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Distinguished Lecturer Program

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

L F Neumann

Petrobras

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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)**

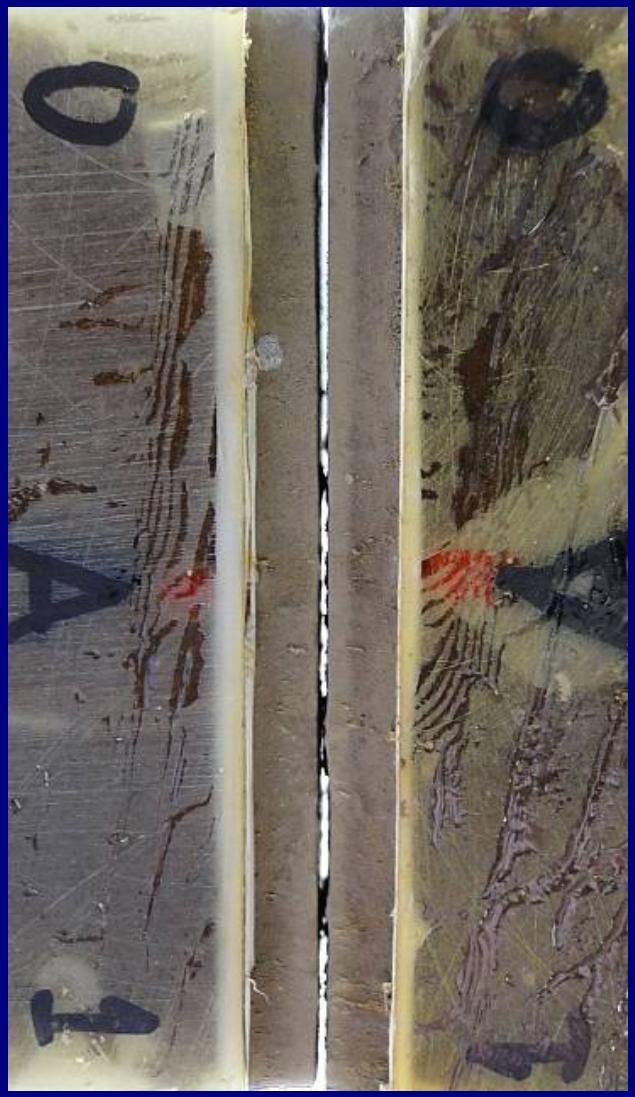
- Acid fracturing is commonly considered as stimulation technique

Sources:* Schlumberger web page; ** Halbouty, M.T., ed. *Giant Oil and Gas Fields of the Decade, 1990-1999*. Houston: AAPG Memoir 78, 2003

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?

