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Can we trust in acid fracturing on deep hard carbonate reservoirs?

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Petrobras
Outline

• Why Acid Fracturing?
• The Challenge
• Experimental Investigation I
• Experimental Investigation II
• Acid Fracture Definition
• Conclusions I and II
• Final remarks
Why acid fracturing?

- It is widely cited that sixty percent of the world’s oil and forty percent of the world’s gas reserves are held in carbonate *

- Many world-class reservoirs are deep (TVD > 10000 ft) and hard (E > 4×10^6 psi) carbonates:
  - Khuff (Middle East) **
  - Barra Velha and Macabu (off-shore Brazil)
  - Artinskian (Caspian sea basin) **
  - Mississipian Madison (Wind River basin) **

- Acid fracturing is commonly considered as stimulation technique

What is an acid fracture?

[...] The success of acid fracturing depends upon heterogeneous dissolution among fractures faces. Conductivity after fracture closure results from uneven etching, because asperities created by the acid hold as pillars to keep a fracture open [...] 

Source: DENG, HILL and ZHU; 2009

Source: NEUMANN, 2011
The challenge

• Acids fractures may close

• Are they really limited to closing stresses lesser than 5000 psi? (DANESHY et al, 1998)

• Reservoir depletion might accelerate acid fracture collapse
The challenge

• Propped fracturing stimulation is not an easy task in deep hard carbonates

• From an operational point of view, the execution of acid fracturing treatment is easier than the execution of propped fracture (SMITH and SHLYAPOBERSKY, 2000)

• So, we come back to the question whether an acid fracture remains conductive in such environment
Experimental investigations

• Two experimental investigations

• The first experimental investigation comprises two steps:
  – Dynamic acid reaction close to reservoir conditions
  – Acid conductivity measurement under crescent confining stress
Experimental investigations

• The second experimental investigation compares acid reaction on:
  – Smooth surfaces from saw cut samples
  – Rough surfaces from samples broke in tensile

• Final result: are the carbonate reservoir candidate to acid fracturing stimulation?
Experimental investigation I
The outline of an acid fracture
Digital imaging

- Define acid etching patterns
- Estimate mass of rock consumed on surface, $\Delta m$
- Estimate fracture face linear roughness, $r_L$ (LIU, 2005)

\[
r_L = \frac{A_{\text{surface}}}{A_{\text{projected}}}
\]

Sample dimensions

$L_{\text{lab}}$ – length: 76 mm, 3.0”
$H_{\text{lab}}$ – height: 31 mm, 1.2”
$P_{\text{lab}}$ – thickness: 75 mm, 3.0”
Acid flow experiments
Acid fracturing window

- Minimum effective confining stress

\[ \sigma_{ef \min} = P_c - P_p \]

- Maximum effective confining stress or measured fracture collapse stress

\[ \sigma_{ef \max} = P_c - 0.5 \times P_p \]

- Minimum conductivity

\[ k_f w = 1000 \text{ mD-ft} \quad \text{or} \quad 300 \text{ mD-m} \]

\( P_c \), closure stress, \( P_p \), porous pressure or reservoir pressure, 
\( k_f \), fracture permeability, \( w \), fracture width
Field case I – well A and B, 14600 ft TVD

Note: in laboratory conditions, effective confining stress equals closure stress
Field case I – well B, flow test after frac
Field case II – well C, 9910 ft TVD

- SPE 94583 – 2300 ft long horizontal well, Albian carbonate, $k_e=0.5$ mD
- Jan/1999, matrix stimulation, start production
- Aug/2004, 05 acid fracs, pinpoint stimulation
- Jul/2007, PBU, 04 open fractures, $x_f$ from 53 ft (16 m) to 70 ft (21 m), and 5000 mD-ft (1524 mD-m) conductivity

$x_f$: fracture half-length, PBU: pressure build up test
Field case II – well C, 9910 ft TVD

Note: in laboratory conditions, effective confining stress equals closure stress
Field case II – Well C production history
Field case III – Well D, vertical, 15000 ft TVD

Note: in laboratory conditions, effective confining stress equals closure stress
Field case III – Well D, vertical, 15000 ft TVD

[Graph showing conductivity versus effective confining stress]
Field case III – Well D production history
Experimental investigation II

tensile fractures vs saw cut smoothed fractures
Etching patterns from saw cut surfaces

Before acid – saw cut

Channel

Roughness

Uniform

Note: dimensions in millimeters, same color scale
Carbonate sample with tensile fracture
CP-38 Etching pattern: tensile

Before acid

\[ \Delta m = 0.76 \text{g} \]

\[ C_1 = 7290 \text{ mD-ft} \]

After acid

Before

\[ r_L = \frac{2149}{1937} = 1.107 \]

After

\[ r_L = \frac{2151}{1937} = 1.110 \]
CP-55 Etching pattern: tensile

Before acid

Before
\[ \rho_L = \frac{2558}{1937} = 1.320 \]

After
\[ \rho_L = \frac{2916}{1937} = 1.505 \]

\[ \Delta m = 10.12 \, g \]

\[ C_1 = 61420 \, \text{mD-ft} \]
CP-40 Etching pattern: tensile

Before acid

Before

\[ r_L = \frac{2145}{1937} = 1.107 \]

After

\[ r_L = \frac{2214}{1937} = 1.143 \]

\[ \Delta m = 6.44 \text{g} \]

\[ C_1 = 199150 \text{ mD-ft} \]

After acid
Conductivity generation

- Nierode and Kruk (1973): “We believe the conductivity measured in these tests is mainly due to the smoothing of peaks and valleys on the rough fracture faces, and is independent of rock heterogeneities due to the small sample size.”

