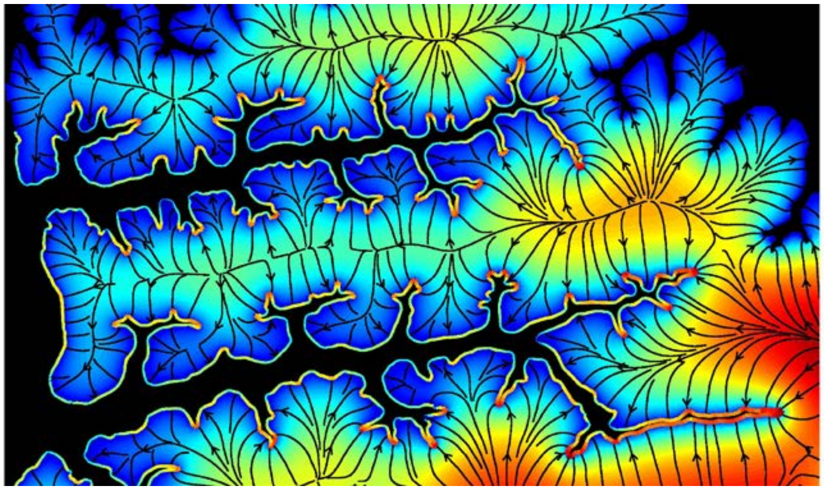
Geophysics and Subsurface Fluid Flow



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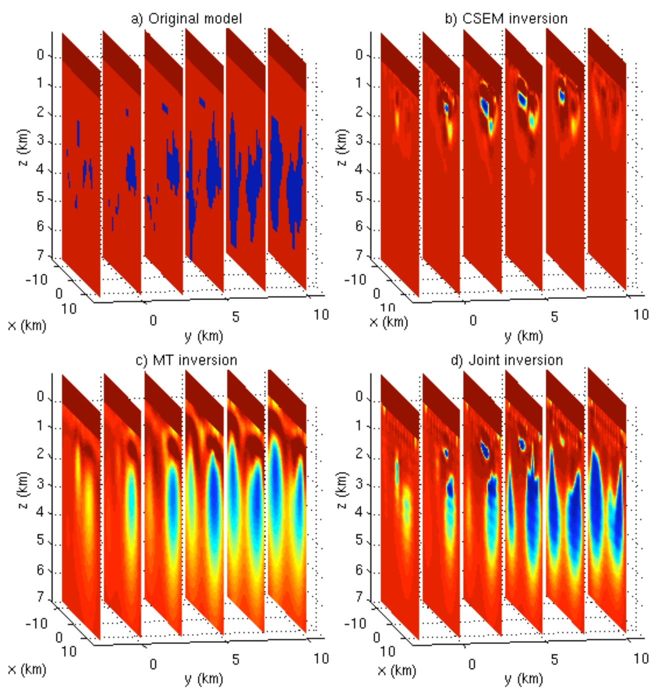

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Geosciences Research Program, Office of Basic Energy Sciences
Gaithersburg, Maryland, March 11-12, 2010

FORWARD

"Geophysics and Subsurface Fluid Flow" is the sixteenth in a series of Geosciences Research Program Symposia dating from 1995. These symposia are topically focused meetings for principal investigators in the program and provide opportunities for our investigators to give presentations on their Office of Basic Energy Sciences' supported research. In addition to the recognition the symposium gives to all of the investigators, we traditionally also recognize one outstanding contribution from a DOE Laboratory Project and one from a University Project. The outstanding contributions are selected by our session chairpersons. We are fortunate to have as guest session co-chairs Prof. Greg Hirth of Brown University, Prof. William Dunne of the University of Tennessee, Dr. Larry Schwartz, Schlumberger/retired and of the Massachusetts Institute of Technology, and Dr. Robert Glass of Sandia National Laboratory. They join our Principal Investigator co-chairs Prof. Akhil Datta Gupta from Texas A & M University, Prof. Russell Detwiler from the University of California at Irvine, Dr. Steve Pride from Lawrence Berkeley National Laboratory, and Prof. Dan Rothman from Massachusetts Institute of Technology. For their efforts on behalf of the investigators I thank them all. We are looking forward to an outstanding series of presentations.

Nicholas B. Woodward
Geosciences Research Program
Office of Basic Energy Sciences
U.S. Department of Energy

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Figure 1: Fluid flow pathways in a shallow soil zone (courtesy of Prof. Dan Rothman, MIT)
Figure 2: Computational inversion for electromagnetic imaging (courtesy of Dr. Greg Newman, LBNL)
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Geophysics and Subsurface Fluid Flow
-Agenda-
Gaithersburg
March 11-12, 2010

Thursday Morning, March 11, 2010

7:30 **Registration/Continental Breakfast**

8:00 **Introductions and Greetings**
Nicholas Woodward, Department of Energy

Session 1: Rock Mechanics and Material Properties
Chairs: Greg Hirth and Akhil Datta-Gupta

8:15 Paul Johnson
Elasticity measurements due to changes in chemistry and temperature probed by nonlinear means

8:40 Bill Klein
A Statistical Mechanic Approach to Damage

9:05 Brian Evans/Yves Bernabe/Wenlu Zhu
Permeability changes in rocks under hydrothermal conditions: creep, brittle deformation and the brittle-ductile transition

9:40 Jay Bass/Dan Farber
Sound velocities and equation of state of water at high pressure and temperature

10:05 **Coffee/refreshments**

10:25 Shenghua Mei/David Kohlstedt/Bill Durham
Rheological properties of Earth's lithosphere: Experimental constraints on low-temperature plasticity of olivine-rich rocks at high pressures

10:50 Jim Berryman
Effective Stress for Fluid Flow in Anisotropic Fractured Rocks: Isotropy to Orthotropy

11:15 Seiji Nakagawa
Compaction-induced seismic anisotropy in fluid-saturated granular media

11:40 Steve Pride
Mesoscale structure, seismic attenuation and granular media

12:05 – 1:30 **Working Lunch -** *Geochemical enhancement of geologic carbon sequestration,* **Energy Frontier Research Center Presentation Lawrence Berkeley National Laboratory - Donald DePaolo -**

Thursday Afternoon, March 11. 2010

Session 2 - Physical Properties and Monitoring

Chairs: Larry Schwartz and Steve Pride

1:35 Roel Snieder
Extracting the static response of the subsurface from dynamic field fluctuations

2:00 Don Vasco
Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide

2:25 Greg Newman
New Advances in Joint Geophysical Imaging

2:50 **Coffee/refreshments**

3:10 Gary Egbert
Inversion of Multi-frequency and Multi-Source Electromagnetic Data

3:35 John Scales
Elastic and electrical properties of rocks at the sub-millimeter scale

4:00 Amos Nur
Computational Rock Physics for Elastic and Flow Properties: The Road Ahead

4:25 Ronaldo Borja
Challenges and advances in large-scale simulations of coupled solid deformation-fluid diffusion problems in geophysics and reservoir geomechanics

4:50 Joel Koplik
Particulate Suspensions in Geological Fractures

5:15 Ruben Juanes
Nonequilibrium physics of multiphase flow in porous media: origin of gravity fingers during infiltration (Early Career Award presentation)

5:40 **Adjourn**

6:30 **Dinner** (On your own)

Friday Morning, March 12, 2010

7:30 **Coffee/Continental Breakfast**

Session 3 – Fluid Flow and Behavior

Chairs: Bob Glass and Russ Detwiler

8:00 Akhil Datta-Gupta
Time-lapse seismic monitoring and performance assessment of CO_2 *sequestration in hydrocarbon reservoirs*

8:25 Art Weglein
Towards a comprehensive response to pressing seismic exploration imaging challenges: Removing multiples and imaging primaries without subsurface information.

8:50 Fredric Gibou
High resolution simulations and experiments for carbon sequestration modeling

9:15 William Gray/Casey Miller
Thermodynamically constrained averaging theory: Recent advances, practical applications, and remaining challenges

9:40 Tony Ladd
The development of an intrinsic heterogeneity during fracture dissolution

10:05 Coffee/refreshments

10:25 Tim Kneafsey
Carbon dioxide-induced, density-driven brine convection: model results and experiments

10:50 David Johnson/Hernan Makse
Dynamic effective mass of granular media

11:15 Martin Appold
Fluid pressure evolution and solitary wave formation in a compacting, hydrocarbon-forming sedimentary basin

11:40 Dan Rothman
Growth of dendritic channel networks incised by groundwater flow

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12:05 – 1:20 **Working Lunch -** Probing the temporal and spatial characteristics of sequestration processes over a cascade of scales **–**
Energy Frontier Research Center Presentation – University of Texas/Sandia National Laboratory – Prof. Sanjay Srinivasan, University of Texas

Friday Afternoon, March 12, 2010

Session 4 – Faults and Fractures

Chairs: Bill Dunne and Dan Rothman

1:20 Jim Boles/Grant Garven
The Geohydrology of Faults in Southern California

1:45 Russell Detwiler
Permeability alteration due to mineral dissolution in partially saturated fractures

2:10 Jose Andrade
Multi-scale calculation of permeability inside compaction bands: from the field to the lab

2:35 Teng-fong Wong
Carbonate compaction and cataclastic pore collapse

3:00 **Coffee/refreshments**

3:20 Libby Ritz
On the mechanical behavior of curved faults: implications for fluid flow and damage zones

3:45 Peter Eichhubl/Steve Laubach
Fracture opening histories, strain and strain rates: implications for fluid flow, time-dependent fracture network attributes, and geophysical response

4:10 Tom Dewers
Pore-scale transport and mechanical properties of mudrocks: From imaging to experiments and modeling

4:35 Laura Pyrak-Nolte
Particle Swarms in Fractures

5:00 Nick Woodward
Concluding remarks

Working Dinner 6-8 PM

Elasticity measurements due to changes in chemistry and temperature probed by nonlinear means

Paul Johnson, Los Alamos National Laboratory
Collaborators: Pierre-Yves LeBas (Post Doc Los Alamos), Bill Carey (Los Alamos), Tim Darling (UNR) and Robert Guyer (Los Alamos/UNR)

Elastic nonlinearity is an extremely sensitive probe of material mechanical damage, at scales ranging from nano to macro. Other fields modulate the nonlinear response, including temperature, pressure, humidity and potentially chemistry. Currently, we are studying the effects of humidity and C02 on the elastic response. Our long-term goal is to apply our knowledge of elastic nonlinear behavior to reservoirs, and at the moment, or focus is reservoirs containing C02.

