Project Title
Models of Natural Fracture Connectivity—Implications for Reservoir Permeability

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Models of Natural Fracture Connectivity—Implications for Reservoir Permeability
Project Personnel and Funding

Principal Project Personnel

Atilla Aydin

A. Role in the project: Co-principal Investigator

B. Principal areas of research and expertise: Structural geology, neotectonics, rock fracture, and fluid flow characteristics of faults and joints

C. Percent time devoted to project: ~20%

D. Education:

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E. Professional employment:

1987-present  Associate Professor, Department of Earth and Atmospheric Sciences, Purdue University, W. Lafayette, IN.

David D. Pollard

A. Role in the project: Co-principal Investigator

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%

D. Education:

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E. Professional employment history:

1986-present  Professor, Dept. of Applied Earth Sciences and Dept. of Geology (joint appointment), Stanford University, Stanford, CA

Models of Natural Fracture Connectivity—Implications for Reservoir Permeability
Additional Project Personnel

Ken Cruikshank
B.S. (1983) Pennsylvania State University; M.S. (1987) University of Cincinnati; Ph.D. candidate Purdue University
Connectivity of Fractures, Arches National Park, Utah

Daniel Helgeson
B.S. (1987) Purdue University; M.S. (1990) Purdue University
Characteristics of joint propagation in the layered sedimentary rocks of the Appalachian Plateau, Central New York

Greg Ohlmacher
B.S. (1974) University of Maryland; Ph.D. candidate Purdue University
Mechanics of vein, fault, and solution surface formation in Bays Mountain, Southern Appalachians

Haiqing Wu
Experimental modeling of fracture networks in brittle layered systems

Scott Zeller
B.S. (1983) University of Wisconsin—Madison; M.S. candidate Stanford University
Numerical modeling of fracture spacing in brittle layered systems

Project Funding History

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Models of Natural Fracture Connectivity—Implications for Reservoir Permeability
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 subsurface 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.
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.

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 fractures form in the brittle coating. This method provides for nondestrutive 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 2A).

Observations in Arches National Park show that the overlapped areas of two joint domains contain joints of both orientations (Figure 2B). The interaction of joints in the overlapped zones allows the relative ages of individual members of each domain to be established.

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 (Figure 3A). 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 3B). The simplicity of the criterion makes it a prime candidate for incorporation into models of propagation for multiple fracture sets.
Bibliography

Published Papers


Abstracts Presented at Scientific Meetings


M.S. and Ph.D. Theses Supported by this Project


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 laminas. 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, in preparation).
Figure 2A: Comparison of fracture sets near a domain boundary. Brittle coating experiment with older set and younger set of cracks at scale of 10 cm. Inset at top shows experimental configuration of the brittle coating on a PMMA substrate.
Map of two fracture sets with domain boundaries at Arches National Park.

Figure 2A: Comparison of fracture sets near a domain boundary.
Figure 3: Plot of interface normal stress versus friction coefficient
Results are shown along with the critical stress ratio criterion (solid line) and the tensile strength shear capacity criterion (dashed line) for comparison. A. Laboratory data from this study. B. Summary of all available laboratory data. The critical stress ratio criterion proposed here explains most of the available data (Renshaw and Pollard, in preparation).