OCT 23 1990

90/10/02/NMC

MEMORANDUM FOR: Ronald L. Ballard, Chief
Geosciences & Systems Performance Branch
Division of High-Level Waste Management

FROM: Neil M. Coleman, Hydrogeologist
Hydrologic Transport Section
Geosciences & Systems Performance Branch

SUBJECT: TRIP REPORT FOR USGS SYMPOSIUM TITLED "FRACTURES, HYDROLOGY, AND YUCCA MOUNTAIN"

During September 13-14, 1990, I attended the subject meeting in Denver, Colorado. This symposium is part of the program established by the USGS Committee for the Advancement of Science in the Yucca Mountain Project (CASY). My trip report is attached, along with copies of abstracts that were made available by the organizers. The next in this series of symposia is tentatively planned for February, 1991.

During the course of this symposium, past hydrogeologic testing at the C-hole site was discussed. This is the location of three boreholes (UE-25c #1,#2,#3) which will be used for multiwell hydrologic tests and tracer tests. The boreholes were drilled during the period from August 1983 to June 1984. Numerous hydrologic tests, including packer, drawdown, and tracer tests, were conducted during 1984 and 1985, according to a 1986 Fenix & Scisson, Inc. document titled "NNWSI Hole Histories" (DOE/NV/10322-14). The results of these tests have not been published. According to the USGS representatives, although a report is in preparation, no estimate is available for its publication date.

Prior to this trip, I contacted our On-Site Licensing Representative, Paul Prestholt, concerning data from past testing at the C-hole site. He submitted a request for this data to the DOE office in Las Vegas. Last week a package of documents relevant to the C-hole testing arrived from the DOE. This package includes a draft USGS memorandum dated March 17, 1986 that summarizes past work done at the C-hole site.

Please contact me if you have any questions about this trip report. I am prepared to brief you on any aspects of this trip.

/S/

Neil M. Coleman, Hydrogeologist
Hydrologic Transport Section
Geosciences and Systems Performance Branch, NMSS

Attachments: As Stated

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TRIP REPORT, SEPTEMBER 13-14, 1990
Neil M. Coleman
Hydrologic Transport Section

USGS Symposium: "Fractures, Hydrology, and Yucca Mountain"

"Fractal Scaling of Fracture Networks in Rock" - C. C. Barton (USGS)

Christopher C. Barton presented this talk and described the general concept of applying fractal theory to geologic structure. Barton's work is an extension of field work conducted at Yucca Mountain. Results of the earlier work were published in a report titled "Fractures in Outcrops in the Vicinity of Drill Hole USW G-4, Yucca Mountain, Nevada." This is report USGS-OFR-89-92, published in 1989, which he coauthored with W. R. Page and T. L. Morgan. The report describes measurements taken on 5,000 fractures at 50 outcrop stations, mainly from rocks of the Tiva Canyon Member of the Paintbrush Tuff.

The work by Barton's team has included so-called "pavement studies," where rock surfaces have been exposed by removing soils and regolith using high-pressure water hoses. In a sense, these studies have created "outcrops" where none existed and provide a basis for comparing fracturing in level terrain with fracturing in existing outcrops. Barton showed slides of several of these pavements, along with the fracture networks that have been revealed and mapped. The investigators went to great lengths to record in detail the patterns and density of fractures in the pavements. My impression is that these pavements record the tectonic history of the Tiva Canyon Member, and may provide insight about the general tectonic history of Yucca Mountain. The pavement surfaces are approximately perpendicular to the prevailing vertical fracture orientations. Thus, the pavements reveal much more information about fracture patterns than could be obtained from vertical boreholes, which intersect very few subvertical fractures.

Barton's team found some unusual structures on several of the pavements. These features were wide fracture zones filled with saprolite. When excavated, these fracture zones appeared trench-like, and were colloquially referred to as "black holes" because of their ability of absorb large quantities of water. They are evidently wide fracture zones that have experienced considerable infiltration and weathering in the past. The fact that these fractures are normally filled with sediments would protect them to a large extent from rapid infiltration. However, if such structures exist in the bedrock beneath washes they may become loci of infiltration during precipitation events of great magnitude. During such events, ephemeral zones of perched saturation may be created in the sediments of the washes, inducing infiltration along preferential flow paths.

It may be possible for the DOE to coordinate some future infiltration tests with additional pavement studies. For example, Activity 8.3.1.2.2.1.3 describes artificial infiltration studies. It is possible, for example, to conduct infiltration studies in areas with thin soils, and later to expose the underlying pavements. Properties of the fracture networks could then be related to the previously measured infiltration rates.

"Modeling Saturated-Zone Ground-Water Flow at Yucca Mountain and Vicinity: Can we adequately simulate fracture flow?" - J. Czarnecki (USGS)

John Czarnecki discussed conceptual models of the hydrogeology at Yucca Mountain. He discussed the large hydraulic gradient located north of the site. This gradient trends northeasterly between well pairs USW G-1 and G-2 and UE-25 WT #16 and WT#6. A fault model has already been hypothesized to account for this gradient. Another conceptual model would involve an increase in saturated fracture abundance from north to south, or an increase in fracture mineralization from south to north. Both cases would indicate an increase in hydraulic conductivities from north to south.

The importance of well USW UZ-1 was discussed in relation to the large hydraulic gradient. This well was originally intended to terminate above the water table. However, at a depth of 387 meters a large inflow of water was encountered which could not be significantly lowered. The well was completed at that depth and instrumented. It was originally assumed that the well had reached a perched zone. However, Czarnecki noted that it is important to determine whether this well actually encountered the water table. If UZ-1 penetrated the water table, then the hydraulic gradient in that vicinity is very large, about 0.5. Such a large gradient, if confirmed, would make a fault model more likely and would argue against models that invoke gradual directional changes in rock properties.

Czarnecki also discussed the C-hole complex and planned testing. In conjunction with hydrologic testing, geophysical studies will be used to characterize the rock volume between the C-holes. Earlier testing at this complex showed evidence for fracture flow based on tracer tests and fluid temperature surveys. He considers that testing at the C-holes will lead to state-of-the-art analyses, but that the results cannot be extrapolated over the entire site. More than one multi-well site will be needed to characterize aquifer properties at the site. This view is consistent with NRC's SCP Comment 20, which states that "Data from tests at additional well complexes are necessary to confirm hypotheses formulated from tests at the C-hole complex."

The following points were noted regarding future hydrologic testing at Yucca Mountain: (1) fracture flow must be assumed; (2) packers must be carefully placed to isolate test intervals; and (3) major production zones can occur in almost any stratigraphic unit due to the role of fractures.

"Response of Groundwater to Seismic Activity" - S. Rojstaczer (Duke U.)

