Research for a better future

Forskning for en bedre fremtid

Can plasticity explain microseismic source mechanisms?

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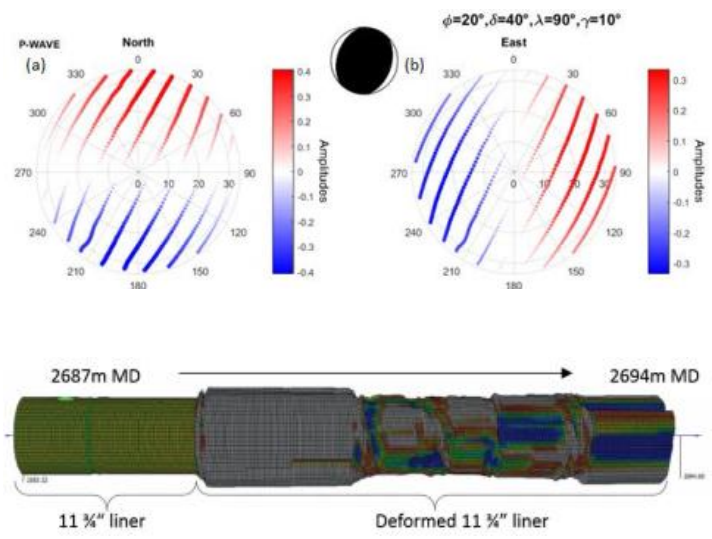
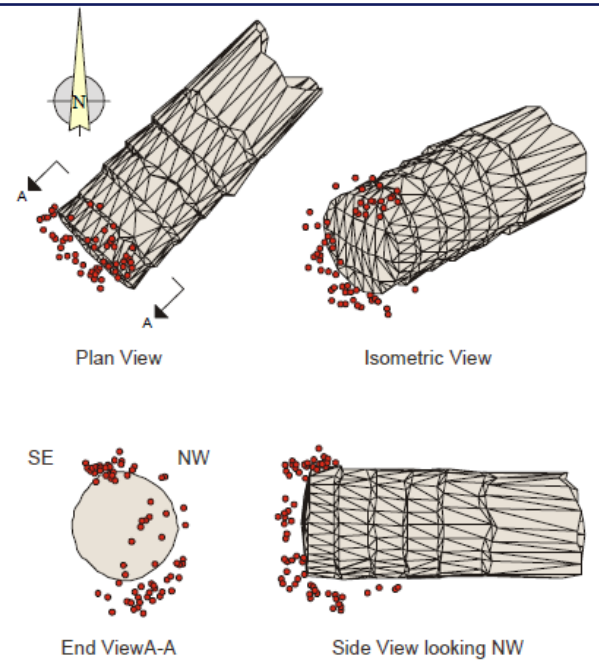
Motivation



- Microseismicity associated with borehole breakout at Grane field, North Sea *(Bussat et al., First Break, 2018; Langet et al., SEG, 2018)*

