It’s the Cracks that Matter: DFN Modeling of Everything Rock

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Research into rock mechanics & fractures have been linked throughout the centuries, and ARMA members have greatly contributed to this ancient body of knowledge.

To steal ideas from one person is plagiarism; to steal ideas from many people is scholarship & research.

Acknowledgments: Bill Dershowitz, Thomas Doe, Steve Rogers, Chris Barton
Divine Guidance – The Oracle of Delphi

Diodorus Siculus 1st Century BC), tells of a goat herder named Coretas, who noticed one day that one of his goats, who fell into a crack in the earth, was behaving strangely. On entering the chasm, he found himself filled with a divine presence and could see outside of the present into the past and the future. Excited by his discovery, he shared it with his villagers. Many started visiting the site to experience the convulsions and inspirations.

Prophetic utterances about fractures & prophecies about the future were sought by some in inverse of Discrete Fracture Network Modeling (DFN). A shrine was erected at the site.
Recognizing the importance of fractures

Image of a fresco in the Sistene Chapel by Michaelangelo
Fractures are important in many areas of rock mechanics...
Block Caving

Source: Society for Mining, Metallurgy, and Exploration, Inc.

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Fig. 9 – A three-boom jumbo
Strength & Stability
Oil
Recovery of Oil, Gas & Water

Water
TASS tunnel within the Äspö Hard Rock Laboratory, Oskarshamn, Sweden

Test various high-flow and low-flow grouting techniques

Excavation Damage Zone (EDZ) study, where large blocks of the tunnel walls were removed using saw cuts to study the fracture patterns created by drilling and blasting
Rock Slopes

http://trendsupdates.com/super-bunker-buster-bombs-on-fast-track-for-u-s-military/
Some Definitions

Fracture – a generic discontinuity

Joint – A Mode I crack

Fault – A Mode II crack
“Joints” are the planes of separation where the rock breaks apart, yet the English word “joint” comes from the Latin word “jungere”, which means to join or unite. This would appear to be a paradox.
Words to Describe “Joints” in Other Languages

Kluft (German): fissure, gap or cleft

Diaclase (French, Spanish from Greek): to break in two

Трещина (Russian): crack, cleft or fissure

So why is “joint” used in English to describe something that is “dis-joined”?
Usage of the Term “Joint” in English – Same as Today

The Oxford English Dictionary (from 1899-1901):
"5. Geo1. A crack or fissure intersecting a mass of rock; usually occurring in sets of parallel planes."

A.J. Giekie (1882):
"All rocks are traversed more or less distinctly by vertical or highly inclined divisional planes termed joints."

R.I. Murchison (1839):
"[Master Joints] They are natural fissures often traversing all the strata in straight and well determined lines"

J. Phillips (1836):
"All the apparent divisional planes of rocks which are not coincident with surfaces of stratification, or laminae of deposition, may in general be called joints."
Earlier Usage

John MacCulloch (1821) uses the term for partings transverse to basalt columns which dissect the columns into tabular prisms:

“...that the most perfect and numerous joints occur in the most regularly formed columns. In the joints, the surfaces in contact are sometimes uneven, at others flat, and others again, alternately, concave and convex...”

The Giant's Causeway

Legend has it that the Irish warrior warrior Fionn mac Cumhail (Finn McCool) built the causeway to walk to Scotland to fight his Scottish counterpart, Benandonner.

Fractures - the font of mythology and religion, then and now...
Robert Bakewell (1815): "Coal strata are generally split or divisible into rhomboidal blocks, by vertical joints,..."

William Smith (1815), in his *Memoir to the Maps of the Strata of England* writes:
"...the collection of water from those natural subterraneous reservoirs, the caverns of hills and joints of rocks, for the supply of canals."
Catcott (1761) in his Treatise on the Deluge:
"These Joints or Openings between the stone in the upper parts of Rocks ought to be distinguished from the natural fissures in the body of the rock, and are distinguishable there-from by various marks, -being generally far more numerous..."

Hooson (1747) in his Miners Dictionary:
"Joynt. They are of several sorts, and is a parting in the Rock, Rider, Ore. or any other Substance in the Mines, their various kinds are Distinguished‘d by their several Names,..."
Even Earlier...