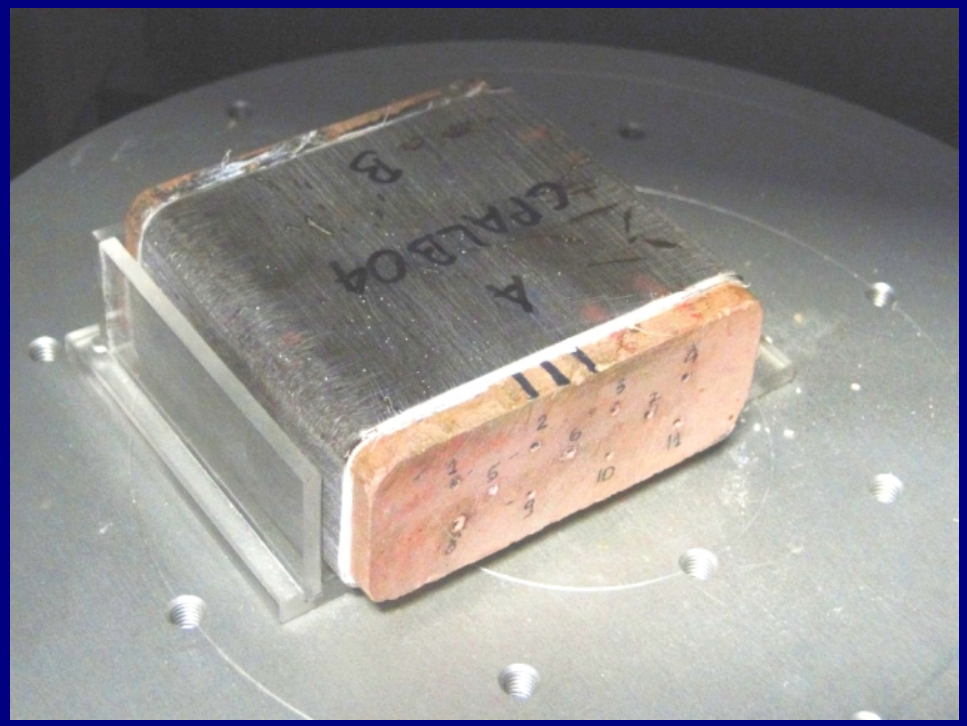
Experimental investigation I

The outlive of an acid fracture

Digital imaging

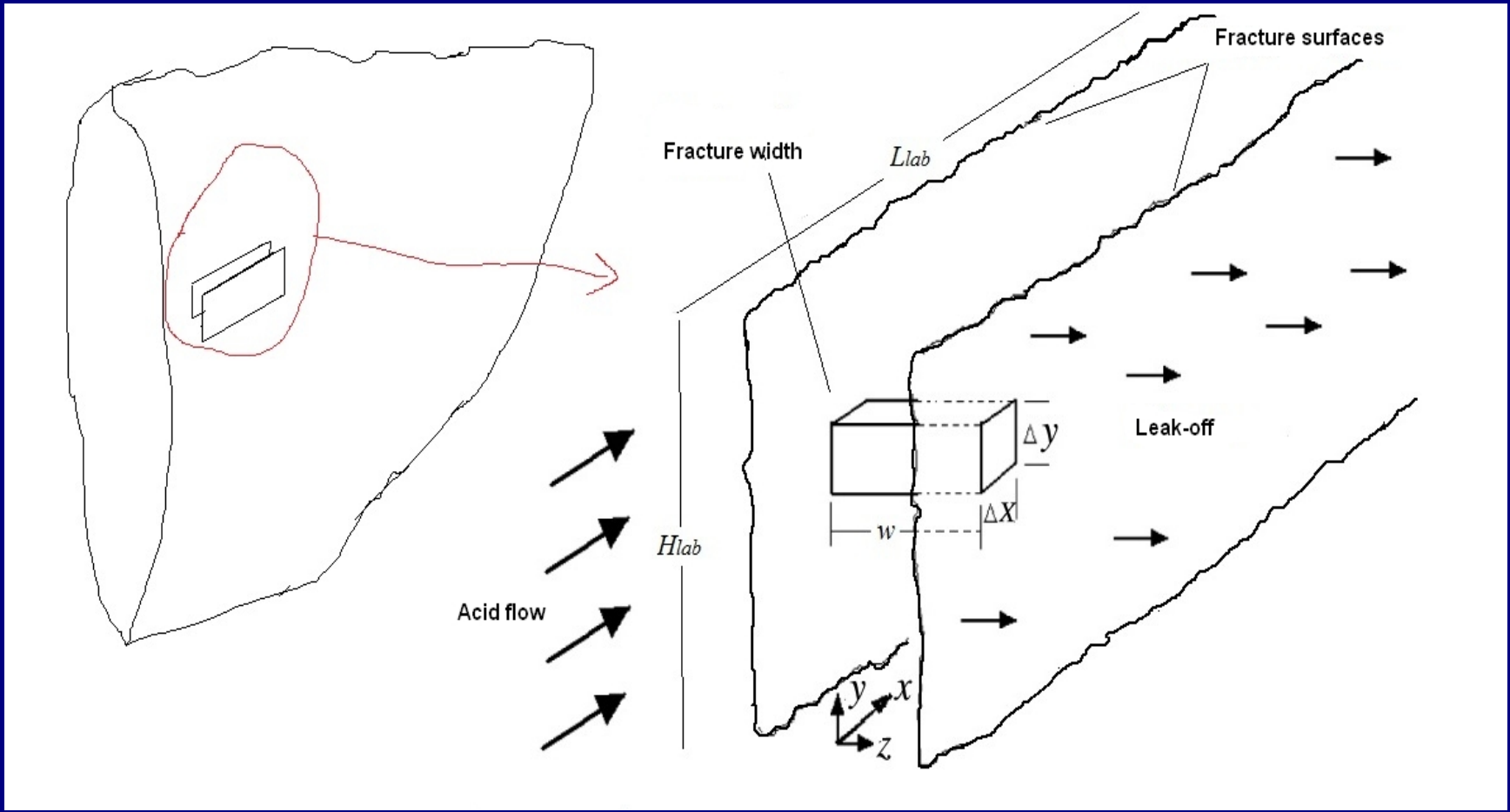
- Define acid etching patterns
- Estimate mass of rock consumed on surface, Δm
- Estimate fracture face linear roughness, r_L (LIU, 2005)

$$r_L = \frac{A_{surface}}{A_{projected}}$$



Sample dimensions
L_{lab} – length: 76 mm, 3.0”
H_{lab} – height: 31 mm, 1.2”
P_{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

