Geomechanical simulation of fluid-driven fracture

DE-FE0002020

Joseph F. Labuz

Civil Engineering

University of Minnesota

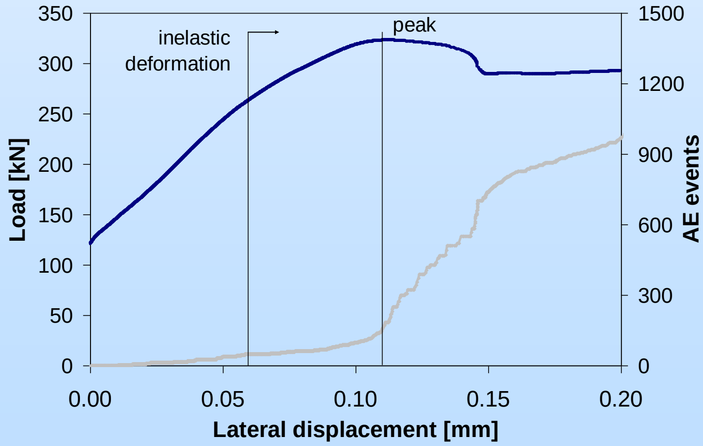
U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

August 21-23, 2012

Presentation Outline

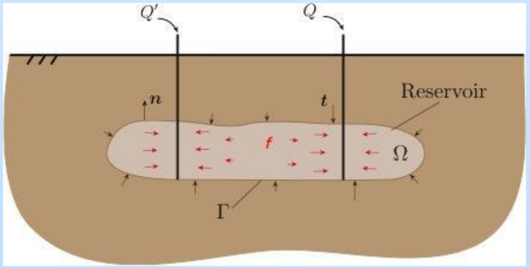
- Benefits statement
- Goal, objectives
- Technical status: fracture code, experimental results (poro, AE)
- Accomplishments
- Summary



UNIVERSITY OF MINNESOTA
Driven to Discover℠

Benefit to the Program

- **Goal: develop technologies to predict CO2 storage capacity in geologic formations.**
- **Benefits statement: develop 3D boundary element code & experimental techniques (poro, AE) to simulate fracture in a porous rock; this work contributes to the ability to predict storage and containment.**



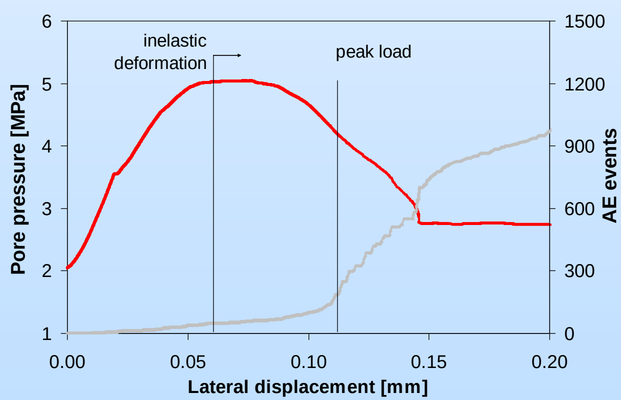
Project Overview: Goals and Objectives

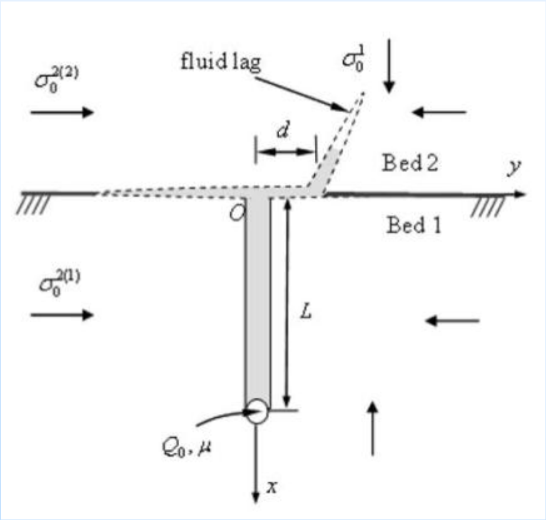
- **Goal: support/train graduate students working on simulation of fracture.**
- **Objectives:**
  - **devise techniques related to laboratory testing of fluid-saturated rock (plane-strain apparatus);**
  - **develop predictive models for the simulation of fracture (3D BEM code);**
  - **establish educational framework for geologic storage issues (poroelastic, exp geomech, BEM).**

Technical Status

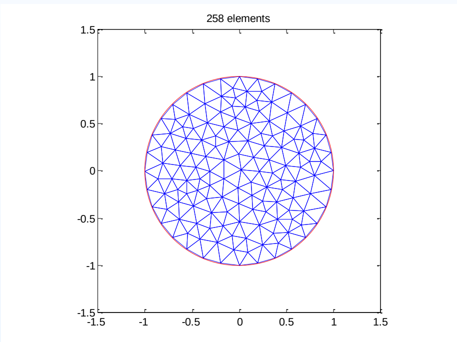
- **Fracture code provides crack displacements of fracture (& stresses); develop arbitrarily oriented cracks & boundaries, higher order approximations & crack tip shape functions; arbitrary body force.**

