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Project Title

Models of Natural Fracture Connectivity—Implications
for
Reservoir Permeability

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Table of Contents

Table of Contents.....	ii
Project Personnel and Funding	1
Principal Project Personnel.....	1
Atilla Aydin	1
David D. Pollard.....	2
Additional Project Personnel.....	2
Michele Cooke.....	2
Ken Cruikshank.....	2
Daniel Helgeson.....	2
Greg Ohlmacher.....	2
Carl Renshaw.....	3
Haiqing Wu.....	3
Scott Zeller.....	3
Project Funding History.....	3
Project Overview	4
Specific Project Objectives.....	4
Importance to the DOE Basic Energy Sciences Mission.....	4
Relationship to Research of Others.....	5
Scientific and Technical Content.....	5
Field Studies	5
Laboratory Model Experiments on Fracture Sets.....	5
Fracture domains	9
Changing direction of loading	9
Bed thickness and joint spacing	9
Strain rate.....	9
Strain cycling	13
Stress relaxation.....	13
Concretions	13
Laboratory Model Experiments on Mixed-mode Fracture Growth.....	13
Physically-based Numerical Models of Fracture Sets.....	15
Fracture propagation across interfaces.....	15
Natural hydraulic fractures	15
Growth of a single fracture set.....	15
Growth and hydraulic properties of multiple single fracture sets.....	18
Project Accomplishments.....	18
Description of Major Results.....	18
Bibliography	21
Published Papers	21
Abstracts Presented at Scientific Meetings	22
Papers and Abstracts in Preparation and in Review.....	23
M.S. and Ph.D. Theses Supported by this Project.....	24
M.S. and Ph.D. Theses in Preparation	24

Project Personnel and Funding

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B. Areas of research expertise: Structural geology, rock fracture mechanics, active tectonics, geomechanics, and fluid flow characteristics of faults and joints

C. Percent time devoted to project: ~15%

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Project Funding History

<u>Institution</u>	<u>Budget Period</u>	<u>Direct</u>	<u>Indirect</u>	<u>Total</u>
Stanford University	09/15/89 - 09/14/90	\$45,338	\$33,473	\$78,811
Purdue University	09/15/89 - 09/14/90	\$40,053	\$16,154	\$56,207
Stanford University	09/15/90 - 09/14/91	\$41,941	\$32,714	\$74,655
Purdue University	09/15/90 - 09/14/91	\$39,549	\$16,451	\$56,000
Stanford University				
Pollard	09/15/91 - 09/14/92	\$56,662	\$31,447	\$88,109
Aydin	09/15/91 - 09/14/92	\$50,843	\$28,218	\$79,061
Stanford University				
Pollard	09/15/92 - 09/14/93	\$60,947	\$33,826	\$94,773
Aydin	09/15/92 - 09/14/93	\$51,117	\$28,307	\$79,487

Project Overview

Specific Project Objectives

Fluid flow through fracture networks in a rock mass depends strongly on the nature of connections between fracture segments and between individual fractures. Therefore the objective of this research project is to develop three dimensional models for natural fracture connectivity using an integrated field, laboratory, and theoretical methodology.

The geometric models we have developed are based on detailed field mapping and observations from outcrops of both massive and layered sedimentary rocks, typical of producing oil and gas reservoirs, or of aquifers. Furthermore, we have used computer simulations and laboratory experiments to investigate the physical mechanisms responsible for fracture connectivity (or lack thereof) as single and multiple sets of fractures evolve. The computer models are based on fracture mechanics principles and the laboratory experiments utilize layered composite materials analogous to sedimentary sequences. By identifying the physical mechanisms of connectivity we can relate the degree of connectivity to the geometry, state of stress, and material properties of the reservoir rocks and, in turn, be in a position to evaluate the influence of these factors on fracture permeability.

Importance to the DOE Basic Energy Sciences Mission

This research has important implications for the energy industry because of the need to characterize fractures in oil and gas reservoirs and to provide conceptual models for the development of fluid flow simulations in such reservoirs. This research also has important implications for environmental remediation related to the storage and migration of contaminants (toxic and radioactive substances) in fractured rocks.

