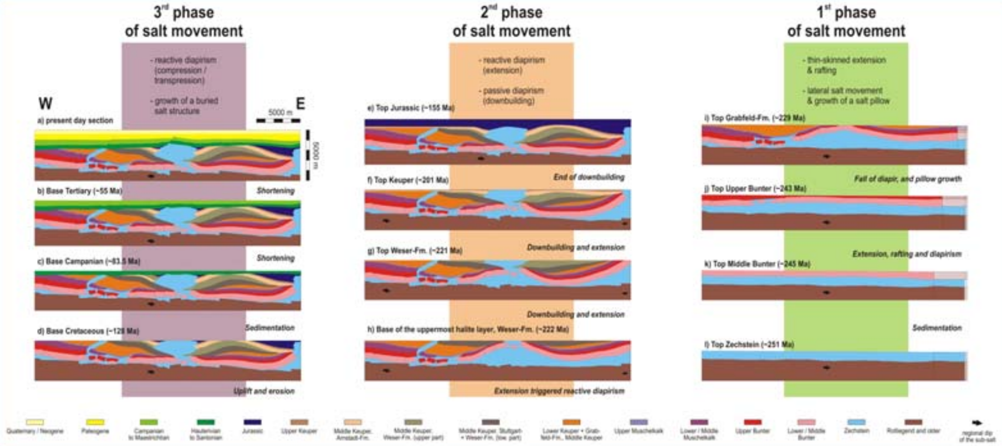
Presenter's Notes:

- Geological interpretation (lowermost) shows **four sedimentary wedges of Keuper age** and the salt flanges of a diapir. The wedges of Middle Keuper 1 and 2/3 show low-angle unconformities and onlaps on the narrowing diapir.
- During detailed tectono-sedimentary analysis at the SW flank of a salt diapir we place salt and sediment dynamics in a sequence-stratigraphic context interpreting the sediment/sediment interfaces not with a classical marine/nonmarine (Milankovitch-controlled) mechanism but with different trigger mechanisms, namely, tectonics and sediment supply.
- The **rate of salt rise versus sedimentation accumulation** controls the geometries.

Accordingly, the unconformities at the base of the sedimentary wedges represent **erosional-event sequence boundaries:**

- **Lowstand Systems Tracts**: erosional unconformities, salt dissolution or minor sedimentation and **salt extrusion of an expanding diapir**. The **salt flanges** were formed during constant salt rise and extrusion on the land surface with no sediment accumulation.
- Deposition during the **Transgressive Systems Tract** causes sedimentary onlapping on a retreating diapir.
- During the **Highstand System Tract** the diapir can be overstepped by sediment.

Retrodeformation study - summary



Kukla et al. 2008

Three-stage salt tectonic evolution:

Each phase of salt movement was initiated by regional tectonics

1. Early Triassic extension (NE-SW faulting) – rafting, initial salt diapirism (Middle Buntsandstein), differential sedimentation, lateral salt flow & pillow growth
2. Late Triassic extension (NNW-SSE faulting) – reactive diapirism, breakthrough, extrusion of salt to the surface, structurally autonomous downbuilding process
3. Beginning Cretaceous to Early Tertiary - compression & inversion tectonics, reactivation of salt movement and diapir shortening

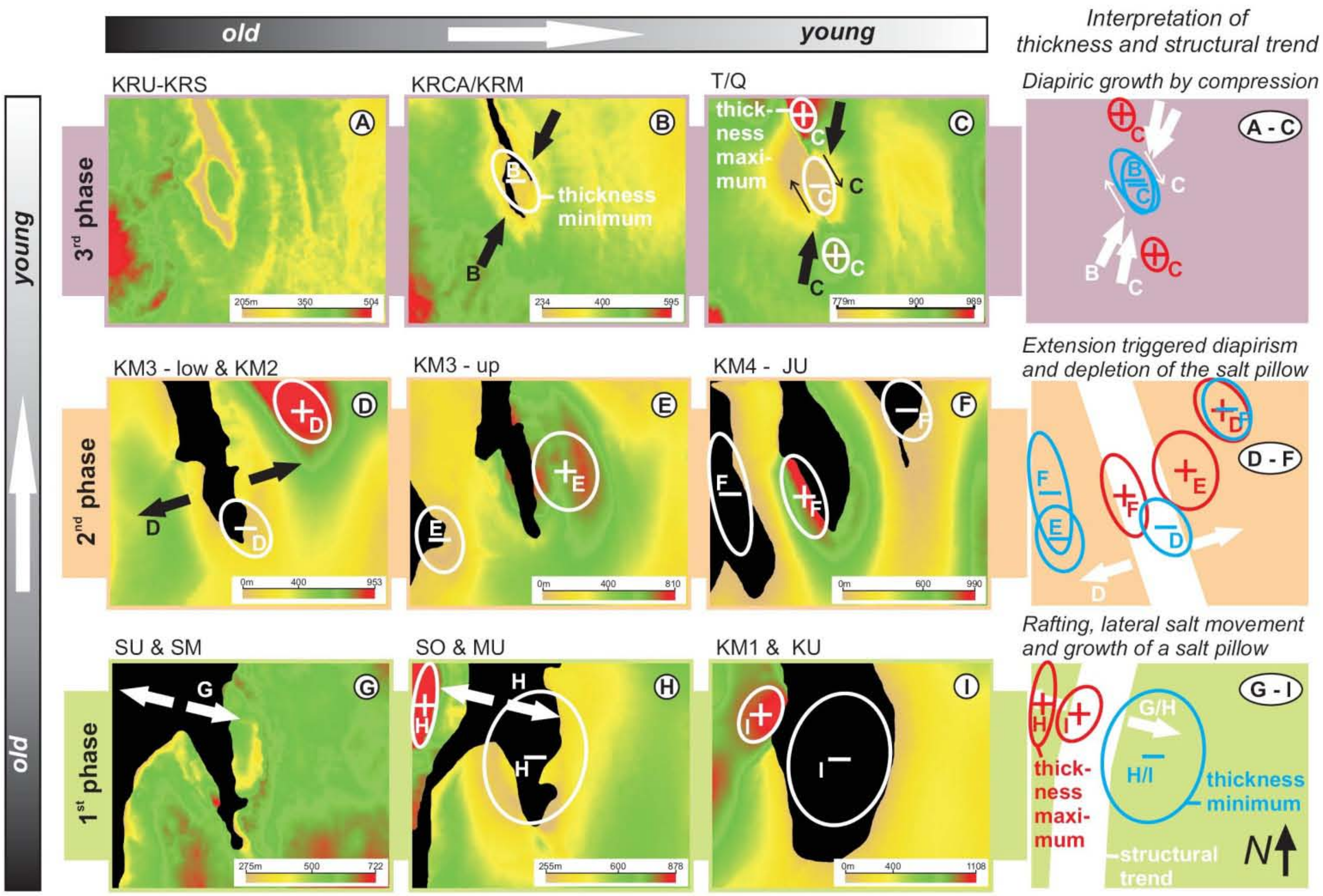
Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes: A next step to understand the dynamics of the system is to retrodeform sections--to unroll sequentially the structural evolution including strain rate quantification.

Modelling is, in principle, back in time, starting at the present section. To have a look at the sequence of events it is better to start sequentially from older to younger.

Geometry – Thickness analysis & structural trends

Click to view Presenter's Notes



- Regional compression and local transpression (B, C).

- Thickness minimum above the salt diapir and no clearly developed rim syncline (B, C).

- Extension (D) and a NW-SE structural trend.

- Depocentres migrate to the diapir and give an outline of the former salt pillow (D-F).

- Thickness minimum areas are located at the depo-centres of the previous phase (E, F).

- WNW-ESE extension and missing Lower Buntsandstein in the NW (G).

- The depocentre migrates to the east and a thickness minimum area evolved in the central part (H, I).

Kukla et al. 2008

1. Revision of tectono-sedimentary model applying modern salt tectonics concepts to this area
2. Distinguish several deformation phases and styles
3. Established a halokinetic stratigraphy
4. Identification of subsurface glacier on seismic
5. Revision of exploration concepts

⇒ Pressure / Temperature / Fluid conditions affecting salt basins

Presenter's Notes:

Maps of vertical thickness and regional stress (4th column), derived from interpretation and retrodeformation.
Approach confirms depocentre migration changes of structural trends through time and thus demonstrates the multistage evolution of the study area in the CEB.

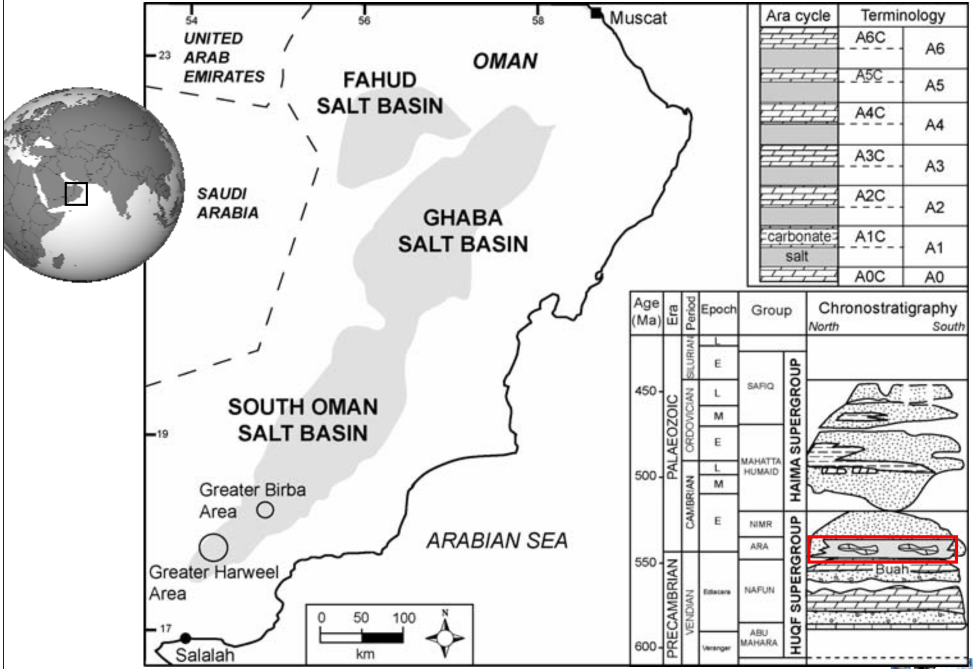
Red colors = thickness maximum.

Light brown colors = thickness minimum of the particular units.

Summary Permian Basin Study: Based on new 3D data we have been able to:

1. Revise the tectono-sedimentary model applying modern salt tectonics concepts to this area.
2. Distinguish several deformation phases and styles.
3. Develop a halokinetic stratigraphy.
4. Identify for the 1st time a subsurface glacier on seismic.
5. Changed exploration concepts.

Neoproterozoic salt basins in Oman



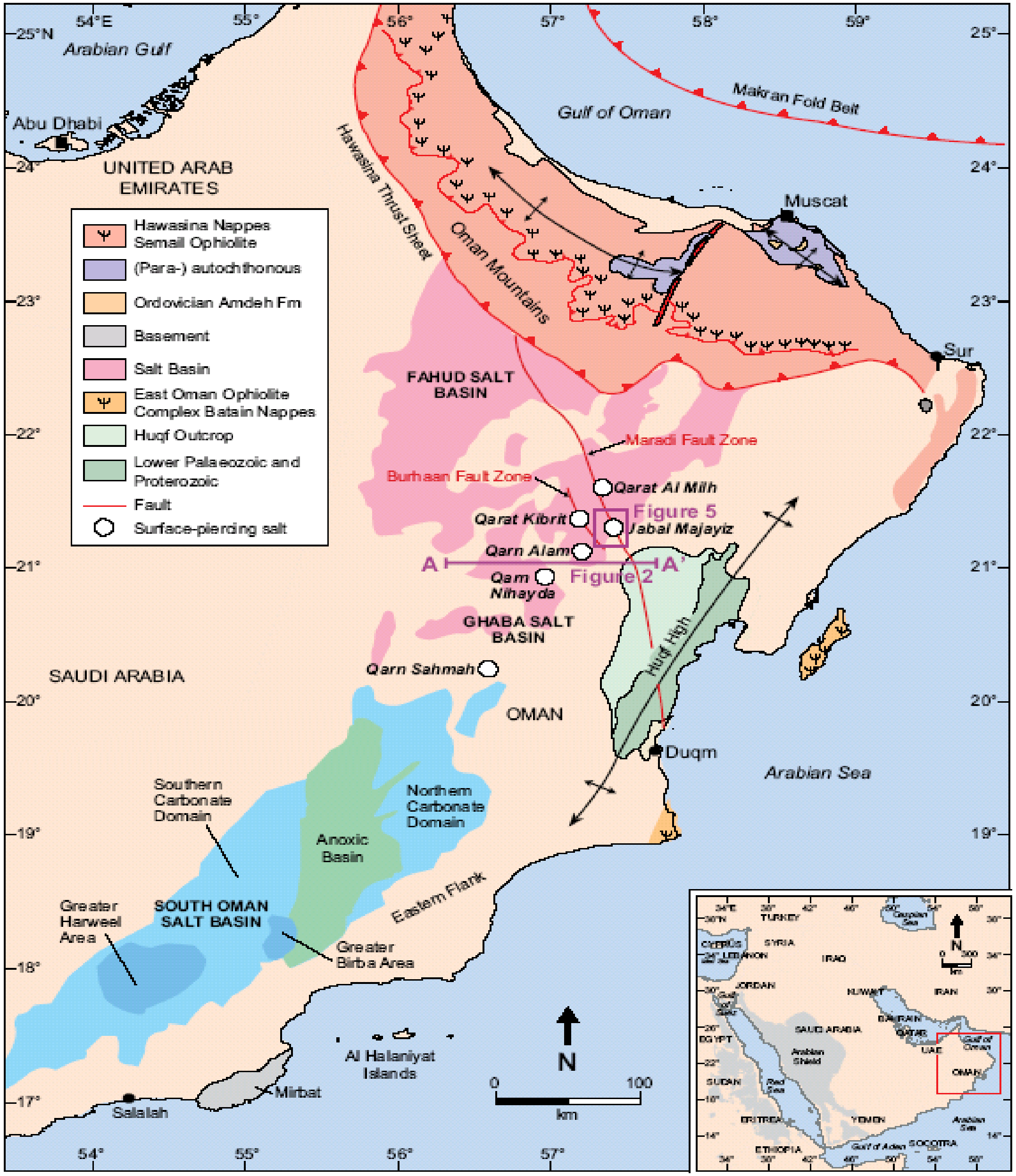
Modified after Peters et al. (2003), Amthor et al. (2005), Filbrandt et al. (2006)

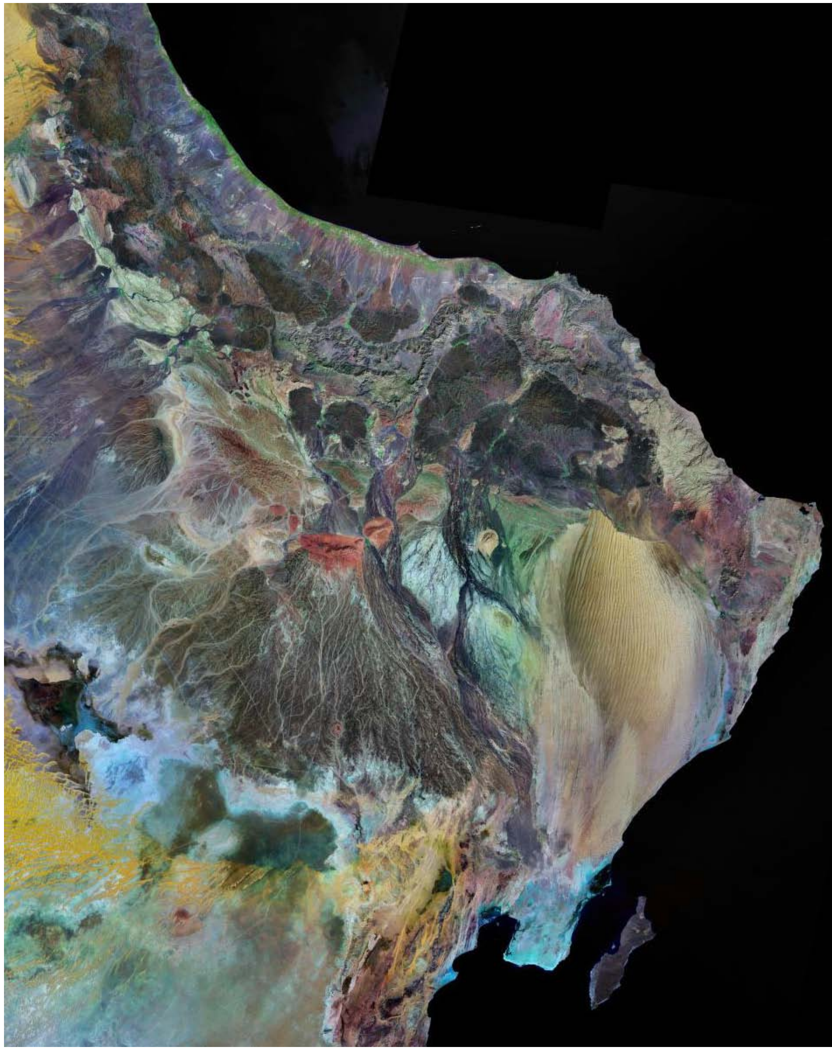
Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes: Southern Oman with 3 major salt basins which developed during the Late Proterozoic and which are known from elsewhere in the Middle East. Neoproterozoic assemblage of clastics, carbonates and salt sequences.

Neoproterozoic salt basins in Oman

Click to view Presenter's Notes





Reuning et al., GeoArabia, 2009

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

RWTH AACHEN UNIVERSITY

Presenter's Notes:

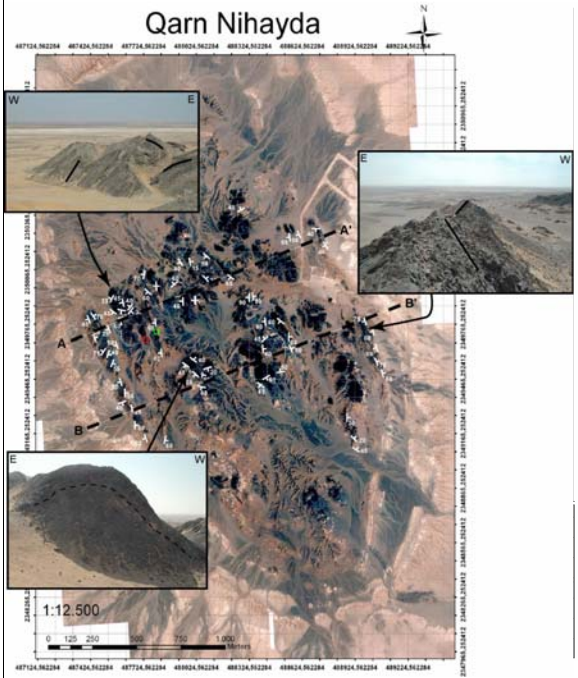
In order to cover some of the aspects just mentioned and leading to the following part of the article (presentation by Janos Urai) the the Neoproterozoic salt basins of Oman are considered.

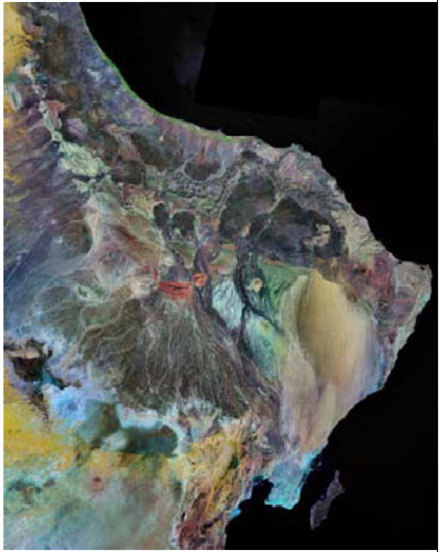
– There, a system which has much similarity with parts of the North Sea, but that will not be illustrated at this point in time.

Southern Oman with 3 major salt basins that developed during the Late Proterozoic and which are known from elsewhere in the Middle East. Neoproterozoic assemblage consists of clastics, carbonates and salt sequences. We study the surface diapirs and the ones buried and producing from 6 km depth.

We interested in this because of surface-piercing diapirs; these have brought to the surface an interesting mix of lithologies which have suffered severe tectonism (see Qarn Nihayda) –
In the next slide: black stained salt and bitumen.

Neoproterozoic salt basins in Oman





Reuning et al., *GeoArabia*, 2009

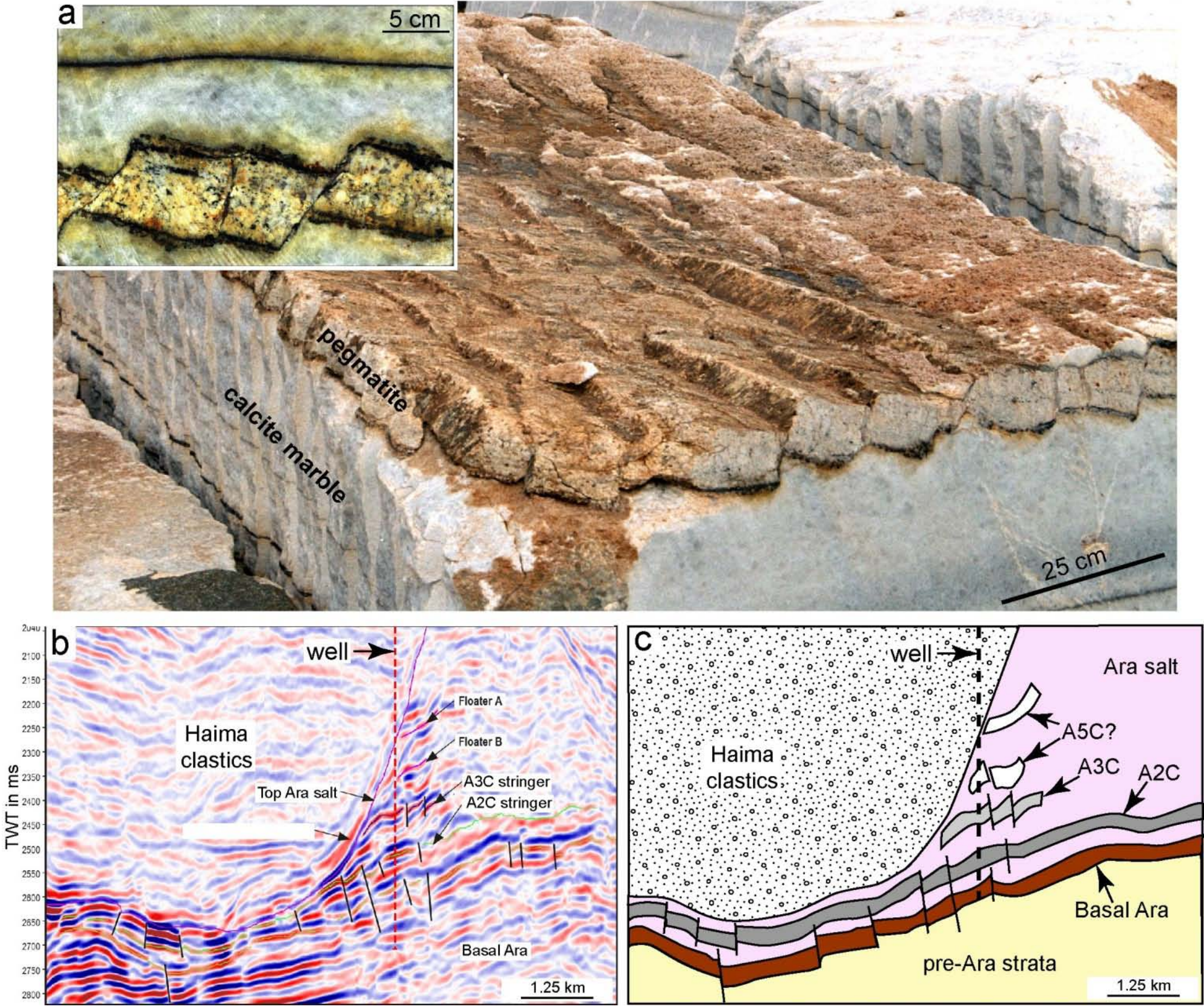
Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes: Black stained salt and bitumen.

Salt flow concepts

Click to view Presenter's Notes

- Boudinaged brittle carbonate/anhydrite rafts moving in salt
- Salt beds considered as <u>pressurized fluid</u> layers overlain by brittle sediment.



Schenk et al. 2007, American Journal of Science

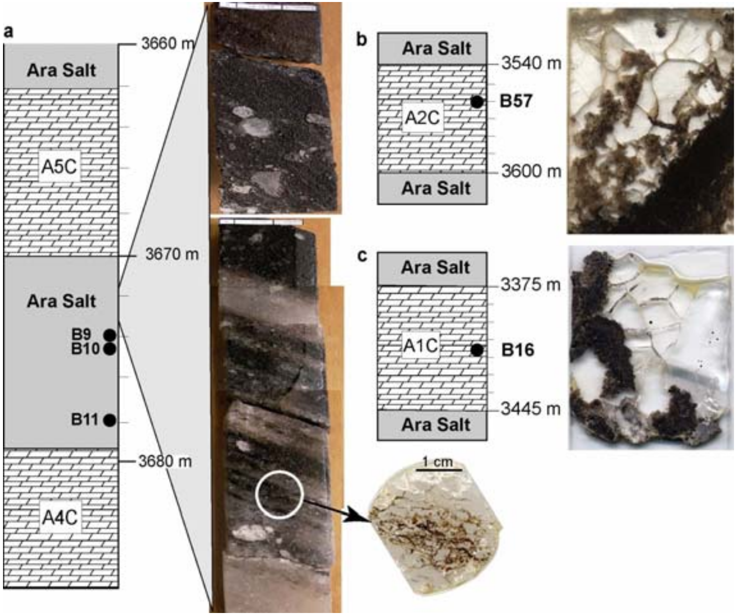
Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter’s Notes:

One aspect not noted to this point is the Pressure/Temperature/Fluid conditions which impact greatly the salt kinematics.
We have seen in the last decade, as well as during this conference) that salt-flow concepts have been changing.
Displayed in the lower images are boudinaged brittle carbonate/anhydrite rafts (called stringers in Oman) moving in salt and developed from anisotropic strain effects during downbuilding/differential loading.

This may be compared with brittle pegmatite floaters with tilted joint blocks overlying soft marble (example from Janos Urai from Greece)

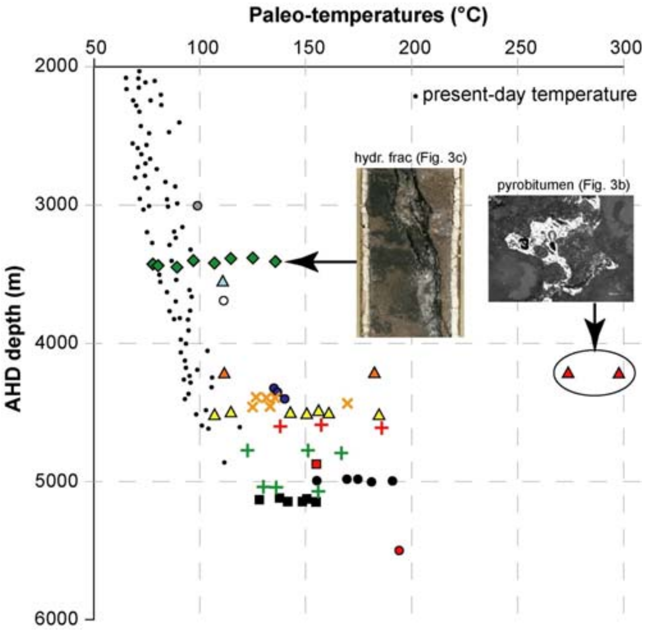
Black salt and bitumen



Schoenherr et al. 2007, AAPG Bulletin 92

Presenter's Notes: Observations from drilling: black salt.
Salt might not be the excellent seal we anticipate it to be: salt can actually dilate, as seen in the Ara Salt Basin where sections of more than 10-m thickness may contain hydrocarbons and bitumen.

