Steve Pride's Recent Research Activities and Research Agenda

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My present research activities can be grouped into four different subject areas: (1) Using recorded seismic amplitudes to obtain information about earth properites; (2) Mechanical breakdown processes; (3) Electrokinetic coupling; and (4) Earthquake processes. I will describe below my recent activities and current direction in these four areas.

In general terms, I like to work on subjects that have received little attention and yet have the potential to become revolutionary new approaches to understanding earth structure and earth processes. I am not married to any one subject area, although "Crustal Physics" might be an all inclusive banner for my work. I attempt to bring ideas from modern physics and applied mathematics to bear on earth science problems, in addition to creating my own original analysis.

Using recorded seismic amplitudes. The vast majority of seismic data that is recorded during exploration surveys is not used. Specifically, the amplitude information on seismograms is typically not modeled. Seismologists use the arrival times of seismic energy and sometimes the amplitude of the first arrival in a transmission experiment, but they do not attempt to exploit all the information that is available on a seismogram. This is because to do so, one must allow in the forward model for all processes that are significantly affecting wave amplitudes and geophysicists still do not know how to do this. Further, when using the entire seismogram, there are problems of "local minima" in data-fit measures that hamper traditional gradient-search approaches to finding the earth parameters. I have just received a \$650k grant from the Basic Energy Science office of the Department of Energy (DOE) to begin addressing some of these issues. Further, Shell Research is currently funding my research in this area at \$80k/year. I have described the current state of the art (and ongoing challenges) of using seismic amplitudes in a recent article [Pride et al., 2003a, *The Leading Edge*, **22**, 518–525]. This article was written at the request of DOE (Nick Woodward) in order to stimulate a DOE-sponsored research initiative on this theme.

The great difficulty is properly allowing for the effects of the heterogeneity that is present at all scales (millimeters to kilometers) in the crust. In a series of recent articles [Pride & Berryman, 2003b, *Physical Review E*, **68**, 0336603; Pride & Berrman, 2003c, *Physical Review E*, **68**, 0336604; Pride, 2004, *Chap. 9 of Hydrogeophysics*, edited by Y. Rubin, Kluwer Academic; and Pride et al., 2004b, *J. Geophys. Res.*, **109**, B01201,doi:10.1029/ 2003JB002639], I have provided models that explain for the first time the relatively large levels of intrinsic seismic attenuation (irreversible loss to heat) measured in the seismic band of frequencies on water-saturated rocks. These models require the presence of heterogeneity at scales of 10^{-3} to 10^{-2} m (note that typical grain sizes in sedimenatry rock are $< 10^{-4}$ m). When a wave squeezes a rock possessing such heterogeneity (which is ubiquitous throughout the crust), the more compressible regions respond with a larger change in the fluid pressure than the stiffer regions. There is induced a fluid-pressure diffusion that attenuates significant amounts of energy.

My current research in this area is focused on using radiative-transfer theory to allow for the scattering losses that occurs when there is heterogeneity at the scale of the seismic wave length (which is always much larger than the centimeter-scale heterogeneity required to explain the intrinsic loss). Combining these theories, it should be possible to separate the intrinsic loss from the scattering loss. Once these ideas are perfected on synthetic examples, the goal is to apply the theory to actual seismic data.

Mechanical Breakdown Processes. One of the oldest geophysical problems is to understand the processes that lead to stress-induced catastrophic failure of rocks. Acoustic emission and other evidence suggests that as stress is increased on rocks at crustal temperatures and pressures, random micro-cracking occurs throughout a sample that then concentrates to bands just prior to the failure of the sample along one of the bands.

Along with my former student Renaud Toussaint [recently hired as a professor of physics at the University of Oslo], I have developed a theory that allows for cracks (or broken bonds in a lattice model) to arrive and interact under applied stress increments. In the model, the surface energy required to open each new crack is a quenched random variable sampled from an uncorrelated probability distribution. We use conservation of energy that says a crack will open whenever the energy required to open it (a random threshold) is less than or equal to the change in the stored elastic energy in the entire system. This principle, along with the quenched disorder in the breaking energies, allows us to exactly determine the probability (pdf) of each possible "crack state" as averaged over quenched disorder [Toussaint & Pride, 2004, *Physical Review E*, submitted]. These pdfs turn out to be Boltzmannians, that could have been equivalently obtained by maximizing the Shannon entropy subject to energy balance constraints.