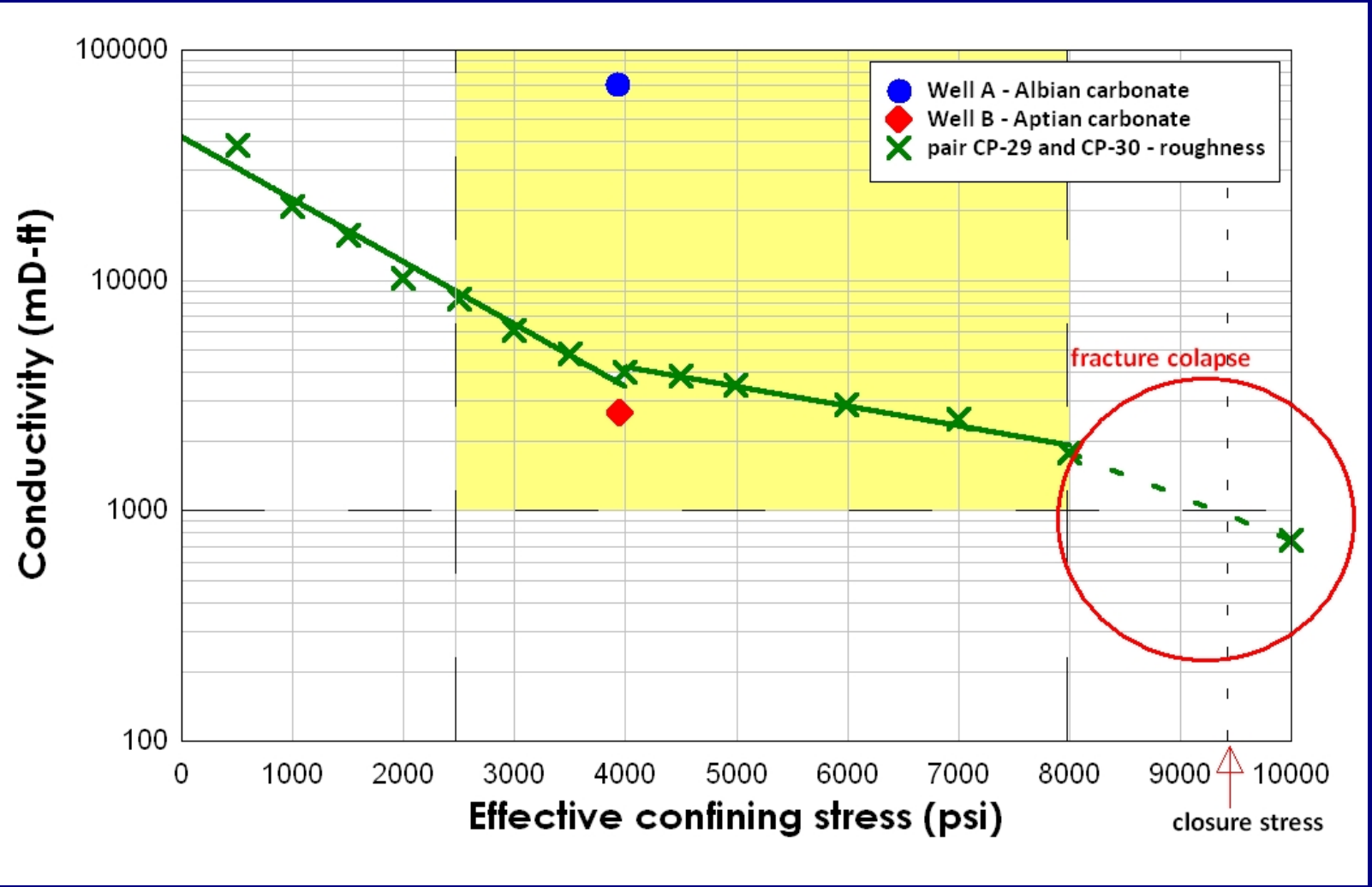
$$\sigma_{ef\,\max} = P_c - 0.5 \times P_p$$

