Introduction to Structural Geol for Rock Mechanics

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Structural Geology? What is the Connection?

Stress applied to Materials produces Strain

In simple linear elasticity this can be written as:

\[ [\sigma] = E \times [\varepsilon] \]

\( \sigma \) = tectonic processes, like crustal shortening or extension, or burial

\( E \) = material properties, like porosity, density, strength, elasticity

\( \varepsilon \) = the result, like folding, stylolitization, faulting and extensional fracturing

If we know how tectonic processes interact with the mechanical properties of the rock, especially the matrix, we can predict deformation characteristics, like fracturing.
HOW AND WHY ROCK FRACTURES
Why Does Rock Fracture in the First Place?

1. Life begins with imperfections ("flaws")
   - Voids, pores, heterogeneities
   - Stresses can be concentrated and raised along their boundaries
   - This rise in stress can overcome the surface energy and lead to crack propagation.
Impact of Stress and Fracture Formation
Shear Failure - Faulting
Why Does a Fracture Stop Growing?

2. A fracture stops growing when the energy available for overcoming the surface energy at the fracture tip drops below a critical value. What variables influence this equation?

- Material properties, like fracture toughness & rheology
- Geometry of the fracture (especially the tip)
- Energy supplied to the fracture
Depositional Environment

DEPOSITIONAL ENVIRONMENTS OF LIME MUD

LOWEST → HYDRAULIC ENERGY → HIGHEST

TIDAL FLAT

PLATFORM INTERIOR (LOWER ENERGY)

RELATIVELY DEEP WATER

MSL

SHALLOW WATER CARBONATE PLATFORM

BASIN
## Geological Classification

**Dunham modified by Embry and Klovan**

<table>
<thead>
<tr>
<th>Allochthonous Limestones</th>
<th>Autochthonous Limestones</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original component not organically bound during deposition</strong></td>
<td><strong>Original components organically bound during deposition</strong></td>
</tr>
<tr>
<td><strong>Less than 10% &gt; 2 mm components</strong></td>
<td><strong>Greater than 10% &gt; 2 mm components</strong></td>
</tr>
<tr>
<td>Contains lime mud (&lt;62.5 μ)</td>
<td>No lime mud (&lt;5%)</td>
</tr>
<tr>
<td>Mudsupported</td>
<td>Grain supported</td>
</tr>
<tr>
<td><strong>Less than 10% grains &gt; 0.03 mm &lt; 2 mm</strong></td>
<td><strong>Greater than 10% grains</strong></td>
</tr>
<tr>
<td><strong>Mudstone</strong></td>
<td><strong>Wackestone</strong></td>
</tr>
</tbody>
</table>

*Embry and Klovan 1971 Bulletin Canadian Petroleum Geology, v 19, p731*
The internal structure of different carbonate facies may vary widely. If the pore space volume, pore geometry, and arrangement of materials with contrasting mechanical properties varies so widely, is it any wonder that the fracturing in different carbonate facies varies equally as widely?
Each facies might have its own fracture pattern development

After James 1979
DOLOMITIZATION INCREASES FRACTURE POTENTIAL

Limestone (calcite) and aragonite (crystalline)

\[ \text{CaCO}_3 \]

Dolomite is

45.7 % (w/w) MgCO_3
54.3% (w/w) Ca CO_3

so Mg/Ca =1

Dolomitization is limestone changing to dolomite

\[ 2 \text{CaCO}_3 + \text{Mg}^{++} \rightarrow \text{CaMg(CO}_3)_2 + \text{Ca}^{++} \]

with a change in density from 2.7 g/cm\(^3\) to 2.87 g/cm\(^3\)
Lithological Influence on Joint Spacing

Ladeira & Price 1981
RECAP: What Influences Fracture Development?

