Webinars

Distributed Fiber Optic Sensing:
The Current State of Oil &Gas Applications and Their Value

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Prepared for the SPE Webinar on Distributed Fiber Optic Sensing Applications (May 16, 2017)

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President

Dennis Dria is president and petroleum technology advisor for Myden Energy Consulting, PLLC (2010-present). He has over 35 years' experience in the oil & gas industry, in a combination of upstream and downstream oil and gas R&D and E&P operating division positions; including 9 years with the Standard Oil Company and 21 years with Shell.

Dennis earned his BS in Physics and Mathematics from Ashland University and his PhD in Petroleum Engineering from the University of Texas at Austin. He is author or coauthor of 26 US patents and 15 technical publications and is a contributing editor to the current SPE Petroleum Engineering Handbook.

He is a Distinguished Member of the SPE and a 2011-2012 Distinguished Lecturer on the topic of "E&P Applications of Fiber-Optic Technologies."

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Distributed fiber-optic sensing in O&G

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- Focus on
  - Upstream - development and operations
  - In-well deployment
- Why choose FOS is useful
- What FOS can do for us

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Why should we talk about fiber-optic sensing?

- No down-hole electronics
  - High temperature
  - Reliability
- Real-time monitoring capability
- Multiple sensing options
  - Temperature, Pressure, Strain and Acoustics
- Well design may limit intervention
  - Build in RT surveillance capability
  - Production logging
  - Well-bore seismic
  - Permanent FO installation: life-of-field monitoring

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What can fiber-optic sensing do for us?

Manage / optimize asset performance

- Thermal recovery management
- Production/reservoir performance optimization
- Injection management
- Stimulation management
- Well integrity
- Geophysical mentoring
- Seismic

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What can fiber-optic sensing do for us?

- Thermal recovery projects
  - Thermal flood injection optimization
  - Reservoir performance
- Production performance optimization
  - Inflow profiling – where does the production comes from
  - Gas and water breakthrough
- Injection management
  - Injection profile & control
  - Out-of-zone injection

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What can fiber-optic sensing do for us?

Stimulation management

Acid (matrix) stimulation optimization

HFS (hydraulic fracture stimulation)

- Diversion
- Frac geometry
- Well spacing

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What can fiber-optic sensing do for us?

Well integrity

P&A considerations (e.g. pressure isolation)

Sand management

Geophysical mentoring

Reservoir strain

Compaction/subsidence management

Cap rock integrity

Seismic

Borehole

Well to well

microseismic

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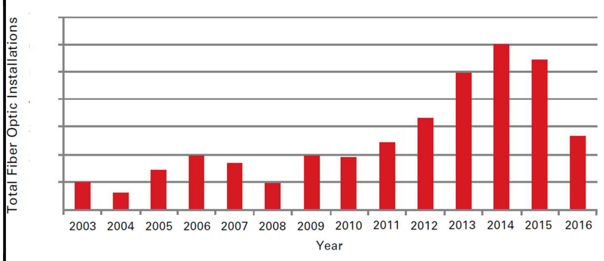
Fiber Optic Installations per Year



SEAFOM vendor survey, graphic courtesy of Eric Holley, Halliburton

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Fiber Optic Installations

More than 4000 permanent fiber-optic installations

- > 3500 onshore
- > 600 offshore (dry tree)
- > 20 subsea (wet tree)

SEAFOM vendor survey

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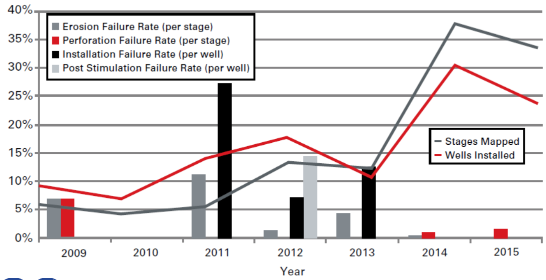
Fiber Optic Installation History
Failure Rate by Mechanism



"Fiber-Optic Evaluation for Unconventional Assets: Eight Year Overview" White Paper, courtesy of Eric Holley & Halliburton

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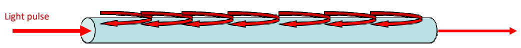
Fiber Optic Sensing – How is it done?

