SPE DISTINGUISHED LECTURER SERIES

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Frac-pack in Ultra Deep Water: Lessons Learned from a Hundred of Well Succeeded Operations

Carlos A. Pedroso

Also thanks to Petrobras
Campos Basin scenario & Sand control evolution

High productivity fracpacks: lessons learned

- Best practices for high productivity wells in high permeability sandstones
- Specific deep water issues

Challenges in deep water, soft rock fracturing

- Importance of TSO
- How to obtain the planned TSO
  - Data collection
  - Correct Analysis

Design and operational questions

Conclusions
Introduction

Campos Basin Scenario:

- Clean, high-permeability (300 to 14,000 mD) sandstones
- From poorly consolidated to unconsolidated sandstones
- Medium to heavy oil (29 to 14 API)
- Water depths ranging from 40 m (130 ft) to 2000 m (6500 ft)
Introduction

1988
PROCAP “1000”

1993
PROCAP 2000

2000
PROCAP 3000
DEPTH

COST

NEED FOR PRODUCTIVITY
Introduction

Deep water
High permeability
Unconsolidated Sands

Scenario

Possible Solutions

Sand Control
High Productivity
Durability

Needs

OHHGP – 200 installations
(dec 2006)

CHFP – 130 installations
Frac pack became…

- Primary option for all vertical/deviated wells, except:
  - Oil/Water or Gas/Oil contact
  - Mechanical constraints (casing, cementing,..)
- In the past: “Can I fracpack?” → Today: “How can I fracpack?”

- Special mechanical cares:
  - The need of special tools
    - Larger volumes
    - Aggressive proppant ramps
Well succeeded fracpack

(FRACPACK DEFINITION)

- Low skin $\rightarrow$ Best practices
- High conductivity fractures $\rightarrow$ TSO as planned
- No remedial acid jobs $\rightarrow$ Both
- No sand production $\rightarrow$ Proper sand control design
Well succeeded fracpack

Skin (Buildup & Falloff Test)

From 1995 to 2005 (71 wells tested)
Best (good) practices

- HSC Overbalance x TCP Underbalance
- Clean up flow prior to fracturing
- Acidizing prior to fracturing
- Riser and casing cleaning
- Internal coated work string cleaning
- Brine Filtration
- Gel and proppant quality

| Well | Permeability (mD) | St扶 | DR | Perforating
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<td>A-1</td>
<td>354</td>
<td>1.9</td>
<td>1.3</td>
<td>Overbalanced</td>
</tr>
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<td>1.6</td>
<td>1.1</td>
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<td>A-3</td>
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<td>0.8</td>
<td>Underbalanced</td>
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<tr>
<td>A-4</td>
<td>460</td>
<td>13.9</td>
<td>2.7</td>
<td>Underbalanced</td>
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<td>860</td>
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<td>A-7</td>
<td>6600</td>
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<td>7.0</td>
<td>Underbalanced</td>
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</table>
Perforations

HSC overbalance x TCP underbalance
<table>
<thead>
<tr>
<th>Well</th>
<th>K (mD)</th>
<th>Skin</th>
<th>DR</th>
<th>Perforation</th>
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<tr>
<td>A3-UB</td>
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<td>A1-OB</td>
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<td>1.3</td>
<td>Overbalance</td>
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<tr>
<td>A4-UB</td>
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<td>13.9</td>
<td>2.7</td>
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<td>A5-UB</td>
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<tr>
<td>A2-OB</td>
<td>1516</td>
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<td>A6-OB</td>
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<td>A7-UB</td>
<td>6600</td>
<td>45.2</td>
<td>7</td>
<td>Underbalance</td>
</tr>
</tbody>
</table>

Field “A”, same reservoir, equivalent operational conditions (1997 to 1999)
Perforating Type x Skin & Damage Ratio

Skin Damage Ratio

Permeability

Skin
DR
K (mD)

Perforating Type x Skin & Damage Ratio

UB
OB
UB
OB
UB
OB
UB

A3-UB  A1-OB  A4-UB  A5-UB  A2-OB  A6-OB  A7-UB
Acidizing prior to fracturing

Main objective: clean perforations

(BHP Data)
Workstring cleaning

Solvent and/or pickling
Casing and riser cleaning
Stimulation boat, gel and proppant

- Frac pack requires specifically designed equipment
- The proppant control must be automated
- HSP (Synthetic) x Sand
- Gel mixed on-the-fly using sea water
- Enzymatic breaker
- Virtually no damage related to the gel system

