

Flow and Performance of Geothermal Doublets in Deep Dinantian Carbonates of The Netherlands*

Jan Ter Heege¹ and Sander Osinga¹

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¹TNO Applied Geosciences, Amsterdam, The Netherlands (jan.terheege@tno.nl)

Abstract

The occurrence and properties of natural faults in fractured reservoirs are key in determining reservoir flow properties, and thereby the success of geothermal energy or oil and gas production from these reservoirs. The quest for exploiting geothermal reservoirs in sedimentary basins with relatively low geothermal gradients has drawn attention to temperature anomalies associated with deep fractured reservoirs. However, low permeability remains a major concern, as the likelihood that fractures are closed or sealed increases with increasing depth. While the E&P industry has been successful in developing tight fractured reservoirs by hydraulically stimulating many horizontal wells, different economics of geothermal projects requires a different approach that involves optimization of doublet placement to achieve optimum flow conditions. Existing subsurface data acquired for oil and gas production can be of great value in such doublet optimization approach. Exploration for new geothermal sites will particularly benefit from site-specific data on fault-related factors like damage zone fracture density, connectivity and permeability. In many cases, such data is lacking during geothermal exploration, but generic relations can be used to constrain typical fault zone architectures, spatial distribution of permeability and characteristics of damage zone fracture populations. Site-specific characteristics of fault and fracture populations can be determined using seismic surveys, outcrop analogues, core material, and laboratory experiments.

In this study, flow and performance of geothermal doublets is modeled for a potential geothermal play in a fractured Dinantian carbonate platform near Luttelgeest in the North of the Netherlands. Fault populations in the carbonate formation were analysed

using 2D and 3D seismic data. Distributions of fault azimuths, dips and lengths are derived from the interpretation of 2D and 3D seismic. These distributions can be used to determine the preferred orientation of faults and apply scaling relations to describe bulk permeability that incorporates specific fault populations from the seismic surveys, typical fault zone architectures from outcrops, and fracture permeability from laboratory experiments. A bulk permeability model is used that describes non-isotropic permeability of individual fault zone using 3D permeability tensors for fault core, damage zone and surrounding intact reservoir matrix, and fractured reservoir permeability by volume averaging the contribution of fault zones or fractures based on the frequency distribution of fault dimensions. The approach ensures that data available prior to drilling, as well as uncertainties are taken into account in doublet performance assessment. Bulk permeability is represented by multiple uniform fracture sets with different orientations in a semi-analytical model for performance assessment of geothermal doublets to analyse the evolution of temperature and pressure for different doublet configurations. The geothermal power for doublet systems consisting of a surface heat exchanger, and multiple injection (“injector”) and production (“producer”) wells that are placed in the fractured Dinantian carbonates was analysed. Factors such as preferred orientations and permeability of faults and fractures, local stress field, and injection/production rates interact to determine the geothermal power of such doublet systems so that optimum placement of geothermal doublet systems can be determined. Optimization of geothermal doublet design can be performed based on multiple model realization based on data of fault and fracture populations from local seismic surveys, outcrop analogues and experiments. Such optimization helps de-risking geothermal exploration and exploitation, as it outlines preferred placement of doublets in terms of optimum flow and cold water breakthrough.

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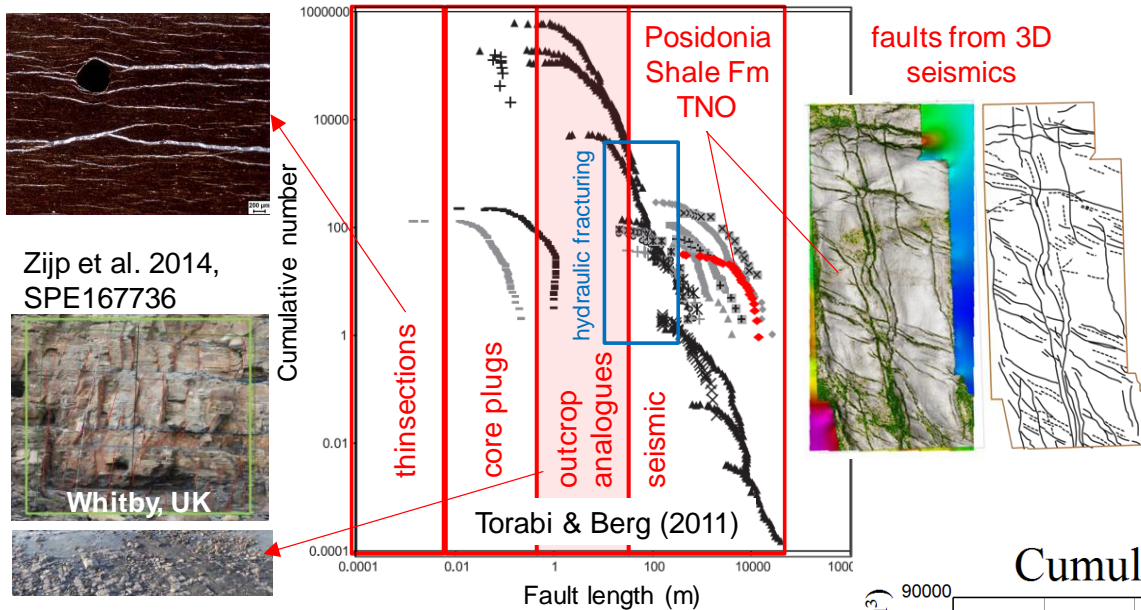


› **FLOW AND PERFORMANCE OF GEOTHERMAL DOUBLETES IN DEEP DINANTIAN CARBONATES OF THE NETHERLANDS**

Jan ter Heege &
Sander Osinga (TNO Applied Geosciences)