Stuart Rojstaczer presented a hydrologic evaluation of the Loma Prieta earthquake in California. This earthquake, of magnitude 7.1, occurred on October 17, 1989. Hydrologic effects of this earthquake include the lowering of water levels in wells, an increase in streamflows by an order of magnitude, and a significant increase in ionic concentrations in affected streams. Rojstaczer developed a simple conceptual model in which the seismic activity caused widespread changes in aquifer properties, including an enhanced fracture network with increased permeability, resulting in increased recharge to streams and a correspondingly lowered water table. Water levels in wells diminished by 10-50 meters.

Regardless of whether Rojstaczer's model is correct, an apparent transient response to seismic activity of aquifer properties and aquifer and stream interactions was demonstrated. Thus, there is evidence that hydraulic conductivity and porosity cannot always be treated as stationary aquifer properties, particularly in regions that experience severe seismic events.

"Hydrologic Analysis of Periodic Strain Waves: Atmospheric, Earth Tide, and Seismic" - D. Galloway

As part of the poster session, Devin Galloway presented hydrologic data from a series of wells at Yucca Mountain, including UE-25 c#1, c#2, c#3, USW H-3, USW H-4, USW H-6, and UE-25 p#1. The data are derived from water level responses to measured changes in atmospheric pressure, earth tides, and seismic energy. A table of the data is attached.

Galloway concluded that water table conditions exist at the C-holes where the water table occurs near the upper contact of the Calico Hills unit. Deeper zones measured in the Bullfrog and Tram members of the Crater Flat Tuff show some hydraulic connection to the water table for stresses of greater than 8-12 hours duration. Aquifer fluid pressures measured in UE-25 p#1 and USW H-4 (in zones below the packer) are hydraulically isolated from the water table for stresses of not less than 10 days duration.

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"Hydrologic analysis of periodic strain waves: atmospheric, Earth tide, and seismic" - D. Galloway (USGS)

ESTIMATES OF RESERVOIR HYDRAULIC PROPERTIES

ESTIMATES FROM EARTHTIDES AND ATMOSPHERIC LOADS

Well Number and Monitored zone	Barometric Efficiency (BE)	Hydraulic Diffusivity $D(cm^2/s)$	Aquifer Porosity n(%)	Specific Storage $\times 10^{-9}$ $S_s(cm^{-1})$
UE-25c#1 Calico Hills/Prow (above packer)	0.80	423	27	13.6
UE-25c#3 Calico Hills/Prow (above packer)	0.80	325	28	14.4
UE-25c#3 Bullfrog/Tram (below packer)	0.87	181-386	10	4.86 9.43 (values from two components of earth tide)
USW H-4 Lithic Ridge (below packer)	0.80	40.4	6	3.17
USW H-6 Tram/Lithic Ridge (below packer)	0.95	23.5	----	----
UE-25p#1 Lone Mt. Dolomite (below packer)	0.75	< 18	0.06	0.03

HYDRAULIC PROPERTIES BASED ON DAMPED WELL RESPONSE TO SEISMIC ENERGY

Well Number	Transmissivity	Storativity
USW H-3 (below packer)	-----	$> 1.0 \times 10^{-4}$
USW H-4 (below packer)	1.05 m^2/day	-----

USGS Committee for the Advancement of Science in the Yucca Mountain Project Symposium

"Fractures, Hydrology, and Yucca Mountain" Symposium Agenda
September 13 & 14, 1990

September 13, 1990

Time	
7:45-8:15	**Registration**
8:15-8:30	**Announcements**
8:30-9:00	**I. Overview -** "The role of fractures in groundwater hydrology", C. Neuzil (USGS-R)
	II. Fracture Generation & Behavior
	A. Descriptive tools
9:00-9:30	1. Fractals - "Fractal analysis of fracture networks", C. Barton (USGS-D)
9:30-10:00	2. Statistics - "Statistical properties of real fracture networks", E. Verbeek (USGS-D)
10:00-10:15	**Coffee Break**
	B. Observational constraints
	1. Field-
10:15-10:45	"Field description and measurement of mesoscopic faults with special application to kinematic and paleostress analyses", S. Minor (USGS-D)
10:45-11:15	2. Fracture mineralization - "Distribution of fracture-lining minerals at Yucca Mtn", B. Carlos (LANL)
11:15-11:45	3. Seismic anisotropy- "Seismic imaging for fracture characterization and crustal definition", E. Majer (LBL)
11:45-1:00	**Lunch**
	C. Models
1:00-1:30	"Void structure and flow in single fractures", Larry Myer (LBL)
1:30-2:00	"The role of factures in underground fluid flow", M. Cleary (MIT)
2:00-2:15	**Coffee Break**
	III. Stress & Strain as Driving Functions for Flow
	A. Regional Stress/strain field
2:15-2:45	"The stress field at Yucca Mountain and in surrounding regions", J. Stock - (Harvard)
2:45-3:15	"Examples of historical height changes in the southern Great Basin", T. Gilmore - (USGS-M)
3:15-6:30	**YMP Posters/Refreshments/Informal Discussion**

September 14, 1990

8:15-8:30 **Recap of Previous Day,** R. Wheeler (USGS-D)

8:30-9:00 "Hydrologic information squeezed from the response of pore fluids to crustal deformation", S. Rojstaczer (Duke)

B. Earthquakes

9:30-9:30 "Earthquakes and fluid flow", J. Rudnicki (Northwestern)

IV. Flow Models

A. Modeling

9:30-10:00 "Modeling flow and solute transport through a variable aperture, partially saturated fracture", R. Healy (USGS-D)

10:00-10:15 **Coffee Break**

10:15-10:45 "Modeling of flow in fracture networks", K. Karasaki (LBL)

10:45-11:15 "Computer modeling of 3-D coupled heat-mass-stress effects", S. Kelkar (LANL)

11:15-11:45 "Flow through variable aperture fractures", J. Smoot (PNWL)

11:45-1:00 **Lunch**

B. Applications to Yucca Mountain

1:00-1:30 "Modeling saturated-zone ground-water flow at Yucca Mountain and vicinity: can we adequately simulate fracture flow?", J. Czarnecki (USGS-D)

1:30-2:00 "Vapor phase flow and transport in Yucca Mtn", G. Zyvoloski (LANL)

2:00-2:30 "Application of discrete fracture analysis to repository characterization and performance assessment", Tom Doe (Golder Assoc.)