In our work applying supercritical C02, and $C02+H_20$ to carbonate rock samples, we measure the mass density of a sample, attach piezotransduers to the sample and then place a sample in a pressure vessel, begin making automated resonance measurements with wave amplitude, and then expose the sample to supercritical $C02+H_20$. The elastic behavior, temperature and pressure are all tracked during an experiment. The automated data collection apparatus automatically provides the resonance frequency proportional to the wavespeed and a measure of the nonlinear parameter α from the resonant peak shift. Remarkably, the nonlinear parameters decrease dramatically after exposure while the resonance frequency proportional to Young's modulus, and the Q remain essentially unchanged. The mass density changes from 2.38 to 2.3 gm/cm^3. Other carbonate rich rocks show similar behaviors. We believe that there is a redistribution of the carbonate phase in addition to a carbonate loss. The precipitation of the carbonate takes place in locations that diminish the nonlinear response, and that may heal the material (closing fractures for instance).

	$K\alpha$	Resonant frequency	Linear Q	Nonlinear Q
Before	3200	16290 Hz	97	110
After	652	16290 Hz	100	30

Table 1. Observations on carbonate-rich sandstone (Pietra Arenaria, Trento, Italy), before and after exposure to supercritical $C02+H_20$ The α term is multiplied by a constant K proportional to the detected voltage (uncalibrated piezoceramics were used for detection). $K\alpha$ decreased by as much as five times, nonlinear Q decreased by three times, while the linear resonance and Q remained approximately unchanged.

In our work studying the effects of water on nonlinear behavior we have had a significant breakthrough. In the first nonlinear experiments ever conducted under essentially lunar dry conditions, we find that the elastic nonlinearity remains intense. These experiments are very difficult to conduct due to the high temperatures involved in drying samples (~400 degrees C under hard vacuum). This result proves beyond a doubt what we believed: the nonlinear response is modulated by humidity but humidity is not the responsible mechanism. It is material mechanical damage, as noted above.

A Statistical Mechanical Approach to Damage

W. Klein
Department of Physics and College of Engineering
Boston University, Boston, MA 02215

Damage, the appearance of defects in materials, has an important affect on various properties of the materials. In addition to causing catastrophic failure through processes such as fracture it also has an affect on other processes such as nucleation in magnetic systems and crystalline solids. In order to understand these effects we have investigated a series of model on which we have created damage.

First we adapt a model introduced to study sand piles. The model involves a lattice where each site has a failure threshold as well as a residual stress. The lattice is initiated by randomly distributing stress to each lattice site. If the stress on a site exceeds the failure threshold the stress is lowered to the residual value and the difference between the stress at failure and the residual stress is multiplied by a dissipation coefficient. That fraction is thrown away and the remainder is distributed to the neighboring sites. We introduce damage by requiring sites to die after a specified number of failures. Once a site dies we can run in two modes. In one we allow stress to be transferred to the dead sites which then becomes lost to the system. In the other mode no stress is transferred to the dead sites but the available stress is shared by the sites that are alive in the stress transfer region.

The parameters of model can be adjusted to study the global load sharing fiber bundle model in one extreme limit and chip board fracture experiments in another. We find that the catastrophic failure mode depends strongly on the range of stress transfer range as well as the mode in which we are running the model. In the long range stress transfer limit the catastrophic failure mechanism resembles the nucleation of a fracture for all values of the parameters. In the short range stress transfer limit the failure mechanism in the fiber bundle limit is a continuous process as opposed to nucleation. In the chip board limit short range stress transfer generates a fractal crack that causes catastrophic failure but the crack does not appear to nucleate.

We have also begun to study the effect of damage in the nucleation process in simple models such as Ising models with vacancies. I will also report on our preliminary results on the affect of damage in nucleation.

Permeability changes in rocks under hydrothermal conditions: creep, brittle deformation and the brittle-ductile transition

Brian Evans[1], Wenlu Zhu[2] and Yves Bernabé[1]
[1]Dept. of Earth, Atmospheric and Planetary Sci., Massachusetts Institute of Technology
[2]Dept. of Geology, University of Maryland College Park

With increasing pressure and temperature, rocks undergo a transition in failure mode from localized brittle fracture to non-localized plastic flow. In the brittle regime, localized fracturing is generally accompanied by dilatancy and permeability enhancement, but non-localized cataclastic, shear-enhanced flow could induce significant reduction of void space and permeability. We formulated a cumulative damage model for quantifying the reduction of permeability in siliclastic sandstones during shear-enhanced cataclastic compaction. Model predictions agreed well with the experimental data, and we concluded that the cumulative damage model did capture the key micromechanical processes operating during cataclastic flow. Similar deformation behavior was observed experimentally in Solnhofen limestone. Within a narrow window of confining pressure and temperature, the deformation of Solnhofen limestone (average grain size of 5 μm and initial porosity of 3-5%) showed transitions from brittle fracture to compactive, shear-enhanced flow, and then from dilatant flow to plastic pore collapse. In the ductile regime, we completed a suite of isostatic and triaxial deformation experiments on aggregates of quartz and calcite at temperatures of 300-800 K, confining pressures up to 300 MPa and various pore pressures. When subjected to triaxial deformation, the aggregates exhibited shear-enhanced compaction, but surprisingly the permeability of these rocks deforming under triaxial loads was not as sensitive to porosity changes as that for the same material during isostatic compaction. Furthermore, the percolation threshold for the triaxially deformed material was lower than that during isostatic compaction. Microstructural analysis show that unlike quartz sandstones where intensive Hertzian fracture leads to grain crushing and pore collapse, porosity reduction in carbonate limestone during shear-enhanced compaction is associated with intensive intragranular microcracking along e-twin lamella. Stress-induced changes in permeability and its anisotropy in carbonate rocks can be significantly different from siliciclastic rocks owing to the interplay between microcracking, crystal plasticity and pore collapse.

Other topics such as the effective pressure law for permeability, micro-modeling of pressure solution creep, network modeling of the effect of pore size heterogeneity and pore connectivity on permeability and the propagation of Biot slow waves, were tackled in our project but will not be included in this presentation.

Sound velocities and equation of state of H_2O at high pressure and temperature

Jay D. Bass, Department of Geology, University of Illinois at Urbana-Champaign and
Daniel Farber, Lawrence Livermore National Laboratory

The vast majority of studies of aqueous geochemistry relevant to terrestrial problems of fluid-rock interaction have been conducted at ≤3 kbar, and the widely used Helgeson-Kirkham-Flowers equation of state for aqueous species is applicable only at ≤5 kbar. However, these limits are unfortunate because there are many deeper environments in which fluid flow and reaction plays a central role. New experimental techniques (based primarily on 3rd generation sources such as the APS and SNS) now make it possible to experimentally investigate the properties of aqueous solutions and, thus, homogeneous and heterogeneous equilibria involving aqueous species and minerals, over a much broader range of pressure and temperature. While thermodynamic data are available for most rock-forming minerals there is a dearth of data available for complex aqueous fluids. While the diamond anvil cell (DAC) has rendered fluids amenable to *in situ* synchrotron, neutron and vibrational spectroscopic measurements, in many ways the sample environment and calibration of high temperature, high pressure measurements in the DAC remain in their infancy. Moreover the amorphous nature of fluids typically requires long collection times and the extreme reactivity of supercritical fluids poses severe experimental constraints on these types of DAC experiments. In order to address these difficulties, we have designed and fabricated a new generation of high temperature DAC capable of operating for extended periods of time (days to weeks) at temperatures to 1100K. In contrast to previous efforts and to put DAC measurements on a firm thermodynamic footing, we have put extensive efforts into calibrating the temperature environment of the sample chambers in our DAC. To date we have measured high temperature sound speeds in H_2O, CO_2 and dilute NaCl-H_2O solutions. Using the newly installed Brillouin spectrometer at the GESCARS beamline at the APS, we have collected data on water to pressures of XX GPa and temperatures of XX K. In general we find that while temperature has a strong effect on the stability of phases in this system, pressure has the major effect on the sound velocities of fluids

Rheological properties of Earth's lithosphere: Experimental constraints on low-temperature plasticity of olivine-rich rocks at high pressures

Shenghua Mei (U. Minn.), D.L. Kohlstedt (U. Minn.), W.B. Durham (MIT)

To provide a better understanding of rheological properties of mantle rocks under lithospheric conditions, we carried out a series of experiments on the creep behavior of polycrystalline olivine at high pressures (~4 to 9 GPa), relatively low temperatures ($673 \le T \le 1273$ K), and anhydrous conditions using a deformation-DIA (D-DIA). Differential stress and sample displacement were monitored *in-situ* using synchrotron x-ray diffraction and radiography, respectively. Experimental results were fit to the low-temperature plasticity flow law $\dot{\varepsilon} = A'_P \frac{\sigma^{11/4}}{T^{1/2}} \exp\left[-\frac{E_k(0)}{RT}\left(1-\sqrt{\frac{\sigma}{\sigma_P}}\right)\right]$. Based on this analysis, the low-temperature plasticity of olivine deformed under anhydrous conditions is well constrained by our data with a Peierls stress of $\sigma_P = 6.2 \pm 0.2$ GPa, a zero-stress activation energy of $E_k(0) = 290 \pm 60$ kJ mol^{-1}, and $A'_P = 2.7 \times 10^{-8}$ s^{-1} MPa$^{-11/4}$ K$^{1/2}$. Compared with published results for high-temperature creep of olivine, a transition from low-temperature plasticity to high-temperature creep occurs at ~1300 K for a strain rate of ~10^{-5} s^{-1}.

