Pinnacle/Halliburton
Hydraulic Fracture Diagnostics and Reservoir Diagnostics

Eric Davis

May 2009
Agenda

• About the Purchase
• Pinnacle Overview
• Fracture Diagnostics
  – Why Map?
  – Microseismic & Tilt Mapping
  – Examples
• Reservoir Diagnostics
• Background Materials
Why are we here today?

Halliburton has acquired Pinnacle assets, including Fracture Diagnostics and Reservoir Monitoring Services.

Software, consulting services and Applied Geomechanics remain with Carbo Ceramics.
How will Pinnacle be managed?

• Retain Pinnacle brand, culture and business model
• Retain existing management team
• Significant investment in North America and international business growth
• Invest in current and future human capital
• Accelerate development of synergetic technologies and workflows in collaboration with other product services lines within Pinnacle and Halliburton
Agenda

• About the Purchase

• Pinnacle Overview

• Fracture Diagnostics
  – Why Map?
  – Microseismic & Tilt Mapping
  – Examples

• Reservoir Diagnostics

• Halliburton – Pinnacle Synergies Additional

• Background Materials
Pinnacle Technologies

- Founded in 1992
- >160 employees today
- Offices in Houston, San Francisco, Bakersfield, Denver, Midland, OKC, Calgary, Beijing
- Provided services to all major producers and service companies
- Over 200 technical papers published
- 2 R & D 100 awards
- 2 Meritorious Engineering awards
- Over 11,000 stages mapped
Top 15 Customers

• EOG
• Devon
• ChevronTexaco
• Quicksilver
• Talisman
• Rimrock
• EnCana
• Samson
• Chesapeake
• Aera
• Antero
• Plains
• Shell
• ConocoPhillips
• PetroCanada
Agenda

- About the Purchase
- Pinnacle Overview
- Fracture Diagnostics
  - Why Map?
  - Microseismic & Tilt Mapping
  - Examples
- Reservoir Diagnostics
- Halliburton – Pinnacle Synergies Additional
- Background Materials
We Know Everything About Our Fracs Except . . .

- Poor fluid diversion
- Out-of-zone growth
- Upward fracture growth
- T-shaped fractures
- Twisting fractures
- Perfectly confined frac
- Horizontal fractures
- Multiple fractures dipping from vertical
How Can Fracture Mapping Provide Value?

• Determine Azimuth
  – Optimize well location to maximize recovery
  – Optimize horizontal well azimuth for best fracture geometry

• Determine Fracture Height
  – Optimize perforating strategy
  – Reduce out of zone growth, potentially increase half-length

• Determine Fracture Half-Length
  – Optimize well location to maximize recovery
  – Optimize Frac Stage volume

• Determine Fracture Coverage in Horizontal wells
  – Optimize Completion Design, Stage size, spacing etc.
**Surface Tilt Mapping**
- Measure Azimuth and Approximate Fluid Distribution in Horizontal Laterals

**Reservoir Monitoring**

**Distributed Temperature Sensing**
- Deployed On Casing or Tubing
- Measure Frac Height/Distribution and Production Response

**Microseismic Mapping**
- Deployed On Fiber-optic Wireline in Treatment or Offset Well
- Measure Frac Height, Length And Azimuth In Real-time
- Calibrate Frac Models

**Downhole Tilt Mapping**
- Deployed Single-Conductor Wireline in Treatment or Offset Well
- Measure Frac Height, Length
- Calibrate Frac Models
## Fracture Diagnostic Technologies