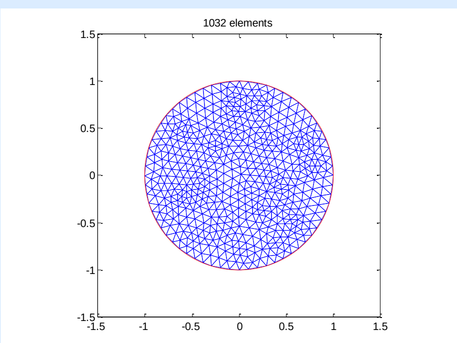
- **Experimental results.**

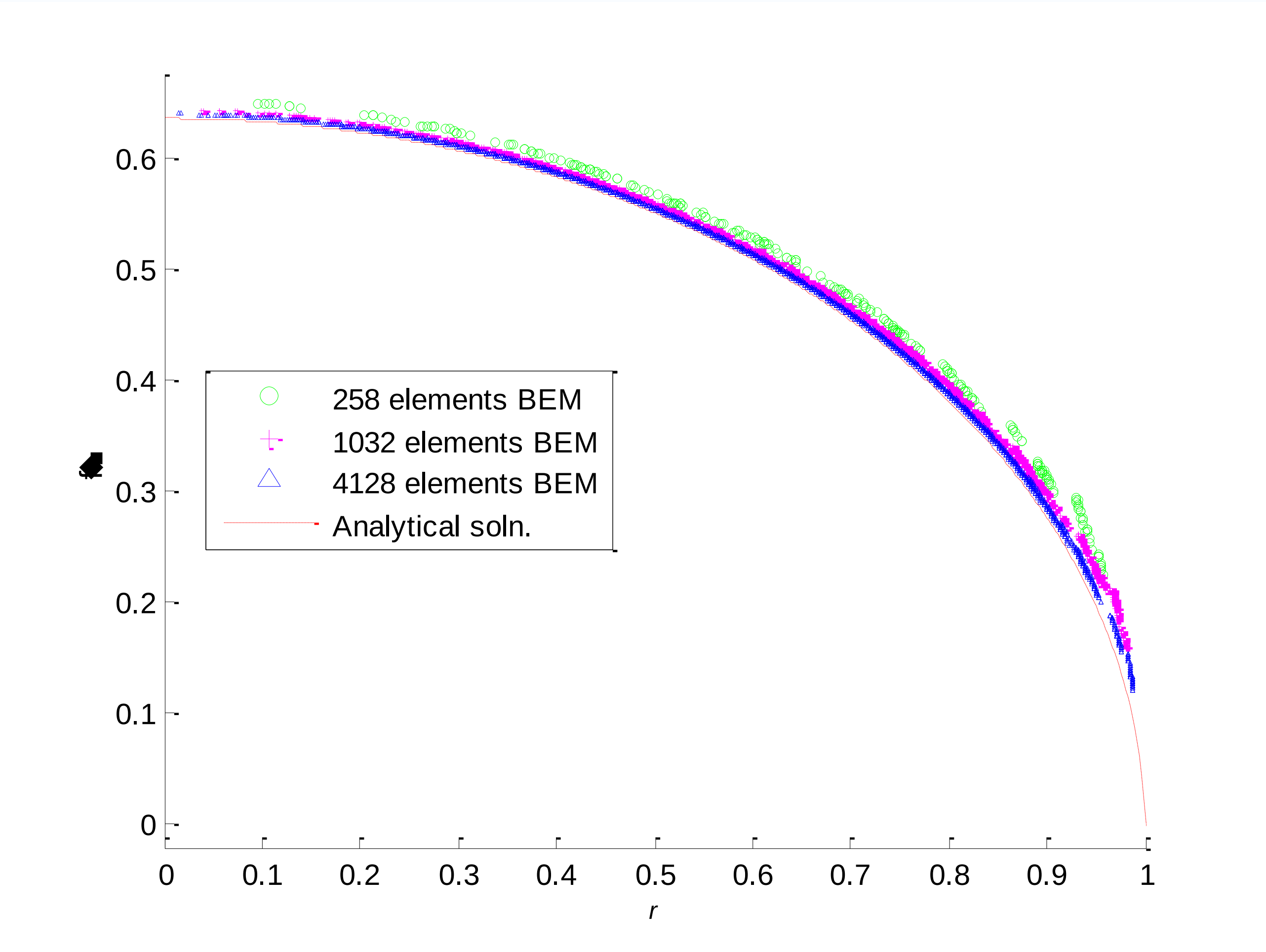




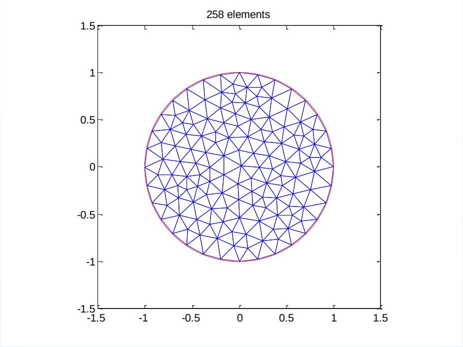
Penny-shaped crack: mode I

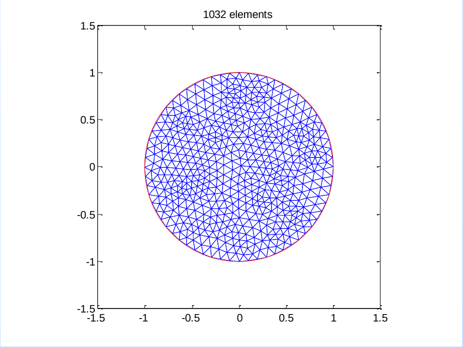


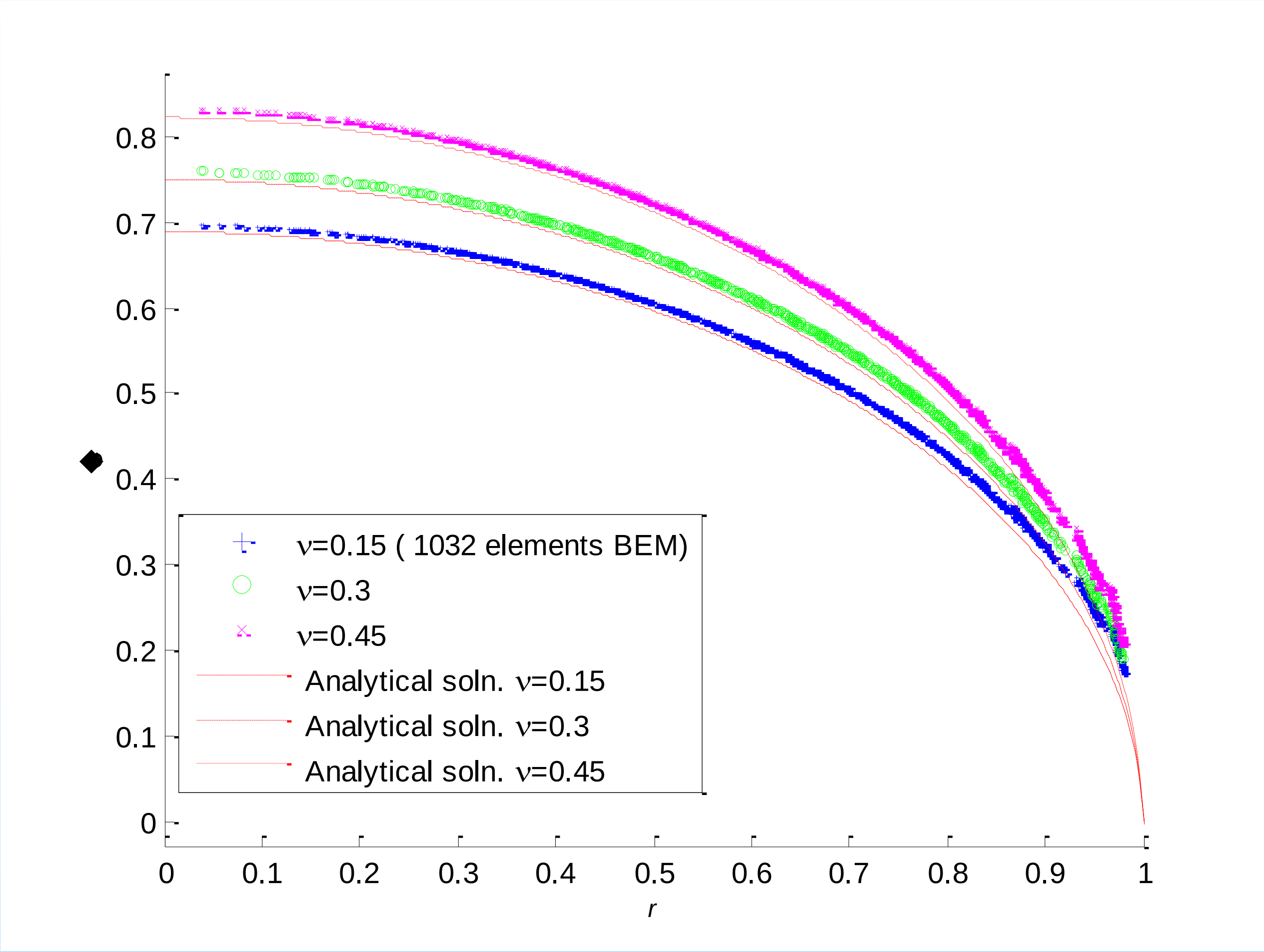




Penny-shaped crack: mode II

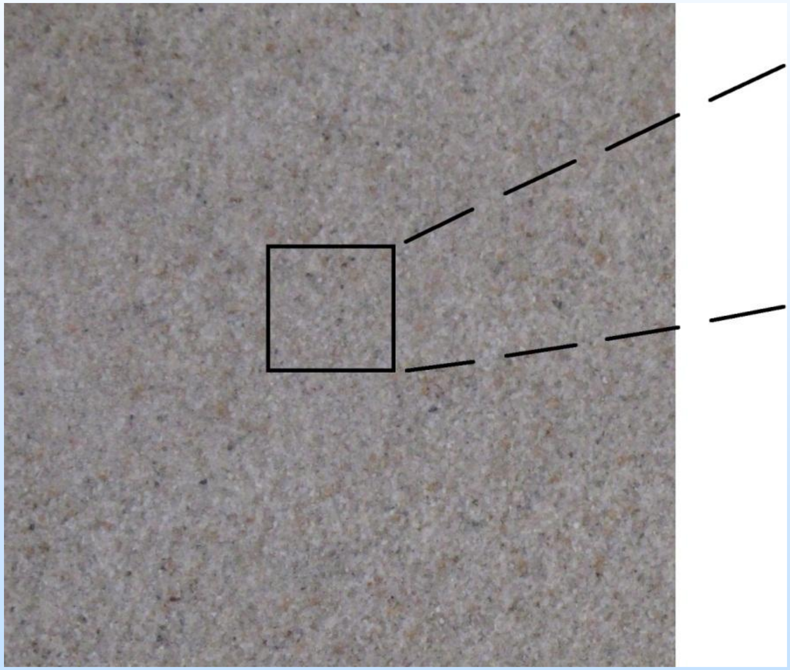




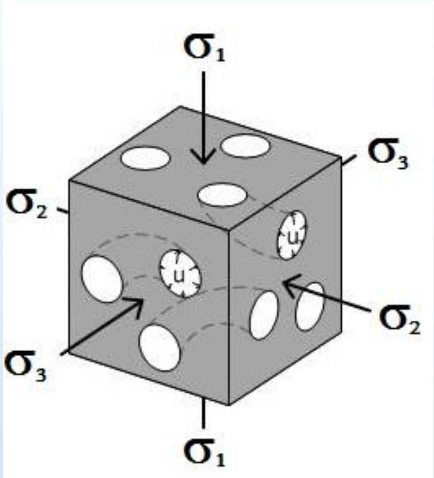


Rock—porous media

Porous sandstone



Representative volume element



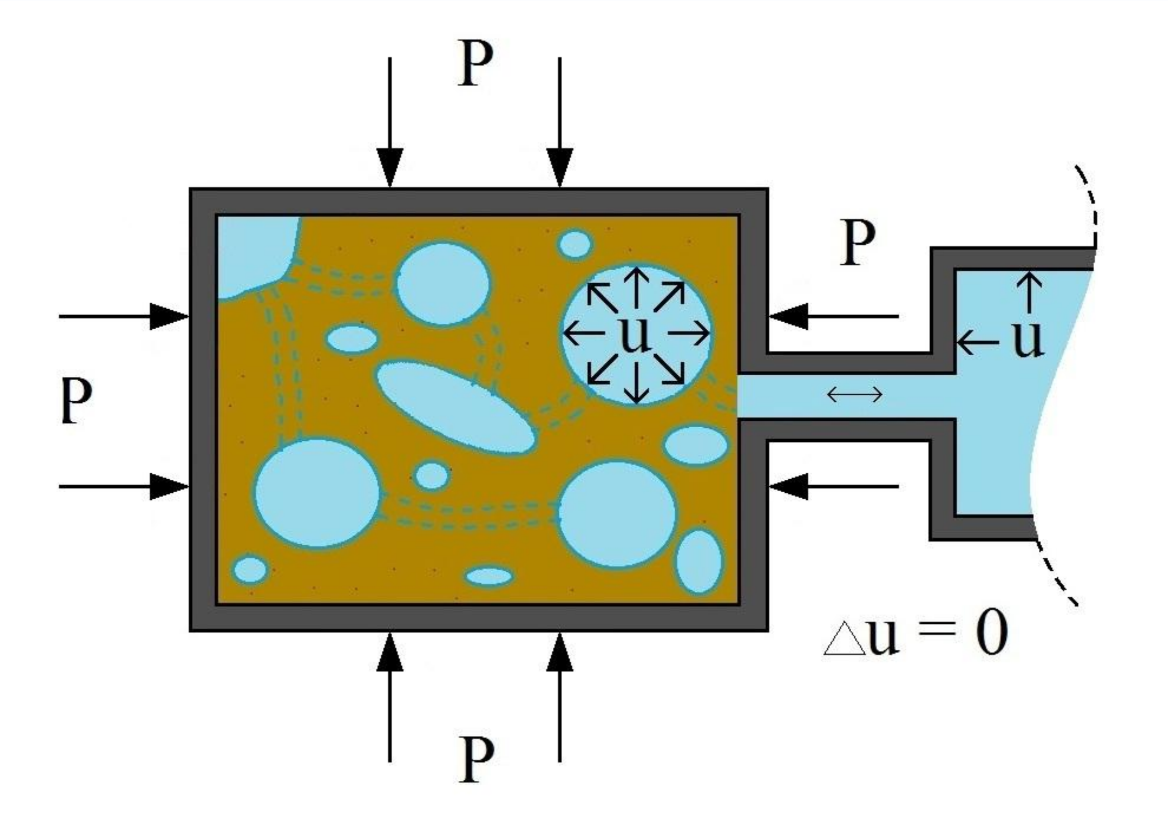
$\phi = V_\phi / V$ = porosity

$P = \sigma_{kk} / 3$ = mean stress

u = pore pressure

University of Minnesota
Driven to Discover℠

Drained condition

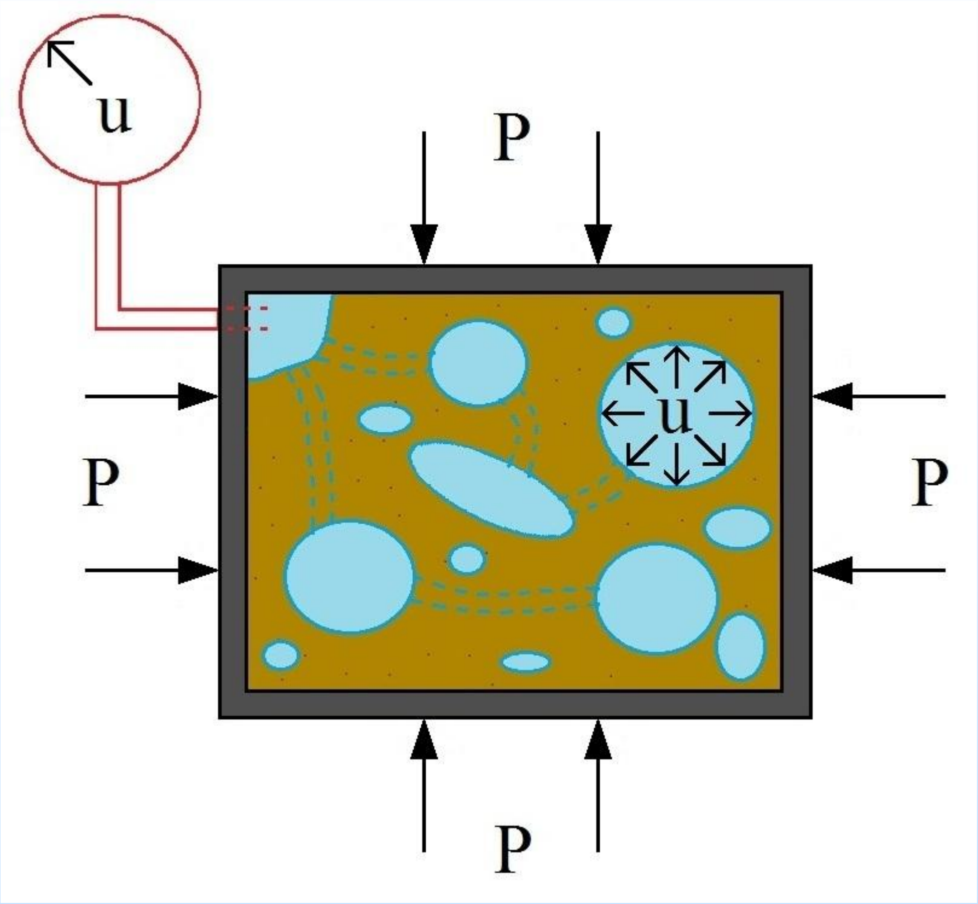


drained: *du* = 0

K = drained bulk modulus

$$K = V \left.\frac{\partial P}{\partial V}\right|_{du=0}$$