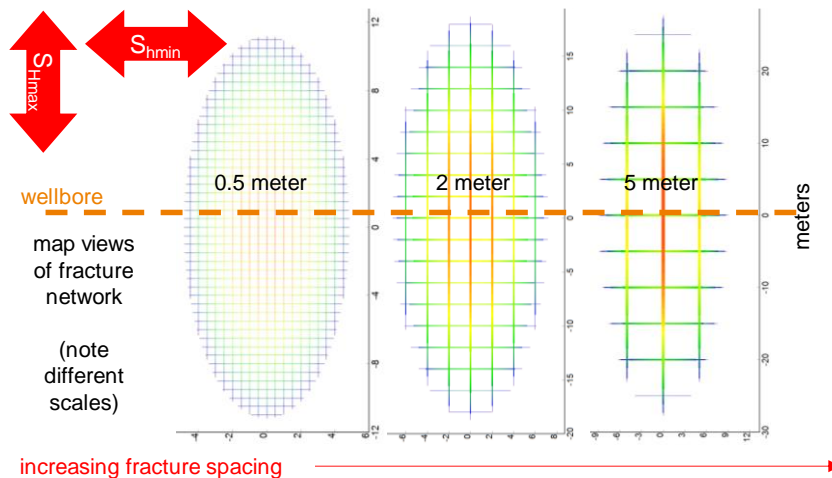
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FAULTS AND FRACTURES CONTROL GAS FLOW

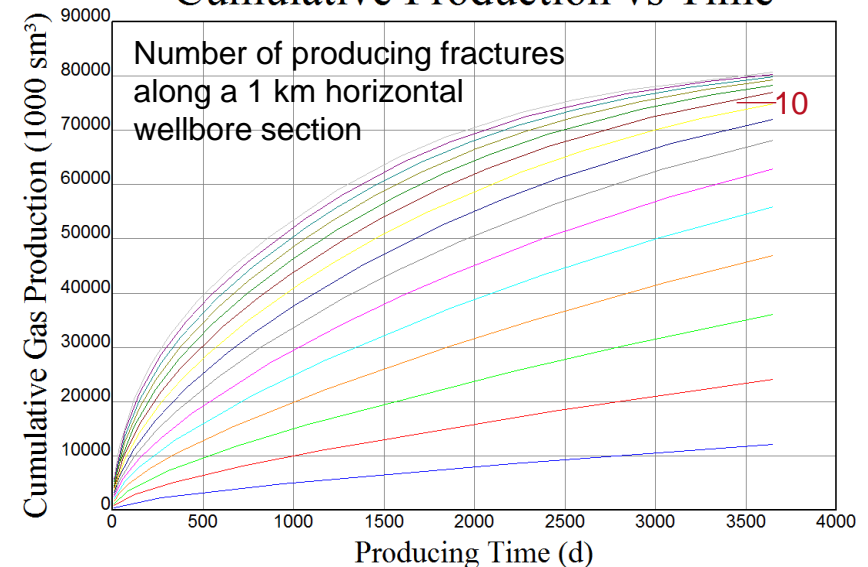


Posidonia Shale Formation:
Faults & fractures at various scales and the relation with gas production (Ter Heege et al. 2014)

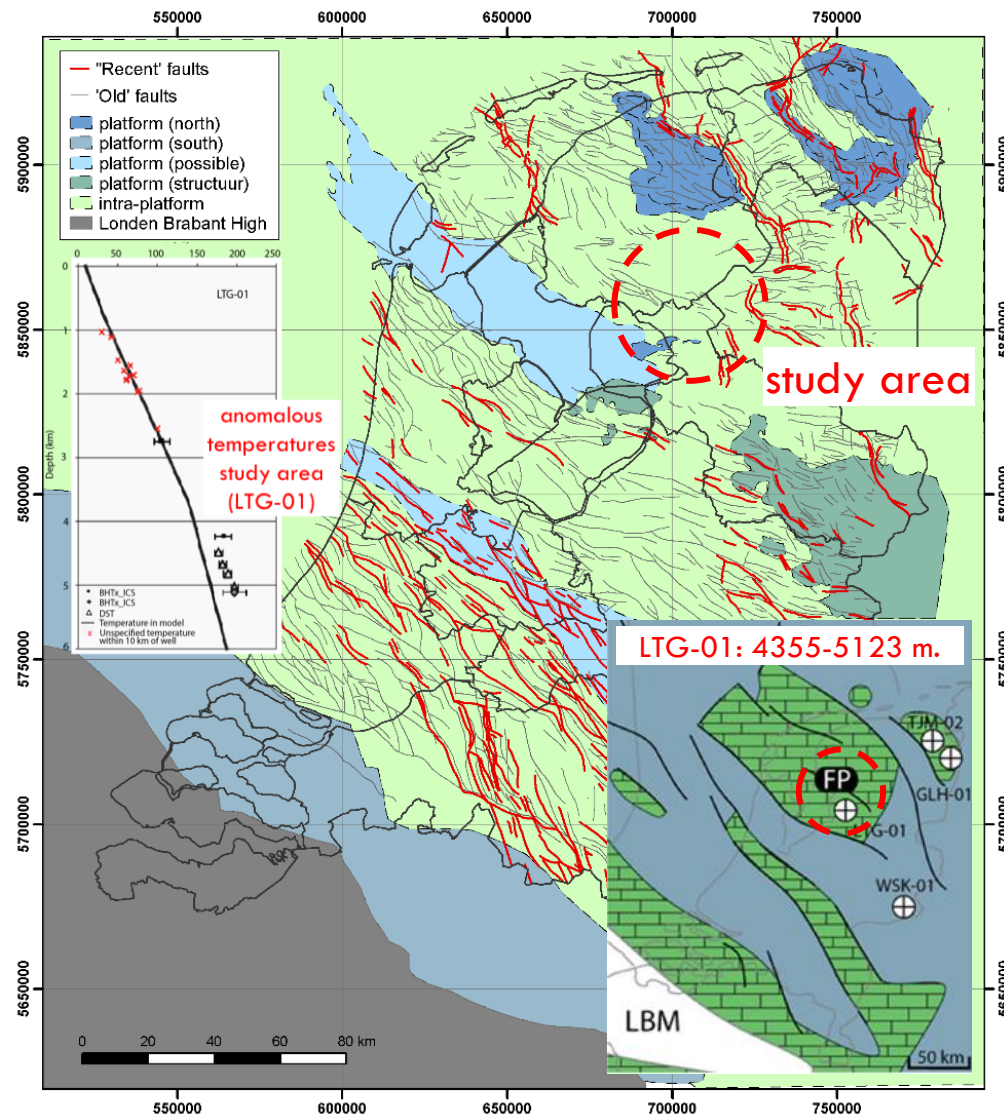
Transverse Fractures	xf (m)	kfwf (mD·m)
1	77.00	200.00
2	77.00	200.00
3	77.00	200.00
4	77.00	200.00
5	77.00	200.00
6	77.00	200.00
7	77.00	200.00
8	77.00	200.00
9	77.00	200.00
10	77.00	200.00
11	77.00	200.00
12	77.00	200.00
13	77.00	200.00
14	77.00	200.00
15	77.00	200.00