### Main Limitations

<table>
<thead>
<tr>
<th>GROUP</th>
<th>DIAGNOSTIC</th>
<th>MAIN LIMITATIONS</th>
<th>ABILITY TO ESTIMATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Length</td>
</tr>
<tr>
<td>Indirect</td>
<td>Net Pressure Analysis</td>
<td>Modeling assumptions from reservoir description</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Well Testing</td>
<td>Need accurate permeability and pressure</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Production Analysis</td>
<td>Need accurate permeability and pressure</td>
<td>[ ]</td>
</tr>
<tr>
<td>Direct, near-wellbore</td>
<td>Radioactive Tracers</td>
<td>Depth of investigation 1'-2'</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Temperature Logging</td>
<td>Thermal conductivity of rock layers skews results</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>HIT</td>
<td>Sensitive to i.d. changes in tubulars</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Production Logging</td>
<td>Only determines which zones contribute to production</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Borehole Image Logging</td>
<td>Run only in open hole- information at wellbore only</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Downhole Video</td>
<td>Mostly cased hole- info about which perfs contribute</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Caliper Logging</td>
<td>Open hole, results depend on borehole quality</td>
<td>[ ]</td>
</tr>
<tr>
<td>Direct, far field</td>
<td>Surface Tilt Mapping</td>
<td>Resolution decreases with depth</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>DH Offset Tilt Mapping</td>
<td>Resolution decreases with offset well distance</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Microseismic Mapping</td>
<td>May not work in all formations</td>
<td>[ ]</td>
</tr>
<tr>
<td></td>
<td>Treatment Well Tiltmeters</td>
<td>Frac length must be calculated from height and width</td>
<td>[ ]</td>
</tr>
</tbody>
</table>
How Can Fracture Mapping Provide Value?

• **Determine Azimuth**
  – Optimize well location to maximize recovery
  – Optimize horizontal well azimuth for best fracture geometry

• **Determine Fracture Height**
  – Optimize perforating strategy
  – Reduce out of zone growth, potentially increase half-length

• **Determine Fracture Half-Length**
  – Optimize well location to maximize recovery
  – Optimize Frac Stage volume

• **Determine Fracture Coverage in Horizontal wells**
  – Optimize Completion Design, Stage size, spacing etc.
Main Project Objective
Determine Far-Field Frac Azimuth Using Microseismic Mapping
Note: Frac lengths and dips are not drawn to scale in this view.
Where Should I Drill My Next Well?

- Azimuth Changes Around Basin
  - Microseismic Monitoring Of 3 Stages In Each Of 2 Well Pairs
How Can Fracture Mapping Provide Value?

- **Determine Azimuth**
  - Optimize well location to maximize recovery
  - Optimize horizontal well azimuth for best fracture geometry

- **Determine Fracture Height**
  - Optimize perforating strategy
  - Reduce out of zone growth, potentially increase half-length

- **Determine Fracture Half-Length**
  - Optimize well location to maximize recovery
  - Optimize Frac Stage volume

- **Determine Fracture Coverage in Horizontal wells**
  - Optimize Completion Design, Stage size, spacing etc.
Did the Frac Stay in Zone?

• Why can’t I pump into zone 2
• Why does zone 3 not produce well

Viewing angle varies by stage to show maximum.
How Can Fracture Mapping Provide Value?

- **Determine Azimuth**
  - Optimize well location to maximize recovery
  - Optimize horizontal well azimuth for best fracture geometry

- **Determine Fracture Height**
  - Optimize perforating strategy
  - Reduce out of zone growth, potentially increase half-length

- **Determine Fracture Half-Length**
  - Optimize well location to maximize recovery
  - Optimize Frac Stage volume

- **Determine Fracture Coverage in Horizontal wells**
  - Optimize Completion Design, Stage size, spacing etc.
Model Calibration for J Sand in the DJ Basin, CO

(SPE 96080)

Uncalibrated

Logs: Well XXY

Layer Properties

TVD (ft) | MD (ft) | GR

-7500 | -7500

8000 | 8000

Rocktype | Stress | Perme | Comps

Concentration of Proppant in Fracture (lb/ft³)

Width Profile

Halliburton

Pinnacle
Model Calibration the J Sand in the DJ Basin, CO

(SPE 96080)

Uncalibrated

Long confined fracture based on microseismic mapping

Calibrated

HALLIBURTON
How Can Fracture Mapping Provide Value?