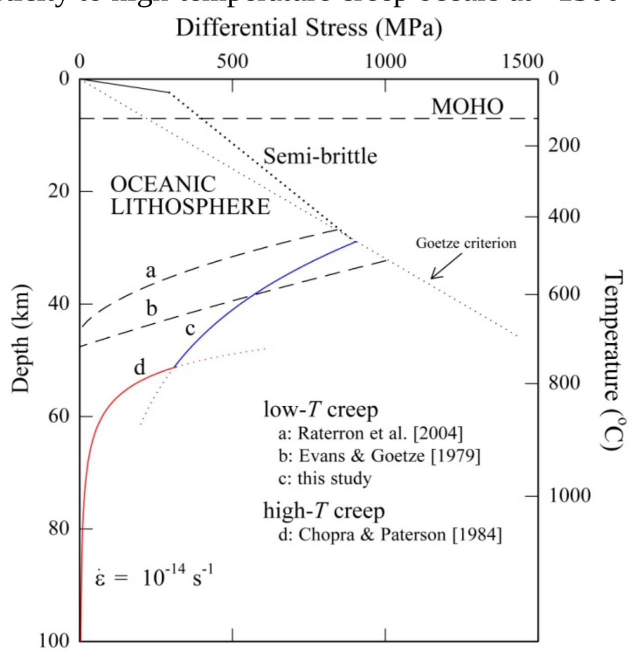

Figure 1. Strength as a function of depth for the oceanic lithosphere deforming at 10^{-14} s^{-1}; modified from *Kohlstedt and Mackwell* [2009]. Oceanic geotherm used in this plot is from *Turcotte and Schubert* [2002, p. 184] with $T_{surface} = 273$ K.

To illustrate the application of our flow law describing low-temperature deformation of olivine-rich rocks under anhydrous conditions, combined with other relevant studies, a strength envelope for the lithospheric mantle is presented in Figure 1. For comparison, the low-temperature laws from *Evans and Goetze* [1979] and *Raterron et al.* [2004] are included. As shown in Figure 1, extrapolation of our flow law from a laboratory strain rate 3×10^{-5} s^{-1} to a geological strain rate of 1×10^{-14} s^{-1} yields a strength for the lithospheric mantle at 873 K, the cut-off temperature for earthquakes in the mantle, of ~500 MPa.

The low-temperature, high-stress flow law for olivine from this study provides a solid basis for modeling tectonic processes occurring within Earth's lithosphere. Since understanding geophysical properties, processes, and rate laws is critical to managing improved production of Earth's energy resources and safe disposal of energy related waste, the results of this study are directly relevant to DOE's geosciences program.

Effective Stress for Fluid Flow in Anisotropic Fractured Rocks: Isotropy to Orthotropy

James G. Berryman
Earth Sciences Division
Lawrence Berkeley National Laboratory

General effective-stress rules have been derived previously for physical properties of isotropic porous rocks, including fluid-flow and transport properties of inhomogeneous porous rocks. Elastic properties of granular media under stress can be both anisotropic and highly sensitive to small changes in the confining stress. Fractured media are similarly sensitive to the confining stress, and to the orientations of the fractures themselves. The fracture-influence parameters that determine the increase in rock compliance, or equivalently the reduction in rock stiffness, due to the presence of individual fractures can be shown to depend on an effective-stress coefficient having the form (1-B), where B is Skempton's second coefficient from soil mechanics. In principle, Skempton's coefficient B can be measured directly, or it can be computed from other known quantities, including the system drained bulk modulus, pore-fluid bulk modulus, porosity, and an average grain modulus. Recent work on effective stress for both granular and fractured porous media, and implications for the transport of fluids will also be discussed.

J. G. Berryman, Effective stress for transport properties of inhomogeneous porous rock, J. Geophys. Res. **97**, 17409-17424 (1992).
S. R. Pride and J. G. Berryman, Goddard rattler-jamming mechanism for quantifying pressure dependence of elastic moduli of grain packs, Acta Mechanica **205**, 185-196 (2009).
J. G. Berryman and S. Nakagawa, Inverse problem in anisotropic poroelasticity: Drained constants from undrained ultrasound measurements, J. Acoust. Soc. Am. **127**, 720-729 (2010).
J. G. Berryman, Poroelastic measurement schemes resulting in complete data sets for granular and other anisotropic porous media, Int. J. Engng. Sci., published online November 5, 2009.

Compaction-induced seismic anisotropy in fluid-saturated granular media

Seiji Nakagawa
Earth Sciences Division
Lawrence Berkeley National Laboratory

The primary objective of this research is to understand how the earth's diagenetic processes including mechanical and chemical compaction affect the seismic properties—anisotropy in particular—of granular sediments. To this end, a series of laboratory experiments have been conducted. The process of sediment compaction is simulated and the resulting seismic properties examined using a specially designed oedometric compaction cell called *Phased Array Compaction Cell*. With this setup, we can determine the five elastic constants of transversely isotropic media from seismic measurements. Also, the effect of sediment grain cementation via mineral precipitation on both seismic velocity and attenuation is examined using a variant of acoustic resonant bar technique called *Split Hopkinson Resonant Bar Test*.

In the first series of experiments, we collected seismic velocity data for granular media with different grain geometry (glass beads and sands). The velocity data were processed to obtain the five elastic constants as a function of compaction stress and porosity. One unique aspect of this measurement is that the "C_{13} component" of the elasticity matrix—which is difficult to measure using conventional techniques during sediment compaction—can be determined from a series of plane waves generated using a phased-array source in the compaction cell. The results indicated that this component stays more or less unchanged for different grain types even when other components of the elasticity matrix can change dramatically. Also, it was found that S-wave anisotropy is generally the strongest at the beginning of the compaction, in contrast to P waves. This compaction cell was also used for examining the effect of pressure dissolution on sediment seismic properties. We simulated the process using halite (rock salt) crystals as analogue sand, which allows the experiment to be conducted within a reasonable time period (several days to weeks), compared to quartz, feldspar, or calcite. During one month of compaction under constant stress and temperature, the grain pack reduced its porosity by 7 to 8 %. This resulted in large linear increases in the elastic moduli and changes in anisotropy, as a function of porosity.

Because most of these experiments were conducted under fluid-saturated condition, we developed explicit formulae for extracting dry moduli of the granular packs from the "wet" moduli, based upon the anisotropic Gassmann's relationship [Collaboration with Jim Berryman, LBNL]. Previously, a relationship that provides saturated moduli from dry, anisotropic moduli was known, but the reverse relationship was not.

Unlike mechanical and pressure-dissolution-induced compaction, another diagnetic process of mineral precipitation and sediment grain cementation generally results in isotropic property changes. Precipitation of minerals can affect both seismic velocity and intrinsic attenuation, by altering the interaction between pore fluids and the solid skeleton. In our preliminary experiments, we used the salt precipitation of halite-saturated brine when mixed with ethanol, producing halite microcrystals within the pores of a small sand pack. Seismic velocities and attenuation of the core was monitored during the salt precipitation via extension and torsion mode vibrations of the sample. The results showed large increases in the P-wave attenuation but only small S-wave attenuation. This is different from the result from our other experiments on methane gas hydrate formation in similar sand packs [Collaboration with Tim Kneafsey, LBNL]: During hydrate crystal formation, both P and S wave attenuation showed large increases, along with increases in velocities. The comparison indicates that the morphology of cement minerals forming within sediment pore space can result in very different seismic signatures.

The Frequency and Stress Dependence of Seismic Properties in Porous and Granular Media

Steven R. Pride
Earth Sciences Division
Lawrence Berkeley National Laboratory

This BES-funded research has been looking into the relation between mesoscopic-scale (or "mesoscale") heterogeneity and the seismic properties of porous rocks. Mesoscales are those larger than grain sizes but smaller than seismic wavelengths over which a porous-continuum description is appropriate. When a seismic wave deforms a porous material having mesoscale heterogeneity in the elastic properties, those zones where the rock frame is stiff respond with a smaller fluid pressure than those zones where the frame is more compliant. The pressure gradients so created equilibrate by viscous fluid flow thus causing energy to be lost. This attenuation (as measured by inverse Q), is at a maximum when in a single wave period, the various mesoscale patches just have time to equilibrate the fluid-pressure gradients. If there is a range of patch sizes present, a broad spectrum can be attained for $Q^{-1}(f)$ where f is frequency. We have been analyzing the attenuation and dispersion associated with different sources of mesoscale heterogeneity using both numerical (finite-difference) modeling and analytical arguments. One question is how much mesoscale heterogeneity is actually present in rocks? To address this, we have built a micro-indentation device that maps the poroelastic moduli over rock surfaces at a resolution down to several grain sizes. Several such maps will be presented for real rocks. Another topic addresses the anisotropic nature of attenuation in porous materials possessing random mesoscale structure characterized by different correlation lengths in the three directions. We demonstrate that a power-law relation holds between peak attenuation and the aspect ratio of the structure (i.e., the ratio of the correlation lengths). We also demonstrate how immiscible fluid structures in porous materials generate attenuation and dispersion. Finally, the stress dependence of the elastic properties of granular media is addressed. By allowing for new grain contacts to develop with increasing strain, we are able to explain the discrepancy that has existed between the measured pressure dependence of the elastic moduli and that predicted by classical Hertzian theory of grain-to-grain contacts. A fit of our new theory to actual lab data is presented.

Geochemical enhancement of geologic carbon sequestration

Dr. Donald DePaolo
Lawrence Berkeley National Laboratory Energy Frontier Research Center

Geologic sequestration of CO2 may be critical for reducing net emissions to the atmosphere over the next century. Current models suggest that CO2 injected into saline formations will be physically trapped as a separate supercritical fluid phase; only after hundreds of years will a significant fraction either dissolve in brine or precipitate as carbonate minerals. Interesting questions for geochemists are whether solution and mineral trapping could be enhanced, or lithologic caprocks could be made self-sealing. Such engineering requires a detailed understanding of the pore scale and smaller scale processes that ultimately control chemical interactions between CO2, brine and minerals. This challenge is being addressed as part of a DOE-sponsored Energy Frontier Research Center. Current research is aimed at manipulating carbonate mineral growth, understanding equilibrium and transport processes in nano-confined pore spaces, relating reactions and fluid flow, making reactive nanoparticles, and developing geochemical tracers.