Cumulative Production vs Time



A POTENTIAL GEOTHERMAL TARGET?

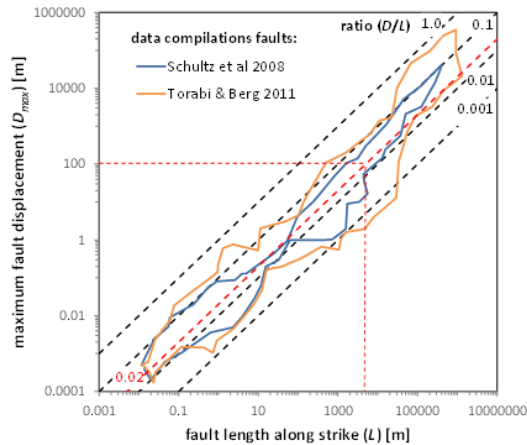
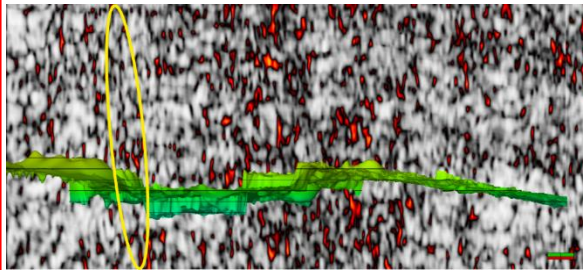


- › Dinantian platform carbonates
- › Population of natural fractures
- › Temperature anomaly (LTG-01)
- › 2D & 3D seismics
- › Well logs (LTG-01)
- › Convection hypothesis

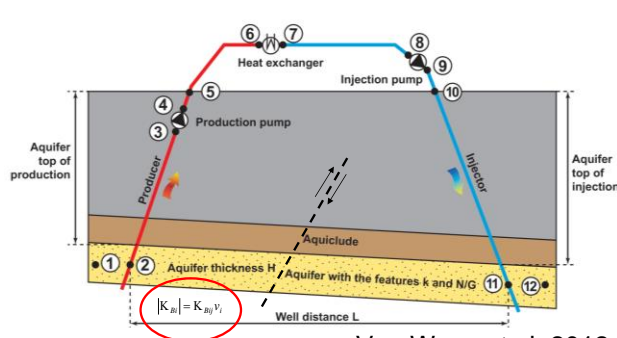
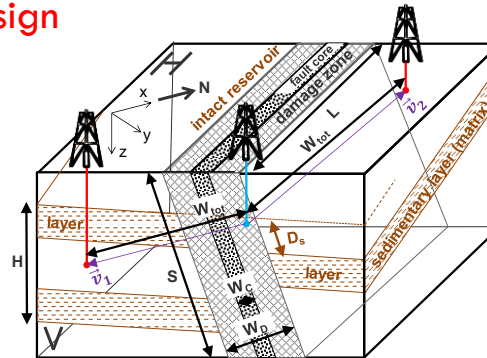
Dinantian carbonate platforms and major faults in the Netherlands (Veldkamp 2016; Lipsey et al. 2016)

DOUBLET PERFORMANCE MODEL WORKFLOW

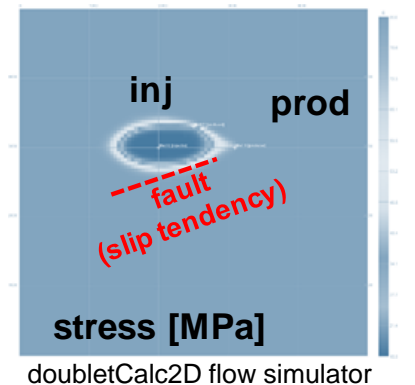
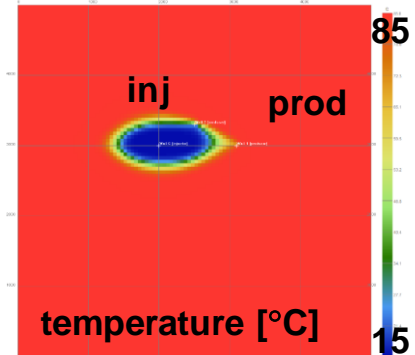
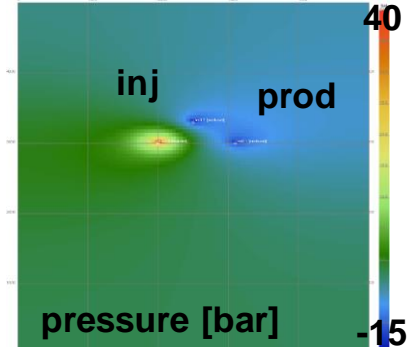
1. fault characterization