- We add: once peak and valleys disappeared unevenly on both fracture faces, those surfaces do not match each other. This surface mismatch generates acid conductivity.
Roughness and tensile pattern

<table>
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<tr>
<th>Area (mm²)</th>
<th>rₗ Before</th>
<th>rₗ After</th>
<th>rₗₜₕ Before</th>
<th>rₗₜₕ After</th>
<th>Area (mm²)</th>
<th>rₗ Before</th>
<th>rₗ After</th>
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</table>

There is not a well defined trend of linear roughness after acid reaction on tensile fracture faces.

Linear roughness can increase, stay equal or even decrease.
Acid fractures are defined as the flow paths resulting from the partial contact of mismatched surfaces created by uneven acid reaction on naturally rough walls of hydraulic induced fracture.

Source: NEUMANN, 2011
Conclusions – part I

• Conductive acid fractures exist in deep hard carbonates reservoirs

• Deep hard carbonates can be successfully acid fractured to increase production

• Lack of confidence in the current acid conductivity models
Conclusions – part II

• The experiment from tensile fractures surfaces reproduced smoothed surfaces like those reported by Nierode and Kruk (1973).

• The experimental results suggest that surfaces mismatch generates acid conductivity.

• We suggest call acid fracture from lab experiments only those derived from surfaces broken in tensile.
Final remarks

- Laboratory work helps to decide and define acid fracturing treatment and techniques.

- After 40 years of research we still are very far to have good model to predict acid fracture conductivity behavior, that is, acid fracturing modeling needs more industry focus.
Final remarks

• We start asking if we can trust in acid fracturing as stimulation technique in deep hard carbonate reservoirs...

• Yes, we can!
Thank you very much for your presence and attention
Your Feedback is Important

Enter your section in the DL Evaluation Contest by completing the evaluation form for this presentation

http://www.spe.org/dl/
Slides to support further questions and/or extended presentation
Experimental investigation I

- Carbonate samples prepared
- RES measured.
- Digital image, before and after acid reaction.
- Acid reaction under dynamic conditions.
- The samples were dried and weighted.
- Conductivity measurements
- Analysis of results.

Note: nothing new here. Since 1962, there are many SPE papers that cover same topic
Carbonate samples

- **Microbial Carbonates** *(RIDING, 2000; AHR, 2009)*
  - stromatolite
  - oncolite
  - thrombolite
  - leiolite

- Outcrops and actual reservoir samples, Aptian and Albian age

$L_{lab}$ – length: 76 mm
$H_{lab}$ – height: 31 mm
$P_{lab}$ – thickness: 75 mm
Conductivity cell

- Confining stress
  - 500 or 1000 psi, 30-40 min
  - Up to 10000 psi

- Rate – Darcy law flow
  - Distilled water 20° C
  - 5, 10, 15 cm³/min
  - $\mu = 1$ cP

- $L = 6$ cm, $H_{lab} \approx 3.1$ cm

- $\Delta P$ measured

- $k_f w$ calculated

$$k_f w = \frac{\mu q L}{H_{lab} \Delta P}$$
Initial conductivity, linear roughness and etching pattern
**RES: Rock Embedment Strength**

**RES:** force required to push a sphere into rock surface to distance equal to the radius of the sphere, \( d_f/d_p = 1 \) (McGlothlin and Huit, 1966), divided by its projected area (Nierode and Kruk, 1973)

**Source:** Neumann, 2011

**Loading:** RES measurements

**Unloading:** Young’s Modulus estimate

**Source:** Neumann, 2011
Initial conductivity, DREC and etching pattern
RES correlation – NEUMANN 2011

![Graph showing RES correlation with C2 and RES values. The graph includes data points marked with 'x' and a dotted line for the proposed adjustment with R^2 = 0.952.](image-url)
 [...] Phineus had warned the Argonauts of the terrifying rocks, called Symplegades [...] When a ship attempted to pass between them, they drove together and crushed her. Euphemus let loose a dove to fly ahead of the Argo. As soon as the rocks had nipped off her tail feathers, and recoiled again, the Argonauts rowed through with all speed, aided by Athene and by Orpheus’s lyre, and lost only their stern ornament. Thereafter, in accordance with a prophecy, the rocks remained rooted, one on either side of the straits [...].

*Robert Graves – The Greek myths*