Extracting the static response of the subsurface from dynamic field fluctuations

Roel Snieder[1], Evert Slob[1,2], André Revil[1], Allan Haas[1]
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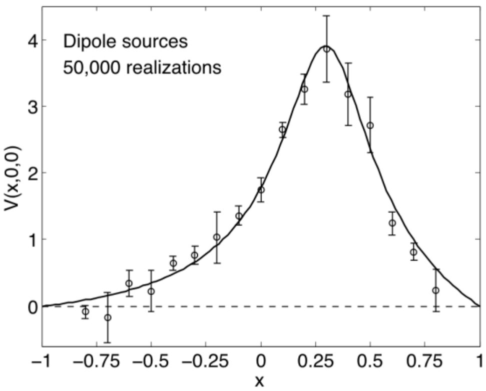
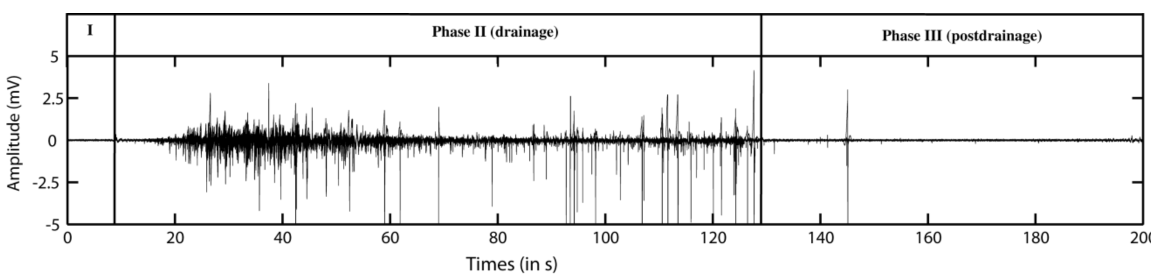
(2) Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, Netherlands



The extraction of the impulse response from field fluctuations has recently received much interest in seismology and acoustics. The central idea is that correlations of random field fluctuations recorded at different locations give the waves that propagate between these receivers (Curtis et al, 2006). We have extended this theory to static fields (Snieder et al, 2010), and show that the theory is applicable to electrostatics and DC resistivity (Slob et al., 2010). This means that one can obtain the Green's function of potential fields from the correlation of quasi-static field fluctuations. A numerical example is shown in the figure on the left that gives the electrostatic response within a conducting sphere. The solid line gives the potential on the x-axis due to a monopole placed off the x-axis, while the circles and error bars give the potential obtained form the cross-correlation of field fluctuations generated by random dipole sources within the sphere. The potential estimated from the quasi-static field fluctuations agrees well with the true potential.

The figure below shows laboratory measurements of electric field fluctuations recorded in a porous medium that is being drained during phase II of the experiment (Haas and Revil, 2009). The field fluctuations have been high-pass filtered to highlight the transients. These field fluctuations are thought to be caused by bursts of the meniscus in pores, these are called *Haines jumps*. Because of charge conservation, such temporal changes in the electric potential must to leading order be caused by electrical dipoles. The possibility to extract static fields from random dynamic field fluctuations opens, in principle, the possibility for continuous monitoring based on static fields obtained from passive field fluctuations. The laboratory measurements shown below that such field fluctuations are generated by flow in porous media.



Curtis, A., P. Gerstoft, H. Sato, R. Snieder and K. Wapenaar, K., Seismic interferometry -- turning noise into signal, The Leading Edge, **25**, 1082-1092, 2006.
Haas, A. and A. Revil, Electrical burst signature of pore-scale displacements, Water Resources Res., **45**, W10202, 2009.
Slob, E., R. Snieder and A. Revil, Retrieving electric resistivity data from self-potential measurements by cross-correlation, Geophys. Res. Lett., doi:10.1029/2009GL042247, 2010.
Snieder, R., E. Slob and K. Wapenaar, Lagrangian Green's function extraction, with applications to potential fields, diffusion, and acoustic waves, New J. Phys., Submitted, 2010.

Satellite-based measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide

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The geological storage of carbon dioxide (CO_2) is likely to be an important tool for preventing greenhouse gases, particularly those emitted from power plants, from entering the atmosphere. However, in order for the storage to be safe and effective the CO_2 must remain at depth. Past experience suggests that the migration of carbon dioxide within the Earth can be complicated and can differ from the movement of injected water or the flow of hydrocarbons. Monitoring will be a key component in determining our success in containing this greenhouse gas. Satellite-based techniques can be more cost effective, more frequent, and less invasive then other geophysical monitoring techniques such as seismic or electromagnetic methods. Interferometric Synthetic Aperture Radar (InSAR), gathered over the In Salah CO_2 storage project in Algeria, provides an early indication that satellite-based geodetic methods can be effective in monitoring subsurface fluid flow related to geological storage. The injected carbon dioxide produces a measurable signal of approximately 5 mm/year of surface deformation induced by the pressure and volume changes at depth. Using inverse methods we are able to infer flow within the reservoir layer and within a hypothesized fracture/fault zone. We find that the fluid pressure changes only occur in the vicinity of the reservoir layer. However, pressure changes associated with the injection of CO_2 have propagated several kilometres within the reservoir, following the suspected fault. One finding from our modelling is that it is crucial to use the best available elastic Earth model when solving the inverse problem. In particular, because the reservoir lies in a low velocity zone, using a uniform elastic model, rather than a more accurate layered model, produces an error of more than 50% in the depth estimate.

New Advances in Joint Geophysical Imaging

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The research design and approach discussed provides a roadmap to tackle the hardest part of the 3D joint geophysical inverse problem - imaging problems involving different geophysical attributes and data types, where there is no established rock physics model to couple the different attributes and data; i.e. electromagnetic (EM), gravity and seismic across different scale lengths. We consider the recent developments for imaging seismic data in the Laplace-Fourier domain a critical step forward in solving this problem. It provides a means to produce a joint image from EM, gravity and seismic data in a self consistent manner using a common structure constraint. Because the transformed seismic data now satisfy a diffusion problem, large scale optimization strategies that have been very successful for EM and gravity can be applied. Hence we can exploit our experience and expertise in such 3D imaging problems to the joint inversion of EM, gravity and seismic data, including our massively parallel solution techniques. Moreover the velocity image obtained from such an imaging process is an excellent choice of a starting model for inversion or migration of the full unfiltered seismic trace. It improves the likelihood of success of full waveform imaging and migration of the seismic trace at its greatest resolution and detail. Under these considerations our approach therefore opens the possibility to image across multiple scale lengths, incorporating different types of geophysical data and attributes in the process.

Inversion of multi-frequency and multi-source electromagnetic induction data

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The goal of our BES project is to make 3D inversion of electromagnetic (EM) geophysical data practical and available to a wide range of users. We consider two aspects of our efforts in this direction. First, we have developed a general abstract formulation of gradient-based search methods for solving regularized EM inverse problems, taking particular account of the multiple transmitters (frequencies, source configurations) commonly encountered. Based on this formulation, we have developed a modular system of computer codes, which can be readily adapted to a wide range of natural and controlled source EM methods. After initial tests on 2D and 3D MT the modular system has been used to quickly develop inversions for other problems, including 3D cross-well (controlled source) EM, and prototype testing for novel observational strategies being developed by industrial collaborators. Current efforts include developing support for parallelization, and for joint inversion of multiple data types.

The modular system also provides a test bed for developing and comparing inversion algorithms, a second focus of our effort. Most recently developed codes for regularized 3D EM inversion have been based on direct minimization of the non-quadratic penalty functional using conjugate gradients (NLCG) or some sort of quasi-Newton approach. A major focus of our research has been on developing practical Gauss-Newton methods. We find that hybrid schemes, based on solving the linear sub-problem through Lancoz bi-diagonalization of the Jacobian offer many advantages. In particular these approaches make practical "Occam" schemes, where the optimal regularization parameter is determined implicitly as the inversion proceeds, and readily allow for linearized resolution and error analysis. The hybrid schemes appear to require fewer forward model solutions in most cases (by roughly a factor of 2), and they suggest even more efficient (factor of 4 or better) approximate inversion schemes.

Electrical and elastic properties of rocks at the sub-millimeter scale

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Using novel quasi-optical millimeter wave EM techniques we have developed an EM analog of near-field optical scanning. With this we can measure the complex permittivity or rocks at a resolution of better than 100 microns. On the other hand, for many years we have used scanning laser vibrometery to measure time-resolved high-spatial-resolution ultrasonic wavefields produced in rocks by pulsed-IR laser excitation. We are currently extending the latter system to a kind of near-field ultrasonic probe that will give us mechanical information at the same or higher resolution than we currently achieve via millimeter waves. At the same time, we are pursuing theoretical analysis of the relation between electrical and elastic properties in granular media at the mesoscale.

Computational Rock Physics for Elastic and Flow Properties: The Road Ahead

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Francis Birch pioneered the field of rock physics – relating mineralogy to seismic velocities in the earth - in the1940's. However it is only recently that the need for rock physics information has taken off exponentially for petroleum exploration and production as well as geological process simulation in general. However physical measurements of rock properties are slow and cumbersome, and often impossible to do or do well. They are therefore very sparse: what is needed are properties not for 10's of samples but 1000's or 10 of thousands samples.

One way to obtain truly massive data sets is through the emerging digital rock physics methodology. This methodology consists of very high-resolution 3D and very fast (minutes) imaging of the pore spaces of rock samples. The images are used to (a) accurately compute bulk properties very fast (minutes) and (b) simulate pore scale processes also very fast (tens of minutes).

Digital rock physics will transform rock physics: It will replace idealized pore space models. It will enable the use of the actual 3D pore space and rock model for all physical properties, it will enable the use of cuttings as a major source of rock properties, provide information for up scaling from pore to core to log and beyond.