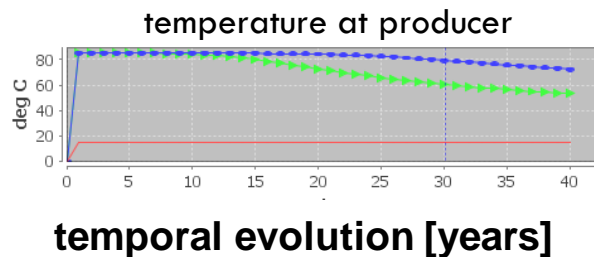
2. permeability model & doublet design



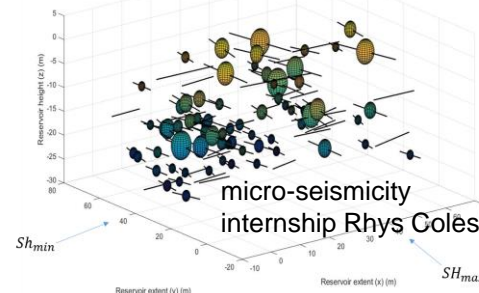
3. flow & mechanics



4. doublet performance & reservoir response

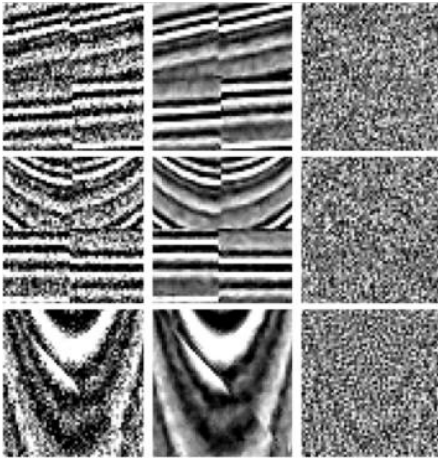


fracture reactivation

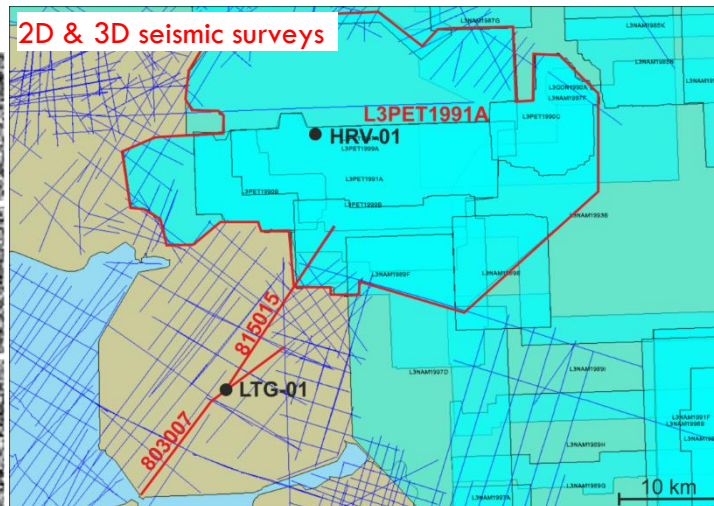


SEISMIC CHARACTERIZATION OF FAULTS

non-local means method



2D & 3D seismic surveys



› Fault detection based on 2D & 3D seismics

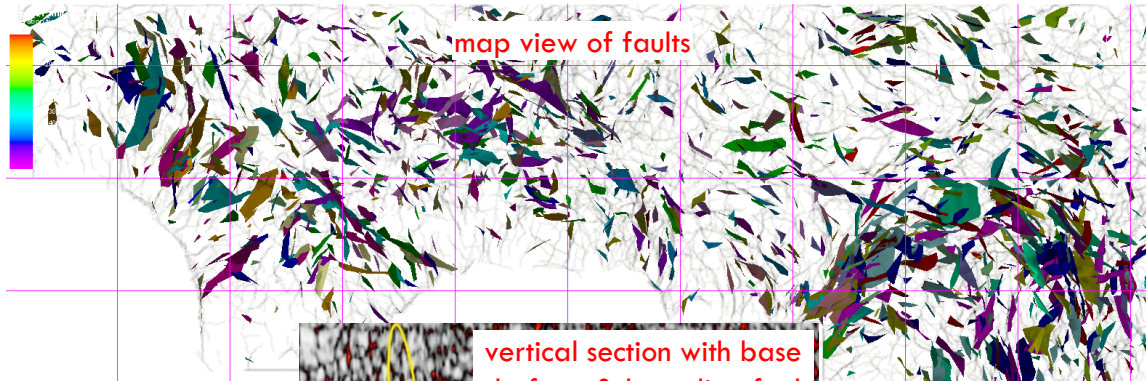
› New de-noising algorithm (non-local means)

› Autotracking of faults

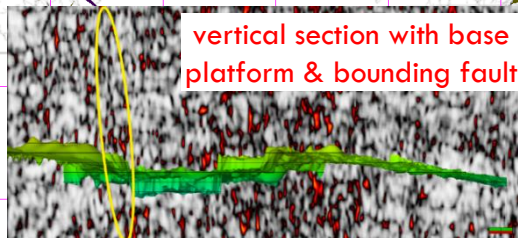
› Characteristics of fault population dependent on de-noising and autotracking parameters

