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

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Table of Contents

Project Personnel and Funding

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

SCHOOL	ATTENDED	MAJOR	DEGREE	YEAR
Istanbul Technical University	9/63 - 6/68	Geol. Engin.	B.A.	1968
Stanford University	9/72 - 1/74	Geology	M.S.	1974
Stanford University	1/74 - 1/78	Geology	Ph. D.	1978

E. Professional employment history:

1978-80	Assistant Professor, Dept of Geology, Technical University of Istanbul, Turkey.
1980-81	Post-doctoral Fellow, Department of Geophysics, Stanford University, CA.
1982-87	Assistant Professor, Department of Earth and Atmospheric Sciences, Purdue University, W. Lafayette, IN.
1987-1991	Associate Professor, Department of Earth and Atmospheric Sciences, Purdue University, W. Lafayette, IN.
1991-present	Associate Professor (Research), Department of Applied Earth Sciences, Stanford University, Stanford, CA.

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:

SCHOOL	ATTENDED	MAJOR	DEGREE	YEAR
Pomona College	9/61 - 6/65	Geology	B.A.	1965
Stanford University	9/65 - 6/68	Geology	Ph.D.	1969
Imperial College of the University of London	9/68 - 6/69	Geology	D.I.C.	1969

E. Professional employment history:

1970-1974	Assistant Professor, Dept. of Geological Sciences, University of Rochester, Rochester, NY
1974-1983	Geophysicist and Project Chief, U.S. Geological Survey, Branch of Tectonophysics, Menlo Park, CA
1983-1986	Associate Professor, Dept. of Applied Earth Sciences, Stanford University, Stanford, CA
1986-present	Professor, Dept. of Applied Earth Sciences and Dept. of Geology (joint appointment), Stanford University, Stanford, CA

Additional Project Personnel

Michele Cooke

B.S. E.(1989) Princeton University; M.S. (1991) Stanford University; Ph.D. candidate Stanford University

Laboratory experiments on mixed mode I-III propagation of fractures

Ken Cruikshank

B.S. (1983) Pennsylvania State University; M.S. (1987) University of Cincinnati; Ph.D. (1991) Purdue University; Postdoctoral student (1991-present) Stanford 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. (1991) Purdue University

Mechanics of vein, fault, and solution surface formation in Bays Mountain, Southern Appalachians

Carl Renshaw

B.A. (1988) Carleton College; M.S. (1990) The Johns Hopkins University; Ph.D. candidate Stanford University
Numerical modeling of fluid migration through physically-based fracture networks

Haiqing Wu

B.A. (1982) Peking University; M.S. (1985) Peking University; Ph.D. (1990) Inst. of Geophys., Chinese Academy of Sciences, Beijing; Ph.D. candidate Stanford University
Experimental modeling of fracture networks in brittle layered systems

Scott Zeller

B.S. (1983) University of Wisconsin—Madison; M.S. (1991) Stanford University
Numerical modeling of fracture spacing in brittle layered systems

Project Funding History

Institution	Budget Period	Direct	Indirect	Total
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

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 resouce 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 Summary

Field Studies

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 1A & 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 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.

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.

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/sec to 10^{-8}/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.

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 co-planar 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.

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.

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 hydrofracing, 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 experimentally-generated fracture sets (Figure 3). 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.

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Renshaw, C.E. and Pollard, D.D., The Development of Fracture Connectivity by Propagation Across Unbonded Frictional Interfaces: An Experimentally Verified Criterion. Submitted to the *International Journal of Rock Mechanics and Mining Science and Geomechanical Abstracts*, December, 1992.

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

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Ohlmacher, G.C., 1991, Mechanics of vein, fault, and solution surface formation in Bays Mountain, Southern Appalachians. Ph.D. Thesis, Purdue University, West Lafayette, Indiana, 210 p.

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M.S. and Ph.D. Theses in Preparation

Wu, Haiqing, in preparation, A model study of fracture generation in layered brittle rocks with applications to predicting dubsurface fracture networks. Ph.D. Thesis, Stanford University, Stanford California, 200p.