2:30-2:45 **Coffee Break**

2:45-4:00 **Wrap-Up -** K. Karasaki (LBL), D. Galloway (USGS-S), D. Gillies (USGS-D)

Abbreviations: USGS-D = USGS Denver, USGS-M = USGS Menlo Park, USGS-R = USGS Reston, PNWL = Pacific NW Lab, LANL - Los Alamos National Lab, LBL - Lawrence Berkley Lab, USGS-S = USGS Sacramento

Void Structure and Flow in Single Fractures

L. R. Myer

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The development of a successful geologic repository in a fractured rock mass requires an understanding of the fluid flow in the fractures as a function of stress.

Tests conducted on natural fractures have shown that single phase flow decreases much more rapidly with stress than would be predicted by a model representing the fracture as two parallel plates. However, after cycling, mechanical measurements indicate that fracture deformation, at least in some rock types, is largely elastic. To begin to understrand this behavior a liquid metal (Wood's metal) injection technique has been developed in order to obtain casts of the void space in a fracture under different normal loads. These measurements show that while large voids remain even at high stress levels, the connections between these voids become more and more tortuous. One approach to modelling single phase flow is to use a stratified percolation model to generate a correlated aperture pattern similar in appearance to the Wood's metal casts. Fracture deformation is modelled as a uniform reduction in all apertures such that all rock deformation is accommodated by a change in void volume. Using a network model, flow is calculated at each stress level. Results show that this approach satisfactorily simulates the observed relationship between aperture change and flow.

As an alternative approach, the areas of contact in a fracture have been modelled by a "carpet" of cones, so that the contact area increases as fracture deformation increases. Assuming fracture deformation is accommodated by a change in void volume, and using an effective conductance to account for increased tortuosity due to the contact area, good

Posters

"GSIS and Fractures at Yucca Mountain"
Downey, Kolm, Turner, and Ervin.

"Rhyolite flow fields as barriers to paleohydrologic flow in eastern Nevada and western Utah at latitude 37°30'N"
E. Anderson, T. Barnhard

"Rock-water interaction in ash-flow tuffs, Yucca Mountain, Nevada: The record from uranium studies"
R. Zielinski

"Fracture influence on seismic velocities, Rainier Mesa to Yucca Mountain"
S. Harmsen

"Determining fracture system geometry from well tests"
T. Doe

"Hydrologic analysis of periodic strain waves: atmospheric, Earth tide, and seismic"
D. Galloway

"Fracture studies in the Welded Grouse Canyon Tuff: Laser drift of the G-Tunnel underground facility, Rainier Mesa, Nevada Test Site, Nevada"
S. Diehl, M. Chornack, H. Swolfs, J. Odum

"Fracture counts from borehole logs"
P. Nelson, R. Snyder

"Structure of the upper crust (0-4 km) at Yucca Mountain"
W. Mooney

"Flow in rough-walled fractures"
Zimmerman, Kumar, Bodvarsson

"Mapping the base of the tertiary with seismic reflection profiles in Crater Flat and Yucca Mountain"
T. Brocher

USGS Committee for the Advancement of Science in the Yucca Mountain Project -

'Fractures, Hydrology, and Yucca Mountain' Symposium Participants

Speakers
C. Neuzil (USGS-R)
S. Minor (USGS-D)
B. Carlos (LANL)
E. Majer (LBL)
C. Barton (USGS-D)
E. Verbeek (USGS-D)
L. Myer (LBL)
M. Cleary (MIT)
S. Rojstaczer (Duke)
T. Gilmore - (USGS-M)
J. Stock - (Harvard)
R. Wheeler (USGS-D)
J. Rudnicki (Northwestern)
R. Healy (USGS-D)
K. Karasaki (LBL)
S. Kelkar (LANL)
J. Smoot (PNWL)
J. Czarnecki (USGS-D)
G. Zyvoloski (LANL)
Tom Doe (Golder Assoc.)
D. Gillies (USGS-D)
D. Galloway (USGS-S)

Poster Presenters
J. Downey (USGS-D)
J. Kolm (USGS-D)
Turner (USGS-D)
E. Ervin (USGS-D)
E. Anderson (USGS-D)
R. Zielinski (USGS-D)
S. Harmsen (USGS-D)
T. Doe (Golder Assoc.)
D. Galloway (USGS-S)
S. Diehl (USGS-D)
M. Chornack (USGS-D)
H. Swolfs (USGS-D)
J. Odum (USGS-D)
P. Nelson (USGS-D)
R. Snyder (USGS-D)
W. Mooney (USGS-M)
R. Zimmerman (LBL)
S. Kumar (LBL)
G. Bodvarsson (LBL)
T. Brocher (USGS-M)

Participants
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C. Boughton (USGS-D)
T. Brady (USGS-D)
T. Brocher (USGS-M)
T. Buono (USGS-LV)
F. Byers (USGS-D)
W. Carr (USGS,Sandia)
D. Chesnut (LLNL)
N. Coleman (NRC)
C. Cope (USGS-D)
R. Craig (USGS-LV)
P. Domenico (USNWTRB)
W. Dudley (USGS-D)
C. Fridrich (DOE-LV)
A. Geldon (USGS-D)
J. Gemmell (USGS-D)
J. Gibbons (USGS-D)
J. Gomberg (USGS-D)
L. Hayes (USGS-D)
D. Hoxie (USGS-D)
P. Justus (NRC)
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E. Kwicklis (USGS-D)
R. Laczniak (USGS-LV)
G. LeCain (USGS-D)
L. Lehman (Lehman & Assoc.)
B. Lewis (USGS-D)
D. Lobmeyer (USGS-D)
R. Lucky (USGS-D)
F. Maestas (USGS-D)
S. Mahan (USGS-D)
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J. Rousseau (USGS-D)
C. Savard (USGS-NV)
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V. Schneider (USGS-R)
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F. Thamir (USGS-D)
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C. Throckmorton (USGS-D)
V. Tidwell (Sandia)
S. Wheatcraft (DRI)
M. Whitfield (USGS-D)

<u>Abbreviations</u>
USGS-R - USGS Reston
USGS-D - USGS Denver
USGS-M - USGS Menlo Park
USGS-S - USGS Sacramento
USGS-LV - USGS Las Vegas
LANL - Los Alamos National Lab
LBL - Lawrence Berkely Lab
MIT - Mass. Institute of Technology
PNWL - Pacific Northwest Lab
CSM - Colorado School of Mines
LLNL - Lawrence Livermore Natl Lab
NRC - Nuclear Regulatory Commission
USNWTRB - US Nuclear Waste
Technical Review Board
Burec-D - Bureau of Reclamation Denver
DRI - Dessert Research Institute

agreement with observed results has been obtained.