› Uncertainty of seismic fault characterization can be taken into account

map view of faults

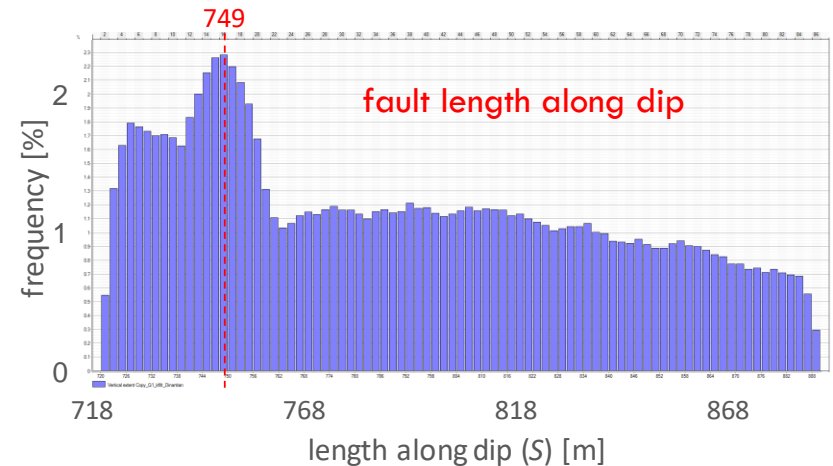
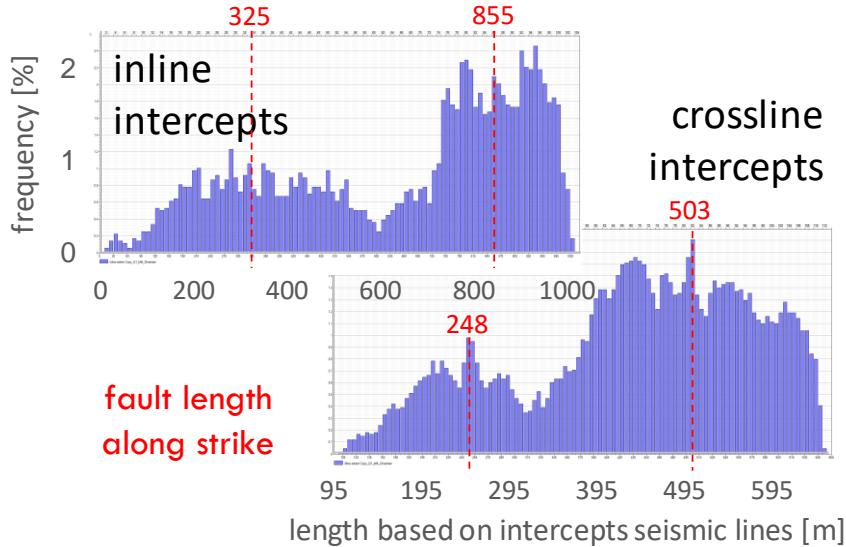
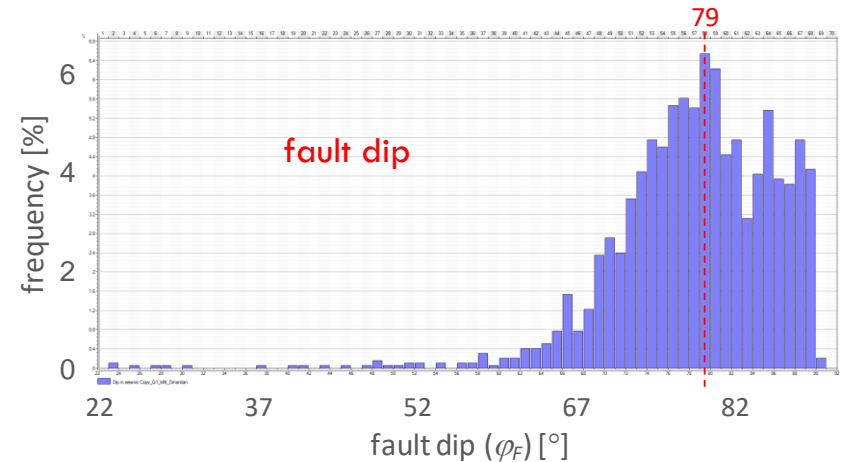
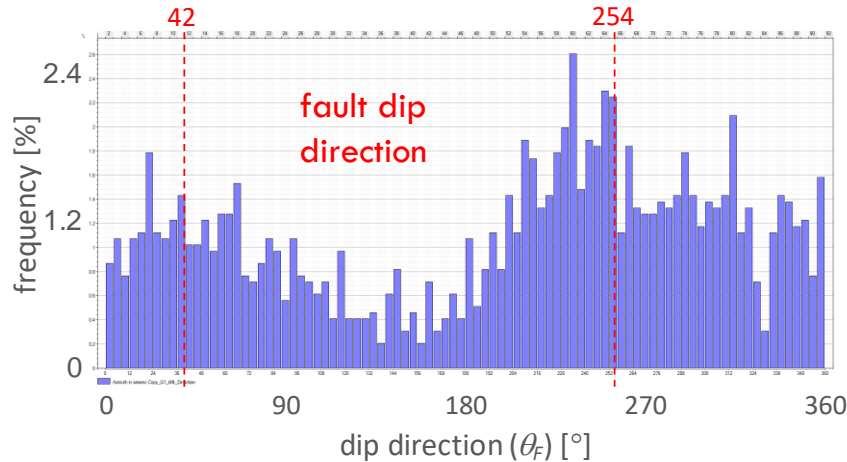


