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
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reference
European Cenozoic Rift System (ECRIS)
Lithosphere extension and rift basin formation

Coupled deformation at different spatial scales

- Upper Crust
- Lower Crust
- Subcrustal Lithosphere
- Asthenosphere

**Stron** (Orange) **Weak** (Blue)
3-D rheological strength models

Cloetingh et al., 2005
Strength evolution of rift basins

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
Maps of integrated rheological strength

Entire lithosphere

Crust only

Cloetingh et al., 2005

Present-day strength of the European lithosphere
Post-rift fault reactivation in the Netherlands

Present-day strength of ECRIS rift systems

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

Cloetingh et al., 2006

Increased seismicity in ECRIS

World Stress Map project
In the Netherlands also many earthquakes occur on pre-existing fault systems.
Roer Valley Rift System (RVRS)

Seismicity and main structural elements

Worum et al. (2004)
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

Post-rift fault reactivation in the Netherlands
Finite element models assessing the role of fault friction are constrained by geometry of the graben system.
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

Worum et al. (2004)
West-Netherlands Basin

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

reactivated faults

erosion

Worum and Van Wees, submitted
Implications of fault reactivation for exploration

Change in fault permeability (along fault and across fault)

- Migration pathways
- Barriers
- Seal capacity

After Ellis et al., 1999
Implications for hydrocarbon exploration

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

Integrated Field Studies

Scaled Physical Modelling

Numerical Modelling

Post-rift fault reactivation in the Netherlands
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
Production induced seismicity

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.