Undrained condition



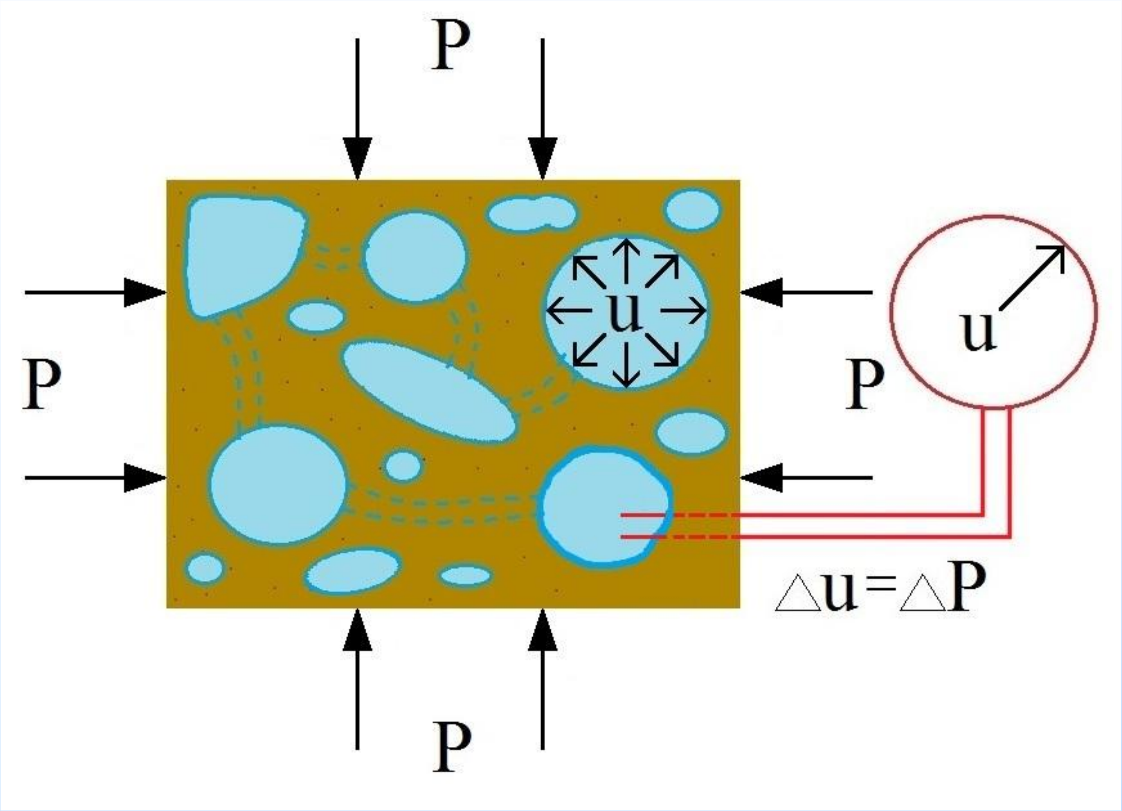
undrained: $dm_f = 0$

$$K_u = V \frac{\partial P}{\partial V}\bigg|_{dm_f=0}$$ undrained bulk modulus

$$B = \frac{\partial u}{\partial P}\bigg|_{dm_f=0}$$ Skempton's coefficient

$$K_f = V_f \frac{\partial u}{\partial V_f}$$ fluid bulk modulus

Unjacketed condition



unjacketed: *dP* = *du*

unjacketed bulk modulus

$$K_s' = V \left. \frac{\partial u}{\partial V} \right|_{du=dP}$$

unjacketed pore bulk modulus

$$K_s'' = V_\phi \left. \frac{\partial u}{\partial V_\phi} \right|_{du=dP}$$

Equations of poroelasticity

$$\alpha = 1 - \frac{K}{K_s'}$$ **Biot's coef (1955)**

effective stress: $P' = P - \alpha u$

$$K_u = K + \frac{\alpha^2 K}{(1-\alpha)\alpha + \phi K\left(\frac{1}{K_f} - \frac{1}{K_s''}\right)}$$

