GEOMECHANICAL SIMULATION OF SEISMIC EVENTS INDUCED BY CO_2 INJECTION AT IN SALAH

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BRISTOL UNIVERSITY MICROSEISMICITY PROJECTS
BUMPS

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ACKNOWLEDGEMENTS

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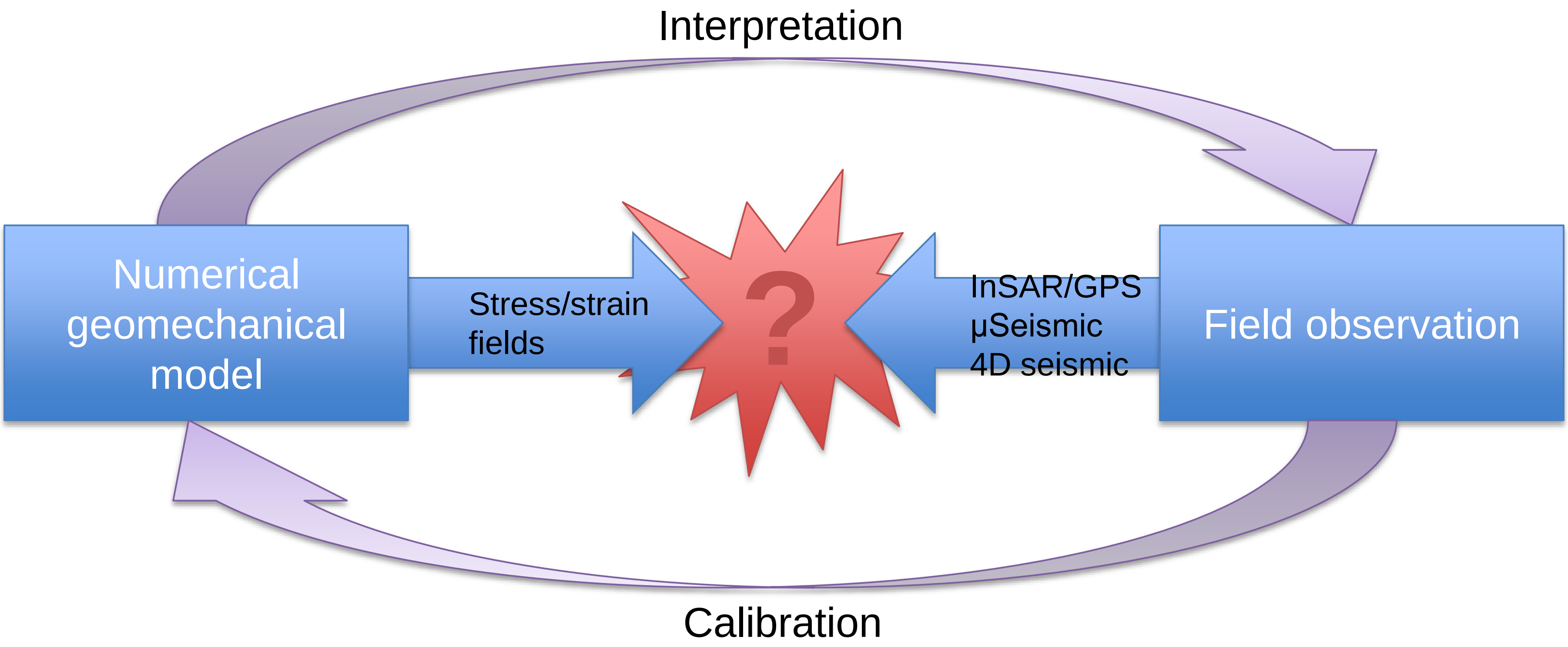
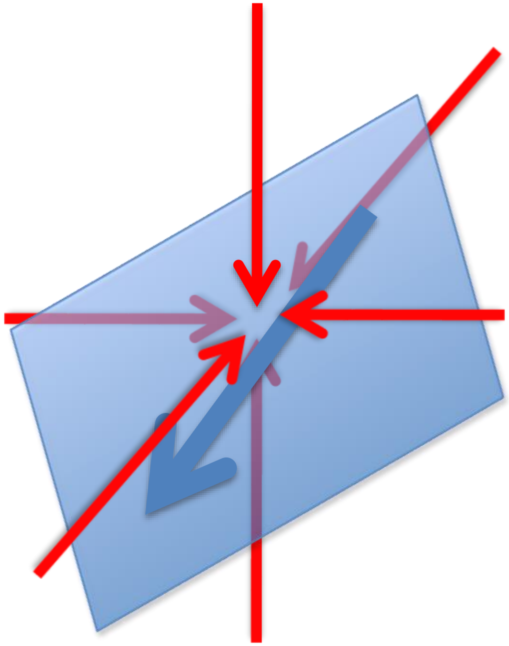
RESEARCH COUNCIL

MOTIVATION


Interpretation
Numerical geomechanical model
Stress/strain fields
?
InSAR/GPS
μSeismic
4D seismic
Field observation
Calibration

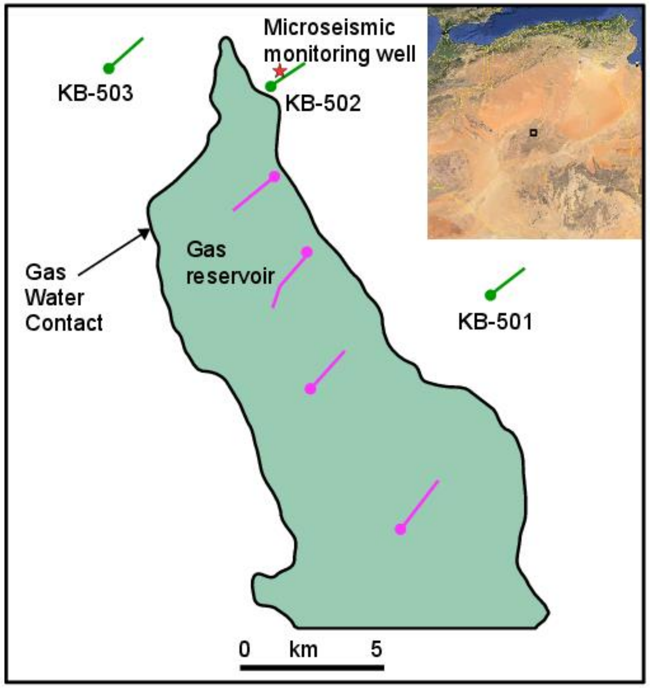
THEORY:

- Mohr-Coulomb theory:
  - Pre-existing plane of weakness set in an applied stress field.
  - Change in stress field leads to failure.