- **Determine Azimuth**
  - Optimize well location to maximize recovery
  - Optimize horizontal well azimuth for best fracture geometry

- **Determine Fracture Height**
  - Optimize perforating strategy
  - Reduce out of zone growth, potentially increase half-length

- **Determine Fracture Half-Length**
  - Optimize well location to maximize recovery
  - Optimize Frac Stage volume

- **Determine Fracture Coverage in Horizontal wells**
  - Optimize Completion Design, Stage size, spacing etc.
Horizontal Drilling

- Larger Area of Contact with Wellbore
- Minimize Fracture Height Growth
- Less Environmental Impact (fewer surface sites)

(a) Vertical Well
(b) Horizontal Longitudinal
(c) Horizontal Transverse
Issues for Horizontal Well Fracturing

- Optimizing wellbore trajectory & reservoir drainage requires knowledge of fracture geometry
- Wellbore Trajectory – high, low, transverse, longitudinal?
- Interval Coverage (fracture height & payzone)
- Wellbore Coverage (along the lateral)
- Diversion & Staging
  - OH, OH packers, CH, perf balls, plug & perf, etc.
- Fracture Execution & Complexity
  - Perforating, wellbore clean-out, initiation, to cement or not

Minimize Complexity, Good Communication to the Formation & Optimum Interval/Lateral Coverage
Microseismic in Horizontal Wells

- Barnett Shale Longitudinal
  - Gel Frac Versus High Rate Waterfrac (Refrac)
  - Increased stimulated volume

Test Well Gas Rate

Gas Flow Rate (Mcf/d)

- Gel Stimulation
  - Waterfrac Refrac

Perforations

Observation Well 1

Observation Well 2

SPE 95568 (Devon)
Agenda

• About the Purchase
• Pinnacle Overview
• Fracture Diagnostics
  – Why Map?
  – Microseismic & Tilt Mapping
  – Examples
• Reservoir Diagnostics
• Halliburton – Pinnacle Synergies Additional
• Background Materials
Pinnacle Reservoir Monitoring
Main Focus Areas

- Any Heavy Oil Steam EOR Field
- Any Long Term Waste Injection Project
- Carbon Capture and Sequestration (CCS) Projects
- Any well where pressure / temperature monitoring is desired

- Future: Monitoring of large offshore projects
How Can Reservoir Monitoring Provide Value?

- Risk avoidance in steam EOR fields
- Steam program optimization
- Cost effective long term monitoring for waste injections
- Cost savings through virtual production or injection logs from fiber optic solutions.
- Identification of fluid movement over time
  - Is that a sealing fault?
  - Where are my drill cuttings going?
  - Is my CO₂ staying in zone?
Surface Deformation
- Tilt, GPS, InSAR

Surface Microseismic
- Special (Rare) Applications

Downhole Microseismic
- Offset and Active Well (Injector or Producer)

Downhole (Deformation) Tilt
- Offset and Active Well (Injector or Producer)

VSP Acquisition
- Near Wellbore Monitoring

Crosswell Seismic Acquisition
- Fiber Optic Temperature and Pressure

Reservoir Monitoring Technologies
Direct Fracture Diagnostic Techniques
Principle of Tilt Fracture Mapping

Hydraulic fracture induces a characteristic deformation pattern.

Induced tilt reflects the geometry and orientation of created hydraulic fracture.

Fracture-induced surface trough

Downhole tiltmeters in offset well

Pick-up electrodes
Gas bubble
Conductive liquid
Excitation electrode
Glass case
Surface Tilt Tool Sensitivity
Tiltmeter Data from a Quiet Site

- Full Moon on 6/20/97
- New Moon on 7/4/97

Date

06/14/97 06/19/97 06/24/97 06/29/97 07/04/97 07/09/97 07/14/97

Tilt (Nanoradians)

0 50 100 150 200 250

NanoRadian Resolution
Surface Tilt Tool Sensitivity
Earthquake Response

San Salvador
13-Jan 10:33 (CST)
7.6 Magnitude

India
25-Jan 21:16 (CST)
7.8 Magnitude
Tilt Mapping

Surface Mapping

Offset Well Mapping
- Fracture Dimensions
- Well Spacing
- Model Calibration

Downhole Mapping

Offset Well Mapping
- Fracture Dimensions
- Well Spacing
- Model Calibration

Active (Injection) Well Mapping
- Fracture Height
- Model Calibration
- Critical Wells

Fracture Orientation
Horizontal Wells
Well Placement
Long-term reservoir monitoring

HALLIBURTON
Tilt Examples

The Big Squeeze 24-Mar-2003 10:00 to 24-Mar-2003 10:10

[Diagram showing tilt examples]
Surface Tiltmeter/GPS Mapping

Mapped Cement Squeeze

Cement squeeze performed at 345'.
Suspect upward channel.
Microseismic Mapping
Obtaining Data From an Offset Observation Well