The connectivity of natural fracture networks is an important component of many sub-surface flow systems. Consequently, our understanding of the geometry of natural fracture networks directly affects our ability to accurately model such problems as waste isolation, ore deposit genesis, natural resource recovery and aquifer remediation.

As many as two hundred oil and gas fields have been identified in which natural fractures play an important role in hydrocarbon production. Knowledge of fractures not only is an exploration tool, but also it is essential for formation evaluation, estimation of reserves, expansion and further development of producing reservoirs, and planning and designing enhanced recovery methods. Furthermore, natural fractures and bedding discontinuities can influence the growth and final geometry of hydrofractures used to enhance production.

In spite of the significance of natural fractures to the petroleum industry, their quantitative study lags behind advances in other aspects of reservoir analysis. For example, very sophisticated reservoir simulation and production models are available, but they require knowledge of the three dimensional distribution of fracture permeability in order for their results to be meaningful. The lack of this knowledge and the lack of proven methods to gain it are urgent problems for the nation's energy industry.

The flow of water in aquifers is subject to similar dependencies on natural fracture systems as the flow of oil and gas. Although fracture patterns are very complex, the systematic nature of most natural fractures gives us confidence that we can reach an understanding of these structures

by using known physical principles. This understanding will help to quantitative the factors that control fluid flow and solute transport problems within the fields of hydrogeology and radioactive waste management.

Relationship to Research of Others

The results of our research are complimentary to geophysical imaging techniques now being developed by others. Typically our field observations provide a more precise and detailed picture of natural fracture patterns than can be resolved using current imaging technology. We can offer realistic examples of what geophysicists are attempting to resolve, thereby providing valuable information for their interpretations and constraints on their results.

Our results also are complimentary to geostatistical models for fractured reservoirs. Those models use geostatistical functions to extrapolate fracture network geometry from limited reservoir data. We are developing simulation models of fracture networks that are based on the solutions to specific boundary value problems of continuum and fracture mechanics and therefore are strongly rooted in the physics of the fracture process. These numerical models are tested using controlled laboratory experiments on the development of fracture sets.

Scientific and Technical Content

Field Studies

Field based research has involved the documentation of the vertical continuity (or the lack there of) of opening mode fractures in multi-layered sedimentary rocks. We have shown that opening fractures often step aside when they propagate across interfaces between dissimilar rocks and particularly across thin shale layers (Figure 1A & B). This result is important because it implies that thin shale layers and alternating dissimilar rocks impede flow in the vertical direction. Our field observations on the vertical connectivity of opening fractures has motivated laboratory and theoretical modeling that have identified conditions under which a fracture terminates at a material interface such as a bedding plane or cross it with either in-plane or out of plane geometry.

Field research has also elucidated the mechanism by which multiple sets of opening mode fractures develop. It is now quite obvious that temporal and spatial changes in the state of stress are responsible for the formation of two or more sets of fractures. These changes produce variations in the orientation of primary (continuous) sets as well as secondary (discontinuous) sets. Each primary set and associated secondary sets define a fracture domain (Figure 2A & B). The most urgent problems identified in the field research are the prediction of orientation of the primary set, the distribution and orientation of secondary sets, and the transition from one fracture domain to another.

A survey of fracture patterns in various sandstone formations of the Colorado Plateau, and experimental simulation of fracture domains as summarized below indicate that fracture domain boundaries provide the best fracture connectivity.

Laboratory Model Experiments on Fracture Sets

This work is based on an experimental procedure wherein a composite material, analogous to sedimentary strata, and made up of PMMA (plexiglass) and a brittle coating are loaded until

Figure 1: Joint geometry in multi-layered sedimentary rocks. A. Joint segment traces in siltstone layers showing side stepping nature of the trace across thin shale laminae. B. Surface ornaments on fracture segments in each siltstone layer indicating that they formed individually and that they were not connected before one side of the face fell off. Both A. and B. were mapped in the field in the Appalachian Plateau, in the state of New York (Helgeson and Aydin, 1991).