- Minimum conductivity

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

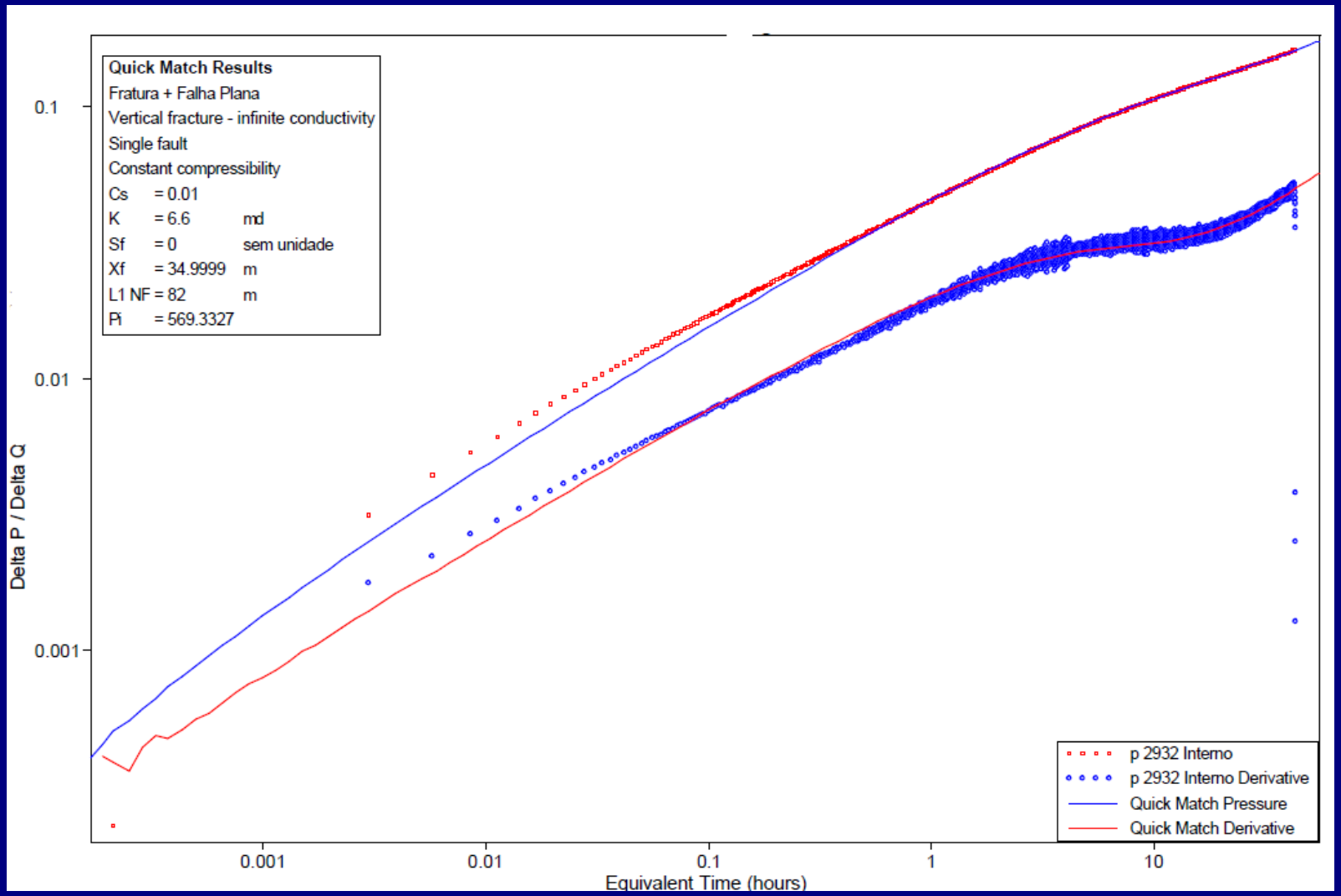
P_c, closure stress, P_p, porous pressure or reservoir pressure,
k_f, fracture permeability, w, fracture width