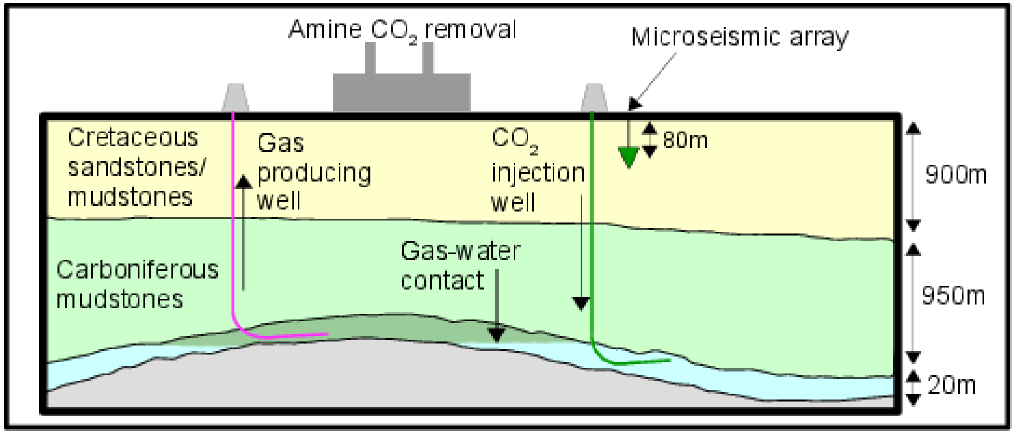


- If we know:
  - The changing stress state,
  - Where the faults/fractures are,
- Can we predict when and where microseismic events will occur?

IN SALAH

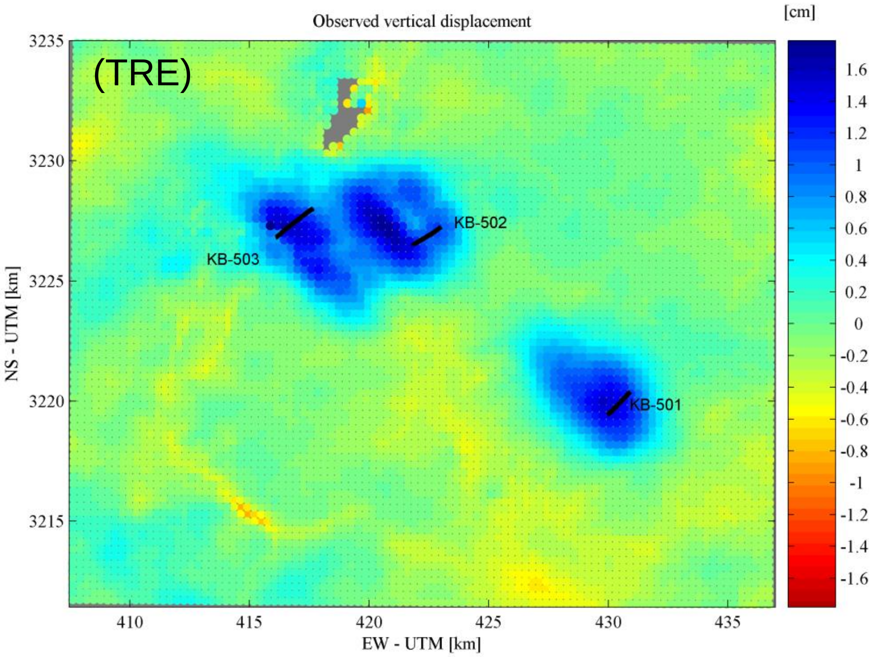


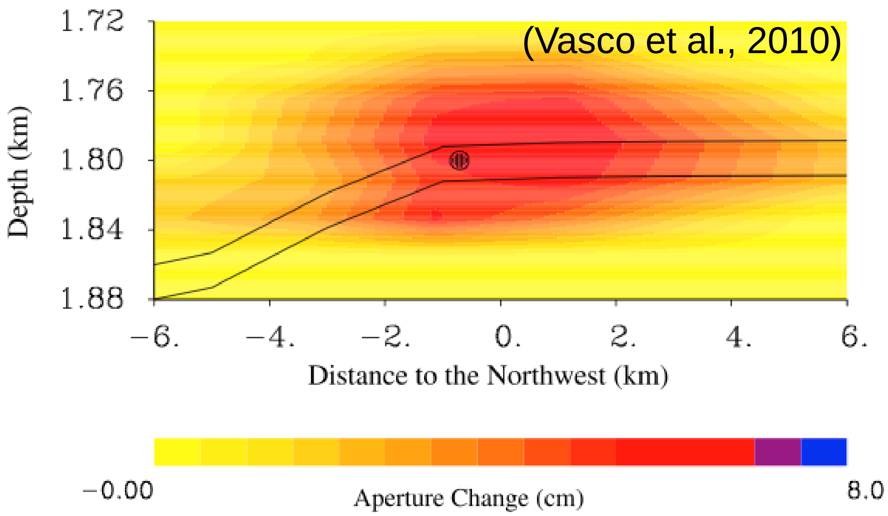
Microseismic monitoring well
KB-503
KB-502
KB-501
Gas Water Contact
Gas reservoir
0 km 5



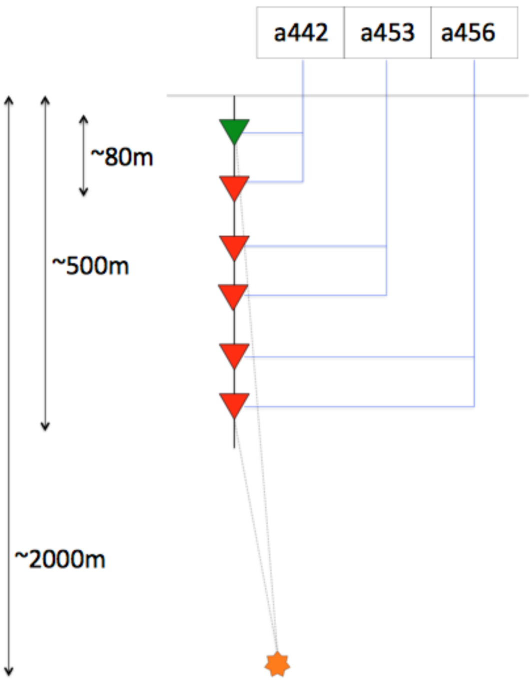
Amine CO_2 removal
Microseismic array
Cretaceous sandstones/ mudstones
Gas producing well
CO_2 injection well
80m
900m
Carboniferous mudstones
Gas-water contact
950m
20m