vertical section with base platform & bounding fault



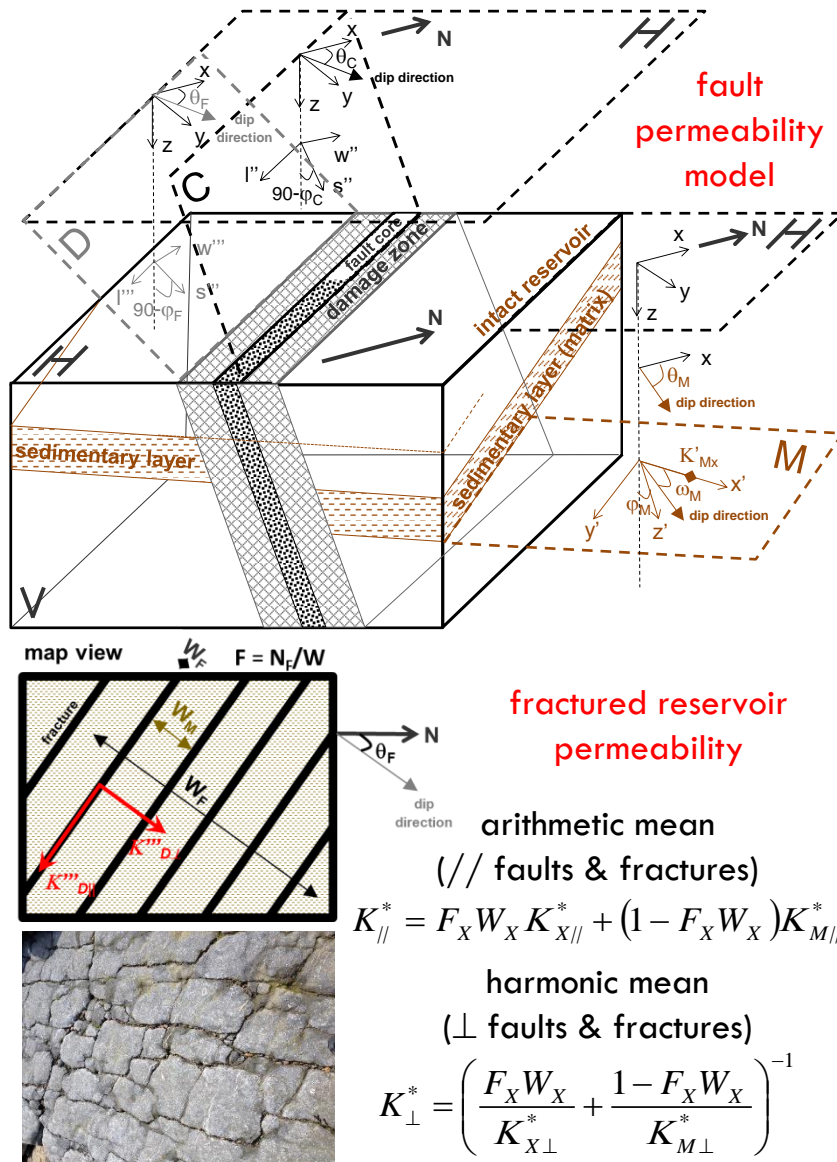
Mapped fault in Dinantian carbonate platform around LTG-01 based on a new de-noising non-local means algorithms (Carpentier et al. 2016)

CHARACTERISTICS OF FAULT POPULATION



Distribution of fault size, dip and orientation from seismic characterization

FRACTURED RESERVOIR PERMEABILITY MODEL



- › Fault permeability model: (1) layered reservoir, (2) fractured damage zone, (3) fault core
- › Fractured reservoir permeability model incorporating population of fault zones
- › 3D permeability tensor based on arithmetic/harmonic mean of matrix & fault permeability
- › Bulk permeability (summation of N_Z faults):

$$K_{B11}'' = \sum_{n=1}^{N_Z} \left[\left(\frac{V_Z}{K_{Z11}''} + \frac{1 - V_Z}{K_{M11}''} \right)^{-1} \right]$$

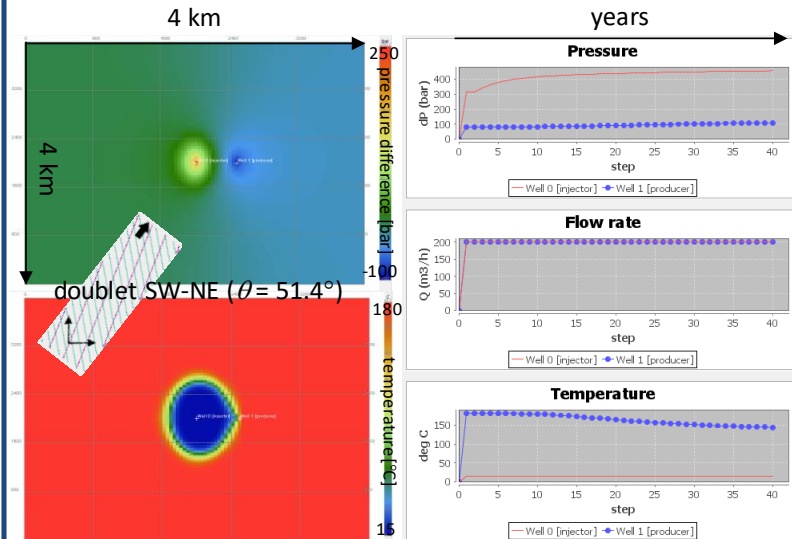
$$K_{Bii}'' = \sum_{n=1}^{N_Z} [V_Z K_{Zii}'' + (1 - V_Z) K_{Mii}'']$$