Paleotemperatures

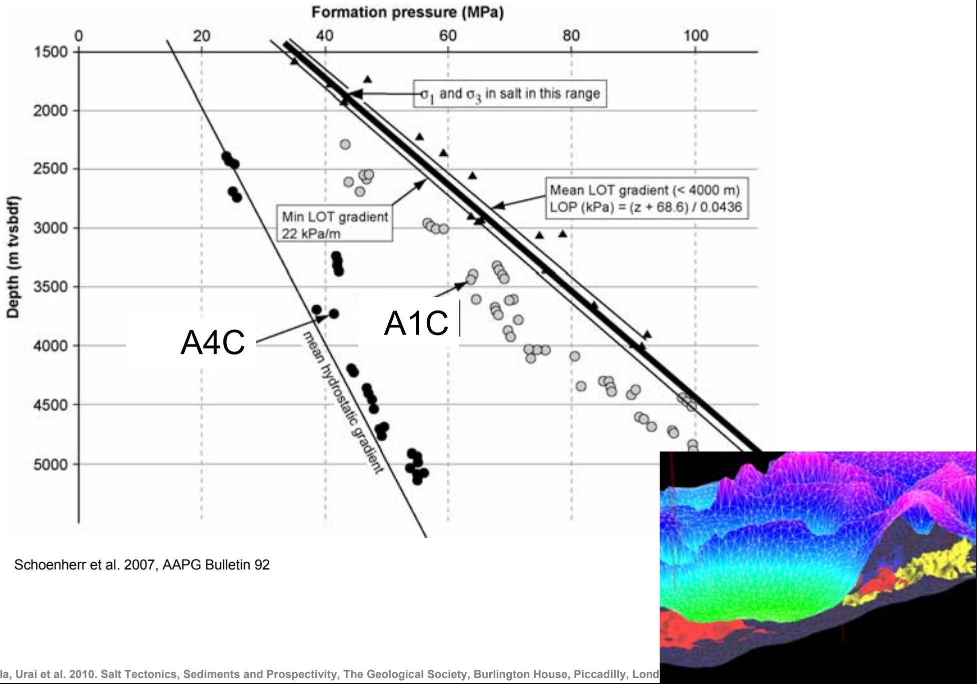


Schoenherr et al. 2007, Org. Geochemistry 38

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes: Paleotemperature analysis on this bitumen show a widespread (and support a) high-temperature hydrothermal event which must have contributed to the pressures observed.

Overpressures in the SOSB



Schoenherr et al. 2007, AAPG Bulletin 92

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, Lond

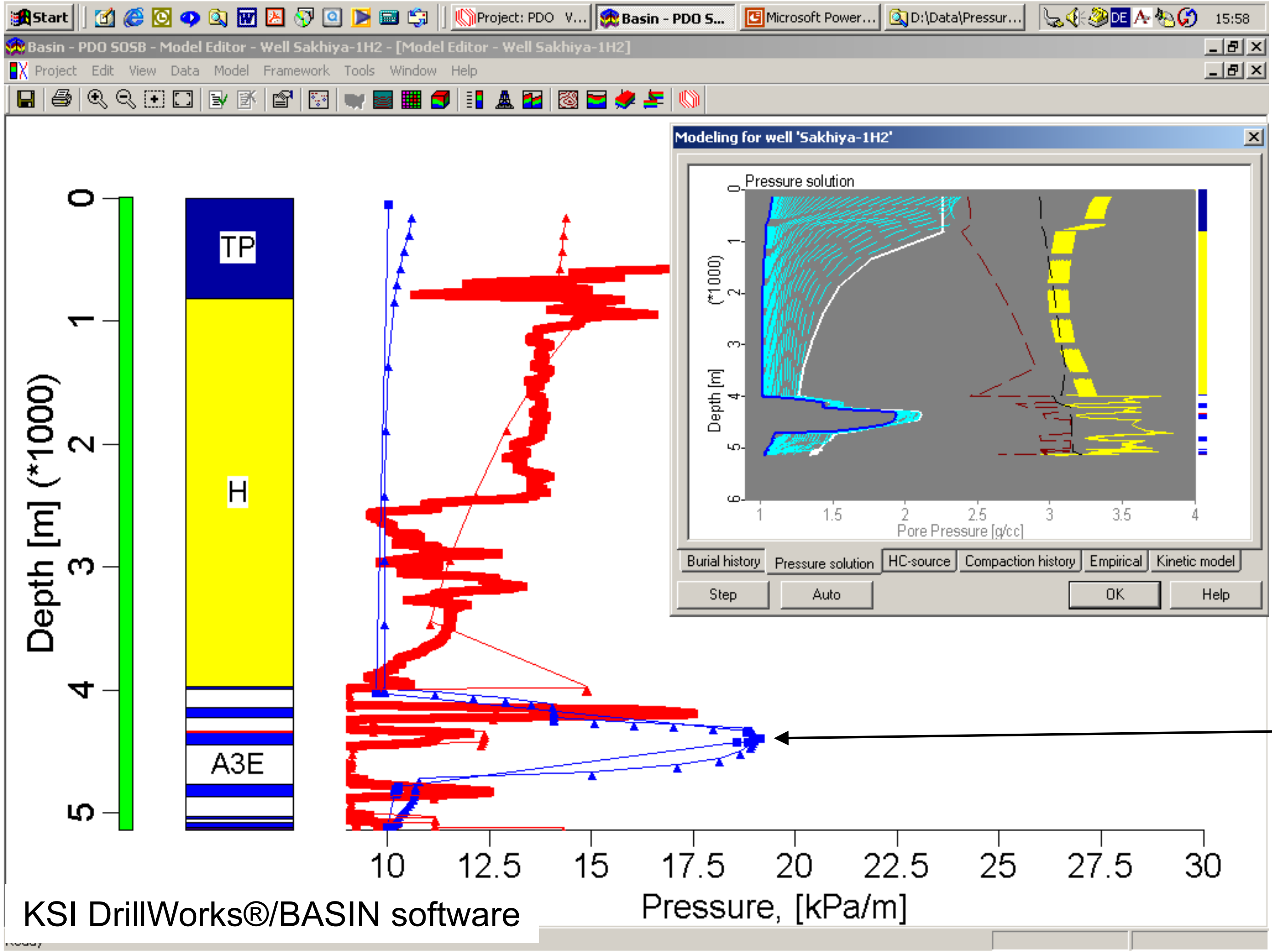
***Presenter's Notes:* We are interested in this basin because of an interesting overpressure distribution!**

In the SOSB, the Ara carbonate stringer reservoirs show two pressure populations: one at hydrostatic pressures (black circles) and one at near lithostatic pressures (grey circles).

Pressure modelling

Click to view Presenter's Notes

- **Best-fit iteration model after multiple inversion runs using a kerogen source term**



KSI DrillWorks®/BASIN software

- **Pressures** & **porosities** fit well data

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes:

Pressure modelling in 1D and 3D confirms early evolution of elevated fluid pressures in the host lithologies and a significant contribution by kerogen maturation.

Model runs of the presently hydropressured wells led in all cases to the development of overpressures.

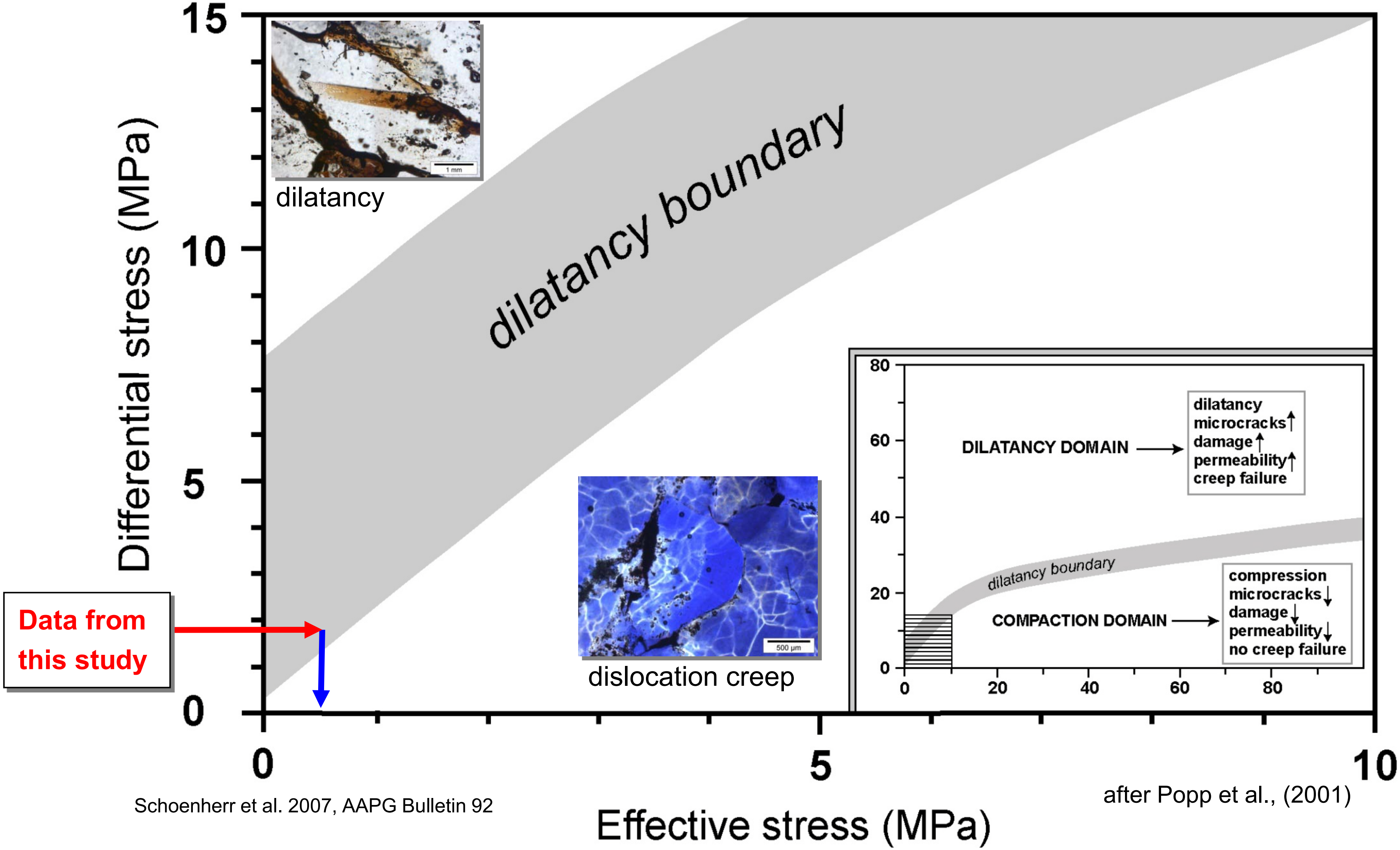
KSI Info (2005) on calculation of kerogen source term:

Currently, this term is calculated in a fairly simplistic way. There is a default temperature vs. generation rate relationship for three fractions: Oil, Gas and Cracked Gas. You can see this on the model Editor if you click on the Kinetic Model tab (extreme right). The amount that is subjected to this calculation is varied by changing the parameters for any specific unit. This is in the calibration step.

In this year's programming, we are adding in the code the ability to vary the kerogen by type, HI, and TOC.

Seal Integrity – halite dilatancy

Click to view Presenter's Notes



Schoenherr et al. 2007, AAPG Bulletin 92

after Popp et al., (2001)

Dilatancy is only possible at near-zero effective stress - i.e., fluid pressure of brine in the Ara Salt must be lithostatic

Presenter’s Notes:

Diagram showing the dilatancy boundary for halite in the differential stress vs effective stress space, derived from laboratory experiments by Popp et al. (in attempts to explain the pressure and hydrocarbon distribution and the sealing capacity of the rock salt).

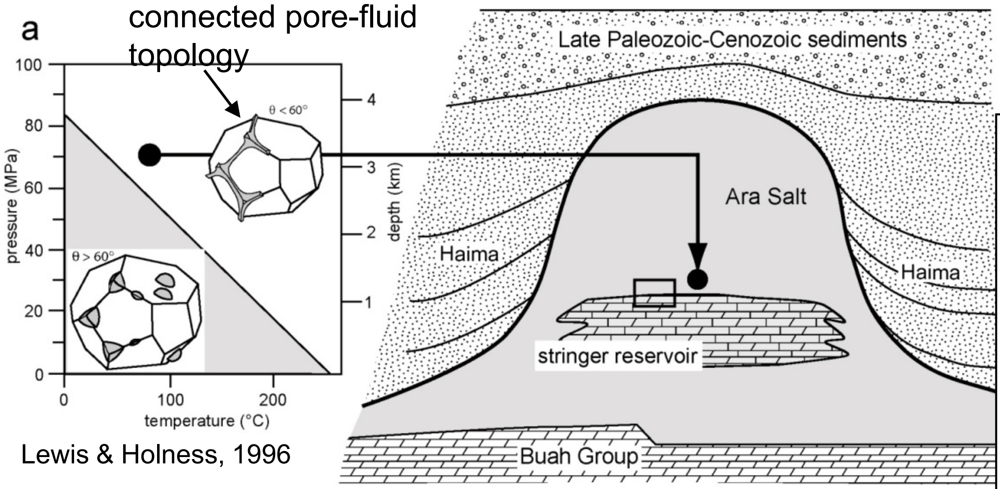
Above this boundary salt behaves dilatant, whilst below the boundary dilatancy and hence the formation of permeability is suppressed by compaction.

<u>Lowermost right:</u> **Paleo-stress analysis of the Ara Salt using subgrain size piezometry indicates maximum past differential stresses of less than 2 Mpa (see arrows). Under such low differential stress conditions dilatancy only occurs at near zero effective stresses, i.e., at fluid pressures close to sigma 3.**

Here, this argumentation is only valid for single phase flow of brine in salt, but as we have seen from the microstructures, there is also solid bitumen, which “used to be” oil.

Leakage conditions of rock salt in the SOSB

Click to view Presenter's Notes



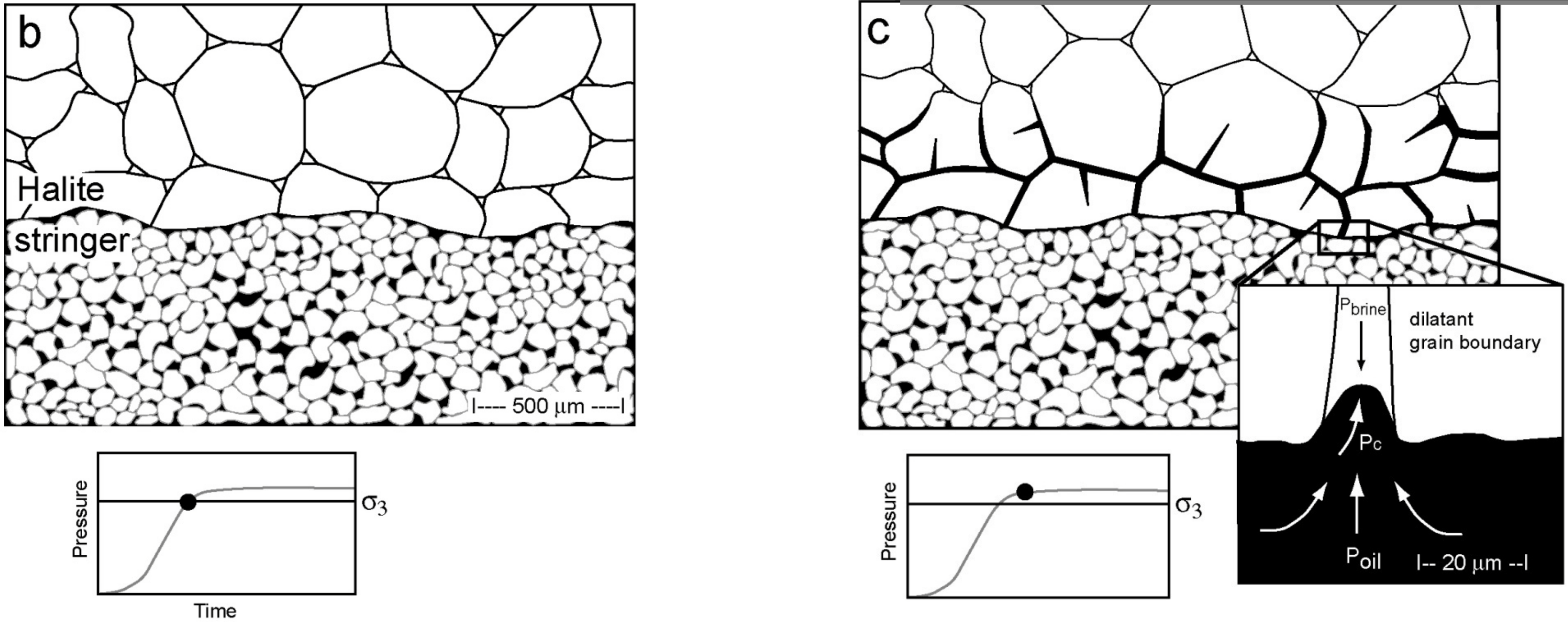
Lewis & Holness, 1996

Schoenherr et al. 2007, AAPG Bulletin 92

$P_{brine} \approx \sigma_3$

$P_{oil} > \sigma_3$

if $P_{oil} + P_{capillary} \rightarrow$ Salt dilates!



Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes:

Leaking conditions of rock salt - Diffuse dilatancy.

General: the microstructure of Ara salt shows clear evidence for dilation by diffuse grain boundary microcracking and intragranular microcracking.

a) According to the model of Lewis & Holness, (1996), we must assume that the Ara Salt originally had a connected pore-fluid topology. **SOSB depths, temperatures** (solid bitumen reflectance) and **dihedral angles match** that model (see our PT data in black dot).

b) No leakage occurs as long as the oil pressure in the stringer (black dot) equals the fluid pressure of the salt, which is at sigma 3.

c) If the oil pressure slightly exceeds the fluid pressure in the salt, the oil displaces the brine by the capillary entry pressure (Pc). Then, the halite grain boundaries start to open, causing the formation of a diffuse dilatancy. This condition can be described by P_{brine} in salt = σ_3 and $P_{oil} = \sigma_3 + Pc$. The sealing capacity of halite in the deep subsurface is exceeded, if this condition is met. Assuming a pore throat radius of 0.05 μm, then the Pc of rock salt is 0.1 MPa. **At this pressure, oil will displace the brine in the triple junction tubes and in grain-boundary inclusions, which in turn dilates the halite grain boundaries, leading to diffuse dilation of the halite grain fabric.**

When oil pressure equals the brine pressure again, the sealing capacity is restored and salt will seal again.

Conclusions

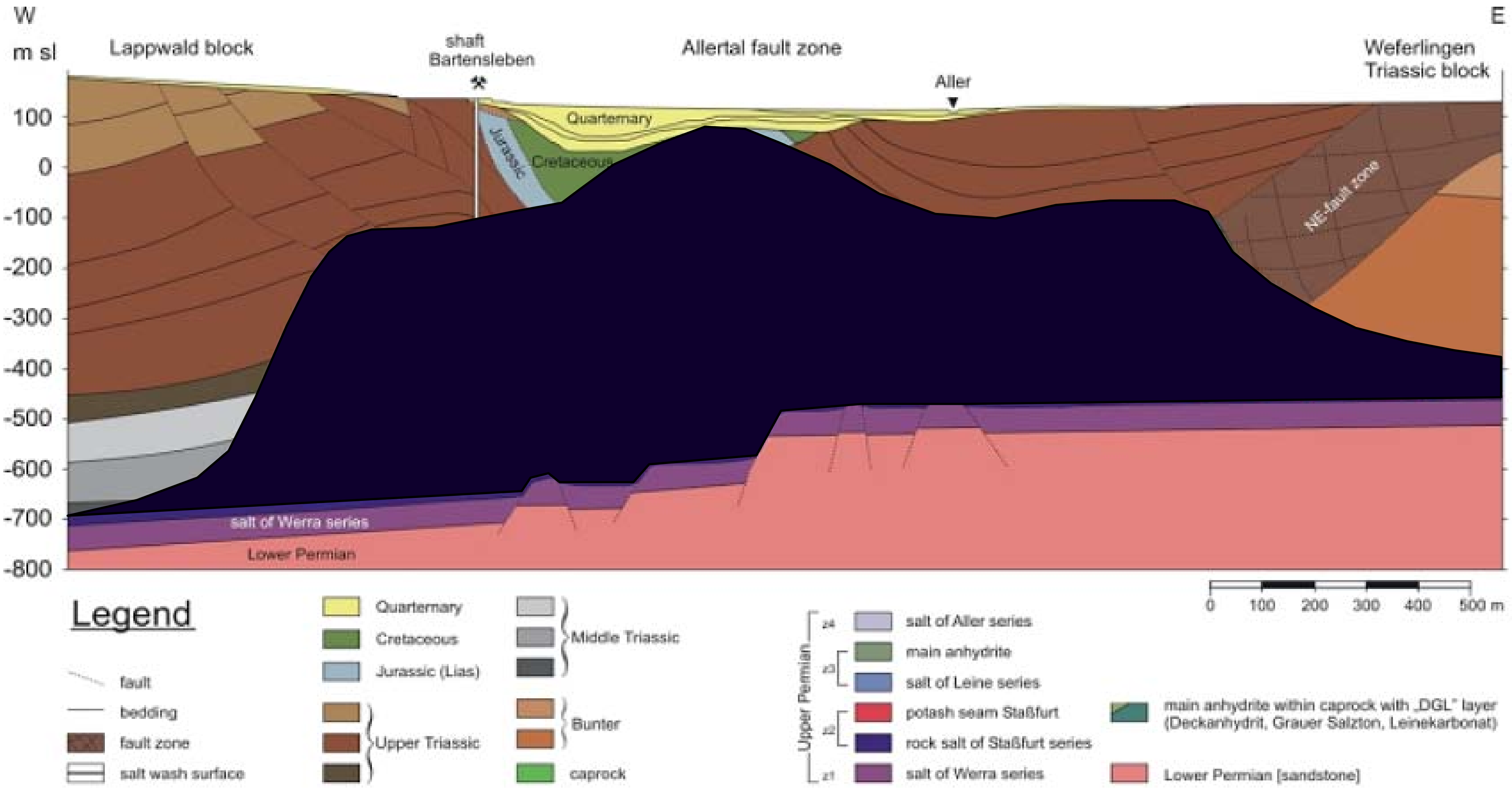
(NASA, MrSID Image Server, see also Jackson et al. 1990)

- Integrated approach of linking seismic techniques with structural restoration techniques, sedimentary sequence analysis and geomechanical analysis unravels a complex, multiphase salt tectonic evolution in the course of changing stress fields in ancient evaporite basins.
- Salt deforms as a viscous fluid and is driven by differential fluid pressure.
- Diffuse dilatancy is considered a major mechanism for fluid flow and loss of sealing capacity in major evaporite basins and generally in the lower crust.

Janos Urai, Peter Kukla, Heijn van Gent, Steffen Abe, Shiyuan Li, Guillaume Desbois, Johannes Schoenherr, Zsolt Schléder, Lars Reuning, Stephan Becker, Martin de Keijzer

PART II: INTERNAL DYNAMICS OF SALT STRUCTURES

Internal structure of salt bodies - who cares?



Salt topseal strength

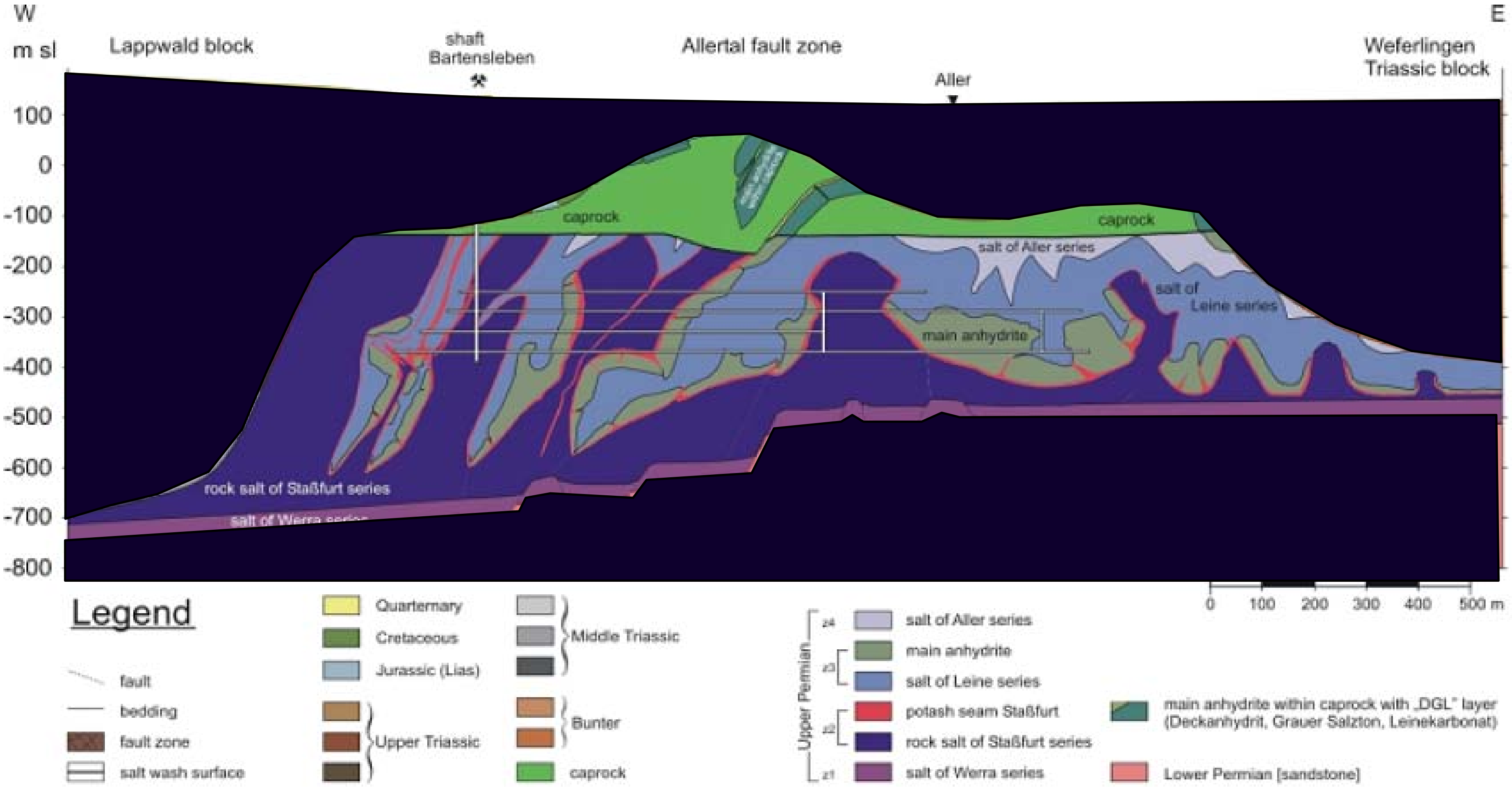
Drilling problems

Storage caverns, salt mining

Morsleben salt dome (Bundesanstalt für Strahlenschutz)

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Internal structure of salt bodies - who cares?

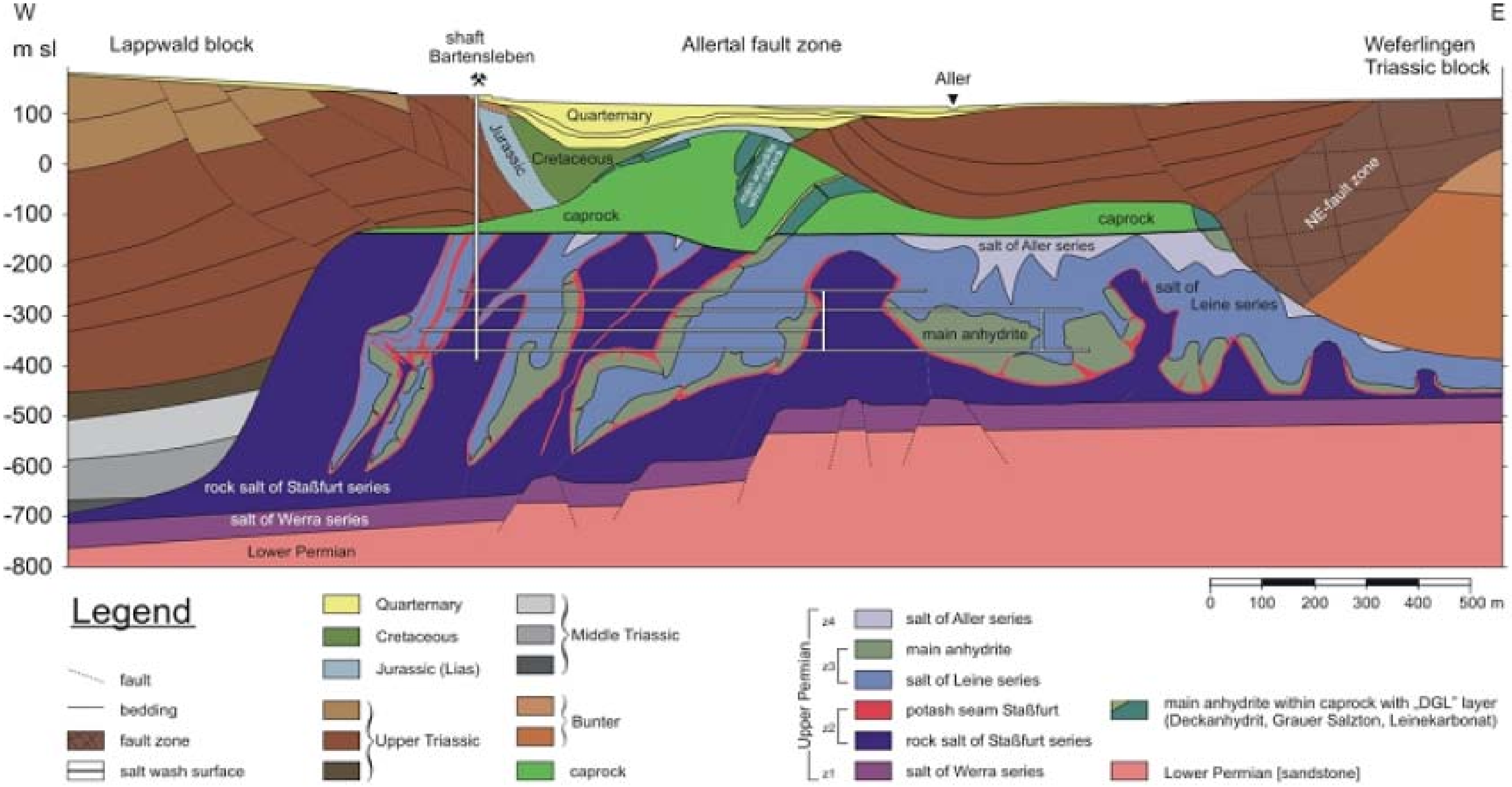


Morsleben salt dome (Bundesanstalt für Strahlenschutz)

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Internal structure of salt bodies - who cares?