IN SALAH

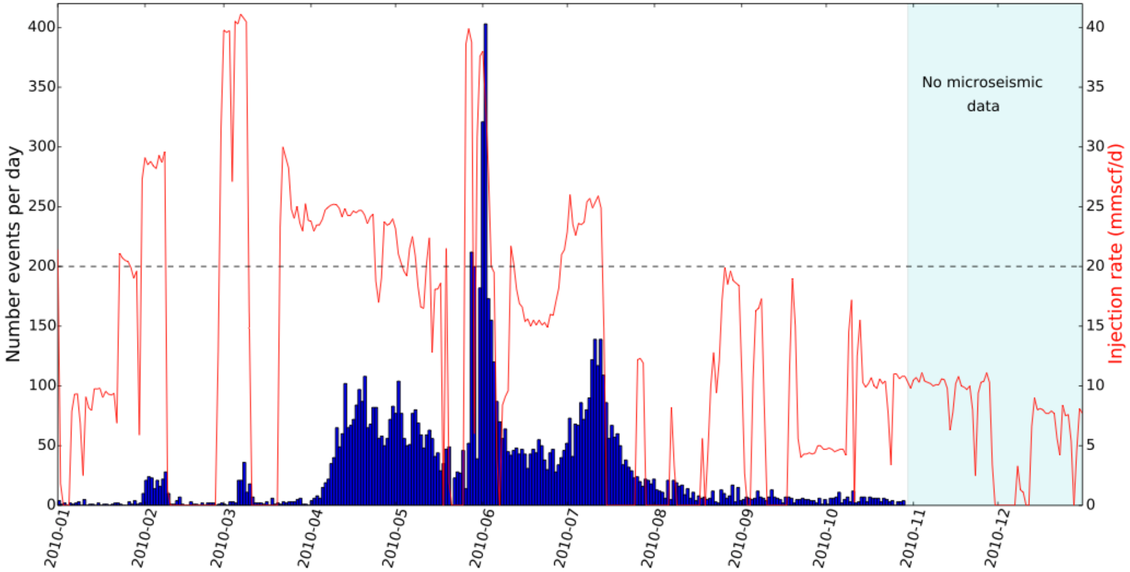

Observed vertical displacement
[cm]
(TRE)
KB-503
KB-502
KB-501
NS - UTM [km]
EW - UTM [km]
3235
3230
3225
3220
3215
410
415
420
425
430
435
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6


(Vasco et al., 2010)
Depth (km)
1.72
1.76
1.80
1.84
1.88
−6.
−4.
−2.
0.
2.
4.
6.
Distance to the Northwest (km)
−0.00
Aperture Change (cm)
8.0

In Salah

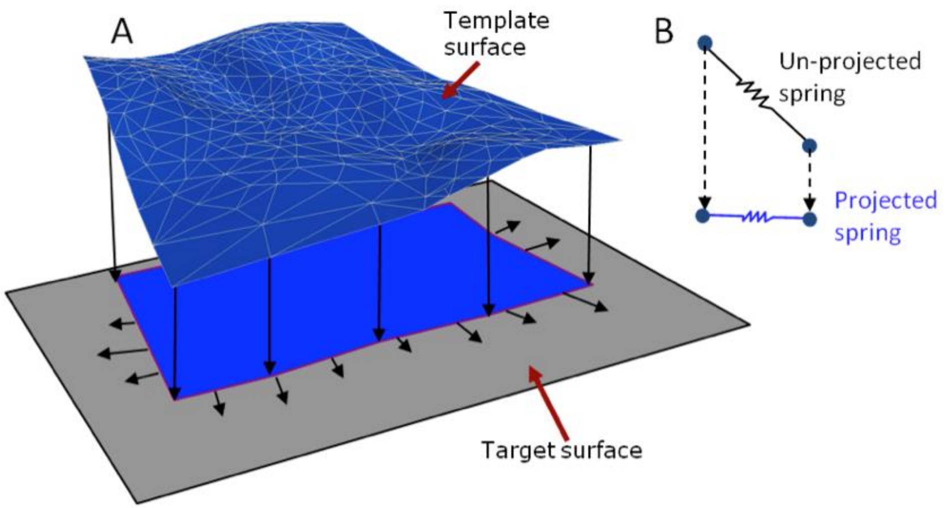


a442
a453
a456
~80m
~500m
~2000m



Number events per day
Injection rate (mmscf/d)
No microseismic data
2010-01
2010-02
2010-03
2010-04
2010-05
2010-06
2010-07
2010-08
2010-09
2010-10
2010-11
2010-12

MODELLING FRACTURES



Geomechanical strain reconstruction algorithm:

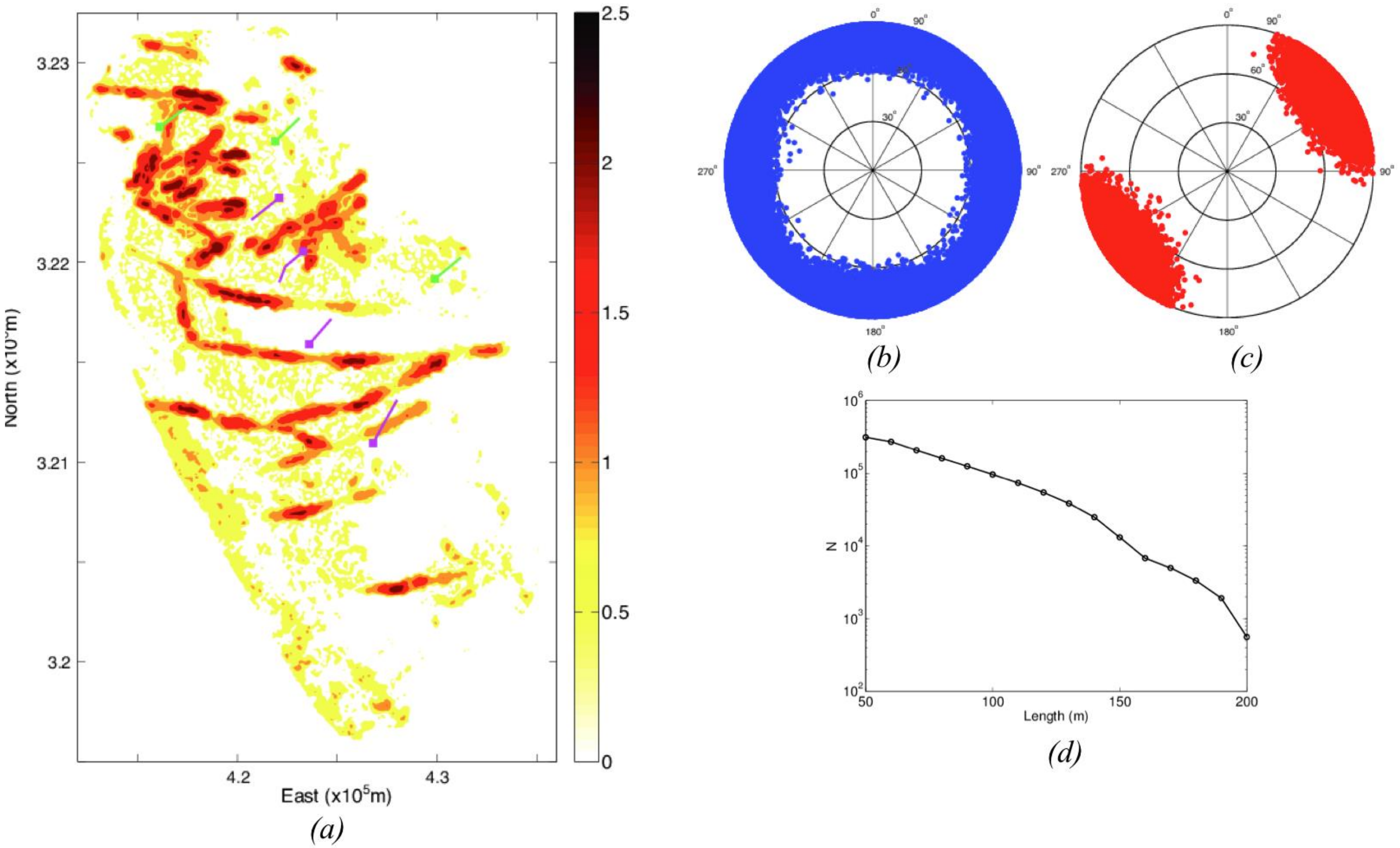
- Structural model of faulted, folded reservoir.
- Reverted to undeformed (flat) template using mass-spring solver.

