Characterization and Modeling of Naturally Fractured Reservoirs: The Role of Outcrop Analogues

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Characterization and Modeling of Fractured Reservoirs: the Big Picture

*iReservoir’s Integrated Approach*

1. Create Equally Probable Geologic Models
   - *Quantify* spatial heterogeneity
   - Identify the *fracture indicators* (curvature, faults, strain, lithology, etc.)
   - Map crack density from fracture indicators
   - Create site-specific *equally probable scenarios*

2. Constrain Geologic Models using *Seismic, Log and Engineering Data*

3. Use *History Matching* to constrain and validate the geologic model
Why Outcrop Descriptions?

1. Spatial heterogeneity at subseismic scale
2. Deformation mechanisms and parameters controlling fracture distribution
3. Reservoir specific statistics

![Diagram showing fracture frequency and length distributions](After Heffer & Bevan (1990))
Outline

1. Why outcrop analogues?
2. Deformation mechanisms from outcrops
3. Example of faults and fractures systems fold and thrust belts:
   - Hierarchical shearing and progressive deformation,
   - Fracture hierarchies and stratigraphic architecture,
   - Factors controlling fracture distribution.
   - Comparison to subsurface.
4. The role of conjugate faulting on fracture localization.
5. Use of outcrop data for geostatistical modeling.
6. Conclusions.

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Deformation Mechanisms from Outcrops

- Tension
- Shear along joints
- Tension and Compression
- Flexural Slip

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Fracturing Mechanisms

Bending

Flexural Slip

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Faults and Fractures in a Fold and Thrust Belt

How are faults and fractures distributed in this Anticline?

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Bolivian Subandean Fold and Thrust Belt

After Labaume et al, 2001
Faults and Fractures at the Abra del Condor Anticline

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Joints and Sheared Joints

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Faults and fractures in this case are the result of hierarchical shearing and progressive deformation. Four main hierarchies identified: (1) joints, (2) small faults, (3) intermediate faults, (4) fault zones.
Fault Zones and Intermediate Faults

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Spacing of Joints

- Mean spacing: 0.49 m
- Bed spacing: ~0.5 m
Spacing of Small Faults

- \( \text{mean} : 4.18 \, \text{m} \)
- \( \text{bedset} \sim 10 \, \text{m} \)

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Spacing of Intermediate Faults

mean : 59.24 m
par. set: 64.5 m
Spacing of Fault Zones

- Mean spacing: 361 m
- Sequence spacing: 367 m
Fracture Spacing and Stratigraphy

**Fault Zones**
- Number of Data: 12
  - mean: 360.8
  - std. dev.: 137.26
  - coef. of var: 0.38
  - maximum: 620.00
  - upper quartile: 465.00
  - median: 335.00
  - lower quartile: 265.00
  - minimum: 120.00

**Intermediate Faults**
- Number of Data: 16
  - mean: 59.24
  - std. dev.: 53.16
  - coef. of var: 0.90
  - maximum: 183.00
  - upper quartile: 85.70
  - median: 46.00
  - lower quartile: 17.94
  - minimum: 2.94

**Small Faults (offset < 1m)**
- Number of Data: 168
  - mean: 4.18
  - std. dev.: 5.69
  - coef. of var: 1.36
  - maximum: 35.81
  - upper quartile: 5.47
  - median: 1.85
  - lower quartile: 0.77
  - minimum: 0.03

- Sequence = 367 m
- Parasequence Set = 64.5 m

**Joints**
- Number of Data: 839
  - mean: 0.49
  - std. dev.: 0.61
  - coef. of var: 1.24
  - maximum: 4.94
  - upper quartile: 0.56
  - median: 0.30
  - lower quartile: 0.14
  - minimum: 0.01

- Bedsets = ~10 m
- Beds ~0.5m

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Factors Controlling Fracture Distribution: Stratigraphy and Lithofacies

Intermediate Fault:
Parasequence set

Sh-Joints/SF:
Bedsets and Parasequences

Joints:
Beds
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Fracture Spacing and Shear Strain

Offset ~ 1km Offset ~ 8 km
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Fracture Spacing and Shear Strain

Small Faults; mean 0.76 m

Intermediate Faults; mean 19.3 m

Joints
Complex Fracture Pattern near Canaletas Thrust

(a) [Image of rock formation with marked fractures]

(b) [Diagram showing fracture pattern with north direction and scale]
Shear Strain and Fracture Density

Scanline

Mean Frequency (Fractures/m)

Estimated Shear Strain

Faults

Fractures / m

Distance (m)
How are Faults and Fractures distributed?