Cooke, M., in preparation, Frictional interfaces and fractures in multilatered systems; applications to bending of rock. Ph.D. Thesis, Stanford University, Stanford California

Figures

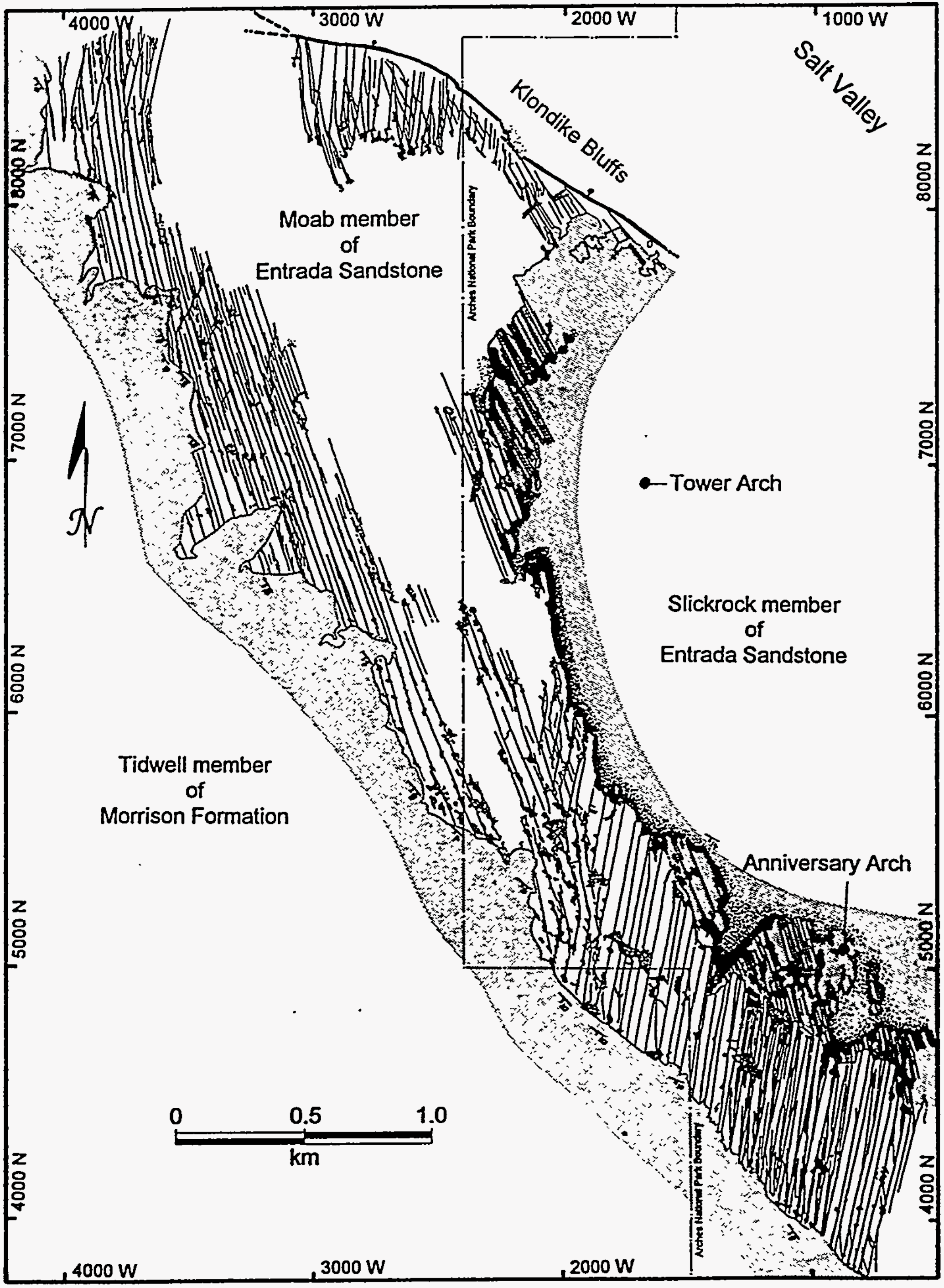

Figure 1A: Multiple sets of joints in the Entrada Sandstone.
These fractures are exposed in southwest limb of the Salt Valley Anticline, Arches National Park, Utah. The NE striking set in the Moab Member (in upper left and lower right of the map) is the oldest. The NW striking sets (one set in the Moab 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).