Finally it will also enable computational experiments (analogous to lab experiments) to simulate a broad spectrum of geological processes involving reactive fluid flow in porous solids, including their transfer under stress and pore pressure gradients i.e., crystallization from melt, metamorphism, faulting and fault healing, creep in rocks (e.g. power law creep), formation of ore deposits, Kerogen maturation, and CO_2 sequestration.

Challenges and advances in large-scale simulations of coupled solid deformation-fluid diffusion problems in geophysics and reservoir geomechanics

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Joshua A. White, Lawrence Livermore National Laboratory

In order to accurately model the behavior of fluid-saturated porous media, it is often necessary to account for the strong coupling between the solid skeleton and the pore fluid. This coupling is of particular interest when studying fault zone processes in geophysics, and is central to many open questions about fault behavior. Increases in pore pressure may tend to weaken faults by reducing the effective normal stress and trigger seismic activity. Dilatancy or compaction within the fault zone plays a crucial role in the prediction of the increase or decrease of fluid pressure, as well as the degree to which fluid exchange is allowed to occur between the fault and its surroundings. Similar applications may be mentioned in reservoir geomechanics. Subsurface rock formations can compact when interstitial fluids are removed from the mineral skeleton, causing the pore fluid pressures to decrease and the effective stress in the mineral skeleton to increase. Pore compaction manifests itself in the form of ground subsidence that can be as large as 30 feet in the case of the San Joaquin Valley groundwater withdrawal, 29 feet in the Wilmington oil fields in southern California, and at least 13 feet in Ekofisk in the North Sea. In an oil field, pore compaction and subsidence can cover an area as large as several thousand feet in width, length, and depth, and can severely damage oil wells and induce collapse of well bores. Large-scale problems like these require high-fidelity simulations of the coupled solid deformation-fluid diffusion processes in both space and time.

In this presentation we will review the conservation laws governing the hydro-mechanical processes relevant to the analysis of coupled solid deformation-fluid flow problems in geophysics and reservoir geomechanics. For the numerical implementation of the conservation laws, we employ a mixed finite element formulation utilizing stabilized low-order finite elements in 2D and 3D. The underlying rationale for choosing a low-order interpolation is to accommodate spatially varying material and geometric conditions. However, low-order finite elements, particularly those employing equal-order interpolation of displacement and pressure fields, have a propensity to exhibit pressure oscillation in the limit of full saturation and undrained loading. To circumvent the unstable behavior of these low-order mixed finite elements, we employ a stabilized discretization capable of suppressing the pore pressure oscillation in the limit of undrained deformation. The presentation will also address some of the more pressing challenges in high-fidelity simulation of coupled solid deformation-fluid diffusion problems, including realistic descriptions of the constitutive laws and boundary conditions, capture of the strain localization phenomena, and the solution of very large algebraic systems of equations specific to the coupled system.

Particulate Transport and Sedimentation in Fracture Systems

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Levich Institute – City College of New York

Geological fracture networks can provide high-throughput pathways for extracting water and hydrocarbons from subsurface reservoirs, but reservoir fluids are usually "dirty," containing solids and contaminants of various types. This project addresses the transport and gravitational sedimentation of suspensions of larger, non-colloidal particles in geological fracture systems. In particular, we take account of the realistic roughness of naturally-fractured rock in terms of self-affine fractal surface geometry. We are now carrying out numerical simulations of suspension flow in fracture joints using lattice Boltzmann techniques, which will subsequently be extended to fracture junctions. In this talk we focus on

(1) Effects of sedimenting onto a fractal rather than smooth surface on fluid and solid transport, and in particular the shape of sediment surface, and

(2) Jamming phenomena, due to high concentrations or obstructions, and in particular effects of random fluctuations in driving pressure.

Nonequilibrium physics of multiphase flow through porous media: Origin of gravity fingering during infiltration

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The simultaneous flow of several fluid phases through a porous medium is a pervasive phenomenon in nature. It occurs, for instance, during infiltration of water into soil, and during the formation of methane hydrates in ocean sediments and permafrost. It is also central to many energy technologies, such as production of oil and gas reservoirs, and CO2 injection into geologic formations. Yet—and unlike flows of a single fluid—our ability to model multiphase flow at the macroscopic scale is still in a stage of infancy.

In this talk, I will present a new mathematical framework to model multiphase flows. The new theory incorporates one basic feature--the system is out of thermodynamic equilibrium. I will present the application of the new theory to infiltration of water into soil, and address a long-standing question in soil physics: why does the infiltration front lead to preferential flow paths, in the form of gravity fingers? This result directly impacts the prediction of travel times of contaminants through the vadose zone, the recharge rate of shallow aquifers, and has implications on the soil susceptibility to desertification.

Time Lapse Seismic Monitoring of CO_2 Sequestration in Hydrocarbon Reservoirs: Characterizing Channelized Reservoirs Using Level Sets and MCMC

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The goal of this project is to assess the feasibility of time-lapse seismic monitoring of CO2 sequestration in hydrocarbon reservoirs using coupled fluid flow, geochemical and seismic modeling. Concurrently we want to develop a formalism for the assimilation of static and dynamic data sources in the reservoir for improved characterization and quantification of uncertainty in performance predictions. The sweep efficiency of the injected CO2 will largely be governed by the competition between the viscous and gravitational forces which in turn are controlled by the horizontal and vertical permeability distribution. The permeability distribution generated based on the static data such as cores, well logs and 3-D seismic must be updated to reconcile with the dynamic response of the reservoir such as pressure, flow rate, fractional flow and the 4-D seismic data, for example time-lapse saturation and pressure. This typically requires calibration via inverse modeling.

We present a novel method for model calibration and uncertainty quantification for channelized reservoirs using reversible jump Markov Chain Monte Carlo (MCMC) methods. Our approach is capable of reproducing completely general channel shapes and geometries. The channelized permeability field is described either by explicit representation of the channel boundaries or by re-parameterization using low-frequency based transforms (for example, the discrete cosine transforms). The parameters representing the channel structure are either the channel boundaries represented by level sets or the transform coefficients in the truncated frequency domain. The parameter space is searched using a reversible jump MCMC, where the dimension of the parameter space is assumed to be unknown. This flexibility in the parameter dimension allows an efficient search of the uncertainty space. To speed up the computation and improve the acceptance rate of the reversible jump MCMC algorithm, we employ two-stage methods where coarse-scale simulations are used to screen out the undesired proposals. We demonstrate the effectiveness of the reversible jump MCMC algorithm using both 2D and 3D examples involving CO2 injection.

Towards a comprehensive response to pressing E&P challenges: Removing multiples and depth imaging primaries without subsurface information

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The US Dept. of the Interior, Mineral Management Service, reported the drill success rate in 2007, in subsalt plays, as 8% in the deep water GOM. The success rate dropped from 20% to 8% from 2000 to 2007. At 150 million dollars per exploration drill, that comes to over 1 billion dollars per success. And that is not sustainable. Seismic E&P challenges derive from the violation of assumptions or prerequisites behind seismic processing methods.

We can classify three types of assumptions: (1) the required data, e.g., aperture, azimuth, sampling, completeness/fidelity and type of data collected and/or extrapolated/interpolated, (2) adequate compute capability and resources, and (3) innate algorithmic assumptions or limitations. Innate algorithmic limitations are not addressable by improved acquisition, azimuth or compute power.

A comprehensive and effective response to seismic E&P challenges must begin with a frank and forthright understanding and recognition of all three very different types of assumptions behind seismic processing breakdown, and dry hole drilling. To address each of these three distinct factors behind seismic breakdown requires a very different type of response. There is a serious danger of defining the problem only in terms of the issues that we know how to address, and hence typically confined to issues concerning data acquisition and compute power. That can be a useful strategy, but on its own does not represent a comprehensive and fully effective response or solution. A comprehensive approach must address all three significant factors behind failure. We recommend starting with the problem that needs to be solved, rather than the problem that we know how to solve. Among innate algorithmic challenges in seismic imaging (frequently occurring beneath a complex overburden, e.g., subsalt, sub-basalt, sub-karsted sediments and/or at or beneath a complex boundary) is the inability to provide either an adequate velocity model above the target, and/or to be able to adequately back-propagate waves and image through a perfectly known velocity model, e.g., a velocity model with both rapid lateral variation and a wide range of dip angles.

In response, we can choose one of two approaches :(1) to improve the prerequisite satisfaction required of current seismic methods or (2) to develop fundamentally new imaging methods that avoid the assumptions that are behind current seismic capability. Both approaches are reasonable, and we recommend and we assume one or the other of these two attitudes : (1) better satisfy the requirements, or (2) completely avoid the need for the requirements, as our response for different assumptions and issues, and under different circumstances and links in the processing chain. Two examples: (1) We need to seek to satisfy (and cannot avoid) data collection and data extrapolation/interpolation demands of all wave theoretic processing, while (2) the need for subsurface information to achieve multiple removal and depth imaging are, in principle, avoidable. The inverse scattering series (ISS) has the unique ability to achieve all processing goals, directly, and in precisely the same manner that free surface multiples are removed, i.e., without subsurface information. The ISS is the only methodology that communicates that message. Among processing goals are: (1) free surface multiple removal, (2) internal multiple removal, (3) Q compensation without Q, (4) depth imaging without a velocity model, and (5) direct non-linear AVO. In this presentation, we will briefly review the logic that communicates that ISS potential, and then we will exemplify where we are in the campaign to mine and apply that potential for addressing seismic E&P challenges. Open issues and plans will also be discussed.

High Resolution Simulations and Experiments for Carbon Sequestration Modeling

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Carbon dioxide sequestration in subsurface formations involves multiphase flow across a range of length and time scales. Ultimately, however, fluids flow through the pores of rocks and understanding pore scale physical mechanisms is necessary to formulate constitutive equations that describe flows at macroscopic scale. We are obtaining a suite of pore-scale experimental data under the range of capillary, gravity, and Bond numbers relevant to CO2 injection into sedimentary rocks filled with brine. Preliminary and continuing experiments have shown that it is possible to visualize and provide quantitative measurements of multiphase flow using silicon micromodels etched with topological properties similar to real rocks. Experiments have been performed under realistic unfavorable viscosity and density conditions.

