Elastic Dislocation Modelling and Coulomb Stress Change Investigations*

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Abstract

Elastic Dislocation modelling based on angular dislocation theory is able to predict displacement fields and the distribution of strain in a poroelastic medium for any slip introduced on a discrete fault. Assuming linear elasticity, the magnitude and distribution of fault-induced stresses can then be calculated and following on from this, the Coulomb stress changes in the surrounding rock can be determined from shear and normal stresses acting upon fractures. In addition, a key application of Coulomb stress change is the ability to determine optimal fracture orientations. Outputs from elastic dislocation and Coulomb stress change modelling have numerous applications for hydrocarbon exploration and production, but a key driver for this new development is the ability to model lateral variation of mechanical properties, such as elastic moduli, strength, and friction. Lateral variations in mechanical properties have not been considered in any of the currently available software packages. For the first time, users have the ability to laterally vary mechanical properties, such as Poisson's ratio, Young's modulus and friction, allowing natural lithological variations to influence the calculation of various stress attributes. We will present details on how Elastic Dislocation Modelling and Coulomb stress change calculations have been implemented in Midland Valley's Move" software. The new module, called Fault Response Modelling, has been specifically designed to offer this higher degree of freedom. Additionally, the user can use two different friction models in the calculation: (1) an apparent frictional model, and (2) a pore pressure responsive model. The application and potential limitations of these two friction models to geological problems relevant to hydrocarbon exploration and production will be discussed using a combination of illustrative examples and case studies. Significantly, the calculations for optimally oriented fracture planes are based on a general tensor description, which allows users to consider any slip direction and an opening or closing component. Various other stress attributes, including slip

tendency, fracture stability and retention capacity can then be calculated for these fractures to assess which fractures are likely to fail in the stress field and potentially act as fluid pathways.

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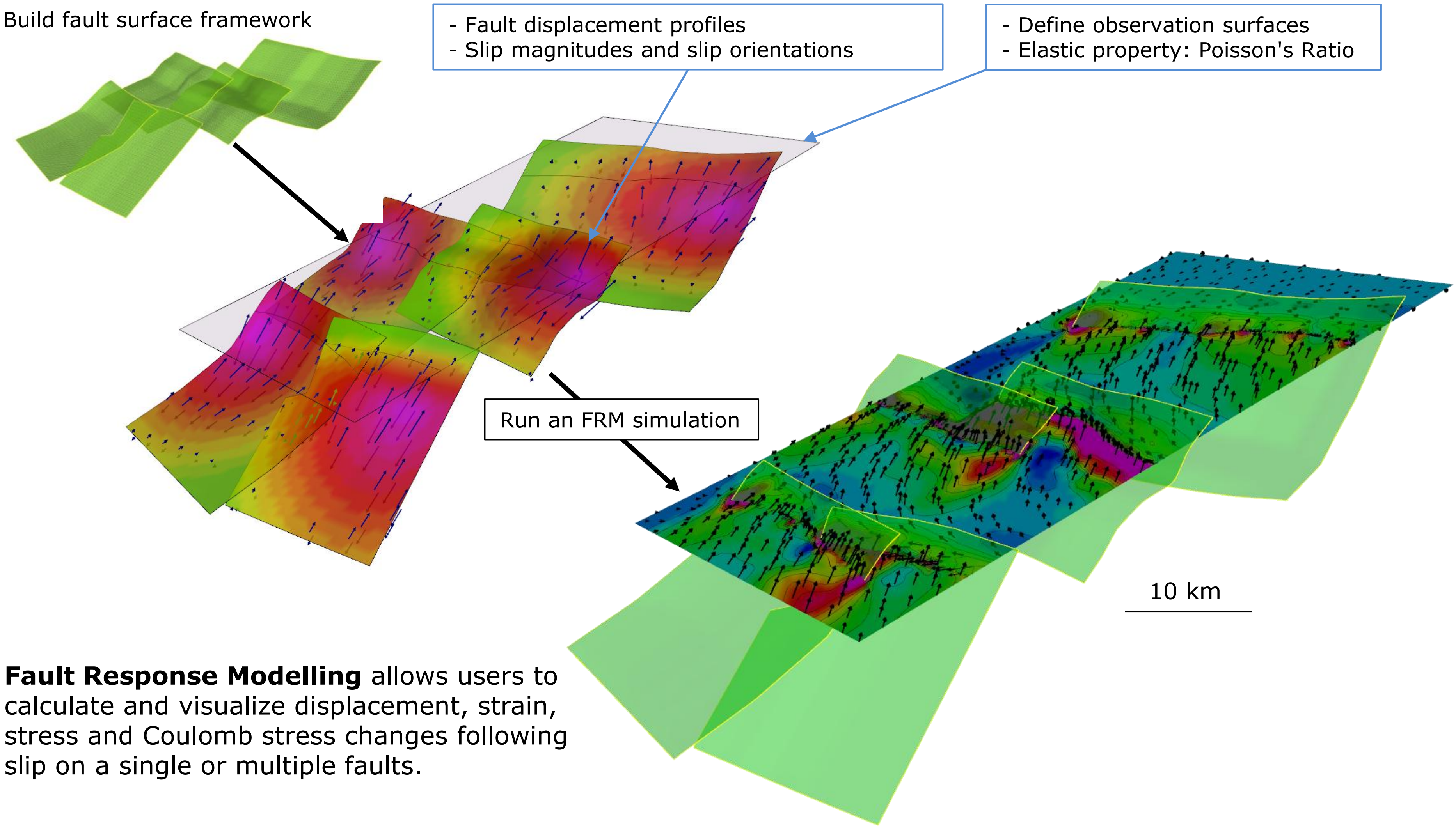
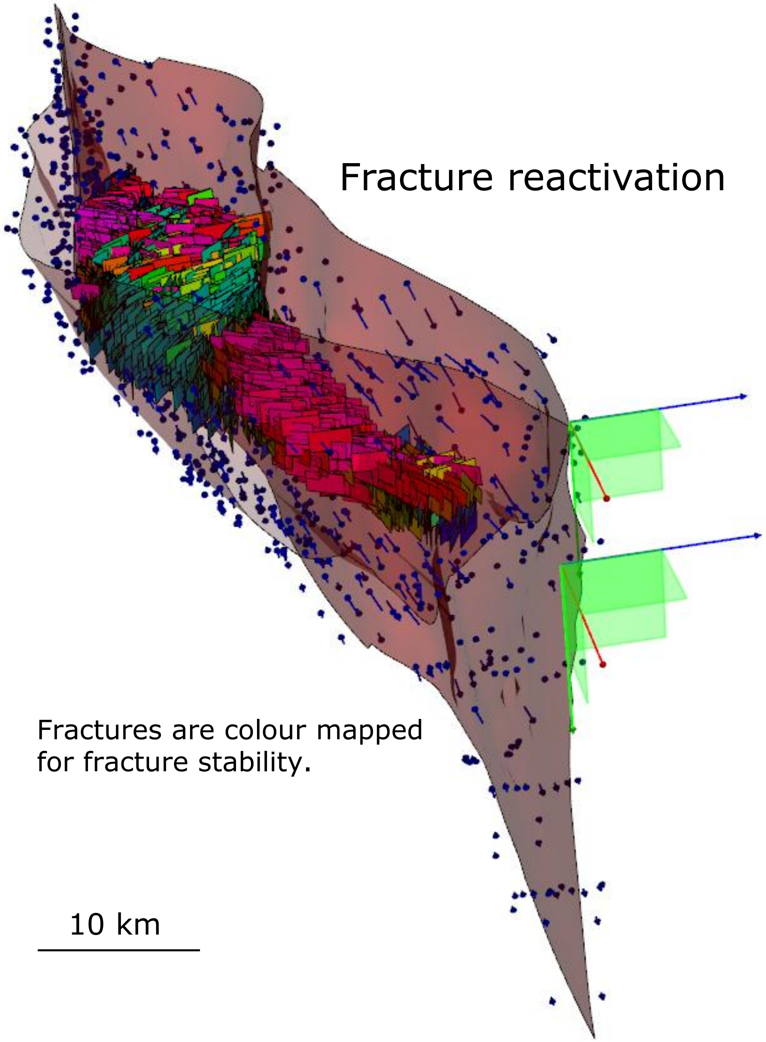
Introduction



Fault Response Modelling allows users to calculate and visualize displacement, strain, stress and Coulomb stress changes following slip on a single or multiple faults.