Strain maps produced by forward model used to populate a fracture model:

- We estimate fracture position, orientation (strike and dip) & length.
- Multiple fracture sets associated with folding and faulting.
- A total of over 300,000 individual fractures modelled.

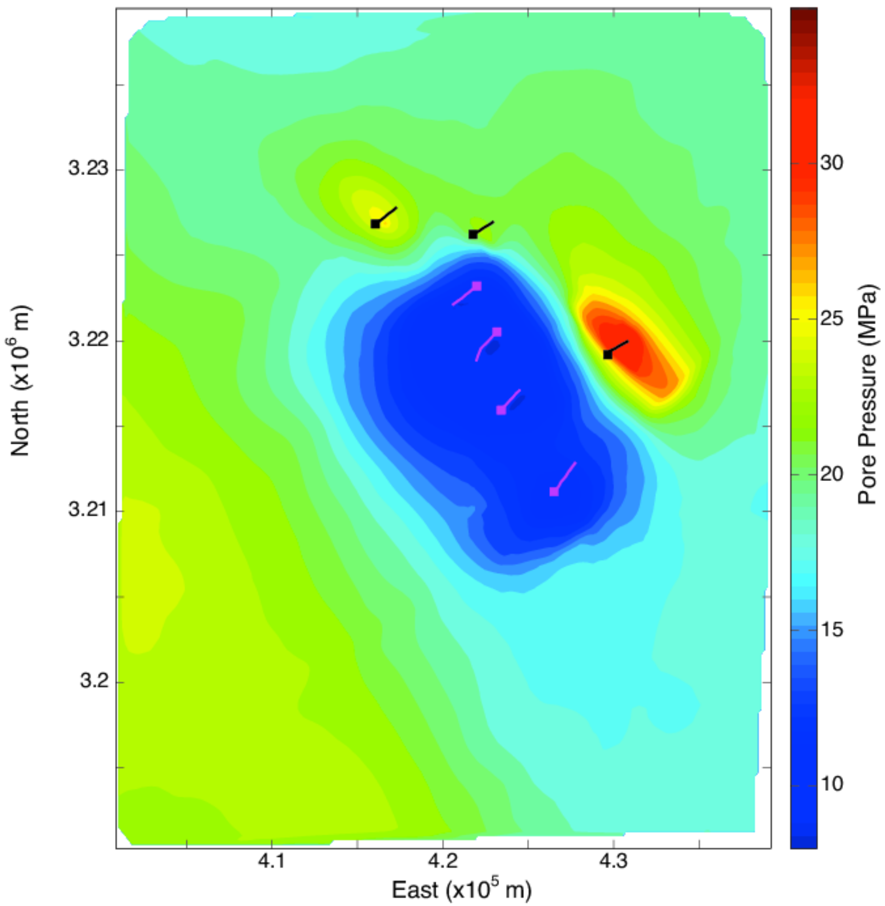
Modelling Fractures

Geomechanical strain reconstruction algorithm



MODELLING STRESS AND PRESSURE

History matched fluid flow/geomechanical model:



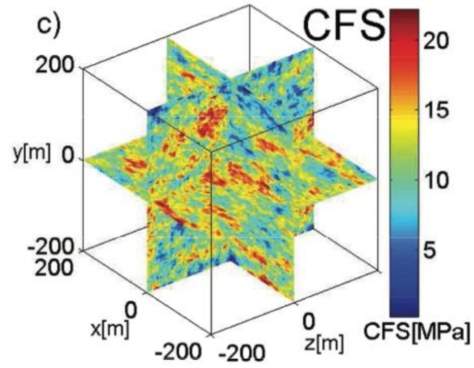
Statistical Variability

Each seed point takes its stress from the nearest model node.

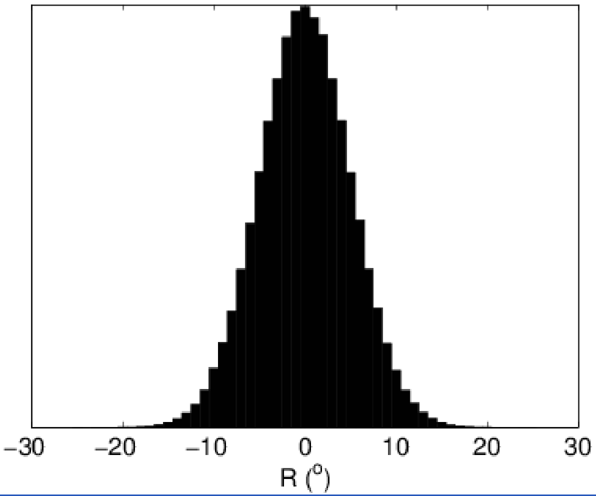
Principal stress magnitudes and orientations are modulated for each fracture to reflect natural variability:

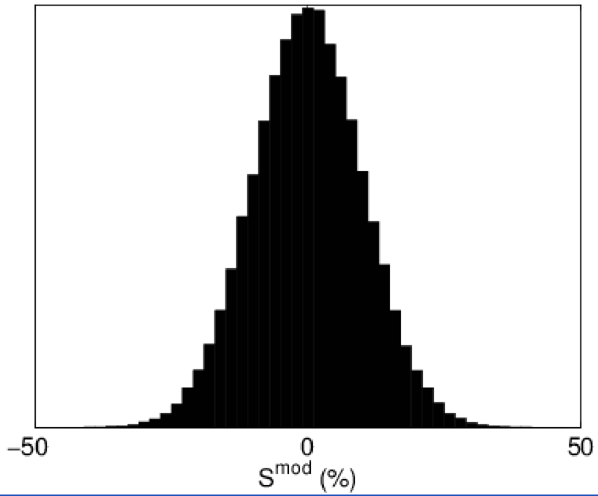
$$\sigma^{f}_{ii} = \sigma^{f}_{ii} + S_i^{mod}\sigma^{f}_{ii},$$

$$\sigma^{f}_{ii} = R\sigma^{f}R',$$



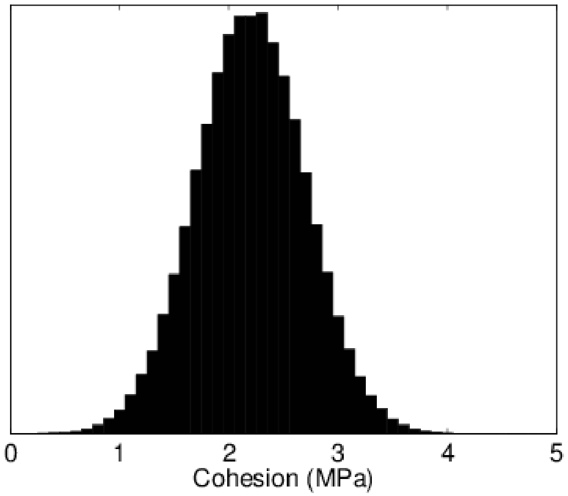
Langenbruch & Shapiro (2013)