Topseal strength, Drilling problems, Storage caverns, Salt mining

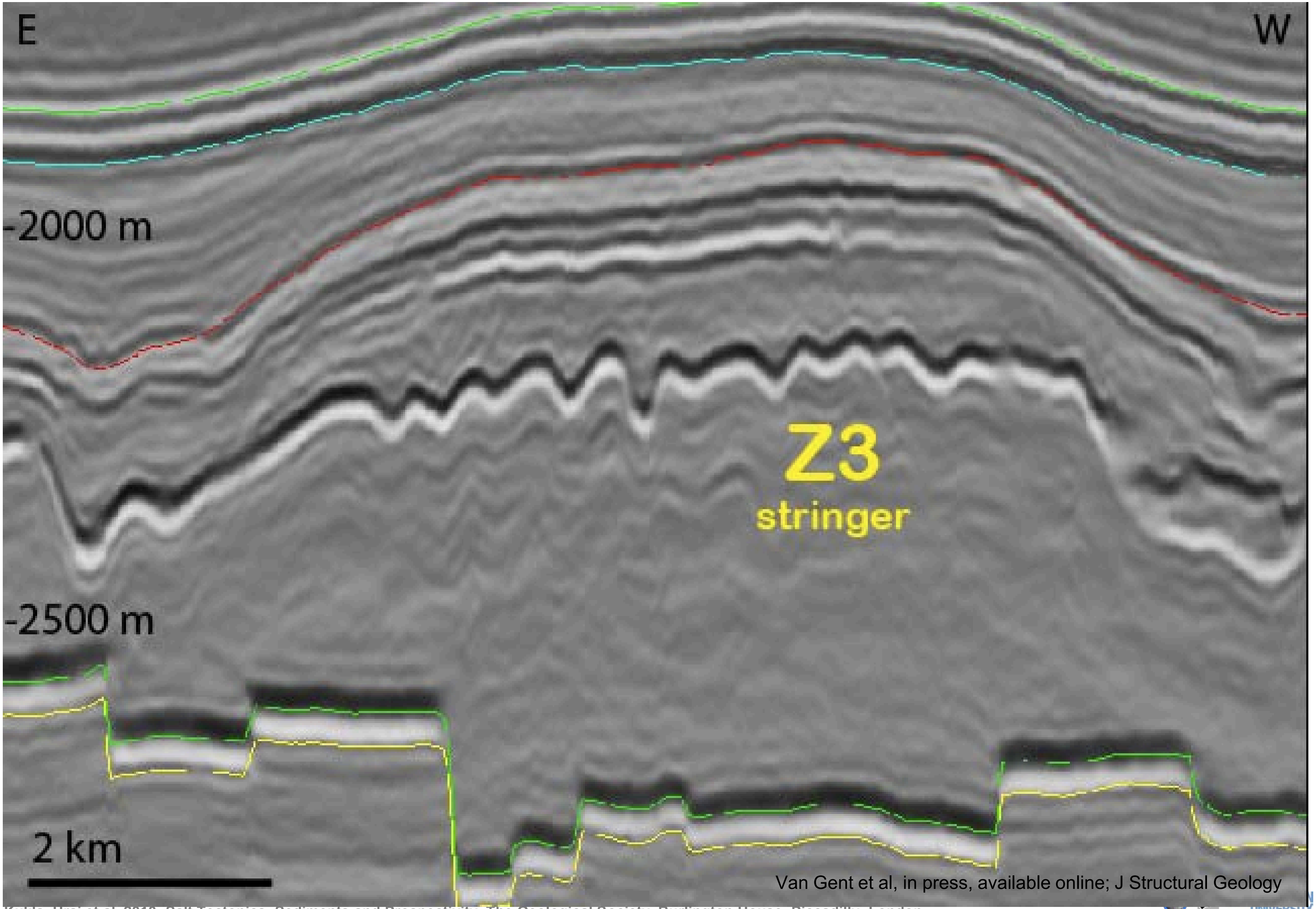


Prediction of internal structure is very difficult

Morsleben salt dome (Bundesanstalt für Strahlenschutz)

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

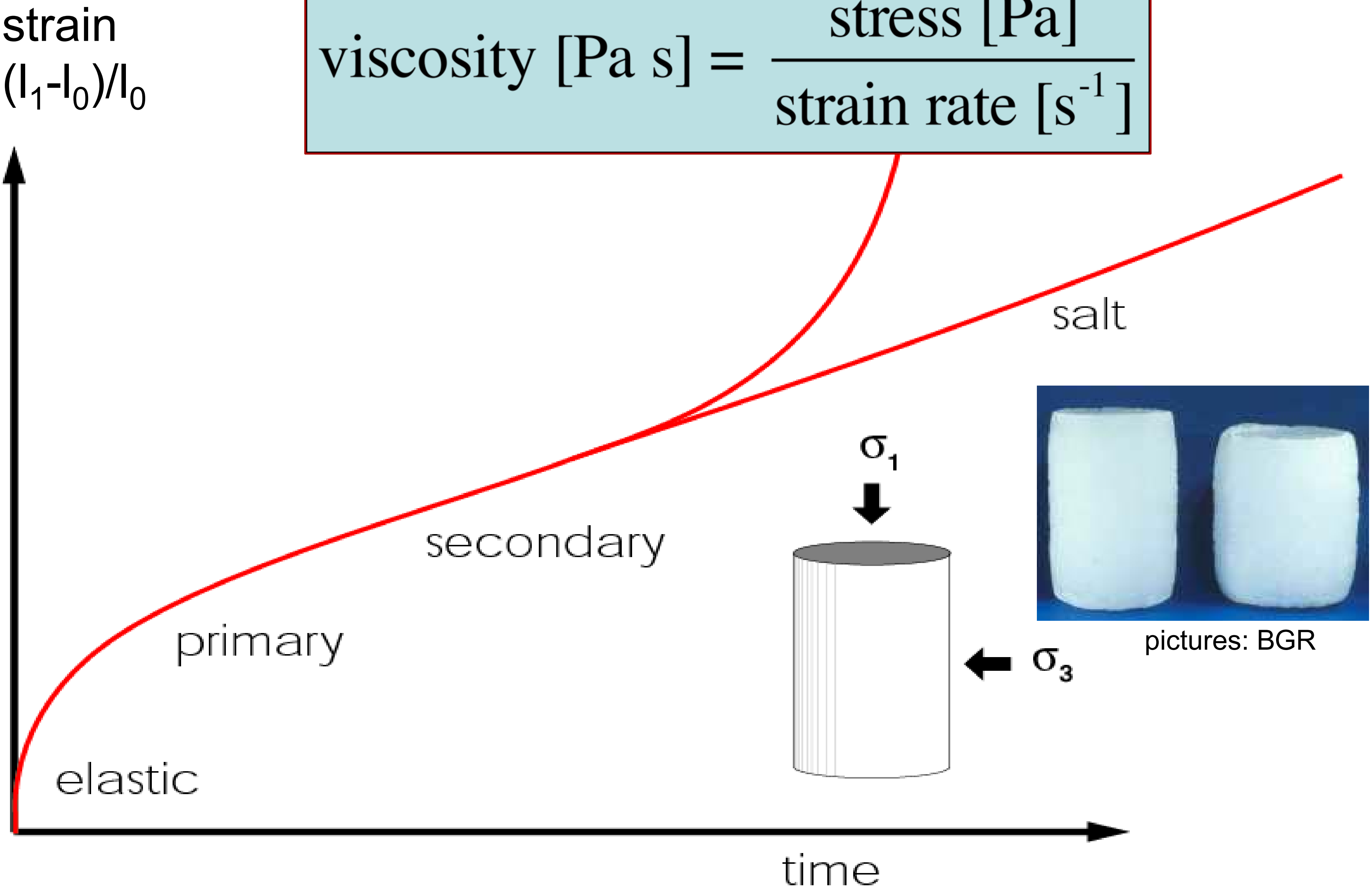
Z3 stringer folds, Groningen area - Heijn van Gent 2009



Van Gent et al, in press, available online; J Structural Geology

Ductile deformation of salt - constant stress

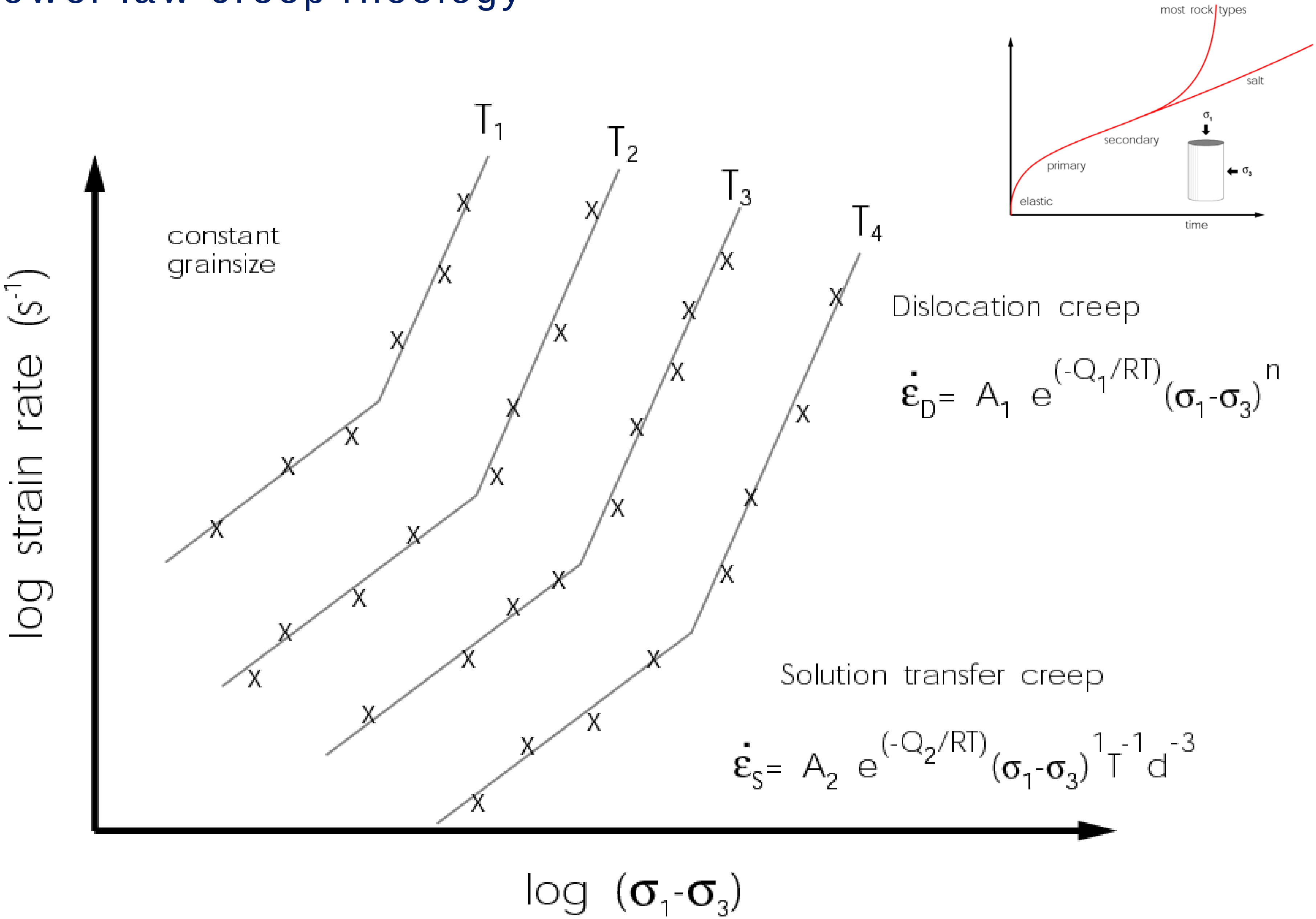
$$\text{viscosity [Pa s]} = \frac{\text{stress [Pa]}}{\text{strain rate [s}^{-1}\text{]}}$$



pictures: BGR

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Power law creep rheology



Dislocation creep

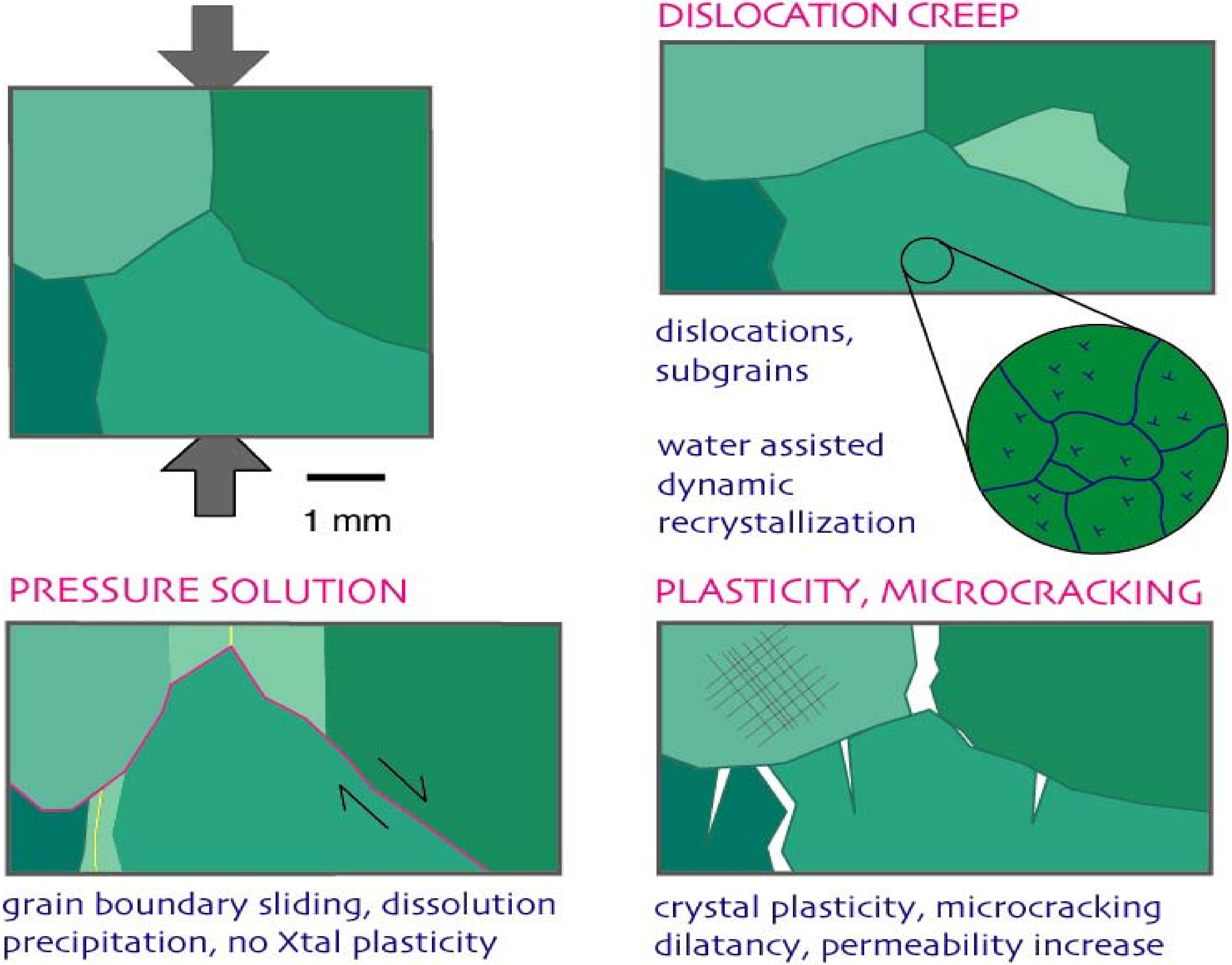
$$\dot{\varepsilon}_D = A_1 \, e^{(-Q_1/RT)} (\sigma_1-\sigma_3)^n$$

Solution transfer creep

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

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Rock salt deformation mechanisms



DISLOCATION CREEP

dislocations,
subgrains

water assisted
dynamic
recrystallization

PRESSURE SOLUTION

grain boundary sliding, dissolution
precipitation, no Xtal plasticity

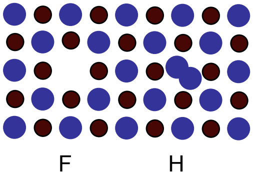
PLASTICITY, MICROCRACKING

crystal plasticity, microcracking
dilatancy, permeability increase

Urai et al. 2008, Springer

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

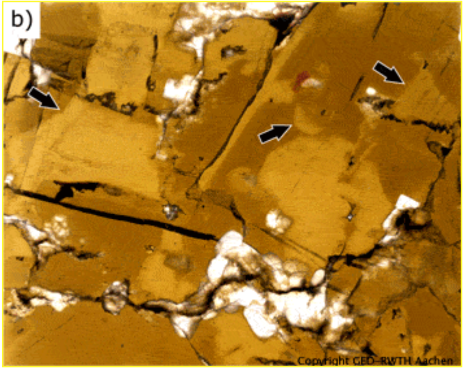
Gamma - Irradiation

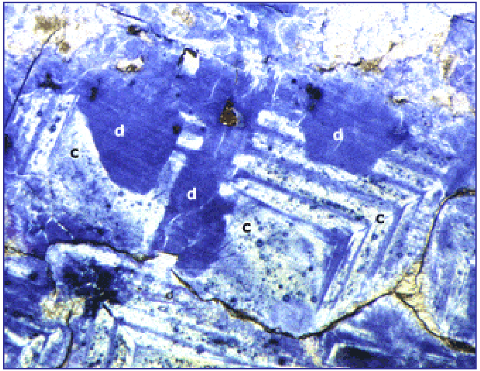


35 ºC - dose rate 1 - 3 kGy/h
total dose about 1.5 MGy

100 ºC - dose rate 4 - 6 kGy/h
total dose about 4 MGy

Schleder and Urai (2005); Int. J. Earth Sciences

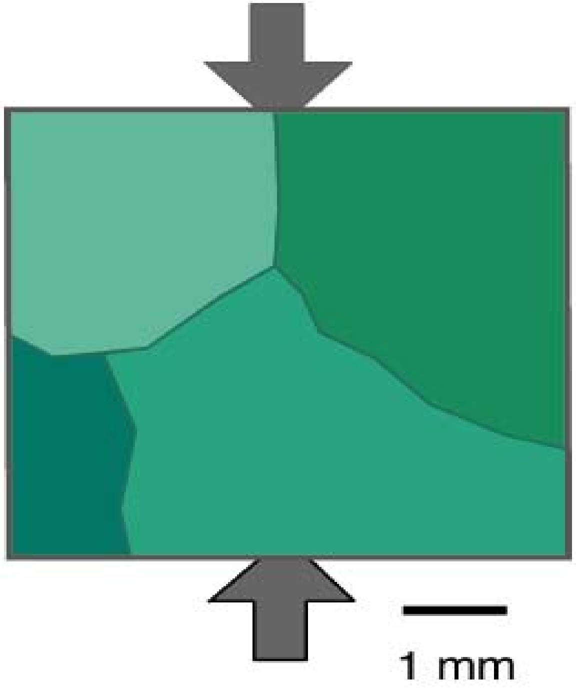




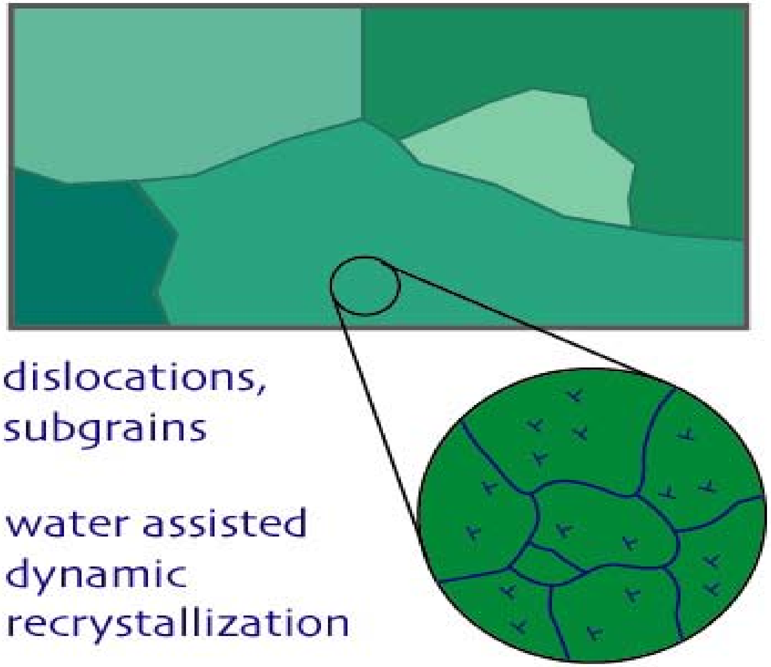
Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Presenter's Notes: **Gray** (Gy)A unit of **absorbed dose** of ionizing radiation. The dose is 1 Gray when the density of the total energy absorbed, in any medium from any type of ionizing radiation, is 1 Joule/kg. The dose can be expected to vary from point to point within the irradiated object. **rad**A unit of **absorbed dose** of ionizing radiation. 1 rad = 10 milligray.

Rock salt deformation mechanisms



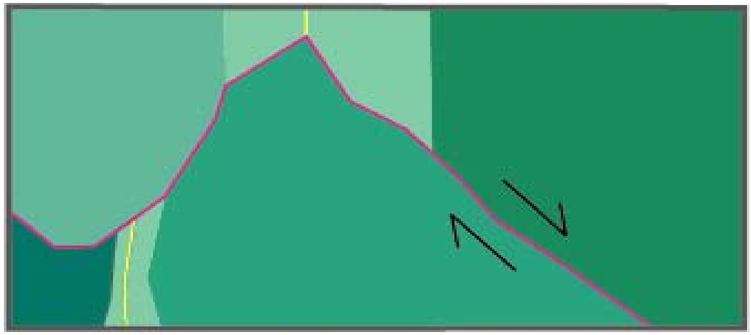
DISLOCATION CREEP



dislocations,
subgrains

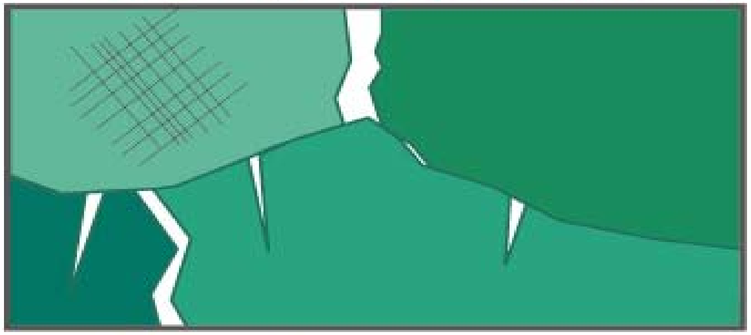
water assisted
dynamic
recrystallization

PRESSURE SOLUTION



grain boundary sliding, dissolution
precipitation, no Xtal plasticity

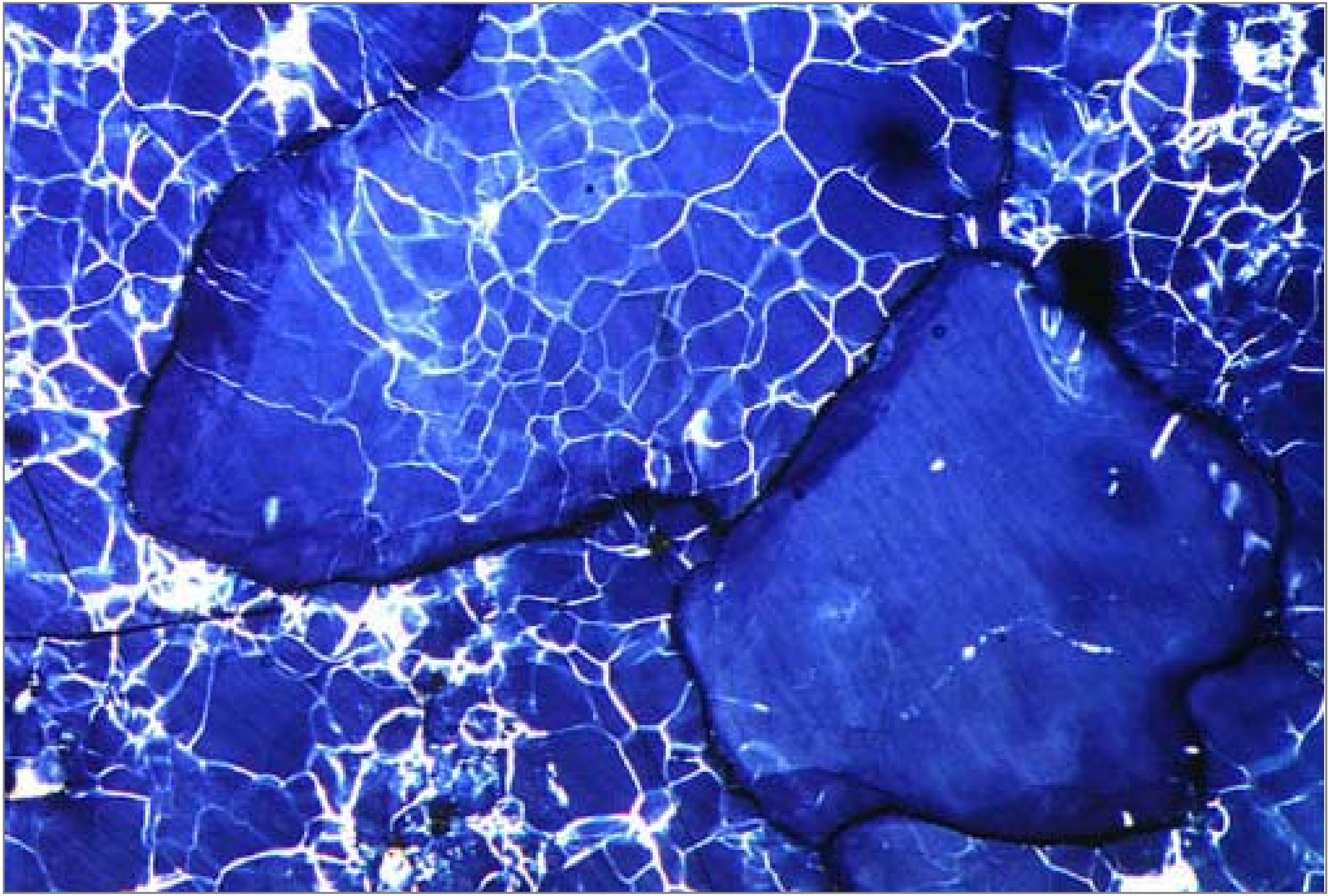
PLASTICITY, MICROCRACKING



crystal plasticity, microcracking
dilatancy, permeability increase

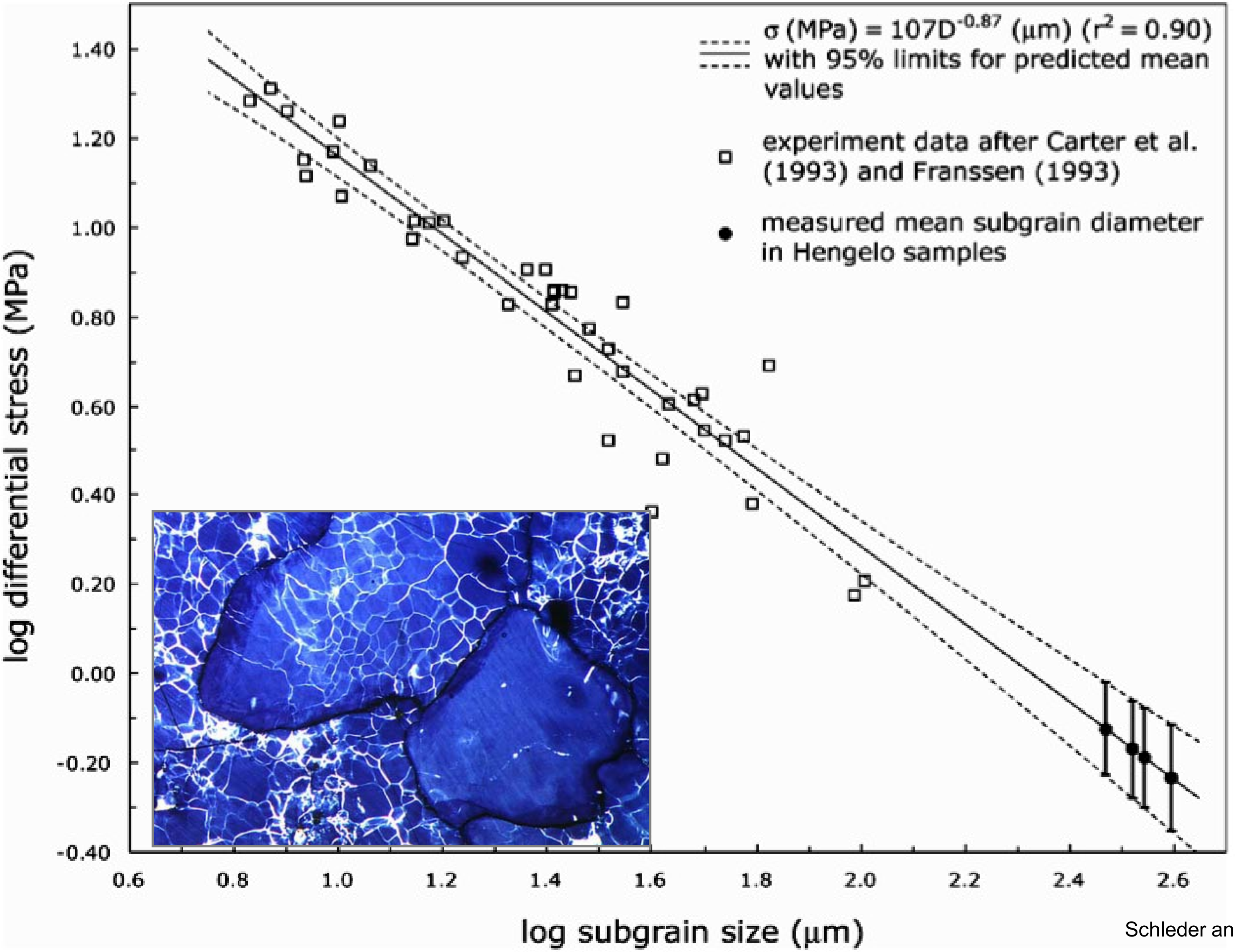
Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Subgrains in naturally deformed rock salt