Two phase flow and capillary pressure characteristics in a fracture under stress have been simulated using the stratified percolation model. As a zeroth order approximation relative permeability of the non-wetting phase is based on the flow through the critical neck of the pattern, that is, the smallest aperture along the connected path of highest apertures. Flow of the wetting phase is based on flow through the critical connection on one or more percolating paths, and includes a scaling correction to account for tortuosity. Results suggest a critical saturation is needed for two phase flow to exist. In the laboratory, mercury porosimetry measurements have been performed on a single natural fracture to investigate its capillary pressure characteristics as a function of applied stress. In addition, flow measurements have been made using mercury as a non-wetting fluid. Results suggest that relative permeability (of the non-wetting phase) is most sensitive to changes in stress at low stress levels. Comparison with modelling results indicates that the relationships between applied stress and both capillary pressure characteristics and relative permeability are sensitive to the form of aperture distribution.

Seismic Imaging for Fracture Characterization and Structural Definition

E. L. Majer, J. E. Peterson, L. R Myer, T. M. Daley
K. Karasaki, and T. V. McEvilly

Center for Computational Seismology, Lawrence Berkeley Laboratory, Berkeley, California 94720

VSP and crosshole tomographic methods are being developed and tested as part of DOE's nuclear waste program for characterizing the Yucca Mountain site. Work has been progressing in the develpoment of models for understanding seismic wave propagation in fractured 3-d heterogeneous media and in field testing fracture characterization methods. These field experiments have been utilizing high frequency (1000 to 10000 Hz.) signals in a cross-hole configuration at scales of several tens of meters. Three component sources and receivers are used to map fracture density, and orientation. The goal of the experiments has been to relate the seismological parameters to the hydrological parameters, if possible, in order to provide a more accurate description of a starting model for hydrological characterization. Results of these controlled experiments indicate that the fractures have a significant effect on the propagation of the P and S-waves. Laboratory experiments indicate that saturation also has a dramatic effect as well. Work involving the verification of the stiffness theory indicates that the theory is valid and at high frequencies (greater than a few kilohertz) the greatest effect is on the amplitude, and at lower frequencies the greatest effect is on the velocity or delay of the seismic waves. In addition to these controlled experiments, multicomponent VSP work has been carried out at several sites to determine fracture characteristics. The results to date indicate that both P-wave and S-wave can be used to map the location of fractures. In addition, fracture that are open and conductive are much more visible to seismic waves than non-conductive fractures. Recent work at the Nevada Test Site indicates that the Paintbrush Tuff is heterogeneous with respect to both P- and S-wave properties. There is observed anisotropy in the shear wave VSP data, but the anisotropy seems to be associated with near surface sediments (100 meters and less) and not associated with the Tuff.

Fracture Counts from Borehole Logs

by P. H. Nelson, R. Snyder, and J. E. Kibler
U. S. Geological Survey, Denver

Fractures detected by the sonic waveform, televiewer, and television tools are composited for borehole H-4 at Yucca Mountain, and plotted as a function of depth alongside the caliper, density, and resistivity logs, as well as a flow log obtained with radioactive tracers. Of the three fracture logs, the sonic waveform provides the least information on individual fractures; almost all disruptions in the waveform occur at depths where fractures are recorded on the televiewer and television. The televiewer provides a lower fracture count than the television; almost all fractures detected by the televiewer are also recorded on the television. The televiewer shows that most fractures are steeply dipping with a median dip angle of degrees (dip angle was not available from the television). The azimuth of the dip vector is roughly WNW. If a dip measurement can be added, then the television is the preferred tool for recording fractures at Yucca Mountain because more fractures are recorded with it than with the televiewer and because it operates in both liquid-filled and air-filled boreholes but the televiewer requires a liquid-filled borehole.

The H-4 flow log shows that the most permeable zones lie in the upper part of the Bullfrog Member and the upper part of the Tram Member of the Crater Flat Tuff. The television log shows these two zones to be among the most fractured zones in the lower 650 m of H-4. The resistivity and density logs indicate that neither zone is altered (zeolitic). The low resistivity zones are interpreted to be zeolitic; in general they are zones of no flow or low flow with few or no fractures. The lower part of the Tram Member is a good example of a low resistivity (zeolitic), no flow unit with few fractures.

The flow log was divided into 37 intervals and a plot of change in percent flow vs. fracture count from television was constructed. The plot shows a number of zones with fractures but no flow, one zone with flow but no fractures, and a scatter of data that shows no obvious increase of flow with increased fracture count. However, when the data are plotted with cumulative flow vs. cumulative fracture count, then a monotonic step-wise curve demonstrates that flow does in general increase with fracture count. There are no prominent single-fracture "thief zones" contributing most of the flow nor are there zones of intense fracturing contributing most of the flow.

FIELD DESCRIPTION AND MEASUREMENT OF MESOSCOPIC FAULTS WITH APPLICATION TO KINEMATIC AND PALEOSTRESS ANALYSES

Scott A. Minor
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As with other types of fractures, faults can have considerable influence on the flow of ground water, acting either as flow conduits or barriers, or both depending on spatial variations in fault characteristics. Physical characterization of faults can be useful to hydrologists in developing realistic ground-water flow models of faulted terranes such as that at Yucca Mountain, Nevada. Perhaps less apparent is the utility of studies addressing the kinematics and causes of faulting, including paleostress determinations. Knowledge of these aspects of faulting in areas of good accessibility can greatly facilitate predictions of overall fault geometries and internal fault structure in nearby subsurface rock masses lacking adequate structural control. Furthermore, deriving orientations and estimating magnitudes of paleostresses associated with various faulting episodes can be valuable in predicting how the same fractured rocks will respond to the present regional stress field and local, man-induced stress changes resulting from repository excavation. In the Yucca Mountain region, mesoscopic faults -- faults that commonly can be seen in their entirety in outcrop and that generally show net offsets of < 5 m -- are best exposed and lend themselves well to detailed observation.

Measurable aspects of mesoscopic faults include: 1) orientation; 2) shape (i.e. deviation from planar geometry); 3) surface dimensions; 4) rake of slickenside striae; 5) net offset (or separation); 6) fault-zone width; 7) aperture; and 8) fault spacing. Important elements of fault zones are composition and structural fabric. Fault zones usually include various combinations and arrangements of fault breccia, clay gouge, and subsidiary fractures, including Riedel shears and tension fractures; any one of these may be lacking in a given zone. Critical in kinematic studies is the determination of slip sense on individual faults using: 1) geometrical relations of various types of subsidiary fractures in and bordering the fault zone, and genetically related to it; 2) asymmetrical polish; 3) tool marks; 4) vesicle smears; 5) arrangement of syn-slip mineral growths; 6) drag folds; and (or) 7) offset features such as marker beds. Important observations concerning the relative age of faults are: 1) presence, type, and spatial distribution of pre-, syn-, and post-slip minerals; 2) cross-cutting relations of faults and slickenside striae; and 3) age constraints from faulted stratigraphic units. Attitudes of bedding, compaction foliations, or other paleodatums and determination of paleomagnetic directions in fault blocks are necessary to test for horizontal- and vertical-axis rotations, respectively.

