Integration of Induced Seismicity and Geomechanics
For Better Understanding of Reservoir Physics

Yusuke Mukuhira
Postdoctoral Fellow (JSPS research fellow)
Department of Earth, Atmospheric, and Planetary Sciences
In collaboration with Michael Fehler

MIT Earth Resources Laboratory
2017 Annual Founding Members Meeting
5.31.2017
Beyond the dots

Microseismicity/induced seismicity

Why do we measure microseismicity/induced seismicity?
• Indicator of pore pressure increase
• Enhancement of permeability/Stimulated rock volume

Method
• Seismology
• Location, magnitude, focal mechanism, source parameters, clustering analysis

Seismological analysis is fundamentally important, but the results of those analyses provide limited additional information.

Integration of microseismic data and other geophysical data make it possible to add further information about induced seismicity beyond the dots.
Two important outcomes

- Know background stress information and focal mechanism of event
  - Determine pore pressure required to cause the event
  - Provides information about pore pressure vs. position and time

→ Pore pressure migration behavior (Mukuhića et al., 2016 JGR)

- Know background stress information and first motion information from stations
  - Stress information helps constrain focal mechanism

→ More information on slipped existing fracture (Mukuhića et al., 2017 in review)
Theory of Induced seismicity and Geomechanics

Geomechanical theory: Mohr Stress circle

Coulomb failure criterion for shear slip
\[ \tau \geq \mu (\sigma - P) \]

Coulomb failure criterion

\[ \tau \geq \mu (\sigma - P) \]

Criterion for jacking
\[ \tau \geq \sigma - P \]

Pore pressure is the most likely trigger mechanism in during hydraulic stimulation
Geomechanical theory:
Minimum pore pressure increase for slip

Orientation of fractures likely to slip can be correlated with pore pressure increase when stress information is available
→ Two outcomes (pore pressure migration & constrain of focal mechanisms)
Granite
Fractured reservoir

Basel EGS project, 2006

GEL Station Network

Shut-in

Injection vs. Time

Large event $M_w 3.4$

Magnitude vs. Time

Distance from Inj. vs. Time

Event Depth vs. Time
Concepts/Methodology

Stress information
- Orientation of $S_{H\text{max}}$: N144E±14°
  - Borehole analysis (Valley and Evans, 2009)
- Stress magnitude
  - $S_{\text{Hmax}}/S_{\text{Shmin}}$: Borehole breakout width
  - $S_{V}$: density logging
    (Valley and Evans, 2015)

Geometry of fault plane
- Focal mechanisms by SED/ETH
  - Reliable FMs based on first motion
    (Deichmann and Ernst, 2009; Terakawa et al., 2012)
- Multiplet fractures
  - Cluster analysis (Asanuma et al., 2008)

Pore pressure increase was estimated based on these information assuming constant friction coefficient of 0.6
Spatio-temporal analysis of pore pressure increase

Hydraulic record

- Lower pore pressure migrates farther and faster
  →Lower pore pressure events occurred along sub-critical fractures that are more permeable than others
- Pore pressure still migrated farther even after shut-in

Observations & Interpretations
Snapshots of one-dimensional pore pressure distribution in relation to distance from injection point:

**Observations and Interpretations**

- Lower pore pressure migrates farther and faster
  - Lower pore pressure events occurred along sub-critical fractures that are more permeable than others
  - Shear slip of sub-critical fracture $\rightarrow$ enhancement permeability $\rightarrow$ pore pressure migrates farther

Migration of pore pressure along sub-critical fractures
Hybrid Focal Mechanism

Concept/Methodology

Problems: Reliable focal mechanism can not be estimated due to poor station distribution

By introducing *in-situ* stress information, we can constrain the range of focal mechanisms

- Polarity consistent focal mechanisms
- Pore Pressure increase required for slip
- Combined polarity and pore pressure information

Only the focal mechanisms which satisfy polarity and stress conditions are possible
Hybrid Focal Mechanism

Results for application to Basel data set

Polarity consistent focal mechanisms

After application of this method

Focal mechanism can exist only in nonzero slip index area

Slip index:
The ease with which fracture can have shear slip.

\[
slip\ index = \frac{WHP - \Delta P}{WHP - \Delta P_{\text{min}}}
\]

Benchmark focal mechanisms

♢: Slipped fault planes
□: Nodal planes

Introduction of *in-situ* stress successfully constrained the range of focal mechanisms
Conclusions

- Integration of induced seismicity data and other geophysical data is crucially important for better understanding on reservoir physics and further exploration of the reservoir.

  - Injection induced seismicity and *in-situ* stress integrated analysis demonstrated the pore pressure migration behavior during the stimulation and after shut-in.

  - *In-situ* stress information helps to constrain the source parameters of induced seismicity.

- The integrated analysis of induced seismicity data and other geophysical data (multidisciplinary approach) will be a key technology for problems associated with subsurface development.
Acknowledgement

- We thank Geopower Basel AG/Geo Explorer Ltd. for providing the microseismic data set and for approving the publication of these results.

- This study was supported by Grant-in-Aid for JSPS Overseas Research Fellow (20160228) and ERL.

Thank you for your kind attention
Backup slides
Future work

- Pore pressure increase
  → Estimate permeability on single fracture from space-time evolution of seismicity

- Hybrid focal mechanism
  → Constrain focal mechanisms by introducing borehole logging data about existing fractures

More constrained focal mechanism
Pore pressure migration behavior

One dimensional pore pressure distribution in relation to distance from injection point before and after shut-in

**Observations and Interpretations**

**During stimulation**
- Pore pressure reached around 15 MPa at 500 m from injection point
- Pore pressure decrease with distance from injection point
  → Because of flow resistance along flow path

**After shut-in**
- Shut-in pore pressure reached around 25 MPa at 500 m
  → Shut-in pressure migration
- Pore pressure distributed randomly in relation to distance
  → Because of disappearance of flow resistance
Introduction of *in-situ* stress successfully constrained the range of focal mechanisms.