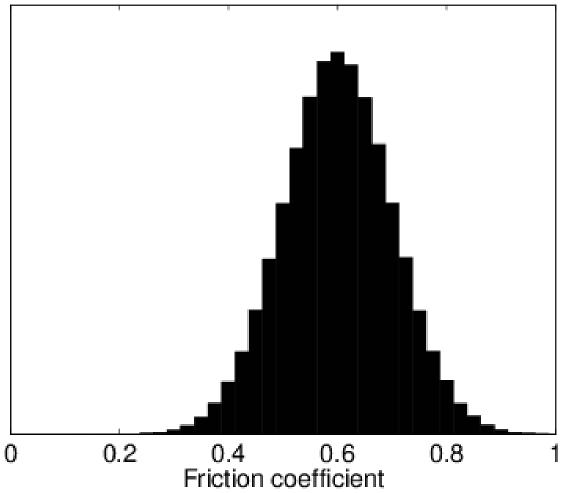




STATISTICAL VARIABILITY

Each seed point is given Mohr-Coulomb values from statistical distributions:





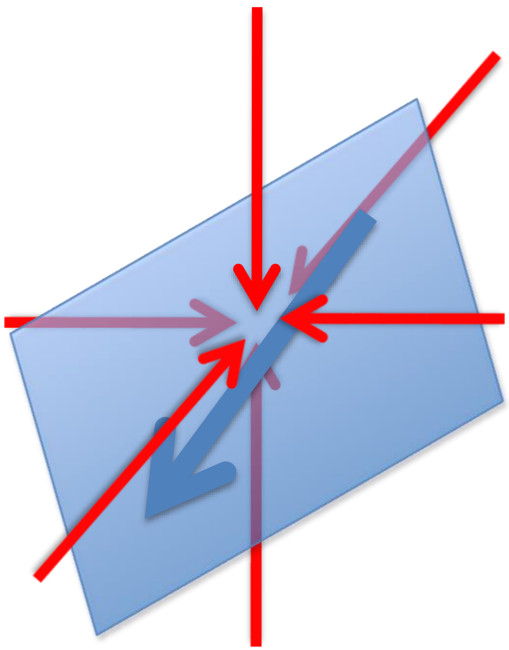
DETERMINING FAILURE

Resolving stress onto fractures:

- $t = \sigma_{ij} n$,
- $\sigma_n = (t.n)n$,
- $\tau = t - \sigma_n$.

Events occur if:

$\tau > \phi\sigma_n + C$



EVENT MAGNITUDES

Stress drop produced by an event is a portion of the shear stress randomly selected between 1 - 100%:

$-\Delta\sigma = d\tau \qquad d = [0.01\ 1].$

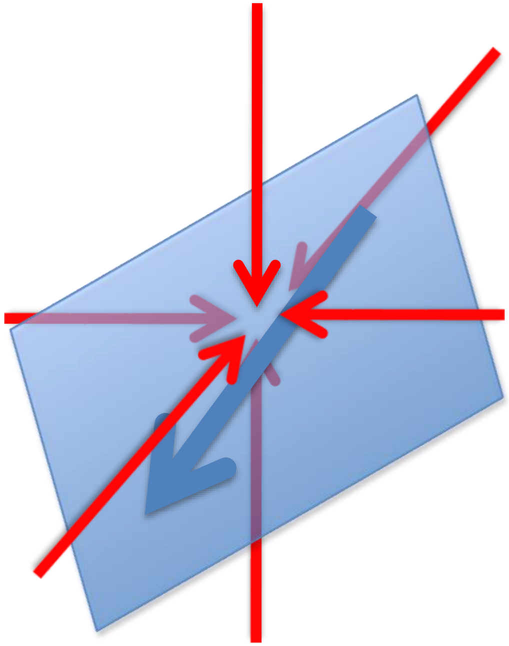
Fault rupture area is a portion of total length between 1 – 100%, multiplied by In Salah reservoir thickness of 20m.

$A = d20L, \qquad d = [0.01\ 1].$

Event magnitude can then be calculated

$M_W = (2/3)(\log_{10}(\Delta\sigma A^{1.5}) - 9.1).$

Focal mechanism is determined from fault plane orientation and slip vector.

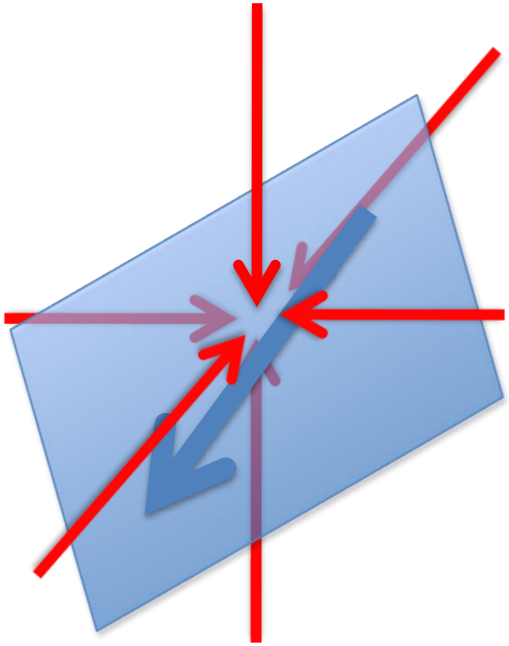


Stress drop is subtracted from stress tensor for subsequent timesteps (Kaiser effect).

MODEL OUTPUTS

Therefore our model gives us the following outputs:

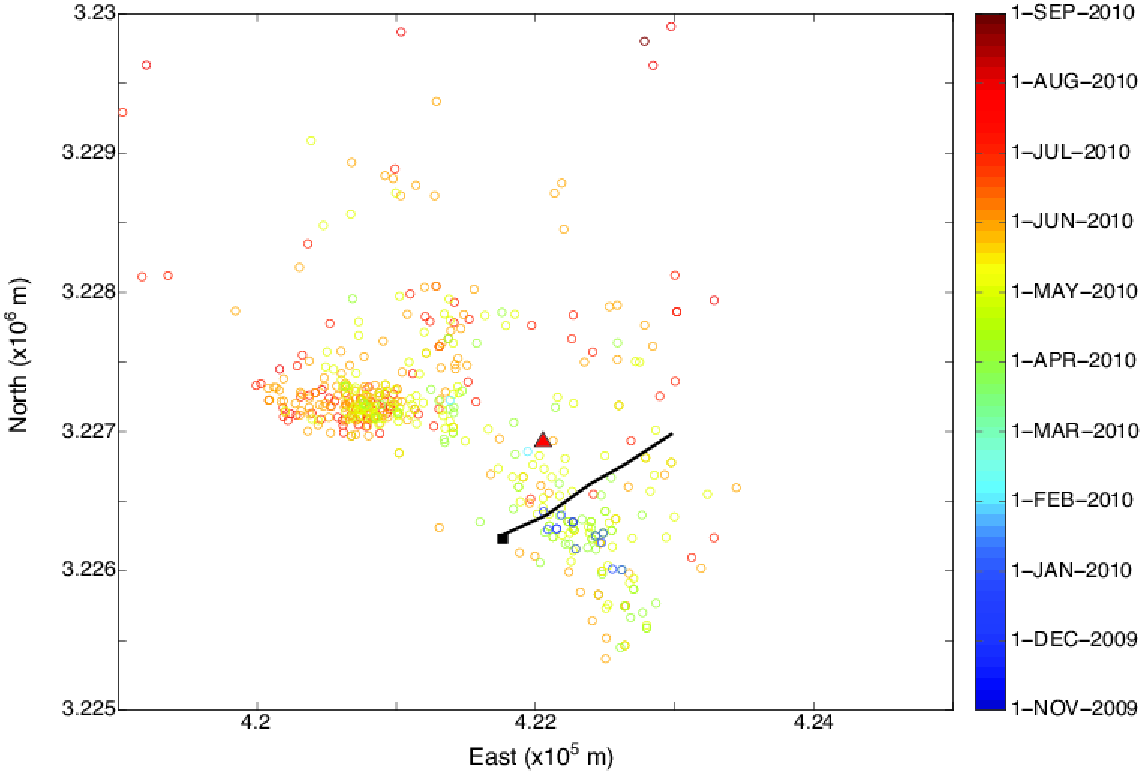
- When an event occurs
- Where it occurs
- Event magnitude
- Event stress drop
- Event rupture dimensions
- Double-couple source mechanism



RESULTS

Our aim is to compare with observations. Therefore we only consider modelled events that:

- Occur from August 2009 onwards,
- Are within 5km of the monitoring well (i.e. close to KB502).



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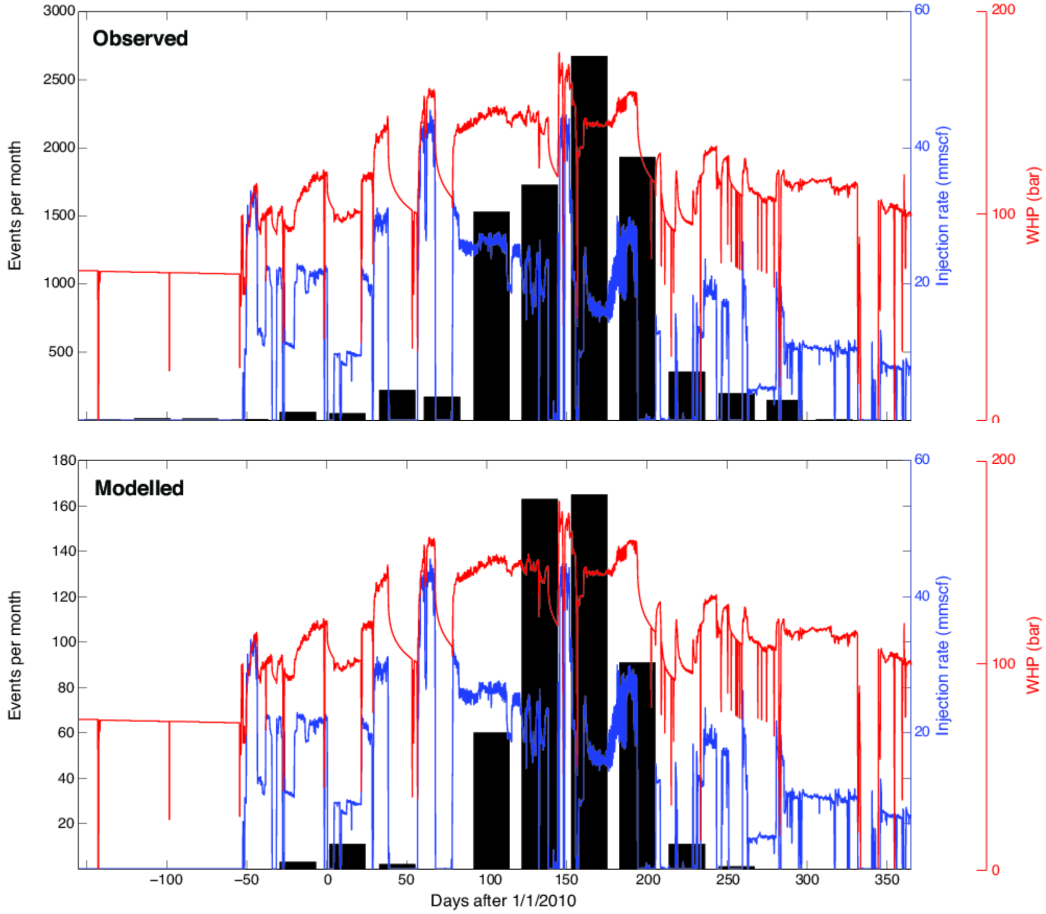
RESULTS

Modelled vs observed seismicity rate



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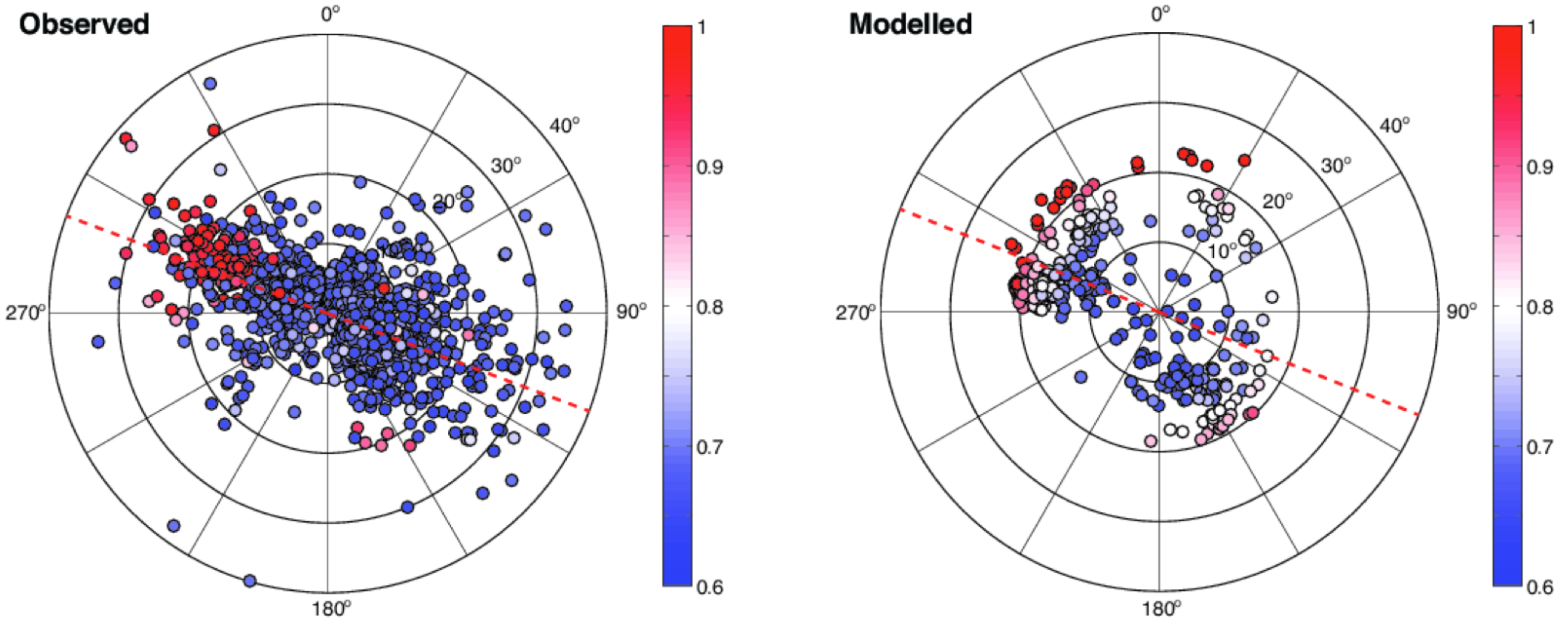
RESULTS