Fault-slip data, which consist of fault and slickenside-striae orientations and slip-sense determinations from one or more field sites, can be qualitatively characterized using equal-area and rose plots. Subsets of the fault data subdivided with the aid of these graphical plots can be inverted using established computational methods to find best-fit orientations of the principal stresses (σ_1, σ_2, and σ_3, where $\sigma_1 \geq \sigma_2 \geq \sigma_3$). The computed ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ is indicative of the relative magnitudes of the principal stresses. Also, extreme values of the ratio, which ranges from 0 to 1, in conjunction with other analytical parameters, indicates that two of the three principal stresses can not be reliably distinguished from each other using the analyzed data subset. A computation-intensive iterative clustering technique can be used to further separate from a mixed-fault data set two or more subsets that are compatible with unique stress solutions and are consistent with known relative-age information. Through this process the faulting and paleostress histories of an area can be more clearly established than is possible through conventional methods.

RHYOLITE FLOW FIELDS AS BARRIERS TO PALEOHYDROLOGIC FLOW IN EASTERN NEVADA AND WESTERN UTAH BETWEEN LATITUDES 37°30′ and 38°N.

by R. Ernest Anderson and Theodore P. Barnhard

Spectacularly straight north-flowing drainages with highly symmetrical cross profiles are developed on Miocene basin-fill strata composed of silicic volcanic clasts within a 100 km^2 area, informally known as Eccles basin in easternmost Nevada, and a 12 km^2 area along Wide Hollow west of Enterprise in adjacent westernmost Utah. In Eccles basin, a separate set of slightly less straight northeast-flowing drainages with strongly asymmetric cross profiles are adjacent to and, in part, overlap the north-flowing drainages. A similar set of strongly asymmetric northeast-trending drainages is present in a 200 km^2 area in southernmost Hamlin Valley in western Utah. In all areas, drainages lack the preferred orientation, straightness, or characteristic cross profiles where they traverse adjacent or underlying pre-basin-fill rocks. Those rocks, principally silicic Miocene volcanics, are commonly faulted, tilted, and erosionally beveled beneath the basin-fill strata. In places, the spectacularly straight drainages are developed on erosional remnants of basin-fill strata that only form a thin veneer atop the deformed Miocene volcanics. In contrast to the volcanics, the basin-fill clastic strata are cut by sparse steep mostly north- or northeast-striking faults and are flat lying to gently tilted.

The drainage-pattern development must be controlled by factors, such as contrasts in degree of cementation, that involve large percentages of the basin-fill strata. Although identification of controlling factors is hampered by poor exposures, study of sparse exposures of the basin-fill and lag debris in Eccles basin suggests that the shoulders of the north- and northeast-trending interfluves are underlain by steep drainage-parallel panels within which vein-type carbonate and disseminated carbonate cement is significantly more abundant than intervening parts of the basin-fill strata. Apparently these panels are more resistant to erosion than the uncemented to weakly cemented sediments of the intervening areas which are, accordingly, etched out into straight channelways during the latest cycle of erosion. This lithologic control of drainage-pattern development is, in turn, structurally controlled by sparse map-scale and smaller drainage-parallel steep faults and fractures. The carbonate was introduced from below into the basin-fill strata by circulation in an ancient fracture-controlled ground-water system. A very high degree of uniformity in physiographic expression in the subject areas suggests uniform average amounts of introduced carbonate such as might be expected in precipitation from a deeply circulating regional ground-water system.

In Eccles basin and Hamlin Valley the conspicuous linear drainage patterns give way northward to normal dendritic patterns in equivalent basin-fill strata. In Eccles basin the boundary between the contrasting drainage patterns is abrupt and trends east-west. The basin-fill strata on both sides of this boundary have a uniform silicic volcanic clast assemblage and appear to have similar average concentrations of carbonate cement. Apparently the chief difference is in the distribution of the cementing material; the distribution of carbonate is uneven and fracture controlled in the topographically high southern parts of the areas and relatively uniform in the lower northern parts. We interpret this difference as a reflection of paleohydrologic conditions related to 1) ponding and rising of shallow elements of a south-flowing regional carbonate aquifer system as it encountered Cenozoic rhyolite flow fields as aquitards, and 2) incomplete mixing of the fracture-controlled rising carbonate waters with shallow local recharge from the siliceous igneous rocks of the Clover and southernmost Indian Peak ranges located south of the areas of basin-fill strata.

Fluid Flow in Rough-Walled Fractures

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Yucca Mountain, Nevada, the proposed site of an underground radioactive waste repository, is composed mainly of volcanic tuffs, some of which are highly fractured. The hydraulic conductivities of the fractured formations at Yucca Mountain are controlled to a large extent by the conductivities of the individual fractures. As it is difficult to measure the permeability of a single fracture *in situ*, it would be advantageous to have a method of relating the permeability to more easily measured properties, such as the fracture roughness profile, percentage contact area, etc. We have used various mathematical models of rock fractures to study the effect of these physical parameters on the permeability.

The effect of the roughness of the fracture surface has been studied using a sinusoidal model of the aperture variation. At low Reynolds numbers, flow in such a fracture is governed by the Reynolds equation. We solve this equation exactly for the two cases of flow parallel to and transverse to the sinusoidal variations, and then use the geometric mean of these two values to estimate the overall permeability. We thereby arrive at an expression for the hydraulic aperture in terms of the mean and the standard deviation of the aperture distribution. The results are in close agreement with the numerical values computed by Brown (J. Geophys. Res., 1989) and Patir and Cheng (J. Lub. Tech., 1978). We have verified that the the results are affected only slightly by the addition of additional sinusoidal components to the aperture distribution.

A different model has been used to assess the effect of contact areas on the permeability. In this model, the fracture is considered to consist of two flat, parallel walls, propped open by cylindrical asperities. A Brinkman-type equation, which is a hybrid of the Navier-Stokes and Darcy equations, is used to model flow through the fracture. This equation accounts for the viscous drag along the sides of the asperities, which has been ignored in previous models. A closed-form expression is derived for the permeability in terms of the percentage contact area, and h/a, the ratio of the aperture to the asperity radius. The results show that for contact areas on the order of 20-30%, the asperities can reduce the permeability by as much as 50% below the parallel-plate value $h^2/12$.

