Post-rift fault reactivation in the Netherlands
implications for exploration and production

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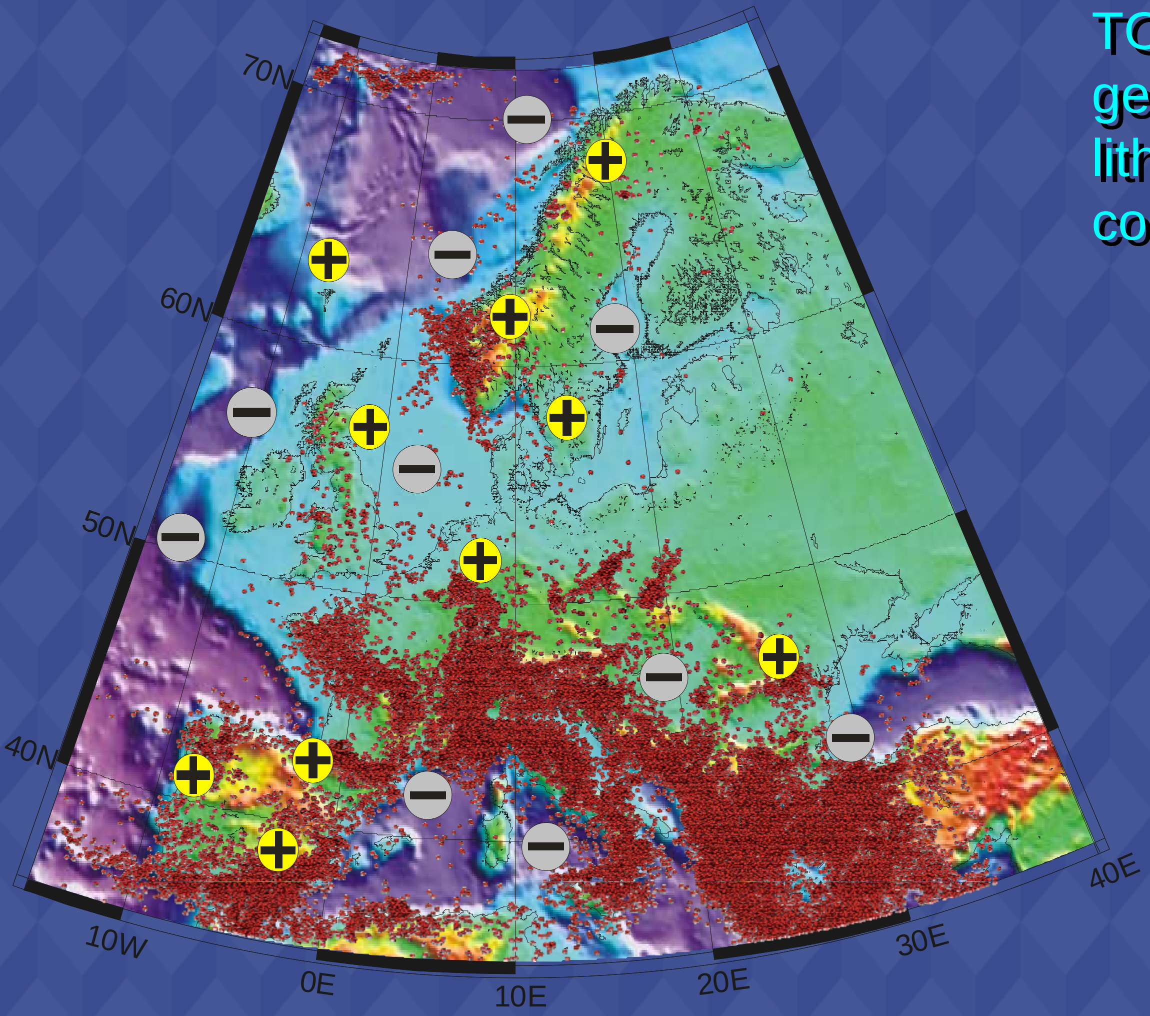
Neotectonic vertical motions and seismicity in Europe



TOPO-EUROPE:
geo-science of coupled surface and lithosphere & mantle processes of continental Europe and its margins

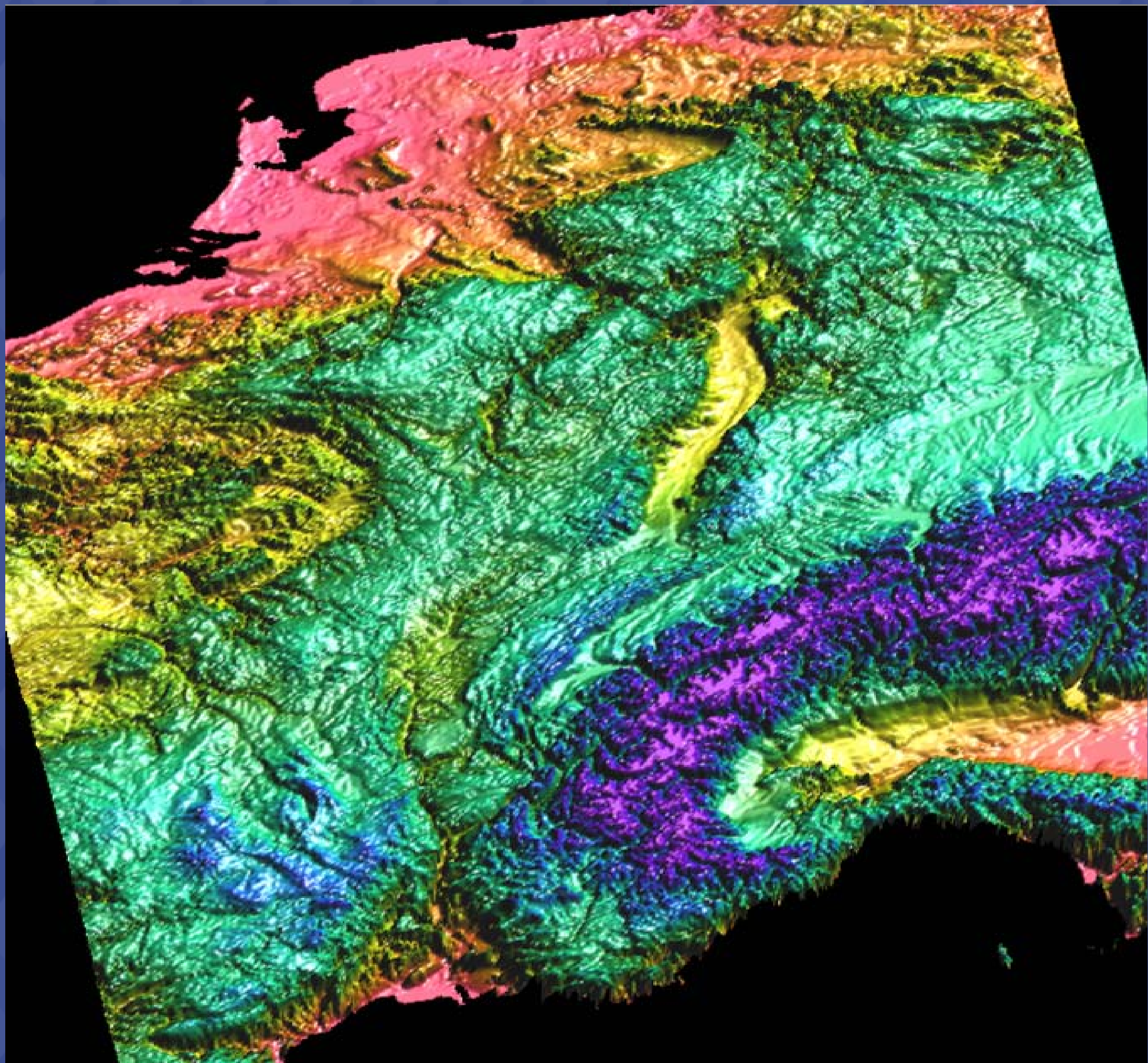
Cloetingh et al., 2007 (GPC)

Contents

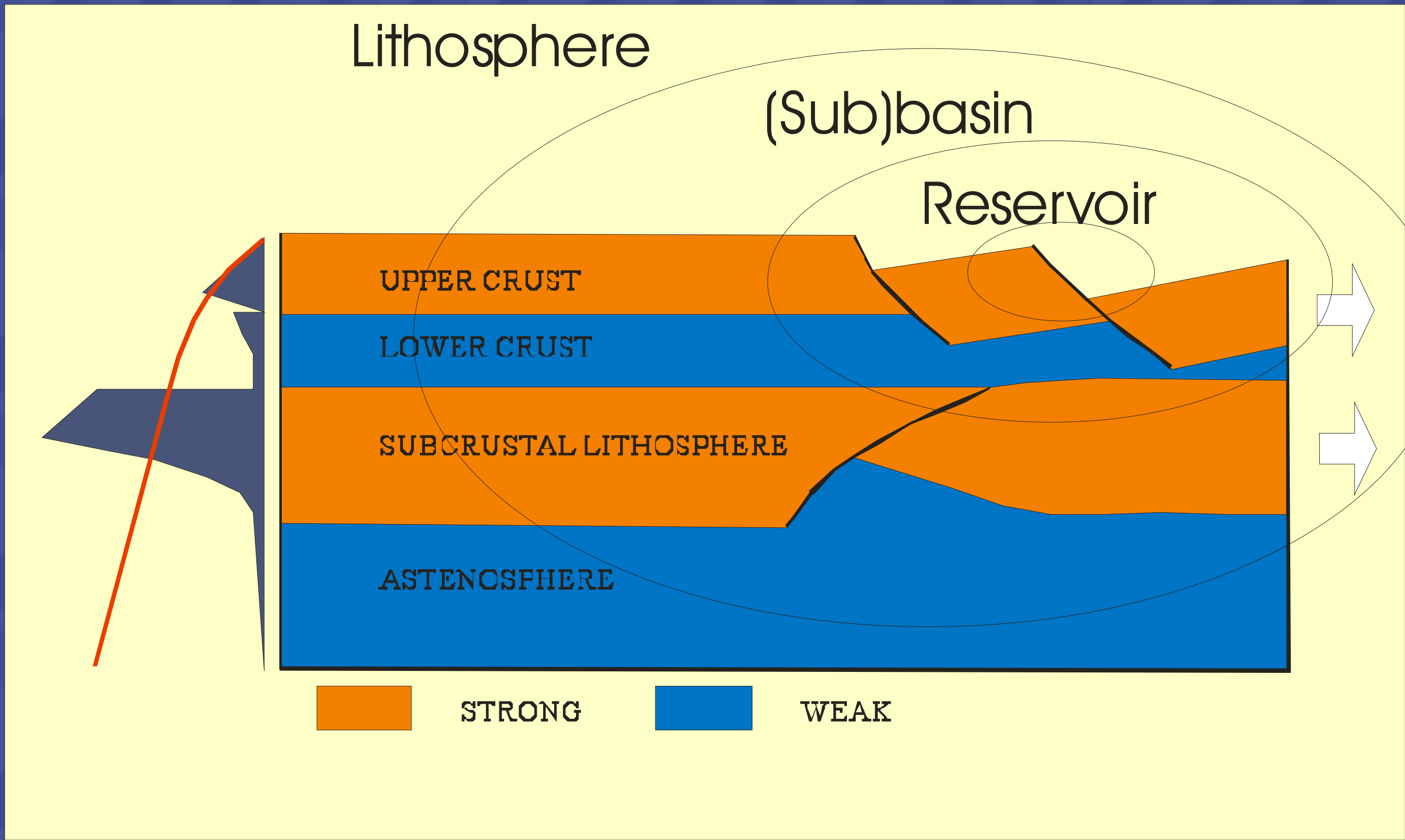
- Strength evolution and seismicity of European rift systems
- Fault reactivation in the Netherlands
  - Roer Valley Rift System: seismicity and reactivation potential
  - West Netherlands Basin inversion
- Implications of fault reactivation for exploration
- Production induced fault reactivation in the NE Netherlands

reference

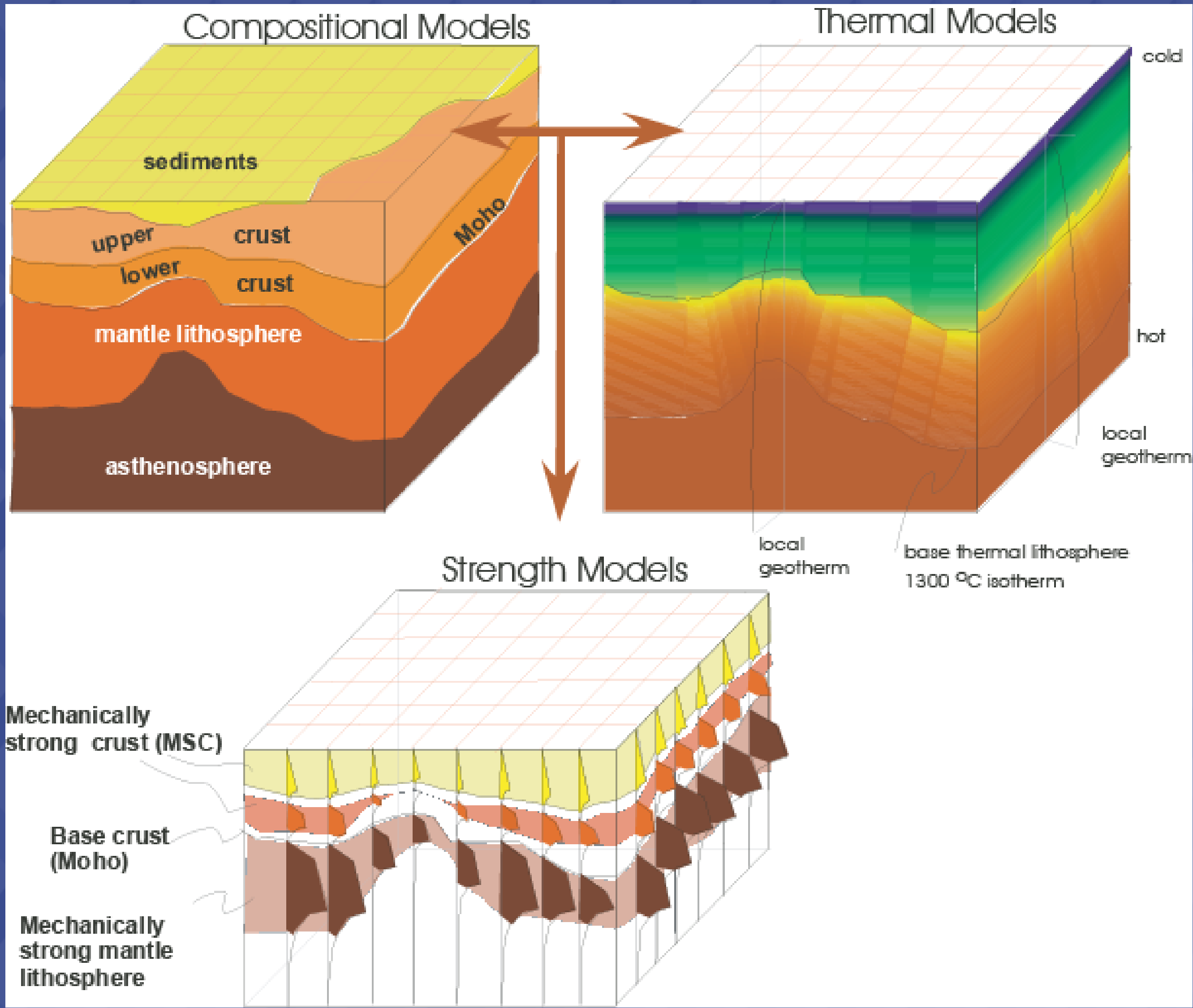
European Cenozoic Rift System (ECRIS)



