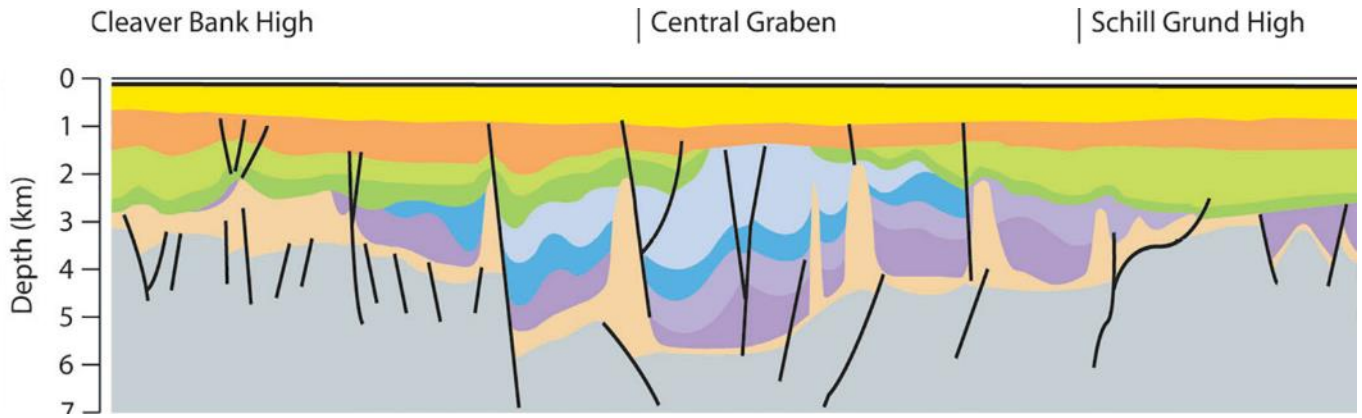
Universiteit Utrecht

TKI GAS
Topsector Energie

Bottom up, the North Sea Central Graben in light of the regional crustal structure



Jeroen Smit, Manfred Lafosse, David Borghouts and Jan-Diederik van Wees

j.h.w.smit@uu.nl

ebn NEPTUNE ENERGY wintershall

The Dutch Central Graben in the regional tectonic framework

Building on the foundations of TKI-1 project: Tectonic Models for shale gas basins (2013-2017):

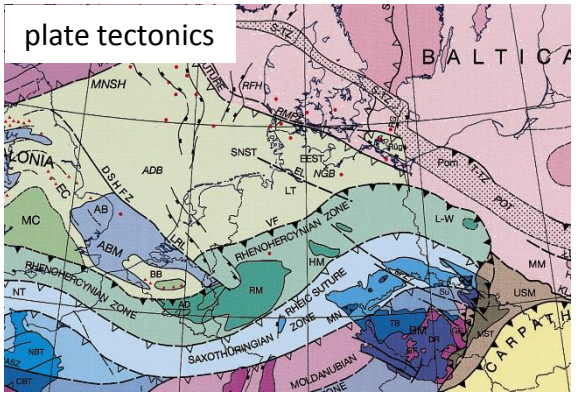
1. Crustal structure of the Southern North Sea
2. The early history of the Southern North Sea Basin, structuration of the upper crust, fault network, basins and highs, …

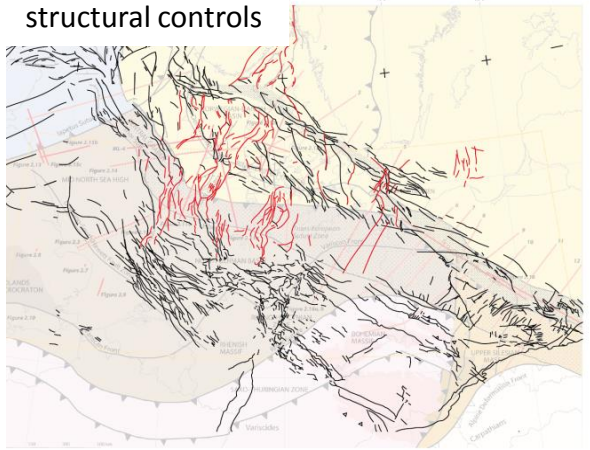
Scales: From Suture to Suture and across Sutures

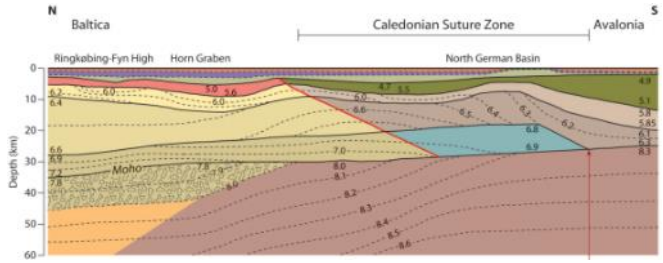
Zoom in

3. The Dutch Central Graben,

From Moho to Qty, Northern Dutch Offshore



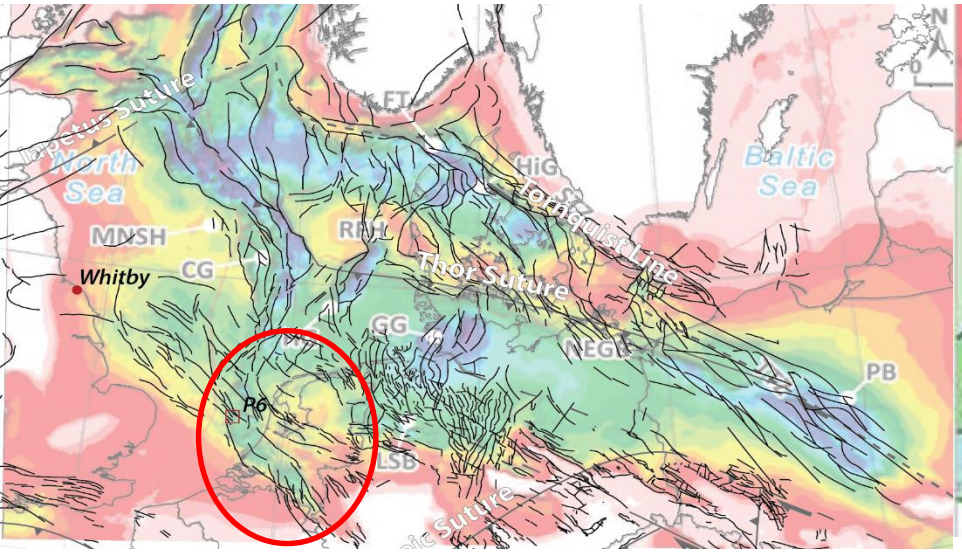


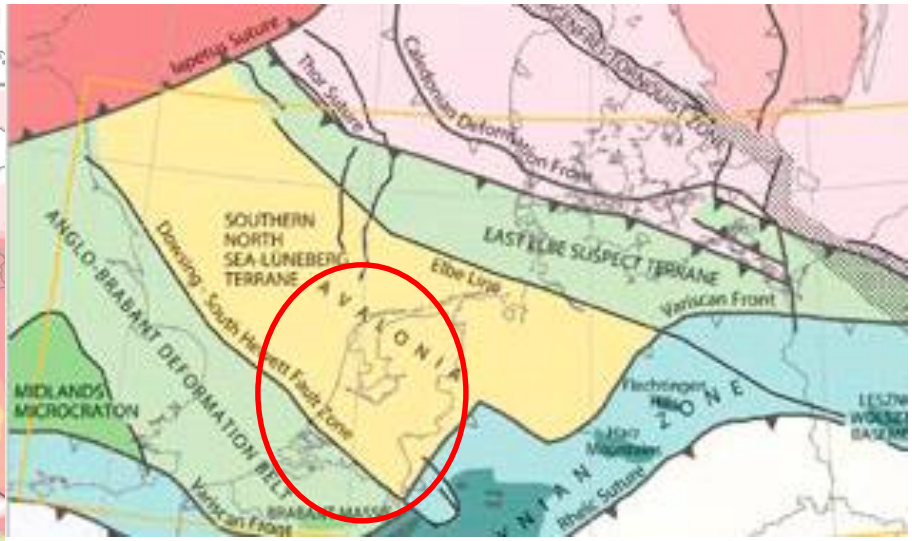


Crustal model

Step 1 : Understand crustal structure of the Southern North Sea and surroundings

Northern Europe: Deep Basins on top of old sutures





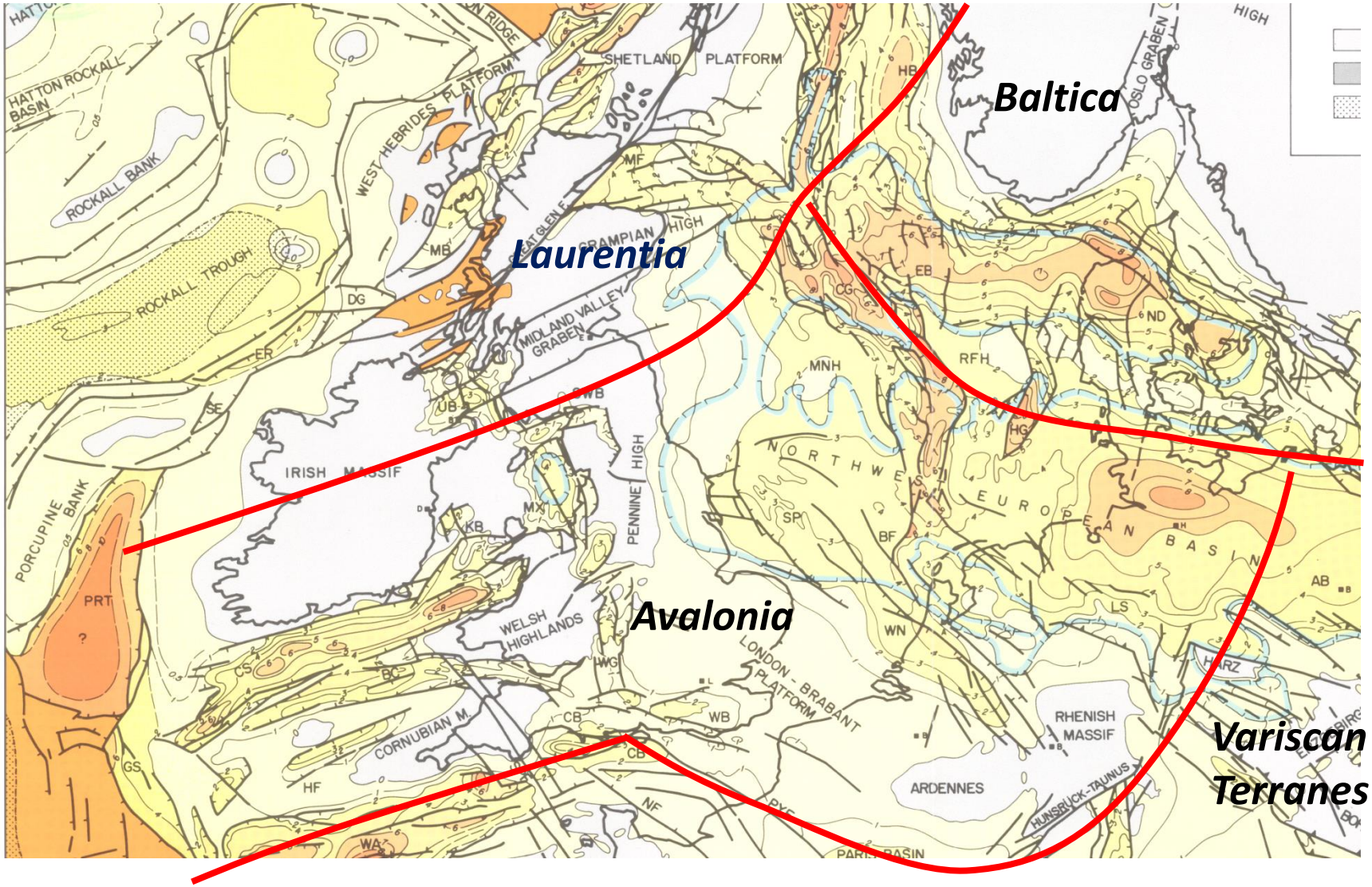
Map from Maystrenko et al., 2012, Faults compiled from diff. sources