Distributed Sensor



Fiber itself is Continuous Sensing Element

Fiber itself is the sensor

Back-scattered light carries information

Distributed sensing options:
DXS X = Temperature, Acoustics, Strain
X = Pressure, Chemical
being developed or early prototype

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Fiber Optic Sensing – Getting It into the Well
Conveyed on casing & production tubing, inside Coiled Tubing

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Photo courtesy of Bill Shroyer

Cable being clamped to casing/production tubing

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Fiber Optic Sensing – Getting It into the Well
(Semi-) Permanent Installation of Coiled Tubing

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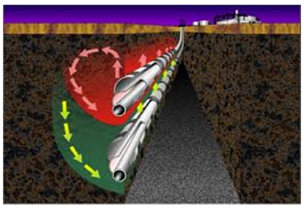

- FO cable is pulled or injected into string of coiled tubing
- CT is used as a means to get the cable to proper sensing depth in the well
- Common use: SAGD installations (e.g. Alberta)

* Courtesy of William Shroyer & SageRider

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Thermal Recovery Applications

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Diatomite steam flood* *(one field/operator, California)*

- **One of three producers will have FO**
- **275 installed out of 400 targeted**
- **Surveillance of steam expansion – improve reservoir-wide performance**

SAGD ** *(Canada)*

- **Steam chamber monitoring**
- **Sub-cooling monitoring/ closed loop feedback & control**

Strain monitoring for integrity

- **Correlate compaction rates with steam volume injected**

* Dria, personal notes from 2015 SPE Workshop on DFOS, Napa,
** 2016, comments from a major service company: "several hundred per year, typically"

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Thermal Recovery / SAGD Applications
DTS & DAS

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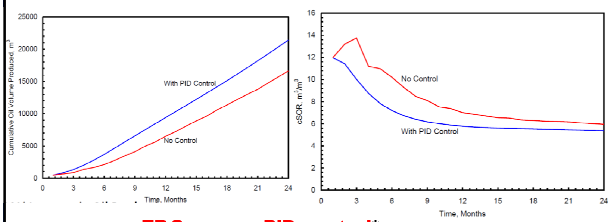

FBG array + PID control*

- **Increase cum oil produced by 20%**
- **Decrease cum steam-oil ratio (SOR) by 20%**

* *Gates (2012), Rapid Routes to Carbon-Efficient Recovery of Bitumen and Heavy Oil. Paper presented at the CMC (Carbon Management Canada) Annual Conference.*

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Production monitoring with DTS gas breakthrough

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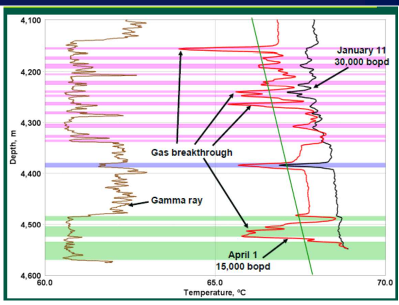

from Pinzon, et al (2007), SPE 110064.

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Production – Inflow Profiling with DAS

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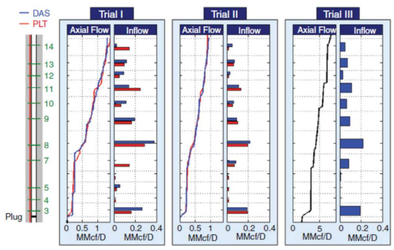

The next step for many companies in the fiber-optic sector involves flow assurance. This screenshot shows the production profiles as estimated from a combination of distributed acoustic sensing (DAS) and production logging tools (PLT) for three sequential production periods in an unconventional gas well. *Image courtesy of OptaSense.*