Coupled deformation at different spatial scales

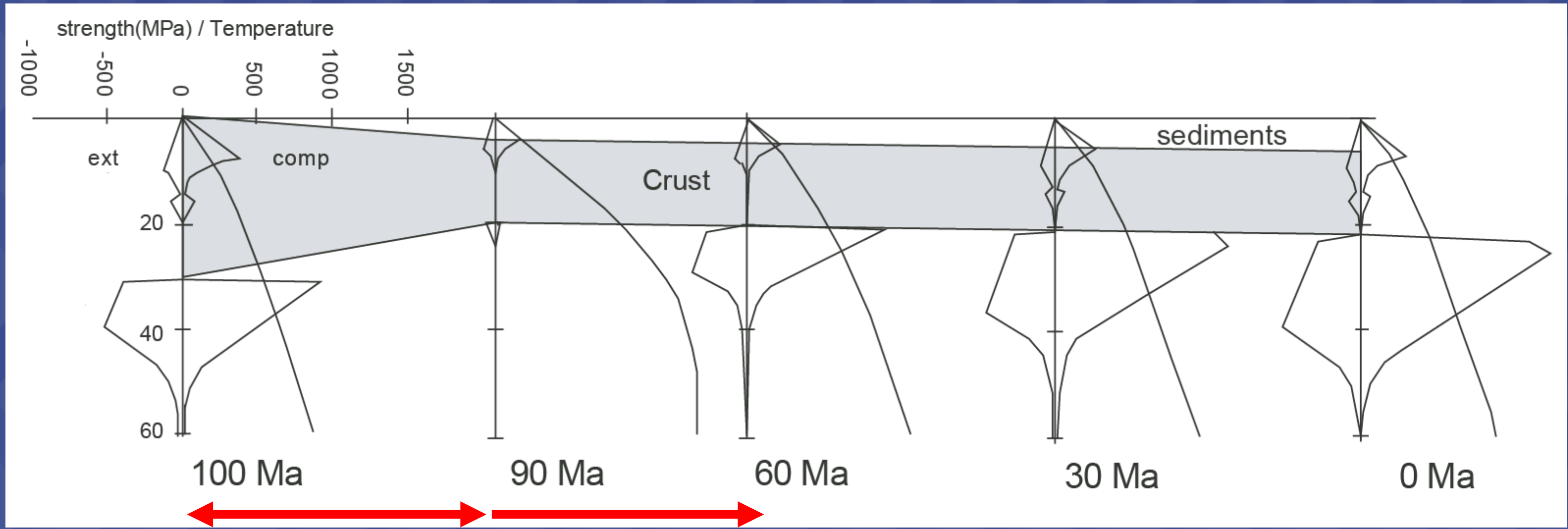


3-D rheological strength models



Cloetingh et al., 2005

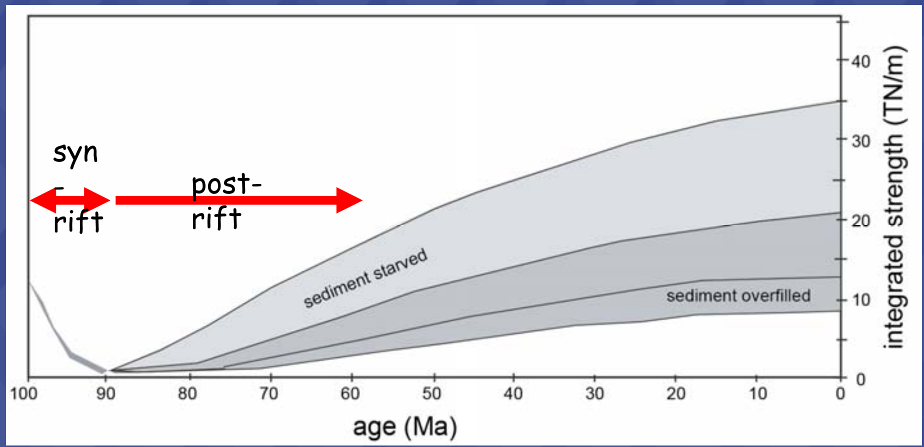
Strength evolution of rift basins



syn-rift

stretching & heating

post-rift cooling



In time the post-rift strength can even exceed the initial pre-rift strength of the lithosphere:

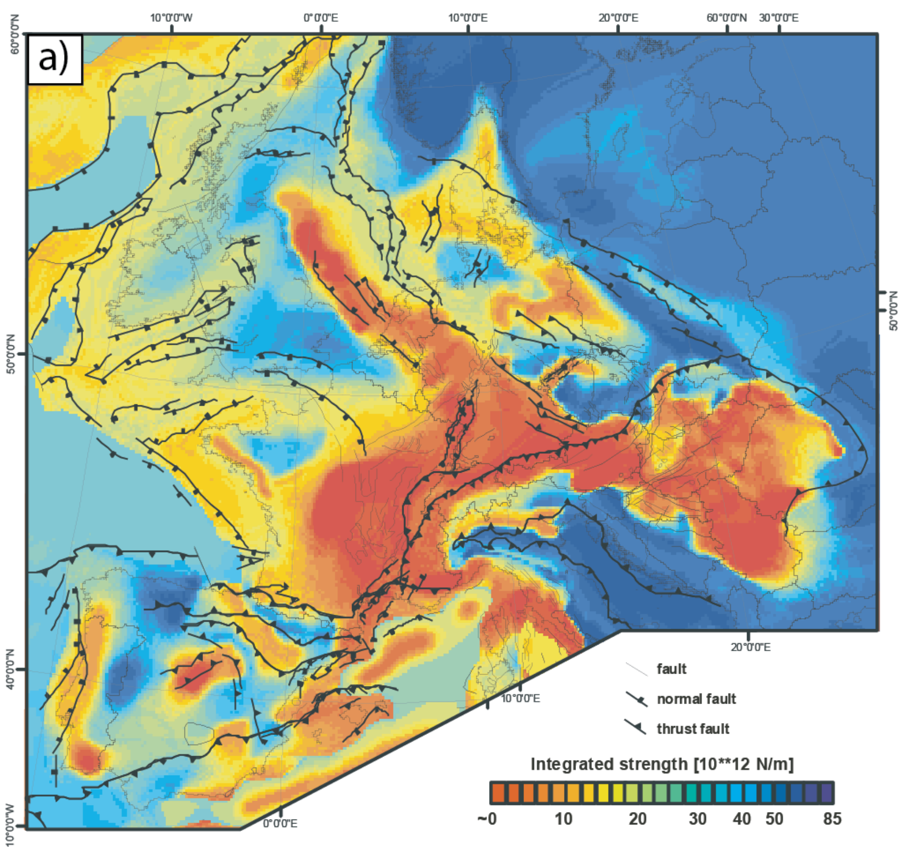
- Young (hot) rifts are weak
- Old (cold) rifts are strong

Ziegler et al., 1998

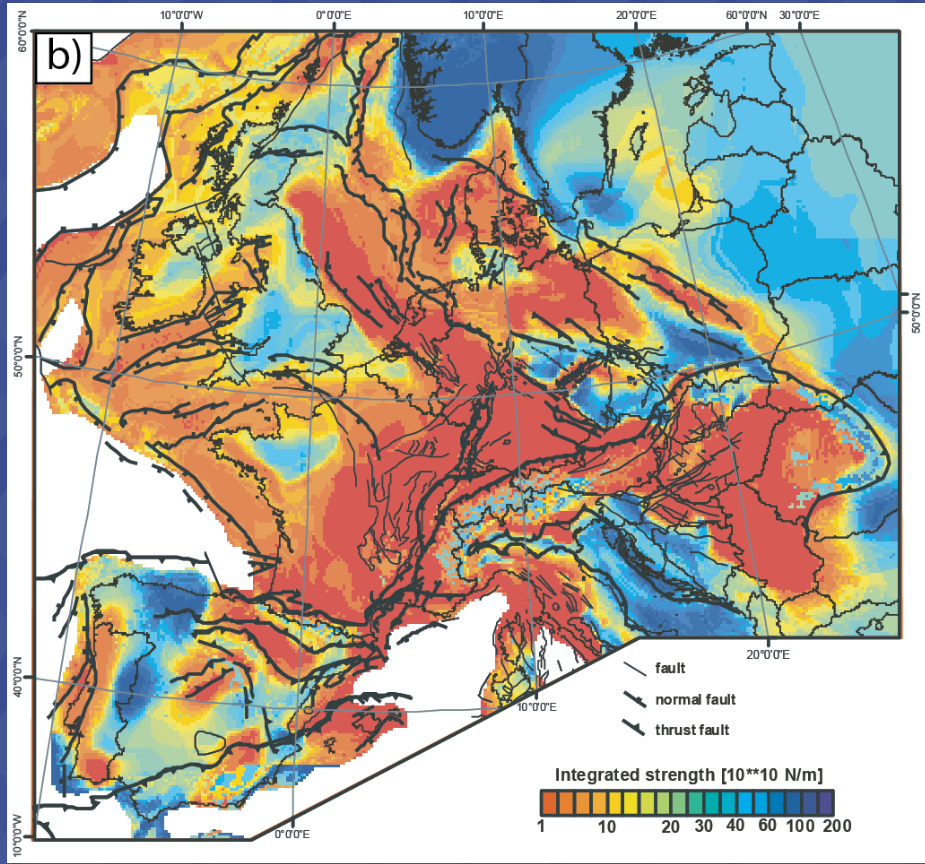
Present-day strength of the European lithosphere