Figure 2A: Multiple sets of joints in the Entrada Sandstone exposed in southwest limb of the Salt Valley Anticline, Arches National Park, Utah. The NE striking set in the Moab Member (in upper left and lower right of the map) is the oldest. The NW striking sets (one set in the Moab Member in the center left, and the other in the Slickrock Member in the upper right side of the map) propagated from the tips of the NE set. The NS striking secondary set in the lower right corner is interpreted to be the upward extension of the joints in the Slickrock (Cruikshank and Aydin, in press).

Figure 2B: Map showing joint pattern in an area of overlapping joint domains. Abutting geometry of the joints of the two sets show that the NW striking joints (central part of Figure 2A) initiated at the tips of the NE striking joints (the set in the lower right corner of Figure 2A) and propagated away. The highest joint density as well as the highest degree of connectivity are in the overlap area (Cruikshank and Aydin, in press).

fractures form in the brittle coating. This method provides for nondestructive test in which whole sets of fracture can form and be recorded throughout all stages of their growth. Different loading configurations, summarized below, have been devised to study the different conditions believed applicable to sedimentary basins.

Fracture domains

Experiments were conducted to produce two fracture domains in which a uniform fracture domain was first produced, then the sample was rotated and loaded with the principle stress at an angle to the first-formed joint set. The purpose of these experiments was to study the effect of different local stress fields on final joint patterns in the intersecting zones. Each type of loading produced a characteristic pattern where the two joint domains overlapped (Figure 3A).

Observations in Arches National Park show that the overlapped areas of two joint domains contain joints of both orientations (Figure 3B). The interaction of joints in the overlapped zones allows the relative ages of individual members of each domain to be established.

Changing direction of loading

The effect of a flaw on the tangential stress distribution along the surface of a short fracture was modeled by small bubbles (10 to 30 μm in diameter) in the brittle coating. Both numerical and experimental results show that flaws which produce the first set of fractures also can produce the second set. Secondary fractures initiate from flaws within a certain range of the angle between the fracture and remote stress orientation. Beyond that range the fractures initiate from the tips of fractures of the first set.

Bed thickness and joint spacing

It has been widely observed that joint spacing is proportional to bed thickness in sedimentary rocks, but the changes of spacing with applied strain (stress) and time are not well known because of the experimental difficulties of modeling. Our experiments provide new information on this problem. Six thicknesses of brittle coating were considered: 0.03, 0.08, 0.13, 0.19, 0.25, and 0.28 mm. The area method, based on quantitative stereological principles, was used to measure spacing, S , and this was found to provide a better measure of spacing than the traditional line method of spacing, D , for poorly developed fracture sets (Figure 4).

The laboratory tests showed that spacing evolves toward fracture saturation and then does not change as the applied strain is increased (Figure 5e through 5g). End-member patterns of fractures are poorly-developed and well-developed where the latter implies fracture saturation. Spacing increases systematically with layer thickness if the fracture set is well-developed (Figure 5h).

Strain rate

In brittle rocks fracture growth can occur at velocities ranging over many orders of magnitude and this results in different fracture patterns and geometries. In these experiments various strain rates from $10^0/\text{sec}$ to $10^{-8}/\text{sec}$ were imposed. Geometric fracture parameters and propagation velocity depend significantly on applied strain rates under the same applied total strain. This suggests that some hydraulic properties such as the reservoir permeability of a fractured rock mass can be affected by changing loading rate.

Figure 3: Comparison of two fracture sets near a domain boundary at scales of 10mm and 100m. A. Brittle coating experiment with older (horizontal) set and younger (inclined) set of cracks. Inset at top shows experimental configuration of the brittle coating on a PMMA substrate. B. Aerial photograph of two fracture sets near domain boundary at Arches National Park.

Figure 4: Comparison of line spacing, D , and area spacing, S , for poorly- and well-developed laboratory fracture patterns. (a) A poorly-developed pattern with short fractures. The right graph is scattered readings of spacing, D , as a function of scanline position, x . Solid line represents the mean spacing, S , defined by the area method. The line method does not provide a consistent measure of spacing for poorly-developed fracture sets. (b) A well-developed pattern where most fractures cross the sample square (Wu and Pollard, in press).