generalized Gassman equation (Brown and Korringa 1975)

$$0 < K \le K_u$$

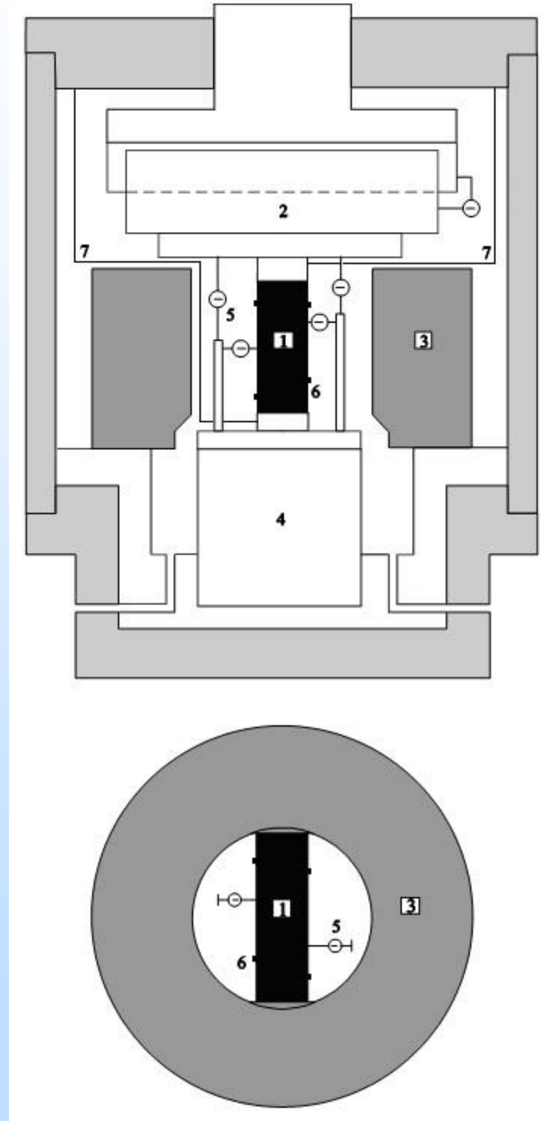
$$B^{cor} = \frac{1}{\left(\frac{1}{B}\right)_{meas} - \frac{V_L}{V}\frac{K}{\alpha K_f}} = \frac{K_u - K}{\alpha K_u}$$

corrected Skempton coefficient (Bishop 1976)

V_L = volume of fluid in system

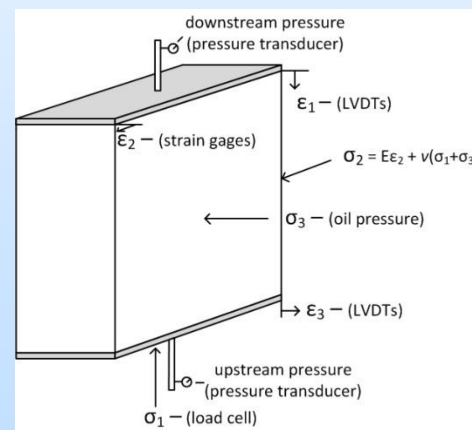
Plane strain testing

University of Minnesota
Plane Strain Apparatus
U.S. Patent 5,063,785



5 LVDTs
8 AE sensors

Specimen size:
100 x 86 x 44 mm

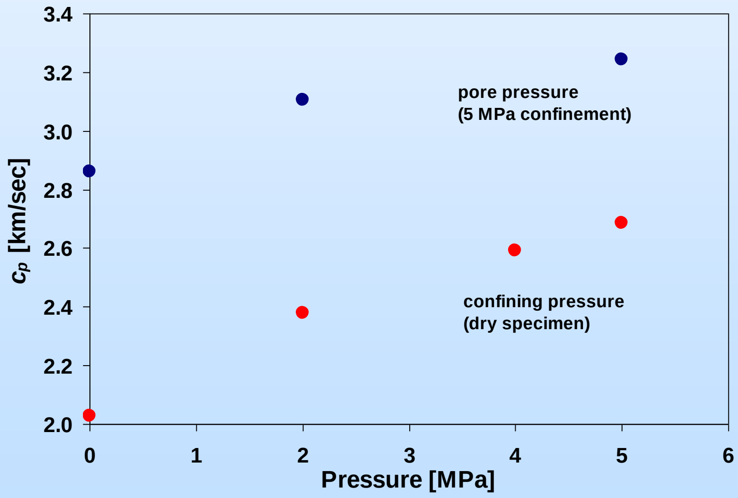


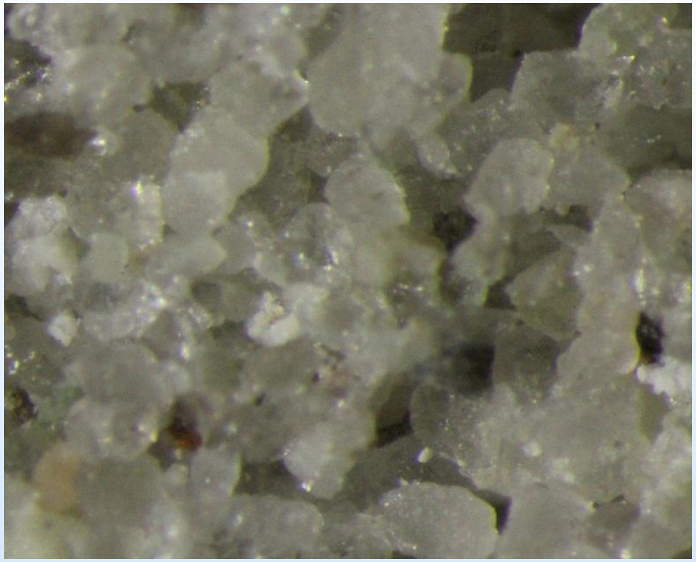
UNIVERSITY OF MINNESOTA
Driven to Discover℠

Berea sandstone

Slightly anisotropic (5% difference for ultrasonic velocities and 10% in UCS)