Pharaoh et al., 2010

Little direct data on basement => confusion

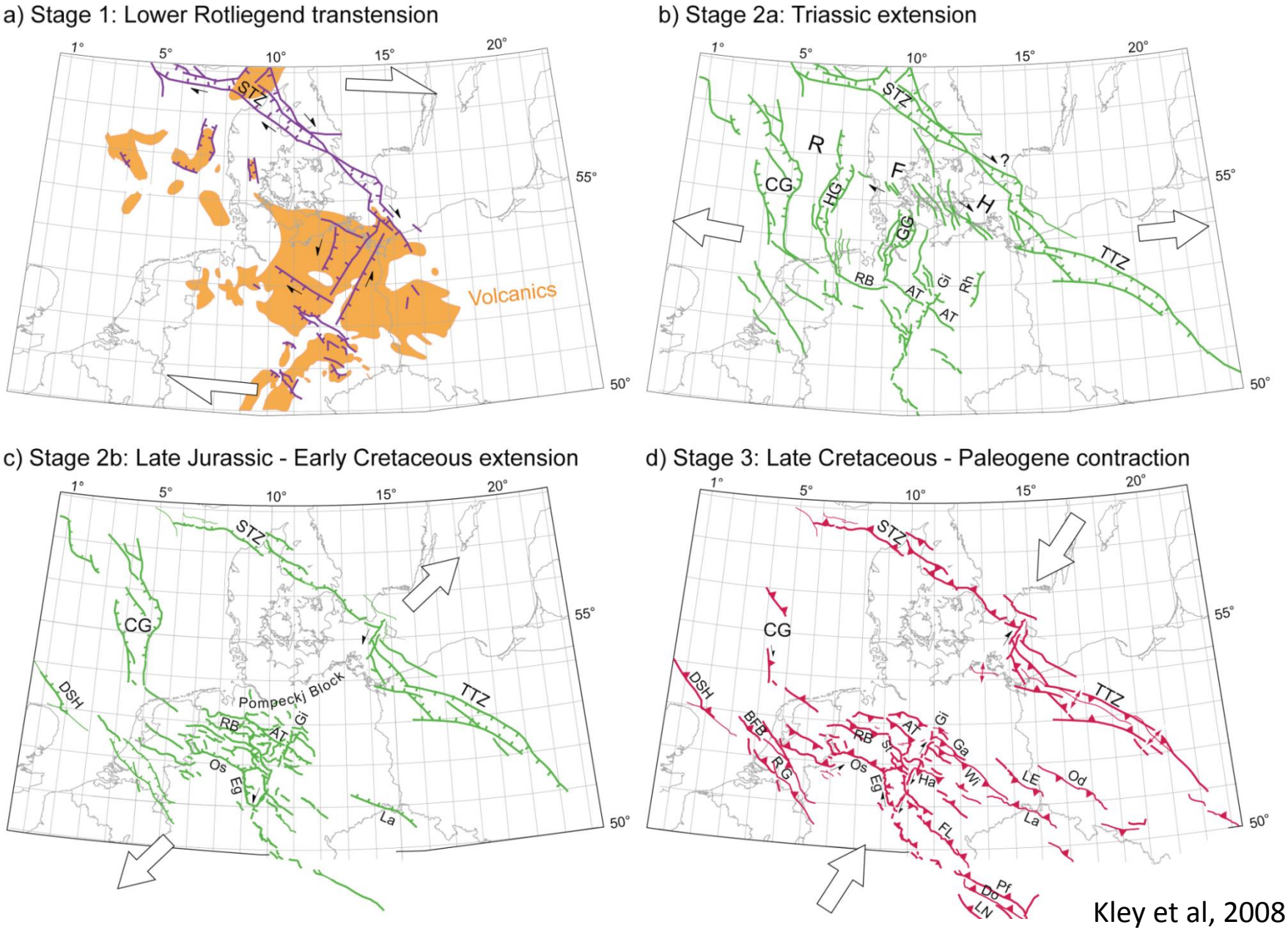
Little chance for new deep seismic lines

complicated fault and basin network



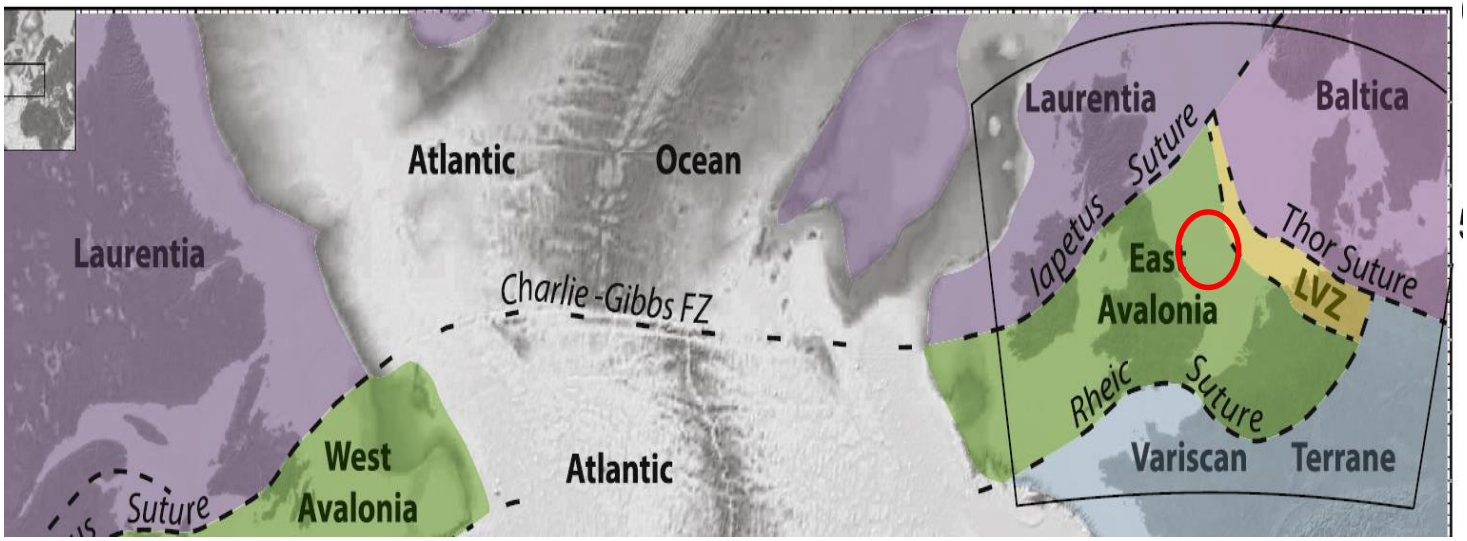
Ziegler, 1990

Multiple tectonic phases since the Late Carboniferous Variscan collision

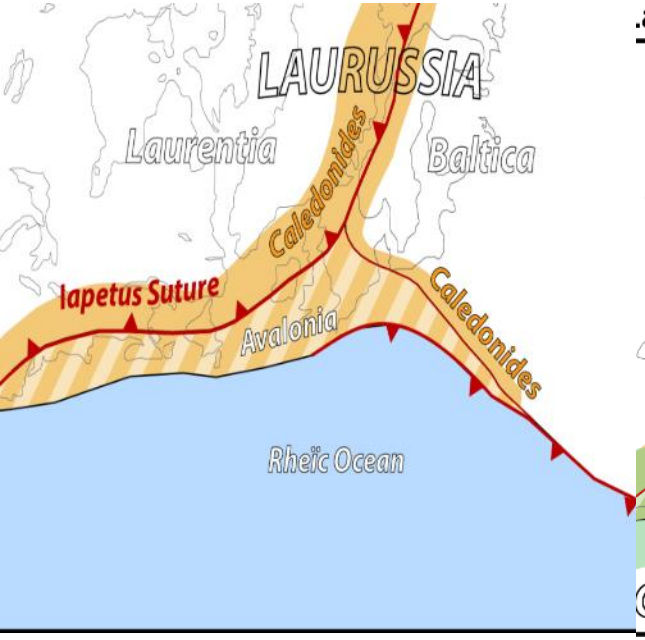


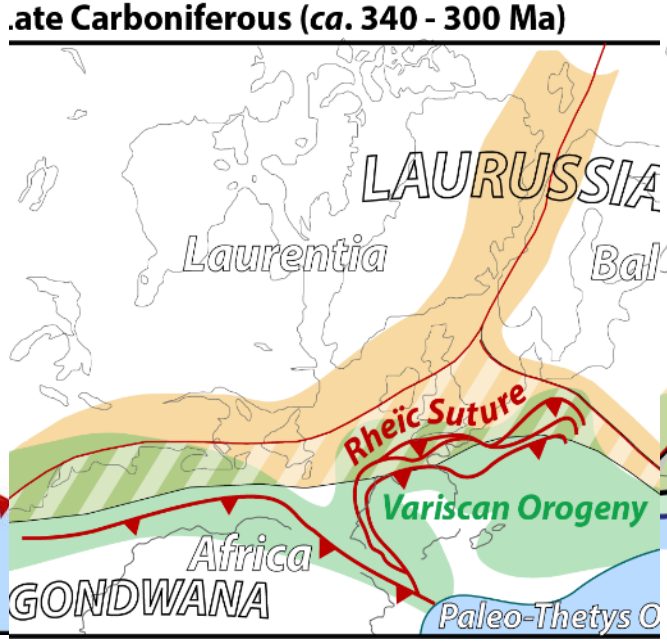
Kley et al, 2008

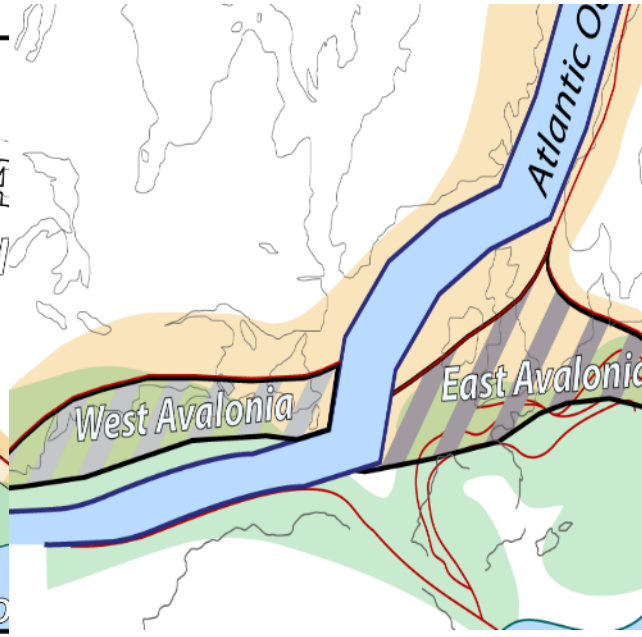
But first : Avalonia, a micro continent



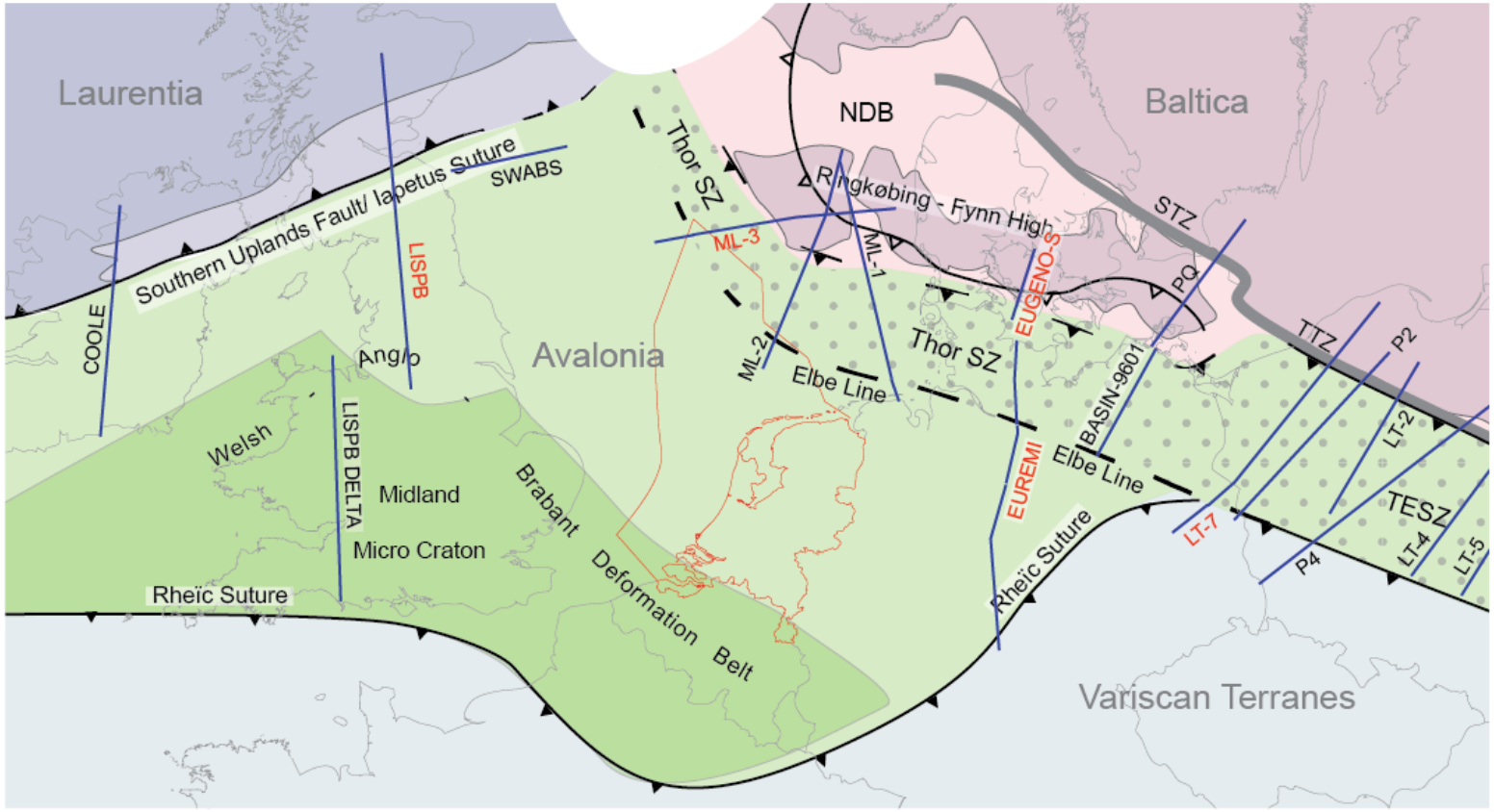
Mid-Paleozoic – Mesozoic







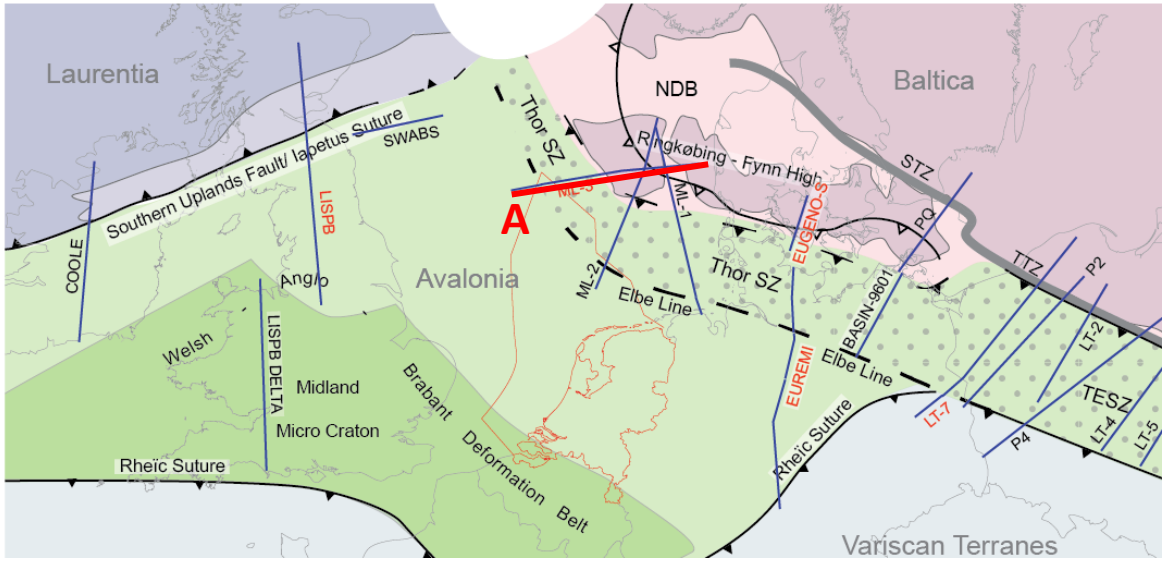
Can we extract more from existing deep seismic lines?