- Joints
- Intermediate Faults
- Fault Zones
- Sheared Joints
- Incipient Faults

~ 400 m
Comparison to Subsurface: Orientation

OUTCROP OBSERVATIONS

(1) Orthogonal Fracture Sets

(2) Dip-Parallel Faults and Oblique Splays

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Comparison of Fracturing Mechanisms

Flexural Slip

Splay joints abutting against bedding surfaces

Splay-confining bedding surfaces

Fracture Localization

Damage Zone

Main Fault

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Comparison with other Areas (Zagros, Iran)
Oblique and Dip-Parallel Fracture Trends

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Conjugate Faults and Fracture Swarms

Small Fault
Conjugate Faults May Localize Tension

Maximum mean tensile stress

Maximum mean compressive stress

Stress distribution due to slip along conjugate faults

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Fracture Swarm within Conjugate Faults

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Implications for Seismic Interpretation

Asymmetric amplitude dimming around normal faults
What we have learned so far:

1. Fractures occur at different scales as a result of hierarchical shearing and progressive deformation.

2. The spacing and dimension of different fracture hierarchies can be linked to stratigraphy.

3. Shear strain and lithofacies are among the main factors controlling fracture density.

4. Antithetic conjugate faults create fracture swarms.
Fracture Modeling

Fracture Density = Fractures / m
Fracture Density = 1 / Spacing

Low Shear-Strain = Low Fracture Density
High Shear-Strain = High Fracture Density

Scanline at Low Shear-Strain Area
Fracture Density Distributions

**Low Shear-Strain Area**
Lognormal Distribution

- Number of Data: 411
- Mean: 3.
- Std. dev.: 2.
- Coef. of var: 1.
- Maximum: 15.
- Upper quartile: 4.
- Median: 2.
- Lower quartile: 1.
- Minimum: 0.

**High Shear-Strain Area**
Normal Distribution

- Number of Data: 84.
- Mean: 29.
- Std. dev.: 11.
- Coef. of var: 0.
- Maximum: 67.
- Upper quartile: 31.
- Median: 27.
- Lower quartile: 23.
- Minimum: 12.

**Combined Data**
Exponential Distribution

- Number of Data: 495
- Mean: 7.
- Std. dev.: 11.
- Coef. of var: 2.
- Maximum: 67.
- Upper quartile: 5.
- Median: 3.
- Lower quartile: 2.
- Minimum: 0.
Conceptual Variation of Fracture Density Distributions

Heterogeneity (Localization)

Low

High

Strain

Low

High

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Conceptual Variation of Fracture Density Distributions

Heterogeneity (Localization)

Low

High

Low

High

Strain

Low

High

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Empirical CDF for Simulation

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Equally-Probable Realizations

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Spatial Correlation of Fracture Frequency

\[ \gamma(h) = 1 - \rho(h) \]
\[ \rho(h) = \frac{C(h)}{C(0)} \]

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Variogram- Based Sequential Indicator

Dip-parallel Faults and Background Joints

Dip-parallel Faults and Oblique Background Joints (Splays)
Stochastic Fault Modeling (SFM) and SGS: Object-Based Indicator

Low Shear-Strain Area

Dip-parallel faults and parallel joints

Stochastic Modeling of Fault Distribution and Architecture

Combination of SFM and SGS: Cookie-cutter Technique

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Object-Based Sequential Indicator Simulation (SIS)

*Intermediate Shear-Strain Area*
Dip-parallel faults and oblique splay fractures

Stochastic Modeling of Fault Distribution and Architecture

Combination of SFM and SGS: Cookie-cutter Technique

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Results from Object-Based Indicator Simulation

Low Shear-Strain Area

Intermediate Shear-Strain Area

Quantiles for Int. Sh-Strain
Mean 2.88
Variance 5.59
Median 2
IQR 3

Quantiles for Low Sh-Strain
Mean 3.54
Variance 11.57
Median 3
IQR 2
Reproducing the Spatial Heterogeneity

Intermediate Shear-Strain Area:

Dip-parallel faults, and oblique splay fractures

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Conclusions

1. Outcrops provide key information about orientation, deformation mechanisms and spatial heterogeneity of fault and fracture systems.

2. In fold and thrust belts fracture systems evolve as the result of hierarchical shearing and progressive deformation, creating different fracture hierarchies.

3. There is a 1st order relationship between fracture spacing and stratigraphic architecture.

4. Shear strain and lithology are key factors controlling fracture density.

5. Antithetic conjugate faults can produce fracture swarms.

6. Object-based SIS can be used to model NFR.