Pore spaces & their geometry
Material properties of the rock
The spatial arrangement and geometry of materials with different properties at many different scales
The nature of the applied stress
THE GEOLOGICAL BASIS FOR FRACTURE NETWORK ANALYSIS

STRUCTURAL CONTROLS
INFLUENCE OF LITHOLOGY
FRACTURE MECHANICS

These are not separate items; together they provide insight into the genesis of fractures and key elements of fracture patterns.
What should an engineer or geologist know about the geology of fractures? 5 Important Concepts:

1. Types of fractures
2. Mechanical layering and its influence on reservoir connectivity
3. Fractures produced during rock folding
4. Fractures produced during faulting
5. Conductive fractures - don’t pay attention to everything the geologist measures!
• Mode I fractures form in pure extension normal to the fracture surface. They are termed *joints*.
• Mode II fractures form in shear parallel to the plane of the fractures and with sliding in the direction perpendicular to the fracture front.
• Mode III fractures form in shear parallel to the plane of the fractures and with sliding in the direction parallel to the fracture front.

Mode II and Mode III fractures are termed *faults*.
TYPES OF FRACTURES

• Joint - a break in the rock with opening displacement only. A Mode I fracture in fracture mechanics terminology.

• Vein - a break containing precipitated minerals

• Fault - a break with shear displacement. A Mode II fracture in fracture mechanics terminology.

Why are they divided this way? Because each group typically has very different geometry and fluid flow properties.
Joints, or Mode I fractures, tend to be smaller than faults and may have characteristics surface morphologies.
Joints can also be much larger...

One Joint!
Note surface morphology that indicates Mode I.
An example of many large joints developed perpendicular to bedding
Joint Nomenclature

Abutting relationships
Mineralized fractures can form barriers to matrix and fracture flow
Faults are very different than joints. They often juxtapose two different rock types with very different mechanical properties, and have a different stress field on either side, leading to asymmetrical fracture development. Faults also have very different hydrologic properties than joints, as we shall see.

LEWIS THRUST
more than 20 km slip
dolomite above only lightly fractured
shale below is incoherent
The concept of mechanical layering is critical to developing 3D fractured reservoir models.

A mechanical layer is one or more rock strata that respond as a single plate to stress. The plate may be warped, as above, or
...the plate may be bent, as below.

In either case, the fractures do not propagate beyond the upper and lower surfaces of the layer.

Layers are often defined by rock units with more ductile rheology, like shales.
The photo below shows an example of mechanical layering.

- Less densely fractured layer in thicker-bedded units
- Densely fractured layer in thin-bedded units
Mechanical layering is important because it controls whether flow takes place in layers only or whether there is good vertical communication throughout the reservoir.
Tensleep Sandstone, Bighorn Basin, Wyoming

Upper Dune Sequence

Cross-bedding

Large joints cutting across bedding
Major joints end at boundary between dunes & interdune sequence
Layer bound extensional faulting

Seismic Sections
Mud-Free fine to very fine-grained sandstones resting on the wall of a submarine channel.

Does lithology, depositional framework or structure effect fracturing?
What is the relation of fractures to depositional features?
Fractures are typically confined to stratigraphic or mechanical layers.

Fracture do not appear to be related to layering.

Multiple mechanical layers, including layers at smaller scales, with fracturing characteristics at each scale.
Example of Hierarchical Fracturing Style

Fracturing is in layers of different scales that may overlap.
FRACTURE GENESIS

Cooling
Gravitational Unloading
Regional Stress
Folding
Faulting

Primarily important for Basement reservoirs.
Primarily important for sandstone and carbonate reservoirs.
Cooling Fractures

How does the reservoir plumbing differ between these two types of fracturing?