Morton (1712) in his Northamptonshire refers to quarrymen's use of the term: “...upright-joints, thorough-joints and gulfejoints...”

Lhwyd (1691) presents an early usage in a letter to Ray: "One naked precipice [on the Glyder Mountain, N. Wales] is adorned with numerous equidistinct pillars, and these again slightly cross'd at certain joynts."
The earliest known usage...mining once again!

The earliest geologic usage of the word *joint*, yet found, appears in Holland's translation of Pliny's Natural History (1601):

“The Bactrian Emerauds ...be in chinks or joints (as it were) of rock...and gathered...when the Northeast Etesian winds do blow ..." 

Why might have Holland chosen the word “joint”?

Consider the original Latin:

*Bactriani. in commissuris saxorum colligere eos dicuntur etesiis flantibus (Book 37, Chap 17:65)*
Pliny

Born 23 CE Como, Italy
Died August 25, 79 (aged 55–56) Stabiae, near Pompeii, Italy
Cause of death Died in the eruption that destroyed Pompeii
Body discovered By friends, under the pumice

Engineers should not ignore geology except at their own peril...

Source: http://en.wikipedia.org/wiki/Pliny_the_Elder
Pliny uses the word *commissuris*, meaning to bind, *join* or combine.

From Latin usage the principal meaning of *commissuris* is a *joining* or *connecting together*.

Why Pliny chose to use *commissura* is not known, but we can now deduce why Holland used the word *joint*.

Holland must have recognized Pliny's intent of a gap or hole and thus he used the word chink to convey that meaning. But so as to be as literal as possible and to convey the essence of Pliny's intent in *commissura*, Holland adds:

“chinks or joints (as it were)."
“Joints” in the Modern World

Your search found 13,000 documents. However, only the first 1000 documents can be viewed.

Edit your search to define a more precise search.
Click the search tips link on the search form for assistance in formulating a more targeted search request.
Why Are So Many Papers Still Being Written About Fractures?

They exist in almost every rock at some scale at some time.

They are really hard to sample and predict.

They influence, often significantly, rock properties such as: strength, deformability, flow, transport.

The way that they influence these properties is hard to write down in an equation.

After 2000 years of worrying about fractures, how do we try to deal with them now?
The New Oracle: Discrete Fracture Network (DFN) Modeling

Why this approach?
Flow in Fracture Networks Occurs in Mysterious Ways

The Bromide Tracer Experiment at the Circle Ridge Field, Wind River Basin, WY

No other breakthroughs were observed for two months

4 days

"Instantaneous"

20 hours
What is the permeability of this house?

What is the most important thing to know about this house if you “drill” from the roof to find water?

Are the pipes and bathtubs random? What controls their location and geometry?

ANALOGIES:
Tubs = Matrix Storage
Pipes = Fractures
Faucets = Wells

The Paradigm of Fracture Flow

Slide courtesy of Tom Doe
Understanding & Modeling the Plumbing is the Key

Streets – 10mD
Roads – 100mD
Highways – 1,000mD

Slide courtesy of Tom Doe & Steve Rogers
DFN models help us to understand the plumbing of the rock mass. Continuum methods cannot match the discrete geological pathways!
Where Does the Data Come From?

- Geophysics
- Downhole image logs & core
- Outcrops
Propagation of Waves - AVAZ
QUANTIFYING FRACTURE NETWORKS FROM ACOUSTIC ENERGY (AE) CLOUDS

\[ E_s = (0.5) \sum (\Delta \delta \Delta \mu A) \]

- \( E_s \): Seismic energy
- \( \Delta \delta \): Stress drop
- \( \Delta \mu \): Slip
- \( A \): Area

Crack Density and AE Emissions

Distance

Acoustic Energy

High

Low

September 15, 2012

http://www.globalgeophysical.com/docs/MICROSEISMIC_TFI%20Brochure%20%5B0711%5D.pdf
Borehole Image Logs
Finding the Elusive Fracture!
Celebration! We have found fractures!
Example Applications

- Oil & Gas
- Nuclear Waste
- Mining
- Water
- Other
DFN Models are useful for sorting out mysteries and legends about reservoir-scale fracture flow.
Many of the gross structural features are consistent with this common tectonic model, but the reservoir scale fracturing is far more complex, and could not be predicted from this simple model.
Field work was combined with well data to create geological cross-sections in key areas.
3D Structural reconstruction is figuring out how to go from this...