for $i = 1, 2$

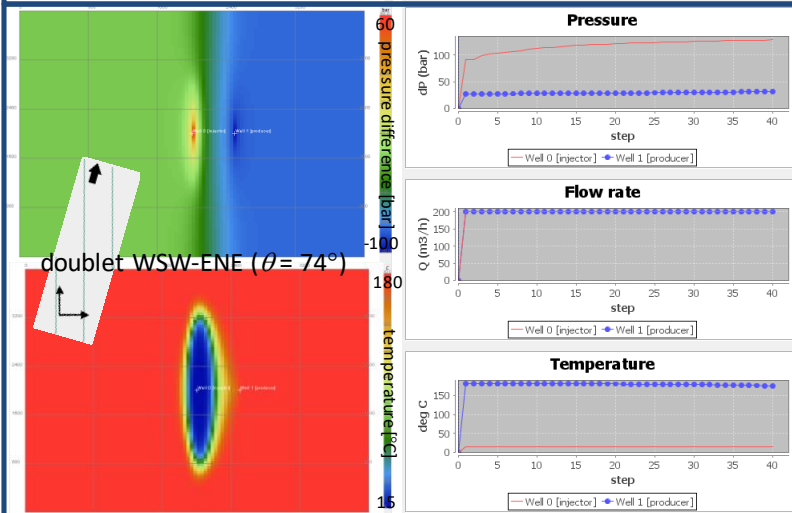
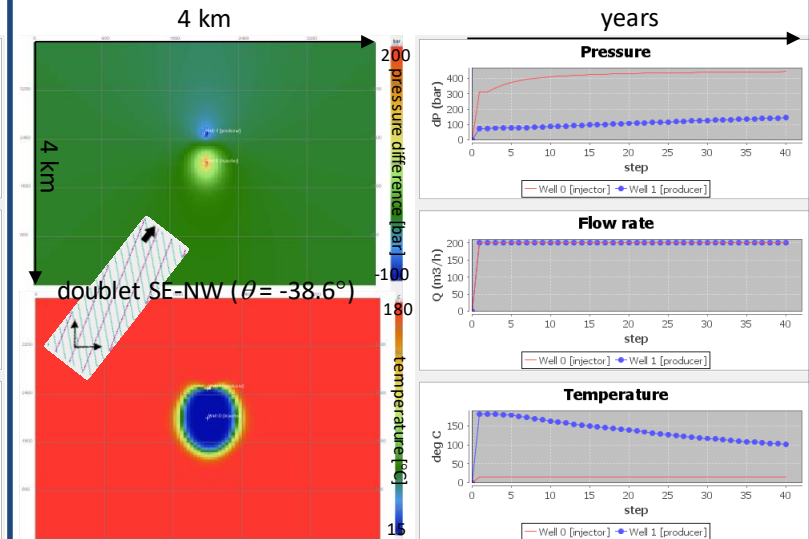
$$K_{Bij}'' = \sum_{n=1}^{N_Z} [(1 - V_Z) K_{Zij}''] \text{ for } i \neq j$$

4 SCENARIOS DOUBLET DESIGN & PERMEABILITY

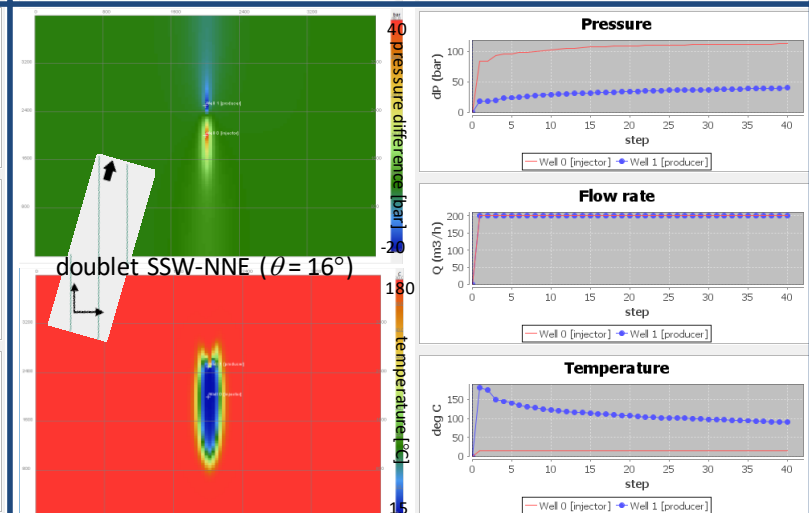
Scenario 1: $K_{Mii}' = 10 \text{ mD}$; $K_{Zii}'' = 600 \text{ mD}$; $K_{B11} = 12.5 \text{ mD}$; $K_{B22} = 37.8 \text{ mD}$



Scenario 2: $K_{Mii}' = 10 \text{ mD}$; $K_{Zii}'' = 600 \text{ mD}$; $K_{B11} = 12.5 \text{ mD}$; $K_{B22} = 37.8 \text{ mD}$



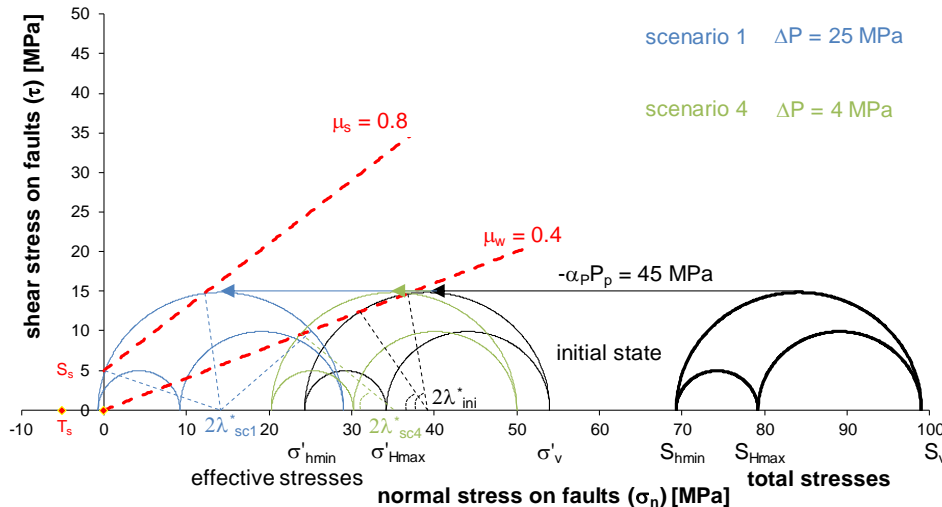
Scenario 3: $K_{B11} = 10 \text{ mD}$; $K_{B22} = 600 \text{ mD}$