Enhanced vertical permeability

Fractured vein forms conductive layer
Gravitational Unloading

Parallel or perpendicular to ground surface
Structural geologists have devised many models for characteristic fracture orientations due to folding. This slide and the next two can be used as a reference for one commonly-used classification.
<table>
<thead>
<tr>
<th>Subset</th>
<th>Fracture Type</th>
<th>α</th>
<th>β</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>Mode 1 Fracture (joint) perpendicularly to ( \sigma_3 ) perpendicularly to bedding</td>
<td>90°</td>
<td>0°</td>
</tr>
<tr>
<td></td>
<td>perpendicular to fold axis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>Styolites perpendicularly to ( \sigma_1 ) perpendicularly to bedding parallel to fold axis</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>L</td>
<td>Longitudinal fractures perpendicularly to ( \sigma_1 ) perpendicularly to bedding parallel to fold axis</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>D1</td>
<td>Conjugate Pair of Mode 2 Shear Fractures</td>
<td>( \gamma/2 )</td>
<td>90°</td>
</tr>
<tr>
<td>D2</td>
<td>Conjugate Pair of Mode 2 Shear Fractures</td>
<td>( \gamma/2 )</td>
<td>-90°</td>
</tr>
<tr>
<td>Subset</td>
<td>Fracture Type</td>
<td>$\alpha$</td>
<td>$\beta$</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------------</td>
<td>-----------</td>
<td>---------</td>
</tr>
<tr>
<td>TA</td>
<td>Mode 1 Fracture (joint) perpendicular to $\sigma_1$</td>
<td>0°</td>
<td>0°</td>
</tr>
<tr>
<td>F</td>
<td>Bedding perpendicular fractures</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>J1</td>
<td>Conjugate pair of shear fractures</td>
<td>90° - $\gamma$/ 2</td>
<td>0°</td>
</tr>
<tr>
<td>J2</td>
<td>$\sigma_2$ parallel to fold axis</td>
<td>90° - $\gamma$/ 2</td>
<td>180°</td>
</tr>
<tr>
<td>C1</td>
<td>Conjugate pair of shear fractures</td>
<td>90° - $\gamma$/ 2</td>
<td>90°</td>
</tr>
<tr>
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Illustration of release (b-c) and extension (a-c) joints in relation to fold geometry

Schematic diagram of Stearns model of fracture orientations related to folding. The red line in the Type I fracture group is a joint or extension fracture, while the orange lines show the orientations of Type I conjugate “shear” fractures. The yellow line shows the orientation of the Type II joint or extension fracture, while the cyan lines show the orientations of the Type II conjugate “shear” fractures. The complete Stearns model contains other fractures not shown in the schematic above.
A Classic Model for Fracturing due to Folding

(Often referred to as the Stearns Model after David Stearns)

**Type I (dip)**
- Extension
- & “Shear”
- Fractures

**Type II (strike)**
- Extension
- & “Shear”
- Fractures
Buckle Folding - Strain Distribution

Maximum deformation at the crest of the fold

Minimum deformation in the flanks of the fold

Stretched outer arc

Neutral surface

Compressed inner arc

Figure 7-63
Flexural Folding - Strain Distribution

Maximum deformation of the flanks of the fold

Minimum deformation at the crest of the fold

Layers Slip
Faulting & Fluid Movement
Terminology for Fault-Related Secondary Fractures

- Riedel shears (R1 synthetic, R2 antithetic)
- Tension fractures
- P shears
- X shears
- Stylolites
- Out-of-plane fractures

Look for these around major faults, but don’t expect to find every feature. The real importance is that there is often a zone around major faults of secondary fracturing, which influences the hydraulic behavior of the reservoir.
Fault Zones and their Structure

- Fault Core
  - Gouge
  - Breccia

- Damage Zone
  - Small Faults
  - Tensile Fractures
  - Veins
  - Folds

- Protolith
  - Regional Structures

*after Caine et al. (1996)*
Conceptual Scheme for Fault-Related Fluid Flow

Distributed Conduit

High

% Damage Zone

Low

% Core

High

Localized Conduit

Low

% Core

High

Combined Conduit-Barrier

High

% Damage Zone

Low

Permeability Structures in Fault Zones

after Caire et al. (1996)
Field Example: SAND HILL FAULT, NEW MEXICO
Structure of the Sand Hill Fault

From Heynekamp et al. 1995
Flow Structures in the Hanging Wall?

This field example shows that, in fact, some fault zones are highly permeable to flow along the fault, but not across the fault.
Granulation Seams
- These form by grain dissolution as a result of local shear. They have reduced permeability.