Application of Fault Response Modelling: Examples

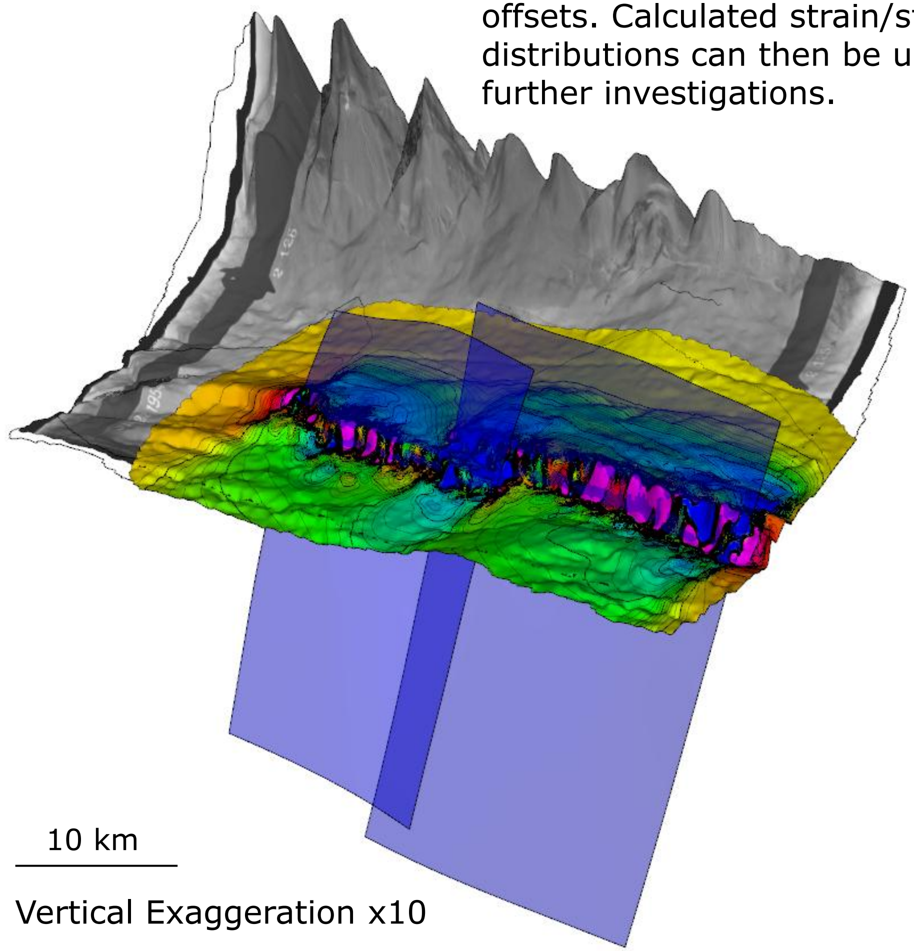


Fracture reactivation

Fractures are colour mapped for fracture stability.

10 km

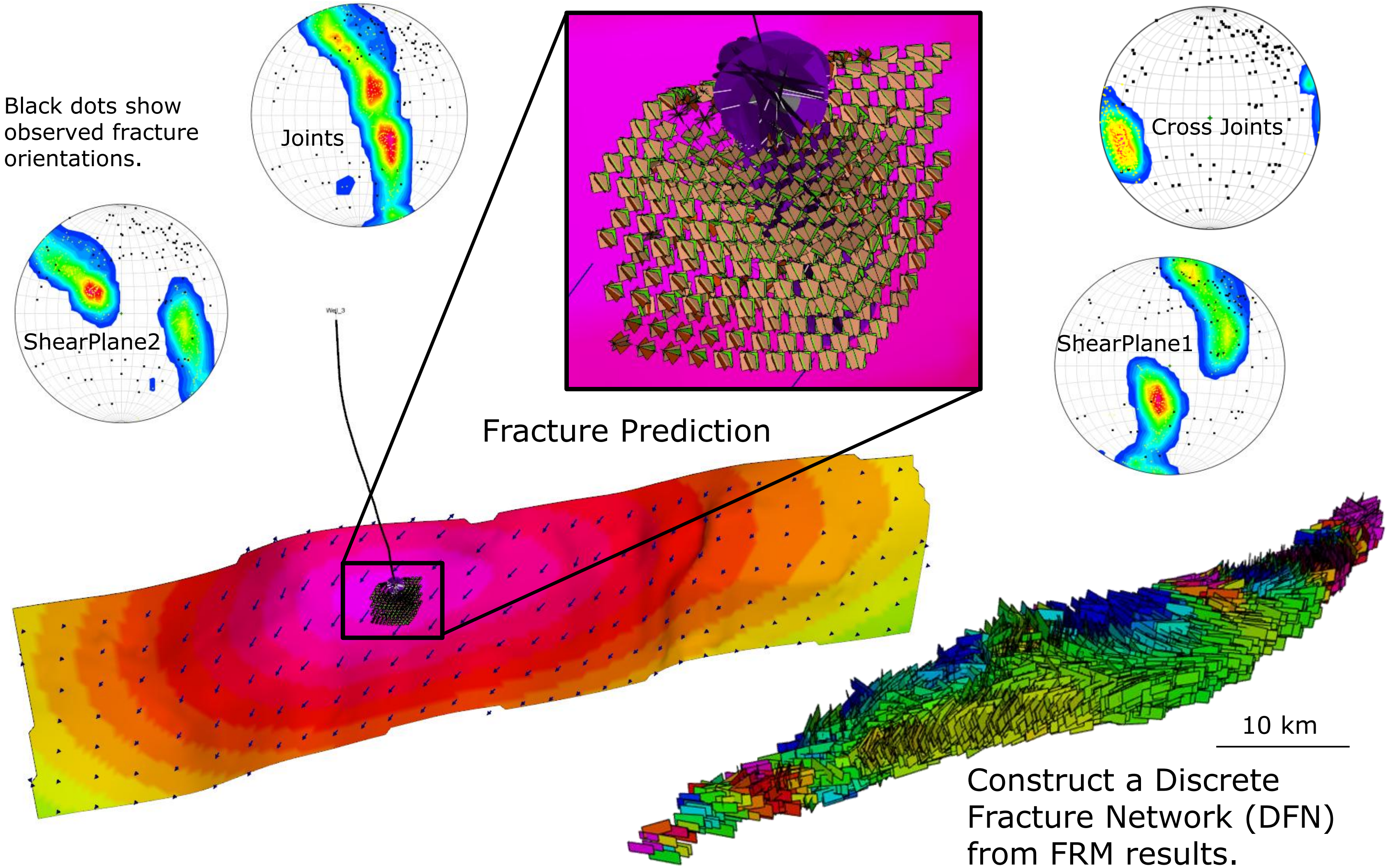
Use forward modelling to simulate the displacement offsets. Calculated strain/stress distributions can then be used for further investigations.