At the same time, we leverage on the novel paradigm for solving partial differential equations on Octree adaptive grids introduced by one of the PIs to develop a three-dimensional computational model capable of solving two-phase flows in arbitrarily complex geometries. We use a level-set method to keep track of the interface between the two phases and an implicit method to capture the physically relevant boundary conditions at the interface. One advantage of this approach is that high density and viscosity ratios can be considered and that re-meshing is straightforward in three spatial dimensions.

Thermodynamically Constrained Averaging Theory: Recent Advances, Practical Applications, and Remaining Challenges

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The movement of fluids and the transport and reaction of species in porous medium systems is a broad area of science that impacts a range of applications including carbon sequestration, nuclear waste cleanup and disposal, geothermal energy production, and the design of hydrogen fuel cells. A common thread in such applications is the routine occurrence of multi-scale systems in which fundamental phenomena operative at a given length scale importantly affect transport and reaction phenomena at larger scales. Traditionally models have been posited directly at the macroscale, where the details of the pore structure, and microscale transport phenomena in general, have been ignored.

Our work is aimed at advancing the thermodynamically constrained averaging theory (TCAT) approach for constructing models of multiphase porous medium systems at a range of length scales in which all variables are expressed in terms of explicitly defined averages of microscale properties, and closure relations are constrained to ensure conditions consistent with the second law of thermodynamics. The results of this approach are models that can be constructed at a range of length scales, explicit definitions of all variables in terms of microscale precursors, hierarchical families of models that vary in sophistication that can be matched to a physical system of concern, and assurance that the models derived are thermodynamically constrained and consistent.

We demonstrate the elements of TCAT and detail the role that conservation principles, thermodynamics, provable equilibrium conditions, upscaling theorems, and constrained closure relations play in the development of TCAT models. We illustrate examples of the theory for megascale and macroscale single-fluid-phase flow showing that a common form of Darcy's law neglects important aspects of the physics of single-fluid-flow for systems with a variation in volume fraction. We also detail recent results from the closure of a single-fluid-phase flow and transport model for non-dilute systems, which responds to shortcomings in extant models. Lastly we consider the case of two-fluid-phase flow in porous medium systems. Conditions under which the standard model reduces to common models are detailed, and we illustrate the natural importance of interfacial areas for modeling two-fluid-phase flow. An aspect of importance is shown to be the need for an evolution equation to model interfacial areas. The derivation of such an equation is detailed.

Closure of TCAT models requires information at the microscale or pore scale. We show approaches for generating model porous medium systems for a range of media types, detail some recent advances in lattice-Boltzmann methods to simulate microscale systems; and we illustrate results from the simulation of a range of microscale systems. We also show how LB simulation results can be used to advance closure relations for a porous medium system that illustrates a novel sort of directional anisotropy.

Finally, we look ahead to the remaining challenges in the development and application of TCAT and discuss elements needed to further advance and apply this theory.

The development of an intrinsic heterogeneity during fracture dissolution

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Modeling the sequestration of CO_2 in carbonate formations must take into account the evolution of permeability through dissolution and precipitation in the fracture network. Theories of fracture evolution typically assume that dissolution is uniform in the direction normal to the flow, and that the front is therefore planar. Under these circumstances, a rapidly eroding front can only penetrate a short distance into the fracture. However, numerical simulations have shown that, in some cases, dissolution is highly non uniform, leading to a much more rapid increase in permeability. Here we show that non-uniform dissolution is the expected behavior on geophysical scales rather than the exception. We present a linear-stability analysis, which shows that a planar dissolution front in an entirely uniform fracture is unstable to infinitesimal perturbations. These perturbations grow exponentially in time and soon begin to interact in a highly non-linear way. We conclude that the evolution of fracture permeability can be better approximated by the growth of localized regions of high permeability, than by conventional models based on uniform aperture growth. In particular, estimates of breakthrough times can differ by orders of magnitude in scenarios of relevance to sequestration. Our results suggest that, after sufficient dissolution, the characteristic length scale of the variation in fracture aperture will be determined by the reaction kinetics and flow rate, and not by the initial heterogeneity of the fracture. We also show that a similar instability can apply to the porous matrix itself.

Density-Driven Brine Convection: A Process for Accelerating CO_2 Dissolution and Enhancing Security of Geologic Storage

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In geologic CO_2 sequestration, CO_2 would be injected into permeable saline formations at supercritical temperature and pressure conditions, and would form a separate phase that is immiscible with the aqueous phase (brine). Supercritical CO_2 has lower density than the aqueous phase and would experience an upward buoyancy force. Accordingly, the CO_2 is expected to rise to the top of the permeable formation, and spread out laterally beneath a low-permeability caprock. This low-viscosity, highly mobile CO_2 could escape from the storage formation wherever (sub-) vertical pathways are available, such as fractures or faults through the caprock, or improperly abandoned wells. Over time, an increasing fraction of CO_2 may dissolve in the aqueous phase, and eventually some of the aqueous CO_2 may react with rock minerals to form poorly soluble carbonates. Dissolution into the aqueous phase and eventual sequestration as carbonates are highly desirable processes as they would increase permanence and security of storage. At the CO_2-brine interface, CO_2 will establish equilibrium locally between the overlying CO_2 plume and the aqueous phase beneath. If the aqueous phase were immobile, CO_2 dissolution would be limited by the slow molecular diffusion of dissolved CO_2 away from the interface. Dissolution of CO_2 is accompanied by a small increase in the density of the aqueous phase, creating a negative buoyancy force that gives rise to downward convection of CO_2-rich brine, while inducing upward movement of brine with low CO_2 concentration. Such density-driven convection could greatly accelerate the rate at which dissolved CO_2 migrates away from the interface between CO_2-rich and aqueous phases, and thereby could greatly accelerate the dissolution of the free CO_2. We have performed numerical simulations, laboratory visualization experiments, and medium pressure laboratory quantification experiments to gain understanding of this convection-dissolution process. We will present results from these investigations showing the occurrence of density driven convection, initiation of the process, and compare numerical and laboratory results.

Dynamic effective mass of granular media

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We develop the concept of frequency dependent effective mass, M(omega), of granular materials which occupy a rigid cavity to a given filling fraction, the remaining volume being air of normal room condition or controlled humidity. The dominant features of M(omega) provide signatures of the dissipation of acoustic modes, elasticity and aging effects in the granular medium. We perform humidity controlled experiments and interpret the data in terms of a continuum model and a ``trap" model of thermally activated capillary bridges at the contact points. The results suggest that attenuation of acoustic waves in granular materials can be influenced significantly by the kinetics of capillary condensation between the asperities at the contacts.

Fluid Pressure Evolution and Solitary Wave Formation in a Compacting, Hydrocarbon-Forming Sedimentary Basin

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The rapid ascent of hydrocarbons and groundwater through thick sections of low permeability strata has been documented in numerous sedimentary basins around the world. For example, in the Gulf of Mexico basin, hydrocarbons are today found largely in Pleistocene and Neogene reservoirs but appear to have ascended several kilometers from older Tertiary and even Mesozoic source sediments over durations of a few hundred thousand years or less, indicating possible flow velocities on the order of 10^{-2} meters per year (m/yr) or more. How such high flow velocities can be attained in low permeability clay-rich sediments has been a longstanding question. However, fluid mechanical theory predicts, and recent seismic data support the possibility that where permeability is a strongly decreasing function of effective stress, fluids may depart overpressured sediments in rapidly ascending pulses or solitary waves. For example, in the Eugene Island minibasin, offshore Louisiana, recent seismic evidence suggests that a fluid pulse may have risen along a growth fault at a rate of 140 m/yr. The purpose of the present research is to evaluate the solitary wave mechanism by quantifying the conditions under which waves arise and their transport capability is optimized.

The first part of this research focused on solitary wave formation and movement in sediments with a viscous rheology. In this context, solitary waves are manifest as regions of elevated porosity within the bulk porous medium and that arise due to buoyancy. Generic models were carried out in the vertical dimension for a porous medium fully saturated with respect to petroleum and took into account sedimentation, compaction, conductive heat transport, and petroleum generation. The models showed that solitary waves can form and have fluxes significantly greater than that of the background fluid flow under the following conditions: (1) low background porosity, on the order of a few percent, (2) high kerogen content in the source sediments, greater than about 10%, (3) low matrix shear viscosity, below about 10^{20} Pa s, (4) high sedimentation rates of at least several mm/yr.

Subsequent research has focused on solitary wave formation and movement in sediments with elastic rheology. In this context, solitary waves are manifest as regions of elevated pore pressure that ascend along a decreasing pressure gradient. Using the BasinMod2D™ software, a cross sectional model has been constructed of pore pressure evolution during the deposition, compaction, and diagenesis of sediments at Eugene Island. The models predict the development of significant levels of overpressuring, as high as 55-60 MPa total fluid pressure at depths of about 4.5 km, that are sufficient to spawn fluid pressure surges along intersecting high permeability faults. These fluid pressure surges may be solitary waves and are best developed when the permeability ratio of the fault to surrounding porous medium is high and the compressibility of the fault zone is low. Calculations thus far have been carried out with water as the only pore fluid, but the results show the pressure surges to cause significant acceleration in fluid velocity in the faults by as much as two orders of magnitude compared to the background fluid velocity, indicating the potential for enhanced hydrocarbon transport.

Growth of Dendritic Channel Networks Incised by Groundwater Flow

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Principal Investigators

Olivier Devauchelle (MIT), Alexander Petroff (MIT), and Michael Berhanu (Clark)
Collaborators

Dendritic channel networks are a ubiquitous feature of Earth's topography. A half century of work has detailed their scale-invariant geometry. But relatively little is known about how such networks grow, especially in natural settings at geologic time scales.

This talk addresses the growth of a particularly simple class of channel networks: those which drain groundwater. Our research is motivated by a field site in the Florida Panhandle, in which channels extending for kilometers have been incised vertically by groundwater flow through tens of meters of ancient beach sands. Our work combines theory, field observations, and laboratory experiments.