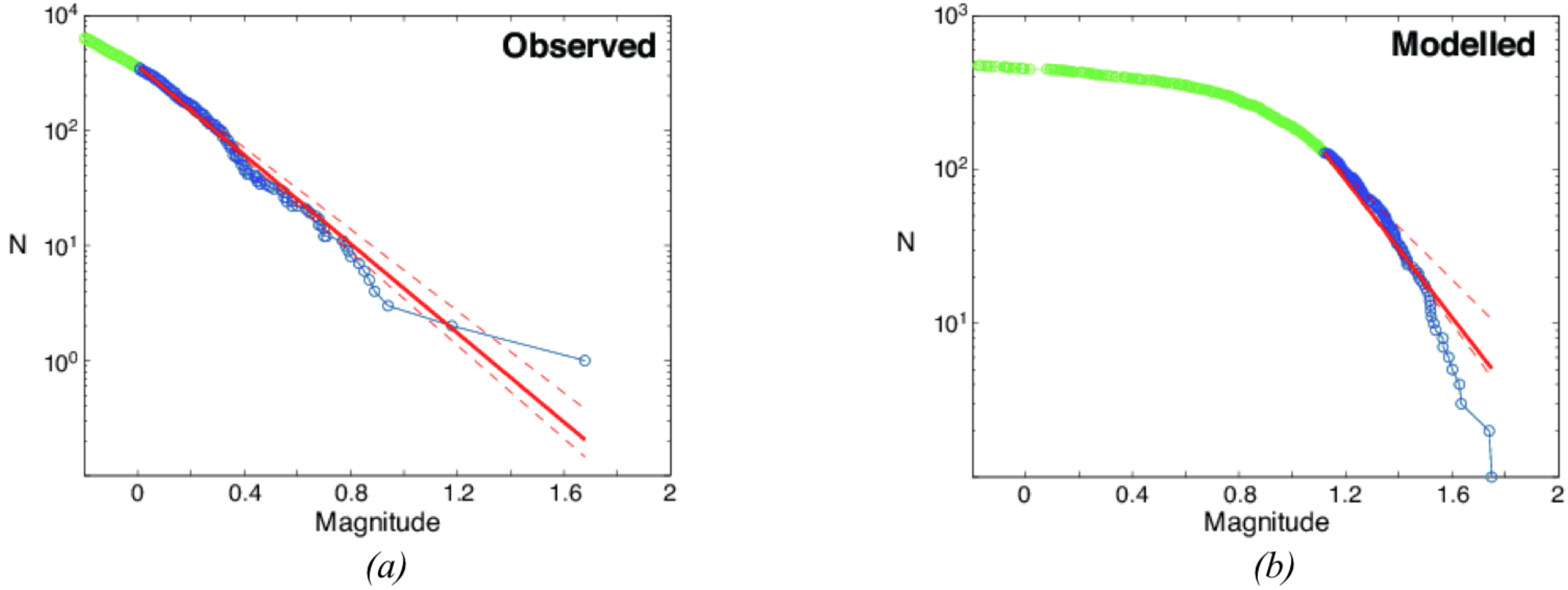
Modelled vs observed event arrival angles and times



(a) (b)