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

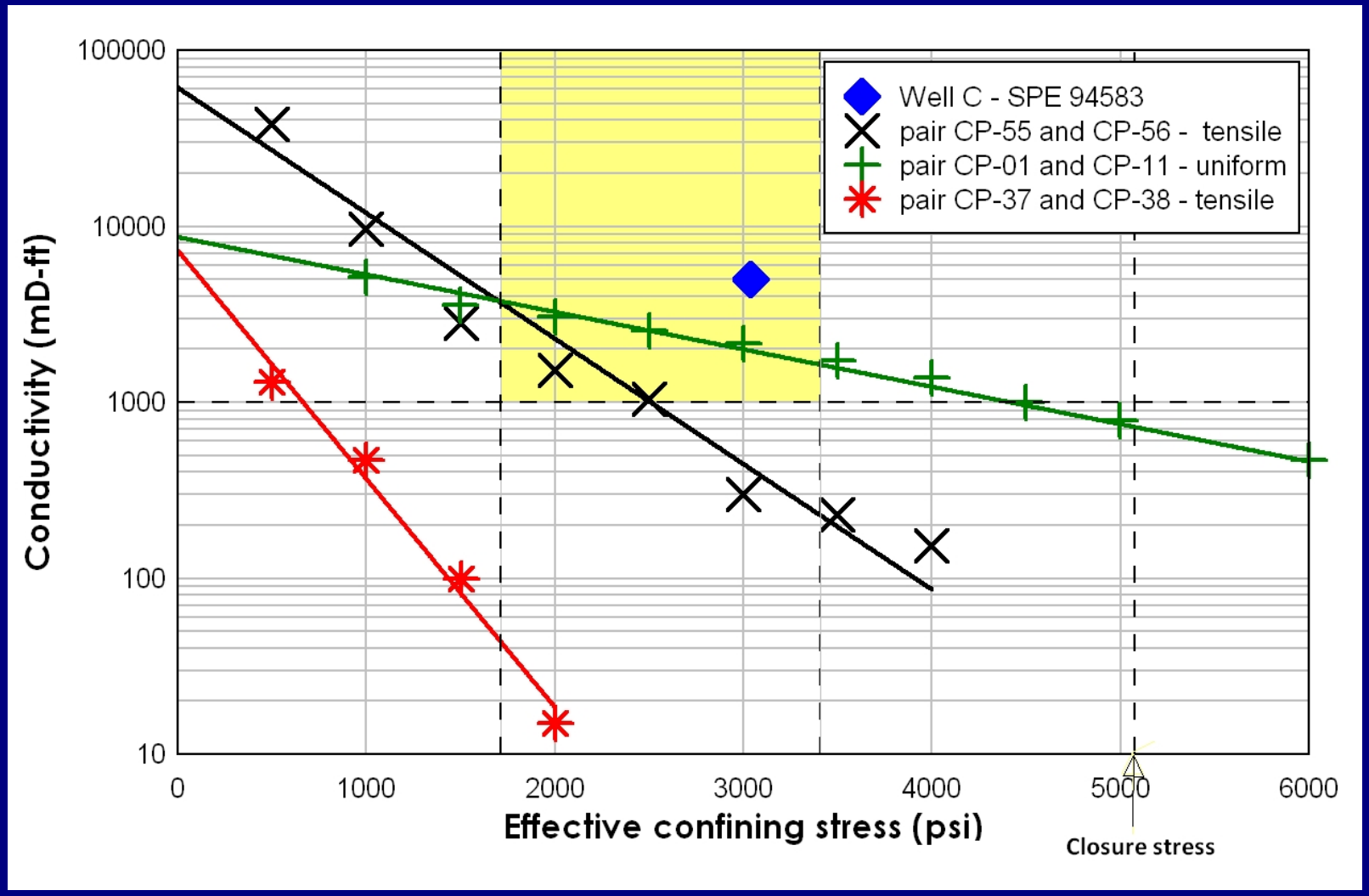


Field case II – well C, 9910 ft TVD

- 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

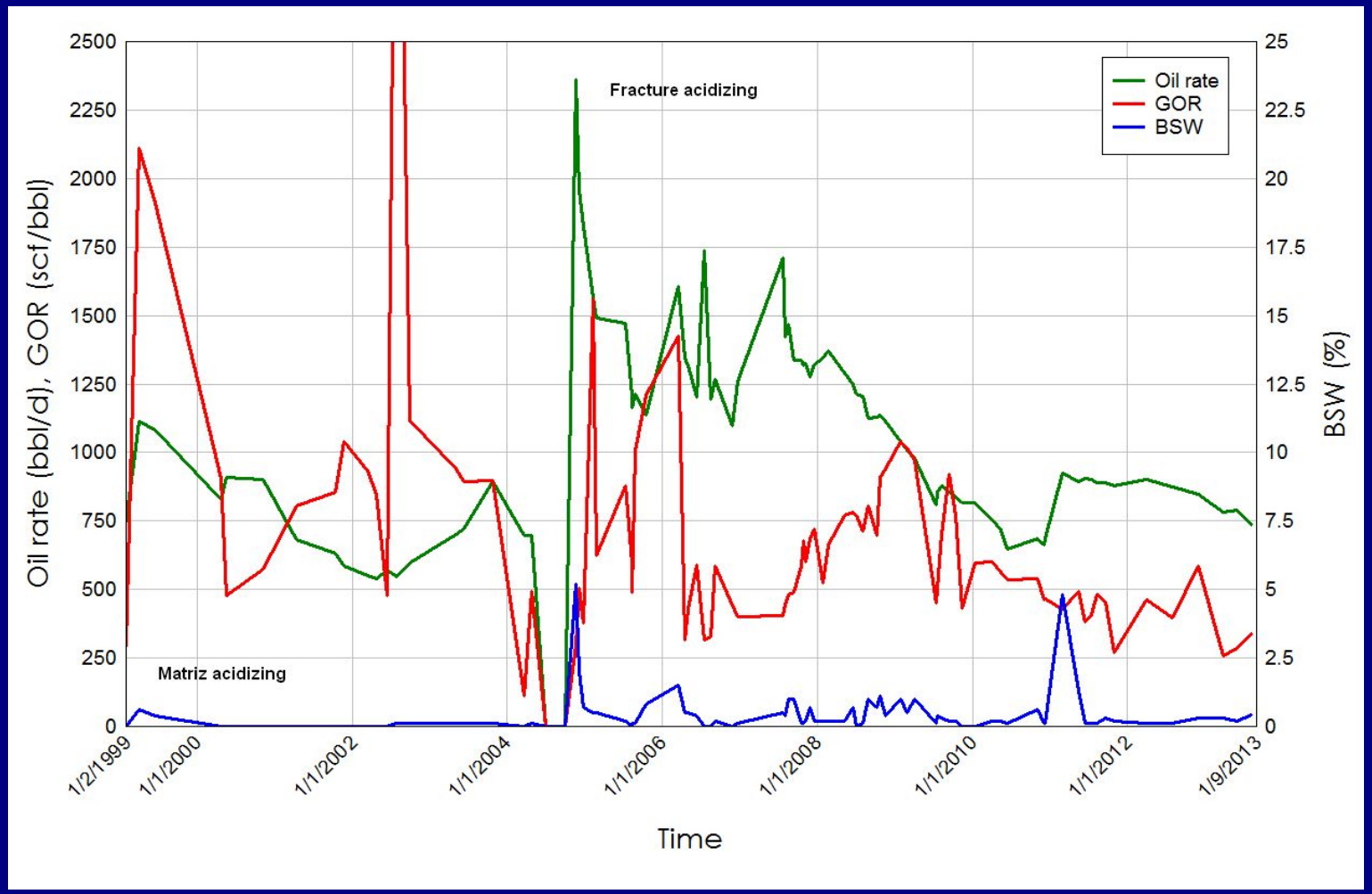
x_f: fracture half-length, PBU: pressure build up test