Figure 5: Spacing versus applied strain for different thicknesses of brittle coating on PMMA substrate subject to bending strains. Each graph represents several different experiments at a particular thickness and with the same applied strain in the range zero to 5.5×10^{-3} . (e) 0.189 mm thick and ten experiments; (f) 0.249 mm thick and eleven experiments; (g) 0.373 mm thick and ten experiments; and (h) least square fitting of data from four different thicknesses (Wu and Pollard, in press).

Strain cycling

Surface textures (hesitation lines or rib marks) commonly found on natural opening-mode fractures (joints) in rock are indicative of cyclic loading. The effect of uniaxial strain cycling on the development of a set of fractures was studied under different strain rates and magnitudes. It was found that few new fractures appear after a certain number of cycles as old fractures keep getting longer. The geometric fracture parameters such as length and spatial density increase rapidly whereas those such as spacing decrease rapidly for the first several cycles and then all tend not to change very much.

Stress relaxation

One possible loading state for fracture initiation and propagation in a brittle rock layer is stress relaxation (constant strain). A constant strain field was transmitted by the model substrate causing changes in number and length of fractures, spacing, spatial density, and propagation velocity. It was found that most new fractures appeared within the first 10 minutes of loading in two- and eight-hour experiments. Increasing lengths of fractures depend on both relaxation time and the applied constant strain magnitude. Propagation velocity decreases very quickly. In general, the longer fractures propagate faster than the shorter fractures; the inner tips of two coplanar fractures propagate faster than their outer tips; and the inner tips of two en echelon fractures propagate faster at first and then slower than the outer tips as the inner tips overlap.

Concretions

Concretions are early-formed sedimentological structures that result from local cementation. The size of concretions ranges from approximately 1 mm to more than 1 m. If the concretion is large enough and is stiffer than the surrounding rocks, it will significantly affect the path of a nearby fracture.

A series of experiments were conducted to investigate the effect of concretions on fracture propagation path and geometry. Four different diameters of spherical (90%) glass beads were used with the brittle coating and PMMA substrate: 0.46, 0.23, 0.115, and 0.0575 mm. A crucial factor is the ratio of the diameter of the glass bead to the brittle coating thickness. If the ratio is greater than about 0.3 the effect of concretions on fracture path is significant, whereas if the ratio is less than about 0.3, the effect is almost negligible and propagating fractures may cut these glass beads without any change of their paths.

Laboratory Model Experiments on Mixed-mode Fracture Growth

Although often idealized as a pair of planar surfaces, natural fractures in rock are 3-dimensional structures and their geometric complexities can play an important role in the mechanical and hydrological behavior of a rock mass. For example, in the fringe region of many joints a set of smaller fractures emerge from the larger parent fracture and twist into a characteristic echelon geometry. Previous laboratory experiments have demonstrated that a set of fractures, similar in geometry to fringe joints can be created in mixed mode I-III loading. However, the dependence of the geometry of these fractures on the details of the loading history has, heretofore, not been well understood.

We have designed an experimental set up which imposes simultaneous tension and in-plane shear to a crack front within a block of PMMA (Figure 6). Our experiments produce fracture geometries that are similar to field observations of natural fractures. This suggests that natural fracture geometries can be interpreted in terms of the mixed-mode loading history. An increase in ratio of applied mixed mode loading increases the twist angle of echelon fractures in PMMA. An opposite sense of mode III loading results in echelon fractures with an opposite sense of twist

Figure 6: A. Twisting fracture produced in PMMA laboratory specimen by a constant actuator load ratio for mode III and mode I. Echelon fracture segments are only local to the breakdown zone. B. This sketch of a helicoidal surface shows the basic twisting nature of the fracture surface away from the breakdown zone. The sense of twist is consistent with the sense of shearing for the mode III loading.

about the parent crack plane. However, preliminary twist angle data are 30-50% of theoretical predictions of this angle.

Analysis of the experiments showed that loading was not simply a mixture of mode I and mode III, but also included some mode II. Future experiments will attempt to simplify the loading and more accurately mimic natural 3-dimensional fracture growth conditions.