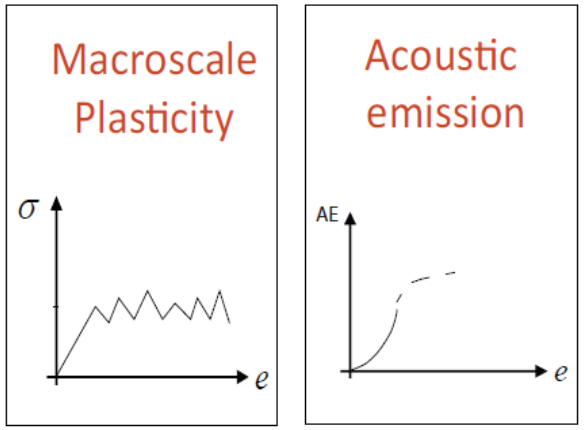


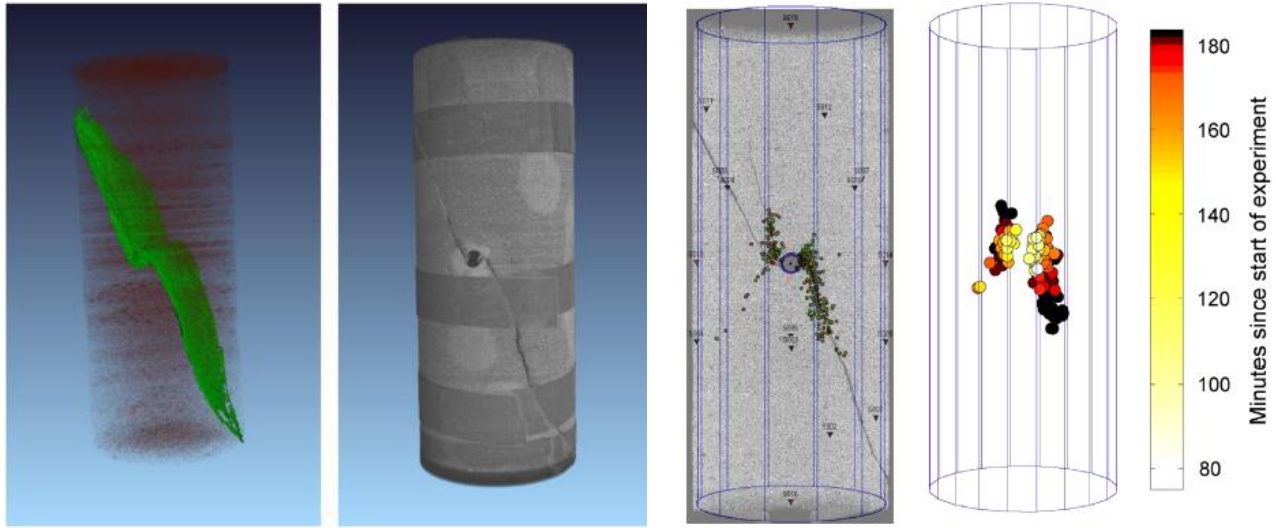
- Microseismicity ahead of the tunnel face where breakouts eventually develop as the tunnel advances *(Read et al., Int J Rock Mech Moin Sc, 2004)*

Microseismicity is observed both in natural conditions and during geotechnical operations. It can be associated with hydraulic fracturing, stimulation of geothermal reservoirs, mining, tunnel excavation and borehole failure. The microseismic events can often be characterized by a complex non-double couple source mechanism. In comparison to normal earthquakes, microseismic events are characterized by smaller amplitudes, higher frequencies, shorter duration, and a more complex source mechanism.

Plasticity and acoustic emission in laboratory experiments

Recent laboratory studies recording the acoustic emission during rock deformation show that onset of acoustic emission is associated with macroscale plasticity in rocks and help connecting the components of the seismic moment tensor with the failure process.





Rock failure in a controlled laboratory experiment is associated with acoustic emission *(Aker et al., 2014, Int J R Mech Min Sc)*

Model

Our model is built on a classical continuum mechanics approach, which uses standard rock mechanical properties. The moment tensor density can be represented by the product of elastic stiffness tensor and the plastic strain tensor. This representation of seismic sources has several useful properties:

i) it accounts for incipient faulting as a microseismicity source mechanism,
ii) it does not require a pre-defined fracture geometry,
iii) it accounts for both shear and volumetric source mechanisms,
iv) it is valid for general heterogeneous and anisotropic rocks, and
v) it is consistent with elasto-plastic geomechanical simulators.

Wave equation

$$\rho \dot{v}_i = \frac{\partial}{\partial x_j}\left(C_{ijkl} e_{kl}\right) - \frac{\partial}{\partial x_j}\left(C_{ijkl} e^p_{kl}\right) + f_i$$

Elastoplastic stress-strain law

$$\dot{\sigma}_{ij} = C_{ijkl}\left(\dot{e}_{kl} - \dot{e}^p_{kl}\right) \qquad \dot{e}^p_{ij} = \dot{\Lambda}\frac{\partial Q}{\partial \sigma_{ij}}$$