Maps of integrated rheological strength

Entire lithosphere

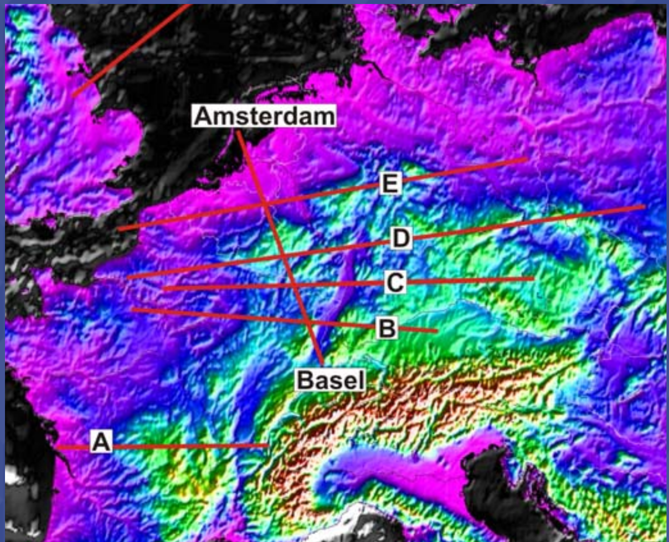


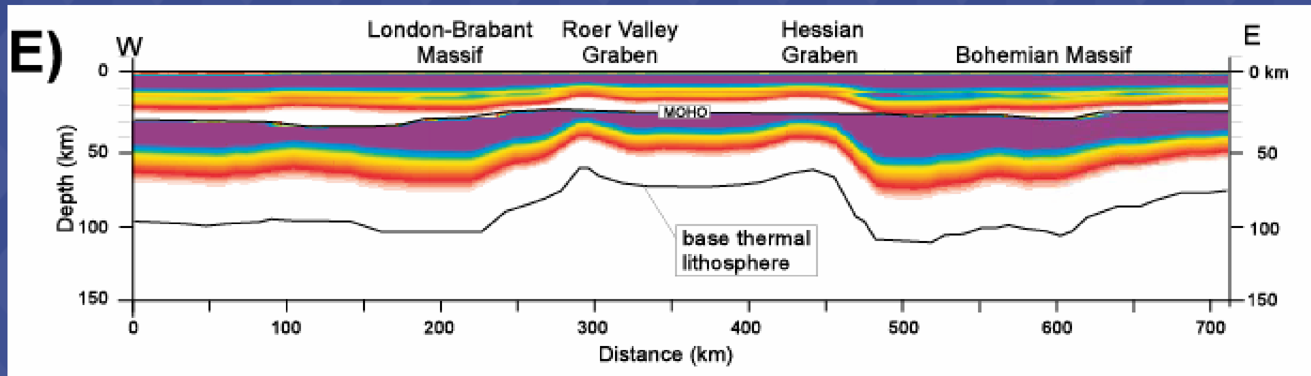
Crust only

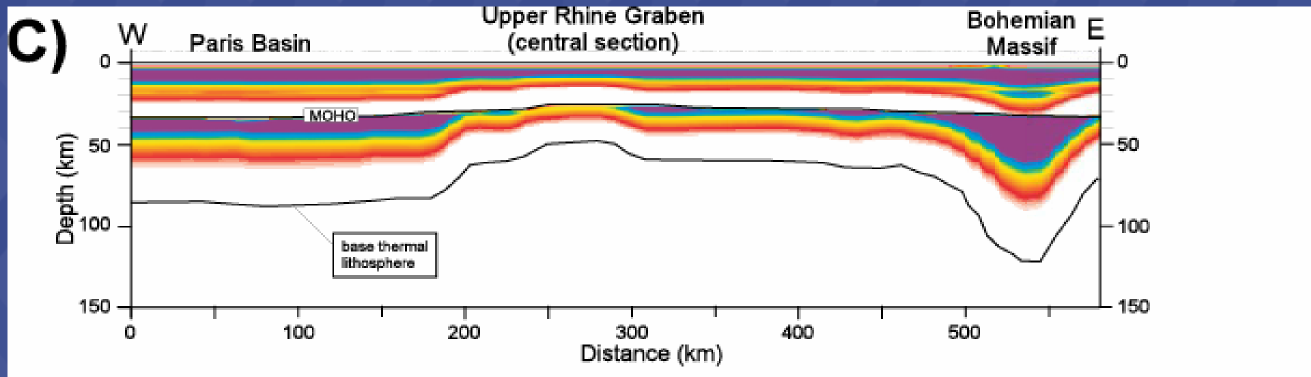


Cloetingh et al., 2005

2-D profiles extracted from the 3-D strength cubes



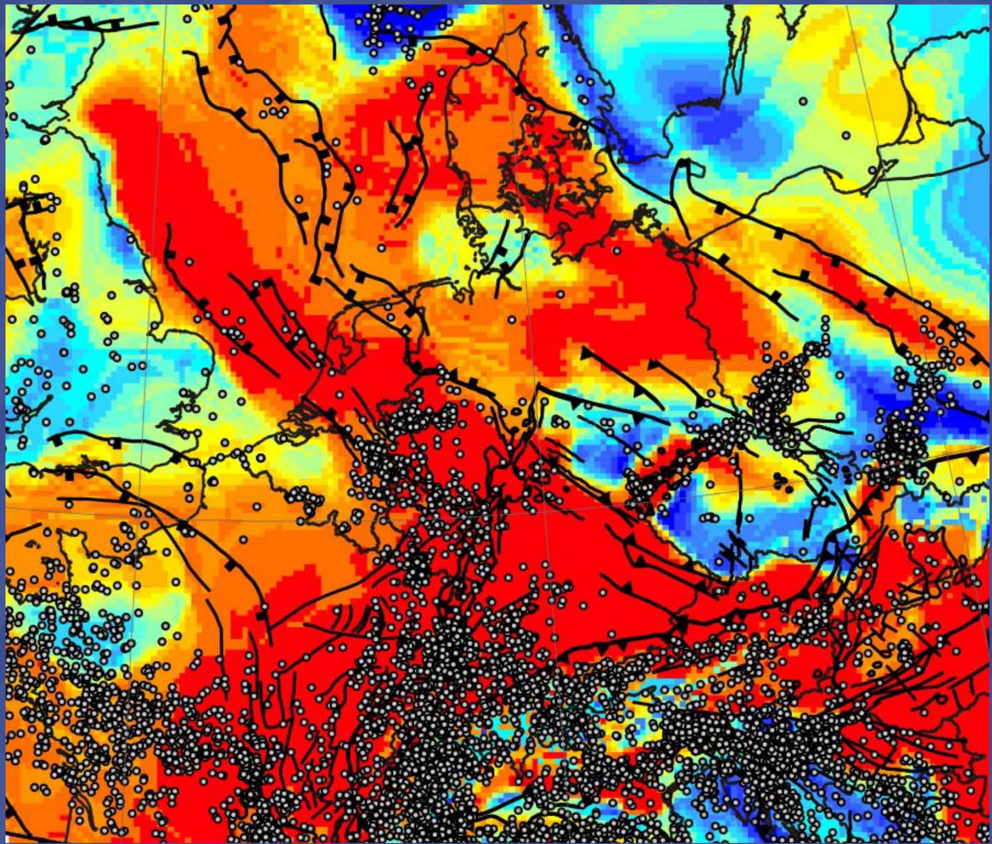




Cloetingh et al., 2005

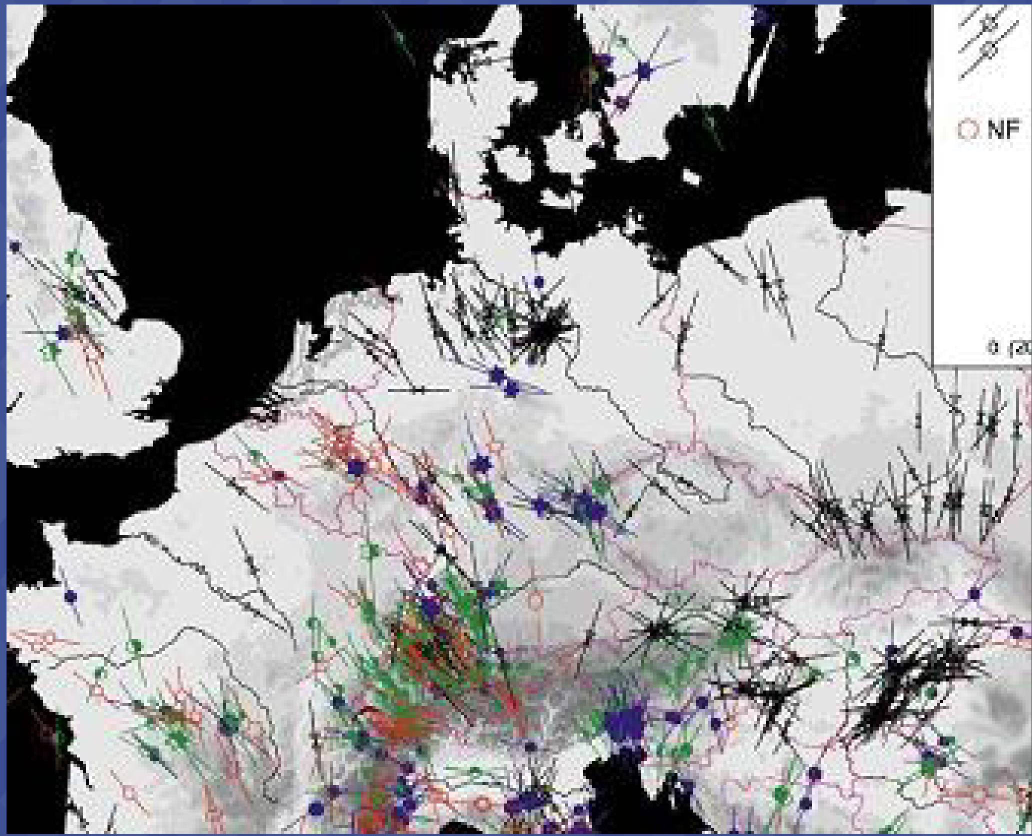
Correlation strong/weak zones with seismicity

Increased seismicity in ECRIS



Cloetingh et al., 2006

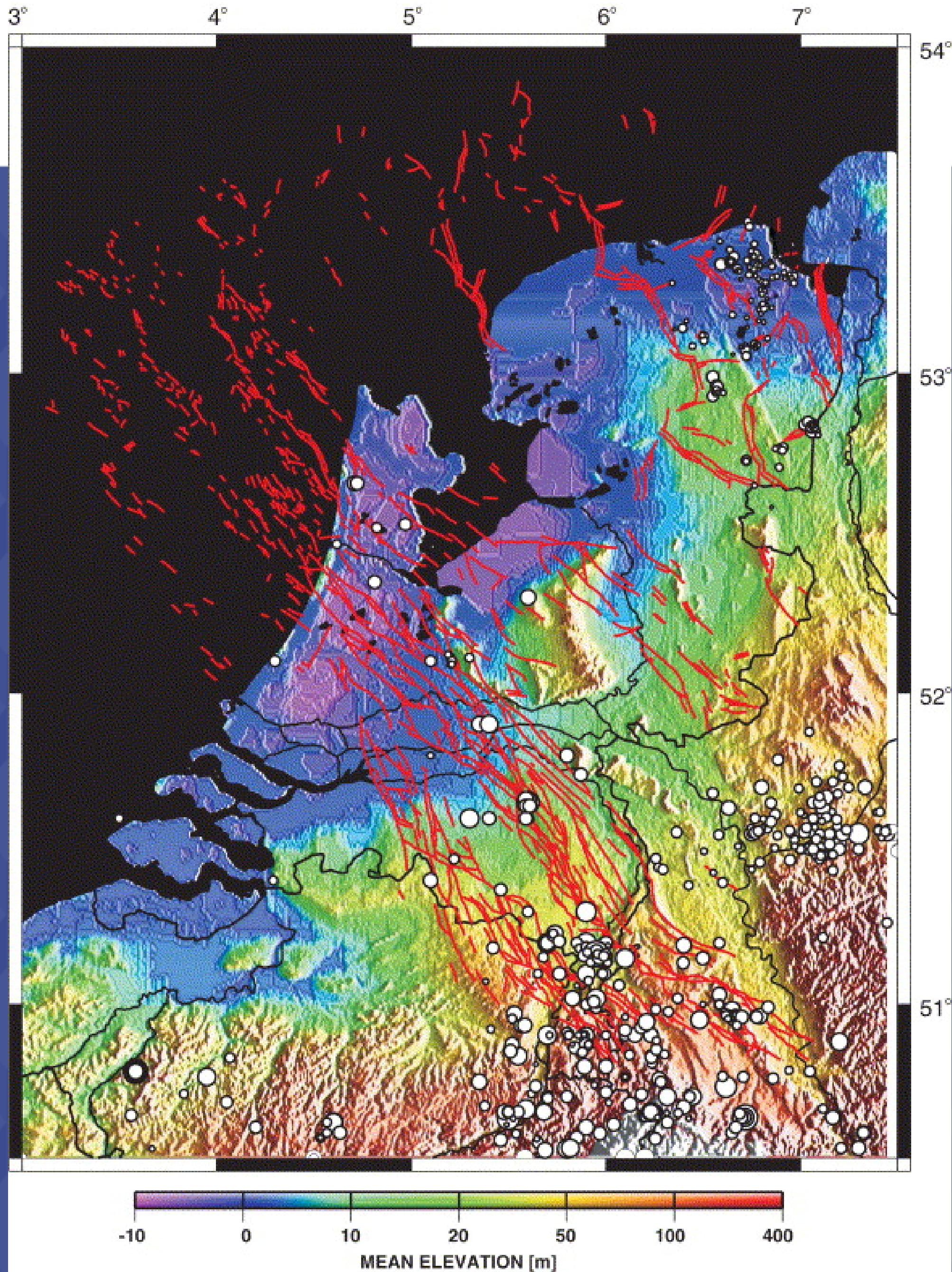
Intraplate stress field



World Stress Map project

Seismicity in the Netherlands

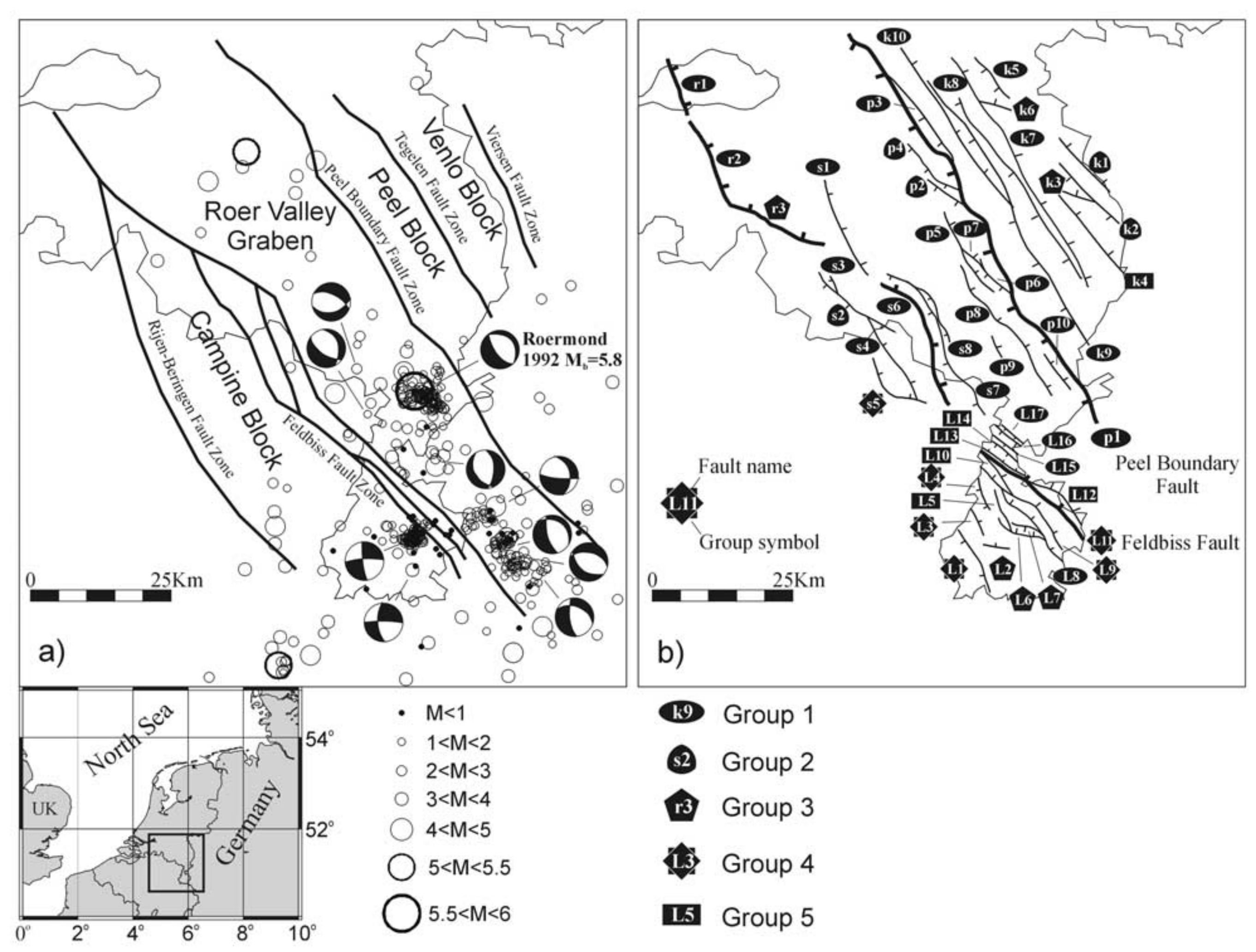
In the Netherlands also many earthquakes occur on pre-existing fault systems



Cloetingh et al. 2005

Roer Valley Rift System (RVRS)

Seismicity and main structural elements



Worum et al. (2004)