Physically-based Numerical Models of Fracture Sets

Our work on the numerical simulation of fracture sets represents a departure from previous fracture investigations in that the problem of network simulation is attacked by modeling the mechanics of fracture formation rather than by randomly generating networks.

Specifically, we have: 1) Developed a simple and experimentally verified model for predicting the propagation behavior, and resulting connectivity, of fractures that propagate into one another; 2) Quantitatively demonstrated the effect of fluid diffusion on fracture propagation and derived fluid-limited fracture velocities; 3) Developed a computationally efficient numerical model of fracture network formation that incorporates current understanding of the physics of rock fracture and that accurately predicts the evolution of experimentally generated fracture sets; 4) Discussed the limitations of the current generation of numerical fracture propagation models.

Fracture propagation across interfaces

Understanding of how a propagating fracture interacts with existing fractures, lithologic boundaries and other material interfaces is essential to both the interpretation of fracture network geometries and to the prediction of fluid migration through the resulting fracture networks. To quantify our understanding of this interaction, we have used a first order analysis of the stresses near a fracture almost impinging upon a frictional interface which is oriented normal to the growing fracture to develop a simple criterion that predicts whether a growing fracture will terminate at or cross the interface. We have performed a series of experimental investigations designed to assess the conditions required for crossing and shown that the experimental results are consistent with the criterion. The criterion accurately predicts the occurrence of compressional crossing in eleven different brittle materials (Figure 7). The simplicity of the criterion makes it a prime candidate for incorporation into models of propagation for multiple fracture sets.

Natural hydraulic fractures

The interaction between multiple fractures propagating in the saturated subsurface is also influenced by the fluid pressure within the fractures. We define natural hydraulic fractures as being fractures having a propagation rate that is limited by the rate at which fluid enters the growing fracture from the saturated material. We have determined natural hydraulic fracture growth rates from a complete poroelastic model of natural hydraulic fracturing. Unlike previous studies of induced hydrofracturing, both the pressure within the fracture and fracture growth rate are determined from the simulation rather than specified as boundary conditions. A comparison of the growth rates predicted by the three different models for an isolated natural hydraulic fracture in various common rock types reveals that natural hydraulic fracture growth rates are primarily controlled by the material conductivity, the storage, and the initial flaw length.

Growth of a single fracture set

A physically-based model for the evolution of a single set of planar, parallel fractures subject to a constant remote stress has been developed. A comparison between experimental and numerical results has shown that the model can accurately simulate the development of

Figure 7: Plot of compressional stress acting across an interface versus the coefficient of friction for the interface including a summary of available crossing data. Results are shown along with the critical stress ratio criterion (solid line) and the tensile strength shear capacity criterion (dashed line) for comparison. The critical stress ratio criterion proposed here explains most of the available data (Renshaw and Pollard, 1991).

Figure 8: A comparison between the experimental and numerical evolution of a fracture set. Fracture sets were experimentally generated at the strain rates indicated using brittle coating techniques (Wu and Pollard, 1991). Many of the small flaws in the numerical simulation do not show up in the experimental simulation because they have not grown long enough to be visible. The thickness of the brittle coating is $\sim 0.02 \text{ cm}$ (Renshaw and Pollard, 1991).

experimentally-generated fracture sets (Figure 8). Once the initial flaw geometry is specified, only one parameter controls the growth of the fracture set. This parameter, the *velocity exponent*, relates fracture propagation velocity to stress concentration at the fracture tip. Monte Carlo sensitivity analyses suggest that this parameter also controls the extent to which fracture growth is concentrated within zones or clusters. Similar analyses suggest that the extent of fracture clustering is less sensitive to the initial flaw density. The permeability of the fracture set is dependent upon the degree of clustering within the network and thus a function of the velocity exponent.