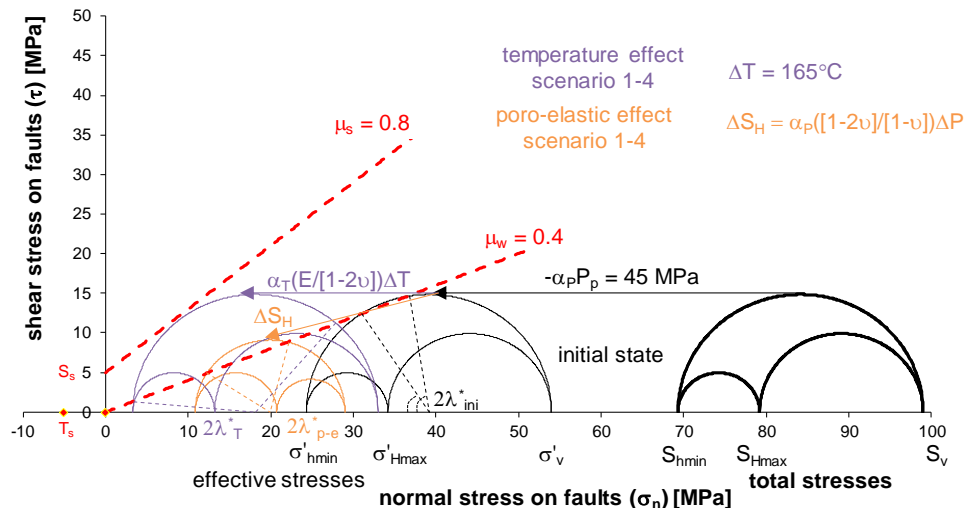
Scenario 4: $K_{B11} = 10 \text{ mD}$; $K_{B22} = 600 \text{ mD}$

RESERVOIR RESPONSE TO DOUBLET OPERATION

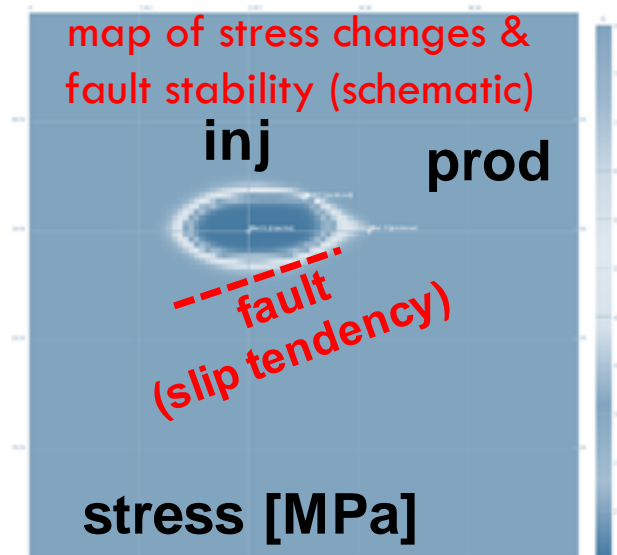
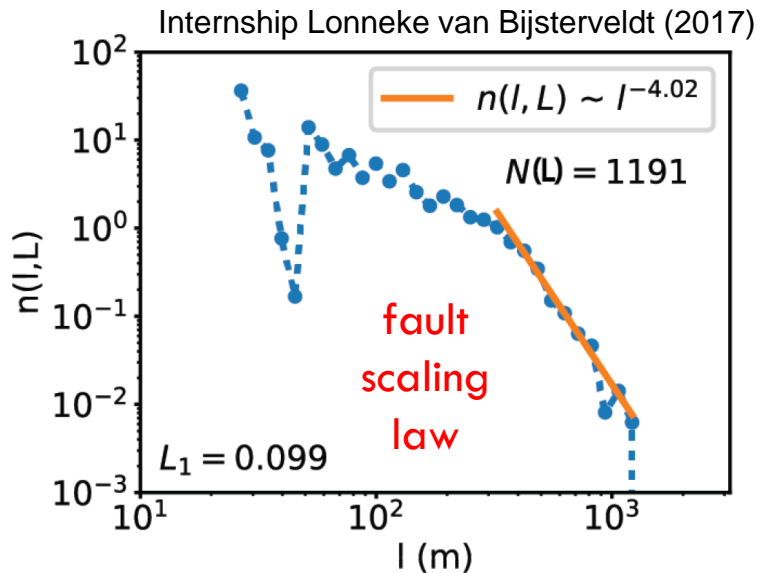
effect of pressure change



effect of temperature change and poro-elasticity



- › **Initial conditions (black):** Some weak faults ($\mu = 0.4$) may be critically-stressed (critical fault angle λ)
- › **Pore pressure effect (blue/green):** Strong faults ($\mu = 0.8$) may become critically-stressed, tensile fractures may initiate
- › **Thermal effect (purple):** Strong faults ($\mu = 0.8$) may become critically-stressed
- › **Poro-elastic effect (orange):** Smaller effect on fault stability compared to pore fluid effect
- › **Increase of reservoir permeability** as critically-stressed fractures have elevated permeability
- › **Decrease of reservoir permeability** due to stress-enhanced solution-precipitation processes
- › **Potential for induced seismicity** if large faults are reactivated



- › Improved incorporation of fault populations from seismic characterization
- › Fix cross flow in flow simulations (cf. current internship Joris Tholen)
- › Better constraints on fractured reservoir permeability
- › Practical scenarios for doublet designs (placement & operation)
- › Trade-off between fault & fracture reactivation and sealing by solution-precipitation
- › Workflow can be used to mitigate problematic induced seismicity by incorporating location of large faults, mapping stress changes and analyzing slip tendency of large faults

- › ***Faults & fractures*** are critical in determining anisotropic permeability and performance of doublets in fractured reservoirs such as the Dinantian Carbonates in northern Netherlands
- › ***Data*** from geological (outcrop) and geophysical (seismic) characterization need to be incorporated in fractured reservoir permeability models to improve upfront predictions of doublet performance
- › ***Optimum performance of geothermal doublets*** can be determined by simulating pressure and temperature evolution for different scenarios of doublet designs and fractured reservoir properties, also capturing data uncertainty (doubletCalc2D)
- › ***The geomechanical response of reservoirs*** to doublet operation can change flow behavior and performance of doublets by changing flow properties of faults and fractures
- › ***Mitigation of problematic induced seismicity*** can be performed by mapping reservoir stress conditions based on simulations, and ensuring doublet operation will minimize slip tendency of large faults



› **THANK YOU FOR YOUR ATTENTION**

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