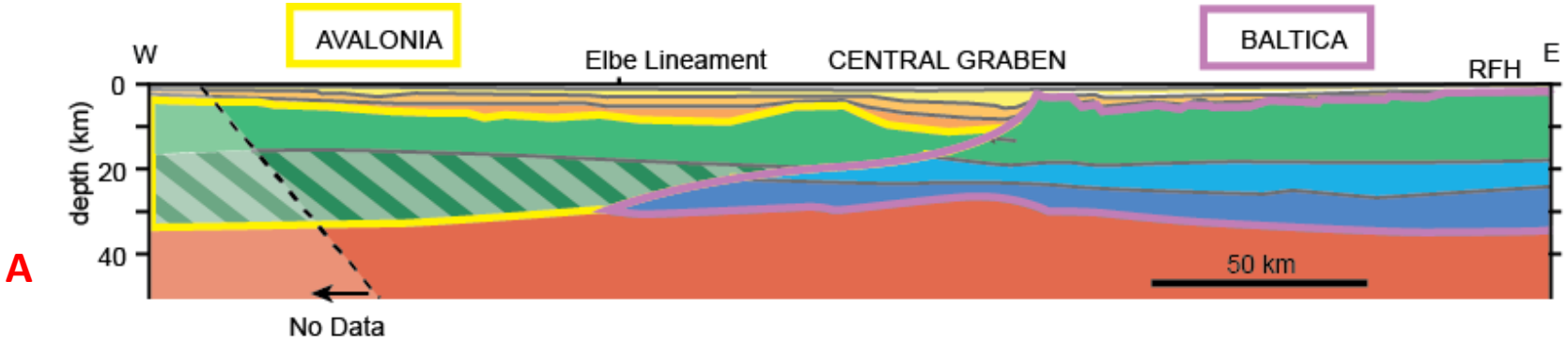
Smit et al, 2016

We compare the velocity structure along deep seismic refraction profiles to extract information on crustal composition and structure

Reinterpretation of deep refraction seismic



Classical interpretation of profile across Central Graben



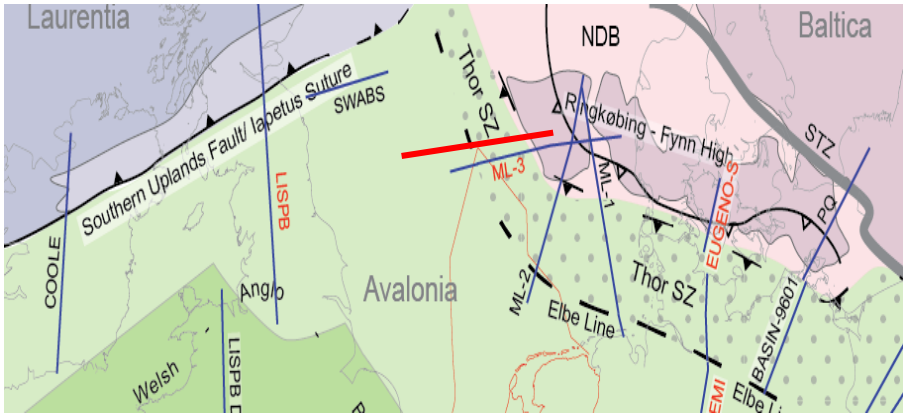
Nielsen et al., 2000; Lyngsie et al., 2007

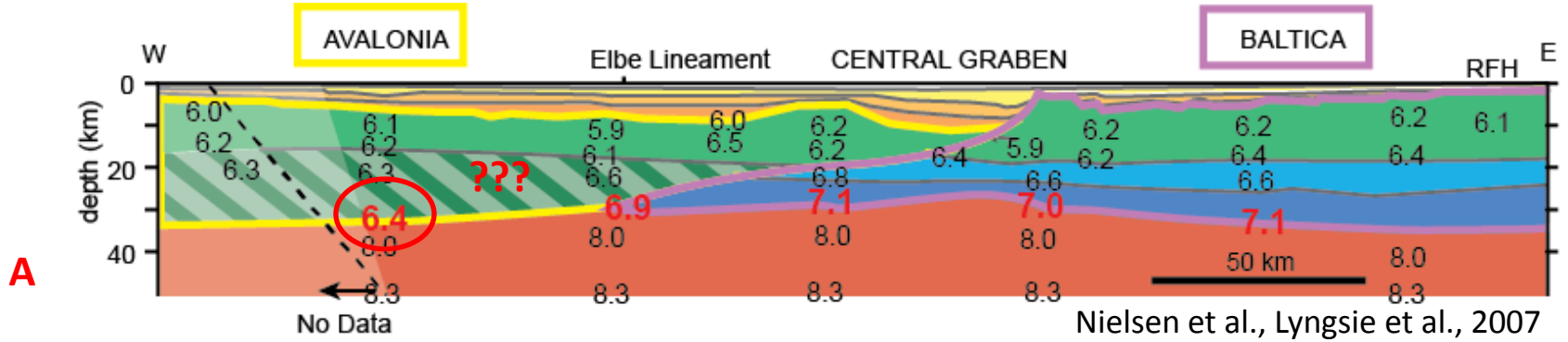
Reinterpretation of deep refraction seismic

Different types of crust of crust have distinct seismic velocities

Especially velocities at the base of the lower crust are indicative

Phanerozoic (Avalonia): 6.6 - 6.8
Cratonic (Baltica): 6.8 - 7.1
(Vp in km/s)





A

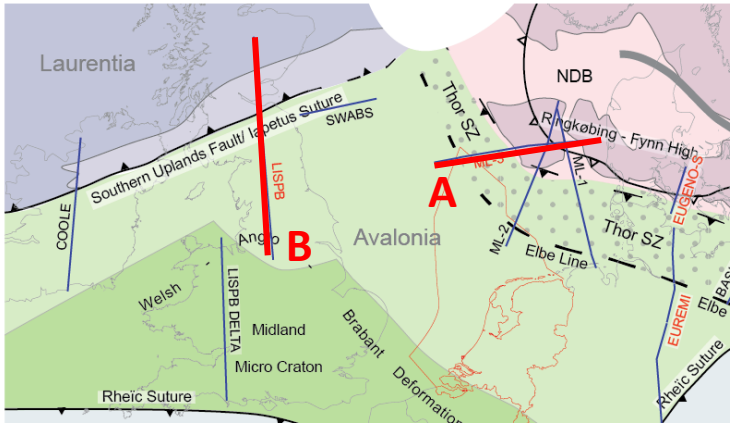
Nielsen et al., Lyngsie et al., 2007

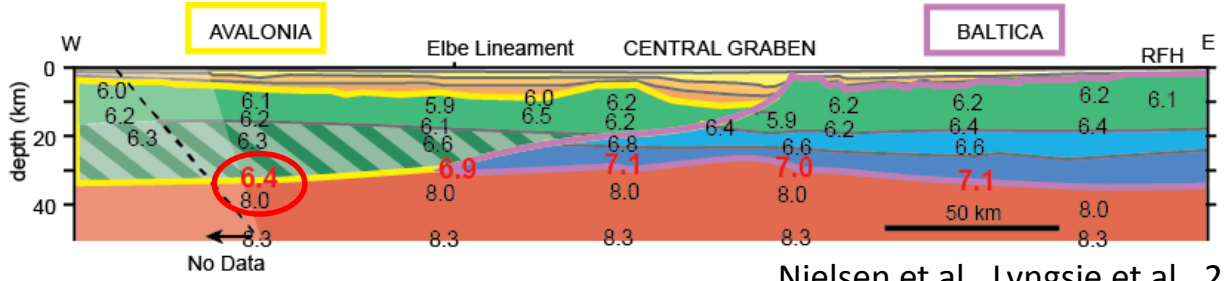
6.4 km/s typical for mid-crustal granites/gneisses and certain serpentinites

Does Avalonian crust have abnormal low seismic velocities ?

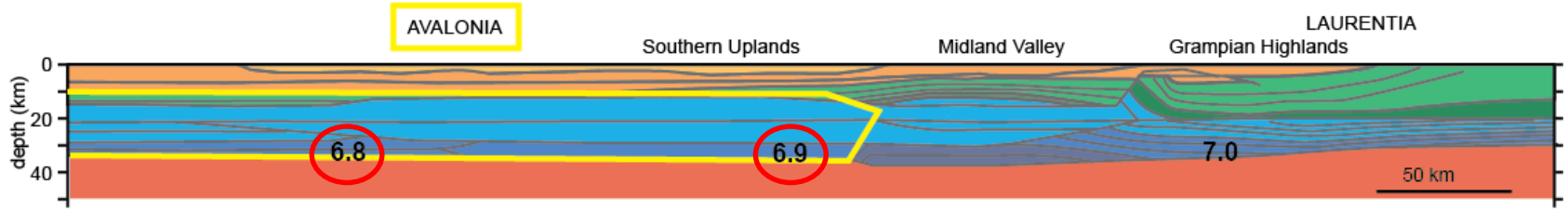
Reinterpretation of deep refraction seismic

Comparison with Avalonia in Britain along Iapetus Suture





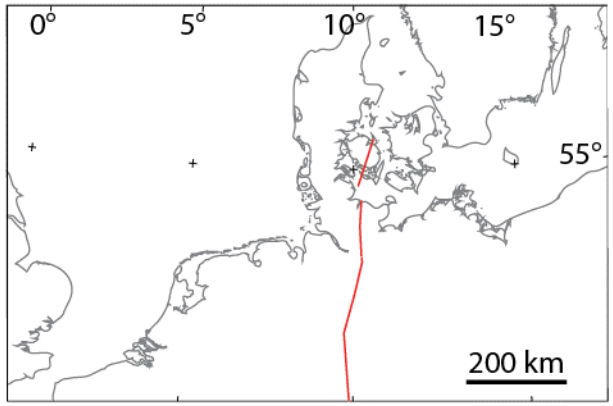
Nielsen et al., Lyngsie et al., 2007

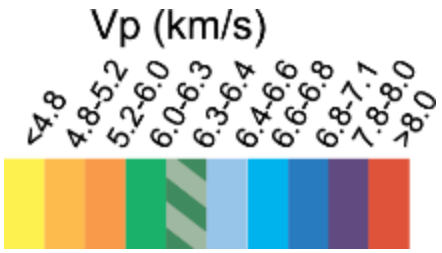


Barton, 1992

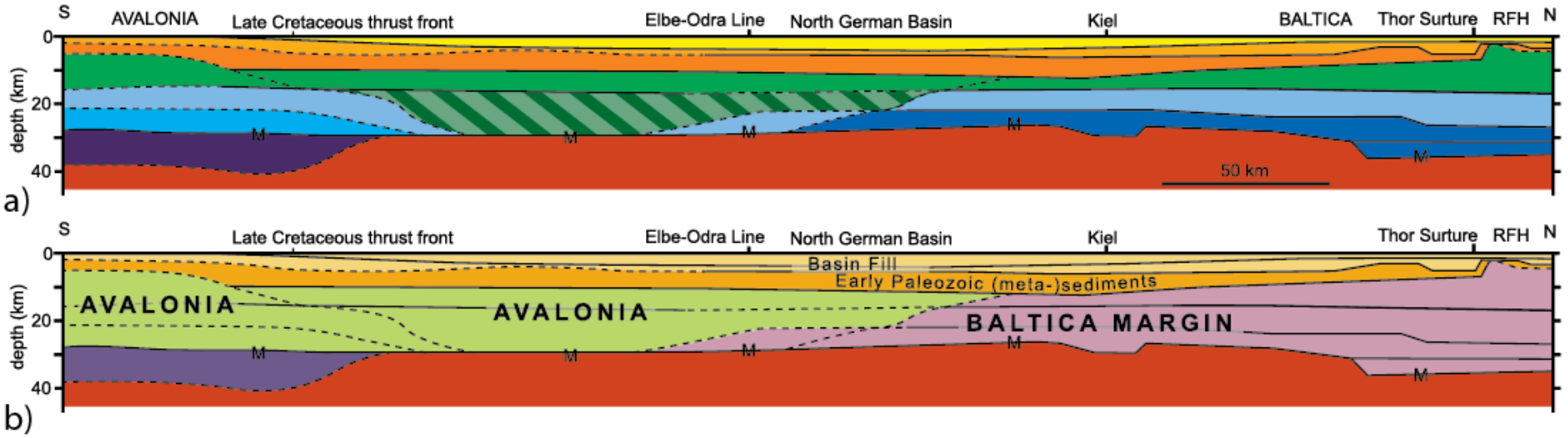
Is the low velocity crust south of Baltica really part of Avalonia?
Where is Avalonia in the North Sea???