Field case II – well C, 9910 ft TVD

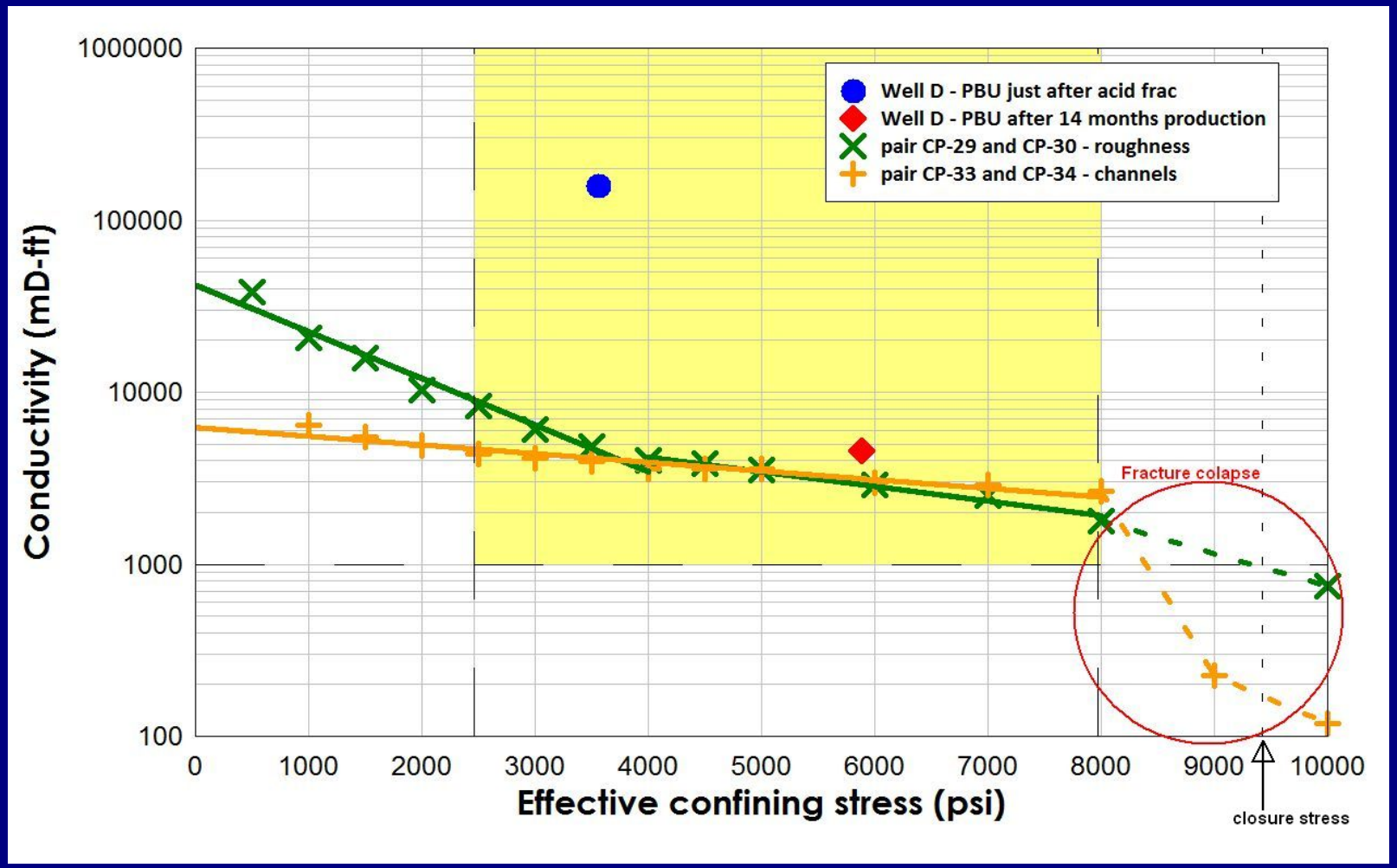


Note: in laboratory conditions, effective confining stress equals closure stress

Field case II – Well C production history