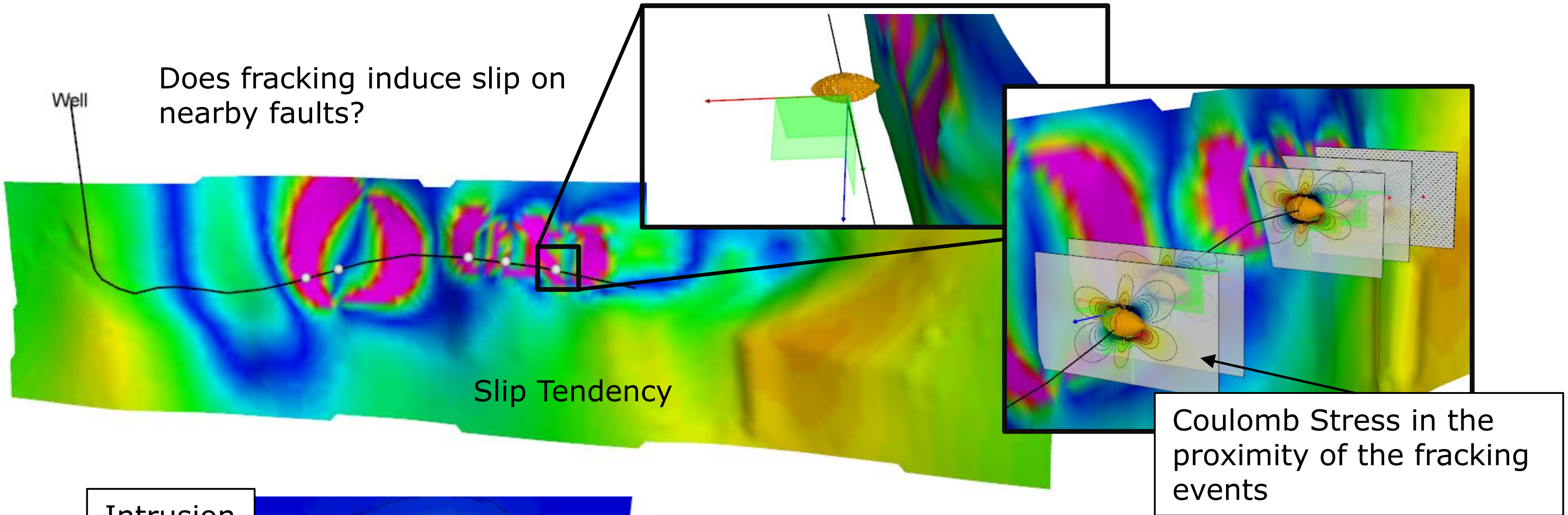
10 km

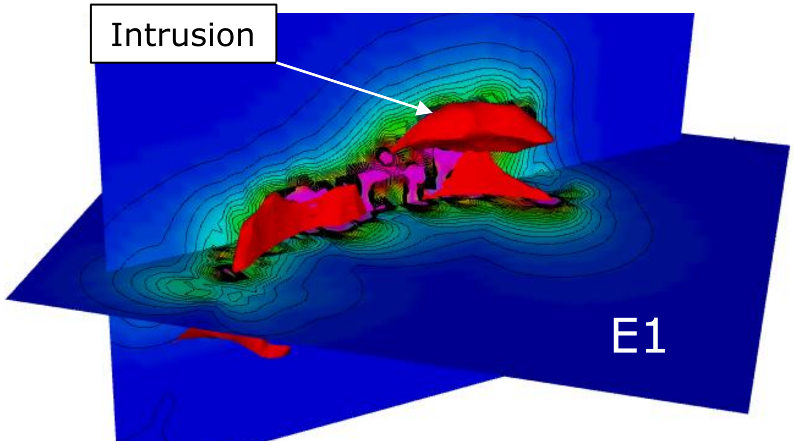
Vertical Exaggeration x10

Application of Fault Response Modelling: Examples

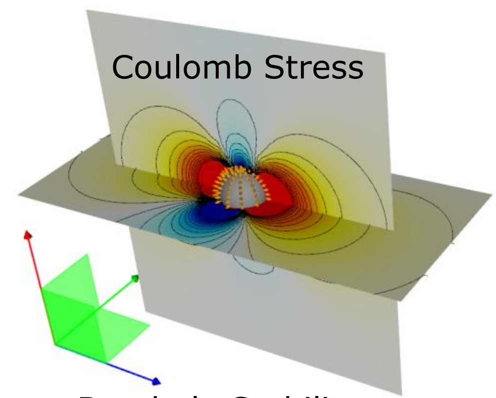


Application of Fault Response Modelling: Examples





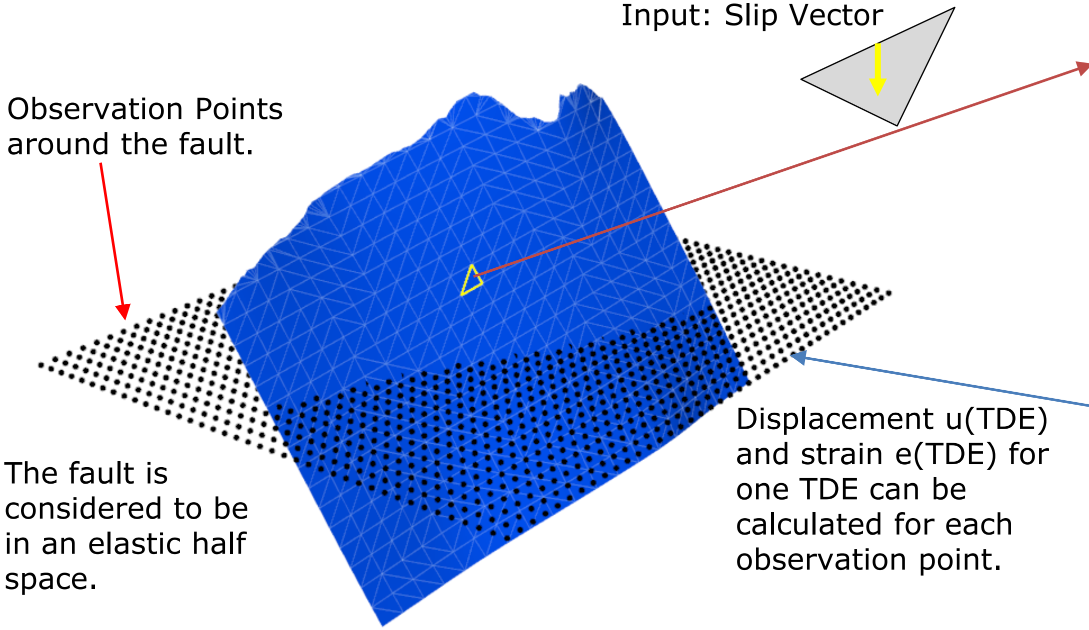
How is the surrounding affected by a 15MPa pressure increase

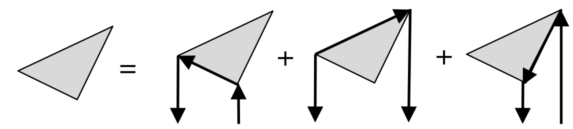


Borehole Stability

Introduction to Fault Response Modelling: Theory

M. Comninou & Dundurs (1975) published the equations for solving the displacement field and the derived strain field for a single angular dislocation. The angular dislocation can be constructed for any polygonal loop by superposition.





The **TDE** (Triangular Dislocation Element) is defined by the summation of three dislocation legs. (Jeyakumaran *et al.* 1992, Meade 2006)

$$u(TDE) = \sum_{k=1}^{3} u(1)_k - u(2)_k$$

$$\varepsilon(TDE) = \sum_{k=1}^{3} [\omega_k^{-1} (\varepsilon(1)_k - \varepsilon(2)_k)\, \omega_k]$$

The **total displacement u** and **strain ε** for each observation point affected by displacement on a triangulated fault surface can then be calculated by superimposing the results from all triangles (TDE).

