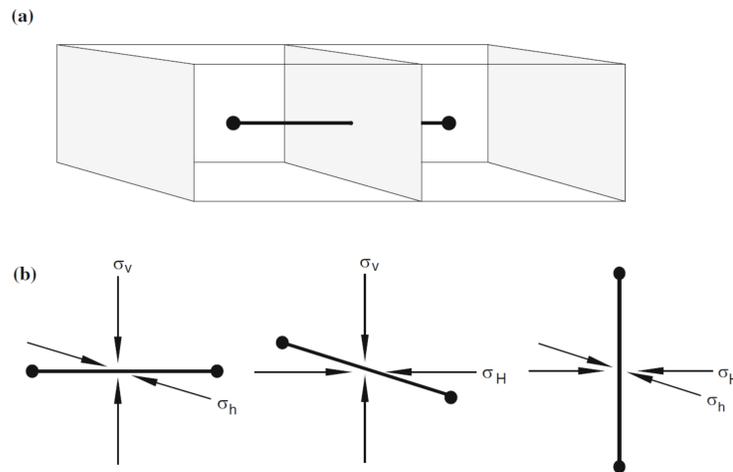


## Introduction

We present a 3D numerical model for hydraulic fracturing and damage of low permeable rock in an anisotropic stress field. The model computes the intermittent damage propagation, microseismic event-locations, microseismic event-distribution, damaged rock volume and injection pressure. The model builds on concepts from invasion percolation theory.

### The model

The simulation grid is regular, and all nearest neighbour cells are connected by transmissibilities, also called bonds. The grid is aligned with the anisotropic stress field, where the bonds are orthogonal to two principal stress directions. An intact bond breaks when the fluid pressure exceeds the least compressive stress and a random bond strength.

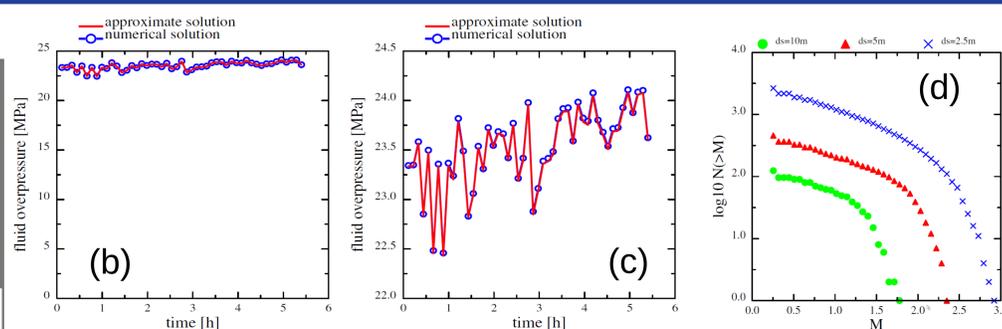
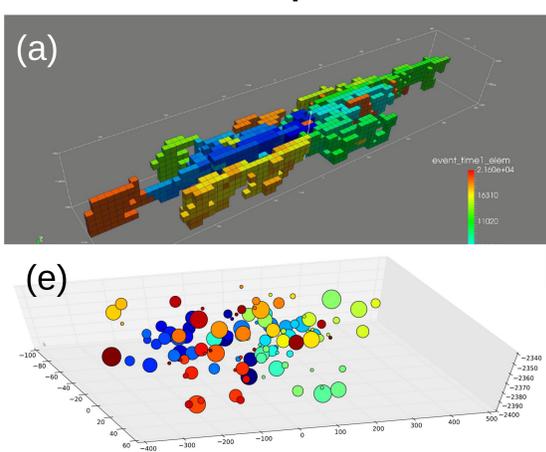


### Damage propagation

Breaking a bond implies that the fluid flow invades the associated broken cell, and the fluid pressure decreases. The damaging process continues during a time step until the fluid pressure is sufficiently low for no more bonds to be critical. The number of connected broken cells during a time step is the event-size, and the log10 of the event-size is the event-magnitude. The new fluid pressure, after a bond breaks, is obtained by solving a transient pressure equation.

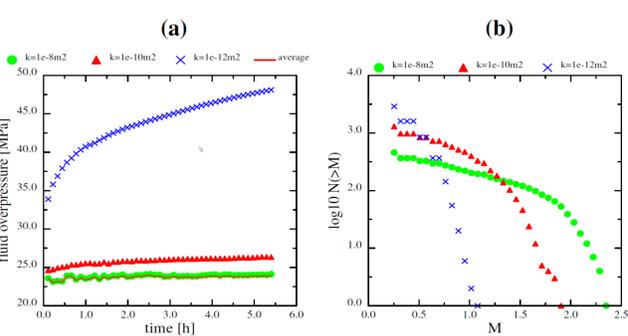
(a) A bond (or a transmissibility) is a hydraulic connection between two nearest neighbour cells. (b) The bonds are oriented orthogonally to the directions of the principal stress.