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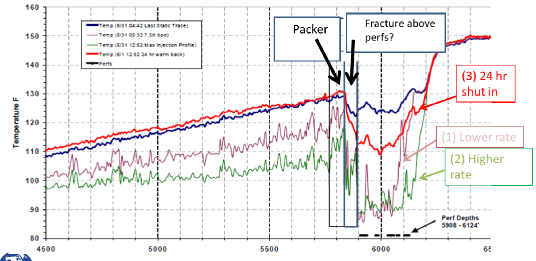
Injection Monitoring – water disposal well
DTS behind casing, monitor for out-of-zone injection

- stabilized temperature profile to indicate injection profile
- warm back to watch for out-of-zone frac



from Huckabee, SPE 118831 (2009)

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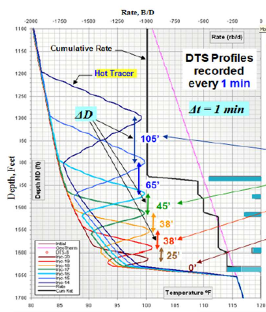
Injection Profiling
DTS "thermal tracer"



$$Rate = Velocity \cdot Area$$
$$= V_{Tracer} \cdot \frac{\pi \cdot ID^2}{4}$$
$$V_{Tracer} = \frac{\Delta D}{\Delta t}$$

V_{Tracer} = 105 ft/min

V_{Tracer} = 45 ft/min

V_{Tracer} = 38 ft/min

V_{Tracer} = 0 ft/min (No flow)

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Rahman, et al., SPE 144116 (2011)

Smart Injector optimization
DAS and DTS
injection distribution - flow control valves

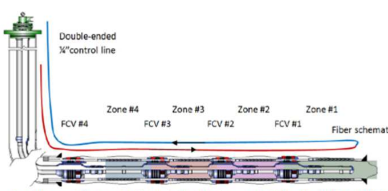

Figure 1—Schematics of the smart injector well with four isolated injction zones with Flow Control Valves (FCV) and a double ended fiber optic cable inside the ¼" control line attached to the outside of the tubing string

from van der Horst, et al. (2015) SPE 175211

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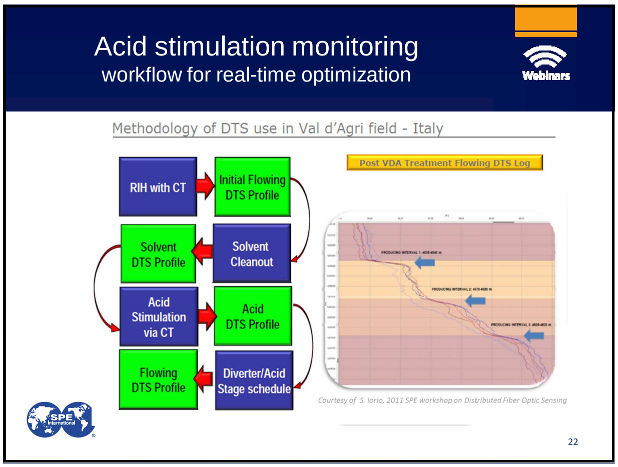

Acid stimulation monitoring
workflow for real-time optimization
Webinars
Methodology of DTS use in Val d'Agri field - Italy
RIH with CT
Initial Flowing DTS Profile
Solvent Cleanout
Solvent DTS Profile
Acid Stimulation via CT
Acid DTS Profile
Diverter/Acid Stage schedule
Flowing DTS Profile
Post VDA Treatment Flowing DTS Log
Courtesy of S. Iorio, 2011 SPE workshop on Distributed Fiber Optic Sensing
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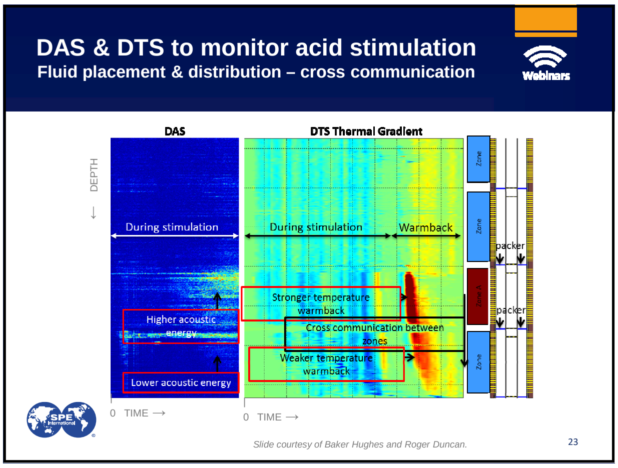