Moment tensor

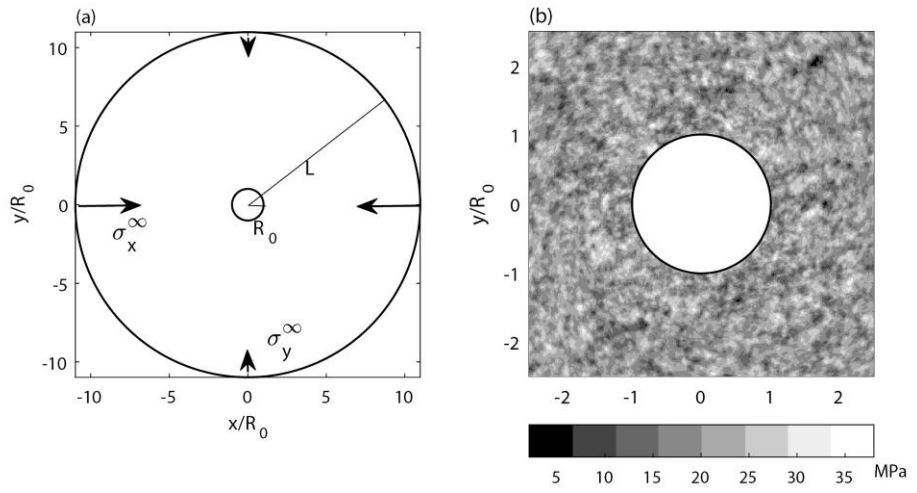
$$M_{ij} = \int_{t_0}^{t}\int_V C_{ijkl}\dot{e}^p_{kl}\, dV dt$$

Indigenous source

$$\gamma_i = \frac{\partial}{\partial x_j}\left(C_{ijkl} e^p_{kl}\right)$$

Numerical example

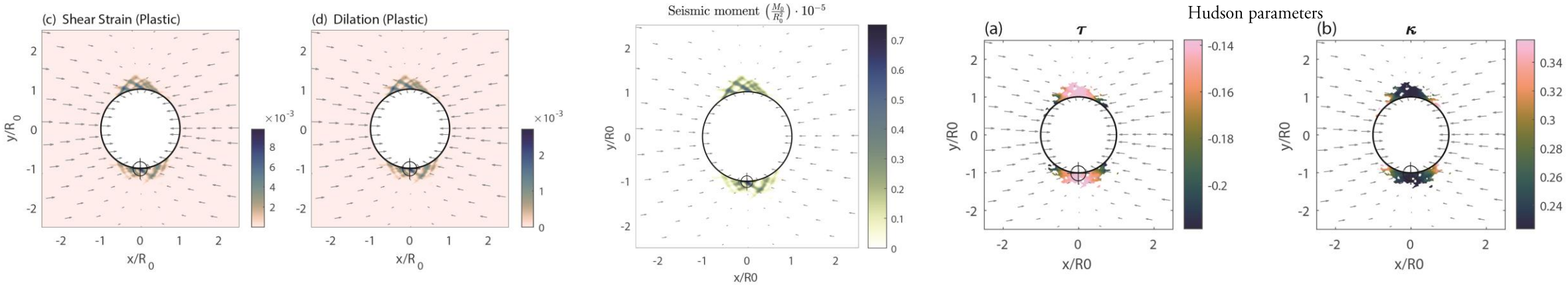
To illustrate our concept, we perform numerical simulations of failure around cylindrical opening (e.g. tunnel or borehole), which is a process extensively studied in the lab and the nature. Failure generating seismic activity will occur when Mohr-Coulomb plastic criterion is reached. Earthquake source mechanisms induced by failure are calculated



Elastoplastic finite-element (FE) code by Yarushina et al. (2010) and Minakov et al. (2019) is used to reproduce failure pattern. We assume random distribution of material parameters such as cohesion and Poisson ratio. Figure shows FE model geometry (a) and a random cohesion field used for model initialization. Stresses are applied at the external radius L. The inner boundary (R0) is free (dry case) or subject to fluid pressure.