We first provide a simple geometric model for the interaction of subsurface flow with the Florida network. The growth of the network is described by two linear response laws. Remarkably, one of these growth laws is reversible, which allows us to reconstruct network history and estimate network age.

We then provide a more detailed model based on a two-dimensional (Dupuit) approximation of the three-dimensional groundwater flow equations. Numerical solutions provide the height of the water table and the fluxes into all parts of the network. Both predictions compare well with our field measurements. The two-dimensional hydrodynamic model also shows that our simpler geometric model is qualitatively correct.

These results address the planform geometry of the network without taking account of its shape. Thus we generalize our approach in two ways. First, we show theoretically how the groundwater flow creates amphitheater-shaped valley heads, and we provide experimental and field observations confirming that elevation contours have a universal shape parameterized only by their width. Second, we predict the longitudinal elevation profile of the channels and show that it compares well to field observations.

Probing the temporal and spatial characteristics of sequestration processes over a cascade of scales

Prof. Sanjay Srinivasan – University of Texas/Sandia National Laboratory
Energy Frontier Research Center

Underground storage of the byproducts of energy production is a critical enabling technology for 21st century energy systems. But without significant improvements in our ability to predict large-scale, long-term transport of multiple fluid phases and components within those phases, we will not be able to design sufficiently reliable storage systems. Significant knowledge gaps exist in our understanding of the emergence of patterns or characteristic behaviors, such as fast-moving preferential flow paths, when geologic systems are driven far from equilibrium. This talk will present the activities of the Center for Subsurface Energy Security for modeling processes associated with complex, heterogeneous mineral and porous rock behavior and their interactions with multi-phase fluids. Biological, chemical and mechanical interactions occurring at the atomic, molecular and pore scales and their ultimate manifestation at the basin scale are being analyzed.

Non-equilibrium effects imply variation in process characteristics at different temporal scales. This necessitates new methods to analyze and reconcile core and field observations. To address these issues we propose a multi-tiered approach that includes outcrop and core-based structural and diagenetic investigations, seismic reservoir imaging, and reservoir monitoring to better characterize subsurface heterogeneity at the basin scale. The talk will present some initial results on statistical scale up of processes that are controlled at the sub-pore scale. These results reveal the emergent characteristic of the scaled up flow and transport attributes. Subsurface fluid reservoirs are inherently discontinuous systems that include opening-mode fractures (joints, cemented veins, and partially cemented or bridged fractures) and shear fractures (faults) that range in size from the grain to the basin scale. Fracture and fault geometry and hydraulic properties are dependent on loading geometry and history, sedimentary architecture, diagenetic (biological and chemical) reactions, and rock physical properties at the time of deformation. This talk will present some initial observations regarding the manifestation of these processes at the field scale at surface-exposed sites of natural active CO_2 seepage (e.g. Little Grand Wash fault, Green River, Utah). The plan is to perform detailed analysis of these interactions using a combination of structural and diagenetic field mapping, petrographic and SEM imaging, mineralogical, elemental, fluid inclusion, and isotopic analyses, subcritical fracture testing, geomechanical modeling of fault-fracture interactions, and geochemical reaction and reaction path modeling.

Geohydrology of faults in petroleum-rich basins, southern California

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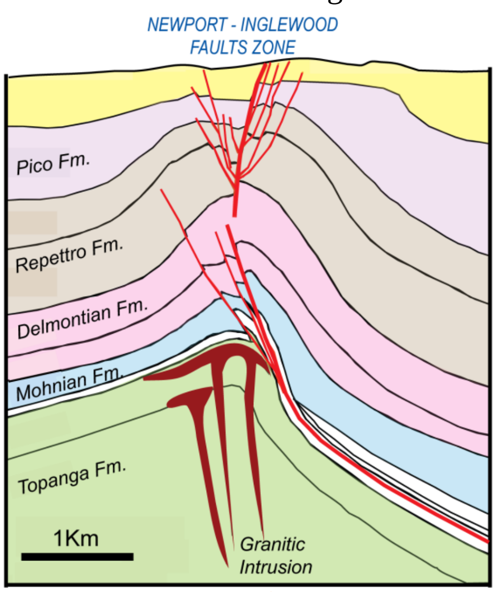
We are studying active faults and petroleum fields in southern California, including the Refugio fault (Transverse Ranges), Ellwood fault (Santa Barbara basin), and the Newport-Inglewood fault zone (Los Angeles basin). Subsurface cores, geophysical data, reservoir pressures-temperatures, fluid discharges, mineralization patterns, fluid inclusions, and structural models are being analyzed to characterize the geohydrologic effects of faults in this transpressional setting. Field data also provide constraints for mathematical models that are being developed for forward modeling purposes. For example, we present reservoir data for fluid fluxes that uniquely constrain fault permeability, for km-scale migration of both water and gas phases. We are also constructing numerical simulations to characterize the fluid flow history of the LA basin for both single- and two-phase fluid migration. Single-phase flow models simulate the basin-scale deformation-driven flow associated with deep basin subsidence and later uplift of the San Gabriel Mtns (Fig. 1). Two-phase flow models characterize a more detailed resolution of the stratigraphy and structure, and constrain rates of petroleum migration associated with the basin margin, where deep faults produced thick stacking of petroleum. Our modeling results suggest a long history of episodic flow from the depocenter towards the south flank of the LA basin and the Palos Verdes Peninsula. The models also predict a strong preference for focused flow along the NIFZ, for fluids and heat.



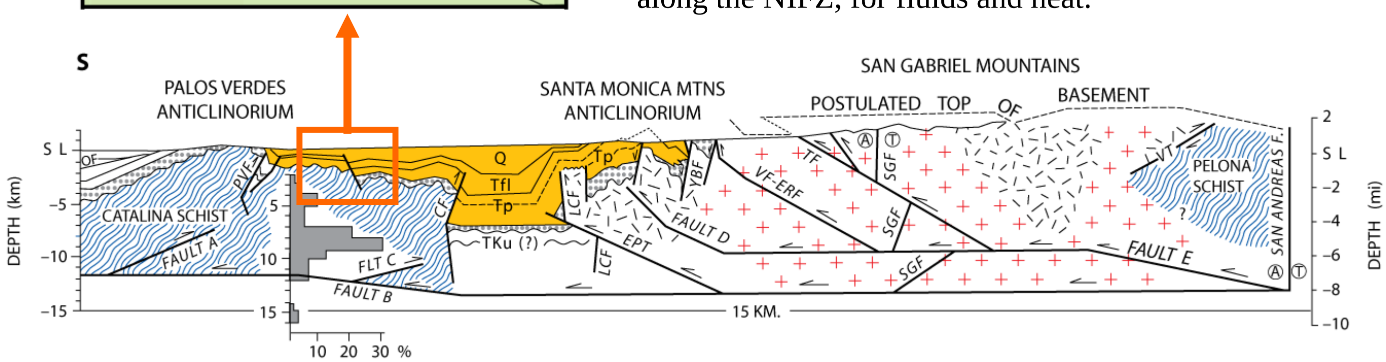


Figure 1. Structural cross section of the Los Angeles basin (Wright, 1991), along a south-north transect, with an expanded profile across the Newport-Inglewood fault zone (Plains Petroleum, per. communication, 2008).

Permeability alteration due to mineral dissolution in partially saturated fractures

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Multiphase flow in the subsurface is important to many problems of interest to DOE, including, CO_2 sequestration, nuclear waste isolation and energy production. All of these problems involve two or more fluid phases, with transport often dominated by flow through fractures. In addition to the complexity introduced by multiple fluid phases, these problems often involve void-space (aperture) alteration caused by mechanical stresses and/or geochemical alteration of minerals. Rigorously predicting the influence of these often coupled processes is beyond the reach of continuum models used to simulate multiphase flow processes in fractured media. Quantifying the limitations of these models and developing improved constitutive relationships demands systematic evaluation of the role of the individual and coupled processes that alter transport properties.

The objective of this project is to develop a quantitative understanding of the mechanisms that control two-phase fluid flow in variable aperture fractures when physical and/or chemical processes deform fracture apertures over time. We present results from experiments designed to explore the influence of an entrapped phase (e.g., CO_2, oil) on chemically induced alteration of fracture apertures. During reactive fluid flow in saturated fractures, the relative rates of dissolved-mineral transport and local reactions strongly influence local aperture alterations and the resulting changes in fracture permeability (or transmissivity). In the presence of an entrapped, residual nonaqueous phase (e.g., CO_2 or oil), the spatial distribution of the entrapped phase influences flow and transport and thus, local rates of chemically induced aperture alteration. Aperture alterations, in turn, alter the balance of forces acting on immobile regions of the trapped phase. The resulting mobilization of the entrapped phase may subsequently alter flow pathways and fracture transmissivity in a manner that defies quantification with simple constitutive relationships.

We present results from quantitative visualization experiments in which fracture aperture and entrapped phase distribution were directly measured at high spatial resolution (75 μm x 75 μm) during reactive fluid flow. The experiments differed only in the orientation of the fracture with respect to gravity, which influenced both the initial entrapped phase geometry and the evolution of the entrapped phase as dissolution altered fracture apertures. The presence of the entrapped phase leads to a much earlier formation of distinct dissolution channels than has been observed in saturated fractures. Compared to a similar experiment in a fully saturated fracture, dissolution in the partially saturated fractures leads to as much as a 6-fold increase in transmissivity after an equal amount of dissolution from the fracture surface (doubling of the mean fracture aperture). Furthermore, the relative influence of gravity determines whether trapped bubbles mobilize due to capillary forces (against prevailing viscous forces) or gravitational forces, which is in the direction of prevailing viscous forces for the experiments presented here.

Multiscale calculation of permeability inside compaction bands: from the field to the lab

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This work presents preliminary data on permeability calculations using 3D X-ray tomography images taken inside and outside compaction bands. Aztec sandstone samples are taken from the Valley of Fire in Nevada and are scanned using the synchrotron APS facility at Argonne National Laboratory. The 3D microstructures inside and outside the compaction bands, formed in situ, are then used to perform lattice Boltzmann computations to estimate the components of permeability in different principal directions. We show that i) the permeability component in the direction perpendicular to the compaction band is reduced by orders of magnitude in the presence of a compaction band, ii) inside the compaction band, there is a strong anisotropy manifested by the permeability tensor, and iii) the Kozeny-Carman relation does a pretty good job at estimating the permeability outside of the compaction band, but fails to estimate the reduction in permeability in the presence of compaction bands.