Porosity = 23%, permeability = 40 mD (at 5 MPa eff stress), density = 2100 kg/m^3 , E = 13-15 GPa, ν = 0.31





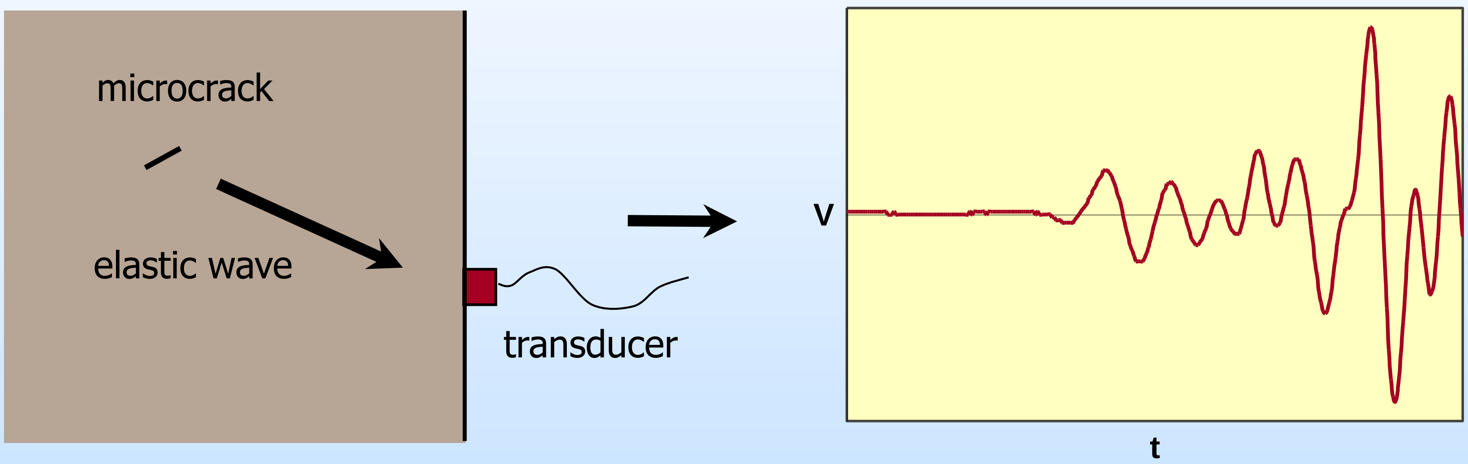
c_p = P-wave velocity increasing with mean stress and pore pressure

Results

Test #	*P [MPa]*	*u [MPa]*	*E [GPa]*	ν	*K*, K_u *[GPa]*	*G [GPa]*
BxBs-6d	6	0	10.9	0.31	9.6	4.2
BxBs-11d	5	0	10.8	0.32	10.0	4.1
BxBs-2u	8.2	2.8	13.2	0.34	13.8	4.9
BxBs-3u	10	3.8	13.5	0.35	15.0	5.0
BxBs-12u	10	3.4	15.3	0.34	15.9	5.9

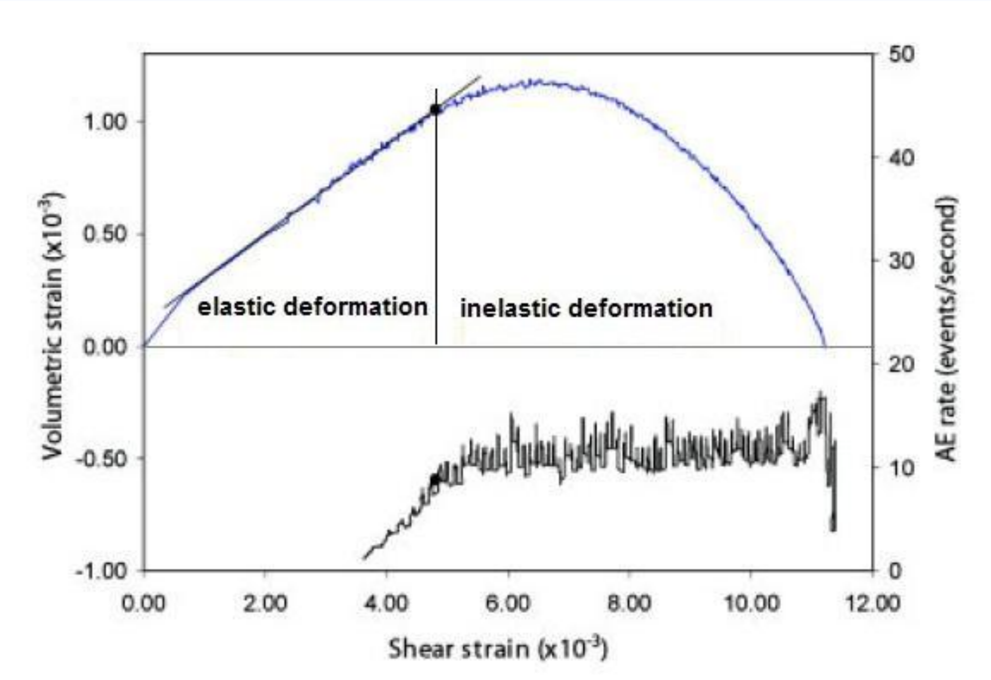
Acoustic Emission

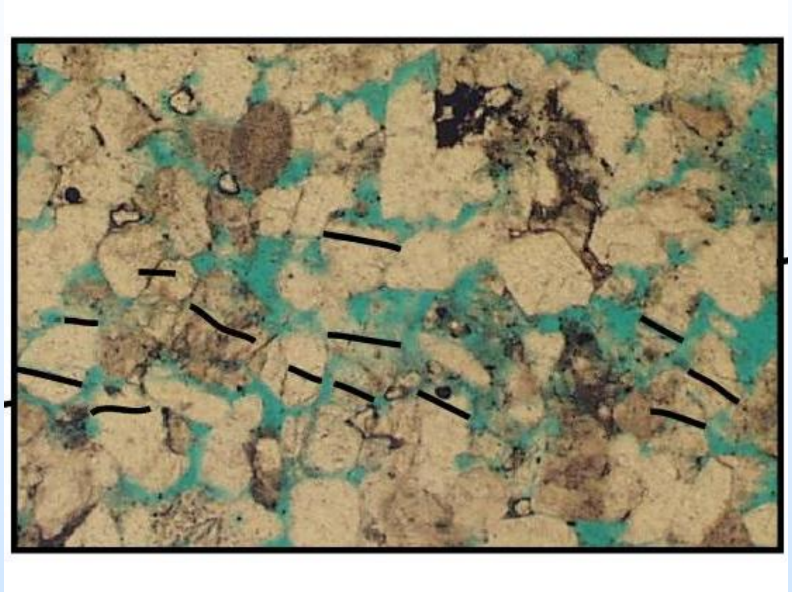
Inelastic response (yielding) of rock is associated with microcracks, which generate elastic waves called acoustic emission (AE).



Transient elastic wave can be recorded by transducers placed on the surface; statistics (rate) and locations (1st arrival) can be studied.

Acoustic Emission



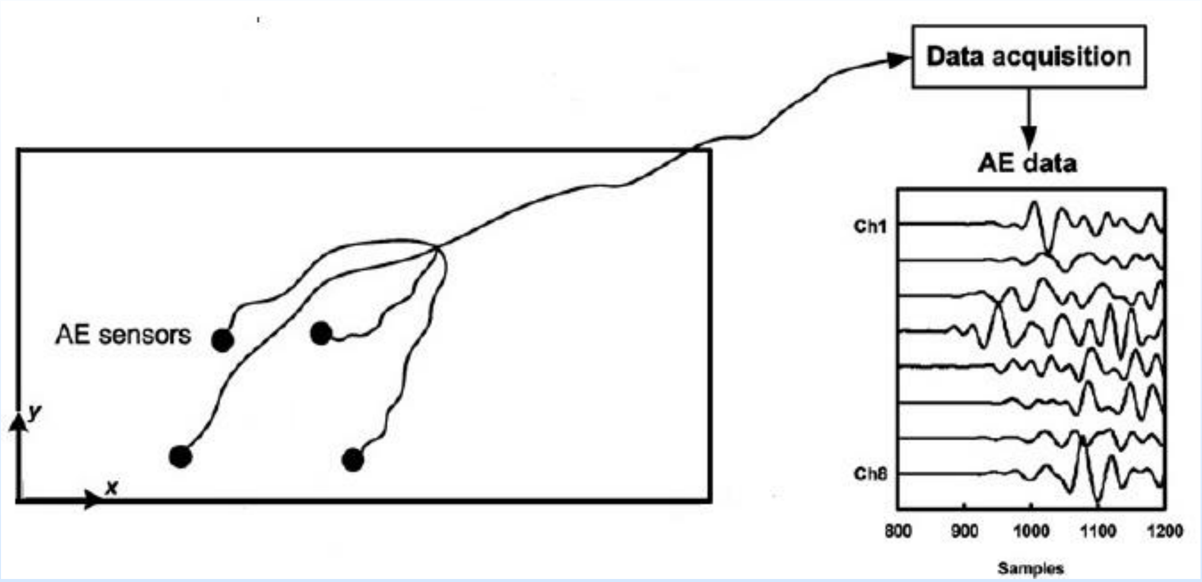


Microphotograph of a fractured rock

In dry rock, increase in AE rate when deformation becomes inelastic.