### Example:



Parameter	Value	Units
Number of time steps	50	-
Number of cells x- and y-dir ( $n_0$ )	99	-
number of cells z-dir ( $n_3$ )	6	-
Length x- and y-directions ( $l$ )	990	m
Thickness ( $h$ )	60	m
System compressibility ( $\alpha_p$ )	$5 \times 10^{-10}$	$\text{Pa}^{-1}$
Viscosity ( $\mu$ )	0.001	Pa s
Damage permeability ( $k_D$ )	$1 \times 10^{-8}$	-
Damage porosity ( $\phi_D$ )	0.15	-
Injectin rate ( $Q_0$ )	150	$\text{m}^3 \text{s}^{-1}$
Simulation time ( $t_{\text{end}}$ )	19,440	s
Factor $f'_1$	0.7	-
Factor $f'_2$	0.85	-
Max strength ( $m_0$ )	10	MPa

(a) The damaged rock volume produced by hydraulic fracturing. A volume of 2916 m<sup>3</sup> of fluid was injected during 5.4 h. The depth interval is from 2340 m to 2400 m. The cell colours give the time of damage. (b) The injection pressure. (c) A zoom-in on the injection pressure. (d) The frequency-magnitude plot of the events. (e) The fracturing events in space and time. The ball size is the event size and the colour is the even time.



(a) The injection overpressure. (b) The frequency-magnitude distribution for three different damage permeabilities.

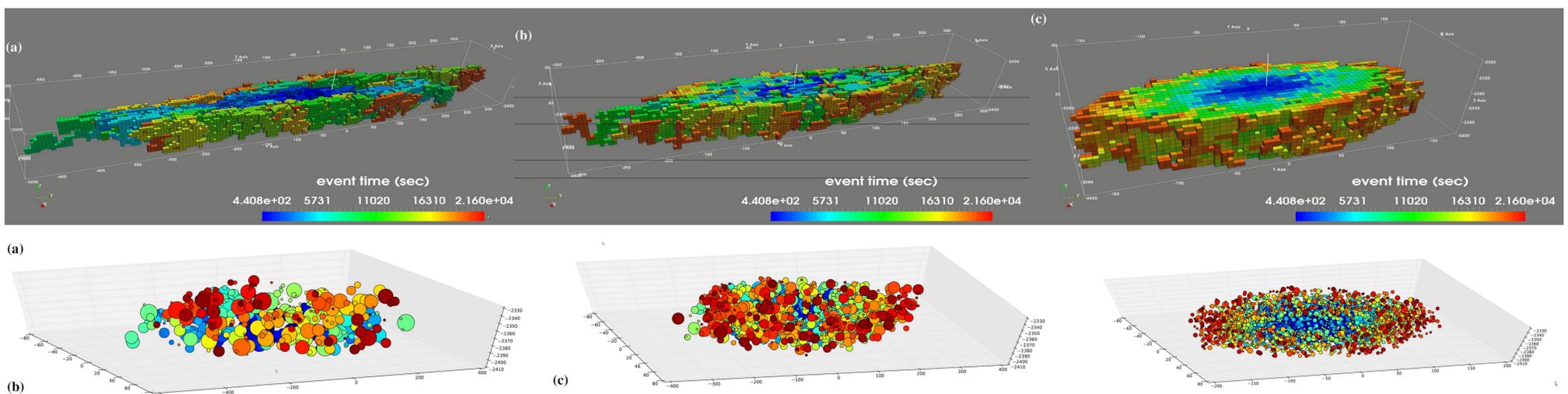
### Injection pressure

Decreasing the damage permeability by two orders of magnitude to 1e-10 m<sup>2</sup> makes a difference. The injection pressure is slightly higher, and the slope of the frequency-magnitude distribution is steeper. A further decrease in the damage permeability to 1e-12 m<sup>2</sup> results in a considerably higher injection pressure, and the slope of the frequency magnitude distribution is even steeper.

### Microseismic event-distribution

The microseismic event-distribution and the b-value depend on the permeability in the damaged rock volume. The b-value increases with decreasing permeability from little less than 0.6 to a value above 3 for the same injection rate and injection volume.

### A case study of Barnett Shale



A large damaged rock permeability gives a percolation like damaged rock volume and an injection pressure that is slightly above the rock strength.

A moderate damaged rock permeability gives a compact damaged rock volume and an increasing injection pressure with time.