Results: Isotropic rock, nonisotropic load

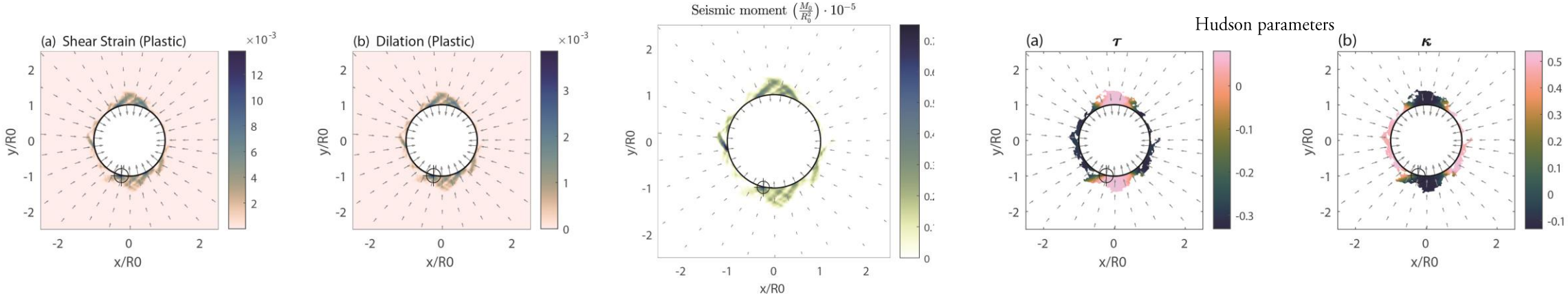
To reproduce typical pattern of borehole (tunnel) failure under tectonic stress conditions, we apply a combined pressure and shear loading at the external boundary



Equivalent plastic shear strain, bulk strain, seismic moment, and Hudson parameters showing formation of shear bands around an opening, which is accompanied by seismic activity. Arrows indicate scaled displacements. The seismic event with largest moment magnitude is shown by the target symbol.

Results: Anisotropic rock, isotropic load

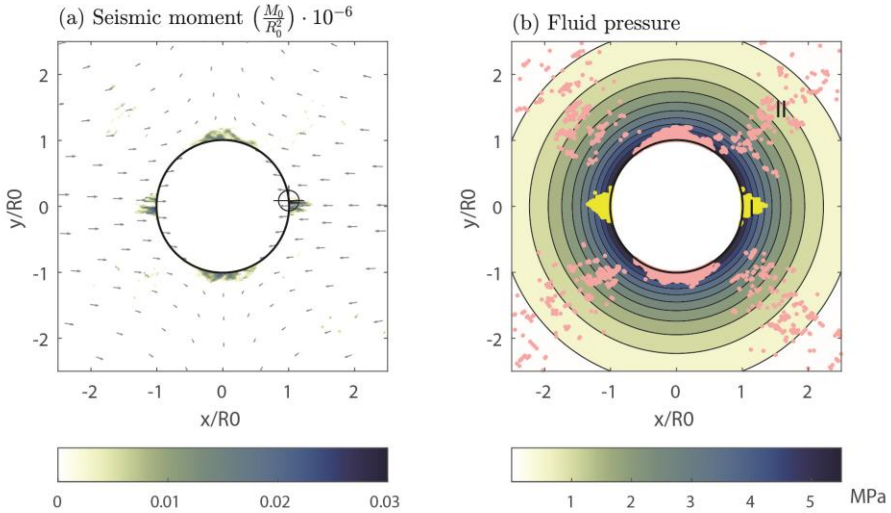
The rock anisotropy can affect both failure pattern and contribute to non-double couple source mechanisms. In this example we consider isotropic pressure applied to transversely isotropic rock with stratification parallel to the x-direction



Equivalent plastic shear strain, bulk strain, seismic moment, and Hudson parameters showing formation of shear bands around an opening, which is accompanied by seismic activity. Arrows indicate scaled displacements. The seismic event with largest moment magnitude is shown by the target symbol.