The Thor Suture between Avalonia and Baltica, today

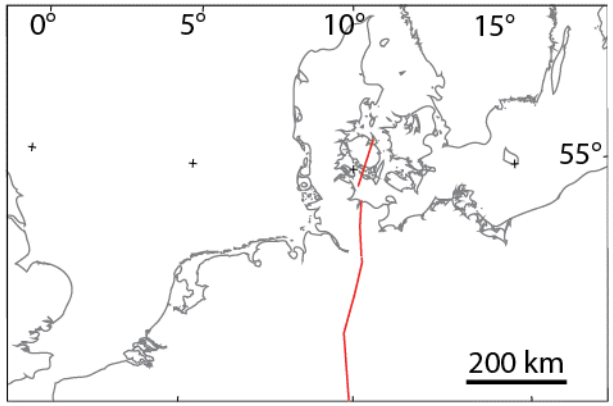


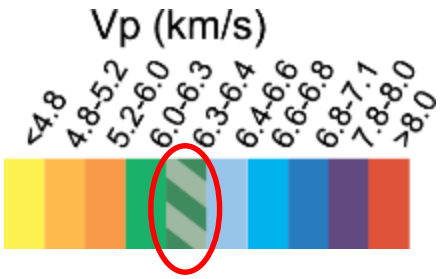


Profile B: European GeoTraverse (EGT)

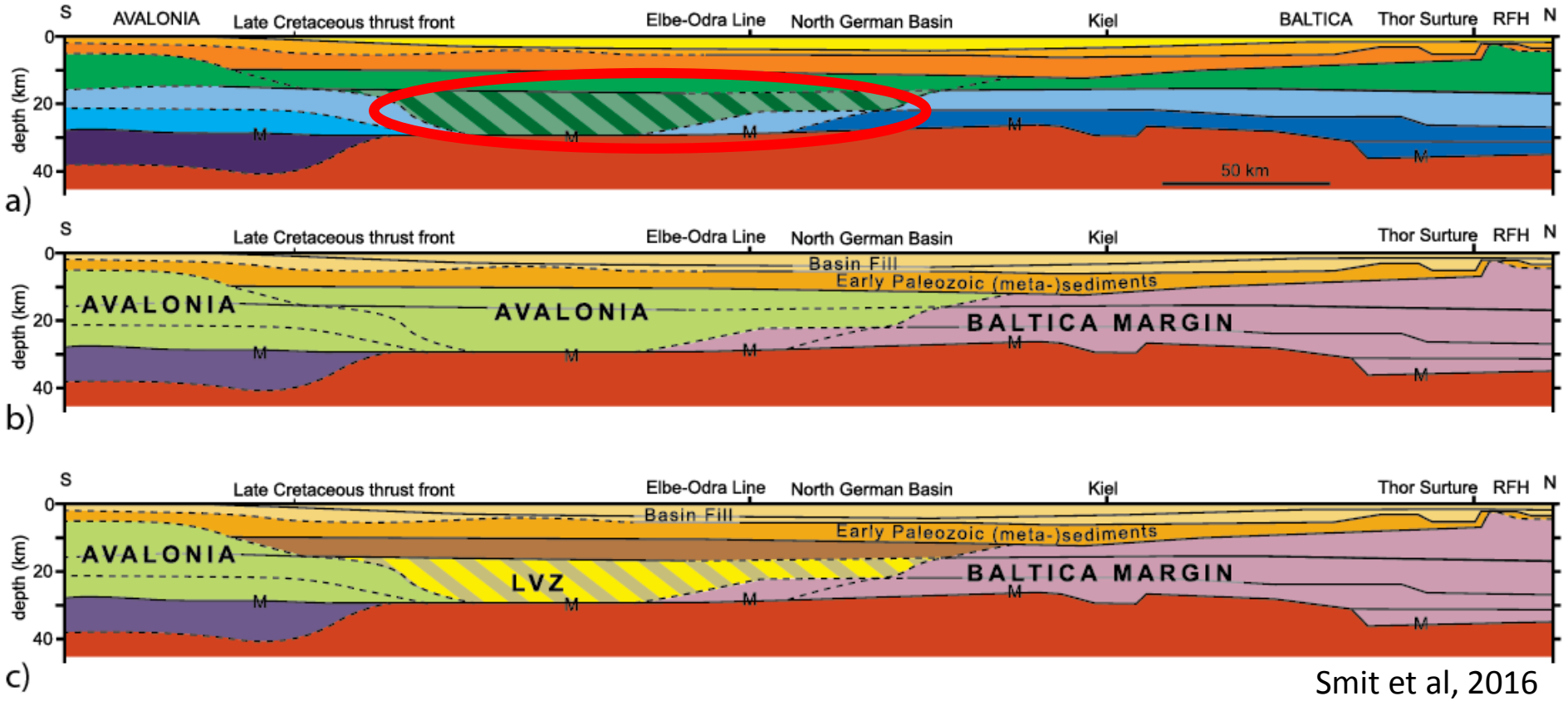


The Thor Suture between Avalonia and Baltica, today





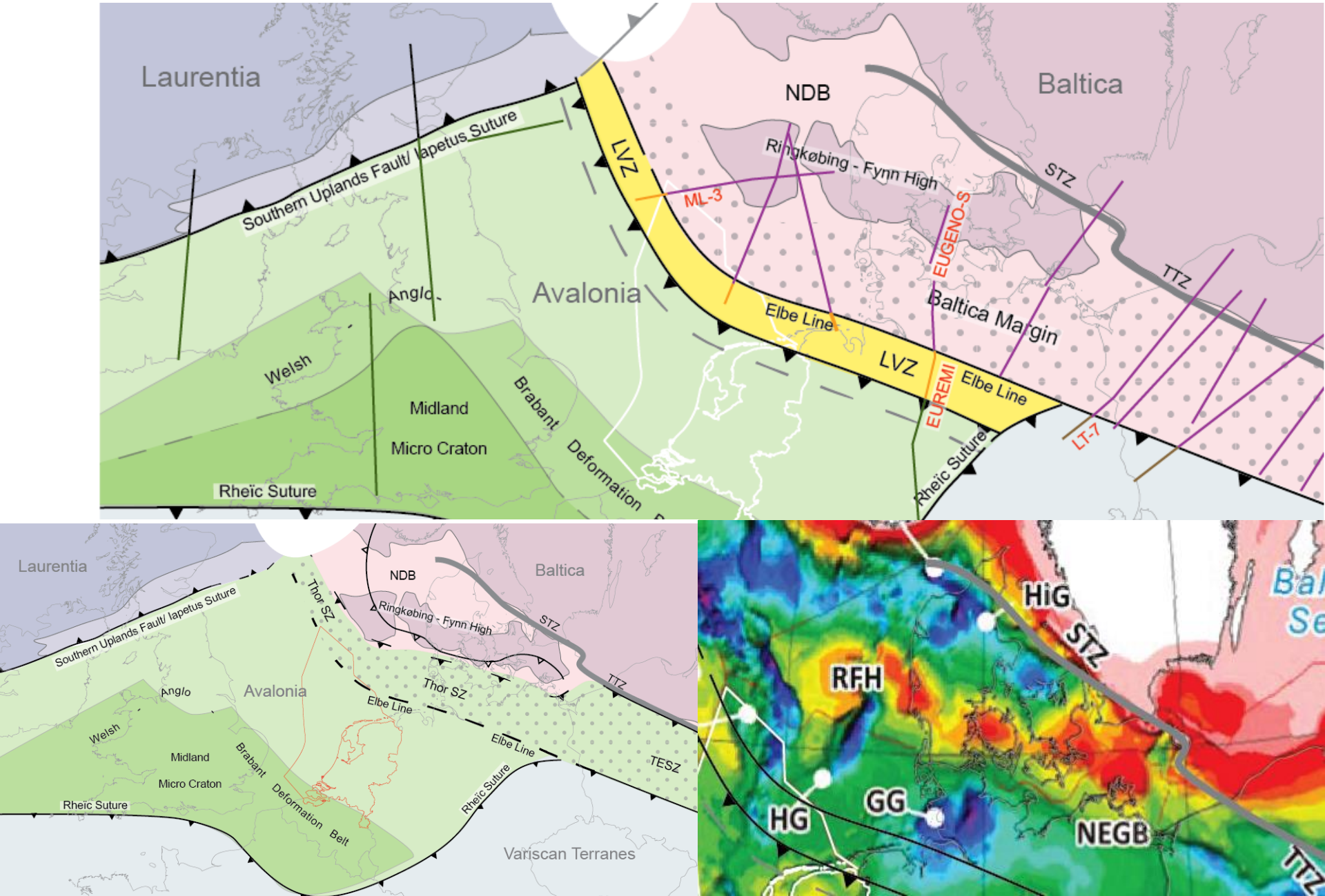
Profile B: European GeoTraverse (EGT)



Smit et al, 2016

A band of low velocity crust separates Baltica from Avalonia

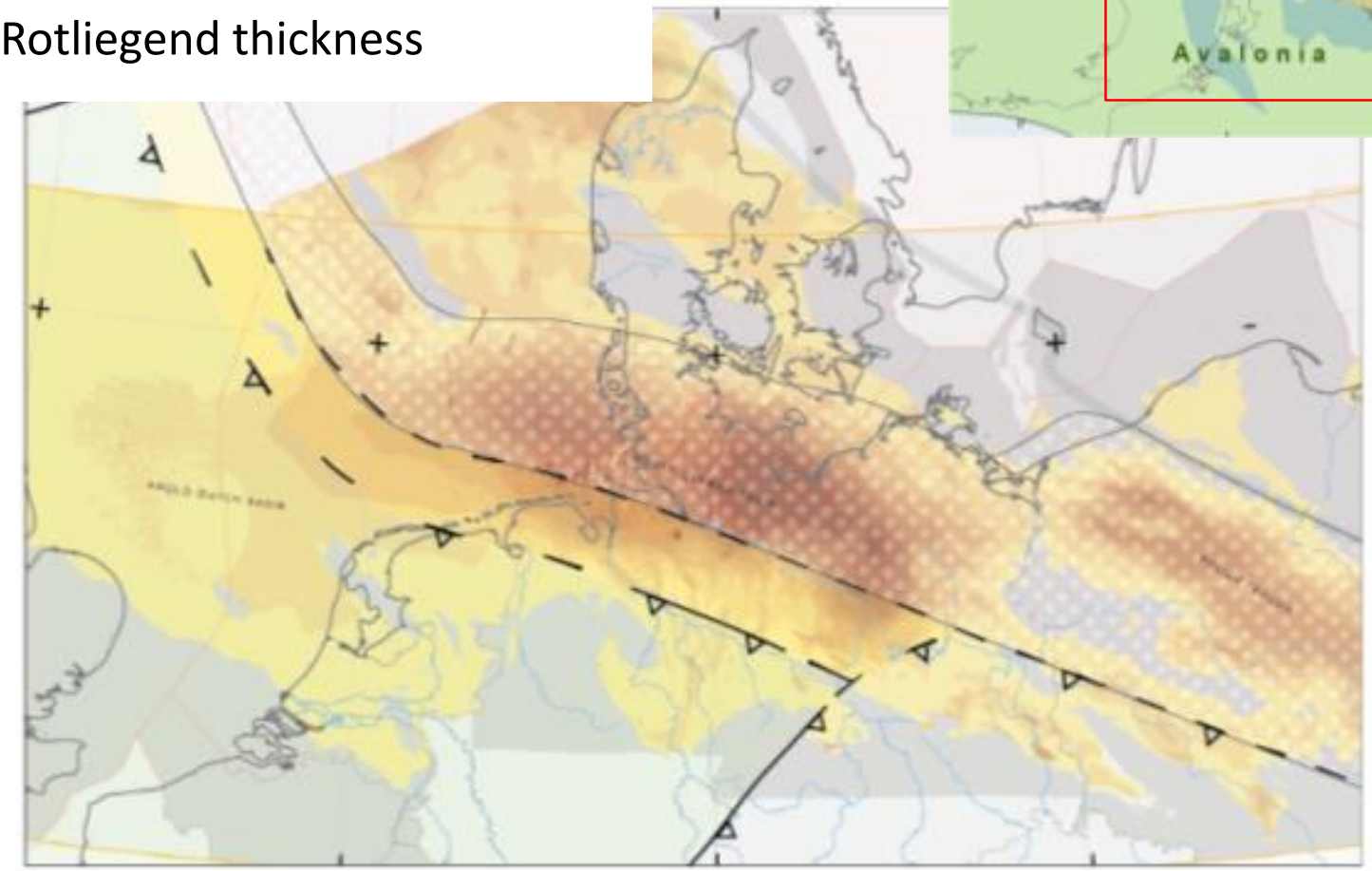
New Plate Tectonic Map based on reinterpretation refraction seismic



Crustal model

Close relation with sedimentary “black hole” of North German Basin

Rotliegend thickness

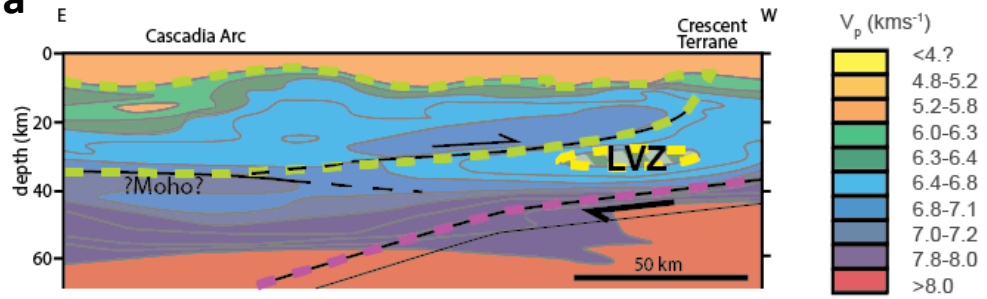


SPBA Atlas, 2010

What is the gap between Avalonia and Baltica, what happened?