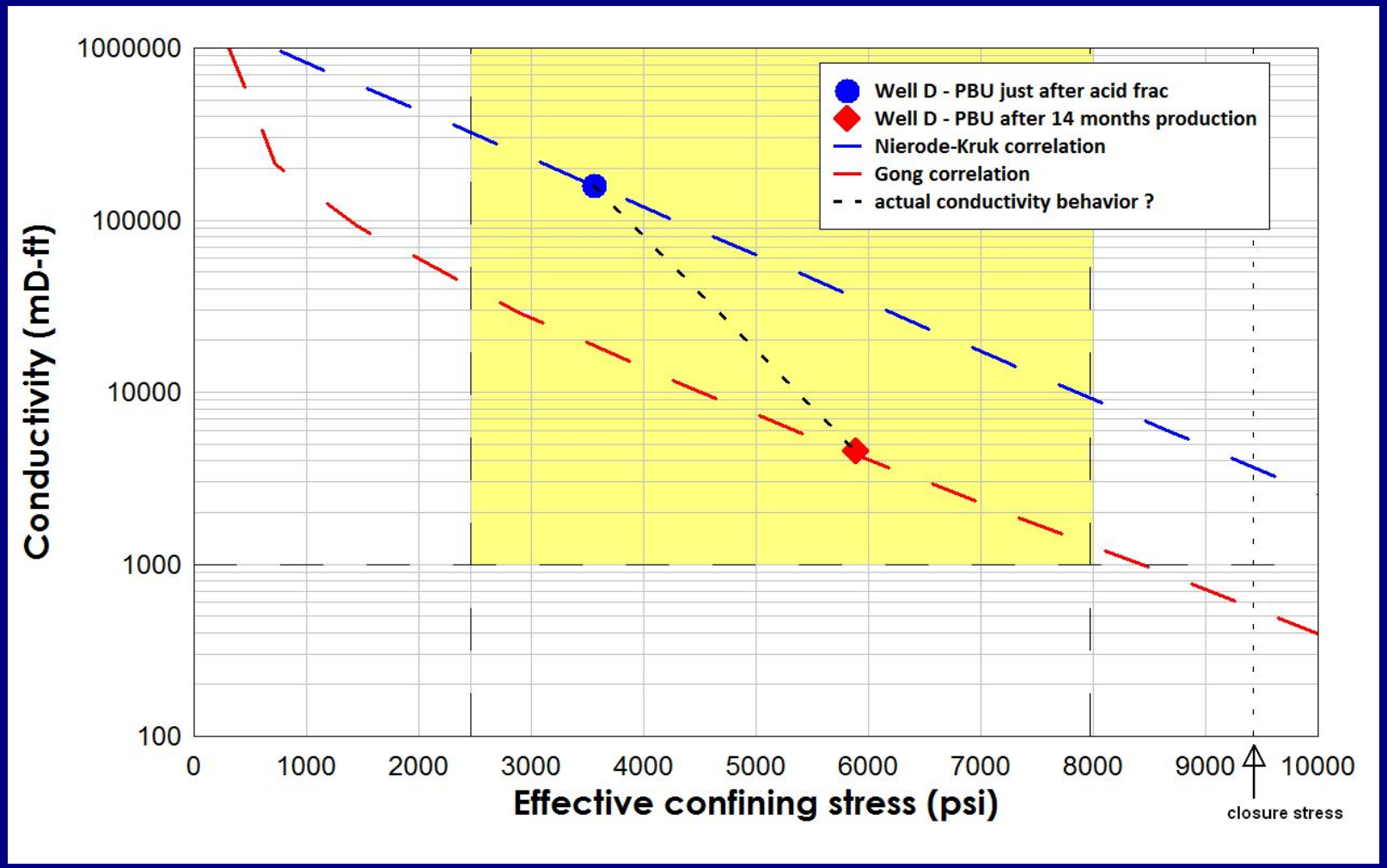


Field case III – Well D, vertical, 15000 ft TVD

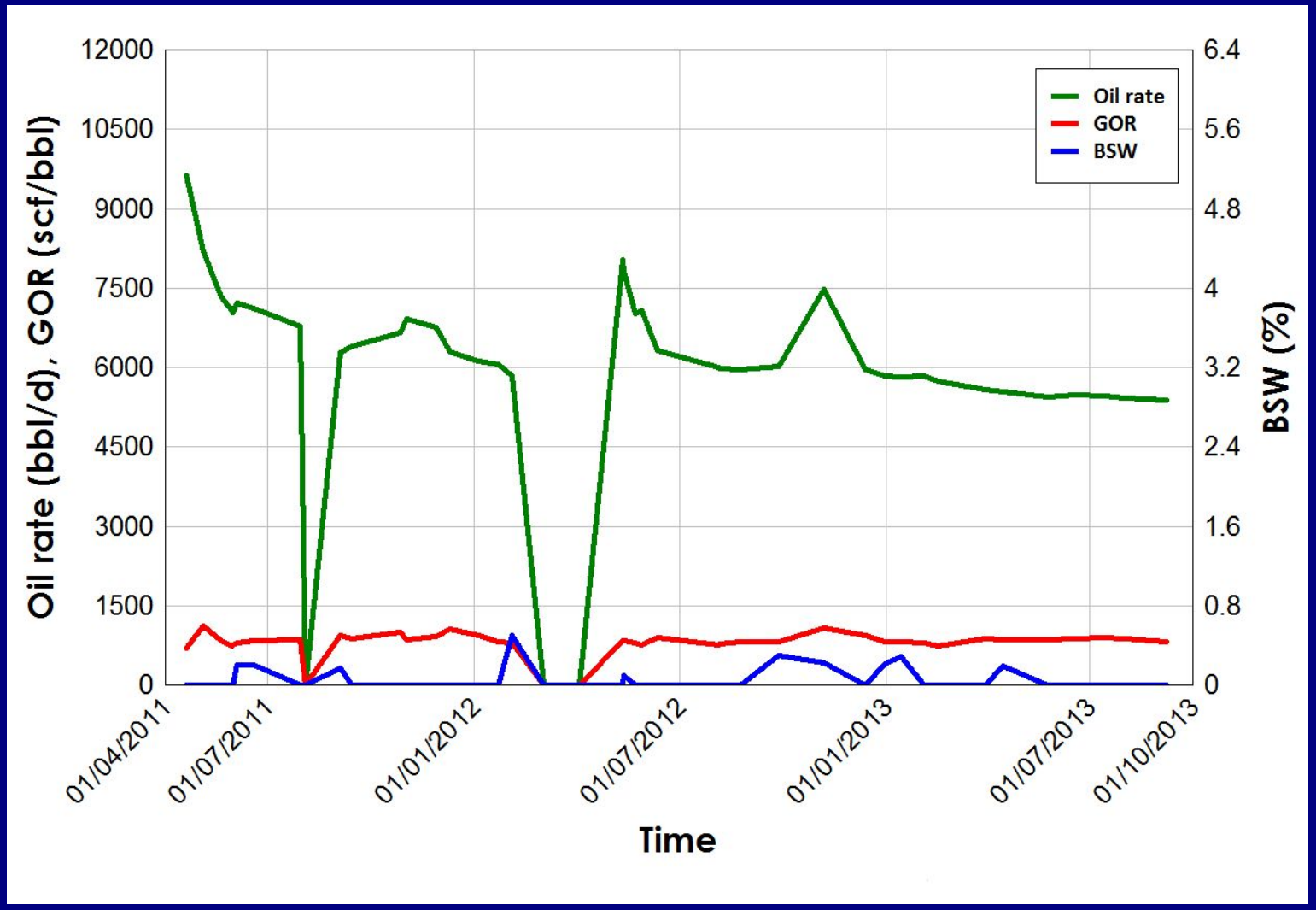


Note: in laboratory conditions, effective