(SPE – 73722)
<table>
<thead>
<tr>
<th>Good practice</th>
<th>Statistic</th>
<th>Cost</th>
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<tbody>
<tr>
<td>HSC Overbalance x TCP Underbalance</td>
<td>YES</td>
<td>HIGH (*)</td>
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<tr>
<td>Clean up flow prior to fracturing</td>
<td>YES</td>
<td>HIGH (*)</td>
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<tr>
<td>Acidizing prior to fracturing</td>
<td>NO</td>
<td>LOW</td>
</tr>
<tr>
<td>Riser and casing cleaning</td>
<td>NO</td>
<td>LOW</td>
</tr>
<tr>
<td>Internal coated work string cleaning</td>
<td>NO</td>
<td>LOW</td>
</tr>
<tr>
<td>Brine Filtration</td>
<td>NO</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>Gel and proppant quality</td>
<td>YES</td>
<td>MEDIUM</td>
</tr>
</tbody>
</table>

(*) +US$ 1,500,000/well due to OB (HSC) perforation
BEST (GOOD) PRACTICES
Deep Water Specific Issues

• High depths with low sediments
  • Low frac gradients
  • Low elastic modulus

• Cooling of injected fluids (4 °C @ sea bed)
  • Increase of frac fluid efficiency
  • Breakers test temperature: -20 F to -50 F

• DP rig and boats (strict and written procedures)

• Hydrates (prevention is better than remediation)
Design issues

- **Tip Screen Out (TSO)** is mandatory
- Data collection
  - Rock Mechanics
  - Calibration test
- Height growth
- Well Deviation

**What is a TSO?**
Tip Screen Out (TSO) is mandatory

Four scenarios for fracpack:

- **The Best**: TSO happens and the fracpack is pumped as planned, with planned net pressure gain
- **Acceptable**: TSO happens but it is followed by a premature screen out, with lower – or higher - net pressure gain
- **Bad one**: TSO does not happen
- **Worst one**: TSO does not happen and a premature screen out occurs
**TSO is the key factor!**

We can stand premature screen out after a TSO even with little net pressure gain (low E. high \( v \)).

(No remedial acid jobs were performed when TSO was obtained)

\[
W(x, 0, t) \approx \frac{4(1 - v^2)}{E} H \Delta p(x, t)
\]

\[W \propto \left( \frac{\mu Q L}{E'} \right)^{1/4} \propto H \Delta p_{net}\]

<table>
<thead>
<tr>
<th>Well</th>
<th>TSO</th>
<th>( \Delta P_{net} ) (psi)</th>
<th>Prop (%)</th>
<th>Skin</th>
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<tr>
<td>A-1</td>
<td>Y</td>
<td>370</td>
<td>88</td>
<td>1.9</td>
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<td>A-2</td>
<td>Y</td>
<td>1050</td>
<td>55</td>
<td>1.6</td>
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<tr>
<td>B-6</td>
<td>Y</td>
<td>300</td>
<td>100</td>
<td>-0.7</td>
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<td>B-8</td>
<td>Y</td>
<td>450</td>
<td>20</td>
<td>4.2</td>
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<tr>
<td>G-1</td>
<td>Y</td>
<td>1100</td>
<td>29</td>
<td>4.8</td>
</tr>
<tr>
<td>B-4</td>
<td>N</td>
<td>Zero</td>
<td>67</td>
<td>21.9</td>
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<td>B-5</td>
<td>N</td>
<td>Zero</td>
<td>100</td>
<td>18.0</td>
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<td>C-3</td>
<td>N</td>
<td>Zero</td>
<td>100</td>
<td>26.0</td>
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</tbody>
</table>
TSO is the key factor...

Reliable data collection → Correct Analysis → Skilled planning

…but it’s not easy!
Reliable data

Rock properties
- Reliable elastic moduli
- Minimum stress direction
  - Imaging fracture
  - Oriented Cores
    - Velan
    - ASR

Leak off data
- Calibration test
  - Surface pressure x BHP
  - Live annulus pressure
  - On site analysis
Elastic Moduli

Simplified Model

“More realistic” Model
Usual simplifications $\rightarrow$ Probable results

"Planned" Fracture

Obtained Fracture
Elastic properties

With...Inverted stress

Good Data !!!