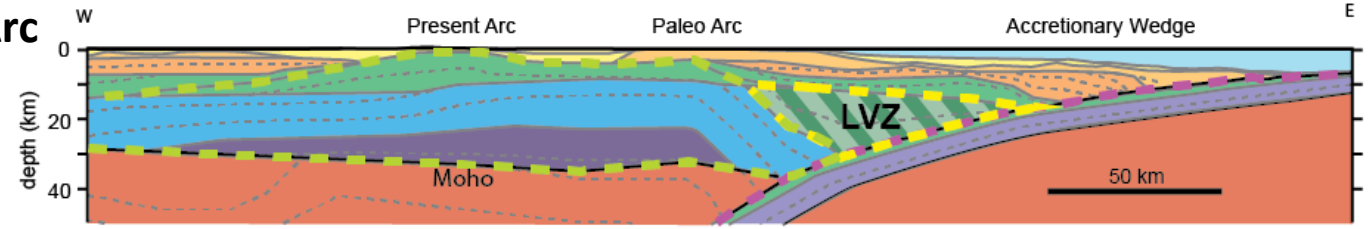
Comparison with active subduction zones

Cascadia



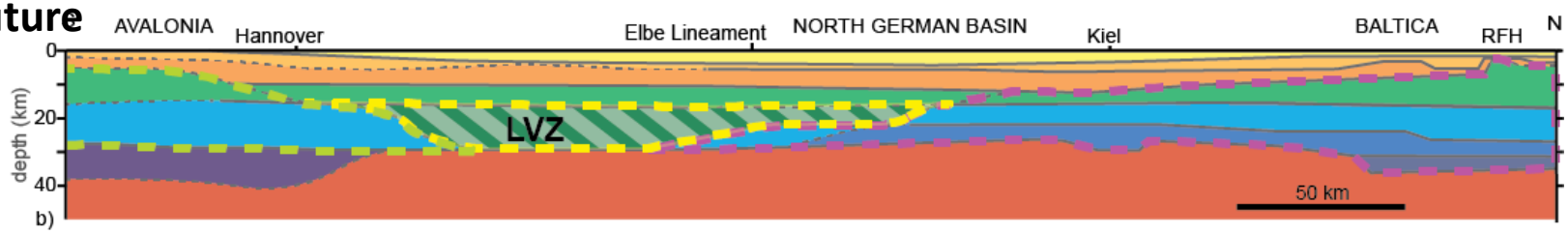
Ramachandran et al., 2006

Kuril Arc



Nakanishi et al., 2009

Thor Suture



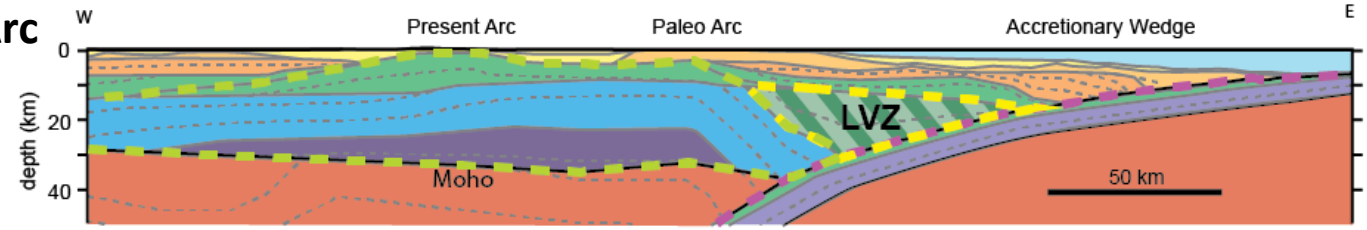
Smit et al, 2016

LVZ's are found in some of the largest active subduction zones

Is the Low Vp Zone along Thor Suture a remnant accretionary complex?

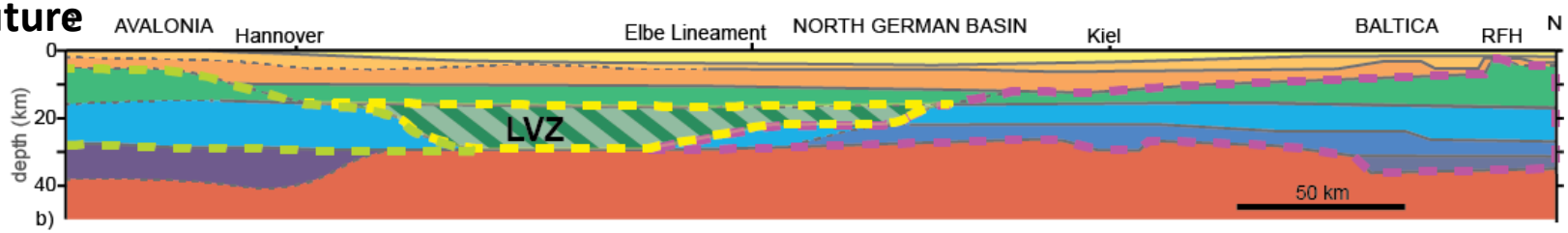
From Kuril Arc to Thor Suture ???

Kuril Arc



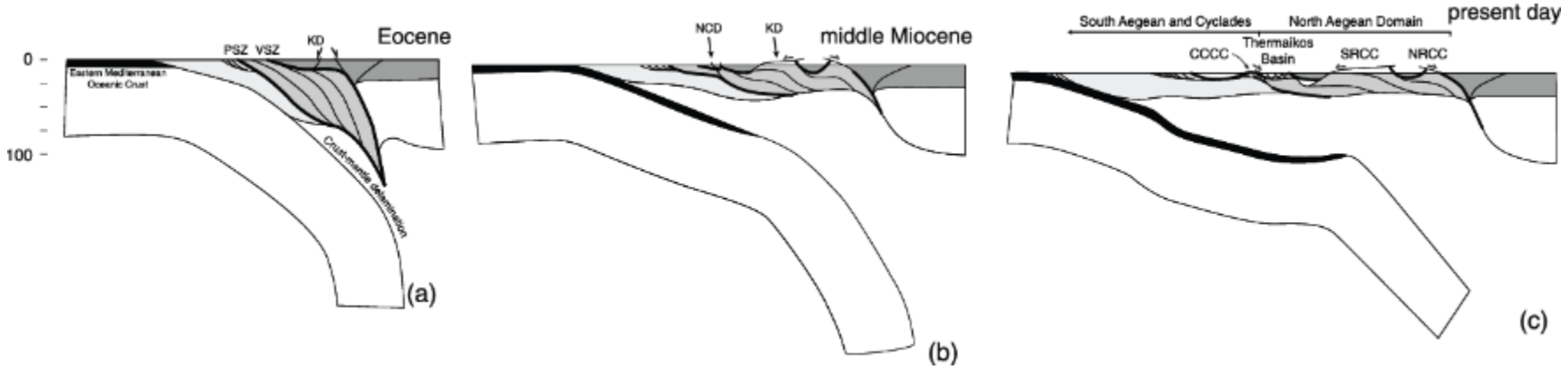
Nakanishi et al., 2009

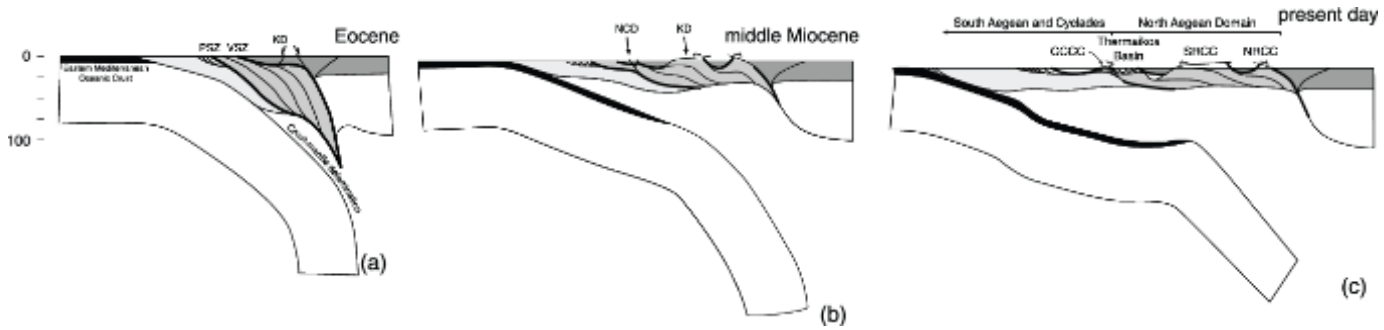
Thor Suture

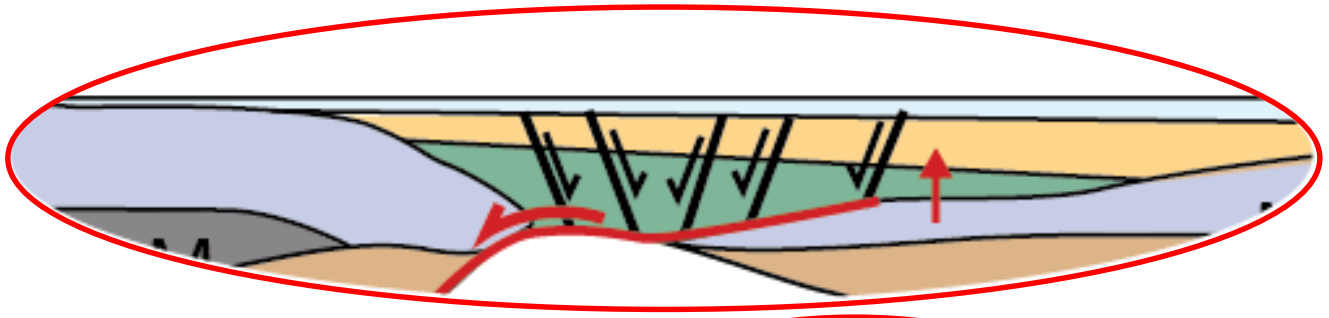


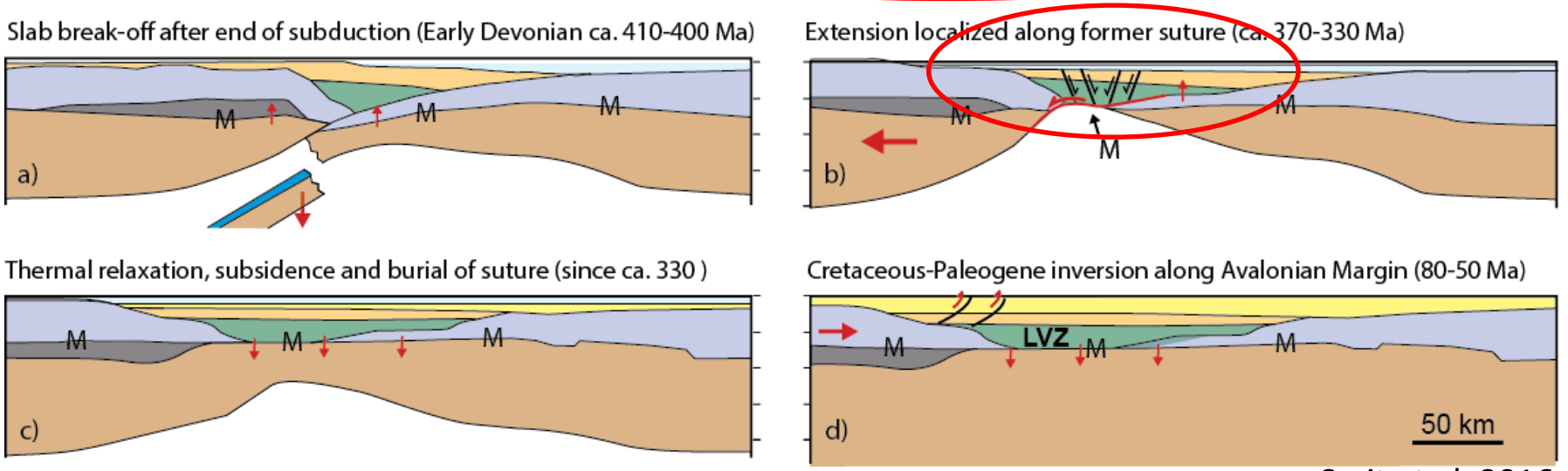
Smit et al, 2016

Inspiration from the Eastern Mediteranean (Kydonakis et al., 2015)









Smit et al, 2016

>50 - 100 km extension along Thor Suture before the late Carboniferous

During Late Devonian – Early Carboniferous ?

CONCLUSIONS

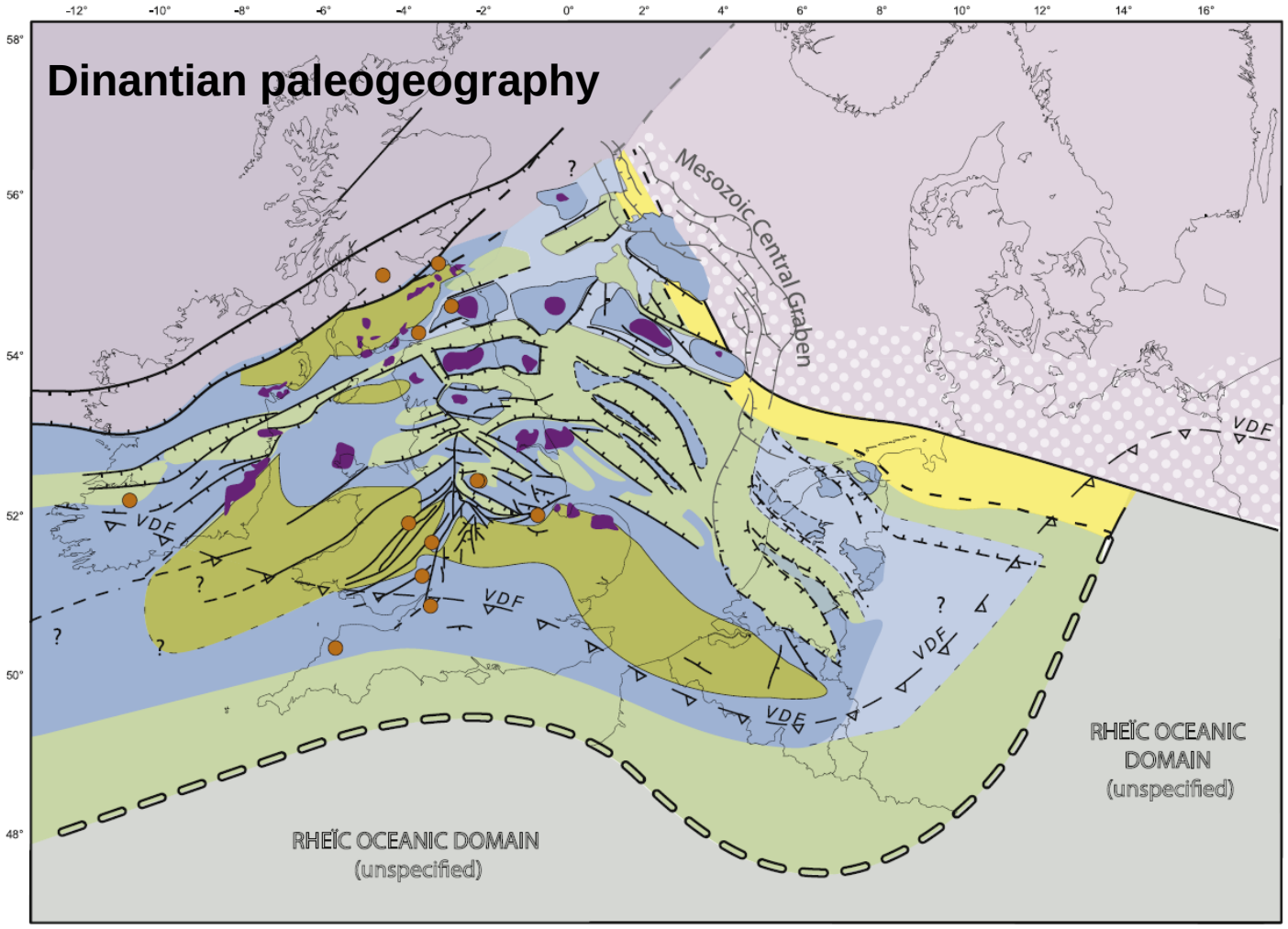
We can revise a crustal map of deeply buried suture zones based on seismic refraction data, regional fault network and basin subsidence inversion patterns

The LVZ forms a 50-100 km-wide separate crustal "unit" between Avalonia and Baltica

The analogy with active subduction zones suggests that the lower crustal LVZ along the TSZ is composed of the remnants of the Caledonian accretionary complex.