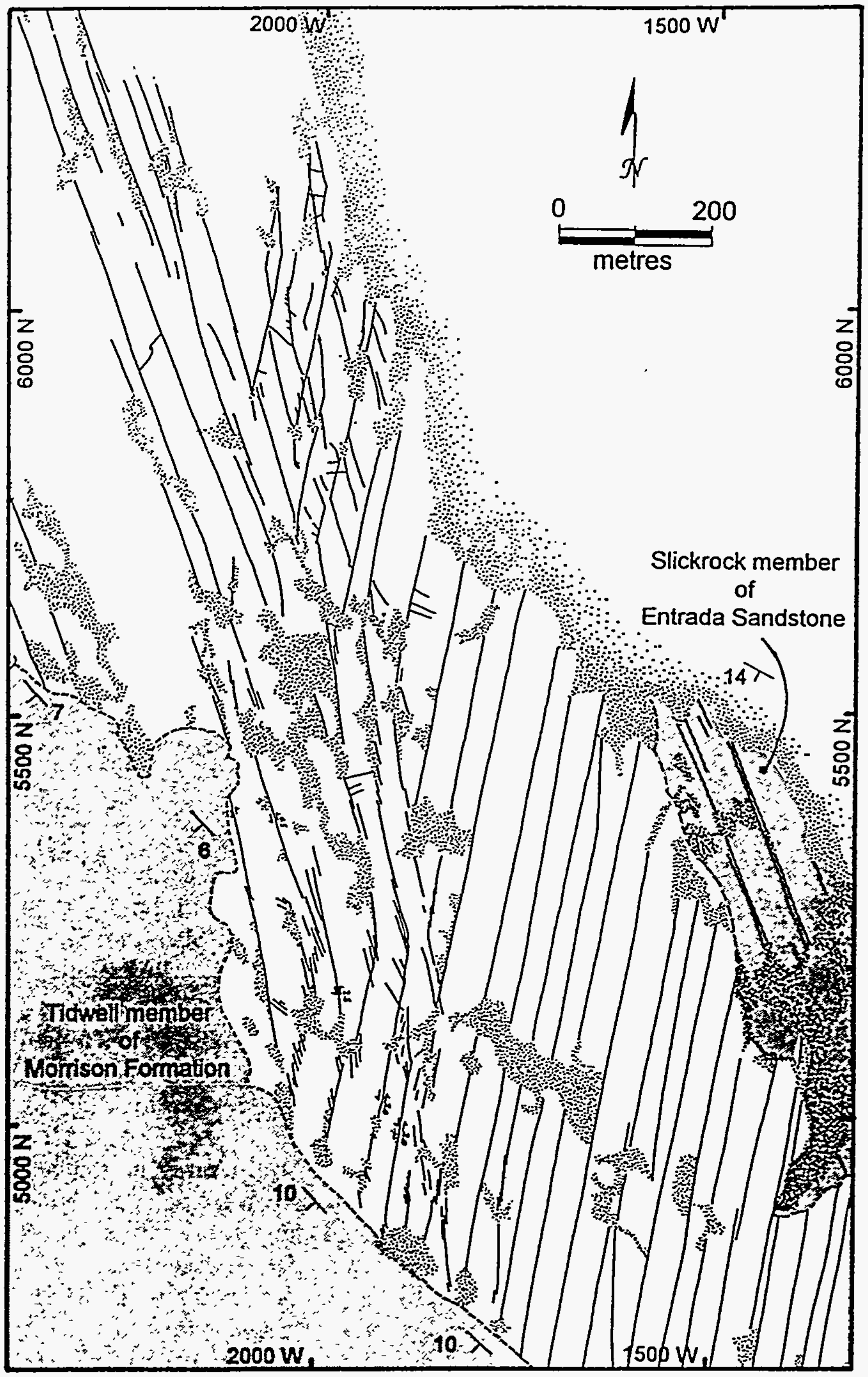

Figure 1B: Map of joint pattern in an area of overlapping joint domains. Abutting geometry of the joints of the two sets show that the NW striking joints (central part of Figure 1A) initiated at the tips of the NE striking joints (the set in the lower right corner of Figure 1A) and propagated away. The highest joint density as well as the highest degree of connectivity are in the overlap area (Cruikshank and Aydin, in press).