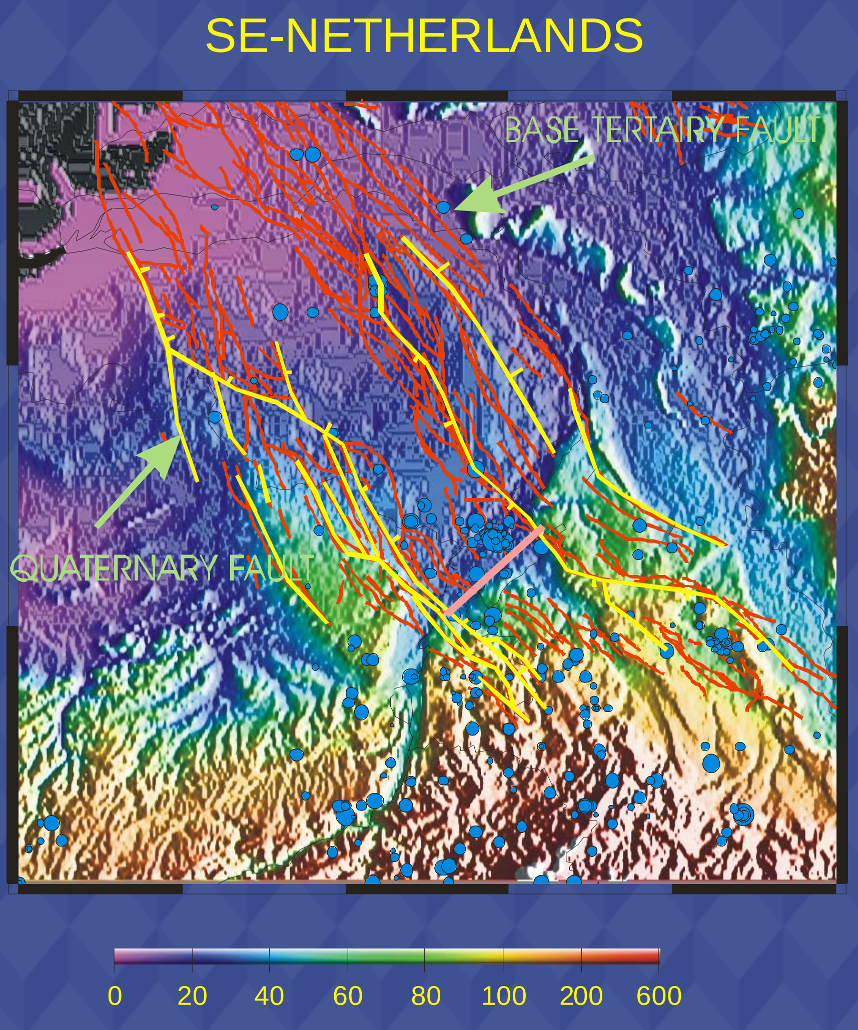
Paleo-seismicity studies in RVRS

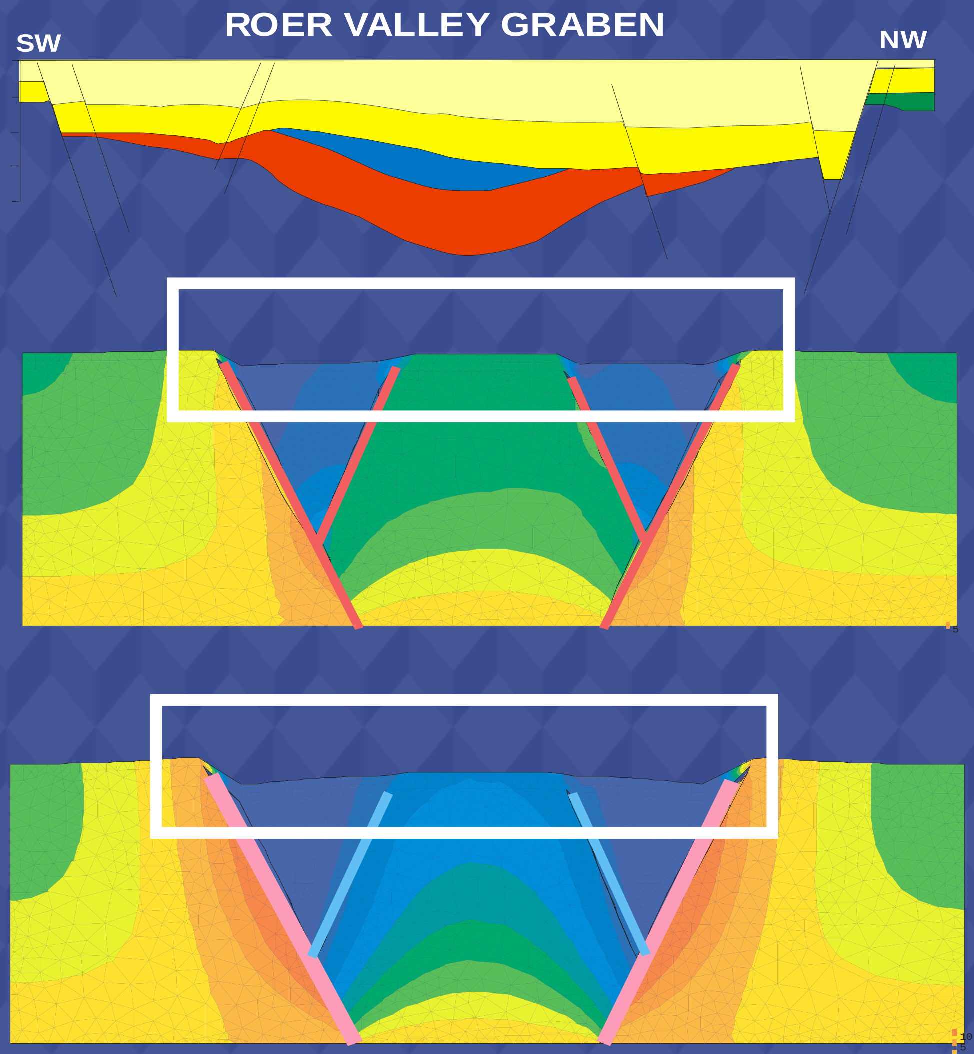
Trenching across the Feldbiss fault zone, a border fault of the Roer Valley Graben (SE Netherlands):

250.000 yr old river deposits (left) have been displaced 5 m downwards along the fault

Houtgast, 2002

Lithosphere memory of faults

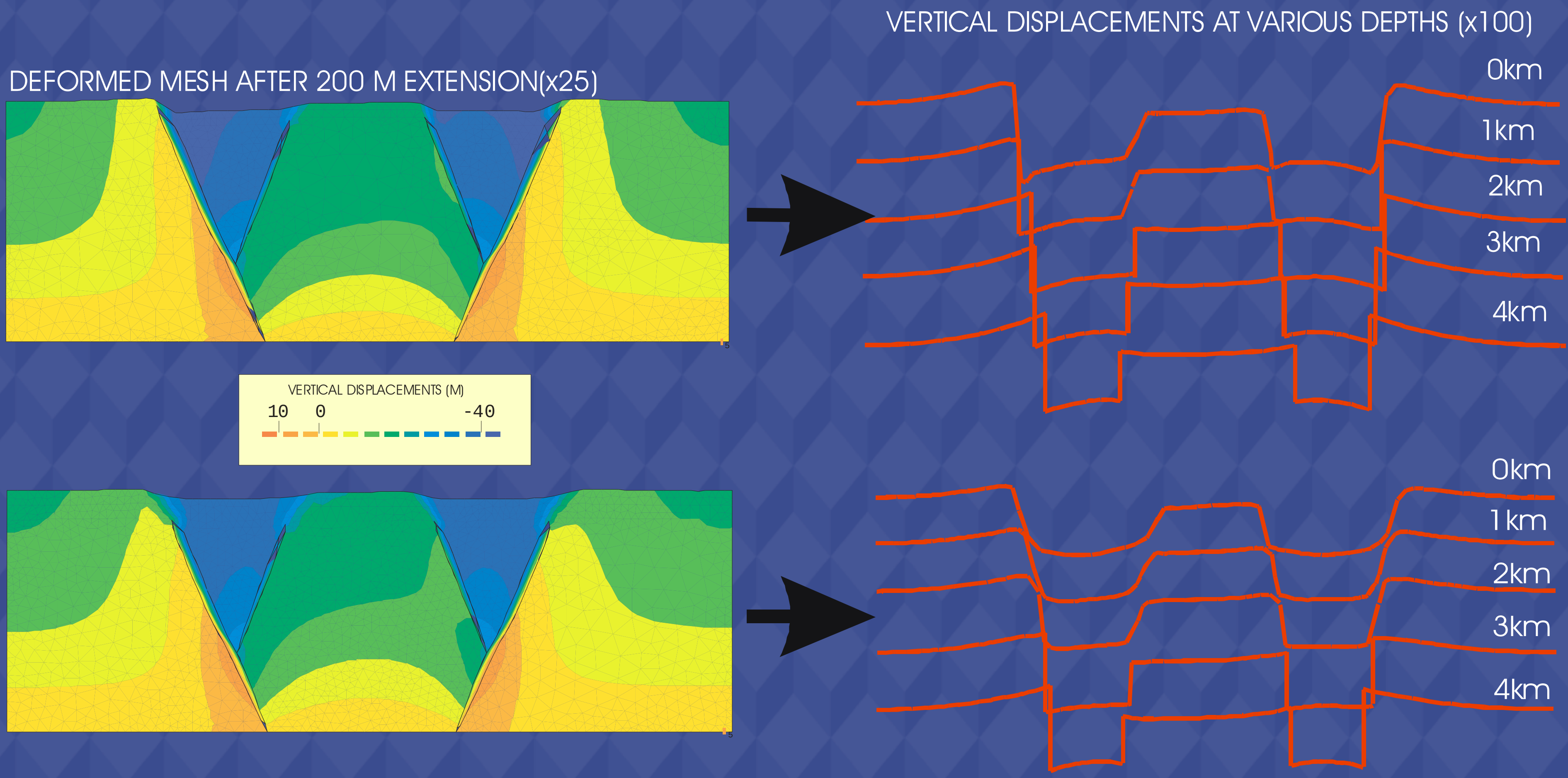




Dirkzwager et al., 2001

Modelling of fault reactivation in RVRS

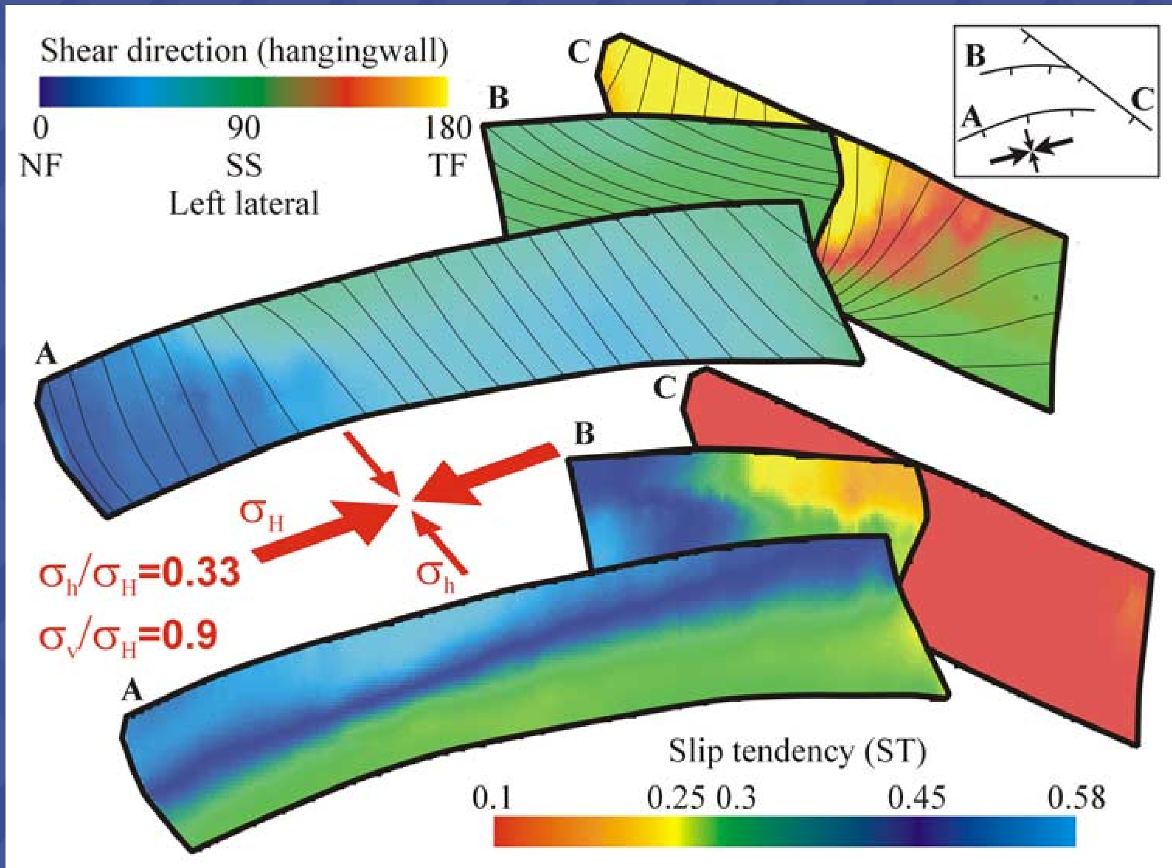
Finite element models assessing the role of fault friction are constrained by geometry of the graben system



Dirkzwager et al., 2001

Potential for fault reactivation

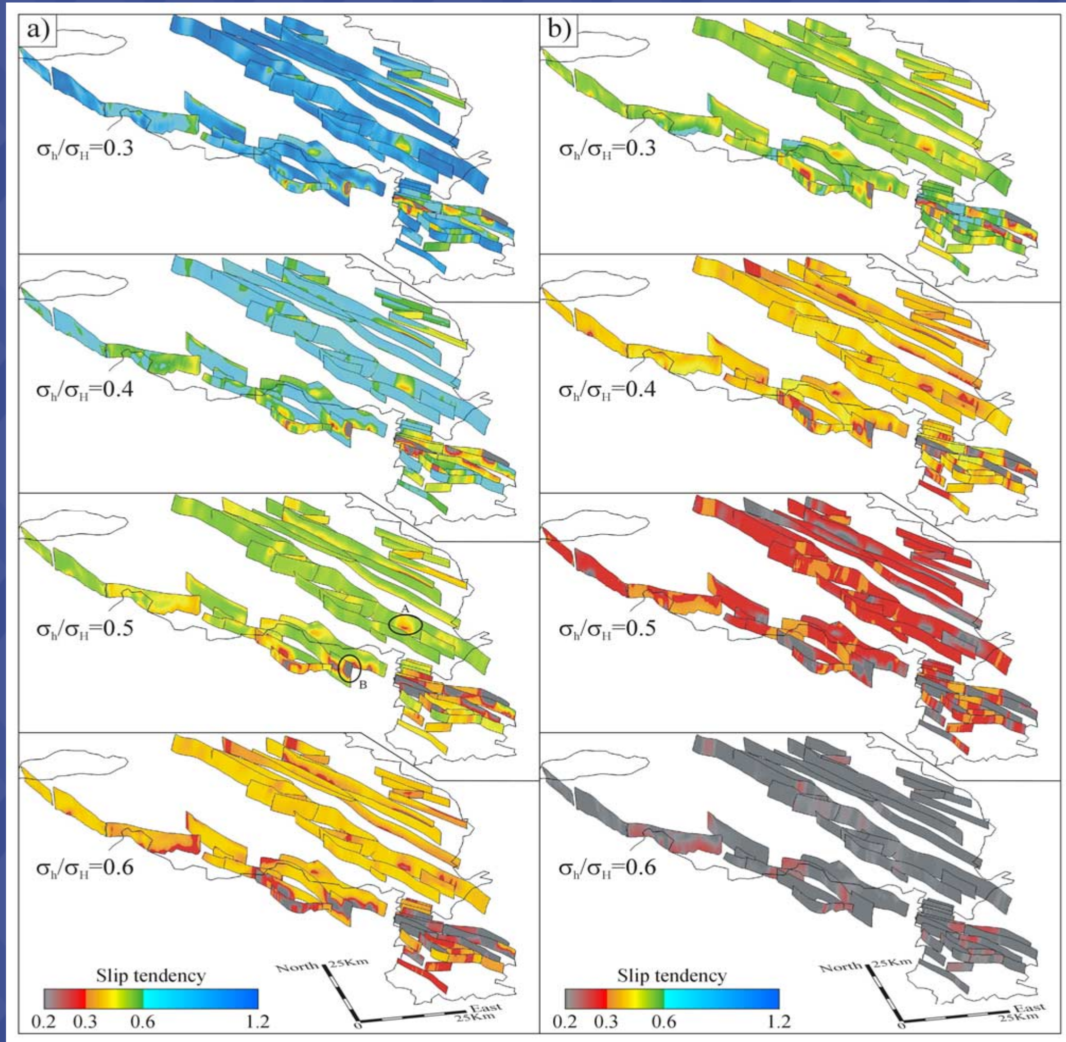
Likelihood of fault reactivation can be quantified by e.g. a slip tendency analysis