Our crack-state Boltzmannians have a probabilistic energy scale (called temperature) that is an explicit analytic function of the applied deformation and quenched-disorder distribution and that has nothing to do with molecular dynamics. For simple models in which damage-point interactions are isotropic in space, our models are isomorphic to an Ising model when interactions are kept to nearest neighbors, and to the percolation model when interactions occur globally [as had been proven in an earlier pubication by Pride & Toussaint, 2002, *Physica A*, **312**, 159–171]. Elastic damage interaction is intermediate between these limits and correspond to power-law interactions in the Ising model. These facts allow us to identify the various possible universality classes for the breakdown transition that is defined to occur when the correlation length of the damage diverges [Toussaint & Pride, 2004, *Physical Review E*, submitted].

This recent article also puts onto a firmer basis our earlier more general work [Toussaint & Pride, 2002a, *Physical Review E*, **66**, 036136; Toussaint & Pride, 2002b, *Physical Review E*, **66**, 036137; and Toussaint & Pride, 2002c, *Physical Review E*, **66**, 036138] in which oriented cracks were allowed to interact anisotropically (using tensors) but in which the probability of observing crack states was obtained by maximizing Shannon entropy.

One of the principle predictions of our interacting crack models is that the only divergence in such systems is in the autocorrelation function of crack damage at the breakdown transition (the free energy and all of its derivatives are divergence free). My former student and I are currently planning acoustic scattering experiments, that will allow the correlation function to be directly determined [under the assumption of weak scattering, the scattered wave energy, as averaged over realizations of quenched disorder, is identical to the correlation function and may thus be measured in the lab]. These experiments, if successful, will be the first to measure the damage correlation in cracking systems, and could provide a means to predict when catastrophic failure of a stressed rock mass is imminent.

Electrokinetic Coupling. I have been a pioneer (along with a group of scientists with whom I have worked at ExxonMobil) in trying to exploit electrokinetic coupling [the phenomenon by which applied electric fields create fluid flow in porous rocks or by which fluid-pressure gradients create electric currents] as an exploration tool. I developed the theory that is used to describe the forward modeling for such applications [Pride, 1994, *Physical Review B*, **50**, 15678–15696; Pride & Haartsen, 1996, *JASA*, **100**, 1301–1315; and Haartsen & Pride, 1997, *J. Geophys. Res.*, **102**, 24745–24769]. Although I took a break from this field for a number of years, I have recently returned to the subject [Pride & Garambois, 2002, *JASA*, **111**, 697–706; and Pride, 2004, *J. Eng. Mech.*, submitted]. The theoretical potential for exploiting electrokinetic coupling in geophysical exploration is great; however, only ExxonMobil has put the ideas to work in the field and their successful results are still highly proprietary. For this reason, I have recently begun performing field tests with a PhD student at Stanford (Seth Haines). Our initial results are successful and we are in the process of writing up for publication some definitive recommendations for the data-collection and data-processing protocol required for successful imaging of the subsurface.

Further, in a recent collaboration with my Berkeley Lab colleague Sejei Nakagawa, we have developed a new method for measuring fluid-flow permeability using electro-osmosis. Our recent laboratory experiments confirm the theory beautifully, and these results will soon be submitted to the J. of Fluid Mechanics.

Earthquake Processes. I have recently become interested in the problem of understanding why there is a delay between when a mainquake occurs and when aftershocks occur. One possibility is that fluid pressure diffuses from regions compressed by the mainshock to regions that were dilated. A dilated region has reduced normal stress on potential slip surfaces and as the fluid pressure increases in such regions, the effective normal stress decreases still further making the surface even more susceptible to unstable slip (an aftershock). Some of the background theory along with some simple numerical modeling has been presented in a recent article [Pride et al., 2004, *J. Geophys. Res.*, **109**, B03302, doi:10.1029/2003JB0002690]. This mechanism has roughly the correct time constant required to explain the time decay of aftershocks. What is more, I have shown in the same article that the electric field accompanying such flow (created by electrokinetics) is large enough to be easily seen on dipole electrode antennas within, say, 10-20 km of an initial M5 (or larger) mainquake. I have recently learned that scientists at the Berkeley Seismological Station have been measuring the electric field near Parkfield California for the past 8 years, and I definetly plan to analyze the data as time permits (apparently, this data has not yet been exploited by anyone).

Further, in collaboration with Professors Doug Dreger and Barbara Romanowicz, I am in the process of writing my first NSF proposal in which we propose to model the sequence of aftershocks that have occured in the aftermath to the December 22, 2003, M6.5 San Simeon earthquake. The goal is to determine the physical mechanism (fluid diffusion or rate-and-state friction) responsible for the spatio-temporal pattern of the aftershock sequence.