RESULTS

Modelled vs observed event magnitudes

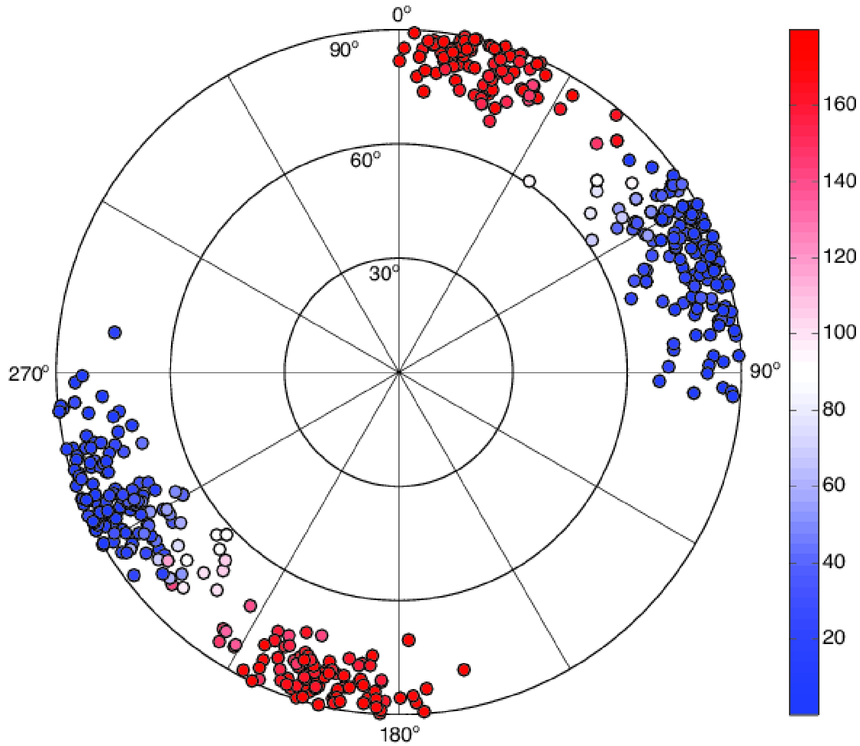


M_{MAX}: Observed = 1.68 | Modelled = 1.7±0.1

G-R *b*: Observed = 2.17±0.1 | Modelled = 2.3 ± 0.3

RESULTS

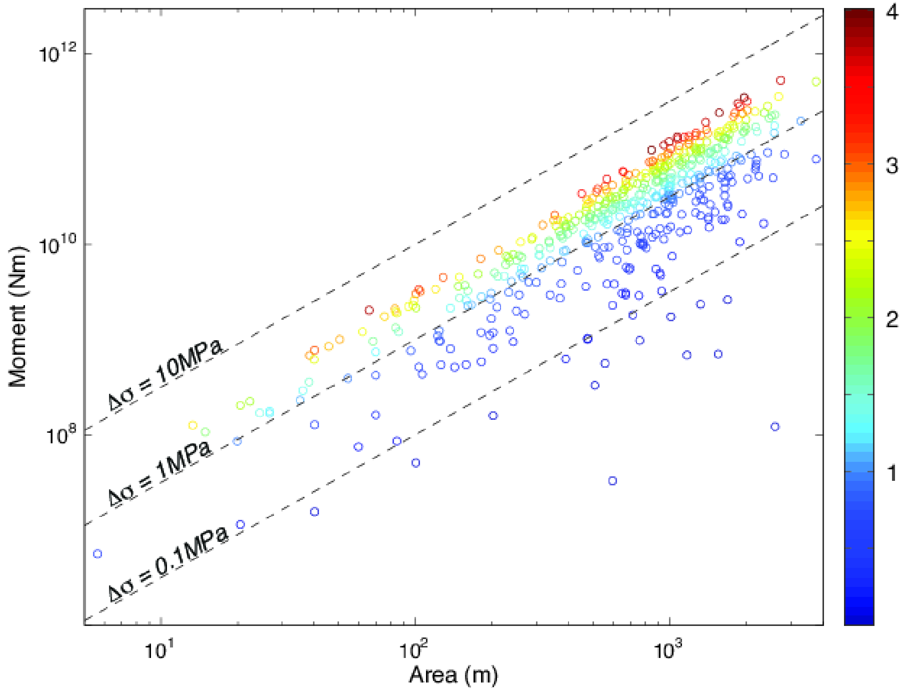
Source Mechanisms



Strike slip events on sub-vertical fracture plane

RESULTS

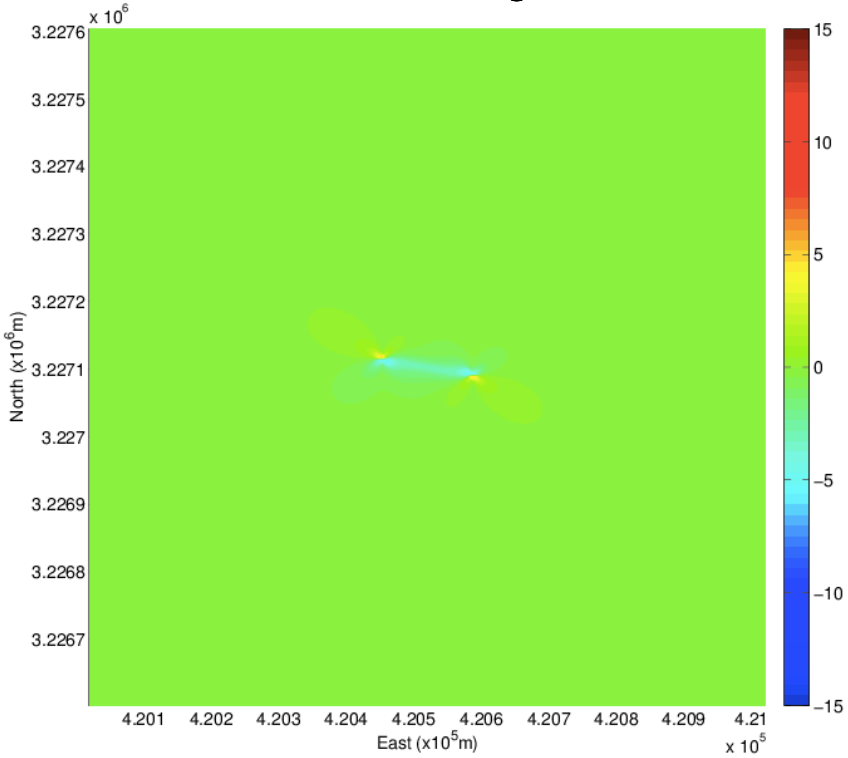
Stress drops and source dimensions:



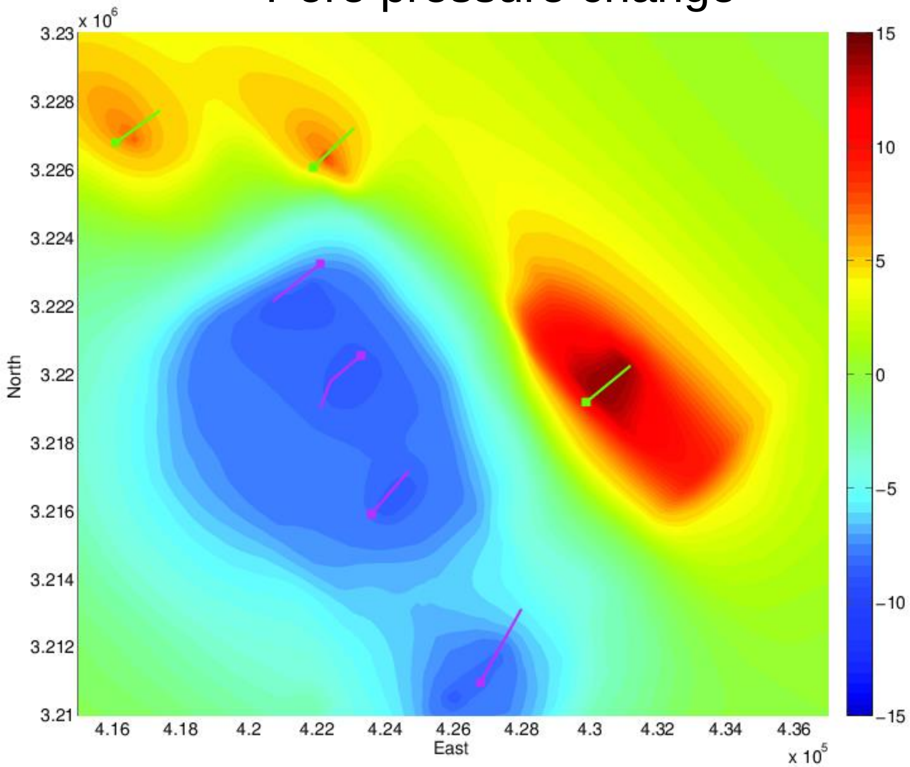
DISCUSSION

Relative importance of pore pressure vs fracture interactions

Static stress change



Pore pressure change



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DISCUSSION

Implications for CO_2 storage at In Salah

- Microseismic data is consistent with other observations at In Salah
  - Reflection seismics
  - Surface deformation
  - Rate vs pressure
- Injection appears to have stimulated fractures in the reservoir, which may extend up to 100 – 200m into the overburden.
- Overburden is 900m thick. Fractures not thought to pose a risk to storage integrity. MS monitoring does not reveal fracture growth with time.
- The extent to which injection has created new fractures, as opposed to made use of existing ones, is uncertain.

CONCLUSIONS:

- Important to link geomechanical models with geophysical observations during reservoir monitoring:
  - Calibrate geomechanical models
  - Interpret geophysical observations

- We use a geomechanical approach to simulate microseismicity in the In Salah reservoir, Algeria.

- Our approach simulates event time, location and source characteristics

- We note good agreement between model and observation, improving our understanding of the impact of subsurface CO_2 injection.

- At In Salah, pore pressure changes dominate over static stress change.

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