DAS & DTS to monitor acid stimulation
Fluid placement & distribution – cross communication
Webinars
DAS
DTS Thermal Gradient
DEPTH
During stimulation
During stimulation
Warmback
Higher acoustic energy
Lower acoustic energy
Stronger temperature warmback
Cross communication between zones
Weaker temperature warmback
packer
packer
Zone
Zone
Zone
0 TIME
0 TIME
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Slide courtesy of Baker Hughes and Roger Duncan.
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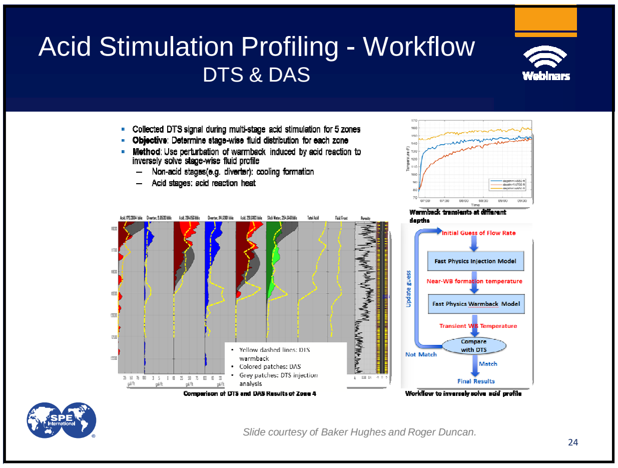

Acid Stimulation Profiling - Workflow
DTS & DAS
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Collected DTS signal during multi-stage acid stimulation for 5 zones
Objective: Determine stage-wise fluid distribution for each zone
Method: Use perturbation of warmback induced by acid reaction to inversely solve stage-wise fluid profile
– Non-acid stages(e.g. diverter): cooling formation
– Acid stages: acid reaction heat
Warmback transients at different depths
Initial Guess of Flow Rate
Fast Physics Injection Model
Near-WB formation temperature
Fast Physics Warmback Model
Transient WB Temperature
Compare with DTS
Update guess
Not Match
Match
Final Results
Workflow to inversely solve acid profile
Yellow dashed lines: DTS warmback
Colored patches: DAS
Grey patches: DTS injection analysis
Comparison of DTS and DAS Results of Zone 4
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Slide courtesy of Baker Hughes and Roger Duncan.
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One Cable, Many Measurements
Unconventional Reservoir "Life of Field"

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	Pre-Frac	Frac	Post-Frac	Flow Back	Production
DTS	Geotherm Acquisition, cementing monitoring, perf monitor	Thermal Tracer - Cluster injection profile	Warm Back: injection profile, fluid entry points, Cross flow; SRV est. (long-term warm back)	Frac fluid placement; stimulation eff.; stage isolation evaluation	Production profile : stimulation effectiveness, cluster & frac stage producibility
DAS	Microseismic*; offset well fracs; offset well mechanical activities; VSP	Mechanical diagnostics, injection profile, MS* frac mapping	Cross flow	Frac fluid placement: Stimulation effectiveness	Production profile: stimulation effectiveness, frac stage producibility

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The potential benefits are out there

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Reported results* from major and independent operating companies

For example: In one Eagle Ford well,

10 of 14 stages showed interstage communication

Diverter response was fairly inconsistent

Multi-Basin look back **

Communication seen in ~ 40% of frac stages

Average pumped volume leaked per stage: 40-45%

Increasing to more than 3-4 perf clusters ➔ non-uniform fluid distribution

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* Wheaton, et al.,(2016) SPE-179149-MS
**Holley and Kalia (2015) URTeC 2151906.