Worum et al. (2004)

Fault reactivation potential of the RVRS

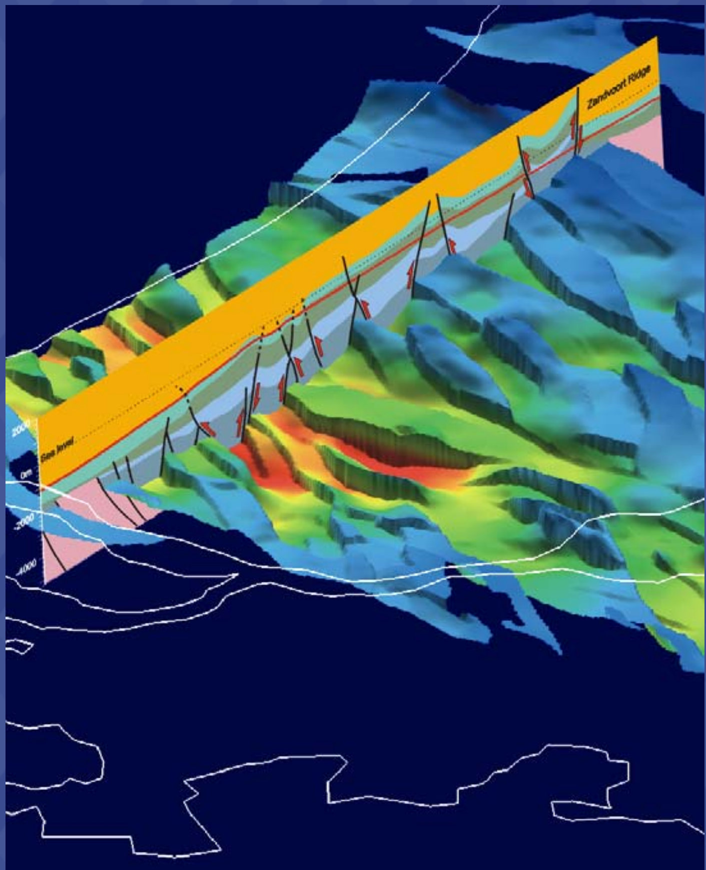
Normal faulting stress regime | Strike-slip faulting stress regime



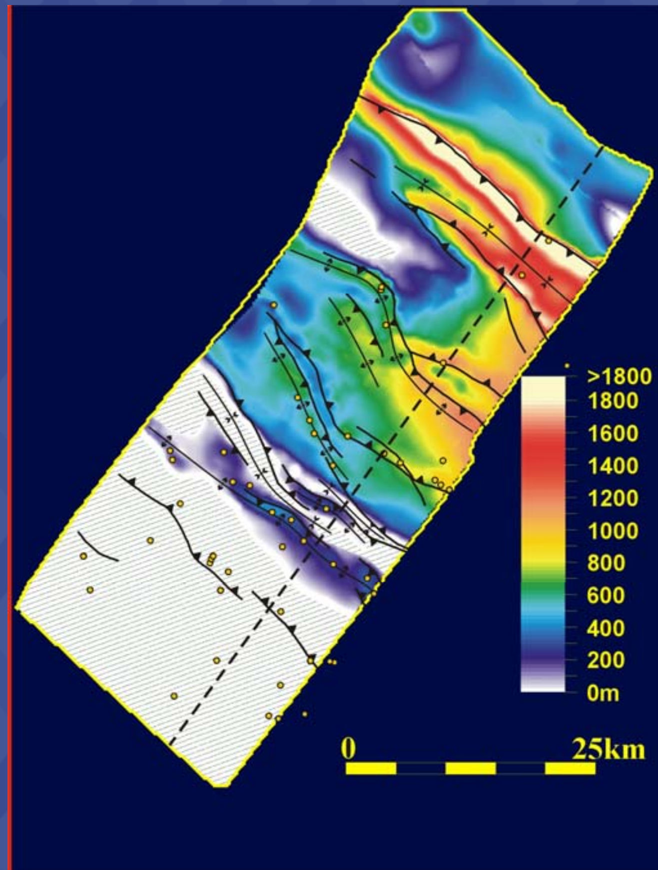
Worum et al. (2004)

Basin inversion: reactivation of the pre-existing weak fault fabric and substantial regional uplift and erosion

reactivated faults

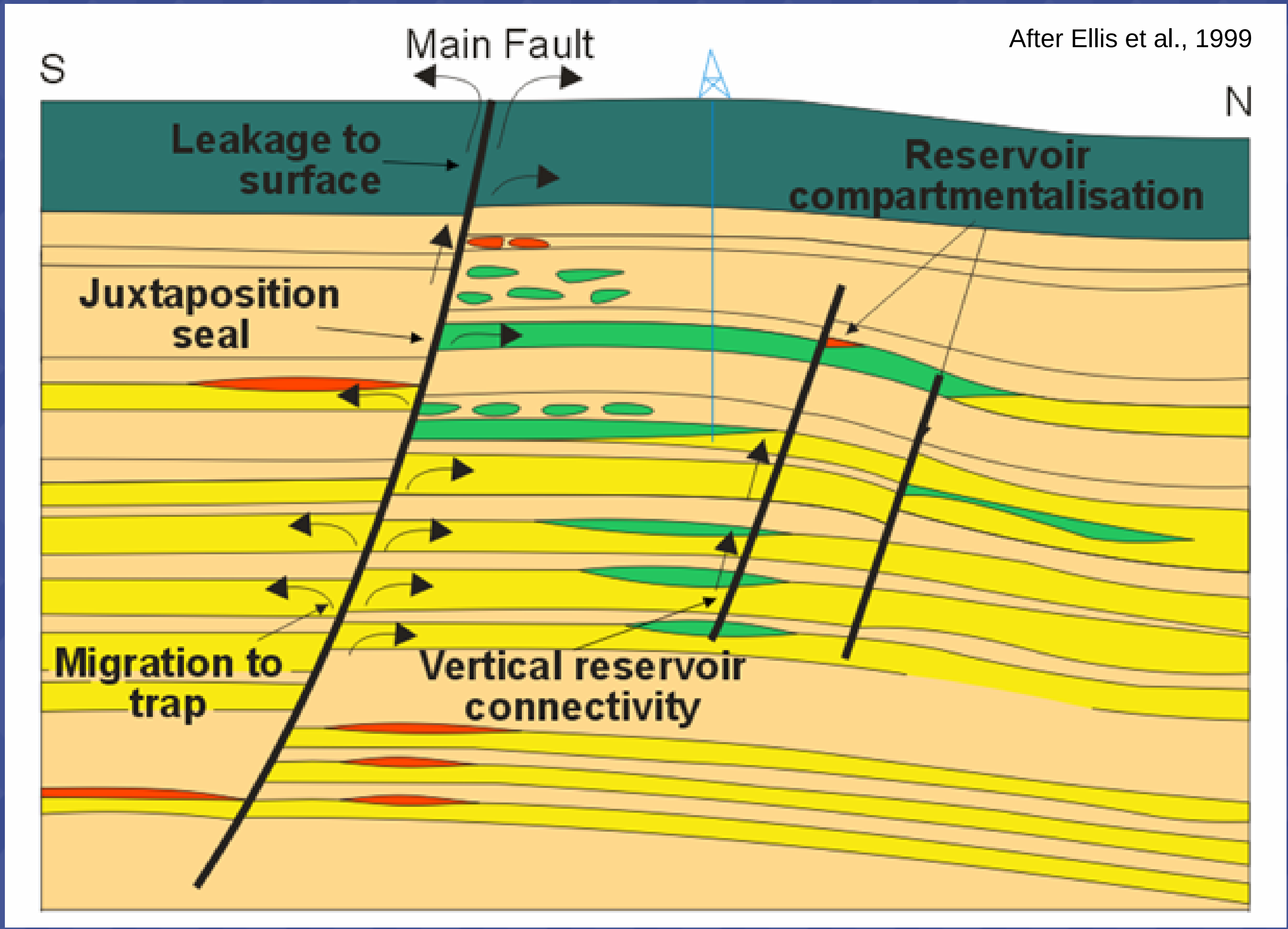


erosion



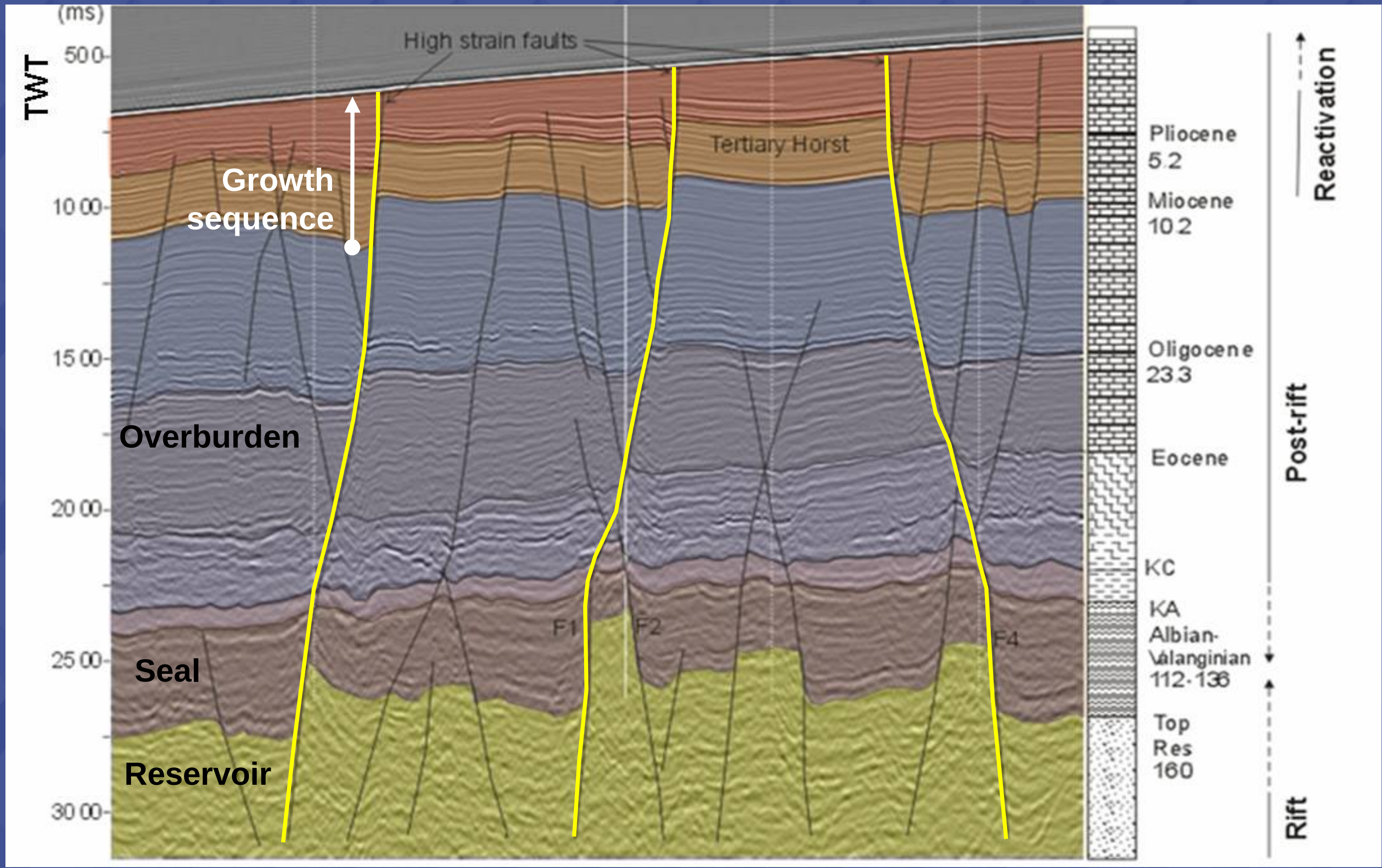
Worum and Van Wees, submitted

Change in fault permeability (along fault and across fault)



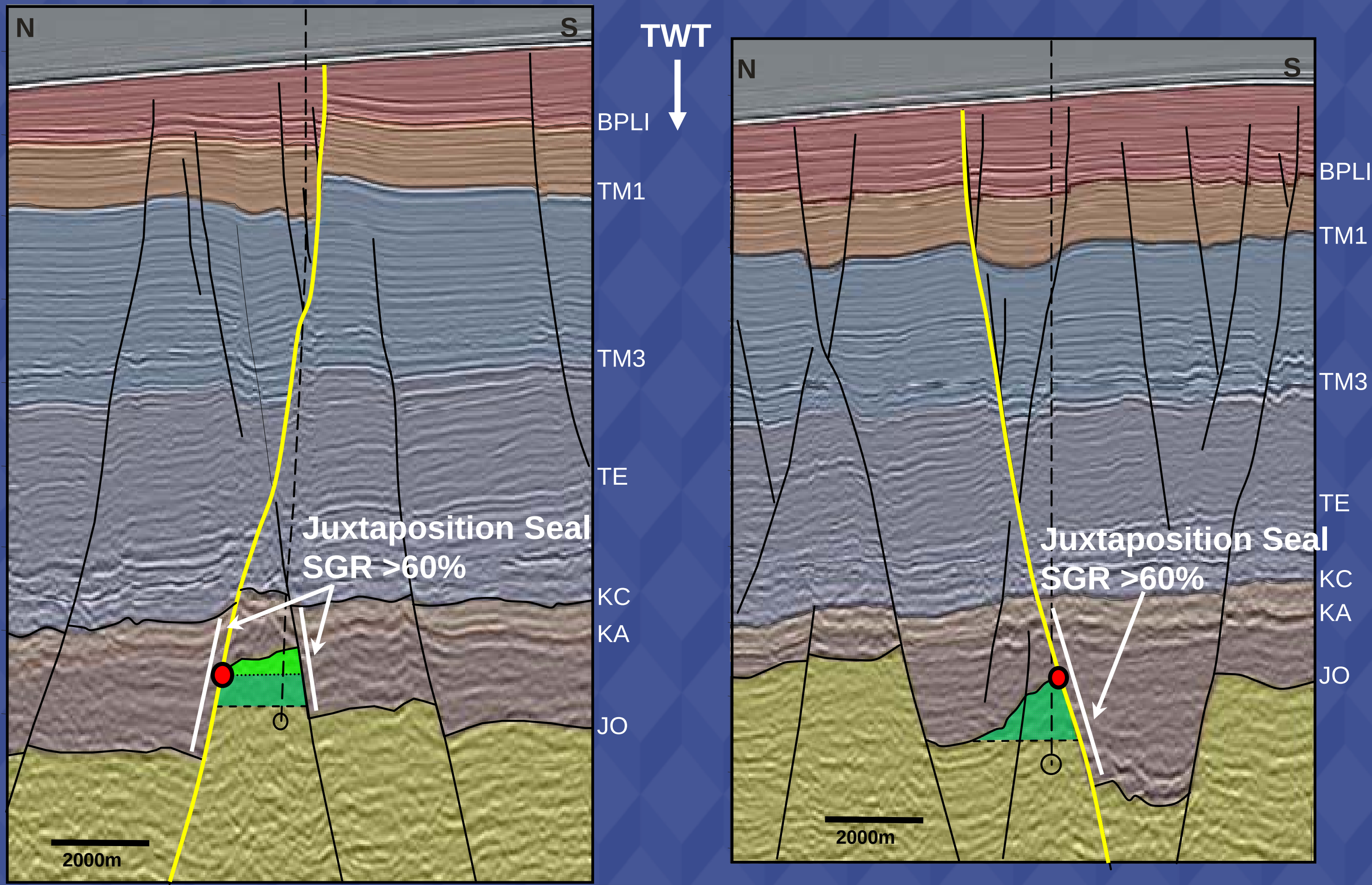
- Migration pathways
- Barriers
- Seal capacity