Hengelo rock salt, Gamma- irradiated, transmited light Schleder and Urai (2005); Int. J. Earth Sciences

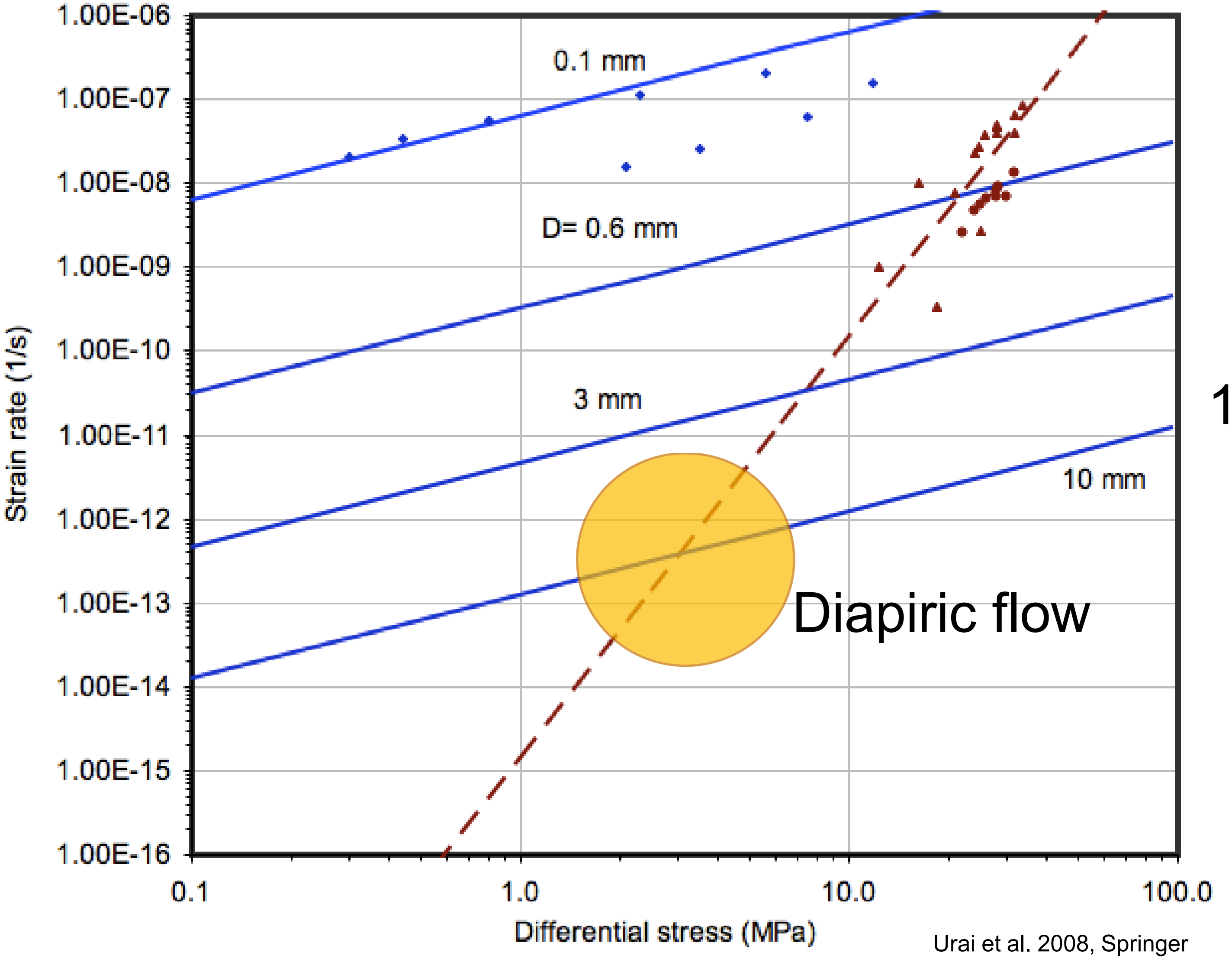
Subgrain size piezometry



Schleder and Urai (2005)

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Rock salt diapiric flow : dislocation creep and pressure solution



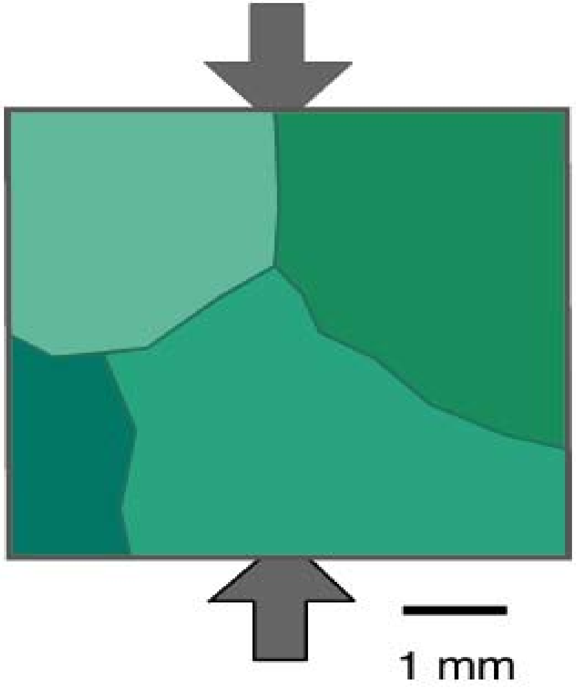
Urai et al. 2008, Springer

10^{19} Pa s

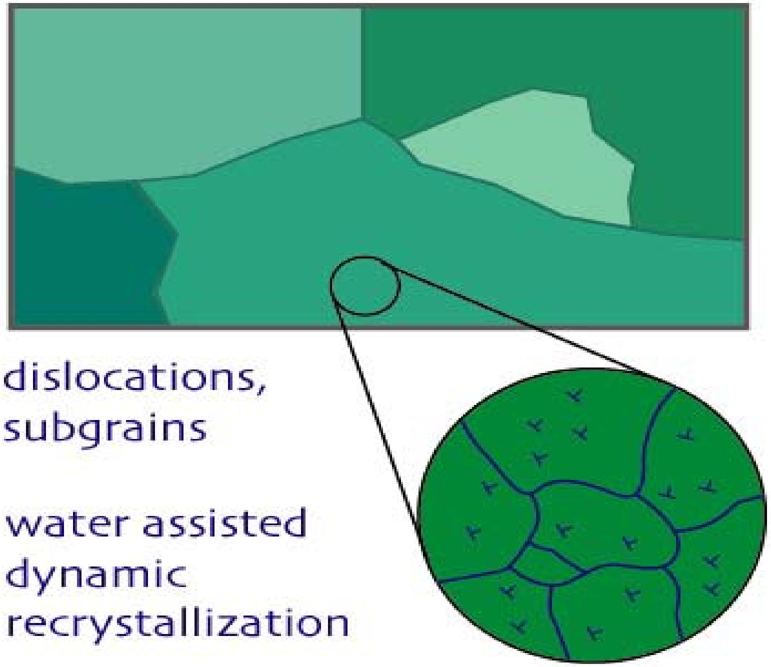
In agreement with rock mechanics tests & microsctructure & movement rates of diapirs (Mukherjee et al., 2010)

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Rock salt deformation mechanisms



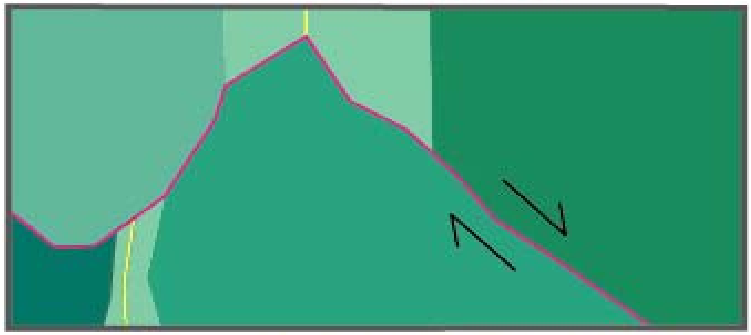
DISLOCATION CREEP



dislocations,
subgrains

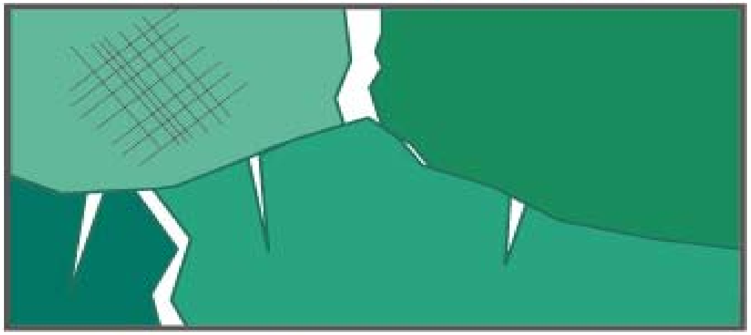
water assisted
dynamic
recrystallization

PRESSURE SOLUTION



grain boundary sliding, dissolution
precipitation, no Xtal plasticity

PLASTICITY, MICROCRACKING



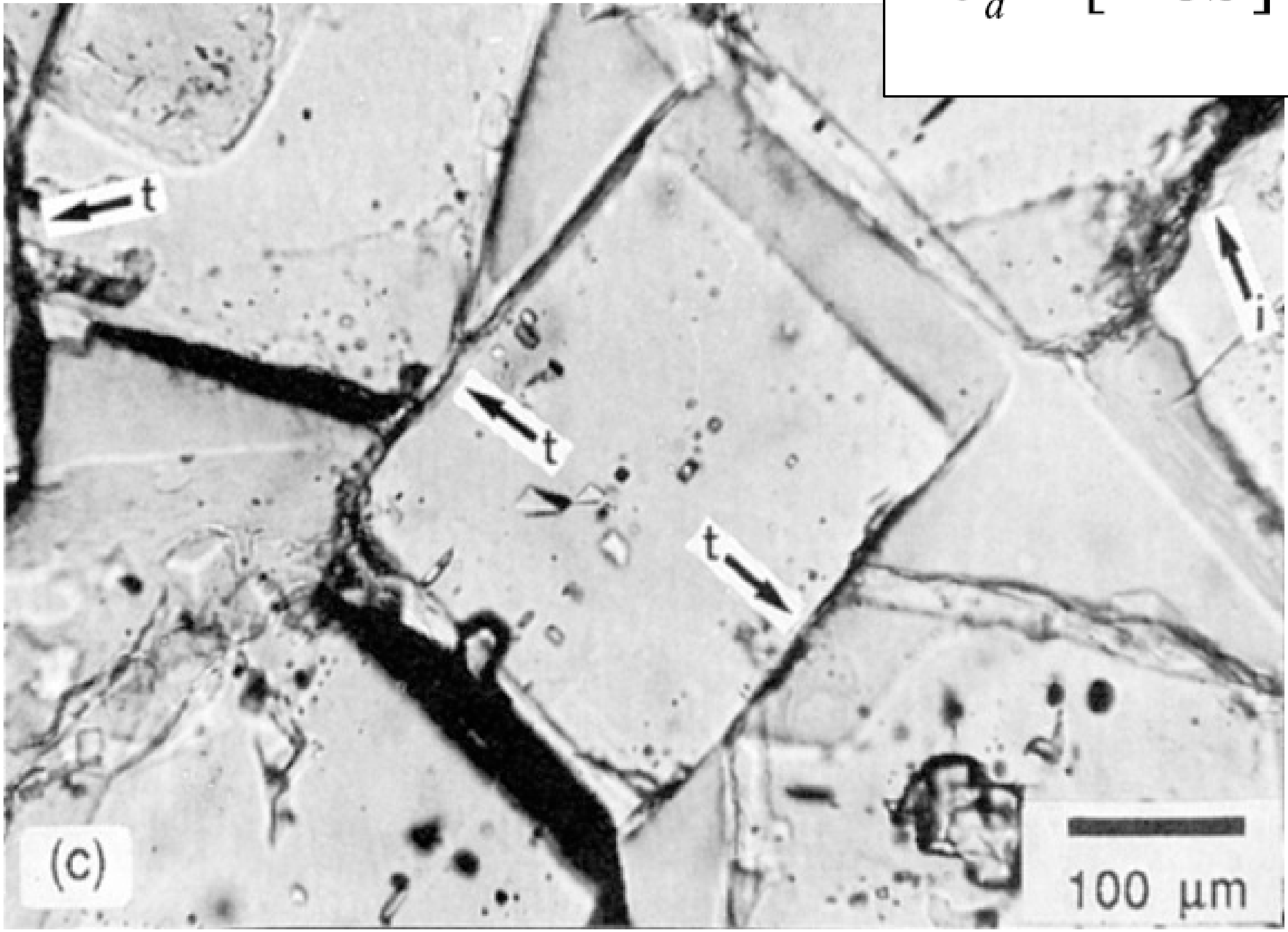
crystal plasticity, microcracking
dilatancy, permeability increase

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Pressure solution creep

Diffusion Control:

$$\dot{\varepsilon}_d = [DCS] \times \frac{\sigma_e}{d^3} \times f_d(\phi)$$



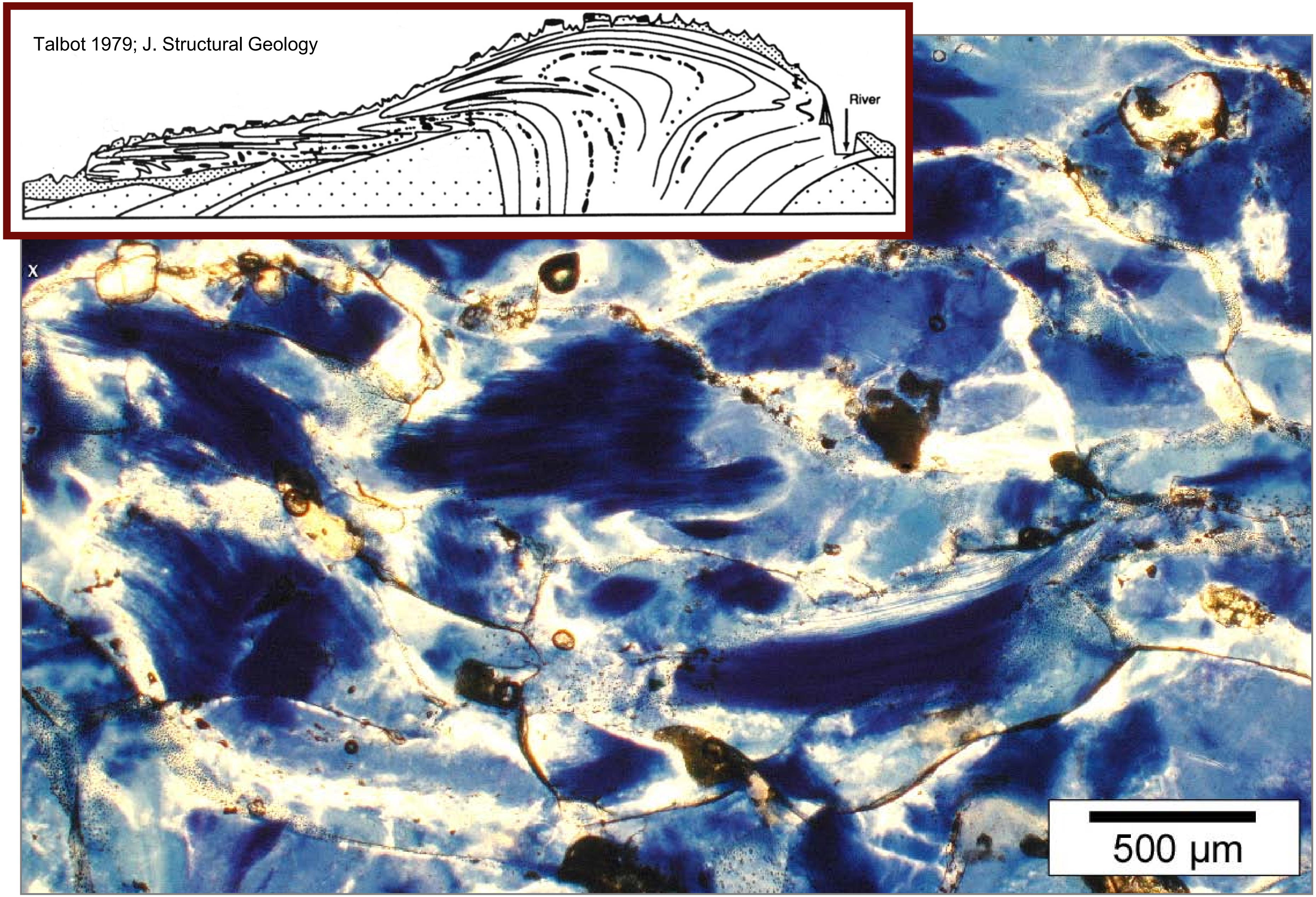
Spiers et al., (1996- 2007) University Utrecht