Growth and hydraulic properties of multiple single fracture sets

We have demonstrated the effectiveness of the proposed computer code using simple networks composed of two orthogonal fracture sets. For comparison, Figure 9 shows the geometries of networks simulated using different values of the flaw density, d_0 , and the velocity exponent, α . Fracture networks having twice the base case flaw density ($d_0 = 0.001$; $\alpha = 1.0$) are spatially more dense than networks having a flaw density of half the base case, but both networks are qualitatively similar in other respects. On the other hand, the fracture length distribution for the case $\alpha = 0.5$ is nearly uniform, whereas the fracture length distribution of the case $\alpha = 2.0$ is highly non-uniform. Fracture growth is limited to fewer and fewer fractures as α increases. From examples such as this one, and from comparisons to natural fracture networks, we are satisfied that the model produces realistic network geometries.

Understanding the physical mechanisms leading to fracture connectivity is important to predicting in-situ permeability and these predictions are of central importance in reservoir simulations and management of reservoirs and aquifers. To illustrate how this can be done, consider a network of the type shown in Figure 9. Carl Renshaw has generated fifty different realizations of this network by starting fracture growth from different random distributions of flaws. In each realization the spatial density of the flaws, the material properties, and the loading conditions were identical. Hydraulic properties of these networks were investigated by fixing the head at a randomly selected point (representing the well) and along a circle of radius r centered at that point (Figure 10). For these simple tests the fracture aperture is constant and the flow follows the well-known cubic law. Within each group of fifty realizations two questions were asked: 1) What is the probability that the network percolates over some distance r ; and 2) Given that the network percolates, what is the mean normalized equivalent conductivity of the network? The answers to these questions depend on the fracture velocity exponent, α , as illustrate in Figure 10.

Project Accomplishments

Description of Major Results

Field research has documented vertical continuity (or the lack thereof) for opening-mode fractures in multi-layered sedimentary rocks. We have shown that opening fractures often step aside when they propagate across interfaces between dissimilar rocks and particularly across thin shale layers. This result implies that thin shale layers and alternating dissimilar rocks diminish fracture permeability in the vertical direction. Field research also has elucidated the mechanism by which multiple sets of opening mode fractures develop. It is now quite obvious that temporal and spatial changes in the state of stress are responsible for the formation of two or more sets of fractures. These changes produce variations in the orientation of primary (continuous) sets as well

Figure 9: Typical orthogonal fracture network geometries after each set has grown for 120 growth iterations. Networks were modeled using the base case velocity exponent and flaw density ($\alpha = 1.0$; $d_0 = 0.001$) except as indicated (Renshaw, Ph.D. thesis).

Figure 10: Model problem and results for fluid flow properties of physically-based fracture network (Renshaw, Ph.D. thesis). Upper illustration shows boundary conditions on hydraulic head used to determine the equivalent conductivity for flow to a well. A. Percent network percolating versus spatial density of fractures for different velocity exponents, α , and different radial distances, r . B. Conductivity versus spatial density.

as secondary (discontinuous) sets. Key problems are prediction of the orientation of the primary set, the distribution and orientation of secondary sets, and the transition from one to another.

Laboratory model experiments have been conducted in biaxial loading for one and two sets of opening-mode fractures in layered brittle materials using brittle coating techniques. These experiments enable us to study the mechanical and geometric characteristics of single and multiple fracture sets. We have designed experiments using pure bending to understand the relative ages and interconnection of multiple fracture sets in folded sedimentary sequences. Lateral discontinuities in fracture geometry are generally related to out-of-plane fracture growth, which is significant for understanding fracture geometry in massive sedimentary rocks. We have conducted laboratory experiments on PMMA blocks subject to mixed mode I-III loading and documented the nature of out-of-plane fracture breakdown into echelon segments as a function of loading history.

Theoretical models studies have focused on the growth of fracture networks, as fluid flow in fractured rock formations is largely controlled by the geometry of these networks. We have explored the physical factors (loading history, material properties, fracture interaction, etc.) that govern network development. A computationally efficient program for generating a single set of primary fractures has been developed. The resulting fracture patterns are consistent with field and laboratory patterns. Development of secondary fracture sets depends upon a criterion that determines whether members of the second set cut across members of the first set. A crossing criterion has been formulated and verified with laboratory model studies. Modeling of the flow properties has begun using the physically-based fracture networks.

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