The present-day geometry most probably originates from Pre-Variscan extension and exhumation during Devonian-Carboniferous rifting.

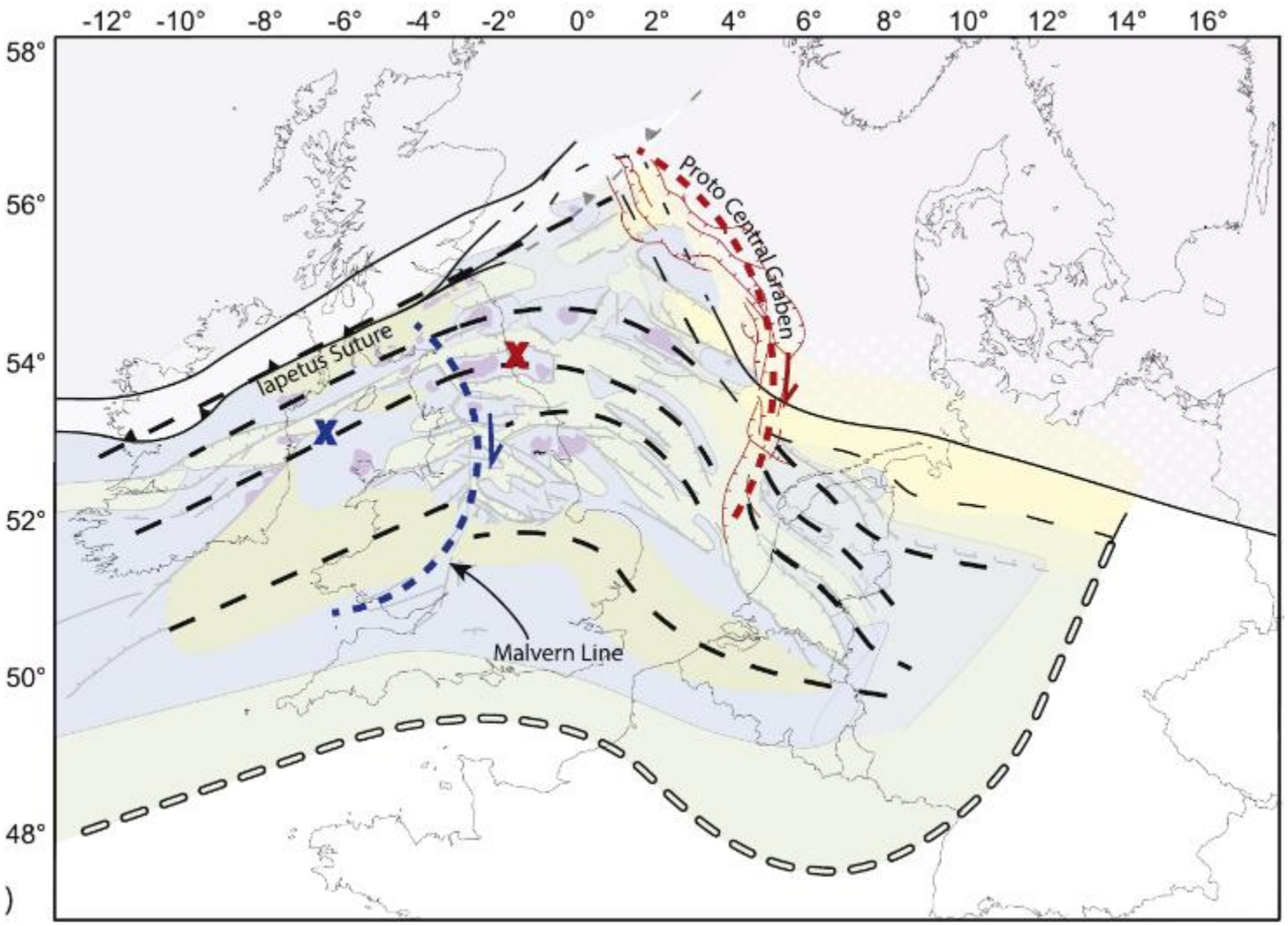
Formation of the Structural Framework



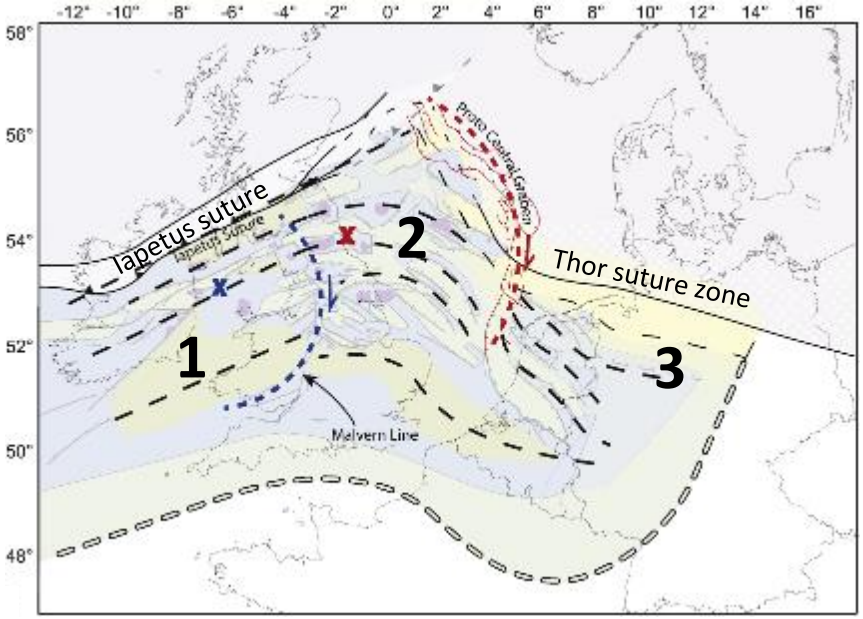
Smit et al, Mar.Petr. Geol., 2018

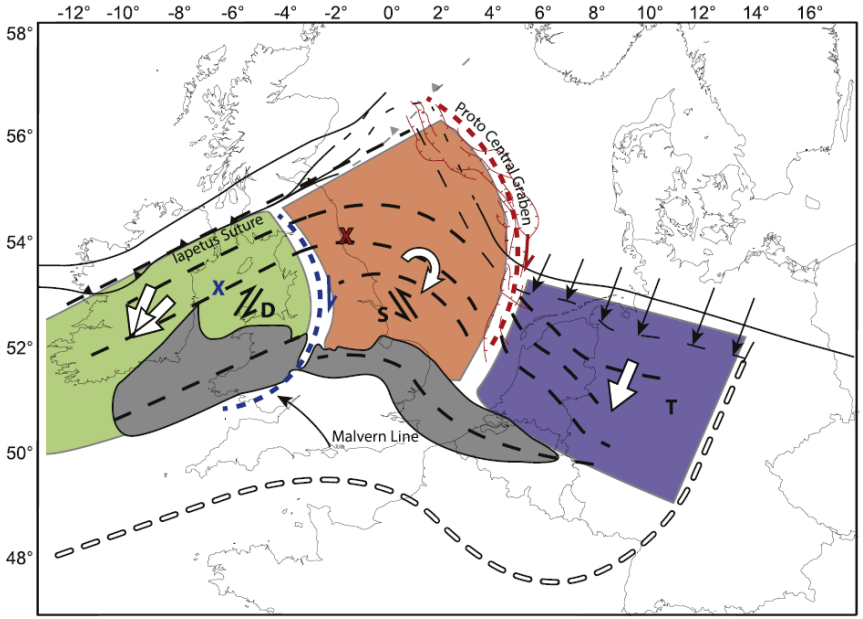
How much of the structural framework can be attributed to the Dinantian extension?

Structural zonation of early Carboniferous Avalonia based on basement trend and deformation style



Smit et al, Mar.Petr. Geol., 2018





Zone 1. west of Malvern Line
- basins are parallel to Iapetus suture
- extension is NNE-SSW to NE-SW

Zone 2. between Malvern Line and proto Central Graben
- Strong rotation, many basins

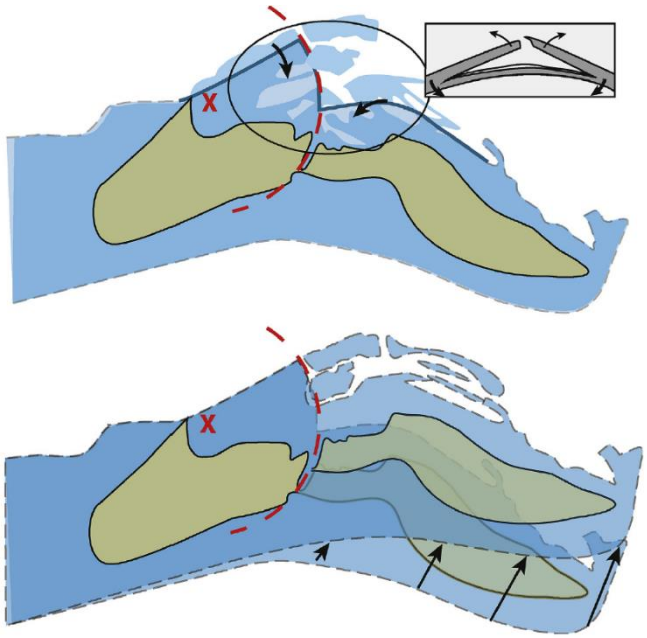
Zone 3. East of proto Central Graben
- Extension localized along paleo-Thor Suture
- extension is NNE-SSW to NE-SW

Proto-Central Graben shear zone separates zones 2 and 3

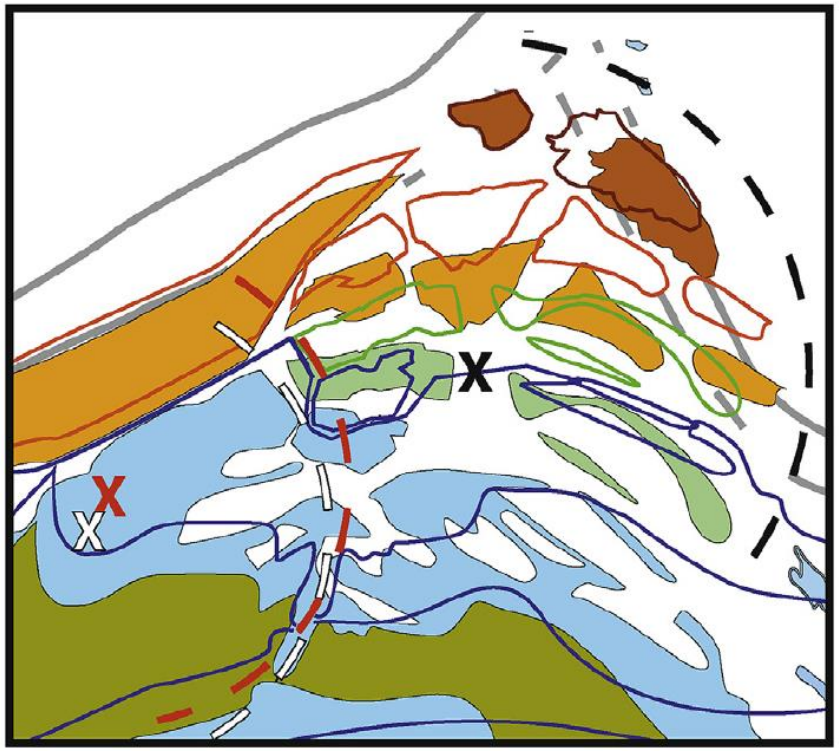
Regional extension is directed ~NNE-SSW to NE-SW