- Fiber optic wireline and 7 conductor
- 6-20 Levels, 3 Component Sensors
- Mechanically Coupled
- Can be deployed under pressure
SAGD Steam Flood Example
Tiltmeter/Strain-Microseismic
High Precision Differential GPS

3-D displacement
Sensitivity:
1-½ mm vertical displacement
½ mm lateral displacement
Pinnacle Technologies
InSAR Technology

Interferometric Synthetic Aperture Radar
“spaceborne radar”

Sensitivity: Can be sub-centimeter displacement under right conditions
InSAR Applications

Steam Induced Oil field heave. San Joaquin Valley, CA. 2005.

Synthetic Aperture Radar (SAR)

- High Deformation Areas: 26.6 cm/year
- Low Deformation: ~1 mm/year
- No Deformation
InSalah Algeria

Pinnacle
Monitoring Program

- 4 year InSAR historical study
- 2 year acquisition of RSAT2 Ultra Fine SAR data
- Surface Tiltmeter Array over KB-501 injector
- Field wide DGPS array
- Reservoir level volumetric & strain studies
SWP Carbon Sequestration
San Juan Basin, New Mexico
Site Location

Pump Canyon CO2 Sequestration
San Juan Basin, NM
Sec 32 / T31N, R8W
Field Installation
Injection/Production from section 32 & surrounding

Producers in section 32

Producers immediately surrounding section 32
Pre-CO2 Injection: < 7/30/2008

~ 2 month settling time for many tiltmeter instruments.

Settling lasts until June, 2008 resulted in ...

Extracted Tilt Signals:


Extracted Tilt Signals:

X: 76.655 microradians       Y: 66.718 microradians
Period 2: CO2 Injection Ramp-up – 7/30/08 – 9/9/08

Extracted Tilt Signals: X: 3.184 microradians       Y: 3.467 microradians

This change is observed at several tilmeter sites

Long-term change in tilt response observed after injection initiation
Period 2: CO2 Injection Ramp-up – 7/30/08 – 9/9/08
Reservoir Strain Computation

- Small volumetric changes calculated
- Theoretical / actual tilt correlation is poor

Reservoir strain from surface tilt

Surface deformation from reservoir strain
Additionally …

Preliminary InSAR observations hint that there is negligible deformation prior to CO2 injection period.

September 21, 2007 –
August 4, 2008
## Surface Deformation Monitoring Technologies

<table>
<thead>
<tr>
<th>Description</th>
<th>Synthetic Aperture (Radar Interferometry (InSAR))</th>
<th>Global Positioning System (GPS)</th>
<th>Tiltmeters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description</strong></td>
<td>Compares the phase change between reflected radar pulses recorded at two different times from space borne satellites</td>
<td>Directly measures surface deformation using a network of surface receivers and a constellation of satellites</td>
<td>Directly measures surface deformation (Tilt or gradient of displacement) using an array of tools</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>Sub-centimeter displacement</td>
<td>1.5 mm (0.06 inches) of vertical displacement</td>
<td>0.005 mm (0.0002 inches) of vertical displacement</td>
</tr>
</tbody>
</table>
| **Key Strengths** | - Broad spatial coverage  
- No ground instrumentation required  
- Monthly monitoring capabilities | - Operates continuously  
- Operable in most weather conditions  
- 3-D displacement monitoring  
- Absolute elevation measurements | - Measures extremely small movements  
- Operates continuously  
- Uses very little power  
- Measurements not influenced by weather |
Fiber Optic Pressure
Pinnacle SILO Enclosure

• Similar to our proven Surface Tilt Sites (over 15 years of experience)
• Installed 5 - 20 ft below the earth’s surface with single 10”-diameter PVC pipe
• Drilled with Rat-hole drilling unit, same as conductor pipe or dead-man anchors
• Eliminates need for doghouse and climate control equipment and associated power
• Stable Temperatures – ideal for electronics and batteries (constant ~60°F)
• Eventually will house most of our reservoir monitoring equipment
  - FOP and DTS
  - RM Computers
  - GPS
  - MSM - Future
Pinnacle SILO Instrumentation