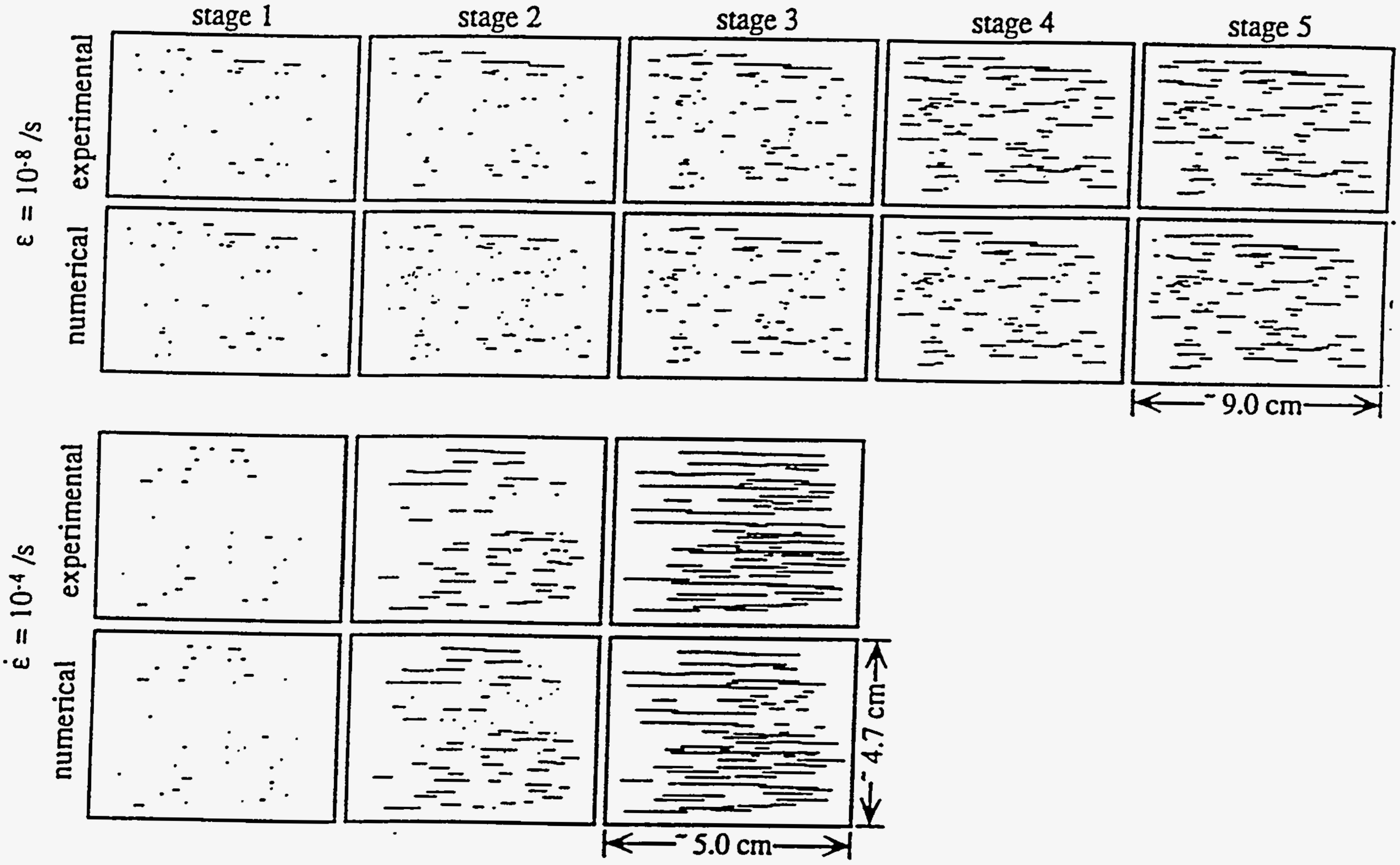

Figure 3: Comparison of experimental and numerical fracture sets. Fracture sets were experimentally generated at the strain rates indicated using brittle coating techniques (Wu and Pollard, 1991). Many of the small flaws in the numerical simulation do not show up in the experimental simulation because they have not grown long enough to be visible. The thickness of the brittle coating is ~0.02 cm (Renshaw and Pollard, 1991).