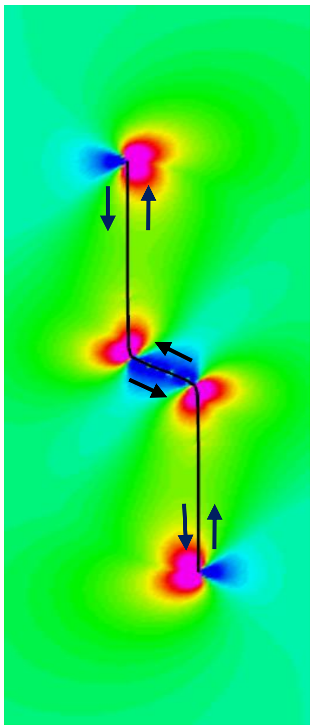
$$u = \sum_{j=1}^{N} u_j(TDE)$$

$$\varepsilon = \sum_{j=1}^{N} \varepsilon_j(TDE)$$

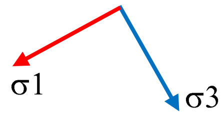
Defining slip on faults: Examples

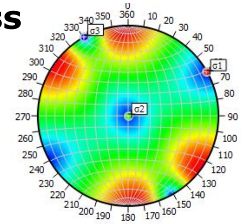
Uniform Slip

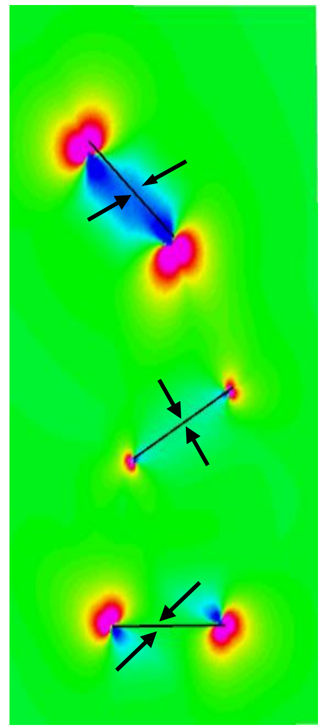
Strike-Slip System



Regional Stress

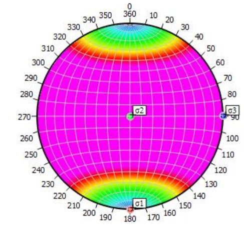


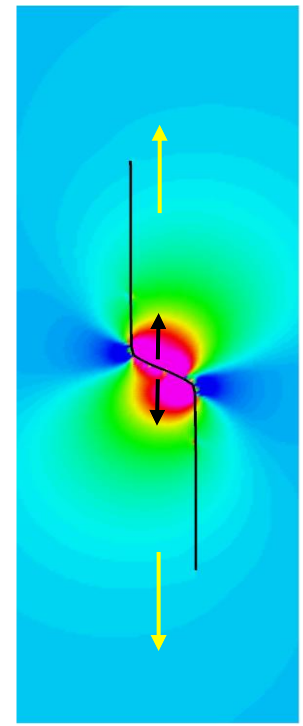




Driving Stress

Releasing Fault Structure





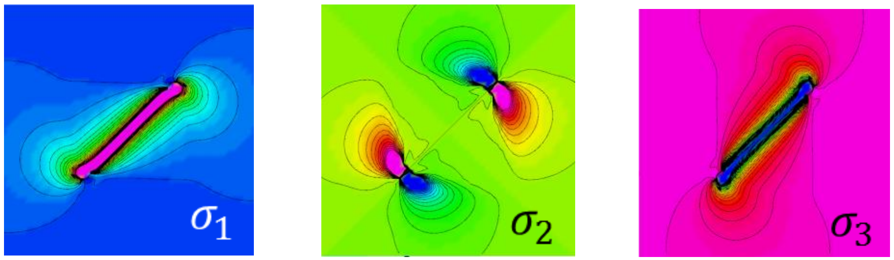
Resulting σ1 stress shown on observation grid

Stress and stress relationships

The stress tensor σ is calculated from the strain tensor using Hooke's law for linear elastic solids

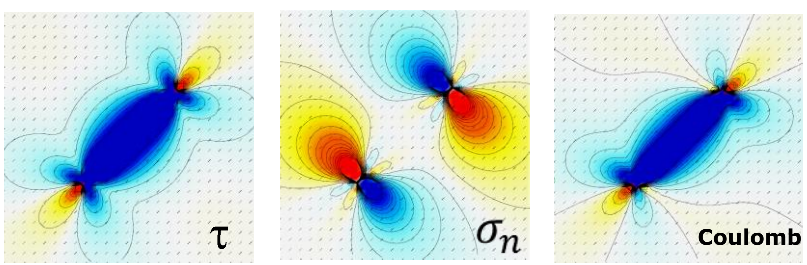
$$\sigma = \lambda \, tr(\varepsilon) \, I + 2\mu\varepsilon$$

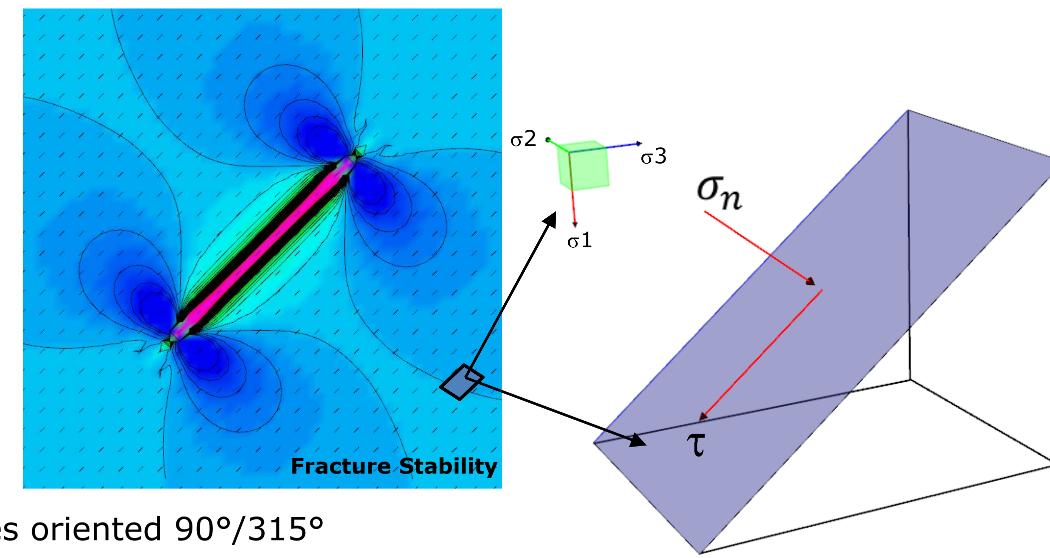
where **tr(ε)** is the trace of the strain tensor and **I** is the identity matrix, μ and λ are the Lamé coefficients



The resulting principal stresses for a vertical strike-slip fault system

With a predefined fracture plane orientation for each observation point, shear and normal stresses and various stress relationships can be obtained