Tensleep & Phosphoria as originally deposited

to this...

What the reservoir looks like today after folding and faulting
Undeforming the Rock Layers

Reservoir in upthrust and downthrust blocks
GETTING TO THIS UNDEFORMED STATE MEANS THAT WE HAVE THE RIGHT FAULT GEOMETRY, THE RIGHT FAULT MOVEMENT HISTORY, AND THE RIGHT FOLDING HISTORY
WE CAN COMPUTE THE FORWARD DEFORMATION HISTORY OF THE ROCK & SEE HOW THAT RELATES TO FRACTURES IN THE RESERVOIR
We measured fracture orientations and intensity in many different locations and structural positions on rock outcrops & compared them to the calculated strain field.
These strain orientations, which indicate the maximum direction of extension during the early folding of the field...

Correspond perfectly in a geomechanical sense with these fracture orientations found in the image log data...

This and many other comparisons showed strong evidence that the strain produced by the initial folding of the field was a good predictor of fracture orientation & intensity.
Intensity predictions matched surface and subsurface data as well...
Red Gully Fault Trace

The blue dashed lines show the down-dip flexure zones that may have formed due to the double plunge of the anticline.

Some of these hinge zones link up across structural blocks to indicate the major upwarp flexure zone during the initial folding of the field.
Is there field evidence that horizontal flexure zones exist?
Example of a radial (dip-parallel) hinge zone. Note the change of dip between panels, and the rubbleization and consequent erosion in the hinge zone.
The Green Valley Fault separates Block 6 (green) from Block 8 (purple), while the Yellow Flats Fault separates Block 8 from Block 9 (cyan).

The Bromide Tracer Experiment showed large-scale validation of the model & the development of fracture superhighways along hinge zones.
Not all fractures are equally hydraulically important
Well Test Matching

All of this... well test simulation is a means of calibrating the DFN to the hydraulic geometry at the scale of interest...

...comes from a single fracture!

CONDUCTIVE vs. NON-CONDUCTIVE FRACTURES
Final Calculation of Fluid Flow Properties Through DFN Transient Well Test Matching
0.2 hours
### MAFIC Group Properties

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Appearance</th>
<th>Filled</th>
<th>VFrame</th>
<th>Outline</th>
<th>Fill Color</th>
<th>VFrame Color</th>
<th>Outline Color</th>
<th>Apply to Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>G3dMaficGroup</td>
<td></td>
<td>true</td>
<td>false</td>
<td>true</td>
<td>false</td>
<td>false</td>
<td>true</td>
<td>true</td>
<td>true</td>
</tr>
</tbody>
</table>

- **VFrame Color**: Apply
- **Outline Color**: Apply
- **Apply to Children**: Apply

**3 hours**

![Graph showing DP vs. Depth](image-url)
30 hours
100 hours
Match for Shoshone 65-20
DFN Model of 3 Imbricate Blocks
The goal of upscaling is to translate the geologist’s model of a fractured reservoir into the engineer’s model.
Transformation of a DFN model into Upscaled Properties
First, we use the strain values calculated through the reconstruction of generate the fracture sets.

Next, the DFN model is clipped against reservoir surfaces.

Clipped DFN model with reservoir bounding surfaces removed.

A geocellular or reservoir simulation grid is superimposed over the DFN model.

Effective fracture-related parameter values are calculated for each grid cell.

The process of calculating effective reservoir properties.
How Reliable Is it?

Before adjusting for conductive intensity (too permeable)

After adjusting for conductive intensity (on the order of 30% of previous)
View is looking down on the structure from the southwest to the northeast. Size of circles indicates magnitude of pressure response. The largest responses were seen in two wells on flexure corridors close to the injector. Most of the responding wells are either in the cyan-colored pod above and left (northwest) of the injector, or along the downdip flexure corridor to the right (southeast) of the injector.
Wells where nitrogen breakthrough was indicated are shown; size of yellow circle at well top indicates the time of breakthrough (large circle indicates slow response; small circles indicate rapid response).