Reported results* from major and independent operating companies

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Significant value:

Understanding and optimizing *individual well performance*

Greatest value:

Extracted learnings used in *new wells/fields*

Calibrate models

Optimize HFS (increase frac efficiency/reduce cost, stimulate more stages)

Increased reservoir understanding ➔ greater EUR

*Gustavo Ugueto & Paul Huckabee (2015) "Application Fiber Optic Technology for Well and Reservoir Management", SPE Webinar broadcast 26 February.

Gustavo Ugueto (2015) "Perforation Cluster Efficiency, Insights form Fiber-Optic Diagnostics" presented at the SPE Workshop on Distributed Fiber Optic Sensing, 11-13 August, Napa, California USA.

*Stan Cullick (2014) "Fiber Optic Fracture and Production Monitoring in Midland Basin Vertical Stacked Pay" presented at the 2014 SPE Workshop on Distributed Fiber Optic Sensing, August 12-14, San Diego, California.

*Trey Lowe (2015) "Fiber-Optic Sensing: The New Must-Have Tool for Unconventional Field Development" keynote presentation at the 2015 SPE Workshop on Distributed Fiber Optic Sensing, 11-13 August, Napa, California .

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Maximize the Value of FO Monitoring: Integrate with multiple measurements

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Model (predict)

Measure
- FO, …

Compare measured with model

Calibrate/update model

Optimize using calibrated model
- NPV, IP, 1 year cum prod, etc.

Permanently installed fiber-optic sensing
– Cased/cemented
– Swell packer isolated

RA and NRA tracers
– Fluid tracers
– Proppant
– Production

Wired and wireless technologies
– Permanent downhole gauges
– Wireless downhole sensors

Intervention-based monitoring (logging)

Fiber optic "Dip-in"

Production logs
– Wire line
– Slick line
– Coiled tubing conveyed
– Tractor conveyed

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from "Design of DTS&DAS Well Installations" (Shroyer & Dria, 2017)

Hydraulic Fracture Stimulation optimization
use data to constrain or calibrate physical models

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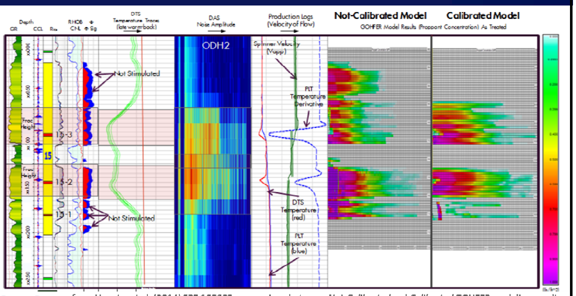

from Ugueto, et al. (2014) SPE 168603: comparison between *Not-Calibrated* and *Calibrated* GOHFER modeling results

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DTS used to validate frac model
(Midland Basin, Texas)

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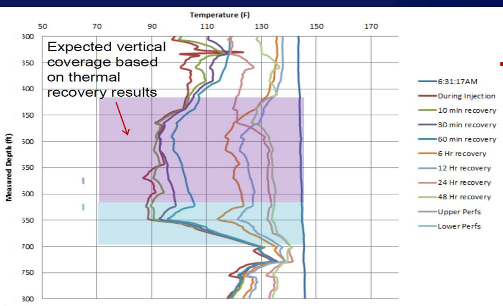

*Stan Cullick (2014) "Fiber Optic Fracture and Production Monitoring in Midland Basin Vertical Stacked Pay" presented at the 2014 SPE Workshop on Distributed Fiber Optic Sensing, August 12-14, San Diego, California.
**Cullick, et al. (2014) SPE-168992 presented at the 2015 SPE Liquids Rich Conference, Midland, Texas..

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"Take-Aways from Fiber Installation" (Midland Basin)

Stimulation

Stimulations are effectively treating targeted zones.
- All perforated intervals are open
- DTS Data indicates that ALL plugs held - no out of zone fluid

Stimulation designs, operations and pre-models delivered planned stimulations
- DTS shows fracture heights can have more vertical coverage per stage - spread across perf clusters.