Reactivated faults can disrupt reservoir seals -> (partial) loss of hydrocarbons



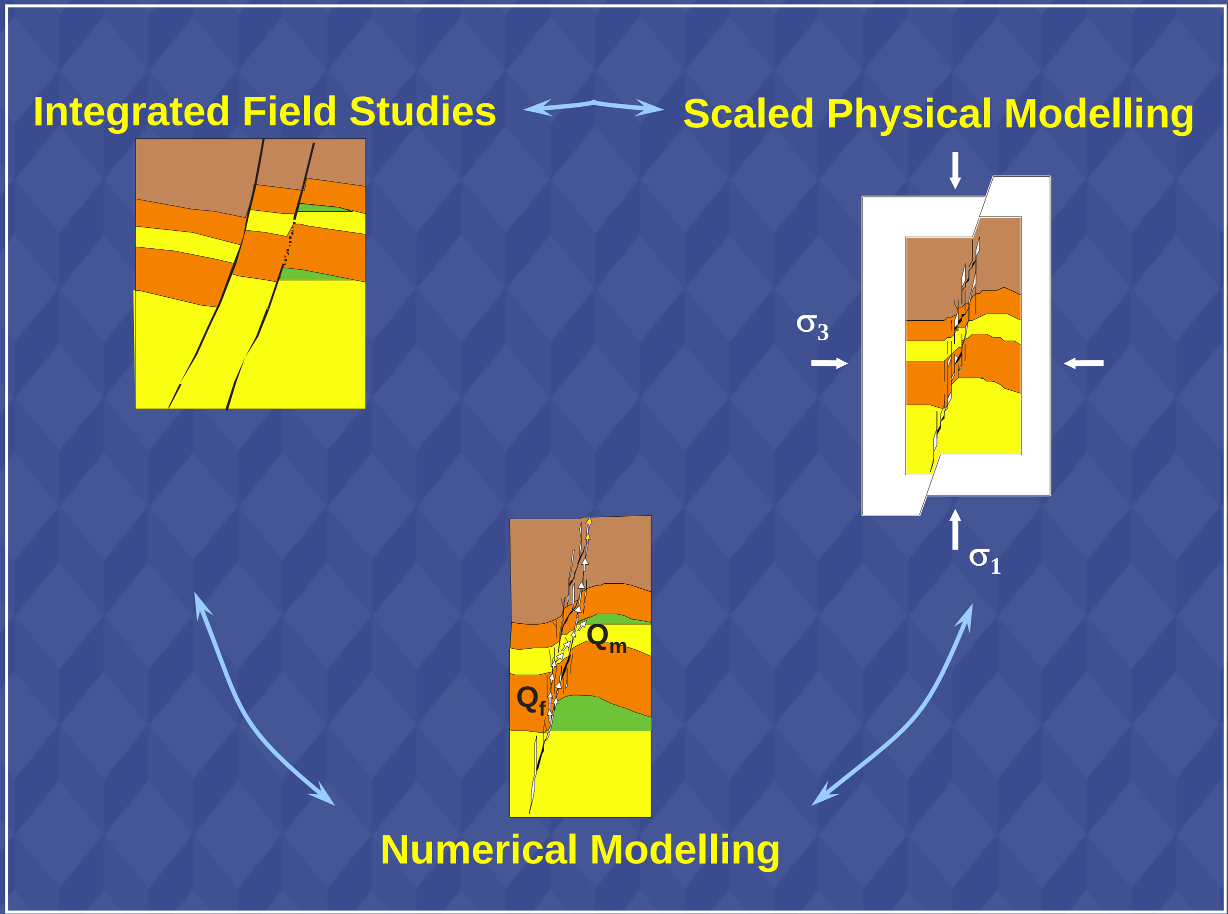
Some faults show more fault slip than others

Implications for hydrocarbon exploration

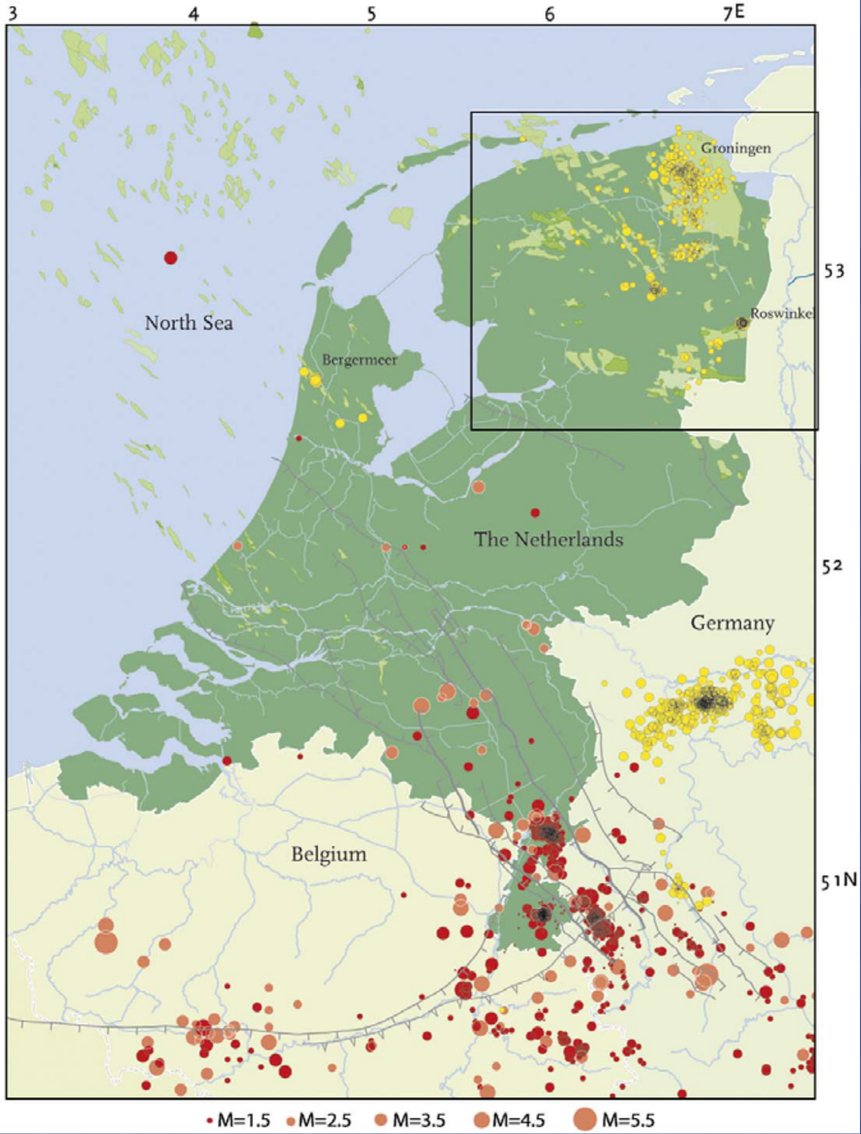


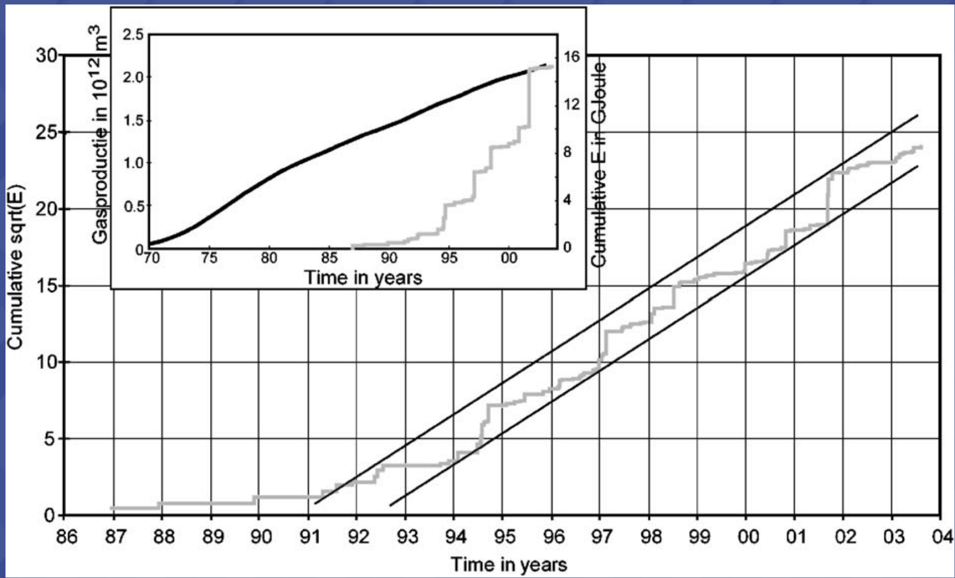
Both traps lost oil; both traps are bounded by reactivated "large strain" faults that were active at the seabed

Dynamic Fault Seal project



Natural versus induced seismicity in the Netherlands

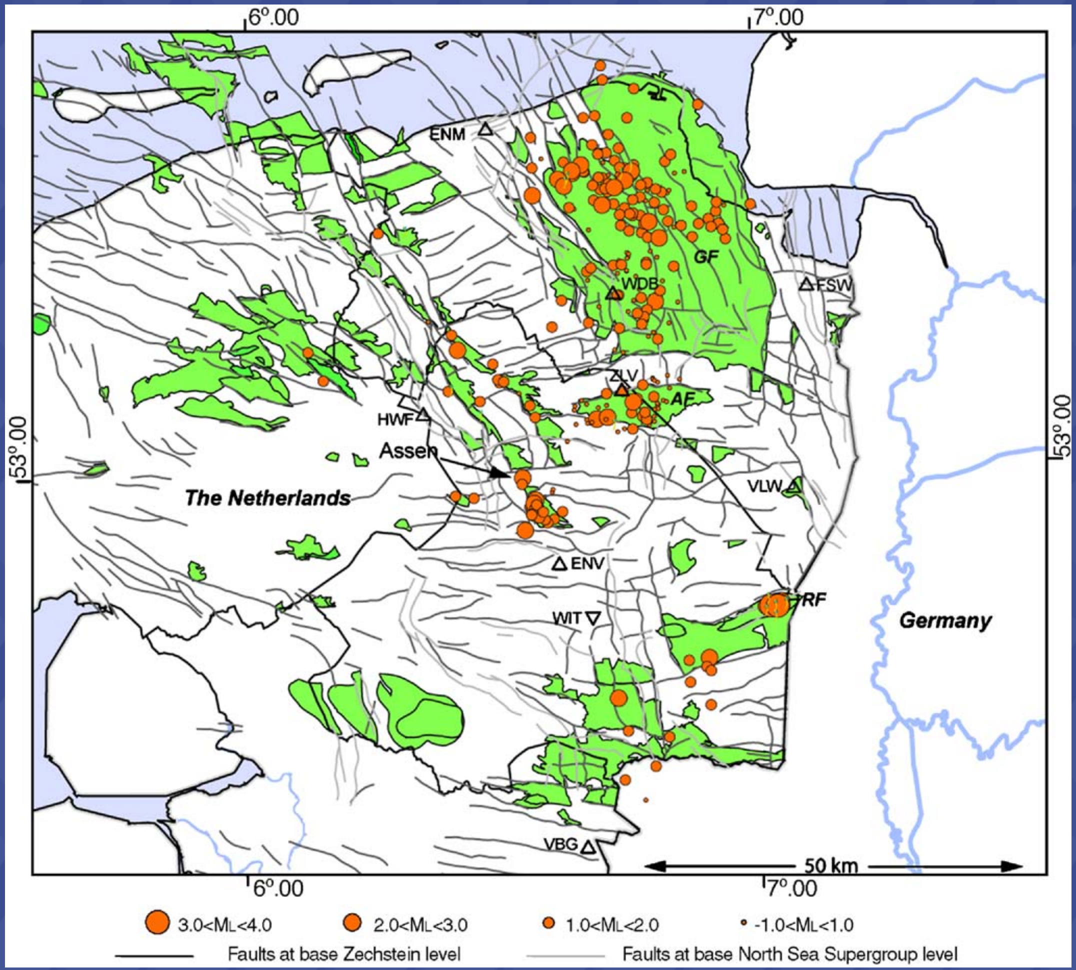




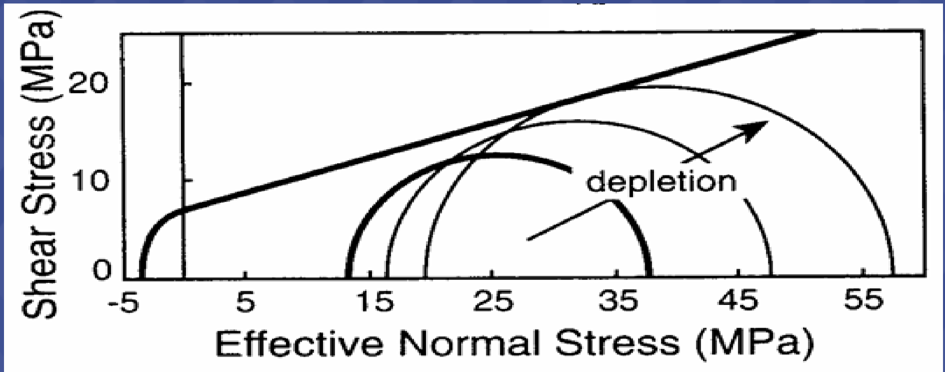
Cloetingh et al., 2006

Van Eck et al., 2006

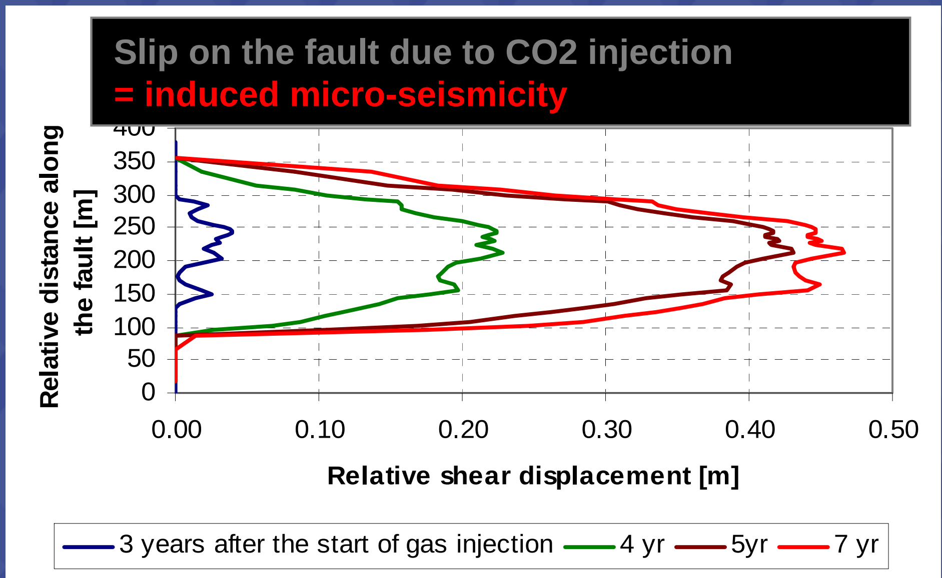
The induced seismicity also occurs predominantly on pre-existing faults



Van Eck et al., 2006



Changes in pore pressure conditions during HC production (injection/depletion) or CO2 storage induce changes in effective stress, ...