USGS/CASY "Fractures, Hydrology, and Yucca Mountain" Symposium (13-14 Sept. 1990; Denver)

Fracture Studies in the Welded Grouse Canyon Tuff: Laser Drift of the G-Tunnel Underground Facility, Rainier Mesa, Nevada Test Site, Nevada

By S.F. Diehl, M.P. Chornack, H.S. Swolfs, and J.K. Odum

Fractures have been studied in the welded Grouse Canyon Tuff in the Laser Drift of the G-Tunnel Underground Facility (GTUF) located in Rainier Mesa about 64 km northwest of Mercury, Nevada. The Grouse Canyon Tuff has similar lithologic properties, stress conditions, and an overburden depth comparable to that of the proposed repository horizon at Yucca Mountain.

Several horizontal boreholes were cored in the Laser Drift as part of the Yucca Mountain prototype testing program. The USGS conducted video surveys in these boreholes using a borehole video camera and video tape recorder. Video tapes of the boreholes were used to detect the presence and orientation of fractures intersecting the boreholes. The number of fractures observed in the video surveys are comparable to those counted and recorded during the examination and logging of the recovered core samples from the boreholes. The video tape recording did offer the advantage of a more accurate count of fractures in rubble zones which were impossible to reconstruct from the core once it had been removed from the borehole.

The boreholes were oriented to intersect the prominent fracture trends (N. 25° E. and N. 40° E.) exposed in the Laser Drift. Most of the fractures are relatively planar with near vertical dips. Mineralization along the fractures usually consists of iron and manganese staining, but one predominant fracture, trending N. 5° E. with a near vertical dip of 86° SE, is filled with clay.

Four microfracture trends which average N. 75° W, N. 29° W, N. 3° E, and N. 70° E were determined from two oriented samples. Microfracture orientations are commonly perpendicular and parallel to welding and are abundant around stress-concentration points of phenocrysts. Authigenic mineral phases are observed to seal microfractures, indicating precipitation of these minerals from fluids moving through the microfractures. Microfractures are filled with adularia and iron, titanium, manganese, and rare earth mineral phases. A few adularia-filled microfractures are parallel to and at 45° to the plane of welding.

The microfractures appear to be extensional in origin. A profile of shut-in pressures from hydraulic fracture testing in two vertical holes near the GTUF site (Warpinski and others, 1981) indicates that the least horizontal stress magnitude in the welded Grouse Canyon is half as much as in the adjacent nonwelded units. This observation implies that the welded unit is in a state of extension, probably due to lateral spreading in the more ductile nonwelded tuff.

Although now located in the unsaturated zone, the hydrous mineral phases that coat fracture surfaces and seal microfractures in the Grouse Canyon ash-flow tuff indicate that fluid movement has occurred along these structures. This is evidence that the microfractures were once well-connected flow paths for fluid movement.

Warpinski, N.R., Northrop, D.A., Schmidt, R.A., Vollendorf, W.C., and S.J. Finley, 1981, The formation interface fracturing experiment—an in situ investigation of hydraulic fracture behavior near a material property interface: Sandia National Laboratories Report SAND81-0938, 82 p.

SOME GENERAL PROPERTIES OF JOINTS AND JOINT NETWORKS IN HORIZONTALLY LAYERED SEDIMENTARY AND VOLCANIC ROCKS--AN OVERVIEW

Earl R. Verbeek and Marilyn A. Grout

The past fifteen years have seen an unprecedented surge in the study of joints, spurred largely by the need to understand the fluid-flow properties of natural fracture systems both to ensure the safe storage of toxic and radioactive wastes and to more effectively recover gas and oil from fractured reservoirs. Joints no longer are the enigmatic features they once were; it is now realized that their properties are related to lithology and to stratal sequence in consistent and understandable ways. The following discussion summarizes some general properties of joints and joint networks and is based on recent work in diverse geologic settings of horizontal to gently tilted sedimentary and volcanic rocks.

Orientations

Strike dispersions of 15^{o}-30^{o} within individual sets are common; barring complications, the data often approximate normal distributions. Smaller dispersions, as little as 5^{o}, have been documented for some early-formed sets within fine-grained, well-cemented, brittle rocks. Strike dispersions tend to increase with increasing thickness of the jointed layer, with increasing grain size, and especially with decreasing degree of induration. The greatest dispersions result from jointing of lithologically heterogeneous units (e.g., a variably cemented channel sandstone) over protracted spans of time during which regional stresses progressively change in orientation; dispersions of 60^{o}-70^{o} have been documented but are uncommon. In such cases, too, strike-frequency distributions for individual sets can be decidedly non-normal. Within any given jointed layer, strike dispersions of the earliest set tend to be least and of succeeding sets progressively greater.

Dips of joints within thin, planar-bedded, well-cemented rocks commonly are within a few degrees of vertical. As with strikes, dip dispersions tend to increase with increasing thickness and grain size of the jointed layer and with decreasing degree of induration; dip dispersions of 20^{o}-30^{o}, and locally more, within thick (>3m), weakly cemented sandstones are not uncommon. The influence of bedding on joint dip is seen in the many places where the dip dispersion for a given set is less than the corresponding strike dispersion.

Dimensions

Heights of joints are influenced primarily by the thickness of the individual depositional units in a stratigraphic sequence and by the degree of lithologic contrast between them. Small joints are characteristic of thinly bedded sequences of contrasting rock type (e.g., limestone or chert layers alternating with shales), whereas the opposite is true for thick, internally homogeneous units (e.g., massive sandstones and the massive upper parts of some ash-flow sheets) and within sequences characterized by low lithologic contrast (e.g., some lacustrine siltstones). Far more common, however, are jointed stratal sequences characterized by variable bed thickness and moderate lithologic contrast between beds; common examples include stacked sequences of point-bar sandstones and siltstones. Joints in such deposits show a predictably wide range in height, from small joints confined to individual siltstone partings to large joints that cut several beds in succession; ranges of two to three orders of magnitude are common.

A rough correspondence between joint height and length is often observed, though few exposures offer sufficient three-dimensional control to quantify the relation. Joint lengths for early-formed joints likely are related to magnitude of driving stress, but for later sets the influence of pre-existing joints becomes increasingly important. Joint lengths for successive sets will tend to be progressively shorter if older joints remain open so that younger joints terminate against them, but no such relation need exist where older joints are healed and younger joints cut across them unimpeded. Here again, as in unfractured rock, driving stress may play a major role in influencing joint length. Examples are known where younger joints are longer on average than those formed earlier.

Frequency distributions of joint length for mesoscopic joints often follow a power-law distribution; i.e., progressively shorter joints are present in increasingly greater abundance than longer ones. The claim of a continuum of the power-law relation to microscopic joints has not, to our knowledge, been demonstrated for any area; most workers, for practical reasons, have imposed an arbitrary lower bound on the lengths of the fractures they measured and thus have left undocumented the most critical part of the distribution. Field observations in several areas have shown that small joints, those with trace lengths of several centimeters or less, are present in lesser numbers than are larger joints of the same set, suggesting that the actual frequency distribution of joint lengths may not be a power-law function for short joints.