Davidson Fiber Optic Pressure Surface Interrogator

SensorTran DTS Surface Interrogator, Proprietary to Pinnacle
What Can You Do With DTS and Pressure Data

Viewer DTS Data
- Identify “large” temperature anomalies
- Identify water or gas breakthrough
- Behind pipe channels
- Identify top of cement, washouts and voids
- Isolation failure (flappers)
- Tubular or packer failures

Pressure Data
- Initial Reservoir Pressure (Bottom zone)
- Overall bottomhole pressure history (flowing and SI)
- PTA

Virtual Production Log
- Production/injection splits by zone
- Analyze “small” temperature variations
- Identify water or gas breakthrough
- Behind pipe channels
- Adding a single pressure point adds significantly to the analysis

Activities Monitored
- Cementing (depends of rig requirements)
- Stimulations/Chemical Injection/Profile Modification
- Flowbacks
- Long-term production and injection
Typical Deployment Casing

- Need Oriented Perforating
- Can map cmtg, frac, flowbacks
- StimWatch
- Ongoing production
- Single Press
Typical Deployment Tubing

- No Perforating Issue
- Lower Cost, daylight operations
- Requires annular BOP
- Can not map cmtg, frac, flowbacks
- Ongoing production
- Single Pressure
Advanced Processing
Virtual Production Log

Example of using temperature instead of spinner to compute flowrates.

Tubing was run too low and blocked production information for all tools except temperature.

Temperature was used to calculate the production profile.
Questions?
THANK YOU
Agenda

• About the Buyout
• Who is Pinnacle
• Halliburton – Pinnacle Synergies
• Fracture Diagnostics
  – Microseismic Mapping
  – Tilt Mapping
• Why Map?
• Additional Background Materials
Microseismic Mapping

- Deployed on Fiber-optic Wireline
- Mechanically Clamped To Wellbore
- Measure Frac Height, Length And Azimuth In Real-time
- Calibrate Frac Models
Microseisms

What Is It?

- A Microseism Is Literally A Micro-Earthquake. Microseisms That Occur During Hydraulic Fracturing Are Caused By:
  - Changes In Stress And Pressure As A Result Of The Treatment
  - By Movement Along Induced Fracture Planes Where Hindered By Irregularities
Receiver Arrays – OYO Geospace System

- DS 250
- DS 150
- Fiber Optic Wireline
  - Fast Telemetry
    - Large Number Of Receivers
      - 32 Maximum Per Well
    - High Sampling Rates
      - 4,000 Samples Per Second

DS 250

DS 150

H2 H1

Tri-Axial Sensors (Geophones)

Vertical Up

Clamp Arm In Back
Microseismic Wireline Deployment & Set-up

- Observation Well
- Treatment Well
- Wireline Unit with 12-Level 3C Tool String

Cranes and Wireline Units

~ 3000 ft
What Information Is Needed For Processing?

- Formation Velocity
  - Advanced Sonic Log (P & S Waves)
  - Perforation Timing
- Receiver Orientation
  - Perforations Or String Shots
    - Known Locations
- Surveys
  - Surface Survey (Well-to-well)
    - Pinnacle Checks With GPS
  - Deviation Surveys
    - Monitor & Frac Wells
Perforation Timing Measurements

• Perforations Or String Shots Are Required to Determine Orientation of Every Tool in Toolstring
  – Use For Velocity Measurements

• Requires A Precise Measurement Of Exactly When It Fired (Not When Voltage Was Increased)

• Pinnacle Has A Patent-Pending Procedure For Measuring The Timing Pulse On The Firing Line

• Velocity Can Be Determined
  – Firing Time
  – Arrival Times
  – Distances (Requires Survey Data)
Sample Rate & Errors

• Monte Carlo Analysis Of Errors
  • Sampled From A Triangular Distribution
  • Arrivals +/- 2 Sample Points
  • 50 Realizations For Each Case
  • Layered Cases For Realistic Behavior
• Error Increases Almost Linearly With Slower Sampling Rate
  • Effect On Depth Is Usually Greater Than Effect On Distance
  • Observe The Difference In The Distribution Of The 50 Realizations For the Two Cases Below
• Depth Errors
  • $1/4$ msec = 4 ft
  • $1$ msec = 18 ft