Zagros - Kuh-i-namak

very fine grain size
solution-precipitation creep
dramatic softening

Landsat https://zulu.ssc.nasa.gov/mrsid/

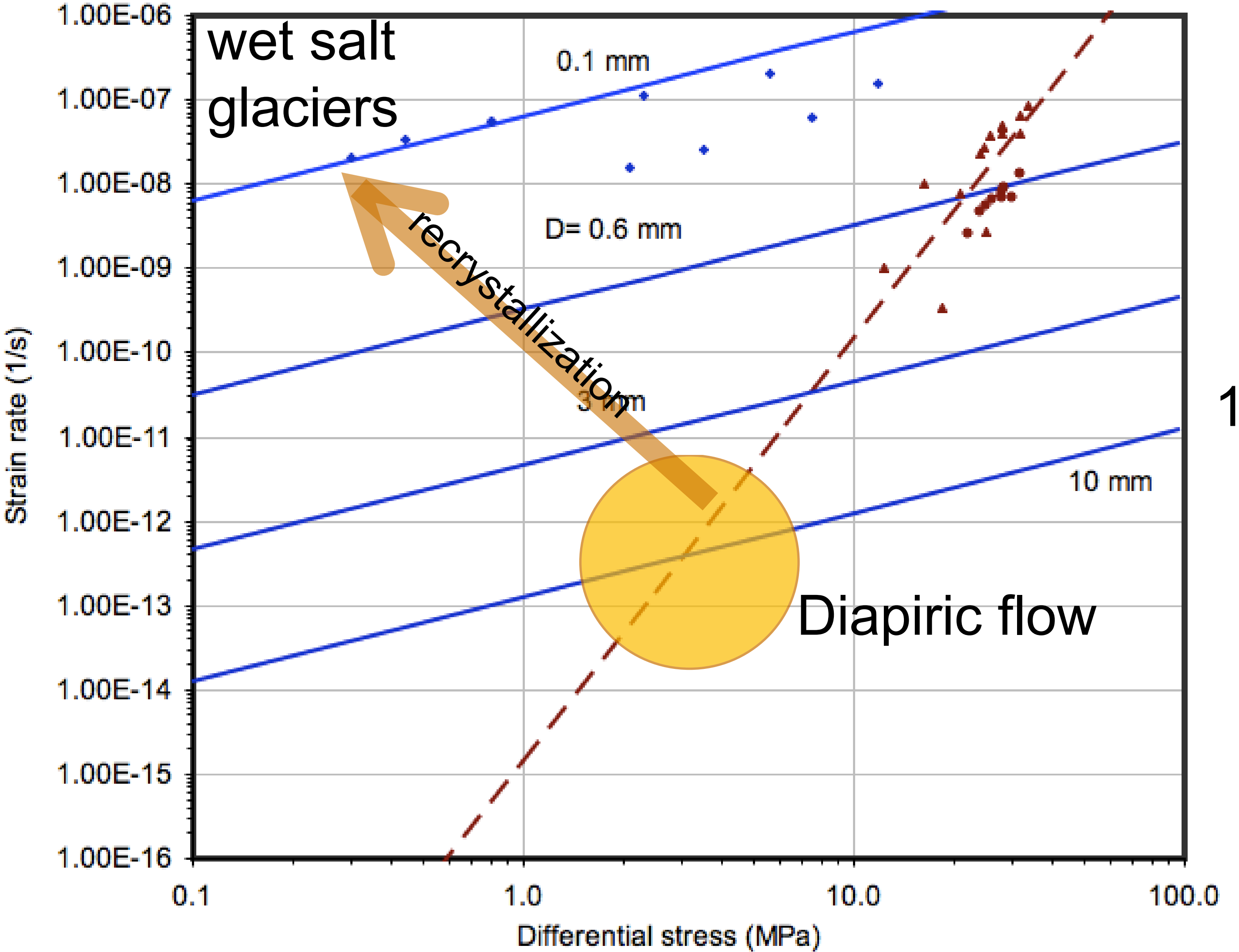
Glacier salt microstructure



Talbot 1979; J. Structural Geology

Schleder and Urai (2007), J. Structural Geology

Cyclic Halite rheology

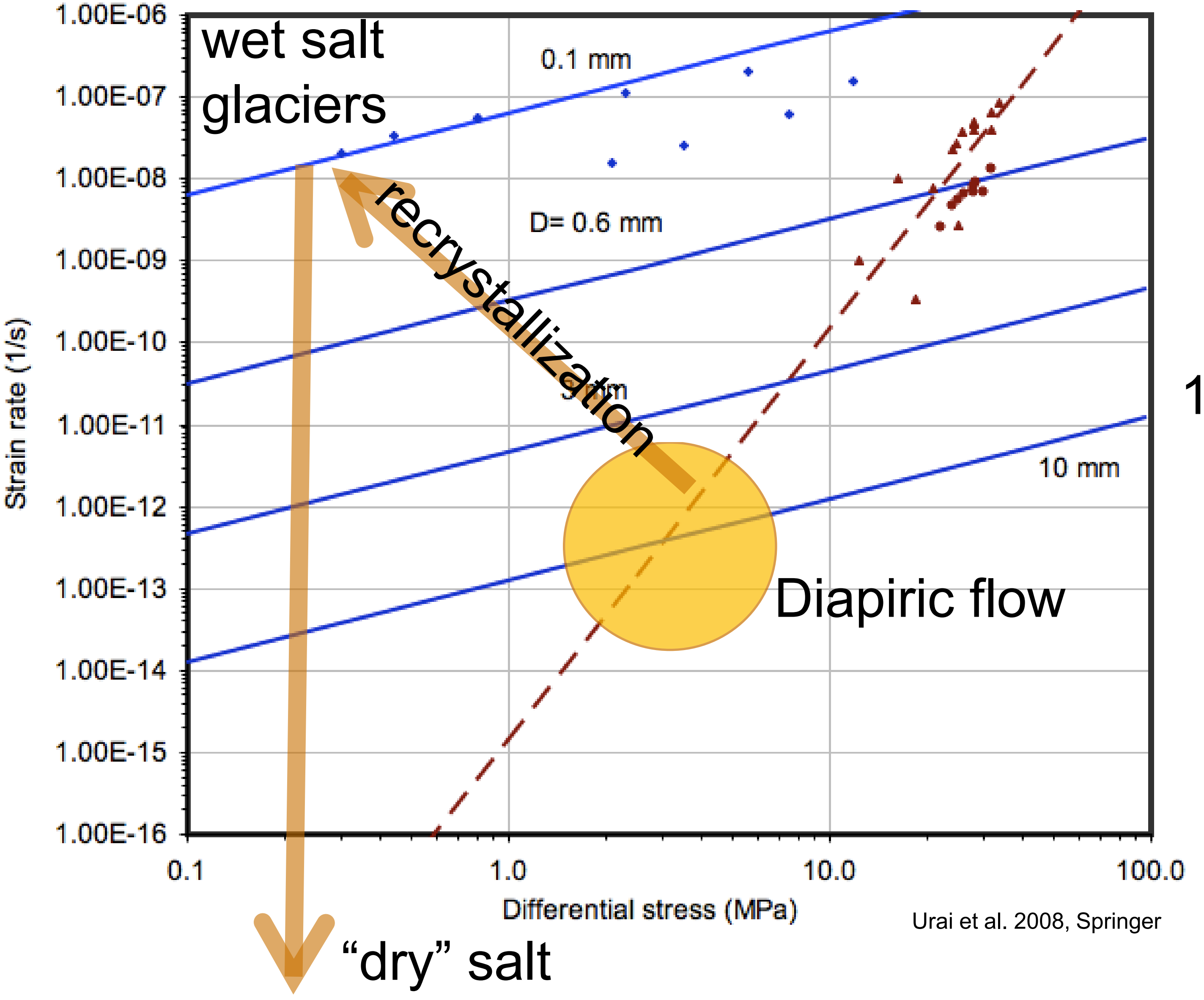


10^{19} Pa s

Urai et al. 2008, Springer

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Cyclic Halite rheology



wet salt glaciers

recrystallization

Diapiric flow

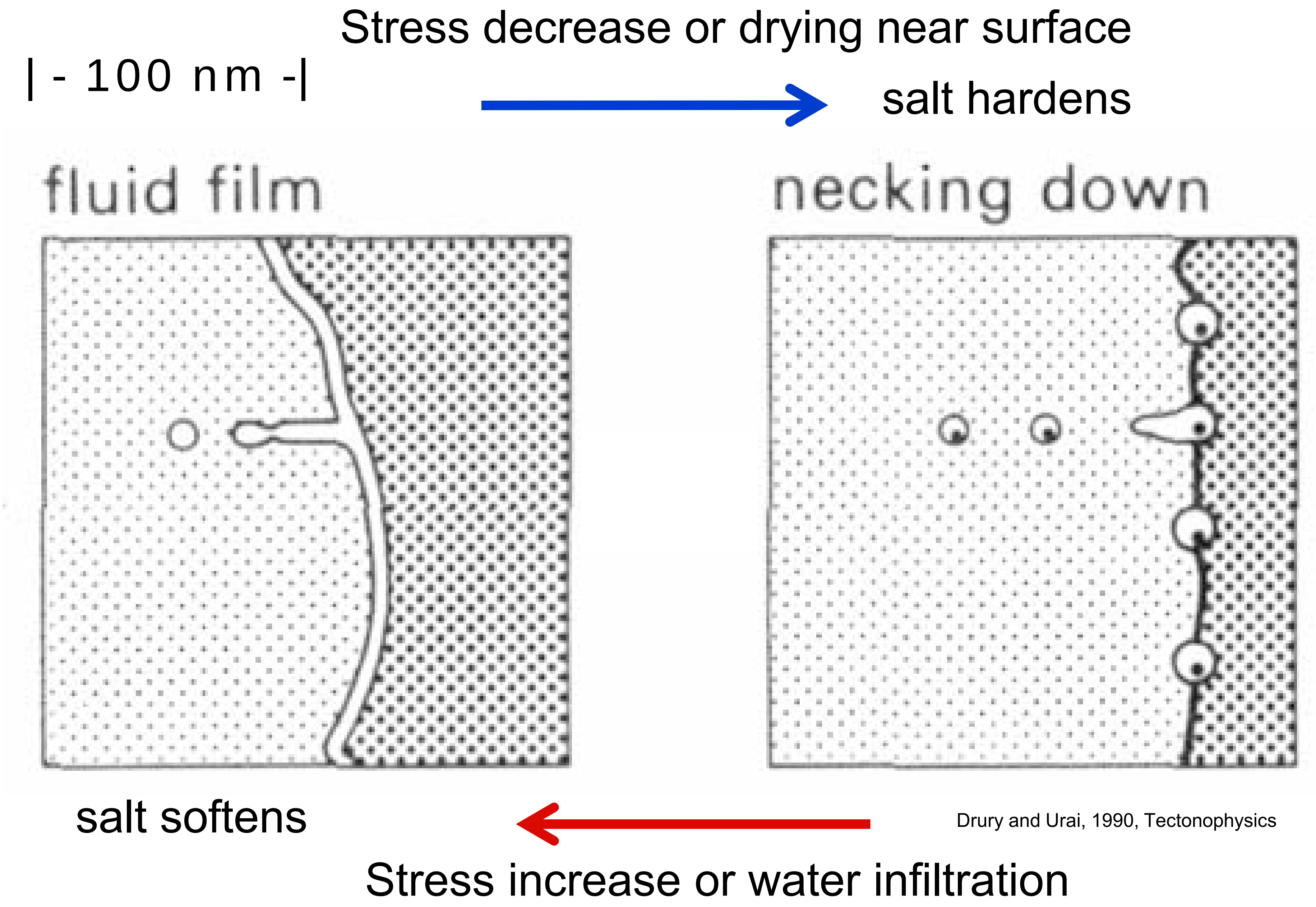
10^{19} Pa s

“dry” salt glaciers

Urai et al. 2008, Springer

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

The healing of of grain boundaries



Stress decrease or drying near surface

| - 100 nm -|

salt hardens

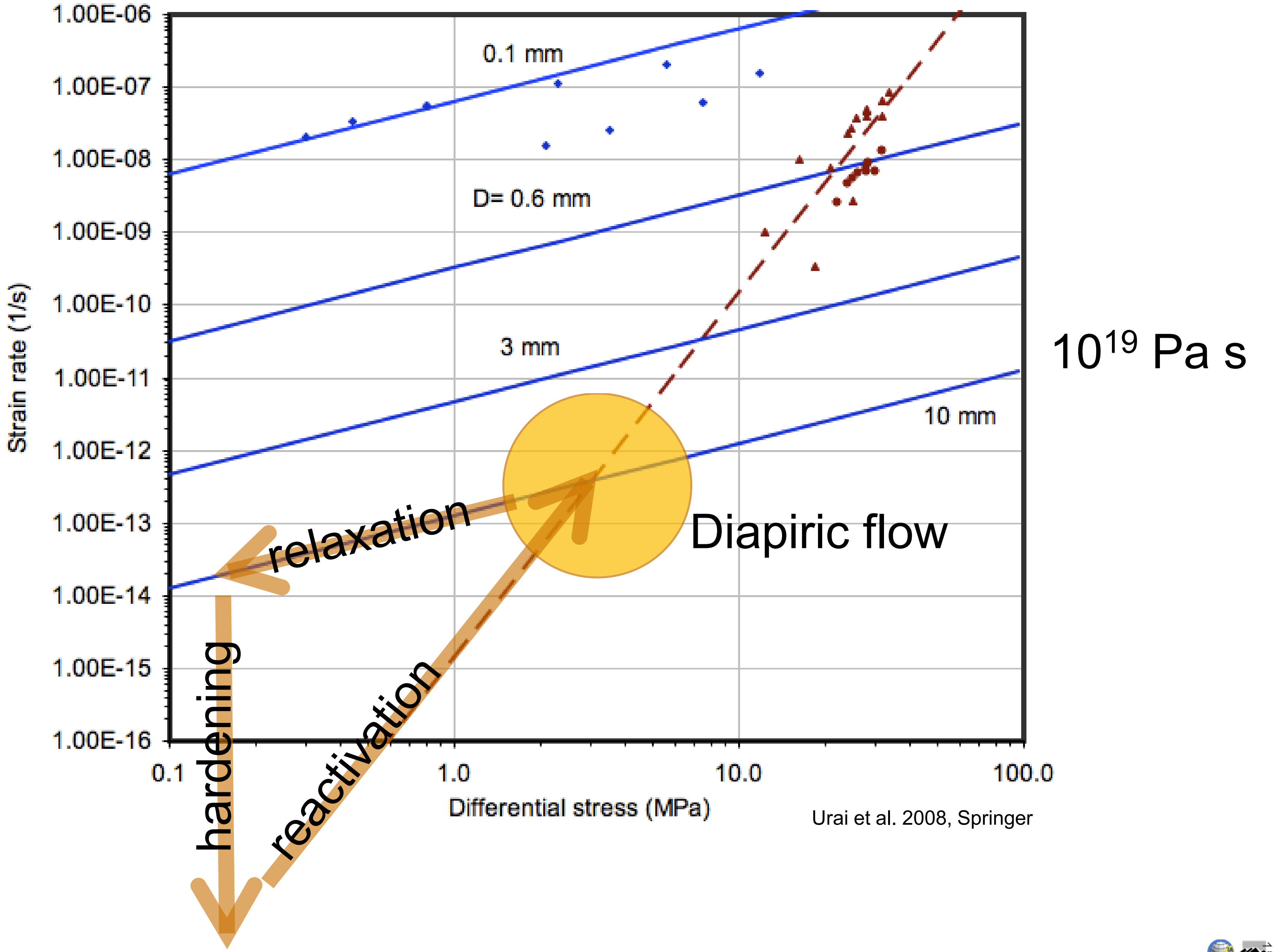
salt softens

Drury and Urai, 1990, Tectonophysics

Stress increase or water infiltration

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Cyclic Halite rheology



10^{19} Pa s

Urai et al. 2008, Springer

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Internal structure

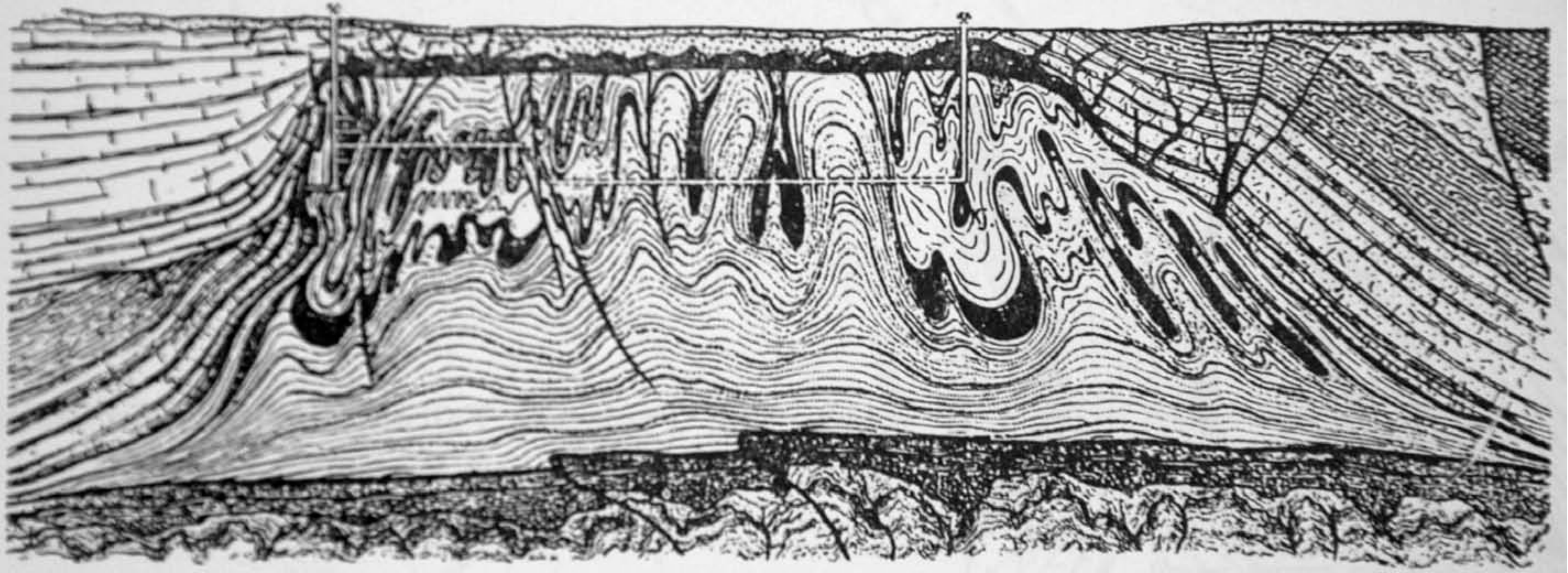


Abb. 164. Schematisches Profilbild eines Salzstocks (nach E. SEIDL).

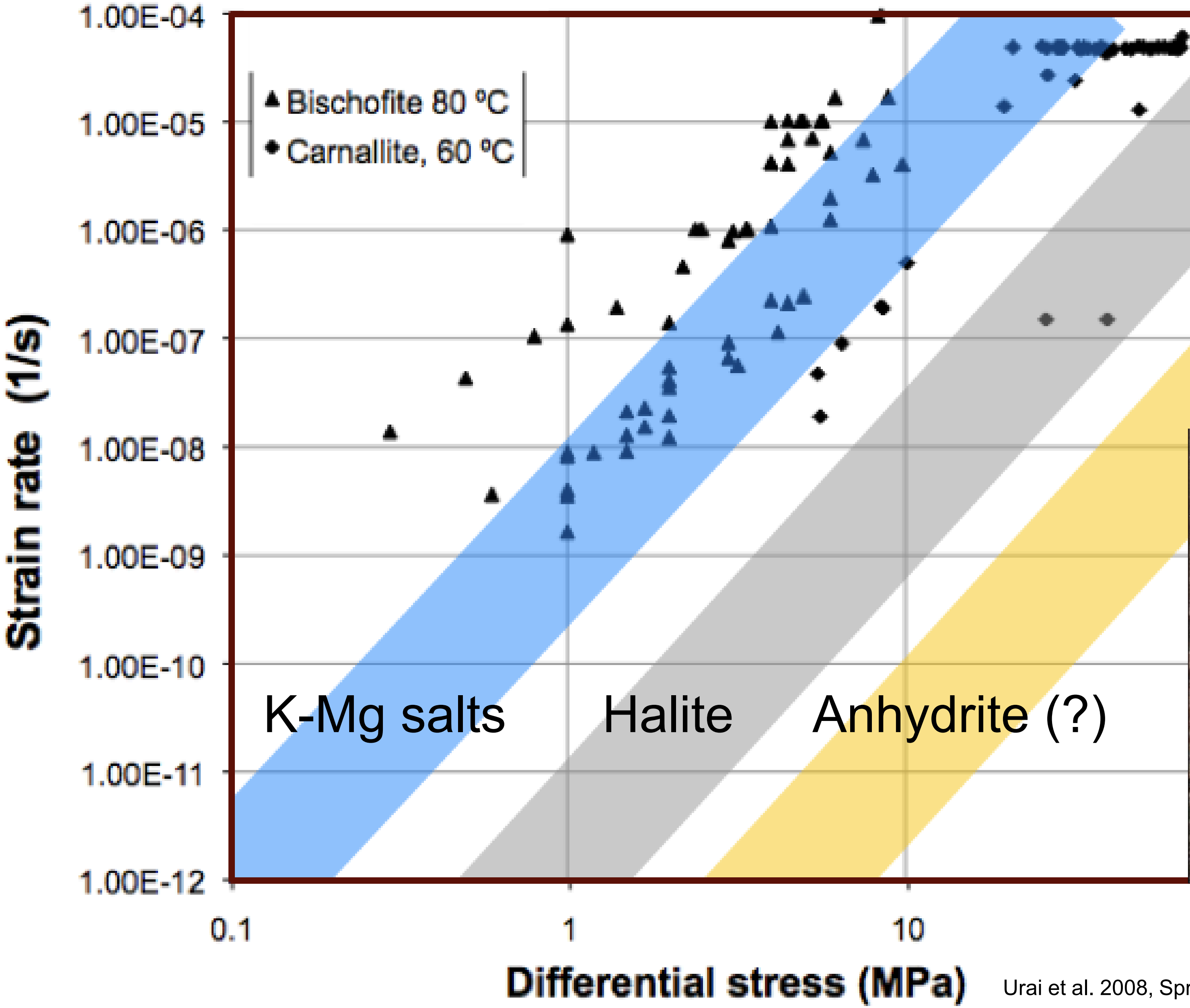
Layered evaporites with K-Mg salts and anhydrite

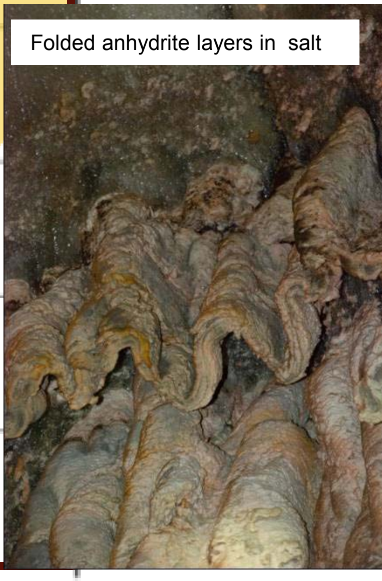
Fulda, 1923, Das Kali

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Rheology of different evaporites

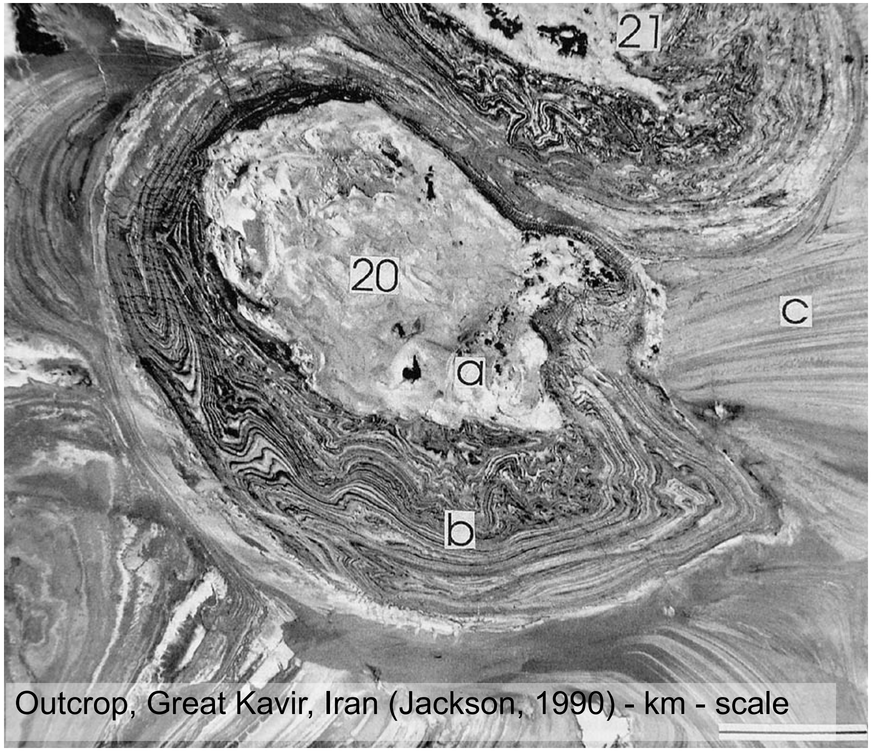
Mechanical layering
folding, boudinage,



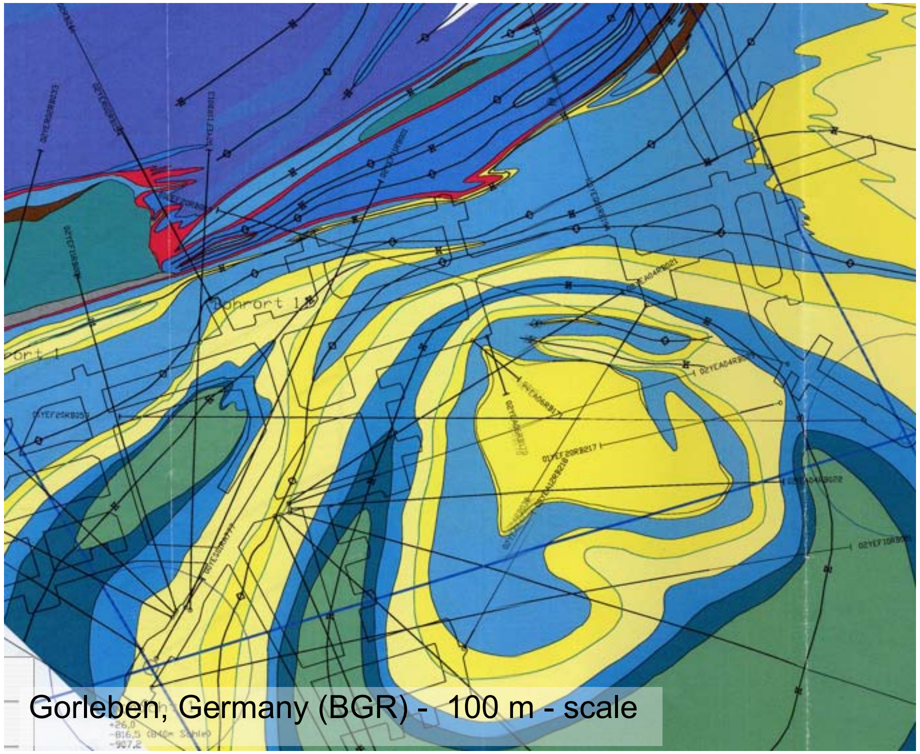

Folded anhydrite layers in salt

Urai et al. 2008, Springer

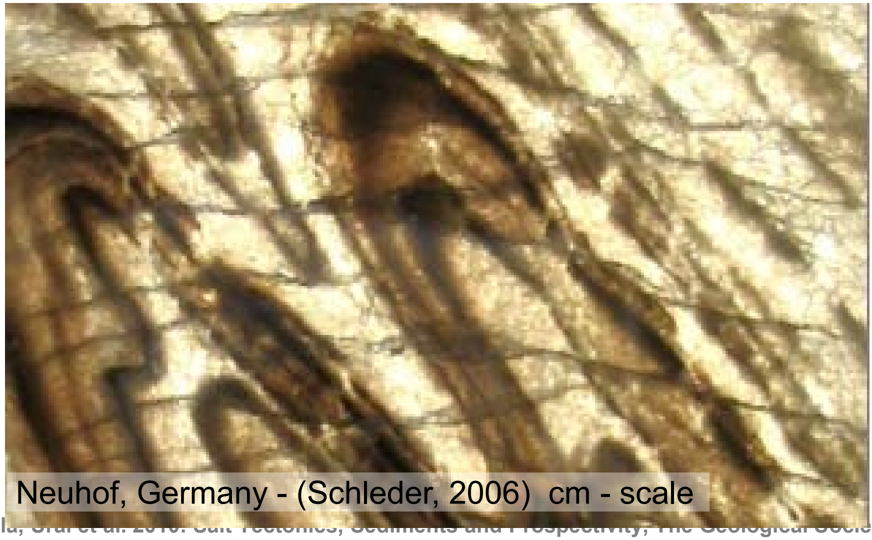
The internal structure of salt bodies is complexly folded



Outcrop, Great Kavir, Iran (Jackson, 1990) - km - scale



Gorleben, Germany (BGR) - 100 m - scale

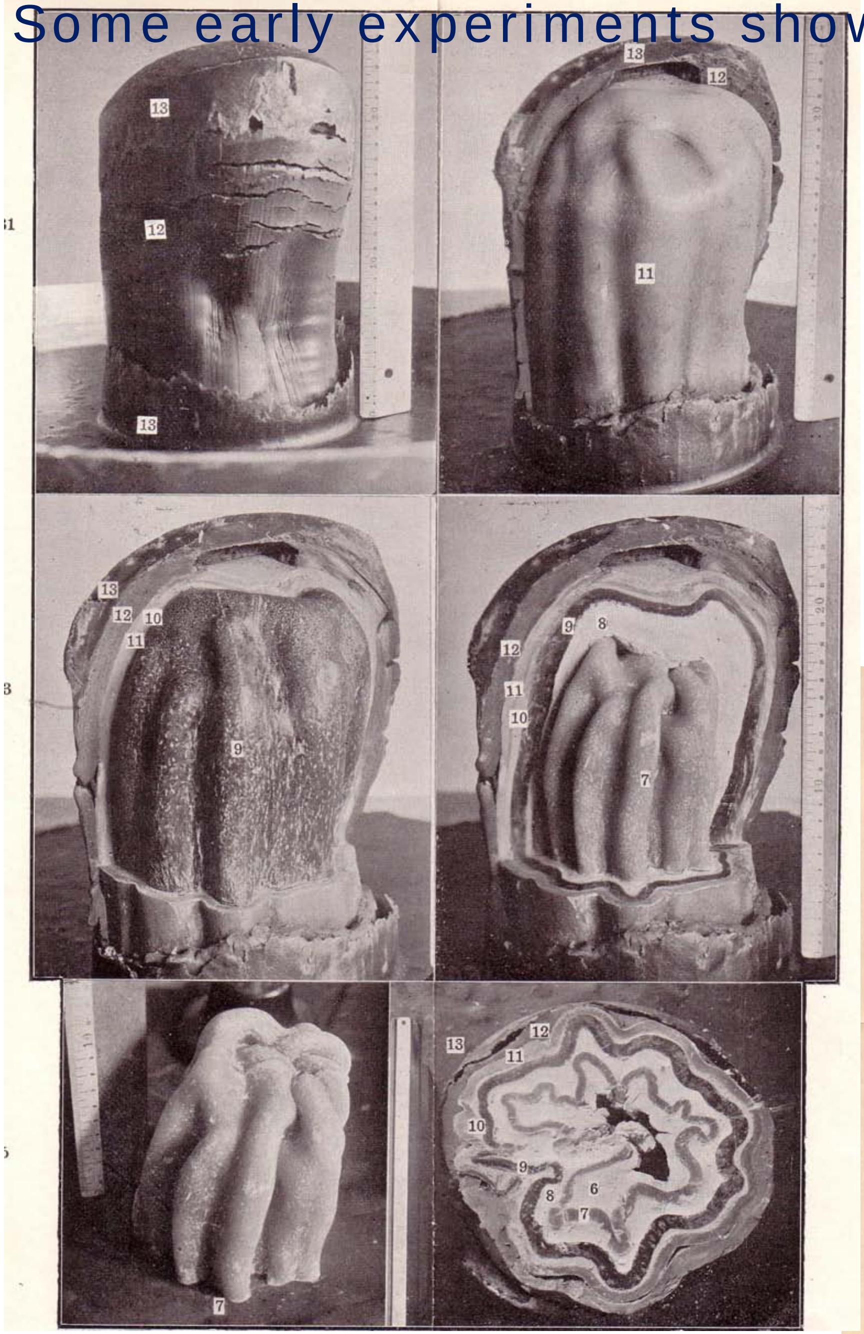


Neuhof, Germany - (Schleder, 2006) cm - scale

Kali und Steinsalz

Kukla, Urai et al. 2010: Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Some early experiments showing folds and boudinage



Escher and Kuenen 1929; Leische Geologische Mededeelingen

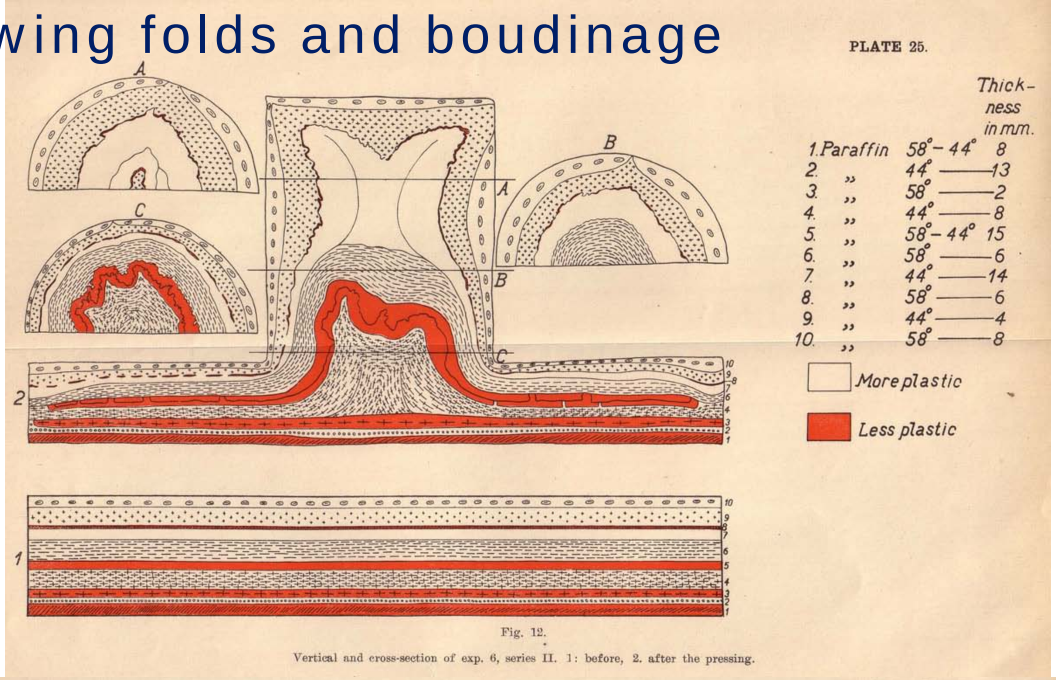


PLATE 25.

		Thick-ness in mm.
1. Paraffin	58° – 44°	8
2. ,,	44°	13
3. ,,	58°	2
4. ,,	44°	8
5. ,,	58° – 44°	15
6. ,,	58°	6
7. ,,	44°	14
8. ,,	58°	6
9. ,,	44°	4
10. ,,	58°	8

☐ More plastic

🟥 Less plastic

Fig. 12.

Vertical and cross-section of exp. 6, series II. 1: before, 2. after the pressing.

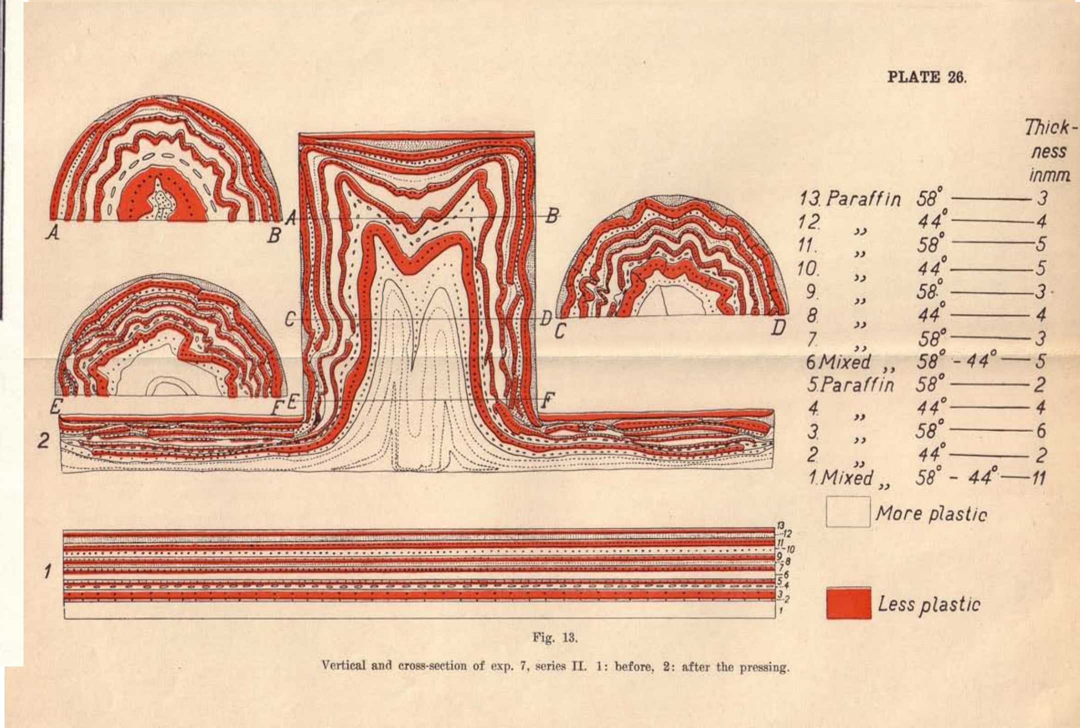


PLATE 26.