Slickwater Fracs and Gel Fracs have similar fracture heights at wellbore

Modeling

Models match observed heights – lends confidence to predicted geometry

Production

DTS data analytics provides zonal profile data over about five months

DTS modeling sensitivity and uncertainty analysis performed

*Stan Cullick (2014) "Fiber Optic Fracture and Production Monitoring in Midland Basin Vertical Stacked Pay" presented at the 2014 SPE Workshop on Distributed Fiber Optic Sensing, August 12-14, San Diego, California.
**Cullick, et al. (2014) SPE-168992 presented at the 2015 SPE Liquids Rich Conference, Midland, Texas..

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"Geo-engineered" Wells – Eagle Ford FO a significant information source

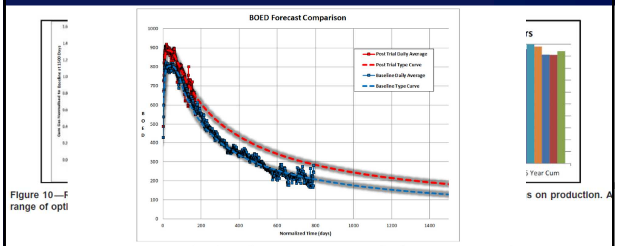


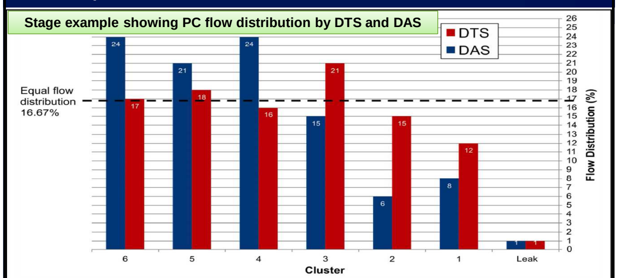
Figure 16—Comparison of production actuals and type curves for baseline design and after optimized designs were implemented.

Field results* showed ~ 15% uplift for average field type curves, using optimized well/completion design

* *Cadwallader, et al. (2015), SPE-178667/URTeC: 2171506.* 32

Fiber-optic frac diagnostics: perf cluster flow distribution

Stage example showing PC flow distribution by DTS and DAS



DTS flow distribution by warm-back analysis
DAS flow distribution by proprietary flow analysis

Halliburton & Carrizo Oil & Gas, Eagle Ford diversion optimization, from *Evans, et al., 2016) URTeC 2459883.*

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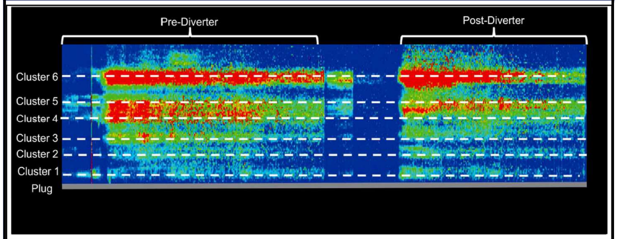
DAS frac diagnostics: perf cluster flow distribution



Stage example showing poor flow distribution that was not improved with diverter

Halliburton & Carrizo Oil & Gas, Eagle Ford diversion optimization, from *Evans, et al., 2016) URTeC 2459883.*

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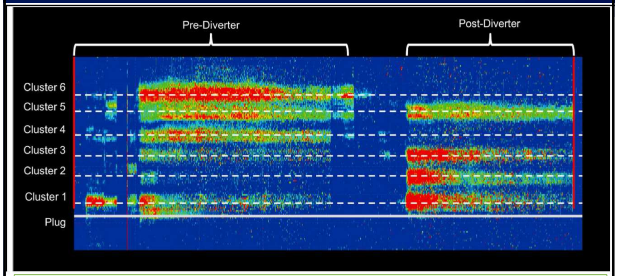
DAS frac diagnostics: perf cluster flow distribution



After diverter treatment design change, improved diverter effectiveness

Halliburton & Carrizo Oil & Gas, Eagle Ford diversion optimization, from *Evans, et al. (2016) URTeC 2459883.*

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Distributed Strain Sensing
measures shape change downhole

- Measurements:
  - Local axial strain and curvature
  - Total compression, transverse displacement, shape change over any spatial interval.
  - Evolution over time, rates of deformation
- Applications:
  - Detect and monitor lithological deformations (compaction, shear planes, etc)
  - Calibrate geophysical models
  - Relate near well-bore changes to water & steam injection programs
  - Optimize voidage replacement programs for produced reservoirs
  - Early detection and classification of mechanical well integrity issues

DSS cable on spool

DSS cable on casing

Slide courtesy of Baker Hughes and Roger Duncan.