Pinnacle

- Arrivals +/- 2 Sample Points
- 50 Realizations For Each Case
- Layered Cases For Realistic Behavior

- Effect On Depth Is Usually Greater Than Effect On Distance
- Observe The Difference In The Distribution Of The 50 Realizations For the Two Cases Below

1/4 msec Sampling

Distribution Of Events For 50 Realizations

Receiver Locations

1 msec Sampling

Distribution Of Events For 50 Realizations

Receiver Locations

One Standard Deviation (ft)

Sample Rate (msec)

HALLIBURTON
Sample Rate & Errors

- The Previous Case Where The Array Is Straddling A Zone Is The Best Case
- Consider A Case Where The Array Is Above The Zone And The Event Is Near The Bottom
  - Errors Can Be Much Greater & Can Cause Interpretation Problems
    - Notice The “Bend” In The Locations, Particularly For 1 msec Sampling
  - Depth Errors
    - $1/4$ msec = 10 ft
    - 1 msec = 45 ft
  - Note The Complex Distribution For 2 msec Sampling In The Inset

100 120

Distance

• Notice The “Bend” In The Locations, Particularly For 1 msec Sampling

Depth

1/4 msec Sampling

Receiver Locations

Distribution Of Events

1 msec Sampling

Receiver Locations

Distribution Of Events
Comparison Of Accuracy

• Pinnacle
  – Depth: 8 ft
  – Distance: 5 ft

  Pinnacle: 12 Receivers @ \( \frac{1}{4} \) msec

• Comp. B
  – Depth: 57 ft
  – Distance: 24 ft

  8 Receivers @ 1 msec
Comparison Of Sensors Used In Microseismic Monitoring

- **OYO OMNI 2400 & SLB GAC**
  - Most Systems Use OMNI 2400 15 Hz Geophones
  - SLB Uses The GAC Sensor

- Using Published Response Curves For Each Sensor

- The Response To Velocity Is Shown In The Lower Curve
  - The OMNI 2400 Geophone Response Is Flat Above About 20 Hz (Out To ~1200 Hz)

- Response To Acceleration Shown At Top
  - The GAC Response Is Flat From ~5 – 200 Hz

- Other Important Points:
  - Microseismic Events Usually Have Most Energy In The 200 – 700 Hz Range
  - Best To Have A Flat Response Over The Range Of Interest

**HALLIBURTON**
QC Report - Confidence Level
QC Report

Event Magnitude vs Distance from Observation Well

- Series Of Faults
  - Identified Easily From Magnitudes
  - Abnormal Propagation
    - Azimuth
    - Vertically

Jonah Field, WY

SPE 102528
QC Report - Event Uncertainty

• Larger azimuthal uncertainty farther from observation well results in wider “fan” of events toward eastern wings of fractures

• Relatively narrow band of events indicates absence of complex (network) growth
Pinnacle’s Microseismic Mapping Advantage

• Experience
  – More Than 3,800 Hydraulic Fractures Mapped Since 2001
  – More Than 90% Of All Microseismic Jobs Mapped Worldwide

• Dedicated People and Equipment

• Superior Equipment:
  – Highest Array Density With Up To 32 Tools In One Array
  – Highest Telemetry Rate At ¼ Ms With Fiber Optic Wireline
    • Record & Analyze Much Higher Frequencies Than Other Tool Systems

• Better Data Quality And Highest Precision Event Location Due To:
  – Number Of Tools & Sample Rate
  – Perf Timing
  – Stacking

HALLIBURTON
Surface Tilt Mapping
Principle of Tilt Fracture Mapping
Direct Fracture Diagnostic Technique

Hydraulic fracture induces a characteristic deformation pattern.