Flexure zones are indicated by dashed orange (strike-parallel) and blue (dip-parallel) lines.
How Do Natural Fractures Influence Hydrofracture Development?

- Importance of natural fractures for a successful well completion known

- Effective utilization of the natural fracture system by the hydraulic fracture CAN allow the well to connect to a significantly enhanced drainage volume.

- However uncertainty exists with respect to the hydraulic fracture & natural fracture interaction

- In a reservoir with a complex fracture system, the resultant stimulated volume is going to be highly complex

- How can we address this?
Dilly Creek Work flow

- With limited data, fracture network uncertainty is high
- Danger of forcing a “history match” with an uncertain model
- Instead vary key fracture properties within sensible bounds and observe simulated micro-seismics
- Compare actual and simulated seismic response to see which fracture geometries most likely

Properties to Vary

- Fracture Intensity
- Fracture Size
- Fracture Shape
- Injection fluid efficiency
DFN Work flow

1. Construct a DFN model for region surrounding well
2. Include information about the well’s hydraulic fracture
   - Pump rate, pressure and duration of each stage
3. Model hydraulic fracture and interaction with original fracture network for each stage based on:
   - Stress field and material properties
   - Material balance of injected fluid and propant
4. Validate model with micro-seismic data
Effects of Transmissivity

Transmissivity low

Transmissivity high

Combined DFN/Elfen Simulation
Network Connectivity

One Joint Set

Two Joint Sets
# Impact of Fracture property on Stimulated Volume

<table>
<thead>
<tr>
<th>Property</th>
<th>Increasing Property</th>
<th>Decreasing Property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fracture intensity</td>
<td>Shorter wider stimulated zone</td>
<td>Longer narrower stimulated zones</td>
</tr>
<tr>
<td>Fracture Size</td>
<td>When it increases connectivity it results in a wider stimulated volume</td>
<td>When it reduces connectivity, the stimulated volume will be narrower</td>
</tr>
<tr>
<td>Fracture Connectivity</td>
<td>Shorter, more circular and isotropic stimulated volume</td>
<td>Elongate and anisotropic stimulated volume</td>
</tr>
<tr>
<td>Fluid Efficiency</td>
<td>Extends the hydraulic frac and limits the lateral extent</td>
<td>Broadens the response and reduces the HF length</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>If connectivity increased, larger stimulated volume</td>
<td>If connectivity decreased smaller stimulated volume</td>
</tr>
</tbody>
</table>
Estimating Stimulated Volume and EUR

Total EUR = 0.48 BCF
Example Value Proposition

Stimulated fractures
4 laterals

Stimulated volume
4 laterals

Stimulated volume of the outer two laterals is approximately equal to the total stimulated volume for the four laterals

Same potential production from \(\frac{1}{2}\) the number of wells
Gaining insight into a mystery: Use of DFN models to explore which conceptual model helps explain the dynamic observations the best
Visualise the Pressure Field

Simulated Production

- Matrix, Lineaments, Hydrofracs
- Matrix, Lineaments
- Matrix, Hydrofracs

Flow Rate, mscf/day vs Time, days

1.00E-01 1.00E+00 1.00E+01 1.00E+02 1.00E+03 1.00E+04

100000

10000

1000

100

10
Figure 1. A concept with multiple canisters without DFN (a) and with DFN (b) based on the disposal-pit-vertical-emplacement concept in a two-dimensional space.

Cs-135 Movement

DFN Model

Darcy Flow Velocity

Hydraulic Head

Residence Time

Modeling Where Radionuclides May Go
Location of the SECARB Black Warrior test site in Deerlick Creek Field, Black Warrior Basin, Alabama.