		Thick-ness in mm
13. Paraffin	58°	3
12. ,,	44°	4
11. ,,	58°	5
10. ,,	44°	5
9. ,,	58°	3
8 ,,	44°	4
7 ,,	58°	3
6 Mixed ,,	58° - 44°	5
5 Paraffin	58°	2
4 ,,	44°	4
3 ,,	58°	6
2 ,,	44°	2
1. Mixed ,,	58° - 44°	11

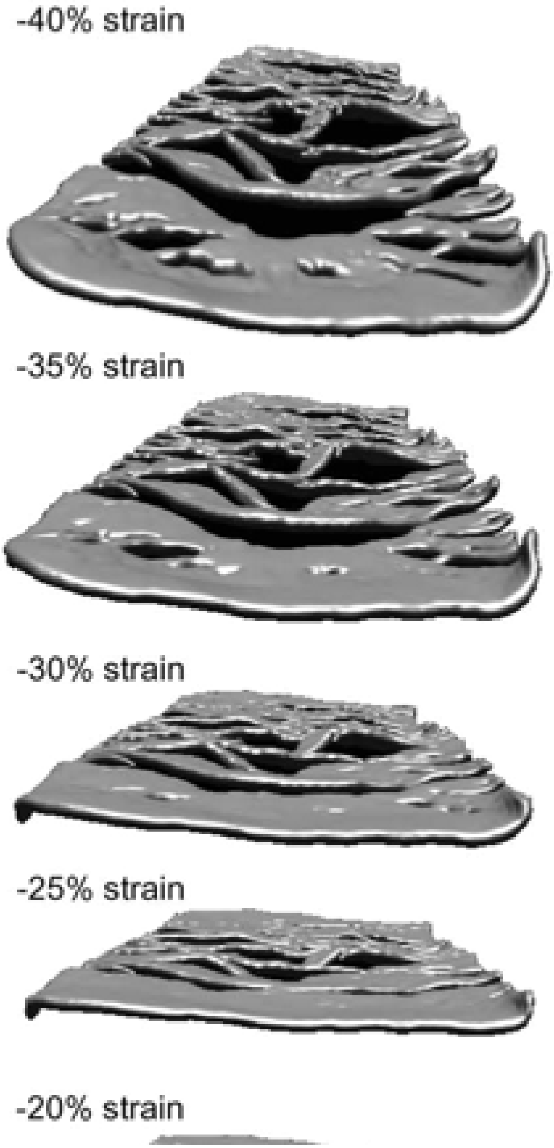
☐ More plastic

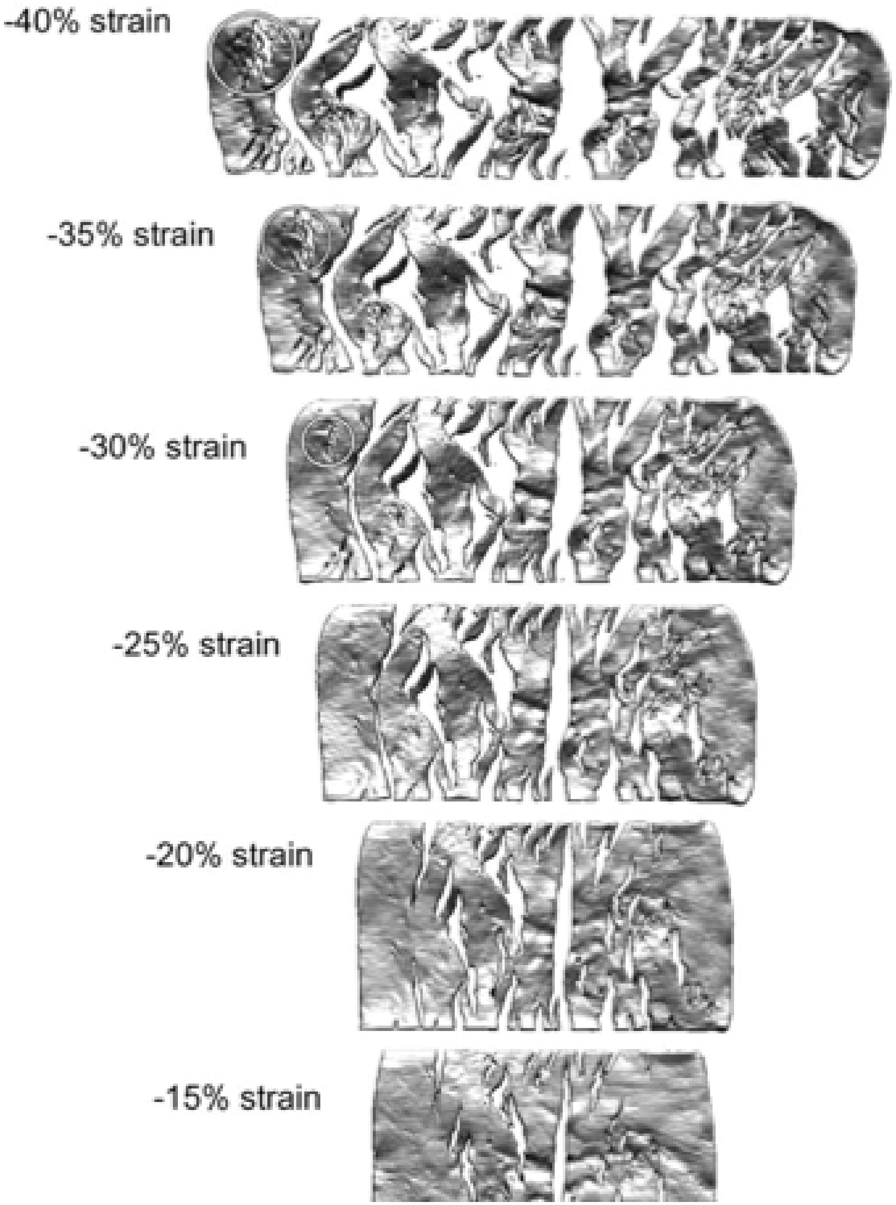
🟥 Less plastic

Fig. 13.

Vertical and cross-section of exp. 7, series II. 1: before, 2: after the pressing.

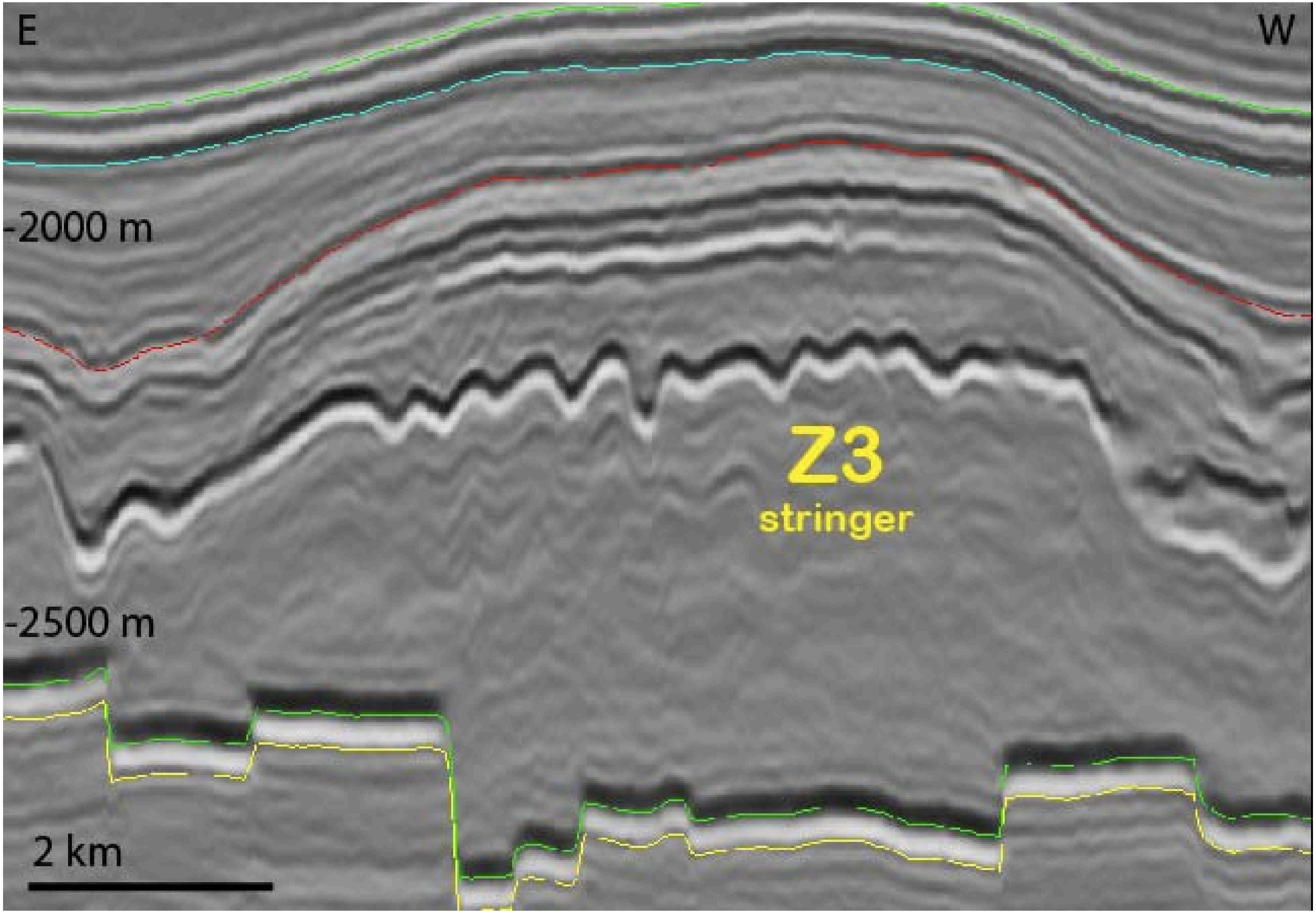
Folding and boudinage in plasticine models





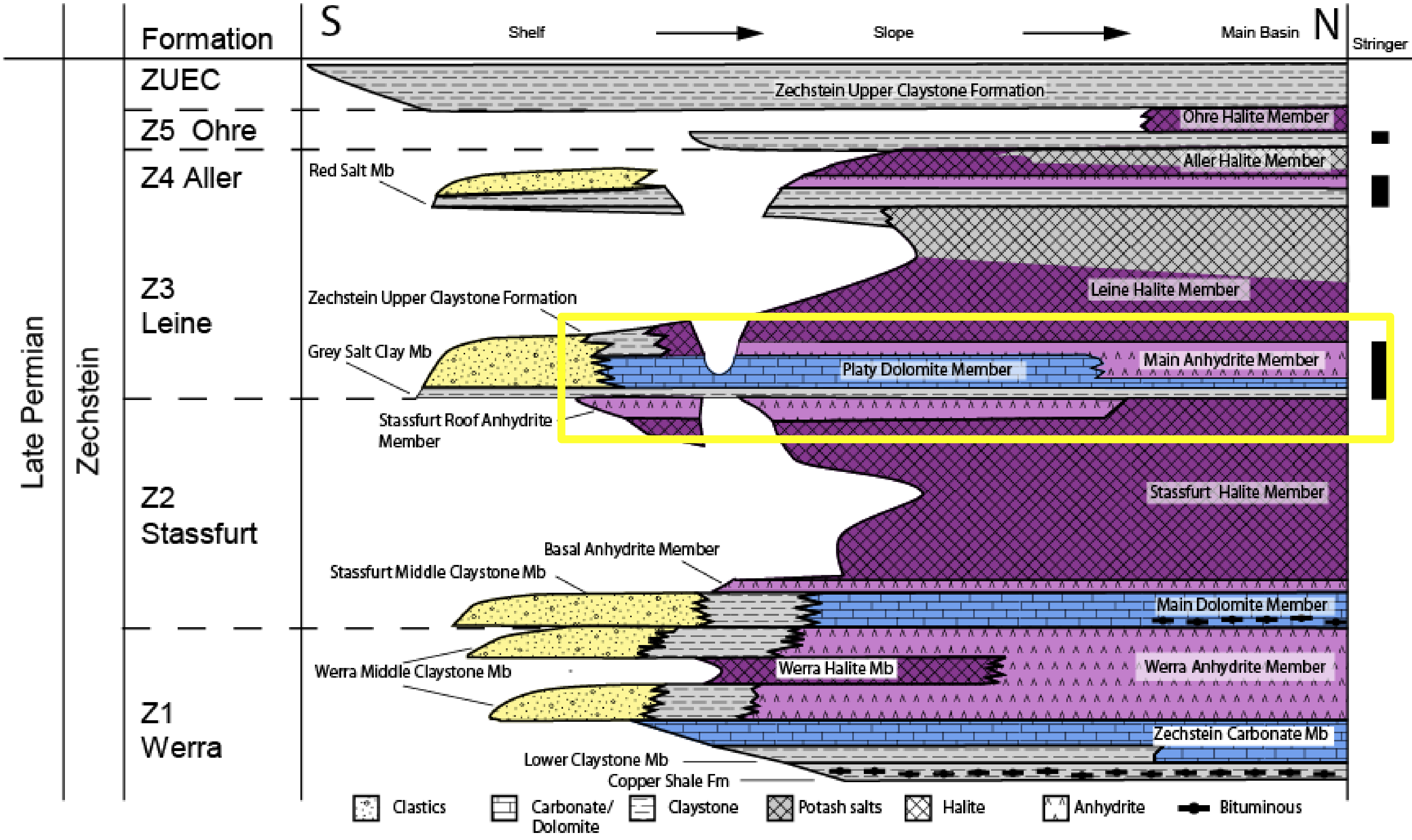
G. Zulauf, J. Zulauf , 2005; J. Structural Geology