Smit et al, Mar.Petr. Geol., 2018

Dinantian Extension



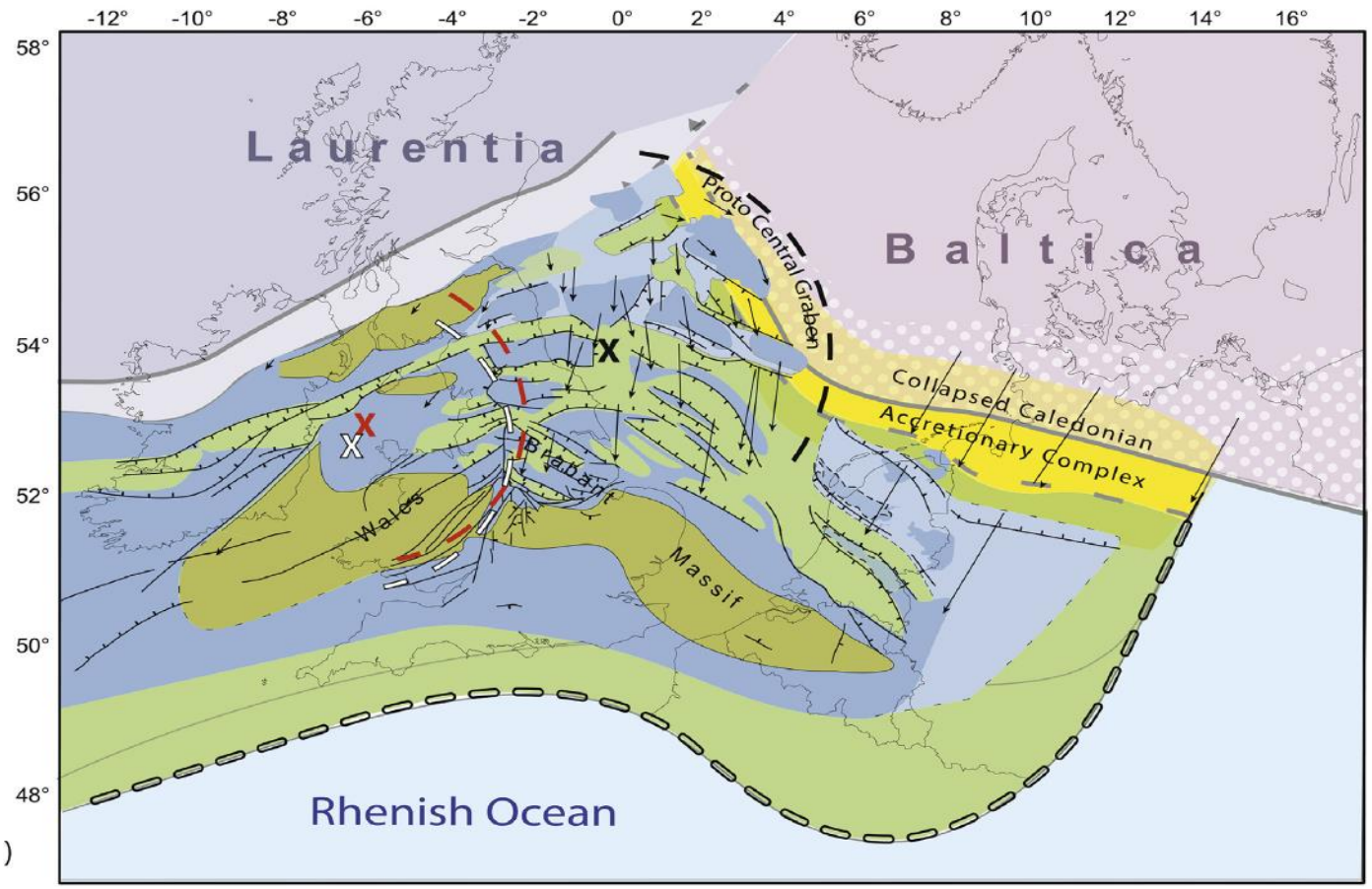
Restoration of Wales-Brabant Massif by rotation along the Malvern Line, a shear zone off-setting the Midlands micro-craton.



Restoration of N-England and adjacent North Sea based on rotation along Malvern Line (red hatched circle segment) and proto Central Graben (black hatched circle segment)

Smit et al, Mar.Petr. Geol., 2018

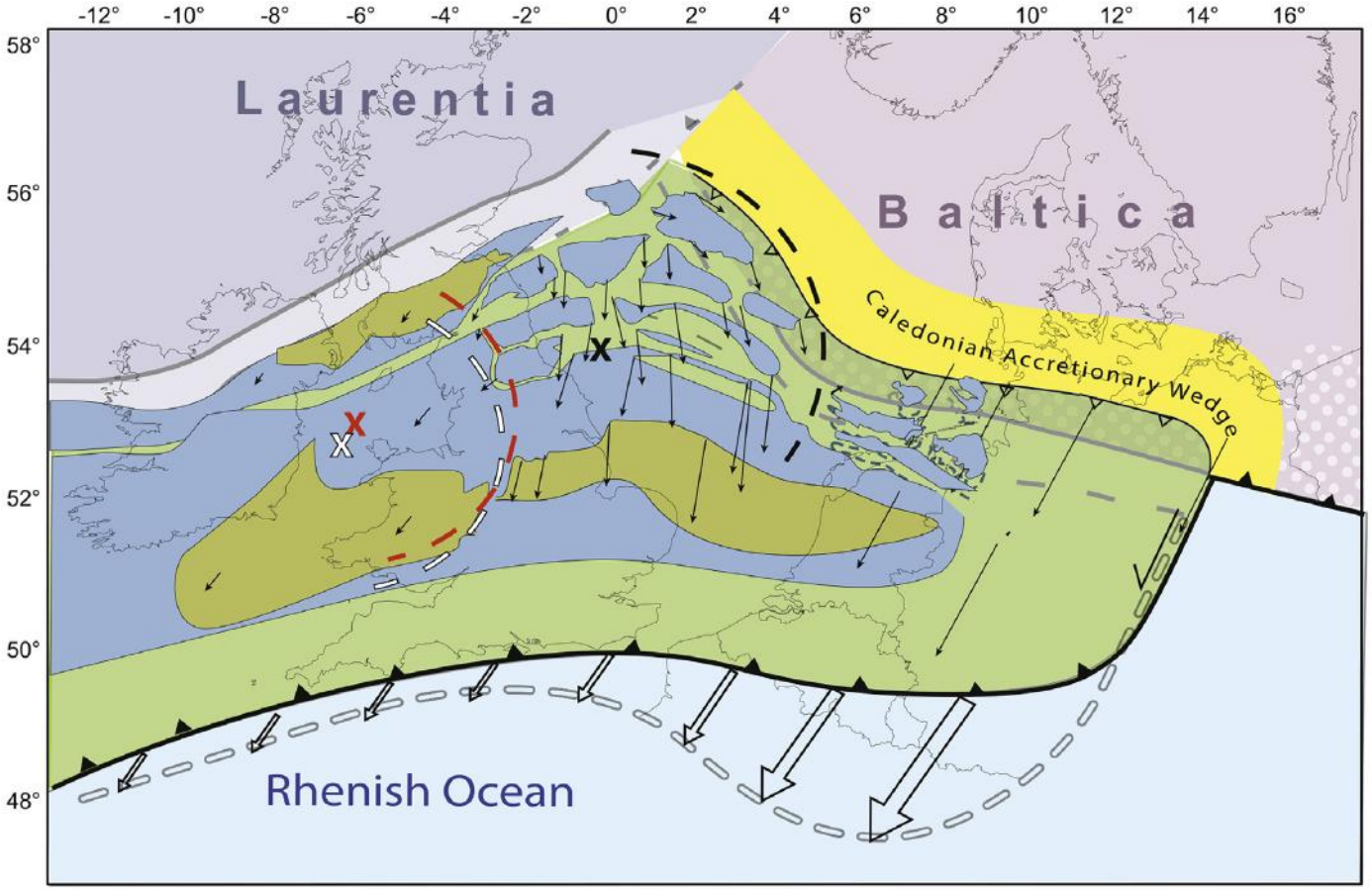
Map view restoration of early Variscan, Lower Carboniferous extension of Avalonia.



Configuration at end of extension with motion vectors (Variscan blocks South of Avalonia excluded). Deformation by SSW-SW directed dextral transtension west of the Malvern Line, rotational sinistral transtension east of it and eduction along Thor Suture with SSW-SW translation with little internal extension that decreases eastward.

Smit et al, Mar.Petr. Geol., 2018

Map view restoration of early Variscan, Lower Carboniferous extension of Avalonia.



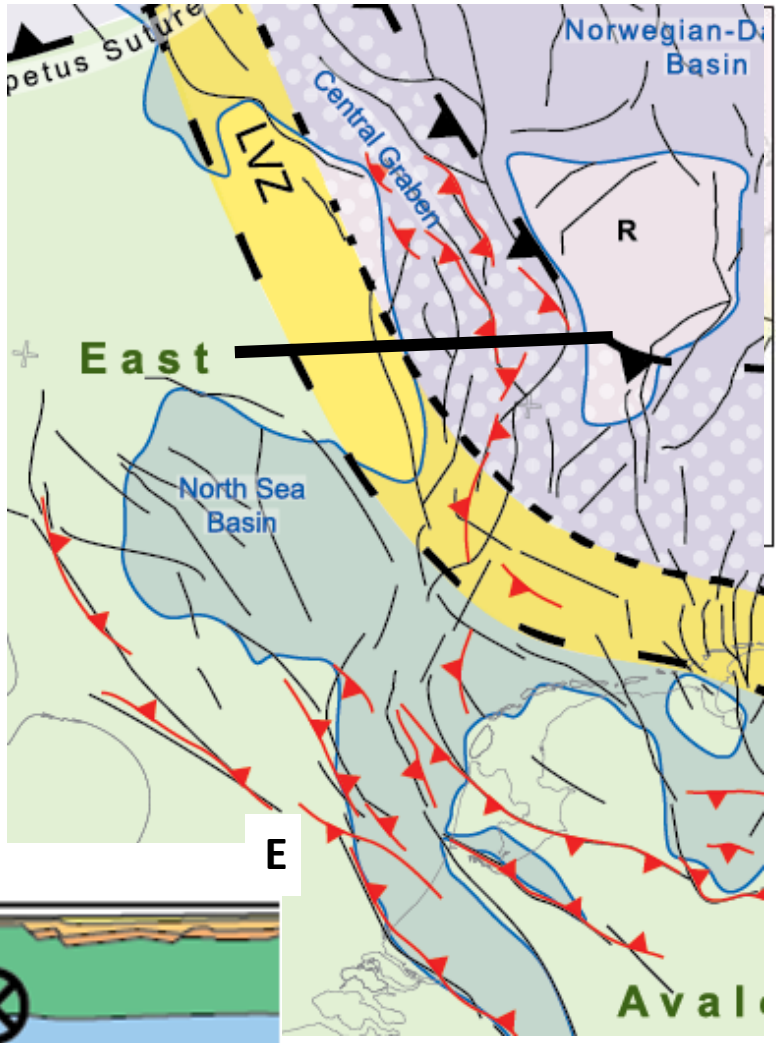
Restored geometry and position of Avalonia before extension.
Similarities with present day supra-subduction settings (e.g. eastern Mediterranean, SE Asia) suggests extension by slab rollback beneath Avalonia's Rheic margin. Result implies subduction of Rhenish Ocean beneath Avalonia.

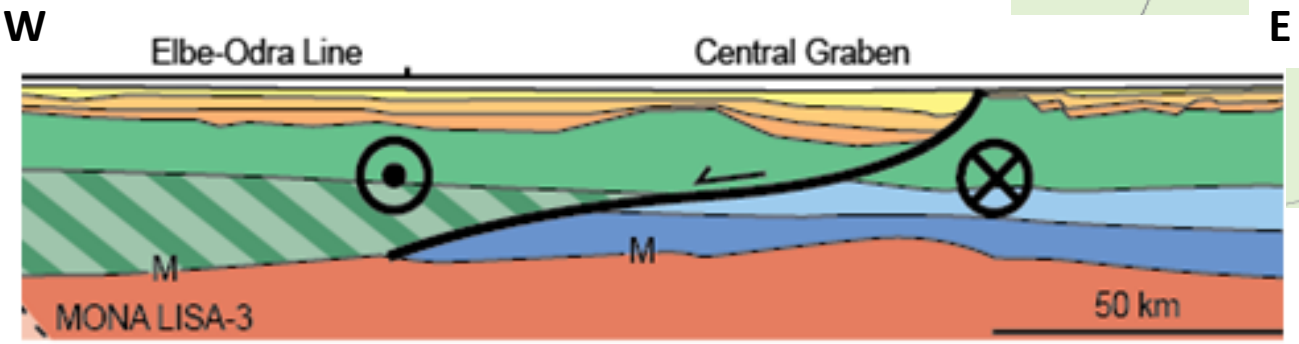
Smit et al, Mar.Petr. Geol., 2018

The Dutch Central Graben

• DCG formed as early Variscan (Dinantian) transform fault

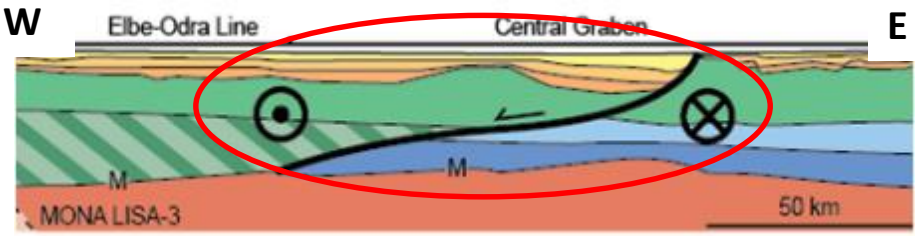
• Tr-Ju extension accommodated by a crustal-scale detachment along contact with Baltica crust, not by classical modes of crustal extension