CO$_2$ Sequestration – Deerlick Test

Jointed DFN model based on stratigraphic relationships in the Jobson 24-14 #11 well and observations of fractures in core and outcrop.
Orientations inferred from FMI data; intensity based on seismic attributes

Analysis shows that the fractures form compartments (The compartments in the model are shown by different colored groups of fractures)
Results of compartmentalization analysis. Note that shallow coal zones are in a compartment that is separate from the reservoir coal zones and that small, stranded joint compartments are stranded between the major reservoir compartments.
Pillars
Failure as a Function of Fracturing

A

B

C

SFU Engineering Geology and Geotechnics Research Group

Sigma 1 - Mpa

10-80 Joints

30-60 Joints

Equivalent GSI=65

Equivalent GSI=25

Sigma 3 - Mpa

0 10 20 30 40 50 60

0 2 4 6 8 10
The fragmentation of the rock mass during caving has a tremendous impact on a number of cave, mining, and processing design decisions including:

- Draw point spacing;
- Equipment Selection;
- Secondary breakage requirements;
- Mill set up & energy requirements

Caving-Pit Interaction

0-90 Joints

30-60 Joints

Pit + Block Caving

Pit Only
Caving-Pit Interaction

- 50° Dipping Orebody
Civil/Geotechnical Engineering

- Grouting
- Slope Stability
Grouting

Efficiency of Grouting – can be checked

- Use Bingham model to approximate grout flow
- Model fractures using DFN representation
- Inject to proposed Grouting Intensity
- Check/simulate groundwater flow thru curtain
- Rerun to optimize – hole spacing etc

Aperture: mm
Travel Distance: m
Depth: m

Graph:
- Horizontal Grout Travel (m)
- Hydraulic Aperture (mm)

Aperture: mm
Evaluate Effectiveness of Grouting

Grouting Efficiency: \( E = 1 - \left( \frac{K_{\text{Grouted}}}{K_{\text{formation}}} \right) \)

Normalized Grouting Intensity

Design Curve = Optimum Volume or Penetration Distance

Twice the effort

Compute groundwater flow across grout curtain through remaining ungrouted fractures in the network
Grouted Fracture Set

Simulated Injection into Fracture Network

Groughtole

1000+ Steps

Injection Time
Visualized to evaluate “Penetration”
Slope Failures – Beichuan (2008)
Rock Slopes
Alternative concepts and approaches for modeling flow and transport in thick unsaturated zones of fractured rocks

K. Pruess
B. Faybishenko,
G.S. Bodvarsson
Calculating Permeability Tensors for Groundwater Flow

Variation of directional hydraulic conductivity in 3-D space

...and a monumental application
Crazy Horse Memorial

- Excavation Simulation

DRAFT
Arbitrary Joint Pattern
Arbitrary Material & Joint Properties
Conclusions

Fractures in rock have been important to humanity for at least two millennia, and probably more in the areas of minerals, energy, water supply and environment.

Despite two thousands years of scholarly investigations, many important questions regarding natural fractures have still not been fully answered.

Discrete Fracture Network (DFN) modeling has been a useful tool in the past two or three decades, and promises to be a tool of ever-increasing importance in the arsenal of rock mechanics practitioners.

And the future?
Only creativity limits what can be modeled

DFN Model by Tom Doe
Thanks!
“He suggested a sequence in which mists and vapours over the sea were impregnated with the ‘seed’ of marine animals. These were raised and carried for considerable distances before they descended over land in rain and fog. The ‘invisible animacula’ then penetrated deep into the earth and there germinated; and in this way complete replicas of sea organisms, or sometimes only parts of individuals, were reproduced in stone.”

Keeper of the Ashmolean Museum at Oxford (an unpaid position, raising money by enticing others to see his curiosities). Fractures are still curiosities that attract attention, and many people who study them have strange ideas...

http://www.oum.ox.ac.uk/learning/pdfs/lhwyd.pdf
Orientations of most passages

Direction of maximum extension

Map annotation and photos courtesy of Laird Thompson, MOBIL
EXPLORING THE APERTURE DISTRIBUTION OF A FRACTURED RESERVOIR

...SOME SOLUTION-ENHANCED FRACTURES ARE NOT PERMEABLE TO LARGE OBJECTS
Understanding the Reservoir from the Inside Out

Orientations of most passages

Direction of maximum extension

Map annotation and photos courtesy of Laird Thompson, MOBIL
Braving dangers in the jungle...

Look up. Stay alive.

Dropbears are a very real danger to all Australians. Almost one in ten Australians has been attacked by a Dropbear, and the rate is even higher for foreign visitors. Don’t become another statistic. Always beware low branches and doorframes. Look up. Stay alive.

Department of Dangerous Fauna Management

Golder Associates