Induced tilt reflects the geometry and orientation of created hydraulic fracture.
Surface Tiltmeter Site

- Installed 5 - 40 ft below the earth’s surface in 4”-diameter PVC pipe
- Deeper boreholes to eliminate “noise” from surface
  - Cultural noise
  - Thermal induced earth surface motion
- Surface array with 16 or more tiltmeters placed in concentric circles around the point of injection (distance from well: 15%-75% of injection depth)
- Tiltmeter data stored in datalogger contained in tiltmeter
- Data collected periodically either manually or by radio
Surface Tiltmeter Fracture Mapping

- Example of Surface Tiltmeter Response
  - Multi-Mode Fracturing
    - Vertical Fractures And/Or Opening Of Cleats
    - Horizontal Fractures
  - Surface Deformation From Individual Components Add Together
    - Superposition

- Vertical-Trough & Uplifts
- Combined-Trough On Top Of Uplift
- Horizontal – Simple Uplift

Halliburton
Poor Diversion in a Long Uncemented Lateral

Note: Frac length and dips are not drawn to scale in this plan view.
Surface Deformation Image

Stage 1 - Well SJU 27-5 #508 07-Aug-2008 13:28 to 07-Aug-2008 14:19

- Vertical
- Tiltmeter Site
- Well Location
- 0.00015 Max Movement (in)
- 0.00004 Min Movement (in)

Northing (ft) 0 1328000 1329000 1329400 1329600 1329800 1330000

Easting (ft) 940000 940200 940400 940600 940800 950000

-10^{-4}

-2 -1 -0.5 0 0.5 1
Treatment Well Tilt Mapping

- Deployed on single conductor e-line
- Magnetic decentralizers
- Slim 1-11/16” tool diameter
- Measure frac height in real-time
- Calibrate frac models
Treatment Well Tiltmeters

- Measure Fracture Height In Vicinity Of Wellbore
- Observe Changes In Height
  - Correlate With Pressure
- Height -> Primary Result
  - Complex Deformation Around Wellbore
SPE Microseismic Mapping Papers – Last 2 Years

- **PT** 2007 108103 Stacking Seismograms to Improve Microseismic Images
- **SLB** 2007 106159 Real-Time Microseismic Monitoring of Hydraulic Fracture Treatment: A Tool To Improve Completion and Reservoir Management
- **SLB** 2006 104570 Using Induced Microseismicity to Monitor Hydraulic Fracture Treatment: A Tool to Improve Completion Techniques and Reservoir Management
- **PT** 2006 102801 Imaging Seismic Deformation Induced by Hydraulic Fracture Complexity
- **PT** 2006 102690 Improving Hydraulic Fracturing Diagnostics By Joint Inversion of Downhole Microseismic and Tiltmeter Data
- **PT** 2006 102528 Hydraulic Fracture Diagnostics Used To Optimize Development in the Jonah Field
- **SLB** 2006 102493 Using Microseismic Monitoring and Advanced Stimulation Technology to Understand Fracture Geometry and Eliminate Screenout Problems in the Bossier Sand of East Texas
- **PT** 2006 102372 Understanding Hydraulic Fracture Growth In Tight Oil Reservoirs By Integrating Microseismic Mapping and Fracture Modeling
- **PT** 2006 102103 Integration of Microseismic Fracture Mapping Results with Numerical Fracture Network Production Modeling in the Barnett Shale
- **PT** 2006 98219 Application of Microseismic Mapping and Modeling Analysis to Understand Hydraulic Fracture Growth Behavior
- PT 2005 97994 Application of Microseismic Imaging Technology in Appalachian Basin Upper Devonian Stimulations
- **XOM** 2005 95909 Logging Tool Enables Fracture Characterization for Enhanced Field Recovery
- **PT** 2005 95568 Comparison of Single and Dual-Array Microseismic Mapping Techniques in the Barnett Shale
- **SLB** 2005 95513 Automated Microseismic Event Detection and Location by Continuous Spatial Mapping
- **PT** 2005 95508 Integration of Microseismic Fracture-Mapping Fracture & Production Analysis with Well-Interference Data to Optimize Fracture Treatments in the Overton Field, East Texas
- **PT** 2005 95337 Effect of Well Placement on Production and Frac Design in a Mature Tight Gas Field
- **SLB** 2005 94048 Hydraulic Fracture Monitoring as a Tool to Improve Reservoir Management
- **PT** 2005 84488 Improved Microseismic Fracture Mapping Using Perforation Timing Measurements for Velocity Calibration
- **PT** 2005 77441 Integrating Fracture-Mapping Technologies to Improve Stimulations in the Barnett Shale

**HALLIBURTON**