.... which may induce fault reactivation.

Local effects:

- change in fault permeability
- change in structural fabric
- stress reorganization

Orlic, 2008

ISES – TNO project:

reproduce/predict the production induced seismicity in the NE Netherlands

1. Build a 3D structural fault model

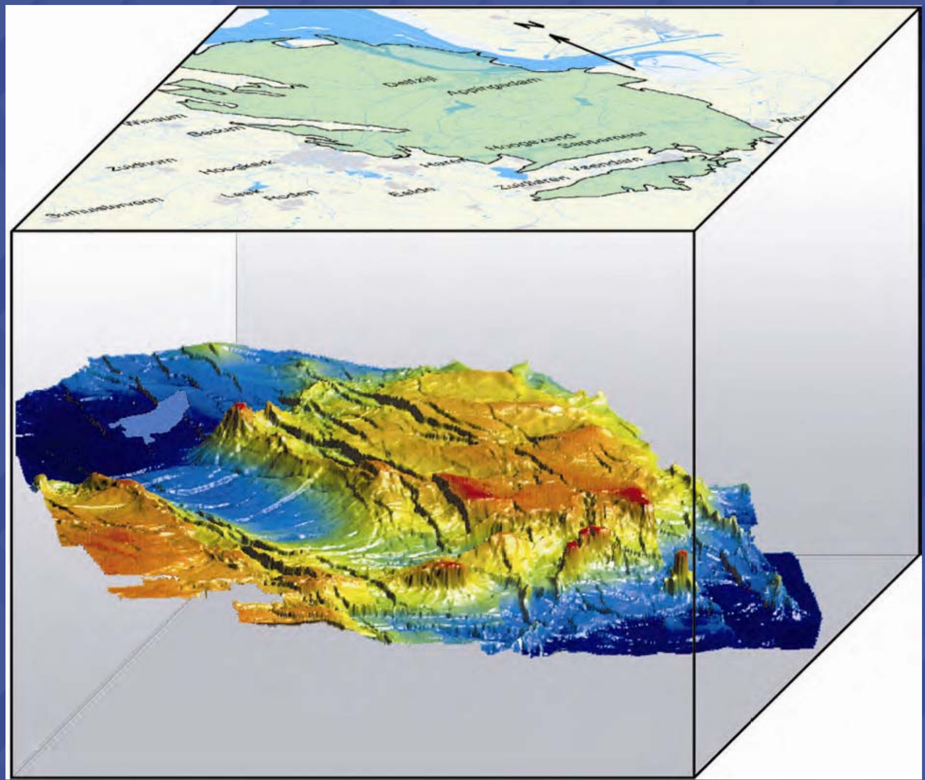
2. Compute 3D stress distribution
   - loading by regional tectonic stress field
   - incorporate effects of reservoir depletion

3. Perform slip tendency & fault reactivation analysis on fault planes

4. Verification/calibration with recorded and historical seismicity
   - Seismological database KNMI
   - LOFAR

Construction of 3D structural fault model

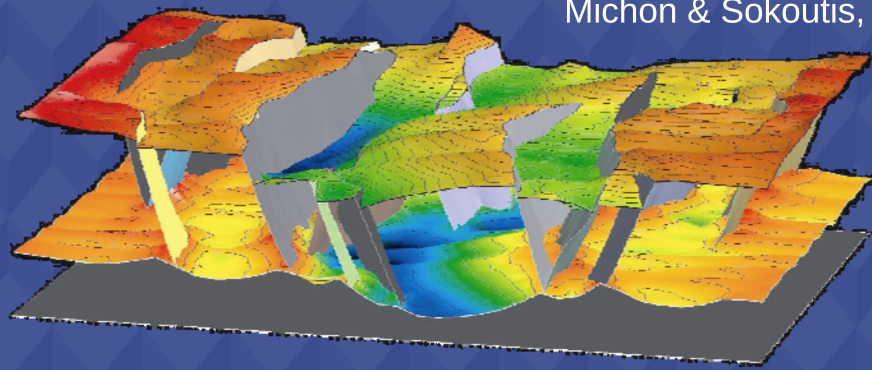
From high resolution 3D seismic data …



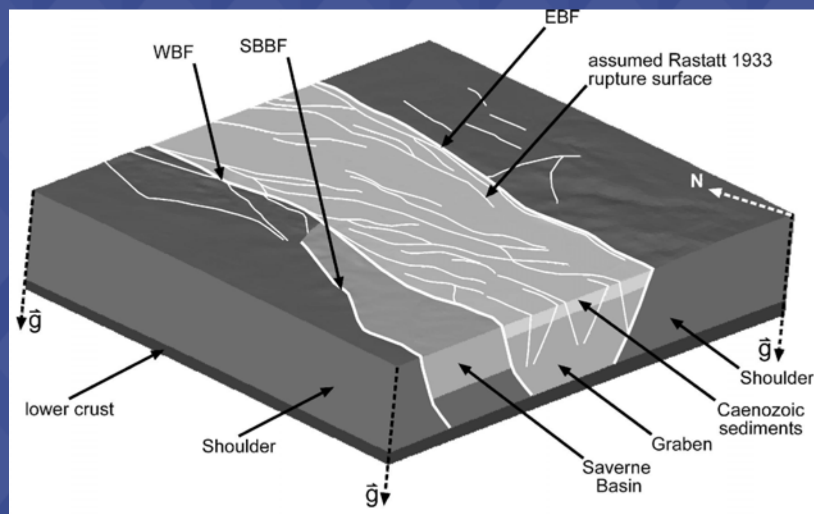
Top of Upper Rotliegend Group
(De Jager & Geluk, 2007)

… to 3D geometry …

Michon & Sokoutis, 2005

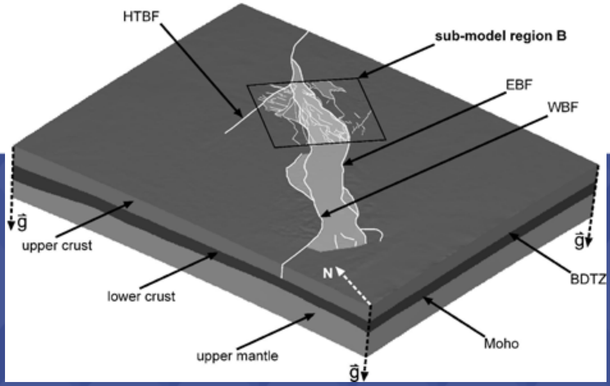


…to a full 3D structural fault model.

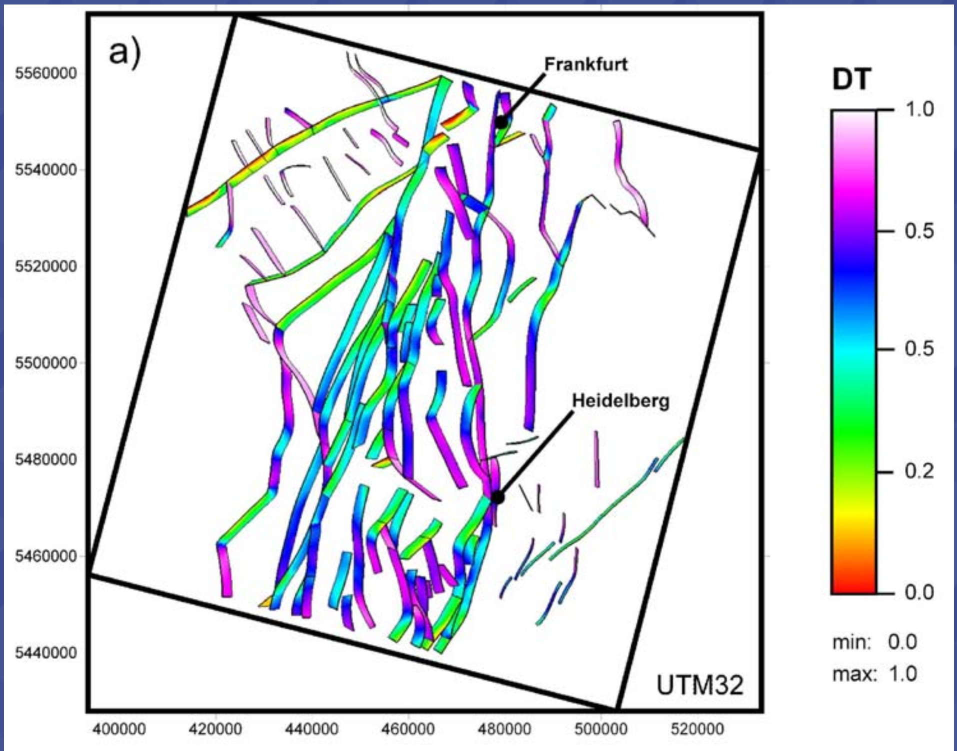


Buchmann, 2008

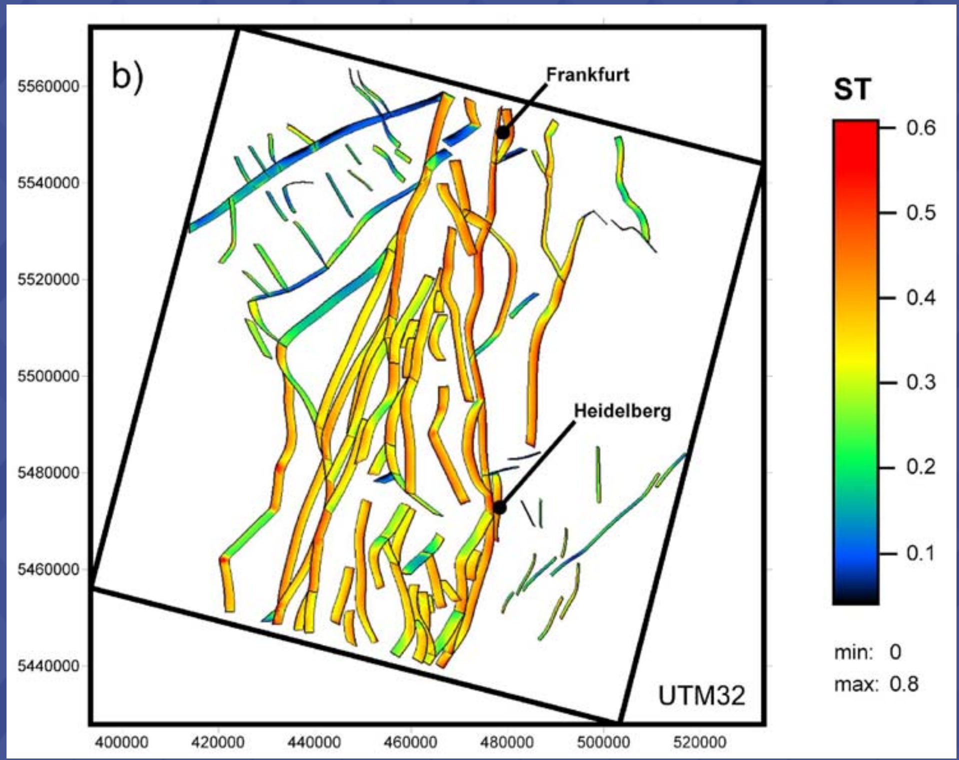
Quantification of fault reactivation potential



Dilation tendency

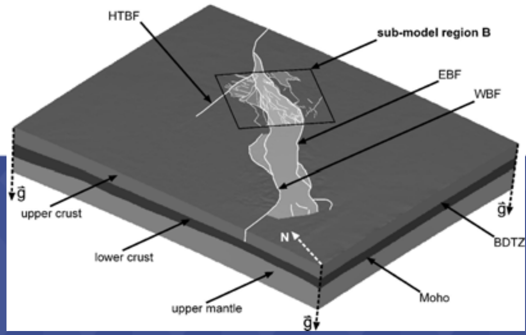


Slip tendency

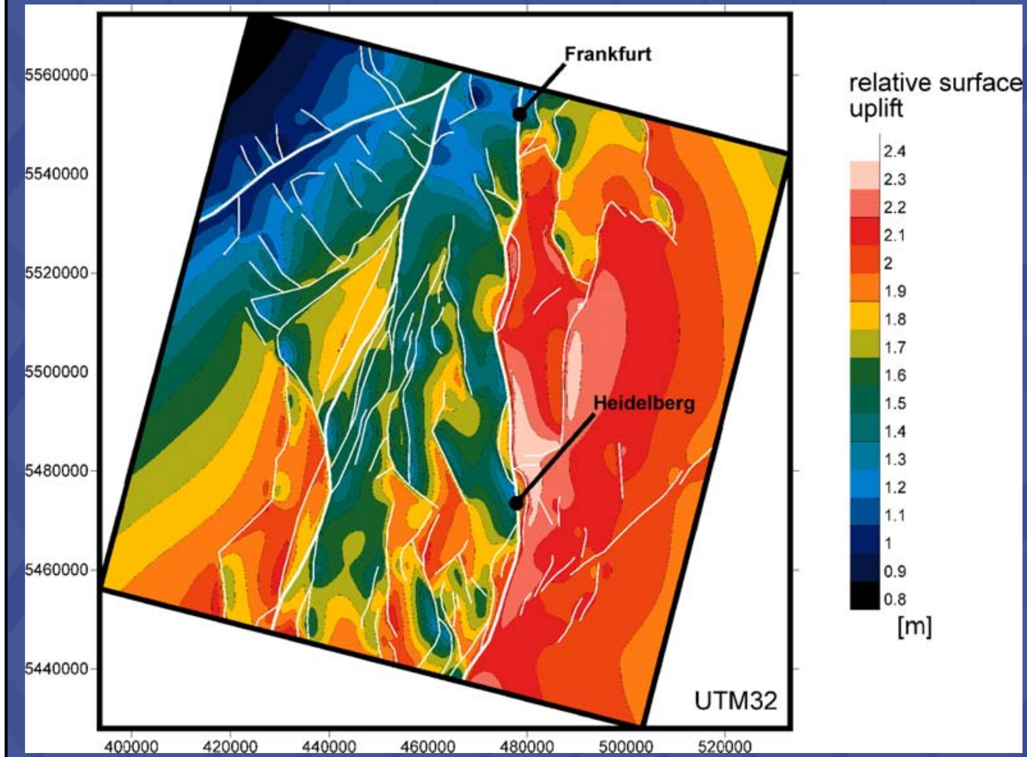


(Buchmann, 2008)