Good

Data !!!
Reliable data

- Reliable elastic moduli
- Minimum stress direction
  - Imaging fracture
  - Oriented Cores
    - Velan
    - ASR
- Calibration test
  - Surface pressure x BHP
  - Live annulus pressure
  - On site analysis

Cross Dipolar Sonic Log
Minimum stress direction

Before

• Imaging after XLOT
VELAN - Velocity Anisotropy

Lower Vp

Diagram showing velocity anisotropy with directions and measurements.
Minimum stress

Normal faults

ASR
Reliable data

- Reliable elastic moduli
- Minimum stress direction
  - Imaging fracture
  - Oriented Cores
    - Velan
    - ASR
- Calibration test
  - Surface pressure x BHP
  - Live annulus pressure
  - On site analysis
Calibration Test

- Calibration tests, with *in situ* analysis, are a need
- FET, 1 or 2 Minifracs, SDT, SRT
- Minifrac, *with BHP*, is always performed
- SRT,
  - To confirm feasibility of treatment
  - To help to restore pre-minifrac leak-off values
  - As primary evaluation of Pc
- FET
  - Primary evaluation of Pc
- SDT
  - Well to formation connectivity

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Pc (psi)</th>
<th>Tc (min)</th>
<th>cw (*)</th>
<th>ef (%)</th>
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<td>5118</td>
<td>2.05</td>
<td>0.0145</td>
<td>15.5</td>
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<tr>
<td>SRT</td>
<td>5113</td>
<td>4.61</td>
<td>0.0068</td>
<td>22.5</td>
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## Minifrac Analysis

### Importance of BHP for high permeability

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<tr>
<th>Well</th>
<th>Surface data (DP)</th>
<th>BH data</th>
<th>Error</th>
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<td>Tc (min)</td>
<td>Ct ft$\sqrt{\text{min}}$</td>
<td>Ef</td>
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<td>A-2</td>
<td>0.90</td>
<td>0.048</td>
<td>6.6</td>
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<td>A-6</td>
<td>0.13</td>
<td>0.086</td>
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<td>A-1</td>
<td>1.23</td>
<td>0.073</td>
<td>13.1</td>
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<tr>
<td>A-7</td>
<td>0.12</td>
<td>0.093</td>
<td>1.7</td>
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<td>A-5</td>
<td>0.43</td>
<td>0.018</td>
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<tr>
<td>A-4</td>
<td>5.06</td>
<td>0.004</td>
<td>22.7</td>
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<tr>
<td>A-3</td>
<td>13.42</td>
<td>0.003</td>
<td>38.9</td>
</tr>
</tbody>
</table>
Live Annulus Data

- BHP data from live annulus is very close to BHP data from electronic gauges
Non ideal pressure decline in soft rock

- Tip extension
- Pressure dependent leak off
- Height recession
Tip Extension

Characteristic shape in G dP/dG: early time data falls below extrapolation of straight line

F_c = 4643 psi
T_I = 32.9%
Pressure Dependent Leakoff

Low K

High K

Pressure Dependent Leakoff

Low K

High K
Height Recession
Temperature logs

Height grow
Temperature Logs
Thick, deviated interval

- Perforation: 2761-2830 (69m)
- Inclination: 64°
- Net pay: 30.5m
- Limited entry perforation prior to mf
- Minifrac: 25 bpm
Thick, deviated interval
Correct analysis helped by temperature log
Thick, deviated interval
Skilled design

- Multiple intervals
- Thin intervals
- Highly deviated wells
- Restricted perforation

Pseudo 3D Models
Planned ...

Obtained
Frac pack in thin sand with high-permeability

- Thin sand, high-permeability:
  - Low compliance
  - High leakoff
  - Narrow fractures

- Low conductivity

- Better results with HRWP

<table>
<thead>
<tr>
<th>Well</th>
<th>TVD (ft)</th>
<th>Fluid</th>
<th>DR</th>
<th>[Prop]</th>
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<td>I-1</td>
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<td>Gel</td>
<td>3.3</td>
<td>10</td>
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<td>G-12</td>
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<td>1</td>
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<td>G-13</td>
<td>10.5</td>
<td>Water</td>
<td>1.2</td>
<td>1-2</td>
</tr>
<tr>
<td>J-5</td>
<td>16.4</td>
<td>Water</td>
<td>1.3</td>
<td>1-2</td>
</tr>
<tr>
<td>M-3</td>
<td>19.7</td>
<td>Water</td>
<td>1.7</td>
<td>1-2</td>
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</tbody>
</table>
Stress anisotropy

Field M-2

- Completely unconsolidated
- Permeability > 2,000 mD
- UCS < 200 psi
- $E < 400,000$ psi

Expected Isotropy

Stress
• 2 stacked fracpacks - 3470/ 3490 m (TVD - 2645/ 2656 m)  
  3435/ 3455 m (TVD - 2627/ 2637 m)