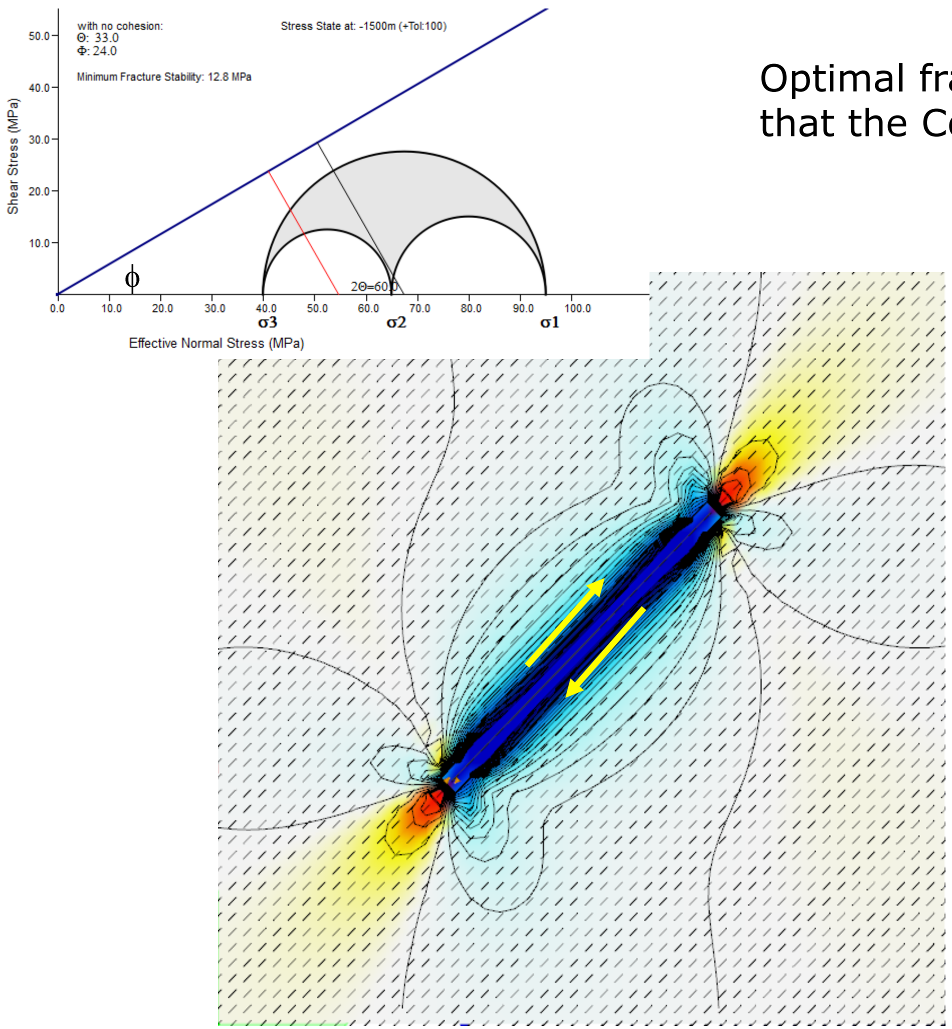




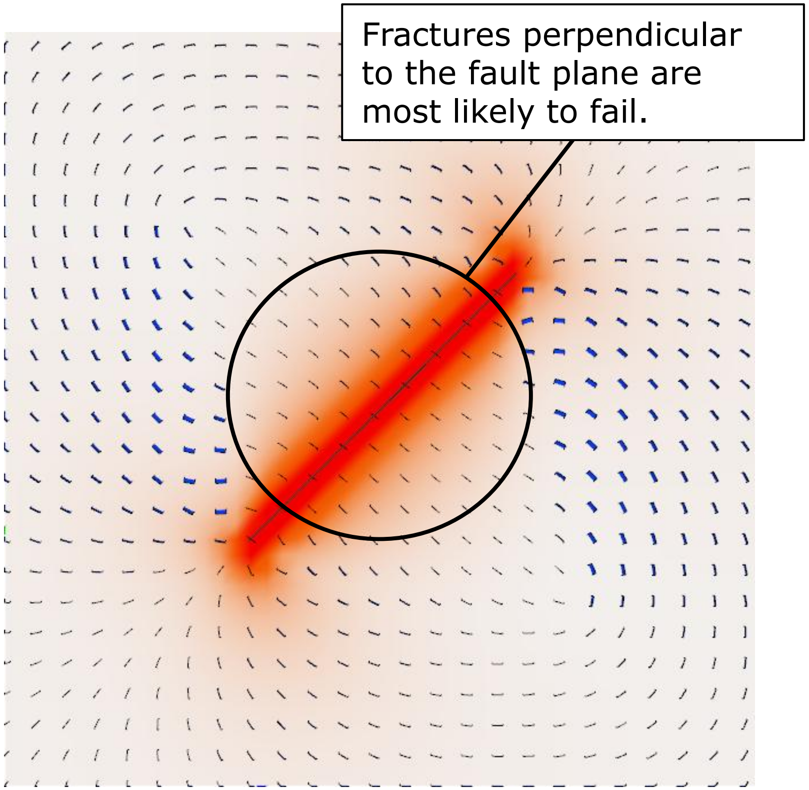
The example shows small-scale fracture planes oriented 90°/315°

Coulomb stress and optimal planes

Optimal fracture planes are oriented in such a way that the Coulomb stress reaches its maximum value.



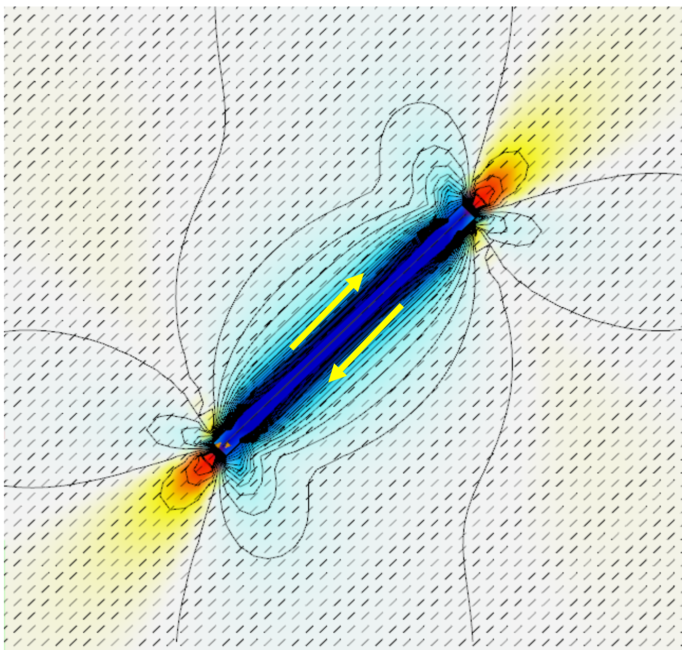
User-defined: 90°/315°



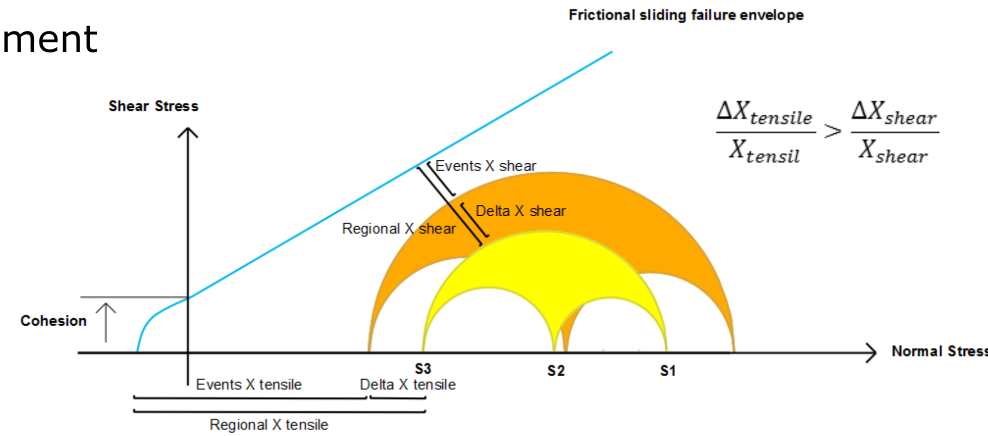
Optimal dip and azimuth

Coulomb stress: Brittle failure investigation

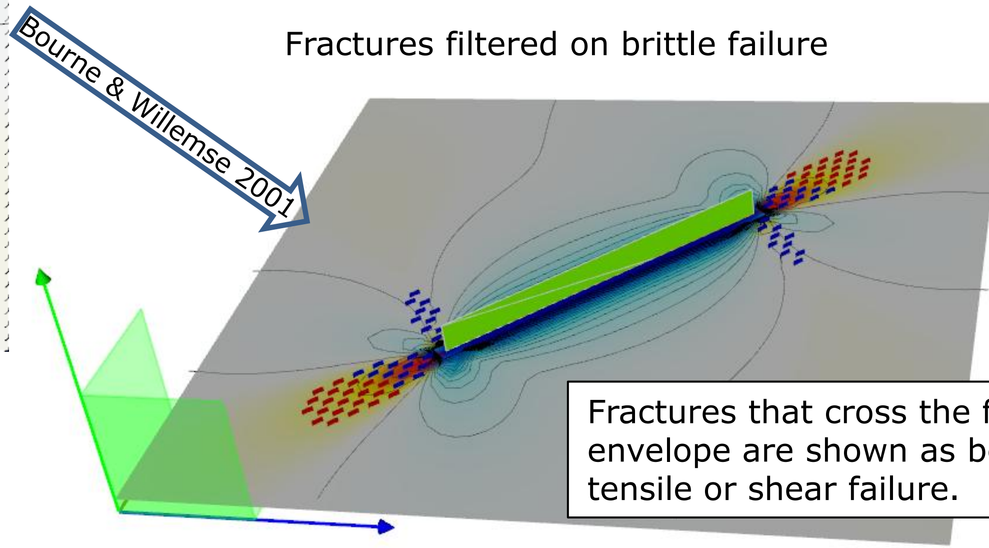
A vertical fault with right-lateral slip displacement