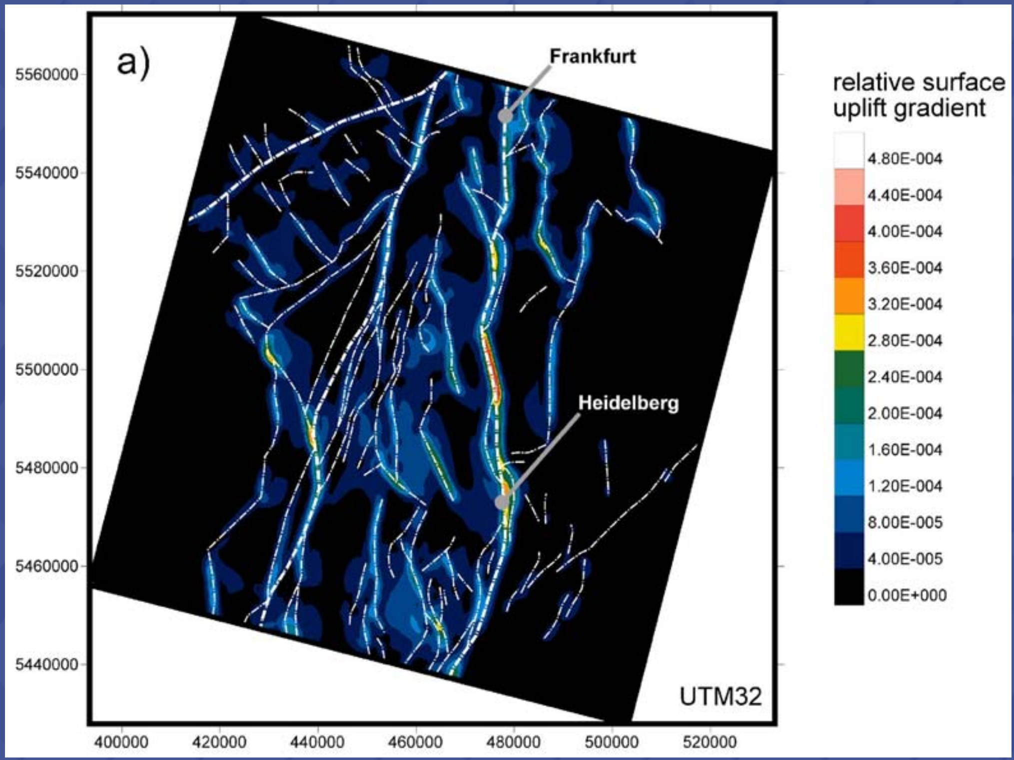
Prediction of surface uplift & subsidence



Surface displacements



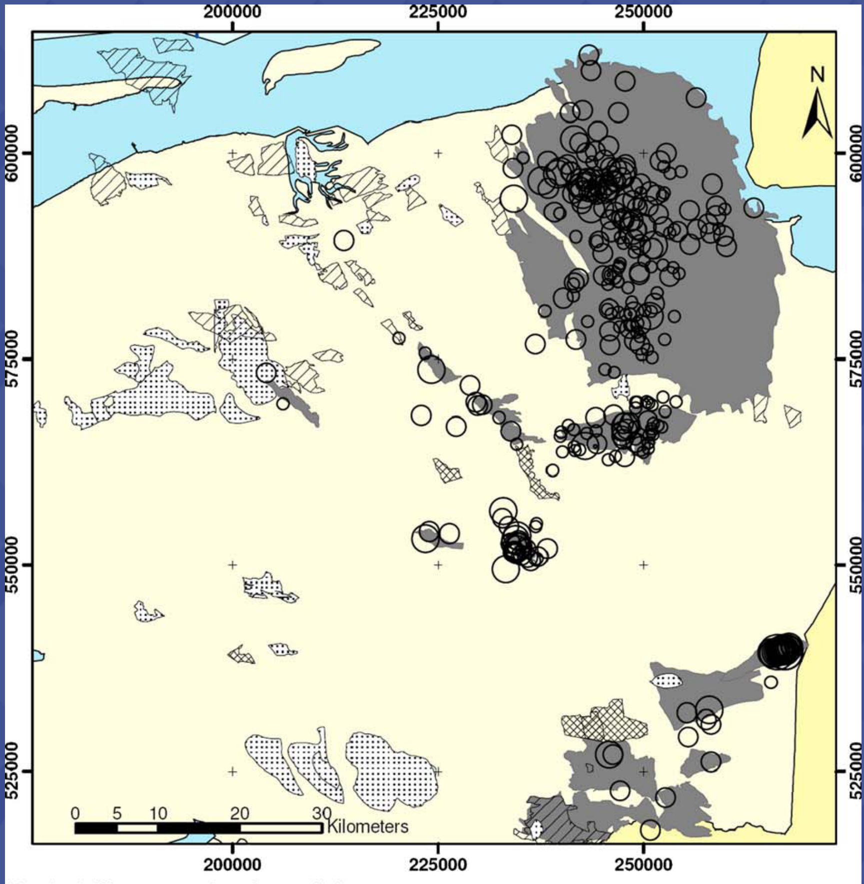
Vertical gradient of surface displacement



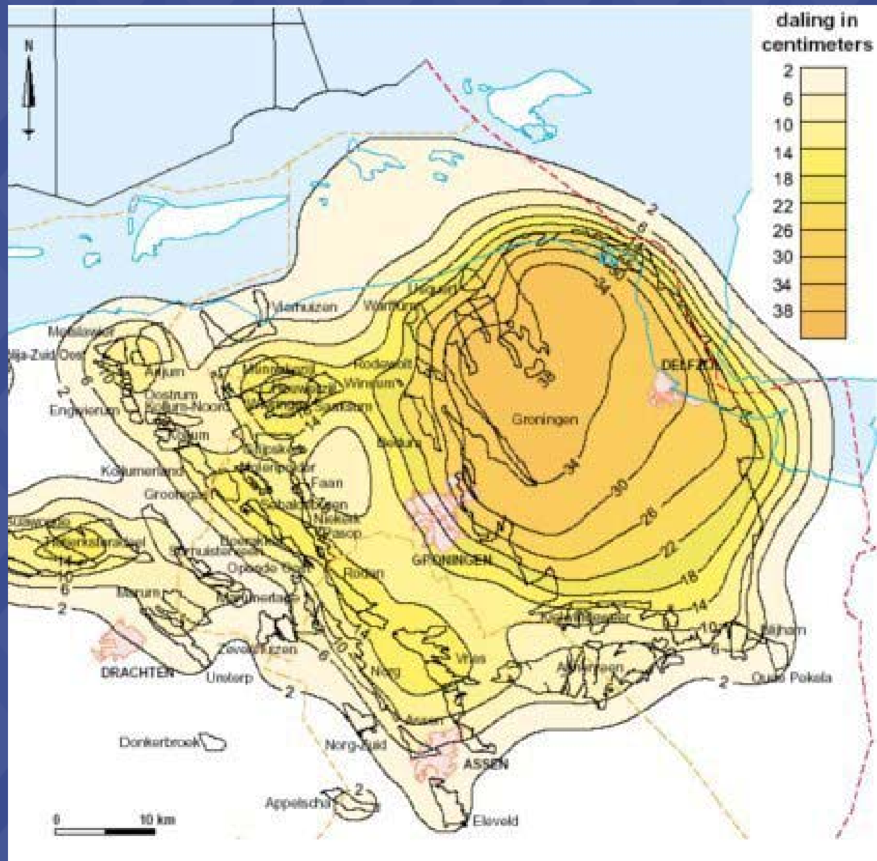
(Buchmann, 2008)

Verification and calibration

Verification with independent seismic hazard studies

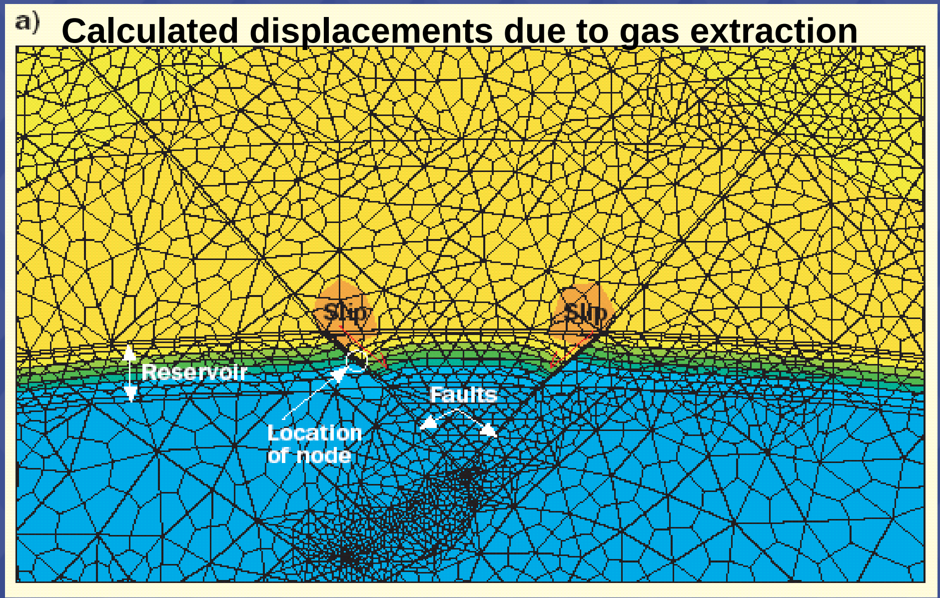


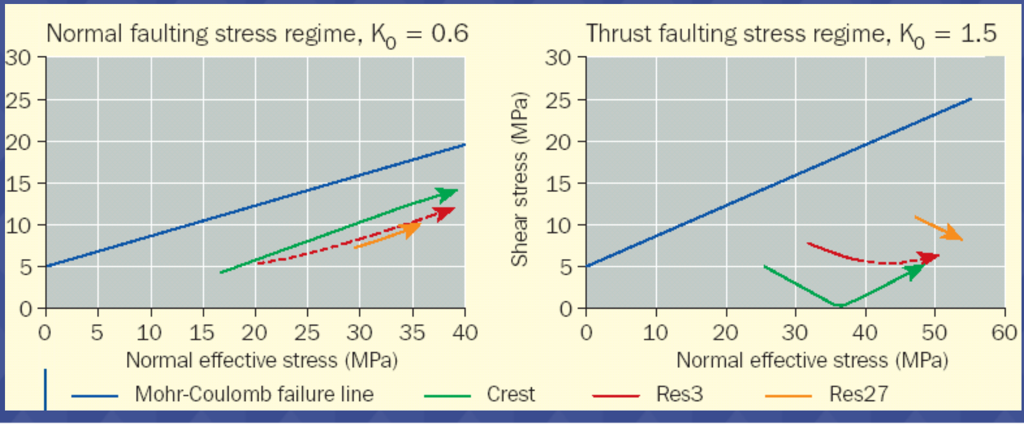
Calibration with measured induced surface subsidence

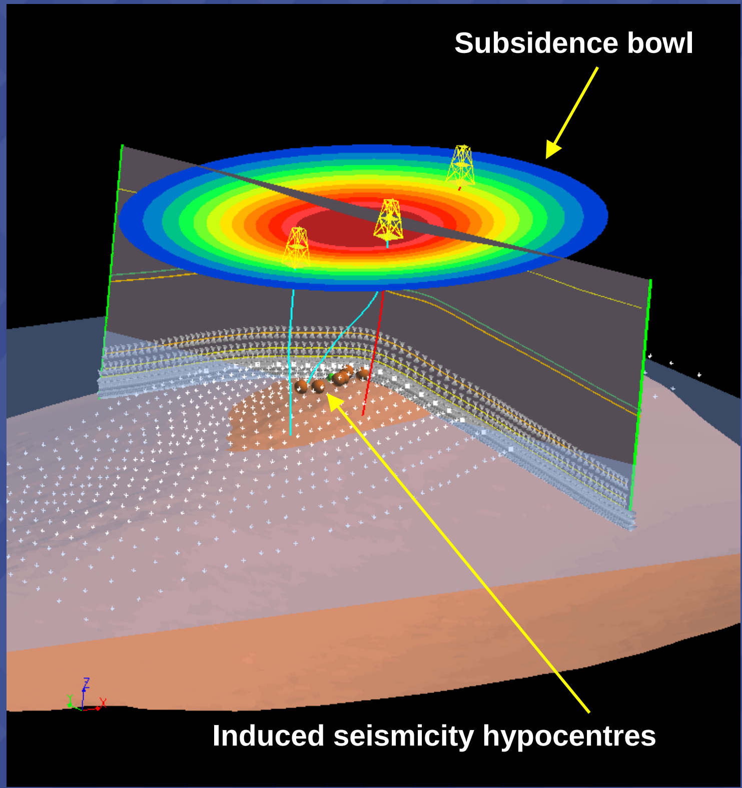


Van Eijs et al., 2006

Local scale modelling of reservoir depletion induced fault reactivation and subsidence







Orlic, 2008

Conclusions

- European ECRIS rift systems are still rheologically weak structures with increased seismicity
- In the Netherlands, earthquakes tend to occur on pre-existing fault planes in the subsurface
- Fault slip and dilation tendency analyses can quantify the fault reactivation potential of pre-existing faults, and thus seismic hazard
- Fault reactivation may affect hydrocarbon recovery at exploration and production time scales