Stylolites.
- These also form as a result of dissolution, and the
Granulation Seams or “Deformation Bands”

(photographs by Atilla Aydin)
Stylolites define area where some of the host rock has been removed due to dissolution.

- **Stylolite associated vein**
- **Stylolite**
- **Old Fracture**
- **Stylolite associated fracture** - flaws enable preferential initiation of fractures
Impact of Stylolites on Network Connectivity

1. Fracture network

2. Zone removed through dissolution

3. Resultant geometry

Stylolites often significantly impact the connectivity of fractured reservoirs

It is common for fractures associated with stylolites to form significant storage
Live Demo – Making a Model Where Fractures are Related to Folding & Faulting
Example of Regional Stress Fractures
Fractures Related to Regional Stress

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<td>D1</td>
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<td>$\epsilon_3$ parallel $\sigma_2$</td>
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Live Demo – Regional Stress Fractures
An important part of understanding the origin and distribution of natural fractures is understanding their chronology. This is because chronology can be used to infer fracture geometry elsewhere in the reservoir, and also provides a means to understand possible local permeability anisotropy.

Chronology (“timing”) describes the order in which fractures were formed, from the oldest to the youngest. It is based on termination or “abutting” relationships among fracture sets. The assumption is that a younger set generally terminates against an older set.
Which Set is the Oldest?

A) NE - SW (in NW corner)
B) NNW - SSE
C) NW - SE
How many fracture sets are there?

Systematic clockwise rotation of the minimum compressional stress.
Not All Fractures that abut are younger!
Not all fractures that abut are younger!

There are 2 situations where abutting relations may mislead if care is not taken. The first, shown to the right, is when joints abut a fault.
The yellow fracture is through-going, while the red fractures terminate against it. This same pattern is seen throughout the outcrop, and the offset on the red fractures is nearly the same on any given fracture.

The red fractures formed first, then were offset by the yellow fracture?  
Or maybe the yellow fracture formed first and the red fractures terminated against it?

What is your interpretation of the chronology shown here?
Actually, neither interpretation is correct.

First shallow joints developed because mechanical layer thickness was thin (yellow fractures)

Much later on, as the rock had solidified and mechanical layers thickened, a younger joint set (red fractures) formed, but twisted at their tops due to the presence of the older (yellow) fractures.
Understanding Timing of Fracturing relative to Structure is Important for Prediction.

What will Well 2 see?
Understanding Timing of Fracturing relative to Structure is Important for Prediction.

Set 1

Set 2

Both Sets Pre-Folding
Understanding Timing of Fracturing relative to Structure is Important for Prediction.
Understanding Timing of Fracturing relative to Structure is Important for Prediction.

Well 1
Well 2

Set 1
Set 2

Both Sets Post Folding
Understanding Timing of Fracturing relative to Structure is Important for Prediction.

Set 1

Set 2 Pre-Folding

Set 1 Post Folding

Well 1

Well 2
Fractures can be very systematic, or not, depending upon stress magnitudes and anisotropy, and mechanical properties of rock itself. Below is an example of a more irregular or non-systematic fracturing style.
Many fracture patterns consist of both systematic and non-systematic fracturing. Are the systematic fractures always the most important? Recall Exercise 1 and the impact of termination!
Terminations are related to another important feature of fracture networks – hydraulic significance!
Fractures are not simple parallel plates!

Figure 10. Internal Structure of “Feature A” (after Winberg, ed., 2000).

(Some of the most interesting and detailed work on building fracture models that do an excellent job of predicting flow and transport can be found in the high-level nuclear waste literature from Sweden, Finland and Japan)
Clastic Dyke intruding along fractures - not all fractures are utilised!
Igneous Dyke intruding along fractures - again not all fractures are utilised!
CONDUCTIVE vs. NON-CONDUCTIVE FRACTURES

All of this... 
...comes from a single fracture!
Geologists are very good at identifying fractures in core, borehole imagery or from seismic.