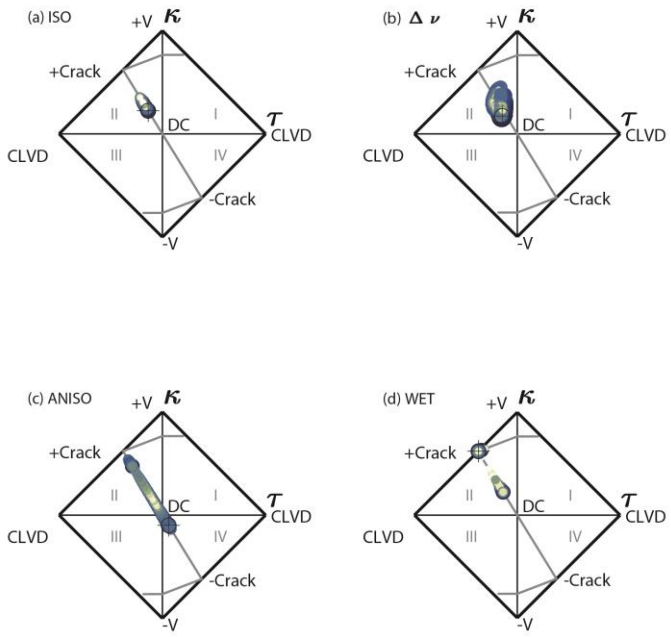
Results: Isotropic fluid-saturated rocks, non-isotropic load

Fluid flow might significantly affect both deformation pattern and seismic source mechanisms. Fluid pressure was added using one-way coupling approach

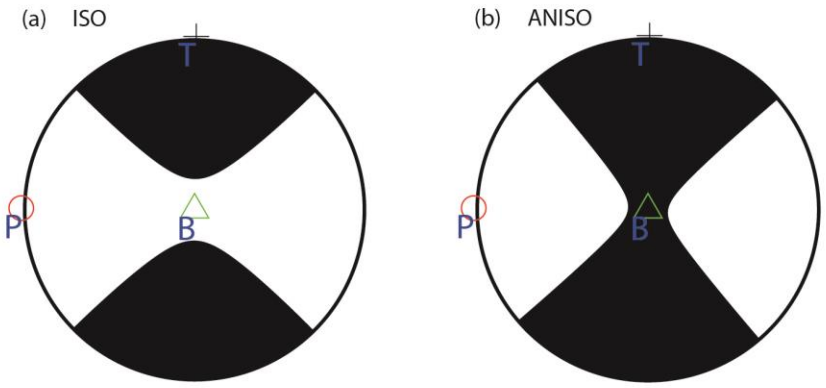


Simulation results show that added fluid pressure inhibits shear failure resulting in overall smaller plastic strain. However, the shear failure at random heterogeneities induced by fluid pressure propagation front results in several small-magnitude shear events away from the borehole (pink dots). Yellow dots show open mode I fractures.

Hudson plot and radiation patterns

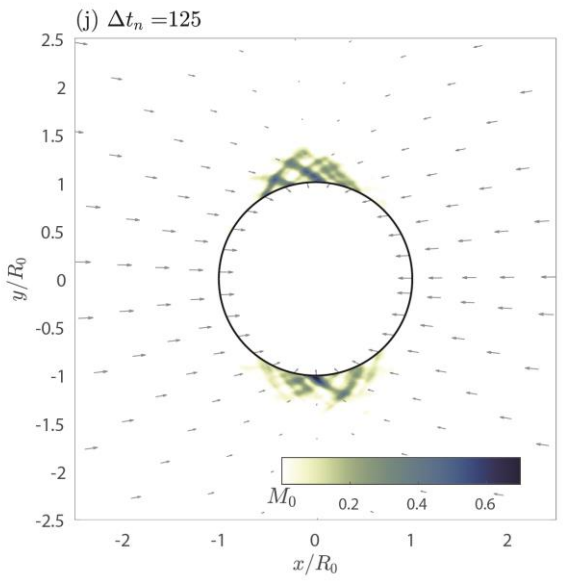


Hudson source type diagrams for (a) isotropic model with constant elastic parameters and random cohesion; (b) random cohesion and Poisson ratio; (c) anisotropic rock; (d) fluid-saturated rock. The theoretical shear crack path is shown by grey line. The color and size of symbols indicates the moment magnitude