Coulomb stress change for fractures oriented 90°/315°



Fractures filtered on brittle failure



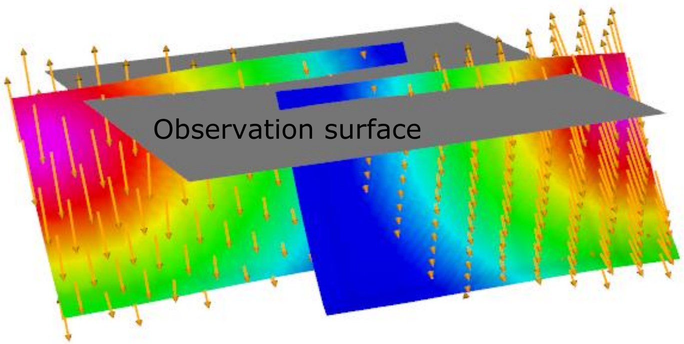
Fractures that cross the failure envelope are shown as being in tensile or shear failure.

Initial Tensile Failure

Initial Shear Failure

Relay zone example: Forward modelling a relay zone

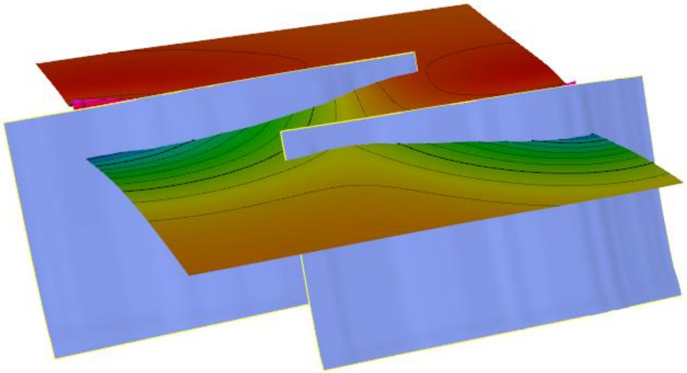
500 m Dip-slip system



The slip on both faults is tapered towards the edges

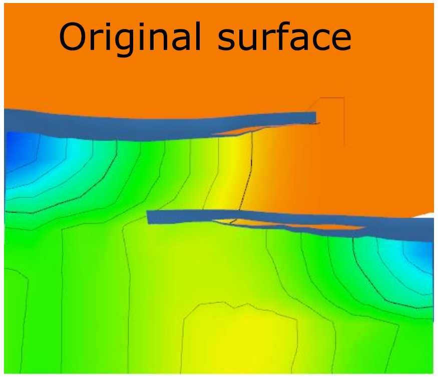
FRM

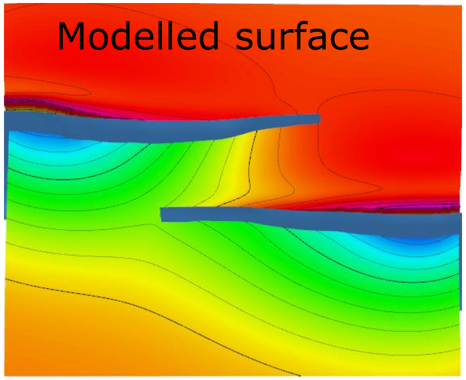
Forward modelling



Displaced surface

This technique allows the user to investigate the **slip orientation** and **slip distribution** on multiple faults. Furthermore, **fracture orientations** can be investigated.

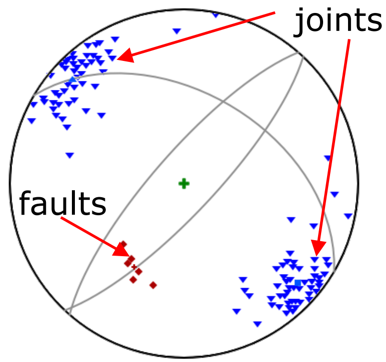




There is a good fit between the original and modelled surface

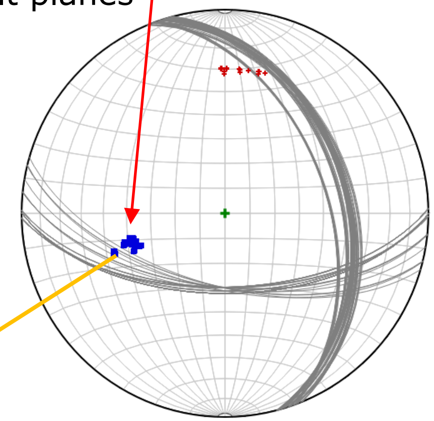
Relay zone example: Joints on a relay ramp

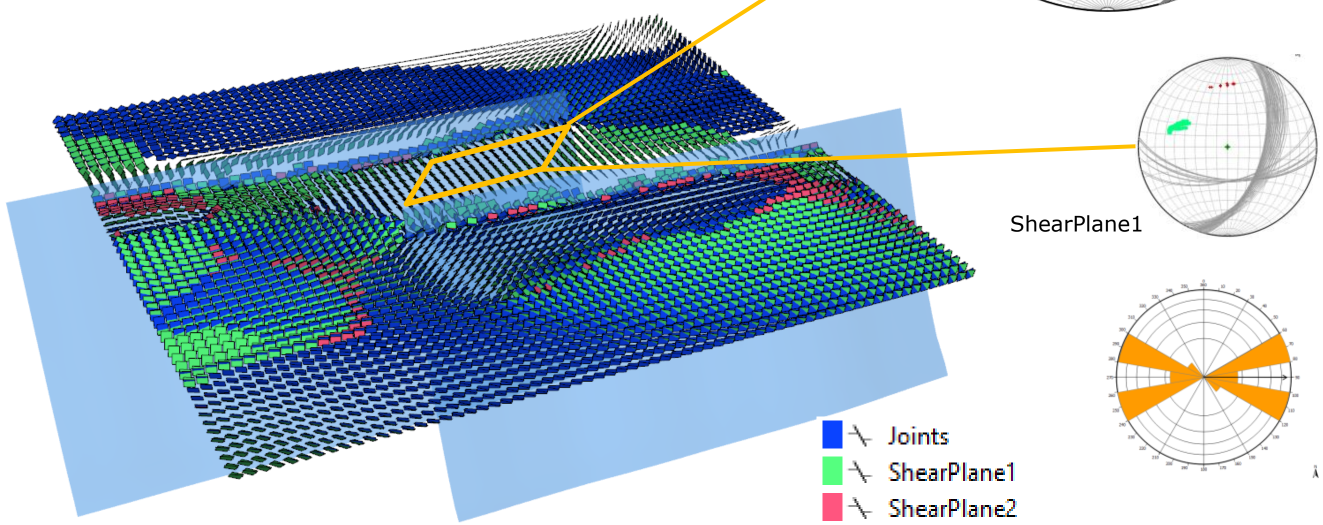
Relay zone, Kilve Somerset, UK.,
[photo taken from http://www.fault-analysis-group.ucd.ie/gallery/]