Unfortunately, most fractures when profiled by a flow meter or some other device with high spatial resolution appear to contribute little to the well’s productivity. The great proportion of production often comes from a very few fractures in well-defined zones.
Orientations of most passages
EXPLORING THE APERTURE DISTRIBUTION OF A FRACTURED RESERVOIR

...SOME SOLUTION-ENHANCED FRACTURES ARE NOT PERMEABLE TO LARGE OBJECTS
Yellow Passage

PASSAGE CONTROLLED BY SINGLE FRACTURE

Green Passage

PASSAGE CONTROLLED BY MULTIPLE STEP-OVER FRACTURES
WHAT SITUATIONS TEND TO MAKE AN “ORDINARY” FRACTURE A CONDUCTIVE FRACTURE?

Robber Baron Cave, San Antonio, Texas illustrates two situations:

1. Large fractures - higher probability of intersecting other fractures and forming a network

2. Fractures that have experienced some shear may have enhanced permeability

*Map annotation and photos courtesy of Laird Thompson, MOBIL*
PERCOLATION IN NETWORKS LEADS TO PREFERENTIAL HIGHLY CONDUCTIVE FLOW PATHS
HORIZONTAL CONDUCTORS

- Horizontal conductors are not fractures per se.
- Horizontal conductors form in fractured reservoirs as well as conventional reservoirs.
- When they form at top of carbonate sequence boundaries (e.g. Michigan Basin), they can extend for many tens of kilometers and rapidly transmit fluids and mass significant distances in short periods of time.
- Horizontal conductors are very low probability features in core or image logs; there might be only two or three in an entire well, compared to hundreds or thousands of fractures. It is hard to appreciate their significance from an image log or core alone. They may also be invisible to seismic.
- These conductors may serve as diversions to the vertical movement of fluids, as well as collectors for vertically moving fluids.
Flow features correlate with the juxtaposition of open-marine and restricted-marine facies.

Figure courtesy of M. Muldoon
“CONVENTIONAL WISDOM”
1. Fracture intensity decreases with depth
2. Subhorizontal fractures cannot be conductive at depth
3. Fracture intensity increases near faults
4. Fracture spacing is inversely proportional to bed thickness
5. Fracture aperture relates to fracture size
- Intensity is high at substantial depths
- Intensity does not increase near faults
Examples of Fracturing Near Faults in a Carbonate Reservoir – Does Fracture Intensity Increase Near Faults?
Bed Thickness and Fracture Intensity – Sometimes it Works, Sometimes it Doesn’t

The CFP plot shown above indicates that neither faulting nor conductive fracturing is related to bed thickness.

Thickness of jointed layer against fracture spacing in the orthogonal orientation to the fracture strikes.

Shows that there is a good correlation for layer bound joints and intensity.
Monkshood Anticline, B.C. Foothills

Chevron Fold (1 km wavelength, 15 km long)
Prophet Formation - carbonate/chert/shale

Some examples of the relations between fracture aperture, fracture size, and other geological factors.
Observations

Fracture aperture
- Most fractures filled with calcite and quartz
- Mean = 0.5 mm, range = 0 to 5 mm

Fracture system porosity
- Mean = 0.5% Range = 0.004% to 5%

Power-law tracelength distribution
- D=2: balance between large and small fractures
- Range: 3 cm to 150 cm
Fracture Sets

Set 1 (red) on backlimb fits expected model
Set 2 on backlimb and both sets on forelimb are tensional but have orientation of shear fractures
Cross plots of Field Data

Trace length, aperture, and intensity are not related
Cross plots of Field Data

Volumetric strain calculated by a line traverse method of Jamison (1989) correlates with aperture and fracture system porosity (but not mean length or intensity)
Joint and Faults are two different things - don’t mix data from one with the other

If there has been significant folding or faulting of the rock, expect characteristic fracture development and permeability features

Mechanical layering and fracture hierarchy are important for understanding both vertical and horizontal reservoir scale fracture permeability

Horizontal conductors may often be missed but are potentially very significant conductive features