Spacings

Spacings of joints are influenced primarily by the lithology and thickness of the jointed layer. For any given lithology a strong relation between mean (or median) joint spacing and layer thickness at the outcrop scale often is evident. The functional form of the relation has been debated, but review of older work supplemented by much new work suggests that equations of the form $\log S = m \log T + c$, where S = median joint spacing, T = layer thickness, and m and c are constants dependent on lithology, hold for the entire range of S and T so far examined. S vs. T values for different joint sets in the same exposure plot as parallel but generally noncoincident lines that express quantitatively the greater abundance of one set relative to another for any given layer thickness. For different rock types the S vs. T values generally plot as lines of different slope; hence, the abundance of joints in one rock type relative to their abundance in another is itself a function of layer thickness.

The above relations hold only where the boundaries between jointed layers are well defined and the individual joints span the full thickness of the layer. Where instead the lithologies are gradational from one layer to another, as among layers defined by different degrees and combinations of welding and devitrification within an ash-flow sheet, the joints, like the rocks, show gradually changing properties vertically. Mechanical contrasts within ash-flow sheets tend to be most pronounced in the lower portions of the sheet, where large differences in degrees of welding and devitrification occur over short vertical distances, and tend to be more obscure within the thick, massive, partially welded to nonwelded tuff that forms the upper parts of some sheets. Complications also arise within layers whose thicknesses are much greater than the heights of individual fractures. The joints in some such rocks, particularly massive sandstones, tend to congregate within zones. Each zone contains multiple, overlapping, closely spaced, and commonly interconnected joints separated by broader intervals of less-fractured rock. Zonal development of joints has been little studied and is incompletely understood.

Interconnections

Joints can terminate either by dying out within the rock, commonly as tapering cracks decreasing gradually to zero aperture, or by abutting pre-existing fractures. In addition, younger fractures can intersect older ones. The relative proportions of "blind" endings, terminations, and intersections commonly are variable from set to set and are a function of the age of a set relative to others in the same rock, the mineralization history of pre-existing sets, and to some degree the spacings of fractures already present. For obvious reasons blind endings are common and intersections rare among members of the earliest joint set, but abutting relations can also be formed in abundance as later-formed members of a set "hook" into earlier ones to form so-called J terminations. Hence, fluid flow through interconnected fractures can be effective in a rock even if only one set of joints is present. Joints of later sets will tend to abut earlier ones if these are open but intersect them if they have been "healed" effectively by mineralization. Variable proportions of abutting and crosscutting relations are common where early joints are incompletely mineralized and lenticular vugs remain, or where the mechanical contrast between mineral fill and wall rock is sufficient to stop the propagation of some joints but not of others. In any case, the degree of interconnection between younger and older joints tends to be very high unless the older joints are unusually sparse and thus widely spaced within the rock. Poorly to moderately interconnected joint networks, in our experience, are rare.

Surface shape

Early joints in many areas of relatively thick and homogeneous rock have roughly elliptical surfaces with their long axes parallel to bedding. As layer thickness decreases and progressively more joints span the full thickness of the layer, the joints progressively approach a more rectangular form, with flat top and bottom edges. Joint surfaces in thinly bedded sequences of high lithologic contrast tend to be long and ribbonlike, quite unlike their counterparts in thicker layers.

Joint surfaces of later sets exhibit a wide range in form dependent on layer thickness, abundance of fractures already present, and the degree to which these earlier fractures interfered with the propagation of the newer fractures through the rock. In relatively thick layers already cut by abundant joints it is common for the vertical dimensions of later joints to exceed the horizontal.

Cross-sectional shape

From field observations it is apparent that many early-formed joints in relatively homogeneous rock have a maximum wall separation near their midpoints and gradually taper to zero width at either end. Cross-sectional shape as a function of joint size has been little studied, but for one area we have shown that wall separations at joint midpoints are linearly related to joint heights (in a vertical cut) over the total height range of 1-360 cm. Joint shape in this area, then, is relatively constant regardless of joint size, and the largest joints possess by far the largest apertures.

No such relation seems to exist for joints of later sets. Instead, where late joints terminate at both ends against open, pre-existing fractures (free surfaces), the wall separations of the later fractures may be roughly constant along their length, in sharp contrast to early-formed joints in the same rock.

STRESS FIELD A'L_/UCCA MOUNTAIN AND IN SURR_NDING REGIONS

Joann M. Stock
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The stress field in southern Nevada is constrained from observations of earthquake focal mechanisms, hydraulic fracturing stress measurements, borehole breakouts, and drilling-induced hydraulic fractures[1,2]. Focal mechanisms indicate normal faulting on NE-striking planes, and strike-slip faulting on variably oriented planes, suggesting a combined strike-slip and normal faulting stress regime at seismogenic depths (5-15 km), with the least principal stress, σ_3, approximately horizontal and oriented NW-SE to E-W. Because both strike-slip and normal faulting mechanisms are observed, the maximum and intermediate principal stresses, σ_1 and σ_2, respectively, may be close in magnitude to one another. Hydrofrac tests at Rainier Mesa and borehole breakouts in drill holes at Yucca Flat and Pahute Mesa give S_h (least horizontal principal stress) directions of N45°W-N55°W and N45°W-N60°W, respectively[3,4].

Magnitudes of stresses within the saturated zone at Yucca Mountain were determined from hydraulic fracturing tests in four wells (USW-G1, USW-G2, USW-G3, and Ue25-p1). In 12 tests from 650-1700 m depth, "new" hydraulic fractures were created to determine the magnitude of S_h. In all cases, the vertical stress, S_v, exceeded both the measured value of S_h and estimates of the maximum horizontal principal stress, S_H. These measurements indicate a normal faulting stress regime, with values of $\varphi=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ ranging from 0.25 to 0.7. The observed values of S_h are close to values at which frictional sliding might be expected to take place on optimally oriented preexisting faults, suggesting that the stress regime may be near failure by extensional faulting. Drilling-induced hydraulic fractures in three of the wells, and borehole breakouts in two of the wells, indicated an S_h direction of N60°W to N65W, in agreement with other stress field indicators.

Three hydraulic fracturing measurements were attempted in the unsaturated zone in USW-G2, but these tests all appeared to have reopened preexisting fractures and hence only place upper bounds on the value of σ_3. An elastic model assuming lateral restraint has been used to predict the magnitudes and orientations of the principal stresses in the unsaturated zone[5], but these have not been confirmed by actual measurement.