What about liquid-saturated rock?

AE system



1. AE sensors (0.3-1.8 MHz, 3.6 mm diameter, PA S9225)
2. Preamplifiers (0.1-1.2 MHz filter, 40 dB gain, PA 1220C)
3. Digitizer (LeCroy 6840 or National Instruments 5112)
4. Amplitude threshold trigger

Location of AE

Four unknowns: (x, y, z) and t, event coordinates and time

Know: (x_i, y_i, z_i) sensor coordinates, t_i arrival time at the i^{th} sensor, c_p P-wave velocity

Distance between the source and the i^{th} sensor

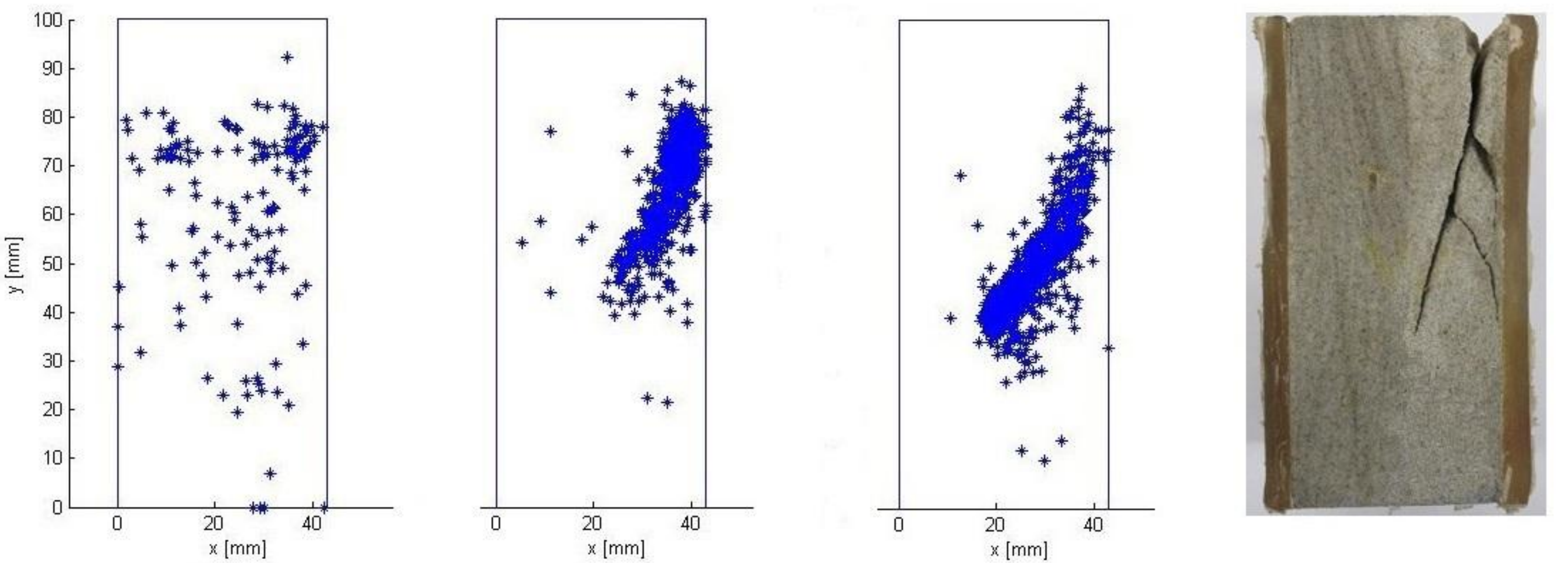
$$r_i = c_p (t_i - t) + \varepsilon_i$$

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$$

Levenberg-Marquardt optimization - minimize I:

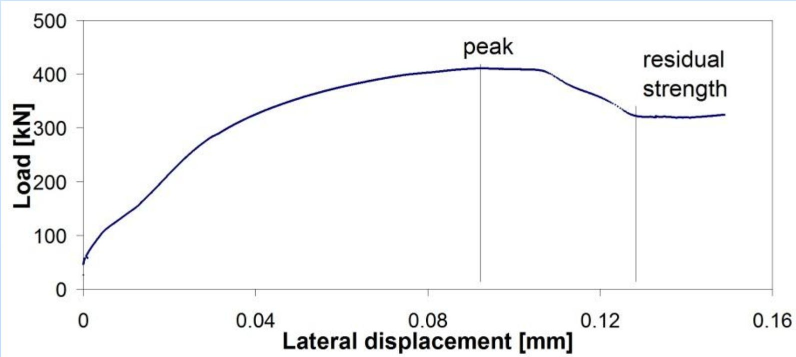
$$I = \sum_{i=1}^{N} \varepsilon_i^2$$

AE locations (dry test)

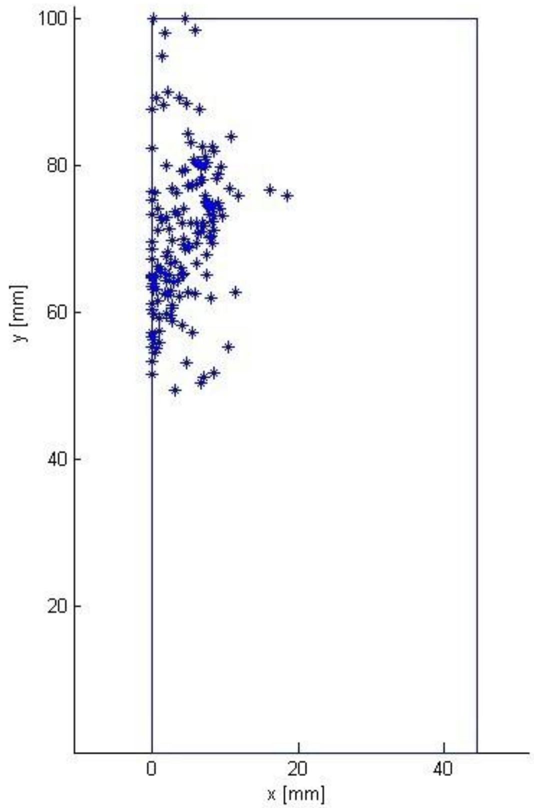


pre-peak | peak - 90% post-peak | 90% post-peak - residual | failed specimen

AE events:
- random before peak
- localized in post-peak



AE locations (unjacketed)



Location of events

Failed specimen

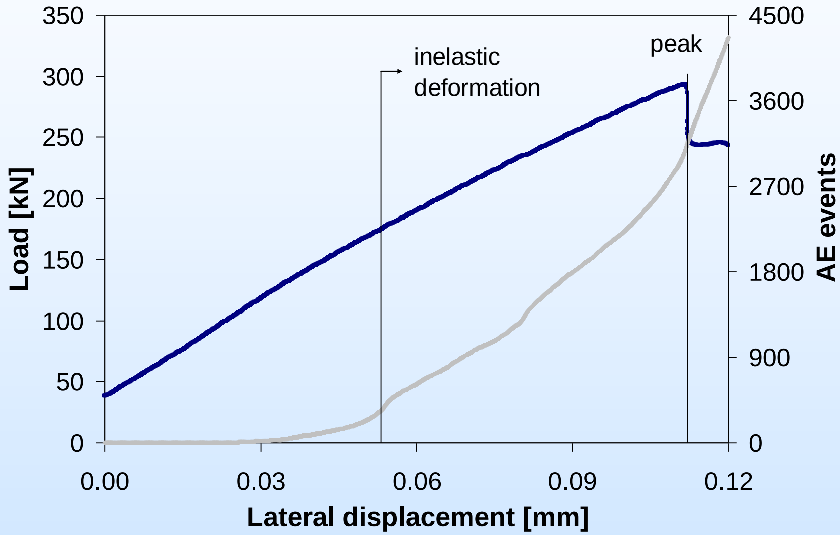
Possible to detect AE locations in liquid saturated rock

