Hydraulic Fracturing for In Situ Stress Measurements –

Method Development and Field Tests at the University of Wisconsin-Madison

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Two Stages of a HF Stress Measurement Test

**Hydraulic Fracturing Test Setup**
- Foot Clamp
- 'Aq' Drill Rod
- Data Cable
- High Pressure Tubing
- Downhole Pressure Transmitters
- Test Interval
- Packers
- Packer Pressure Gage
- Flow Meter
- Test Interval Pressure Gage
- Hydraulic Pump
- Recording Unit
- A/D
- PC
- Laptop Computer
- Chart Recorder
- Power Supply

**Impression Packer Test Setup**
- Wireline
- Winch
- Packer Pressure Gage
- Hydraulic Pump
- High-Pressure Tubing
- Orienting Tool
- Scribe Line
- Impression Packer
- Impression Sleeve

Test yields HF attitude, i.e. $\sigma_h$ direction

**Test yields** $P_c$ and $P_s$
Development of HF method for in situ stress measurement: Brief History

1. Hubbert and Willis (H&W), 1957, using theory of elasticity, show that both breakdown and shut-in pressures are controlled by the in situ stress field.


3. H&F, 1970, suggest that recorded Breakdown and Shut-in pressures during HF could be used to compute the magnitudes and directions of the local principal stresses, i.e. HF could be used to determine the local state of in situ stress.
**Recorded Breakdown Pressure** \((P_c)\) and **Shut-in Pressure** \((P_s)\) and the **Principal Horizontal Stresses**

**Elastic Model**  
*Hubbert and Willis, 1957*

**Requires:** Vertical Hole and Hydrofrac, Impermeable Rock; and based on:
- ‘Maximum Tensile Stress’ criterion
- ‘Effective Stress Law’
- Theory of linear elasticity, leading to:

\[
(P_c - P_o) = T + 3(\sigma_h - P_o) - (\sigma_H - P_o)
\]

\[
P_c = T + 3\sigma_h - \sigma_H - P_o
\]

**Poroelastic Model**  
*Haimson and Fairhurst, 1967*

- It incorporates the effect of stresses due to flow of HF fluid into the rock:

\[
(P_c - P_o) = \left[ T + 3(\sigma_h - P_o) - (\sigma_H - P_o) \right] / K
\]

where \(K = 2-\alpha (1-2u) / (1-u)\); \(\alpha = 1-C_r/C_b\)

\(\alpha\) is known as the Biot constant

\[
P_s = \sigma_h
\]
Pressure (Test-Zone, Packer)-Time; Flowrate-time Record

Test 9: 67.89 m Measured Depth

Test Zone  Packer  Flow

Time, min

Pressure, MPa

Flow, lpm
Maximum Tensile Stress Criterion of Failure
Hydraulic Fracture Orientation and In Situ Stress Directions

\[ \sigma_v = 3.5 \text{ MPa} \]
\[ \sigma_h = 12.5 \text{ MPa} \]
\[ \sigma_H = 12.5 \text{ MPa} \]

\[ \sigma_v = 14 \text{ MPa} \]
\[ \sigma_h = 7 \text{ MPa} \]
\[ \sigma_H = 9 \text{ MPa} \]

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\[ \sigma_{v} = 4000 \]
\[ \sigma_{H} = 2000 \]
\[ P_c = 4450 \]

Hydrostone

\[ \sigma_{H\text{Min}} = 1800 \]
Hydraulic fractures originate and extend in the direction normal to minimum principal stress, even in jointed or foliated rock (example: Martinsburg Slate).
Typical Tools for Detecting HF Orientation

Impression Packer

Borehole Televiewer (Ultrasonic Logging Device)
First Deep HF Stress Measurements: 1971
Rangely Oil Field, CO (Site of Induced Seismicity)
HF-based State of Stress at Rangely, CO
Depth: ~2,000 m
HF-Predicted vs. Measured Pore (Reservoir) Pressure Leading to Earthquakes
HF-based State of Stress, Pre-excavation, at Helms Pumped Storage Plant, Sierra Nevada
Helms Pumped Storage, Sierra Nevada, original and corrected layouts resulting from knowledge of HF-based state of stress prior to excavation.
HF-based In-situ Stress Orientation in Southern Wisconsin
State of HF-based Stress at a Site of Future Underground Nuclear Power Plant - Darlington, Ontario
HF-based State of Stress at URL, Manitoba

The Underground Research Laboratory (URL)

Stress (MPa)  Max. Stress dir.

The State of Stress at URL based on HF tests
State of Stress around the Michigan Basin based on HF Measurements at Depths of 0-200 m and at 0-1300 m
Wireline Straddle-Packer for HF Tests down to 500 m

Not applicable in very deep wells
State of Stress in the Michigan Basin based on HF Measurements of 0 - 5000 m

Oil Derrick for HF Stress Tests in Michigan Deep Well

Michigan Deep Well
HF-based State of Stress in the Mid-Continent down to 5 km
Hydraulic Fracturing is recognized by ISRM as an accepted method of in situ stress measurements.