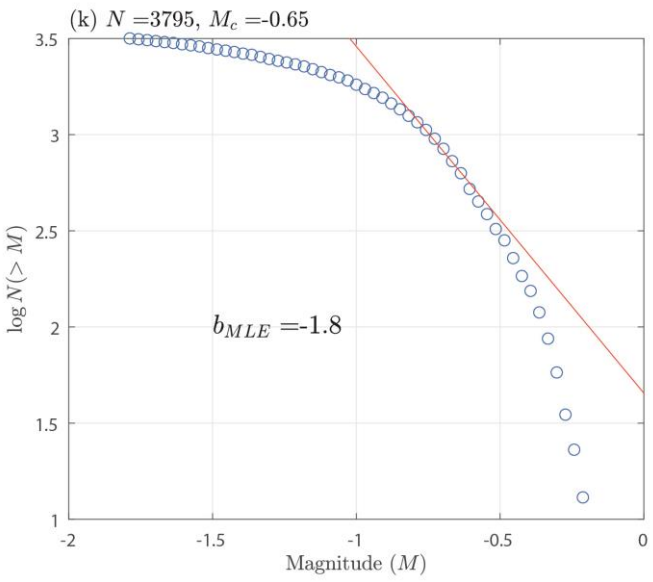


P-wave “beachball” diagram for failure in (a) isotropic media, (b) anisotropic media considered above

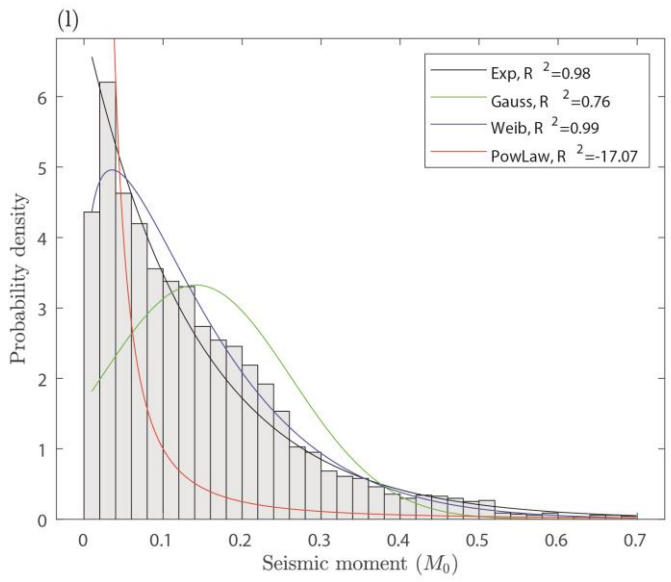
Statistics of seismic events: isotropic dry rock



Normalized moment magnitude spatial distribution



Cumulative number of events (N) above magnitude M (blue circles) and GR-type distribution with exponent b_{MLE} (red line)



Probability density distribution of the seismic moment compared to various parametric distributions: power-law (red), Gaussian (green), exponential (black) and Weibull (black). The R-square value shows the error of a fit for each distribution type.

Conclusions

- We suggest a simple mathematical model that highlights theoretical links between stress state, geomechanical parameters and conventional representations of the moment tensor such as Hudson source type parameters.
- The model does not require a pre-defined fault geometry and does not consider slip on pre-existing faults.
- The 2D numerical examples apply to the borehole stability problem and facilitate joint analysis of rock deformations and seismic moment tensor data.
- The orientation of borehole breakouts depends on both tectonic stress and anisotropic elastic parameters. Spatial analysis of moment tensor solutions can reveal the relative contribution of material anisotropy versus tectonic stress.
- Our approach is compatible with existing geomechanical and seismic wave propagation solvers and enables their closer integration for microseismic monitoring.
- The model describes well the moment tensor and Hudson diagrams from laboratory data
- The probability density distribution of the seismic moment depends on the distribution of geological heterogeneities among other factors
- The classical straight line does not work as for tectonic earthquakes, but the general pattern for microseismic events is similar
- The model is also applicable in 3D