153 events were located with error less than 3 mm

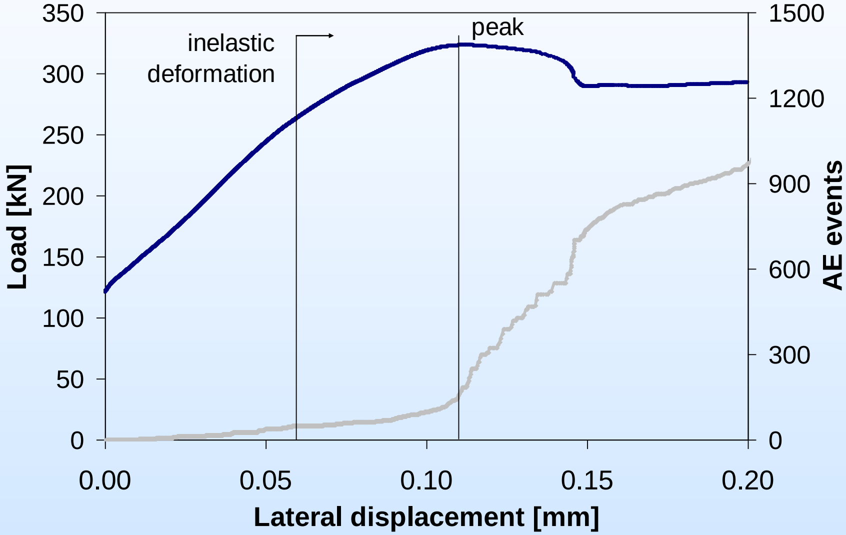
Failure mechanism – axial splitting

AE rate - load

Drained



Undrained



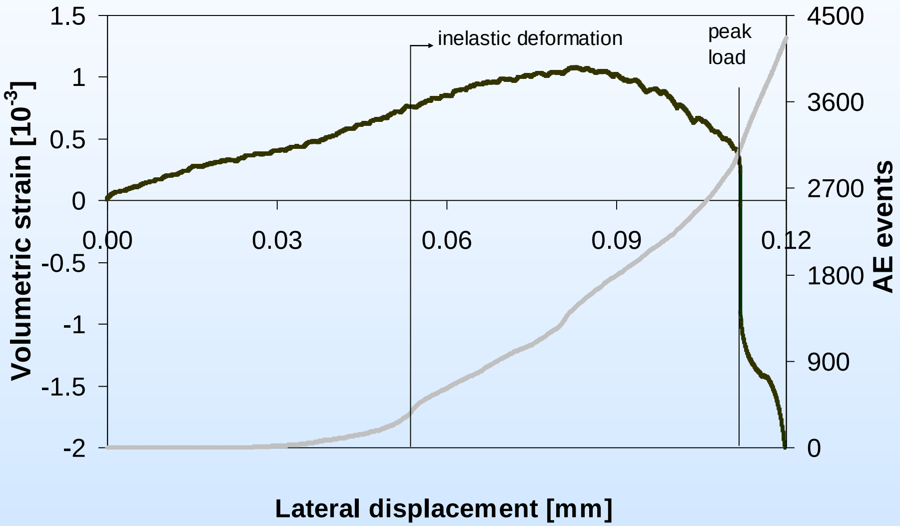
Drained:
2700 events in pre-peak

Undrained:
170 events in pre-peak

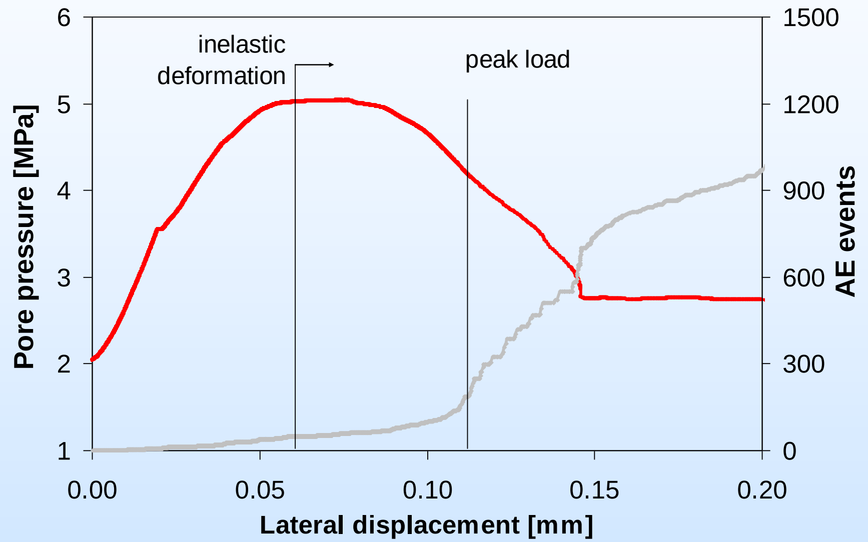
UNIVERSITY OF MINNESOTA
Driven to Discover℠

AE rate - deformation

Drained



Undrained

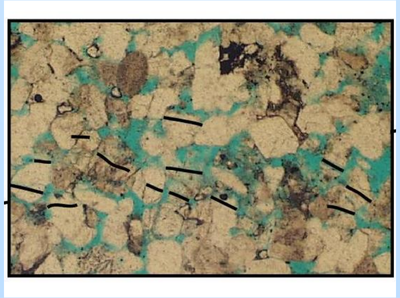


Drained (rates):
inelastic 130 events/min
post-peak 410 events/min

Undrained (rates):
inelastic 3 events/min
post-peak 210 events/min

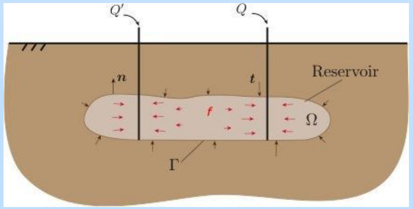
Accomplishments to Date

- BEM code to simulate crack propagation; needed to assess storage/containment.
- Poroelastic parameters from drained and undrained plane-strain compression; needed to predict reservoir response.
- AE rates found to be different under drained and undrained conditions; *rock's tendency to dilate delayed under undrained condition*. To assess reservoir response, inelastic behavior must be understood.