Internal structure from 3D seismic
Z3 stringer folds, Groningen area



Van Gent et al, in press, available online, J Structural Geology

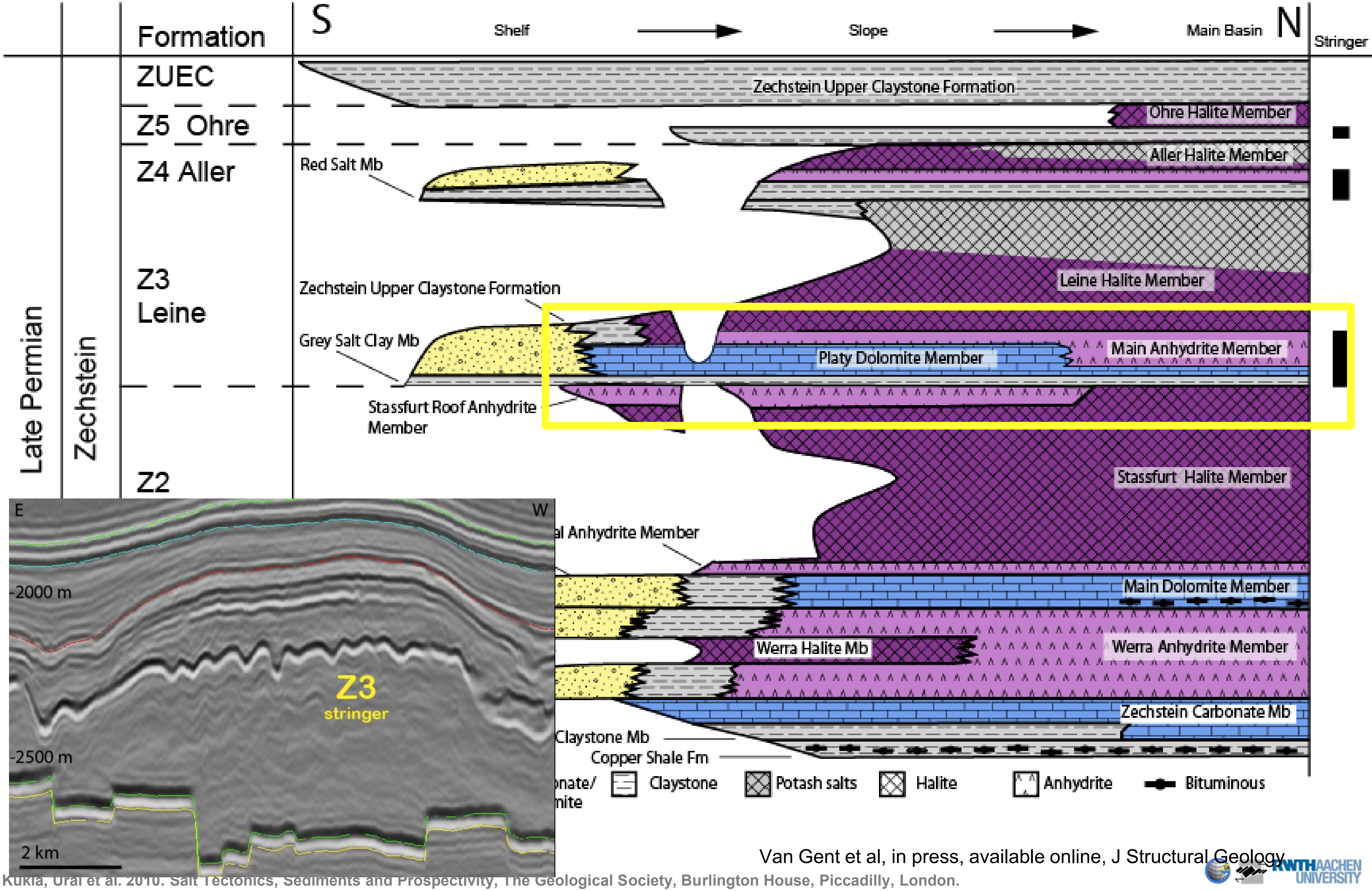
Z3 stringers



Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

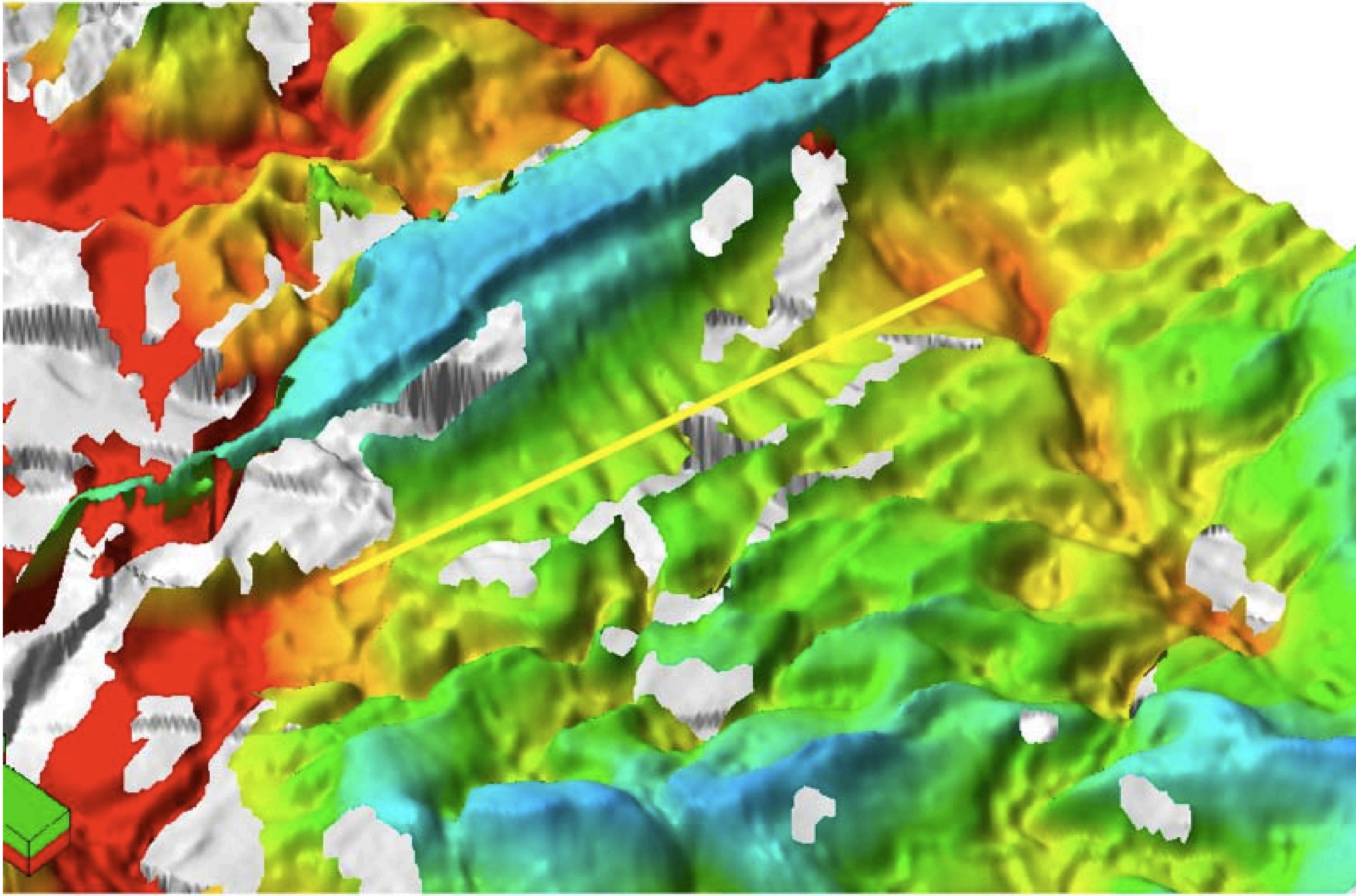
Z3 stringers



Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

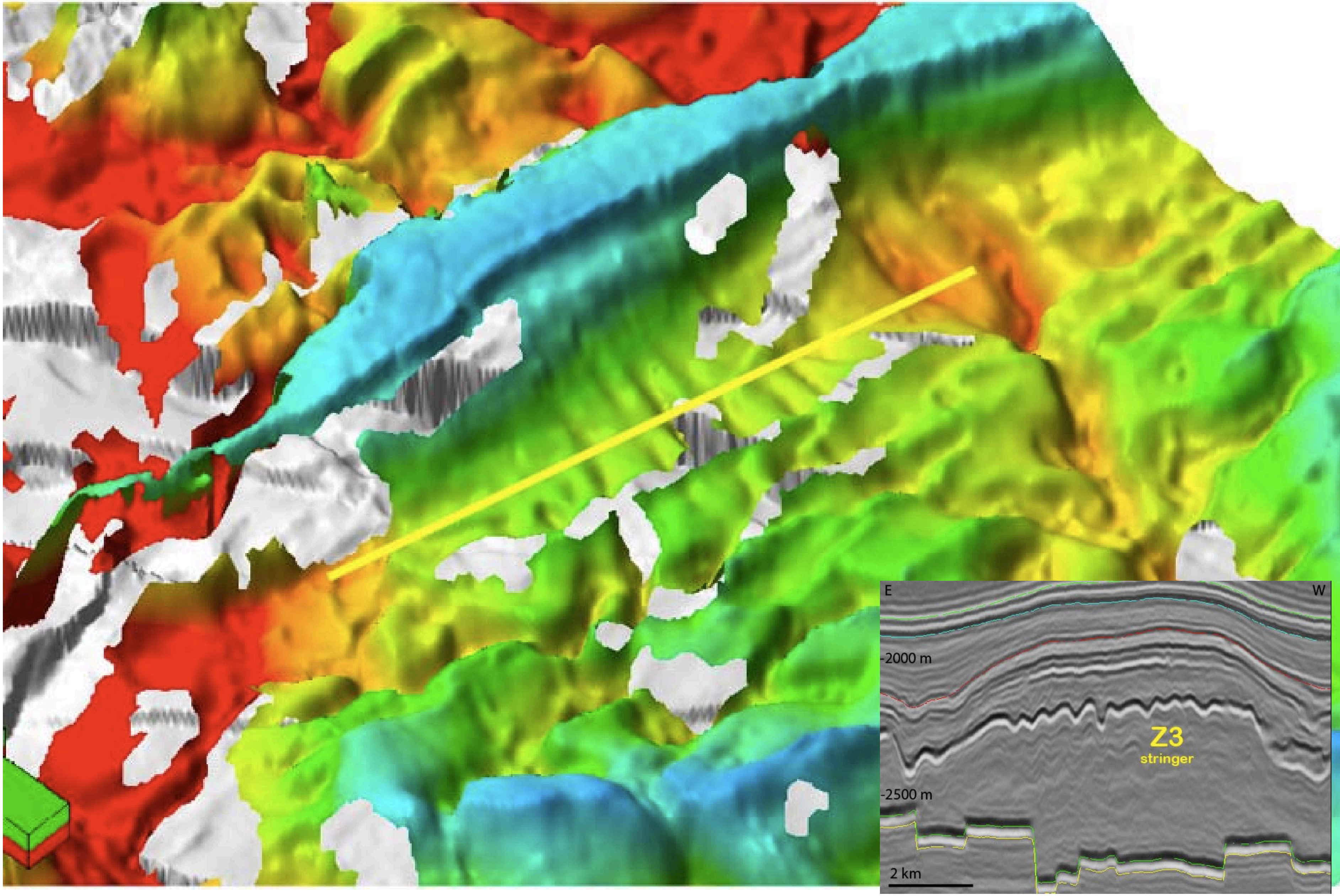
Z3 surface in Groningen area



Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

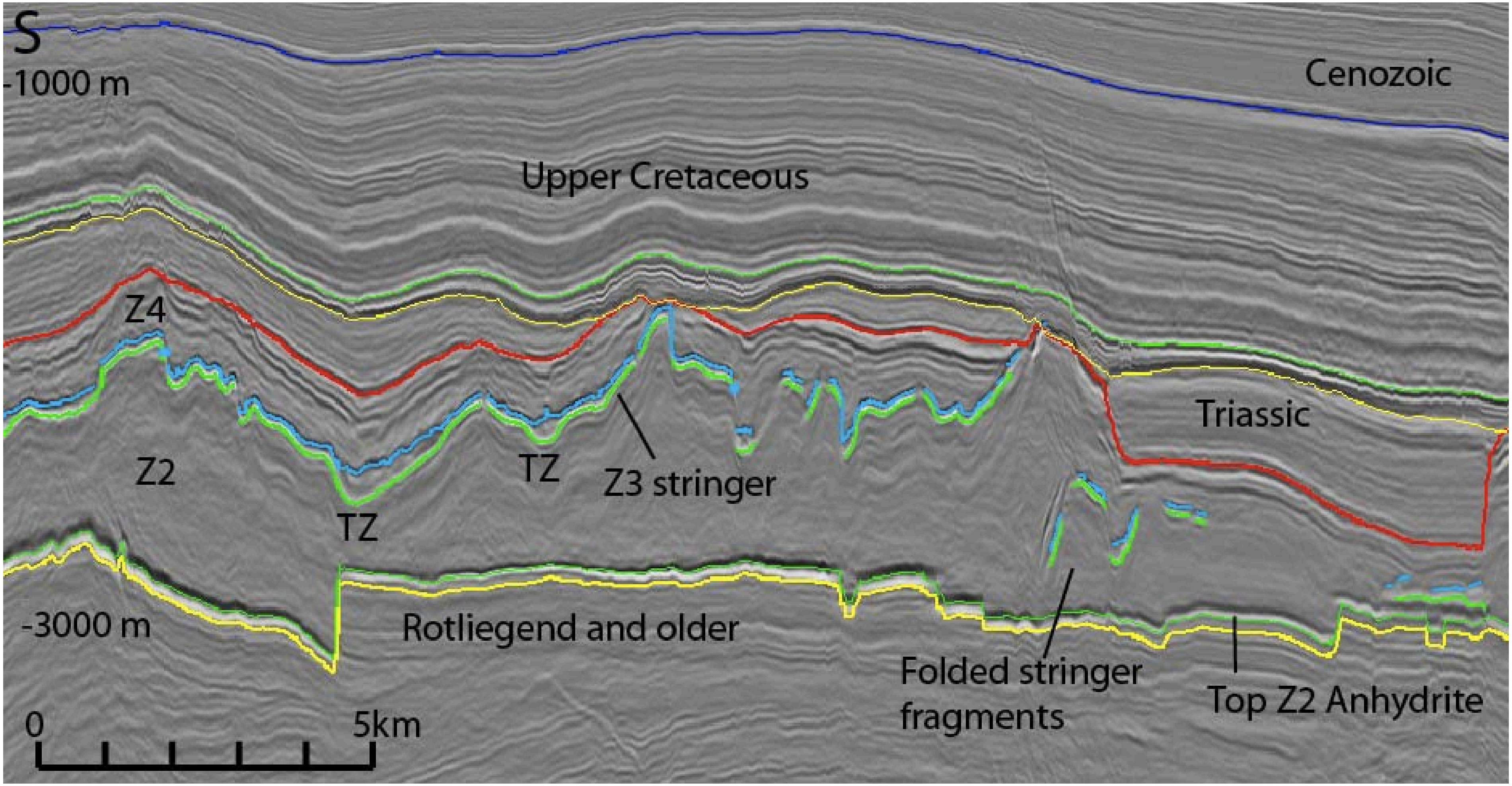
Z3 surface in Groningen area



Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

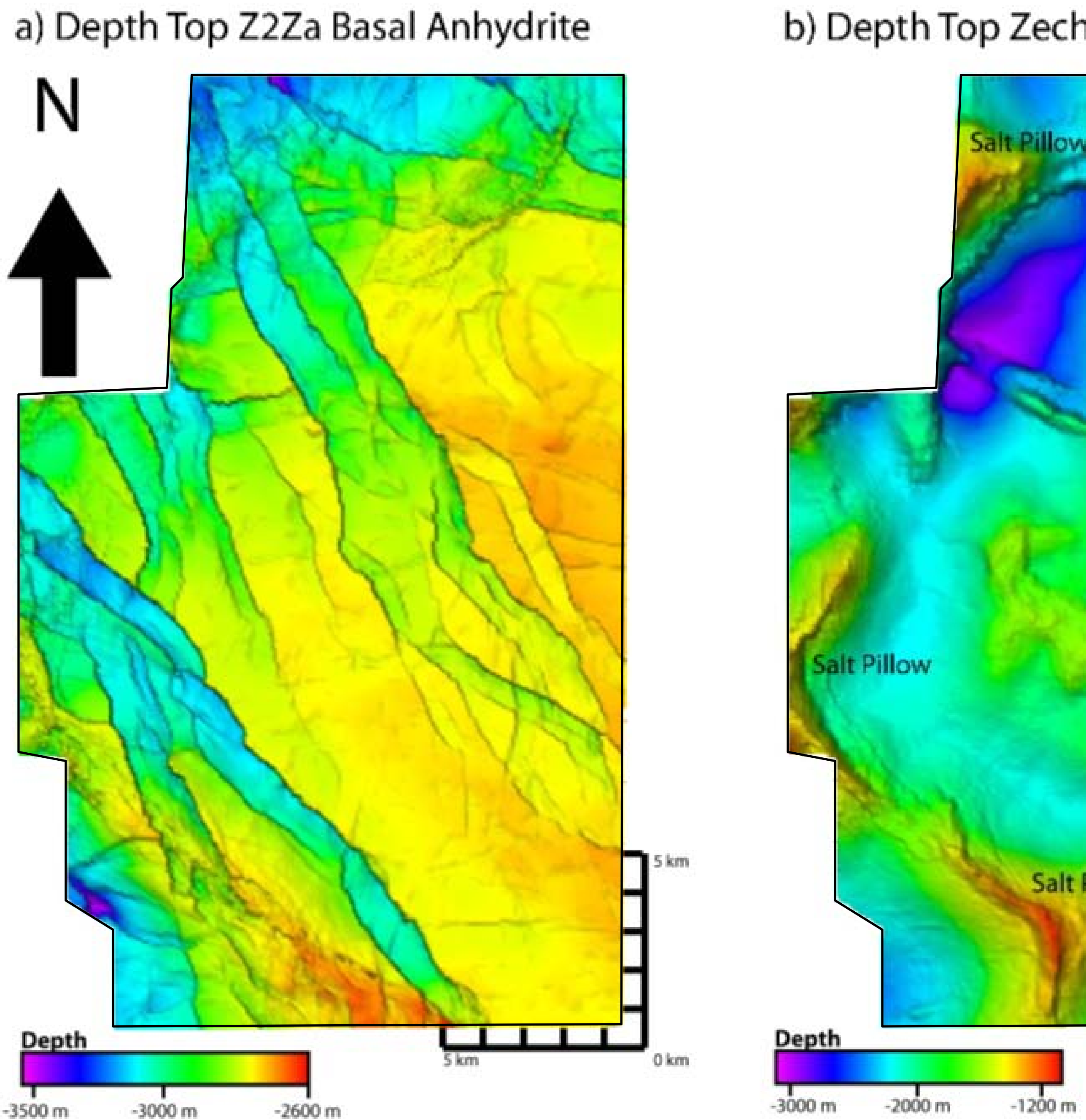
Thickened zones



Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Top and base salt structure

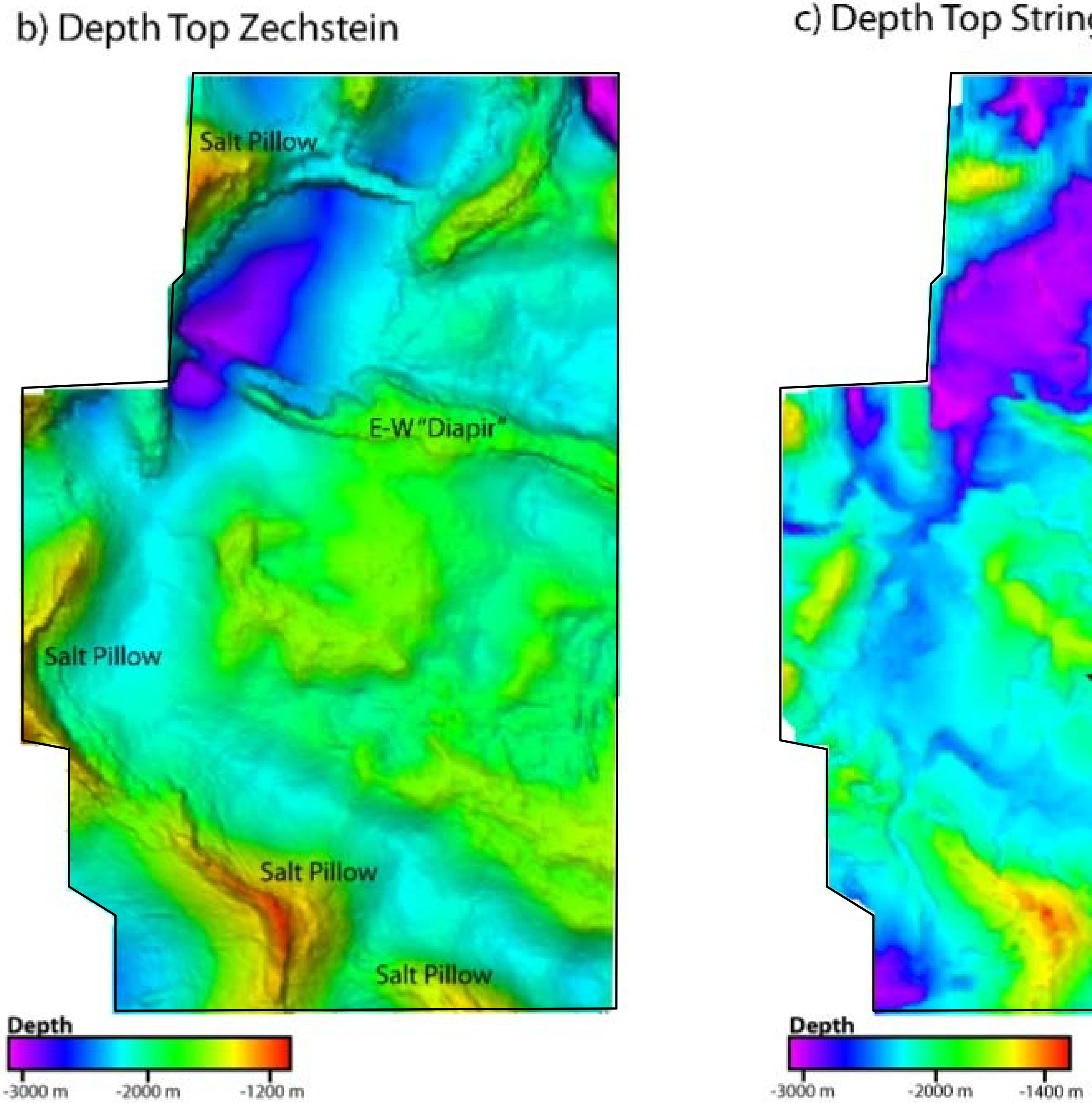


a) Depth Top Z2Za Basal Anhydrite

b) Depth Top Zechstein

Van Gent et al, in press, available online, J Structural Geology

Large scale stringer structure is harmonic with top salt



Van Gent et al, in press, available online, J Structural Geology

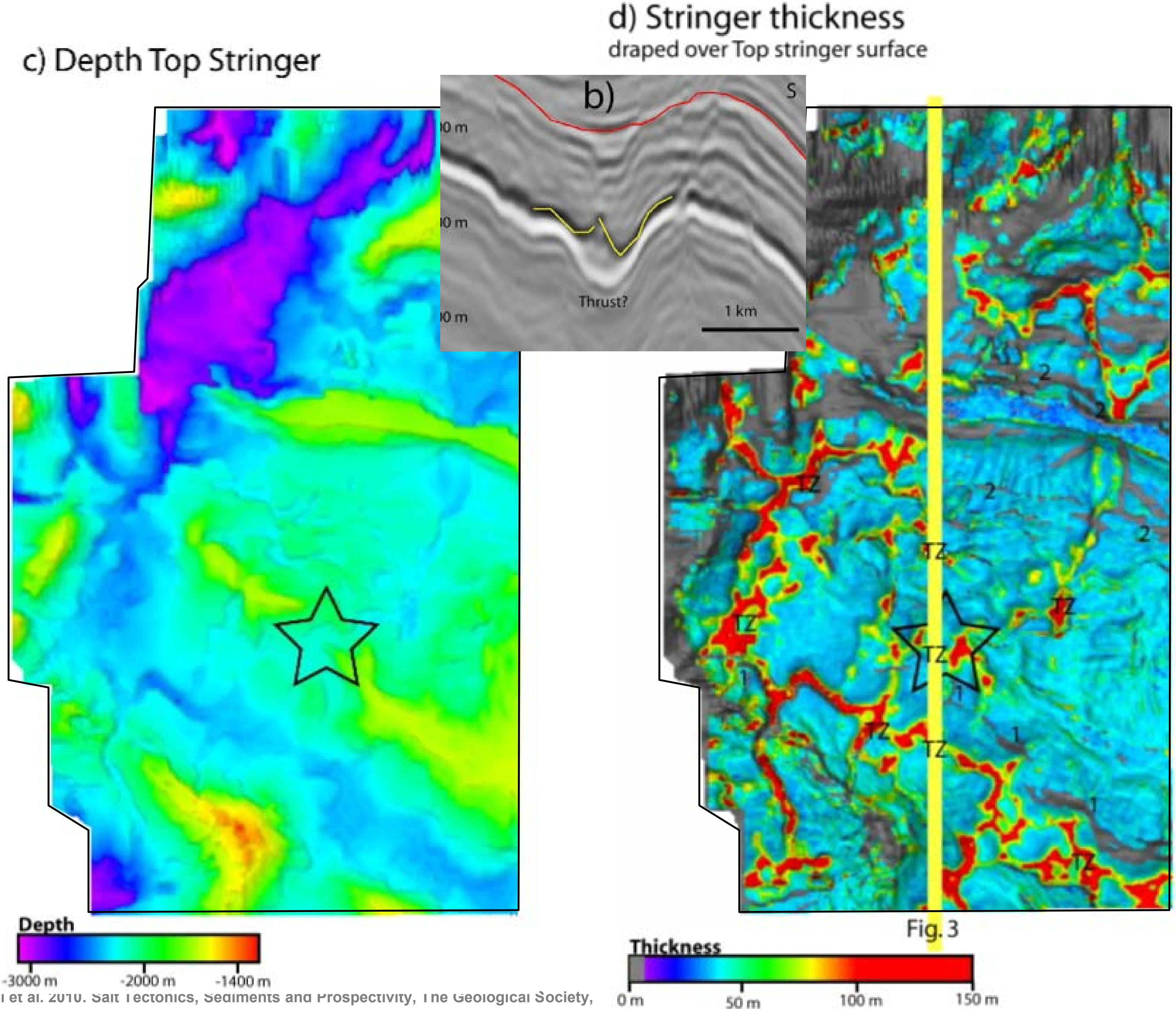


Fig. 3

Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society,

Thickened zones form regional branching networks

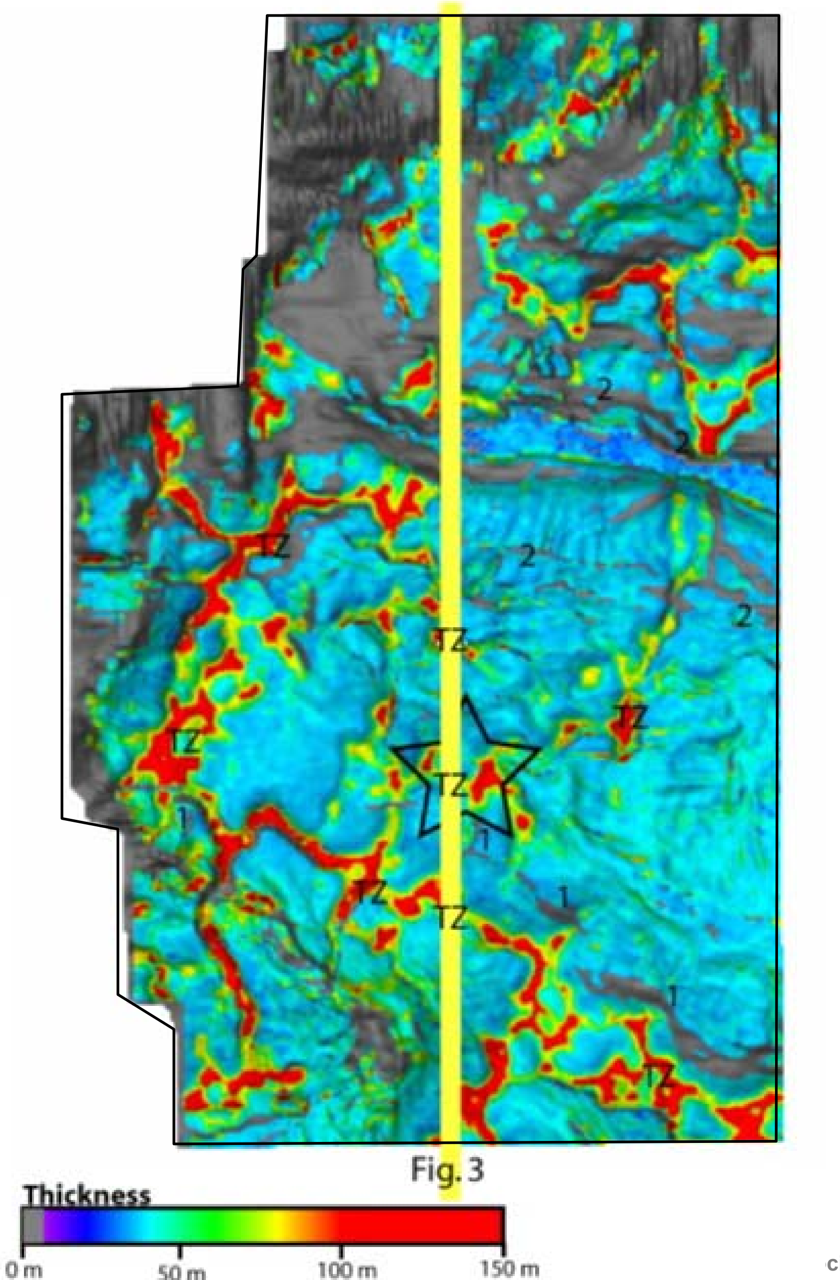
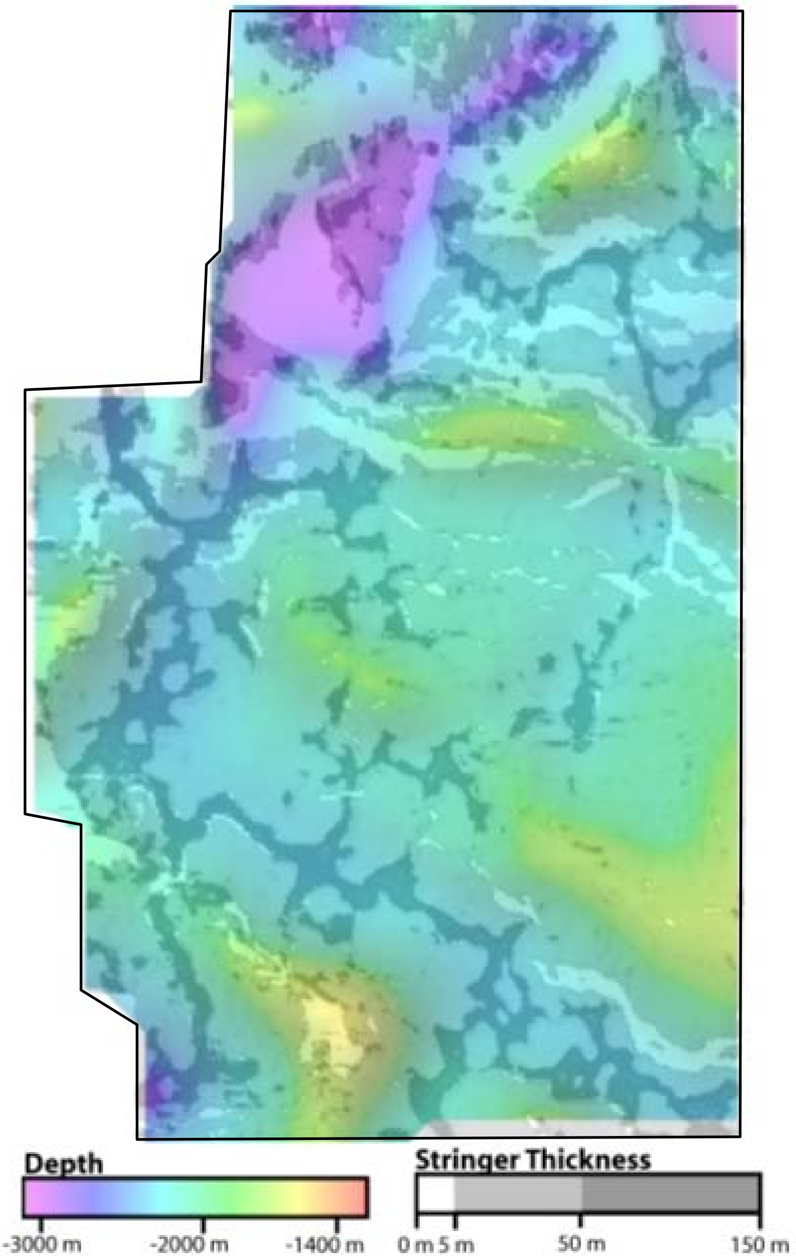