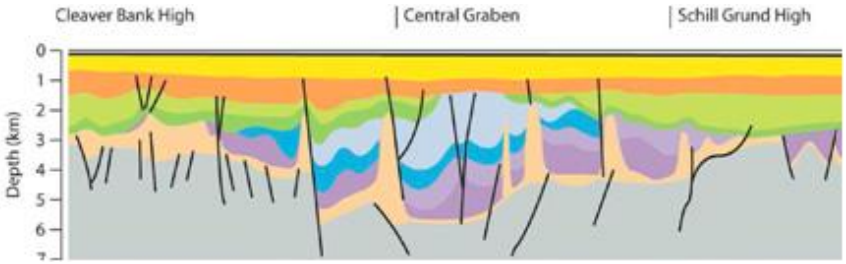
Smit et al, Geology, 2016

The Dutch Central Graben (DCG): Not a classical crustal extension

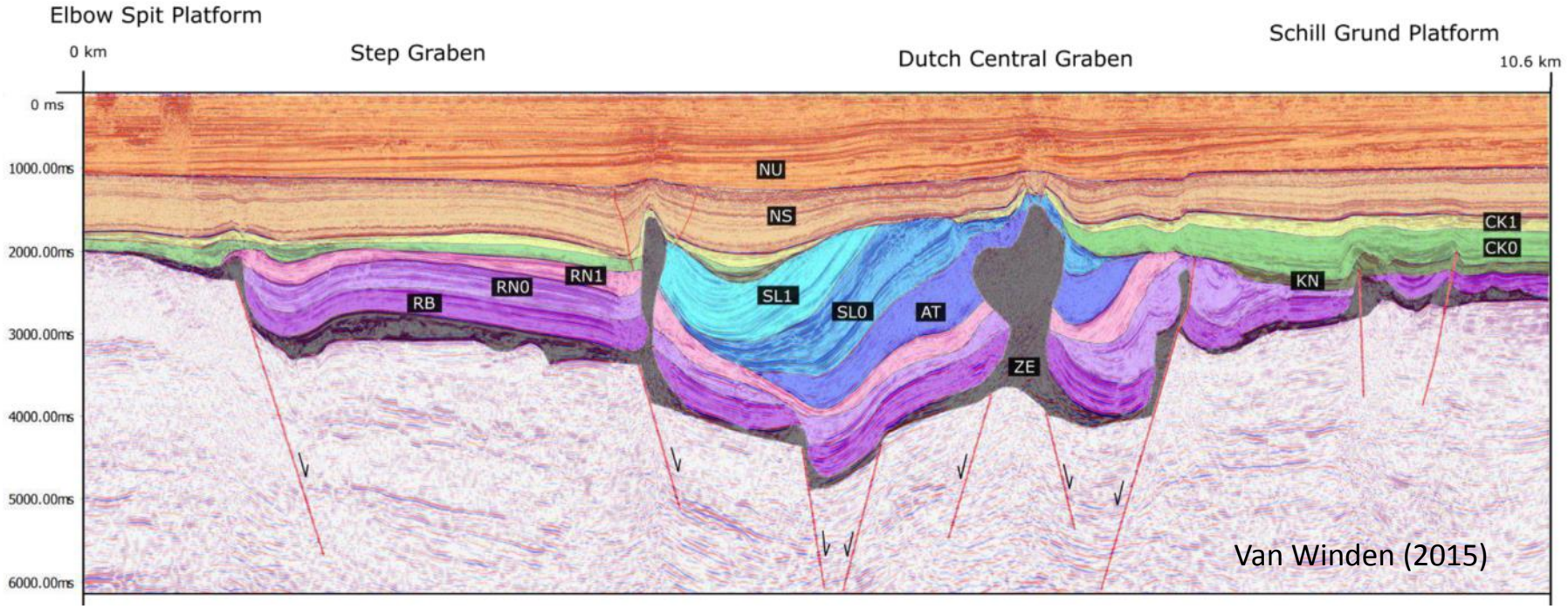


Crustal scale cross-section

Smit et al(2016)



SPBA (2010)

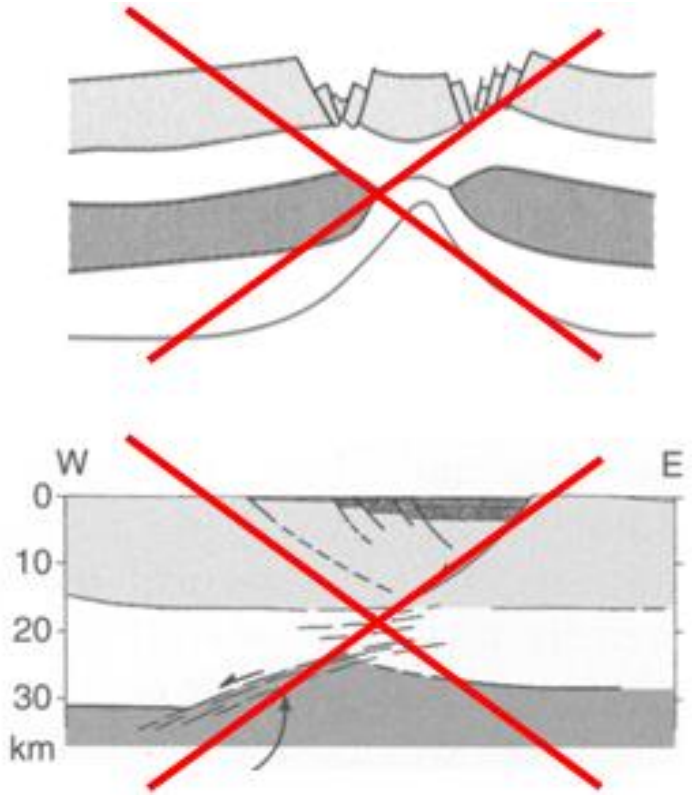


Van Winden (2015)

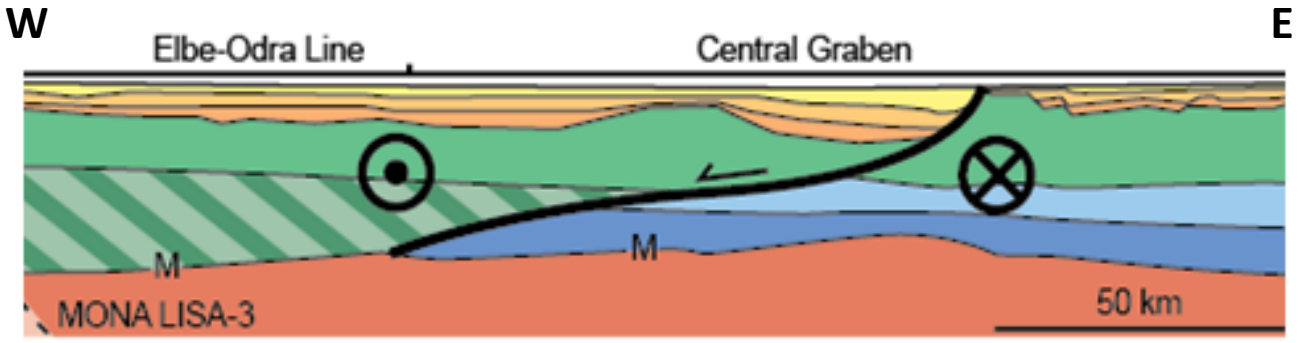
Building on the foundations of TKI-1: Tectonic Models voor shale gas basins

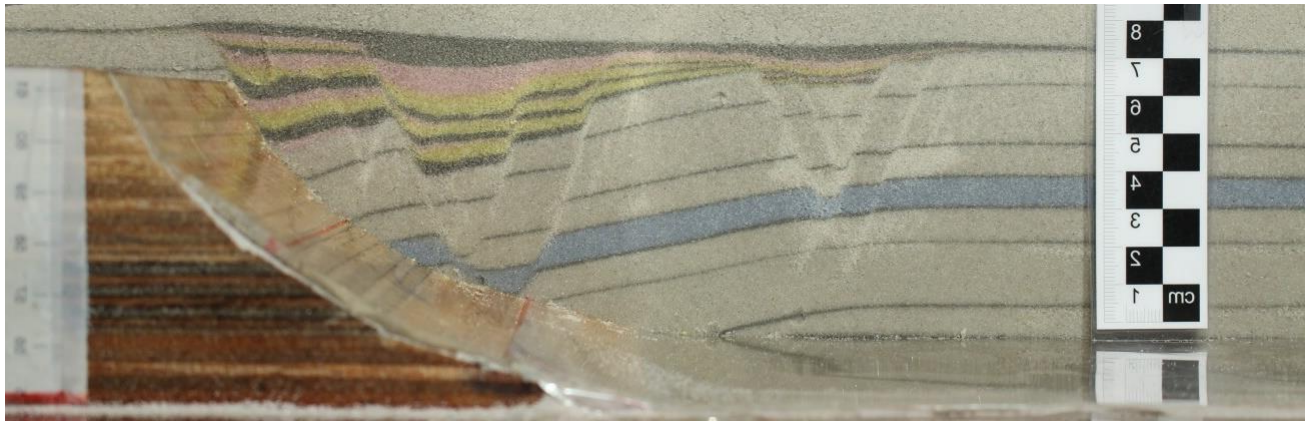
- DCG formed as early Variscan (Dinantian) transform fault

- Tr-Ju extension accommodated by a crustal-scale detachment along contact with Baltica crust, not by classical modes of crustal extension



Brun (1999)





Tectonic Laboratory experiment, carried out at the Utrecht Univ. TecLab
(MSc thesis of David Borghouts, in prep.)

The **DCG** is one of very few North Sea basins that have undergone each tectonic phase that are all preserved in stratigraphy

The DCG contains the best preserved stratigraphic record of all North Sea basins

The DCG is the place to get info that elsewhere is gone

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To do

- **Tectono-seismostratigraphic interpretations**
- **Structural restoration** based on results TKI-project "Tectonic Models I"
- **Gravimetric modelling**
- **Analogue tectonic modelling** to experimentally test hypothesis
- (optional) **Themomechanical modelling** of the regional extension in the Dutch Central and Step grabens
- (optional) **Stratigraphic forward modelling** to predict distribution lithologies

Aim

To decipher the temporal and spatial distribution of faulting and vertical motions combined with a quantification of the associated sedimentation and erosion.

Thus creating the basis for improved models of hydrocarbon distribution as well as geothermal exploration potential onshore.

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Tectonic Models II, the Dutch Central Graben

Focus on the implications of the new model on Dutch basin development for the past 350 Ma with a focus on the Central Graben area and its flanks.

The **Central Graben** is one of few North Sea basins that have recorded each tectonic phase, therefore the DCG is a prime candidate to apply outcomes of TKI project “Tectonic Models I”

A natural follow-up project of TKI -1 project “Tectonic models for shale gas basins”

RLS³: Reactivated, Long, Straight, Small-offset and Sealing:

Quantification of the Dekeyser Faults System, a new TKI proposal

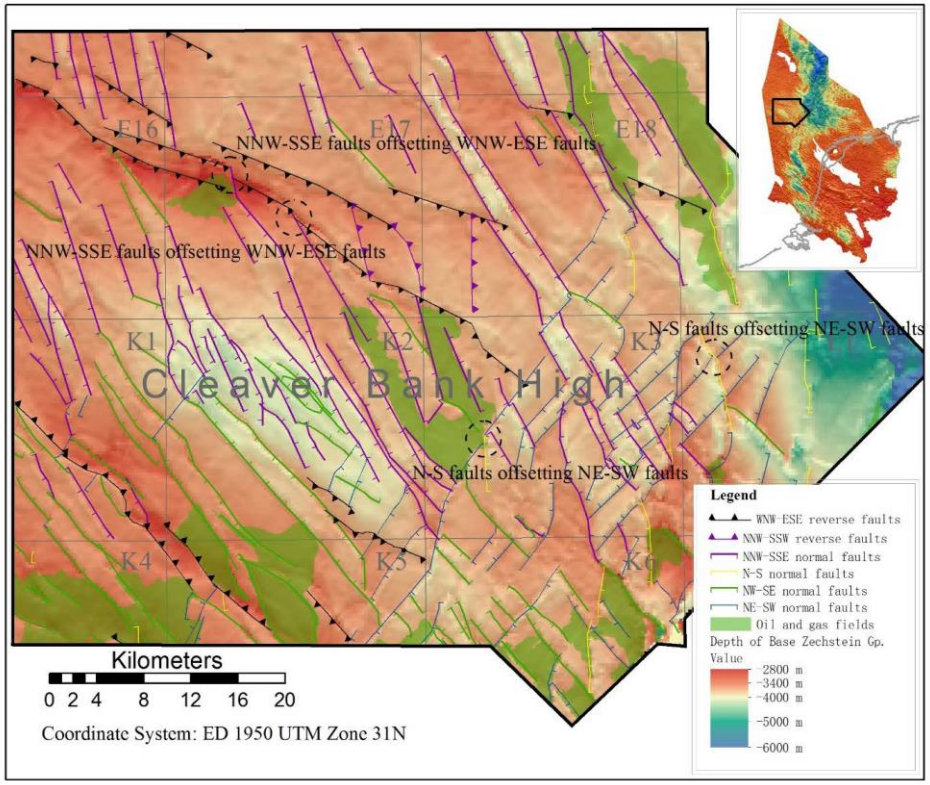
- mapping the distribution of the Dekeyser faults across the Netherlands offshore (and onshore depending on data quality)

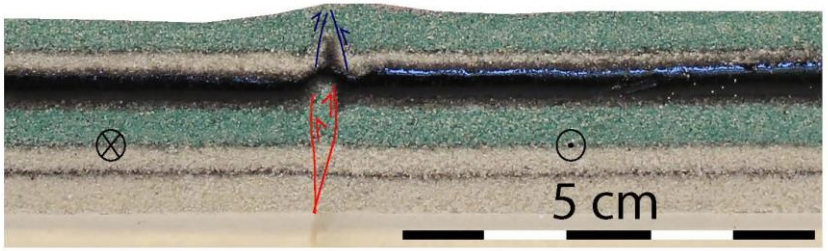
+ their length, spacing, variations in orientation etc. (UK depending on data availability)

- Place the Dekeyser Faults in a regional tectonic scheme

- elaborate a fault zone evolution and stress model from seismic analysis and tectonic laboratory modelling

- Higher resolution analysis of sealing characteristics





TKI geo energy at Utrecht University

Genetic understanding of mechanical and fluid flow/sealing properties of deep fault and fracture systems

- Tectonic Models for basin analysis at single-to-multi-basin scales
- Constraining fracture and fault system evolution from sedimentary and structural evolution analysis and forward models
- Physics and lab-based underpinning of conceptual models (e.g. sealing/fluid flow, seismicity) incorporating multiscale processes & properties

- ***Methods***
  - Improved deep crustal structural analysis
  - combined field and HPT lab study
  - Multi-scale physics-based forward models
  - Tectonic/stratigraphic models for basin analysis at single-to-multi-basin scales

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TKI GAS
Topsector Energie

Thank you

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wintershall

j.h.w.smit@uu.nl