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Real-Time Geophysical Monitoring
Compressive & Tensile Strain

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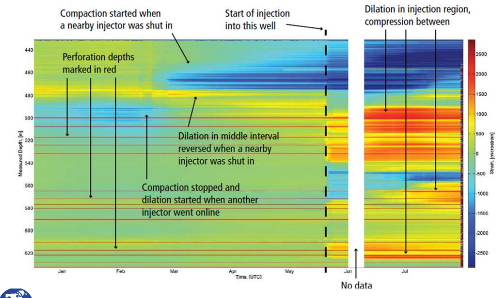

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Slide courtesy of Baker Hughes and Roger Duncan.

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In-Well Seismic
DAS acquisition

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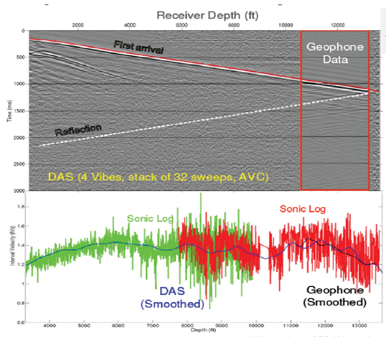

Zero-offset VSP

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With permission, SEG 2011, J. Mestayer, et al.

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In-Well Seismic
Multi-offset DAS acquisition

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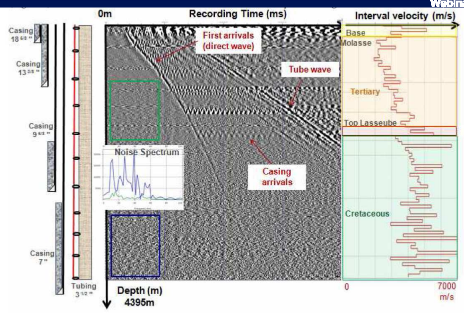

Figure 4 Rousse-1 well completion (left), Single sweep record at well head location (middle) and derived velocity profile after 20 sweep stacking (right)

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From Barberan, et al. (2012) EAGE Conference & Exhibition / SPE EUROPEC.

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Microseismic Monitoring
Event Location Using Multiple Sensor Locations

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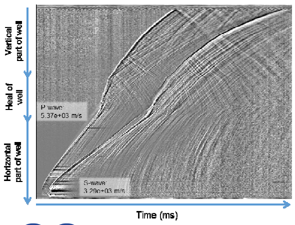
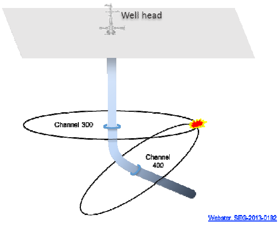
- Detection of low frequency, high magnitude (>-1.5) microseismic events initiated at reactivated faults.
- Geolocation using 1 component (1C) sensor possible using shaped array localization





Webster, SEG-2013-0182

Slide courtesy of OptaSense.

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Temporary Deployment - Fiber Optic Sensing
Intervention methods – similar to logging

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Coiled tubing with fiber

Small diameter coil/semi-stiff composite rod with fiber

Wireline: Hybrid fiber-optic/electric cable

- Vertical deployment alone or with logging tools
- Tractored down, frequently with logging tools

Slick line with integral fiber, often with memory PLT or P/T gauge

- DAS & DTS
- Production Logging
- Sand Detection
- Leak Detection
- Borehole seismic

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Summary

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Many advantages of DFOS

Real-time, Life-of-Field Applications

Applications in virtually every reservoir/production scenario

Unique information provided in real-time

Information allows design change to optimize a process

Information used to optimally control operations

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