• PI - 31 (m³/ d/ kg/ cm²)

• DR - 2.9
Vertical well

- Interval -2671/2718 m
- PI - 133 (m³/d/kg/cm²)
- DR - 1.1
## Highly deviated well

<table>
<thead>
<tr>
<th></th>
<th>Deviated</th>
<th>Vertical</th>
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<tbody>
<tr>
<td><strong>Fracpack</strong></td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td><strong>MD perforation (m)</strong></td>
<td>20 + 20</td>
<td>53</td>
</tr>
<tr>
<td><strong>TVD perforation (m)</strong></td>
<td>11 + 10</td>
<td>47</td>
</tr>
<tr>
<td><strong>Inclination (gr)</strong></td>
<td>58</td>
<td>zero</td>
</tr>
<tr>
<td><strong>PI (m3/d/kg/cm2)</strong></td>
<td>31</td>
<td>133</td>
</tr>
<tr>
<td><strong>Specif PI (m3/d/kg/cm2/m)</strong></td>
<td>1.47</td>
<td>2.83</td>
</tr>
<tr>
<td><strong>DR</strong></td>
<td>2.9</td>
<td>1.1</td>
</tr>
<tr>
<td><strong>Prod Rate (total/oil) (m3/day)</strong></td>
<td>1430/1430</td>
<td>2700</td>
</tr>
<tr>
<td><strong>Prod rate (total/oil) (m3/day)</strong></td>
<td>1442/883</td>
<td>2500/1500</td>
</tr>
</tbody>
</table>
Restricted Perforation

Aug/2006 → 12 operations well succeeded
Next steps

- Fully 3D simulation
- Green FP
- Multiple zones in one trip
Conclusions

- The perforation method, OVB or UND, with or without clean up flux has little importance to the final results of a well done/well designed fracpack.

- TSO is the key for a successful fracpack in high-permeability formations.

- Reliable data, calibration test, BHP data and in situ design is the key for high permeability fracturing.

- Non ideal pressure decline is observed during minifrac in soft rock formations.
Conclusions

- In off-shore fracpacks, temperature log can identify fracture height.

- For thin, well confined reservoirs, HRWP attain better results than fracturing with gel.

- Even for completely unconsolidated sands, stress anisotropy affects fracturing results → Vertical (or verticalized well) is better.

- Do not perforate the entire interval to obtain TSO.

- Good practices result in lower skins.
More Questions
Carlos Alberto Pedroso

Carlos.pedroso@petrobras.com.br

Phone: 55 22 99862010
Back up & Complementation
FRACPACK – Definition

Combination of the fracturing with gravel pack

High permeability fracturing job pumped with screens (GP assembly) installed
Tip screen out (TSO)

Planned and controlled Screen Out at the Tip of the fracture, interrupting its propagation. The continuity of gel and proppant pumping causes the fracture width increase, which is proportional to the increment of the net pressure. The TSO may happen with the arrival of the proppant at the tip of the fracture, demanding a very precise design.
Tip Screen Out

1 pound of Proppant

1/2 gallon of gel

1 gallon of gel

1 pound of Proppant

TSO
Tip Screen Out

Well – Top view
Sand Control Options

Cased & Perforated

Cased Hole Gravel Pack

Slotted Liner / Screen in Open Hole

Expandable Screen

Open Hole Gravel Pack

Cased Hole Frac Pack

After Darell Wood
Expandable Screen

O.L. Field  Venezuela

- Cased & perforated
- Heavy oil
- Swabbing for 4 hrs for testing $\rightarrow$ sanding
- Decided to remove Expandable Screens
- Hot spots
Expandable Screen

Hot-Spots
Expandable Screen
Cased & Perforated
Expandable Screen

Partial Expansion
Conclusions from Service Company

Fail occurred due to heavy oil flowing through “restricted” perforations

Indication: Do not run expandable screens into cased producers wells
<table>
<thead>
<tr>
<th>Well</th>
<th>Type</th>
<th>L (m)</th>
<th>Screen</th>
<th># (μm)</th>
<th>Q (bbl/d)</th>
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<tbody>
<tr>
<td>M-1</td>
<td>In</td>
<td>115</td>
<td>Compliant</td>
<td>150</td>
<td>23200</td>
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<tr>
<td>M-3</td>
<td>In</td>
<td>1138</td>
<td>Compliant</td>
<td>250</td>
<td>39700</td>
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<tr>
<td>M-4</td>
<td>In</td>
<td>1008</td>
<td>Compliant</td>
<td>250</td>
<td>&gt; 40000</td>
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