The water level in the holes at Yucca Mountain ranged from 385 m to 752 m below the surface. Measured values of S_h were less than surface hydrostatic pressure (the pressure of a column of water reaching the surface in the drill hole). Under these circumstances, favorably oriented water-filled fractures might propagate if the fluid pressure were to increase. This may have happened during drilling in three of these holes, as circulation of drilling fluid could not be maintained back to the surface and large volumes of drilling fluid were lost at depth. Long vertical fractures visible on the borehole televiewer logs from these holes are interpreted to be hydraulic fractures formed during drilling. These drilling induced hydraulic fractures, in conjunction with the low S_h magnitudes, are important because they suggest a dynamic balance between the magnitude of S_h and the height of the water table. Thus, a substantial rise in the water table in the future might lead to the opening of pre-existing fractures, or the propagation of new hydraulic fractures, thereby drastically affecting the saturated zone hydrology at Yucca Mountain.

(1) Stock et al., Jour. Geophys. Res. v. 90, 8691-8706, 1985.
(2) Stock and Healy, *in* USGS Bulletin 1790, pp. 87-93, 1988.
(3) Springer and Thorpe, Rep. UCRL-87018, LLNL, 1981.
(4) Warren and Smith, Jour. Geophys. Res. v. 90, 6829-6839, 1985.
(5) Swolfs et al., *in* USGS Bulletin 1790, pp. 95-101, 1988.

[for CASY conference, September 13-14, 1990]

Modeling of Flow and Transport in Fracture Networks

by

Kenzi Karasaki, Amy Davey, John Peterson,
Kevin Hestir, and Jane Long

Field evidence of fracture controlled flow in hard rocks is presented. Such evidence includes a lack of hydrologic connections between boreholes and highly localized and fracture-associated transmissivities in boreholes. Difficulties associated with interpretation of field measurements and making of model inputs are discussed. The problem of scaling up is identified to be one of the most important issues. Porous medium models and fracture network models are compared and the limitations of both approaches are discussed. It is noted that the largest difference between the two approaches lies in the input geometry rather than in the fundamental numerical techniques. The importance of the conceptual model and the philosophy in the application of numerical models is emphasized. Recent developments in modeling of flow and transport in fracture systems are introduced. An advection-dispersion code that uses mixed Eulerian-Lagrangian, adaptive gridding technique is outlined. An equivalent discontinuum model and new inversion techniques are introduced. An example use of an interated function system model, that is applied using the past C-hole hydraulic test data, is shown.

Fractal Scaling of Fracture Networks in Rock

Christopher C. Barton (U.S. Geological Survey, Box 25046, MS 913, Federal Center, Denver, CO 80225

The mathematical construct of fractal geometry is well suited to quantify and model spatial and size-scaling relations within complex systems that are statistically self-similar over a broad range of scales. My results show that natural fracture networks in rock follow a fractal scaling law for fractures ranging in length over ten orders of magnitude, from microfractures in tectonically deformed quartz and plagioclase grains to transform faults in the South Atlantic sea floor. Detailed measurements of two-dimensional samples of three-dimensional fracture networks in rocks of dissimilar age, lithology, and tectonic settings show fractal dimensions in the range 1.6-1.8. The small range in fractal dimension implies that a single physical process of rock fracturing operates over this wide range of scale, from microscopic cracks to large, intra-plate fault systems.

Field evidence has established that rock fracturing is an iterative process in which preexisting fractures influence the formation of subsequent fractures (such behavior is characteristic of fractal processes). Fracture networks are not random but evolve from initially ordered to increasingly disordered patterns, and they become more complex with time as new fracture generations are added to those that already exist. The spatial distribution of fractures within the network evolves as fractures are sequentially added to the network. The fractal dimension, which is a quantitative measure of the spatial distribution of the fracture traces, ranges from about 1.33 in early stages of network development to 1.80 for mature networks. The fractal dimension of each successive fracture generation is less than that of the preceding generation, but the fractal dimension for the cumulative network increases as each new generation is added. The fractal behavior implies that fracture-network development is governed by a nonlinear equation. Fortunately, the ability of fractal mathematics to accurately quantify and model the spatial and size-scaling properties of the system is not dependent on specific knowledge of this equation.

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FRACTALS AND THEIR USE IN THE PETROLEUM INDUSTRY

C.C. Barton and P.R. LaPointe, Editors

American Association of Petroleum Geologists, Book Series
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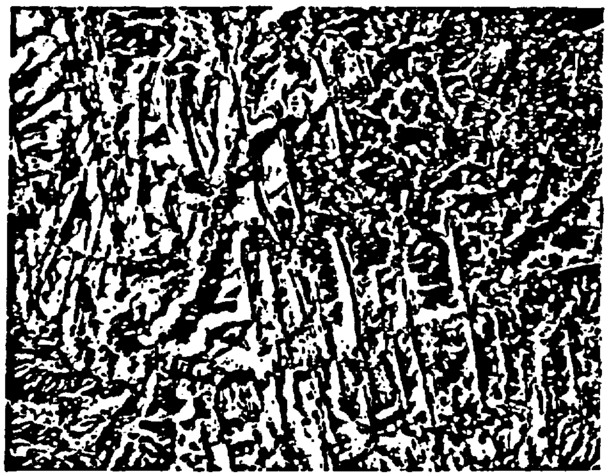

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FRACTAL GEOMETRY AND ITS APPLICATION IN THE PETROLEUM INDUSTRY

Date: April 11, 1990 (in conjunction with AAPG annual meeting)
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Fractal geometry provides a means of mathematically describing and modelling the complex patterns which earth scientists and engineers map, measure, and describe in ever-increasing detail. Fractal geometry is a branch of mathematics for quantifying how the geometry of self-similar systems changes from one scale to another. The geometry of a fractal pattern is represented by a fractional number, termed the fractal dimension. Many geologic patterns have been shown to be fractal, including reservoir heterogeneity, size and spatial distribution of pores, sequences of stratigraphic thickness, size and spatial distribution of petroleum reservoirs, fracture networks, porous-media flow, tributary river patterns, and topography. This one day short course is an introduction to the concepts of fractal geometry including the concepts of self-similarity and self-affinity, generation of synthetic fractals, methods for measuring the fractal dimension, self-similar distributions, and specific applications of interest to the petroleum industry.

Instructors:

Christopher C. Barton is a research geologist and G.K. Gilbert Fellow at the U.S. Geological Survey in Denver, Colorado.

Paul R. LaPointe is a principal research geologist and acting director of geological interpretation techniques at ARCO Oil & Gas Co. in Plano, Texas.

Alberto Malinverno is a post-doctoral research scientist at Columbia University's Lamont-Doherty Geologic Observatory in Palisades, New York.