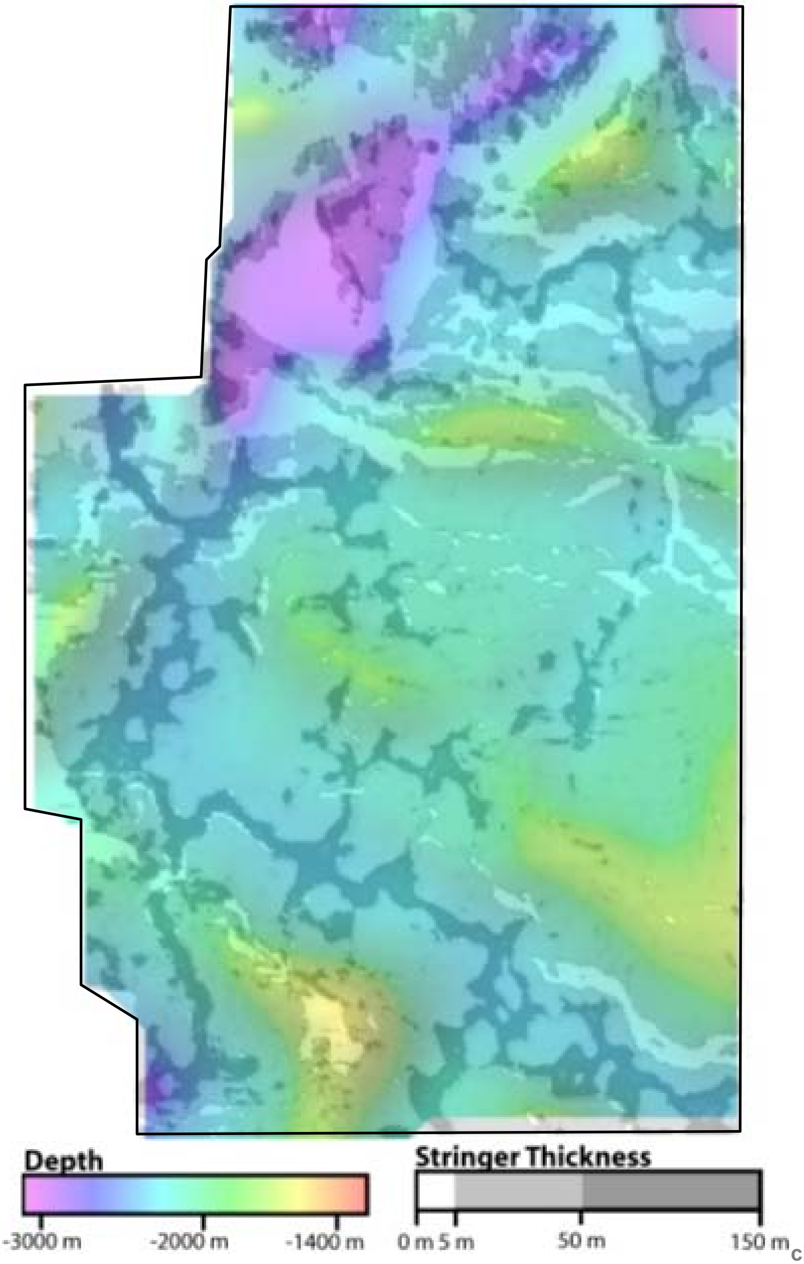
Fig. 3

Thickened zones are always in salt withdrawal areas

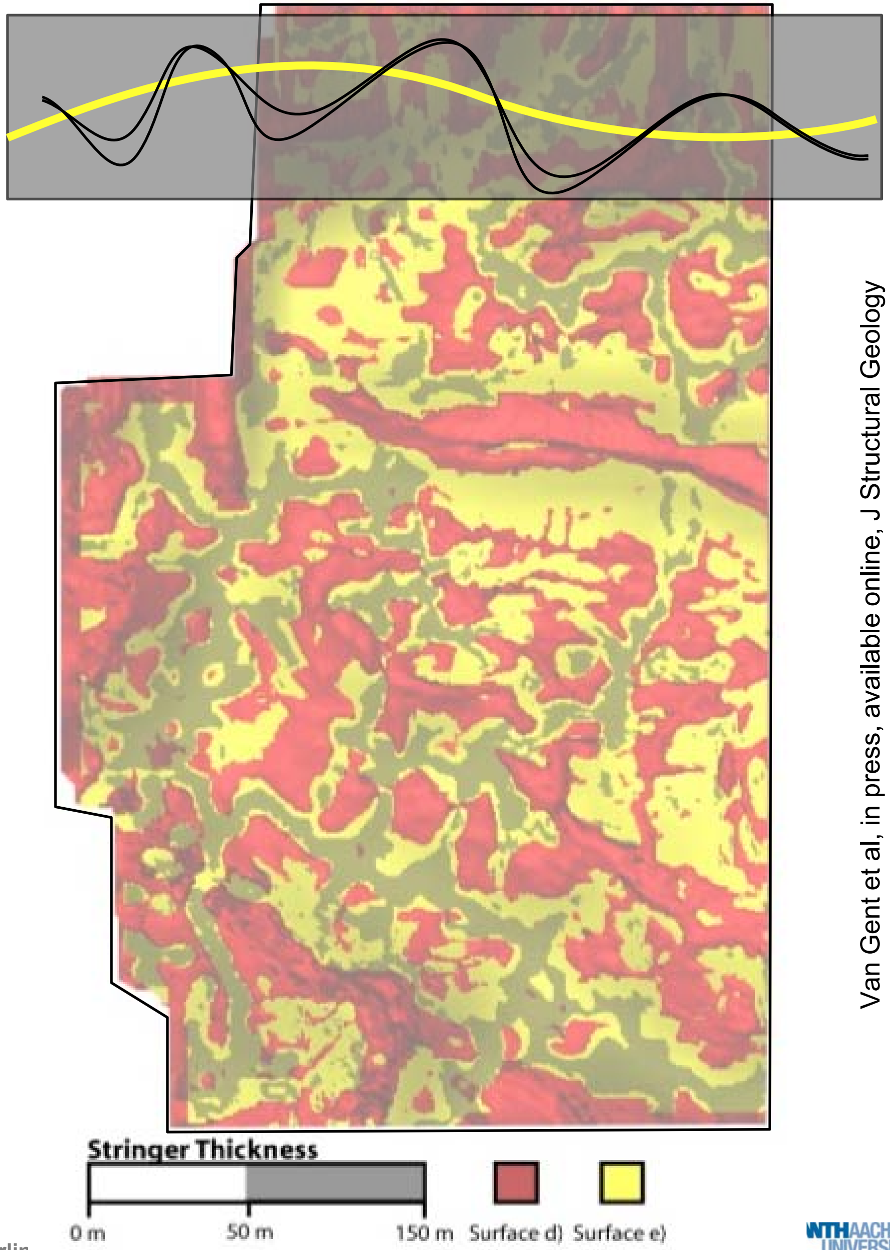


Van Gent et al, in press, available online, J Structural Geology

Thickened zones are always in salt withdrawal areas



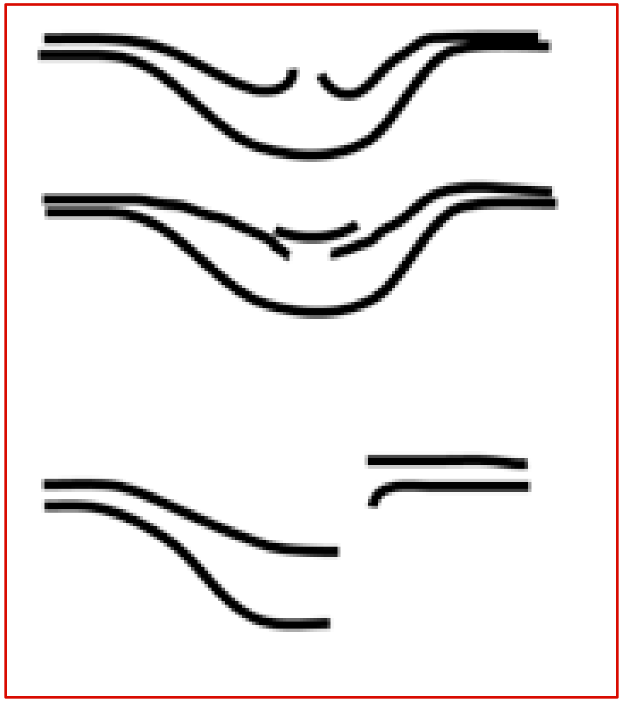
Thickened zones are always synclines

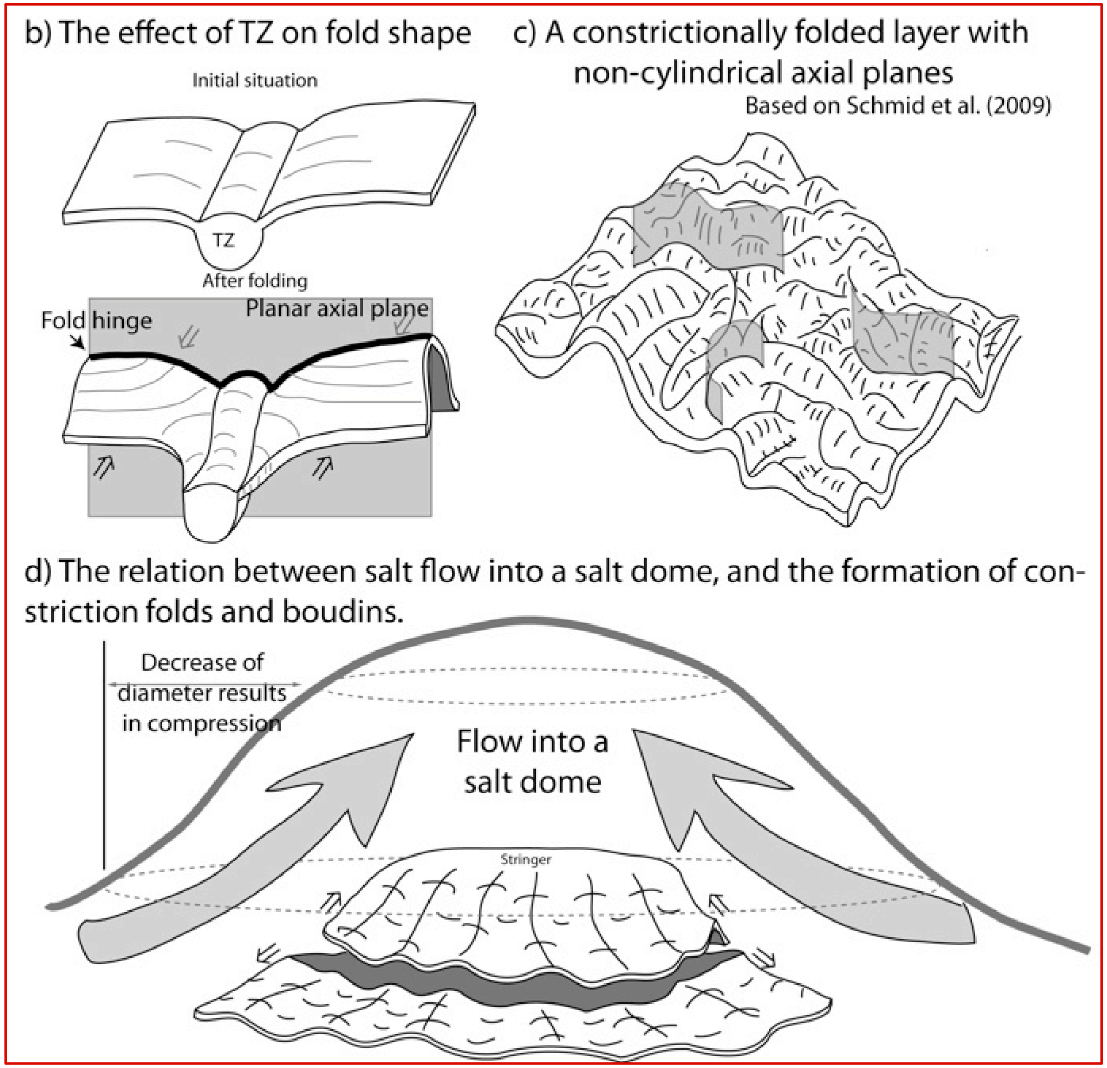


Van Gent et al, in press, available online, J Structural Geology

Summary of interpretations

1 -
Thickened zones are dissolution- related collapse structures





b) The effect of TZ on fold shape

c) A constrictionally folded layer with non-cylindrical axial planes

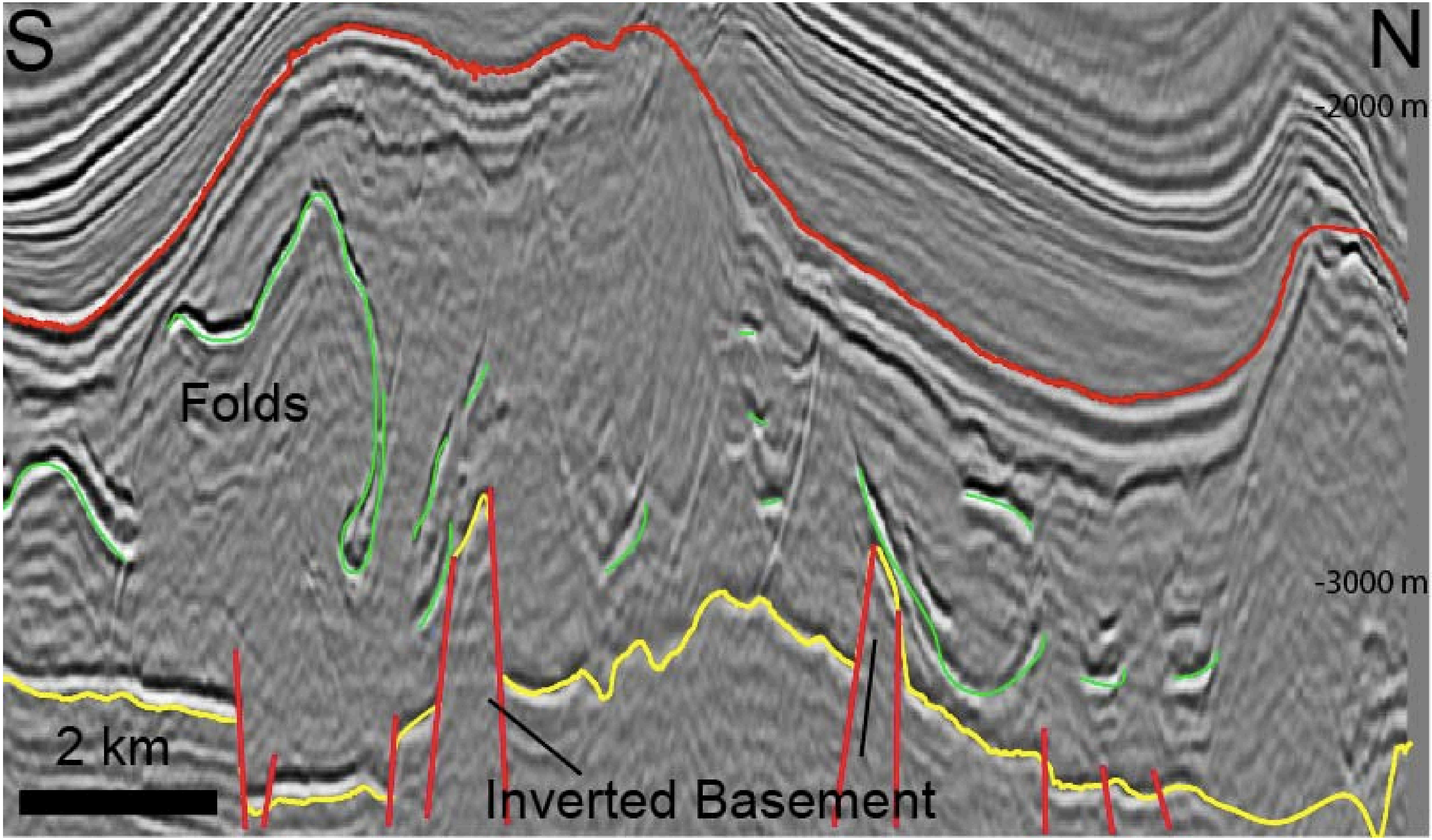
Based on Schmid et al. (2009)

d) The relation between salt flow into a salt dome, and the formation of constriction folds and boudins.

2 - Early structures have strong effect on internal structure and on Zechstein topography

Van Gent et al, in press, available online, J Structural Geology

Western offshore area -

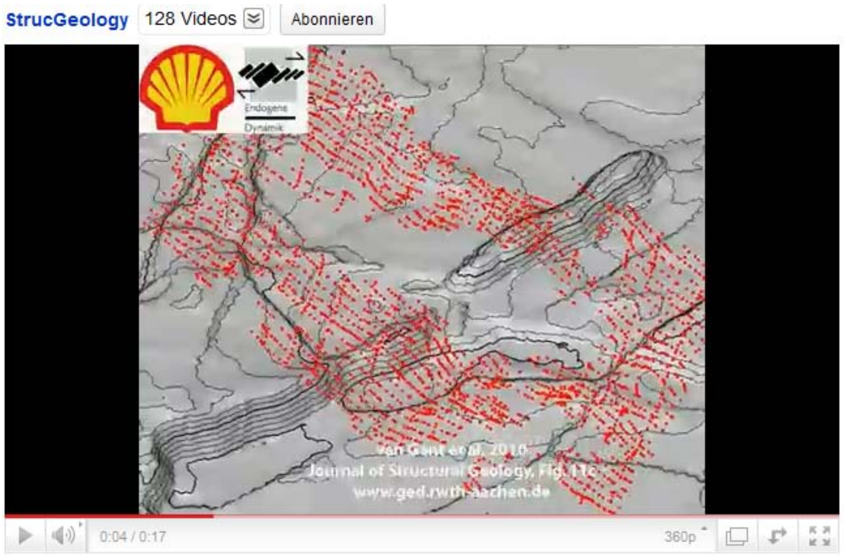


Stringers don’t sink over geologic time

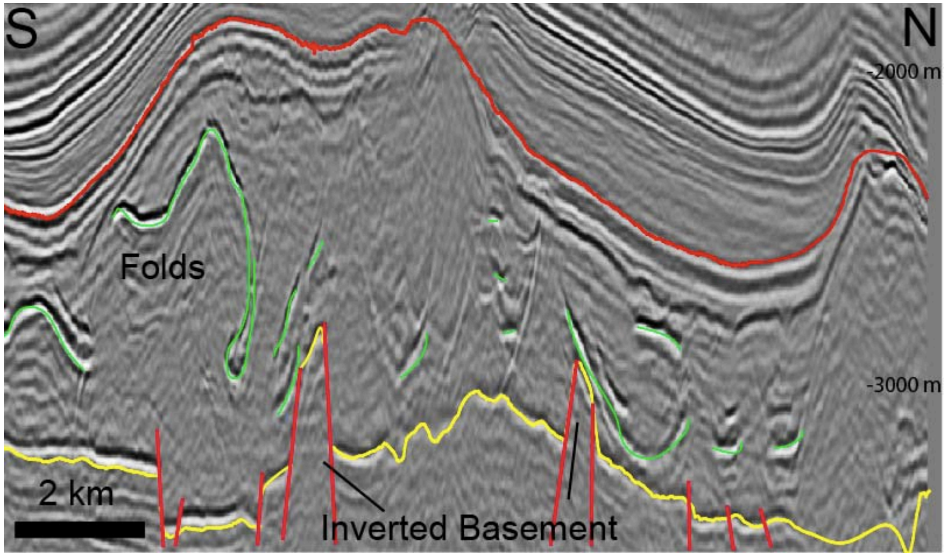
Van Gent et al, in press, available online, J Structural Geology

W-offshore stringer structure

click to view movie on YouTube

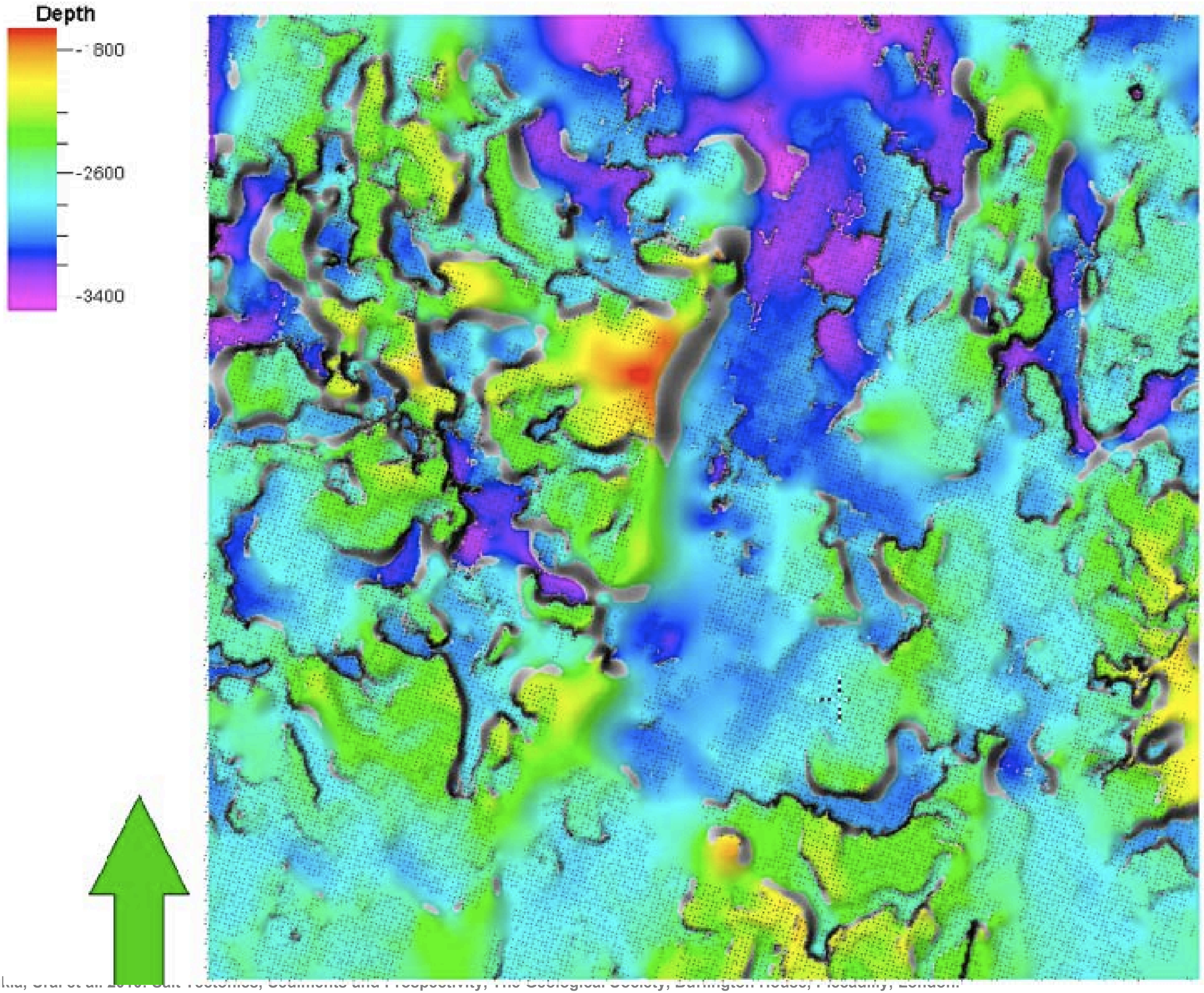


click to view movie on YouTube



Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

W- offshore - interpolated stringer surface

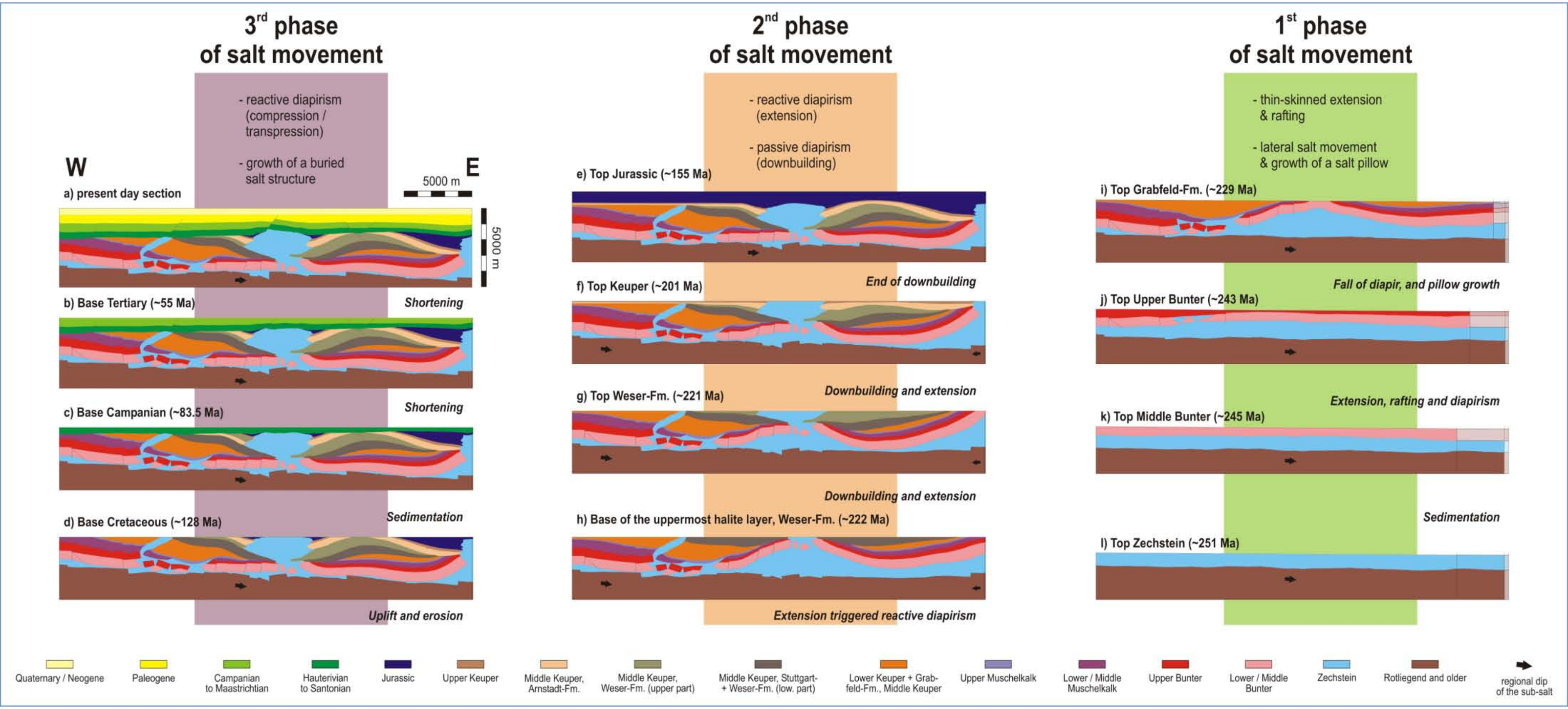


Van Gent et al, inpress, available online, J Structural Geology

Kukla, P.A. et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Prediction of internal structure – Step 1

Kinematics of suprasalt sequence

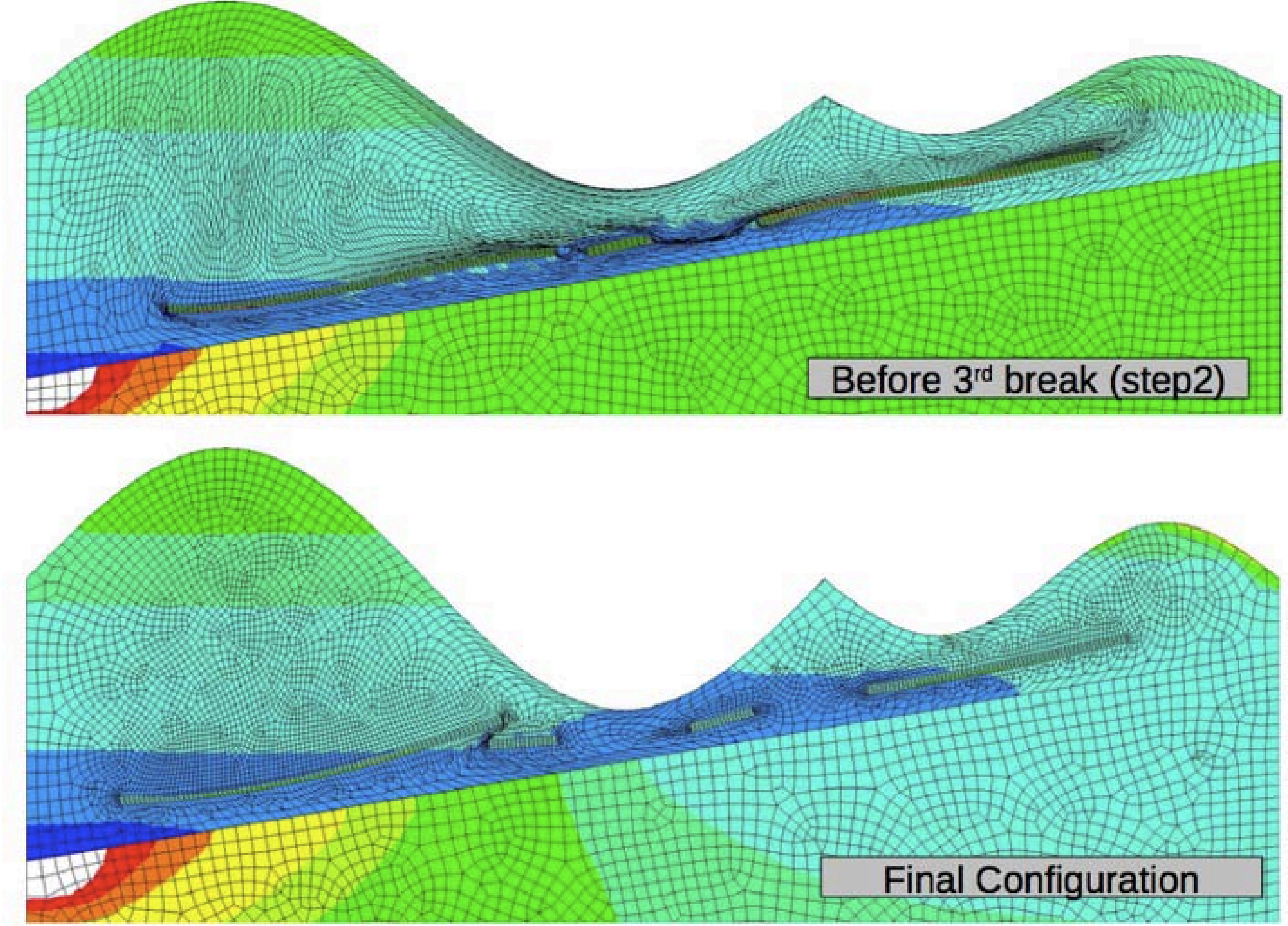


Kukla et al. 2008

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

Prediction of internal structure - Step 2

Finite element modeling driven by reconstruction of suprasalt

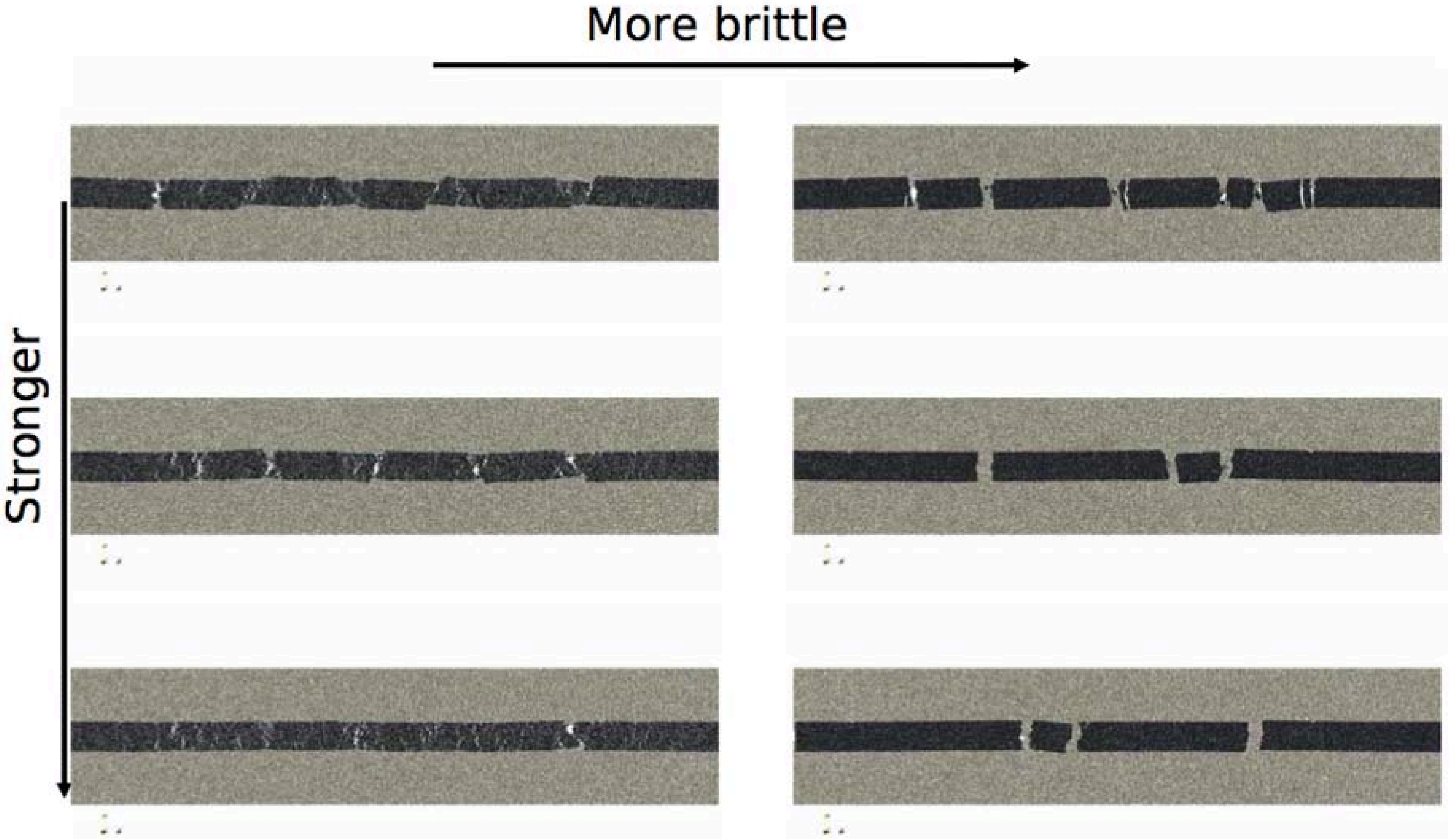


Li et al, accepted; Geol. Soc Special Publication on Salt

Kukla, Urai et al. 2010: Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

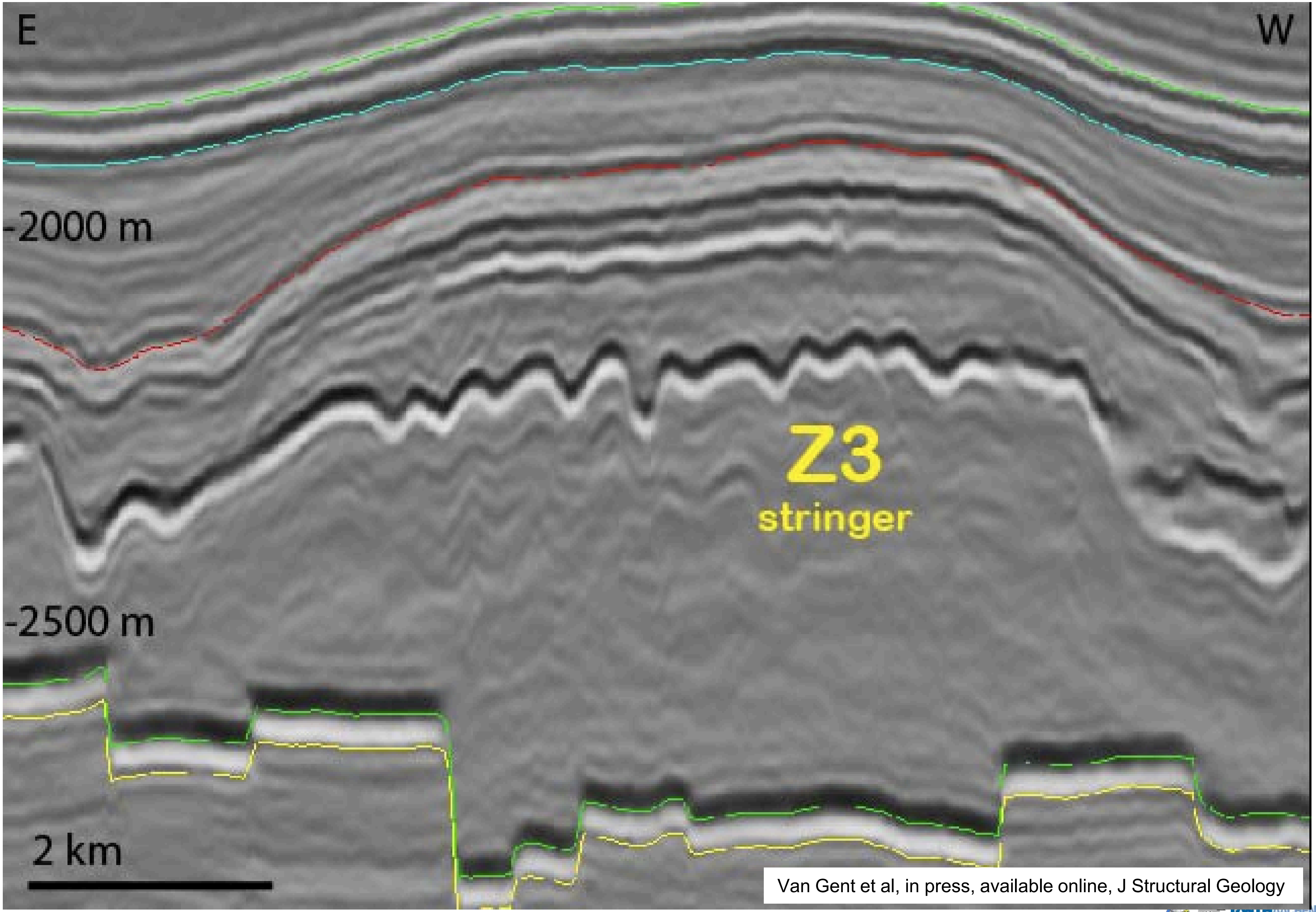
Prediction of internal structure - Step 3

Rupture process modelled using DEM



Steffen Abe, unpublished work

Compare results with observations



Van Gent et al, in press, available online, J Structural Geology

Kukla, Urai et al. 2010. Salt Tectonics, Sediments and Prospectivity, The Geological Society, Burlington House, Piccadilly, London.

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RWE Dea

GDF SUEZ
REDISCOVERING ENERGY

HALLIBURTON
(Knowledge Systems Inc.)

midland valley
the structural geology experts

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