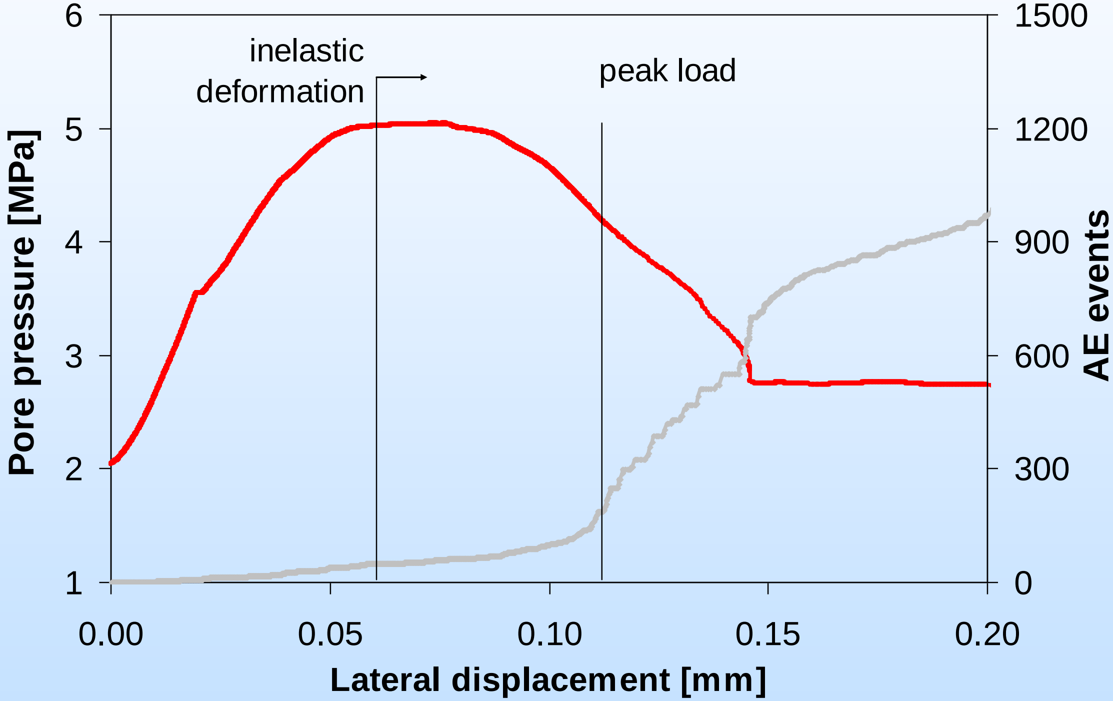


Summary

- Key Findings: 3D BEM fracture code with body forces; poroelastic parmeters from plane strain compression testing.
- Lessons Learned: saturation critical.
- Future Plans: assessment of risks related to fracturing of the reservoir and the caprock; heterogeneity of rock mass; body force (pore pressure gradient induced) a significant feature.



Appendix

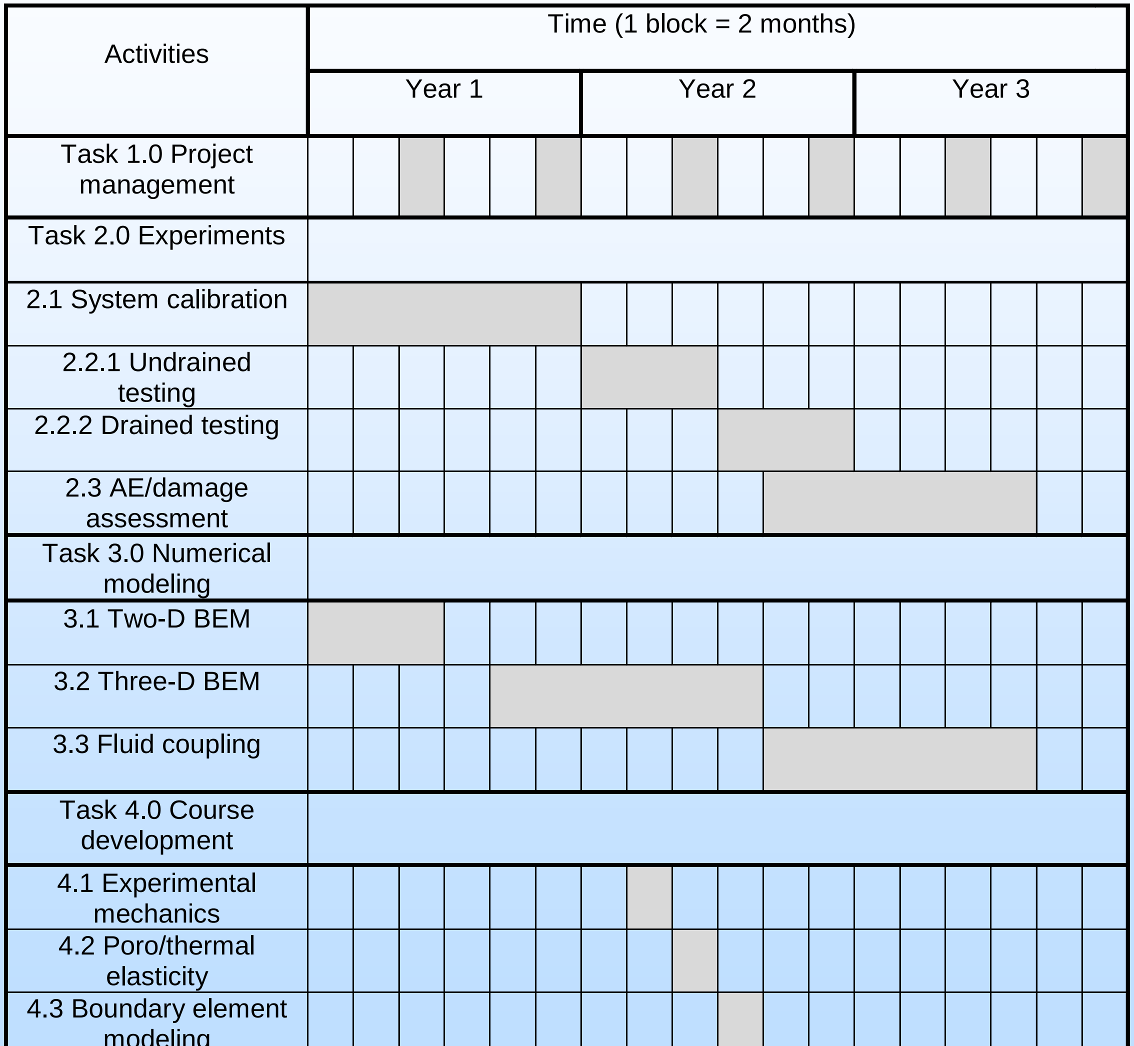


UNIVERSITY OF MINNESOTA
Driven to Discover℠

Organization "Chart"

- **J.F. Labuz, PI: experimentalist, with two patents; fracture and strength of rock, acoustic emission. E. Detournay, co-PI: poroelasticity, hydraulic fracturing. S. Mogilevskaya, co-PI: applied mathematician, boundary integral methods, especially modeling fracture propagation.**
- **R. Makhnenko, D. Nikolski: Ph.D. students; A. Pyatigorets: Ph.D., partial support; J. Meyer: M.S., partial support.**

Gantt Chart



Activities
Time (1 block = 2 months)
Year 1
Year 2
Year 3
Task 1.0 Project management
Task 2.0 Experiments
2.1 System calibration
2.2.1 Undrained testing
2.2.2 Drained testing
2.3 AE/damage assessment
Task 3.0 Numerical modeling
3.1 Two-D BEM
3.2 Three-D BEM
3.3 Fluid coupling
Task 4.0 Course development
4.1 Experimental mechanics
4.2 Poro/thermal elasticity
4.3 Boundary element modeling

Bibliography

- **Refereed**
  - Mogilevskaya, S.G., Crouch, S.L. 2012. Combining Maxwell's methodology with the BEM for evaluating the two-dimensional effective properties of composite and micro-cracked materials. Computational Mechanics. In print, DOI: 10.1007/s00466-012-0735-5.
  - Pyatigorets, A.V., Mogilevskaya, S.G. 2011. Evaluation of effective transverse mechanical properties of isotropic viscoelastic composite materials. Journal of Composite Materials. 45, 2641 - 2658.
- **Proceedings**
  - Nikolski, D.V., Mogilevskaya, S. G. and Labuz, J.F., 2012. Three-dimensional Boundary Element modeling of fracture under gravity load. Proc. 46th U.S. Symposium Rock Mechanics, 24-27 June, Chicago, IL, ARMA 12-450.
  - Mogilevskaya, S. G., Labuz, J.F. and Crouch, S. L., 2012. Extension of Maxwell's methodology for evaluating the effective properties of rock. Proc. 46th U.S. Symposium Rock Mechanics, 24-27 June, Chicago, IL, ARMA 12-446.

Bibliography

- **Proceedings**

  - Makhnenko, R.Y. Labuz, J.F. 2012. AE in saturated rock under plane strain compression. Proc. Acoustic Emission Working Group 54th Meeting (AEWG-54), Princeton, NJ, 21-22 May 2012.
  - Makhnenko, R.Y., Ge, C., Labuz, J.F. 2012. AE from undrained and unjacketed tests on sandstone. Proc. 46th U.S. Symposium Rock Mechanics, Chicago, IL, 24-27 June, ARMA 12-581.
  - Makhnenko, R., Labuz, J.F. 2012 Drained and undrained plane strain compression of porous rock. Proc. XXIII International Conference of Theoretical and Applied Mechanics (ICTAM2012), Beijing, China, 19-24 August, paper FS10-020.
  - Nikolski, D.V., Mogilevskaya, S.G., Labuz, J.F., 2011. Three-dimensional boundary element modeling of fractures under gravity load. Symposium International Association for Boundary Element Methods. Brescia, Italy 5-8 September, p. 237.