Joint characteristics across a relay ramp, Kattenhorn *et al.* 1999

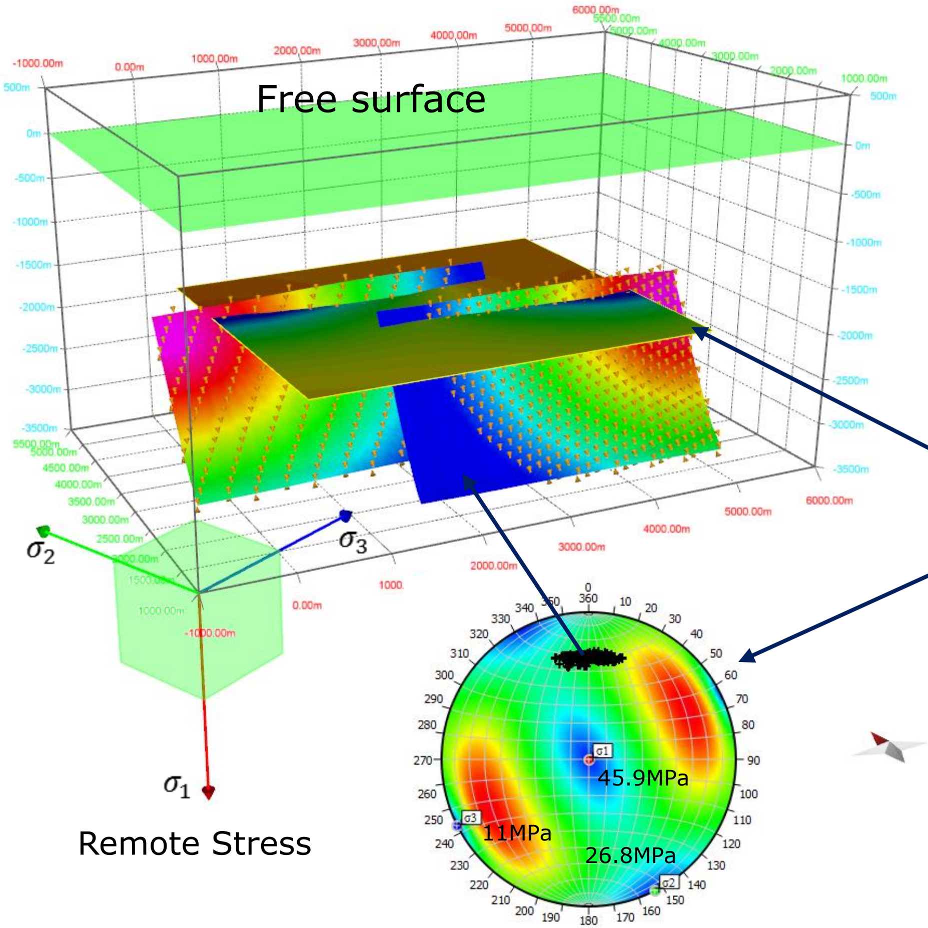
Modelled joints on the relay ramp are perpendicular to the fault planes



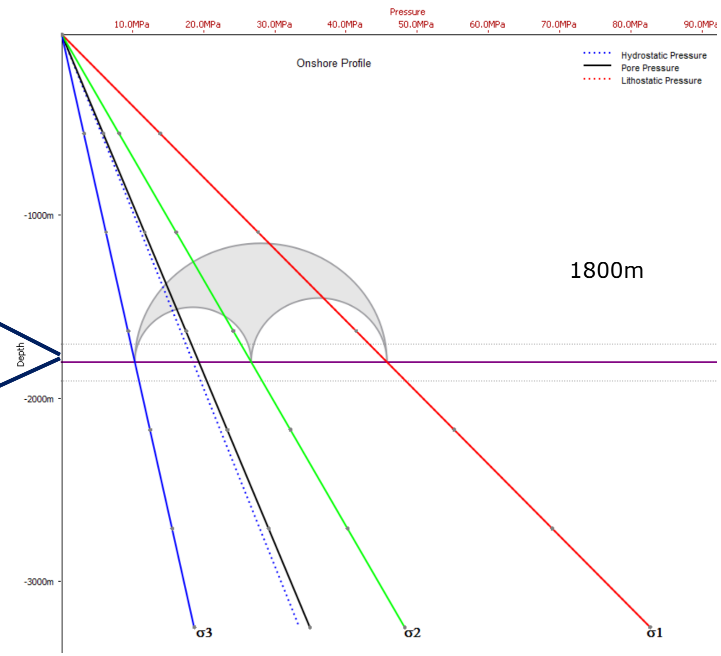


Relay zone example: Brittle failure investigation

If rock strength and remote stresses are taken into account, the induced slip magnitude must be considered as a fraction of the total amount of slip. Strains are considered to be so small that changes of geometry are neglected as the loads are applied, this is necessary to fulfil the constitutive laws for elastic isotropic materials.



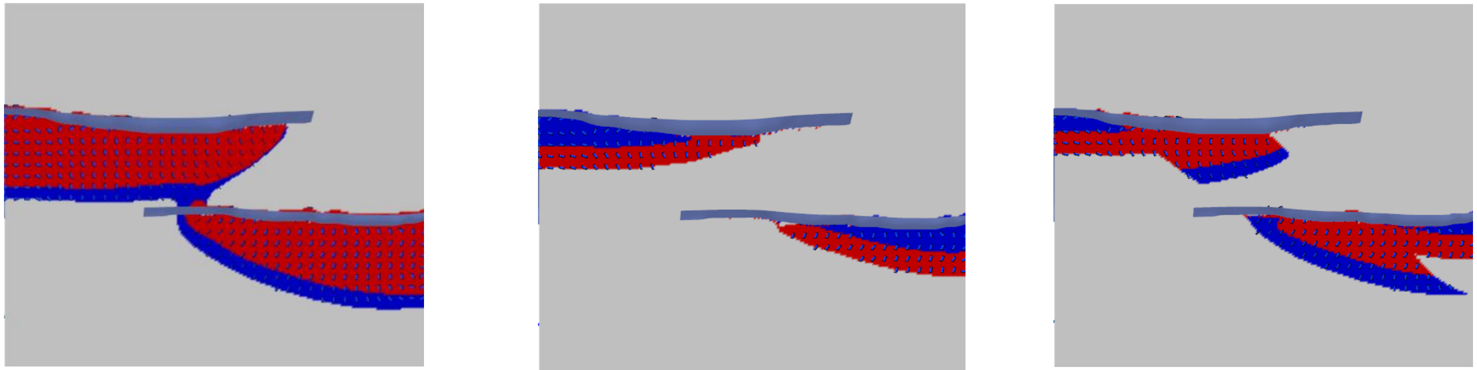
In this case study, 1 m of slip was taken into account. The free surface and the pressure profile have to be set up properly.



σ1 is equal to the overburden pressure with an average rock density of 2600 kg/m^3.

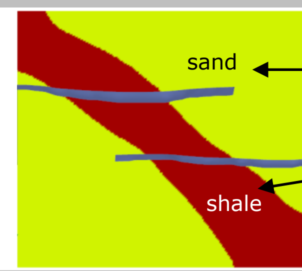
Relay zone example: Brittle failure on joints

Under hydrostatic conditions:



Cohesion: 1 MPa
Friction: 30°

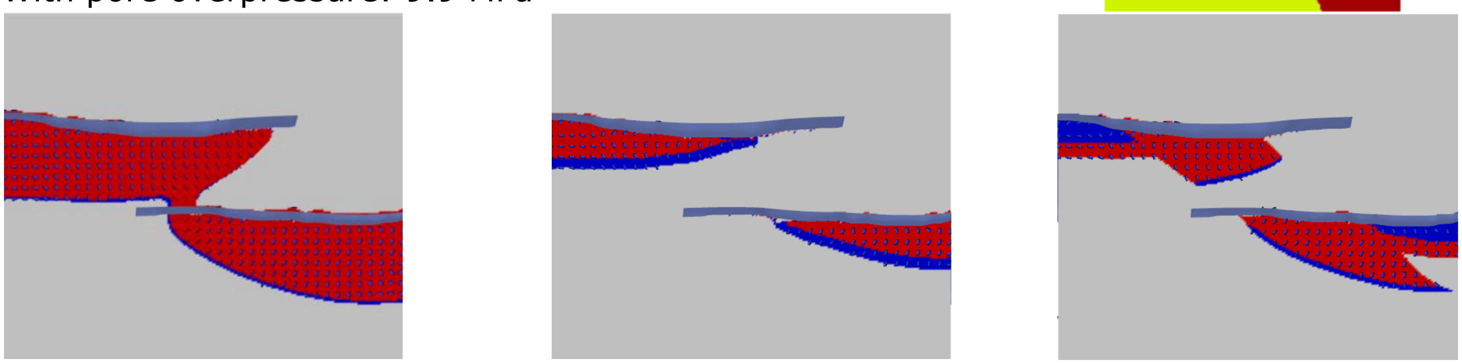
Cohesion: 5 MPa
Friction: 40°



Cohesion: 8 MPa
Friction: 40°

Cohesion: 2 MPa
Friction: 20°

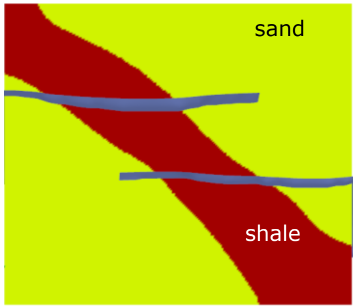
With pore overpressure: 9.9 MPa



Initial shear failure | Initial tensile failure | No brittle failure

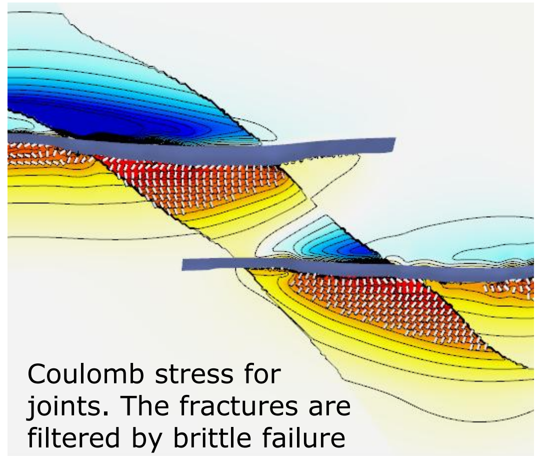
Lateral variation of rock properties

Model Set-up



Shale:
Poisson's Ratio: 0.4
Young's Modulus: 70 GPa
Cohesion: 2 MPa
Friction Angle: 20°

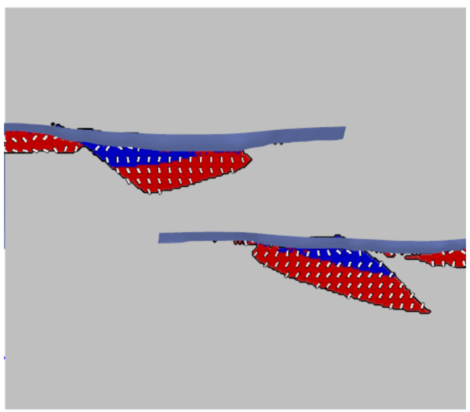
Sand:
Poisson's Ratio: 0.2
Young's Modulus: 15 GPa
Cohesion: 8 MPa
Friction Angle: 40°

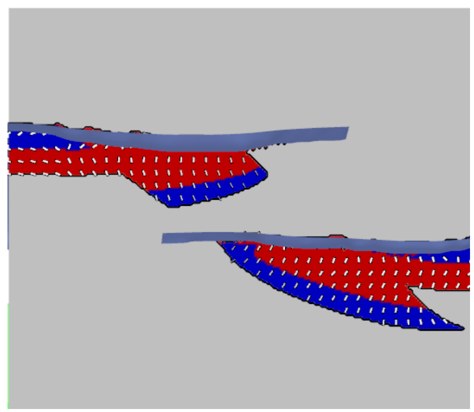

Coulomb stress for joints. The fractures are filtered by brittle failure

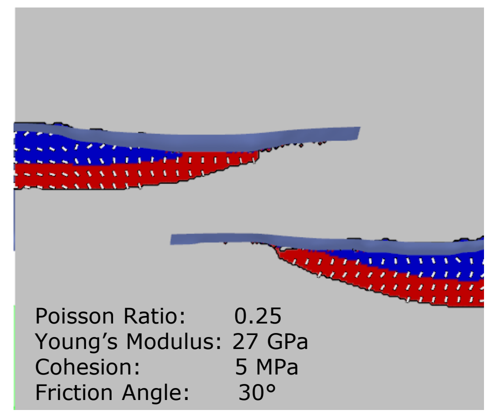
Be aware: Elastic dislocation theory and Hooke's law are based on a homogenous material approach. Hence natural heterogeneity is not considered in the way that one rock influences the other.

However, with this approach, a complex model can be easily set up and, with a single model run, different locations can be investigated at the same time.

<u>Comparison of brittle failure in joints using different input settings</u>


Lateral Variation of **all** rock properties.


Lateral variation of cohesion and Friction Angle only.

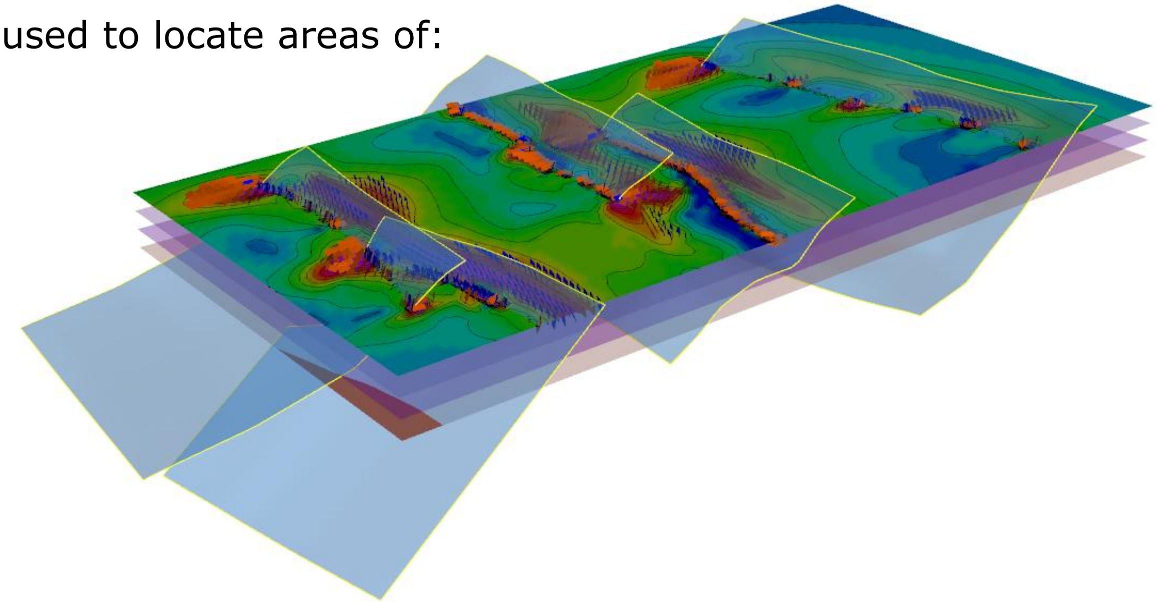


Constant average for all rock properties.

Initial shear failure | Initial tensile failure | No brittle failure

Summary and conclusions

- Fault Response Modelling is based on elastic dislocation theory:
  - Displacement and strain is calculated by inducing slip on faults
  - The influence of a stress-free surface can be modelled
- Fault Response Modelling can be used in a forward model sense with the aim of:
  - Investigating slip orientations, magnitudes and fault displacement profiles
  - Investigating fracture orientations
- Fault Response Modelling can be used to locate areas of:
  - Brittle failure
  - Tensile and shear failures
  - Optimal orientations
- The influence of remote stresses and rock properties can be investigated.



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