Carbonate Compaction and Cataclastic Pore Collapse

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The analysis of compactant failure in carbonate formations hinges upon a fundamental understanding of the mechanics of inelastic compaction. Our microstructural observations have revealed fundamental differences in the micromechanics of compaction between carbonate and clastic rocks, even though they have very similar phenomenological behaviors. In a limestone compaction derives primarily from pore collapse that initiates at the larger pores, and microcracking that dominates the deformation in the periphery of a collapsed pore. The pore space complexity in a carbonate rock is such that for us to capture these micromechanical processes, it was necessary to appeal to a model treating the limestone as a dual porosity medium, with the total porosity partitioned between macroporosity and microporosity. The representative volume element is made up of a large pore which is surrounded by an effective medium containing the microporosity. Cataclastic yielding of this effective medium obeys the Mohr-Coulomb or Drucker-Prager criterion, with failure parameters dependent on porosity and pore size. An analytic approximation was derived for the unconfined compressive strength associated with failure due to the propagation and coalescence of pore-emanated cracks. For hydrostatic loading, identical theoretical results for the pore collapse pressure were obtained using the Mohr-Coulomb or Drucker-Prager criterion. For nonhydrostatic loading, the stress state at the onset of shear-enhanced compaction was predicted to fall on a linear cap according to the Mohr-Coulomb criterion. In contrast, nonlinear caps in qualitative agreement with laboratory data were predicted using the Drucker-Prager criterion. Our micromechanical model implies that the effective medium is significantly stronger and relatively pressure-insensitive in comparison to the bulk sample.

On the mechanical behavior of curved faults: implications for fluid flow and damage zones

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Understanding the mechanical behavior of non-planar fault surfaces is a first order problem for geologists and geophysicists who are working on the brittle deformation of rock in Earth's lithosphere at length scales from meters to hundreds of kilometers. There is abundant evidence from outcrop investigations of faults that non-planar geometries can lead to opening and closing along portions of curved faults, and that the style and intensity of off-fault damage is spatially correlated with geometric irregularities. The normal displacement discontinuity (opening) of the fault surfaces has important implications for the frictional resistance to slip, because opening reduces the compressive stress to zero and admits fluids into the fault. Furthermore, the local stress perturbations related to these relative motions have important implications for the style and distribution of damage, which in turn can alter the flow regime in the nearby rock mass.

We use two-dimensional numerical solutions for quasi-static elastic boundary value problems to investigate both circular arc cracks and sinusoidal wavy cracks as models for faults under general biaxial loading conditions. The analytical solution for a circular arc crack has been used widely to study curved crack behavior in an otherwise homogeneous and isotropic elastic material. For certain orientations and magnitudes of the remotely applied loads, portions of the crack will close, causing the analytical solution to fail due to violation of the traction-free boundary condition. In fact the analytical solution permits the crack walls to interpenetrate. A two-dimensional displacement discontinuity method is combined with a complementarity algorithm to solve the problem for partially closed circular arc cracks with friction. Taking the arc crack as a model for a fault with curvature, the range of conditions for partial opening is investigated. Opening is spatially associated with the lee side and closure with the stoss side of the fault surface. In general, an increase in friction is found to decrease the length of opening along a curved fault. As an extension of the circular arc crack, the wavy crack problem can be analyzed as linked circular arc segments or a sinusoidal curve using the same numerical method to model the stress and displacement perturbations. We evaluate the deformation and local stress states due to slip on these structures for a range of tectonic loads and evaluate the off-fault damage related to local stress perturbations.

Fracture opening histories, strain and strain rates: implications for fluid flow, time-dependent fracture network attributes, and geophysical response

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We present fracture petrology observations and modeling, fracture size scaling measurements, and geomechanical model results that constrain fluid flow, time-dependent fracture network attributes, and geophysical response of natural fracture systems. A parameter that can be readily measured in natural fracture populations is the opening or aperture, so it is a good attribute to use for constraining fracture mechanics model results. The nature of preserved aperture distributions in fractures suggests that mineral precipitation and fracture growth often occur simultaneously. In addition to mineral precipitation in the fractures, there will also be concurrent mineral precipitation in the matrix rock around the fracture. This mineral precipitation, in both the fracture and the host rock around it will act to preserve fracture opening. We used a fracture mechanics model to examine the feedback between these aperture propping mechanisms and fracture network growth. Field observations indicate that fractures often have power-law aperture distributions, probably a consequence of feedback processes, such as the mechanical interaction between fractures and interaction between fracture growth and cementation. Our work shows that only certain degrees of interactive feedback will generate a power-law distribution. Mechanical interaction without diagenetic propping of apertures does not result in a power-law aperture distribution, but power-laws do result from diagenesis active during fracture propagation. Long-term strain rates for geologic processes are characteristically in the range of 10^{-13} to 10^{-17} s^{-1} as measured by a variety of techniques, including geodetic techniques, radiometric dating of tectonic and structural processes, and through stratigraphic correlations. We present strain rates for populations of opening-mode fractures in sandstone in deep basinal settings. Fracture strain is obtained by collecting aperture-frequency data for microfractures along scanlines in weakly deformed sandstone. Opening durations of macrofractures in the same population are then obtained through detailed microthermometry of fluid inclusions in crack-seal fracture cement, combined with textural reconstructions of the fracture opening history. Temperature data are then correlated with known burial history models to obtain the duration of fracture opening and the fracture opening strain rate. Fractures in deeply buried sandstone of the East Texas basin, a passive margin setting, opened over 48 m.y. with a strain rate of $5x10^{-19}$ s^{-1}. Similar strain rates are obtained for the Piceance intermontane basin of Colorado. These ultraslow strain rates compare well to long-term intraplate seismic strain rates suggesting that rates of fracture opening are controlled by intraplate tectonic deformation processes.

Pore-scale transport and mechanical properties of mudrocks: Imaging, modeling and experiments

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Shales and other mudrocks are the most abundant rock type in sedimentary basins, and are being increasingly implicated as unconventional gas reservoirs, caprocks for carbon sequestration, and, in some parts of the world, repositories for nuclear waste. Pore-scale topology, transport, and mechanical properties of these important rock types are being investigated to better understand the variety and structure of mudstone pore types, and to improve coupled thermal-hydrological-mechanical-chemical modeling of shales/mudrocks for these and other applications.
Samples of six mudstone units from fresh and not-so-fresh cores, with a range of environments of deposition from offshore marine to alluvial floodplain and overbank deposits, are characterized by a variety of imaging and analytical techniques. Dual focused ion beam/scanning electron beam microscopy is used to construct 3D databases, with 15.6 nm voxel size, of pore networks, sedimentary structures, and diagenetic features. Used in tandem with TEM/EDS and XRD methods, 3D geometries of pore-lining mineralogy are constructed. Medial axes and other properties of pore networks are constructed using 3DMA (Lindquist et al., 1999), which permits calculation of specific surface area, interconnected porosity, non-connected porosity, pore throat size distributions, and other network statistics from the image data. Digital properties are compared to pore statistics obtained from mercury porosimetry. These reveal a variety of pore types, including slit-shaped pores occupying space between and within compacted clay packages, unconnected pores in compaction shadows around silt- and clay-size matrix-supported quartz grains, and pore structures associated with microstylolitic structures, among others. Larger connected pore types are imaged in 3D using laser scanning confocal microscopy and include pedogenic/illuviation structures, as well as crack-like pores interpreted to be a result of dehydration. Organic laminae in one marine shale show interconnected tube-shaped pores, adjacent to siliciclastic laminae with interconnected “slot” pores, and as such this shale displays both “oil-wet” and “water-wet” transport pathways.

Particle Swarms in Fractures

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In the next 10-20 years, nano- and micro-sensor engineering will advance to the stage where sensor swarms could be deployed in the subsurface to probe rock formations and the fluids contained in them. Sensor swarms are groups of nano- or micro- sensors that are maintained as a coherent group to enable either sensor-to-sensor communication and/or coherent transmission of information as a group. The ability to maintain a swarm of sensors depends on the complexity of the flow paths in the rock, on the size and shape of the sensors and on the physical interactions among the sensors, fluids, and rock surfaces. In this study, we investigate the effect of fracture aperture and fluid currents on the formation, evolution and break-up of colloidal swarms under gravity.

Transparent cubic samples (100 mm x 100 mm x 100 mm) containing synthetic fractures with either uniform or non-uniform aperture distributions were used to quantify the effect of aperture on swarm formation, swarm velocity, and swarm geometry using optical imaging. A fracture with a uniform aperture distribution was fabricated from two polished rectangular prisms of acrylic, while a fracture with a non-uniform aperture distribution was created with a polished rectangular acrylic prism and an acrylic replica of an induced fracture surface from a carbonate rock. A series of experiments were performed to determine how swarm movement and geometry are affected as the walls of the fracture are brought closer together from 50 mm to 1 mm. During the experiments, the fracture was fully saturated with water. We created the swarms using two different particle sizes in dilute suspension (~ 1% by mass). The particles were 3 micron diameter fluorescent polymer beads and 25 micron diameter soda-lime glass beads. The swarm behavior was imaged using an optical fluorescent imaging system composed of a CCD camera and illuminated by a 100 mW diode-pumped doubled YAG laser.

A swam was created when an approximately 0.01 g drop of the suspension was released under gravity into the water. The swarm density is slightly greater than water and falls faster than the terminal velocity of an individual particle in water. The cohesiveness of the swarm was maintained over 50 mm to 95 mm even in the presence of fluid currents as the swarm velocity decreased with decreasing fracture aperture. The ability to form and maintain a swarm is strongly affected by fracture geometry. For instance, in a variable-aperture fracture, swarms break-up in the large-aperture portions of the flow path.

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