confining stress equals closure stress

Field case III – Well D, vertical, 15000 ft TVD



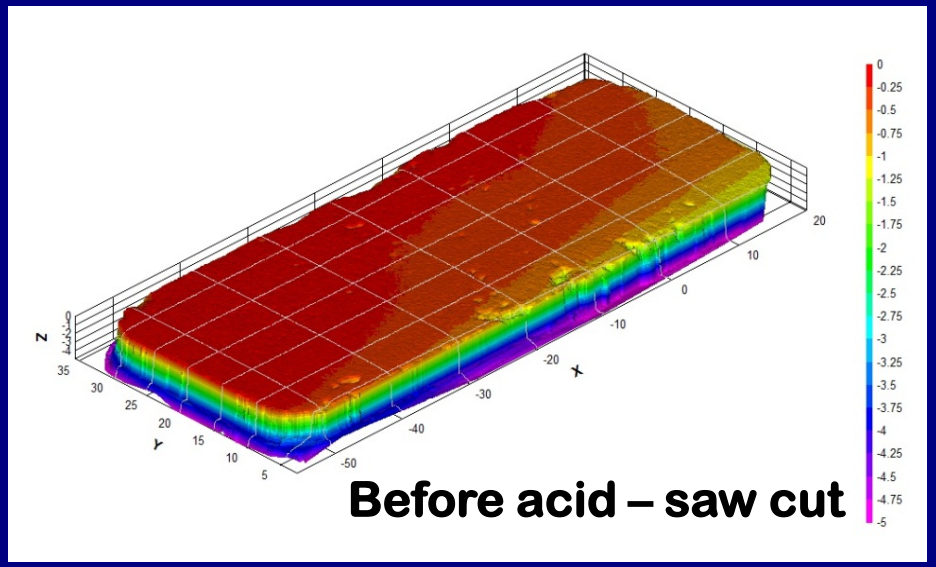
Field case III – Well D production history

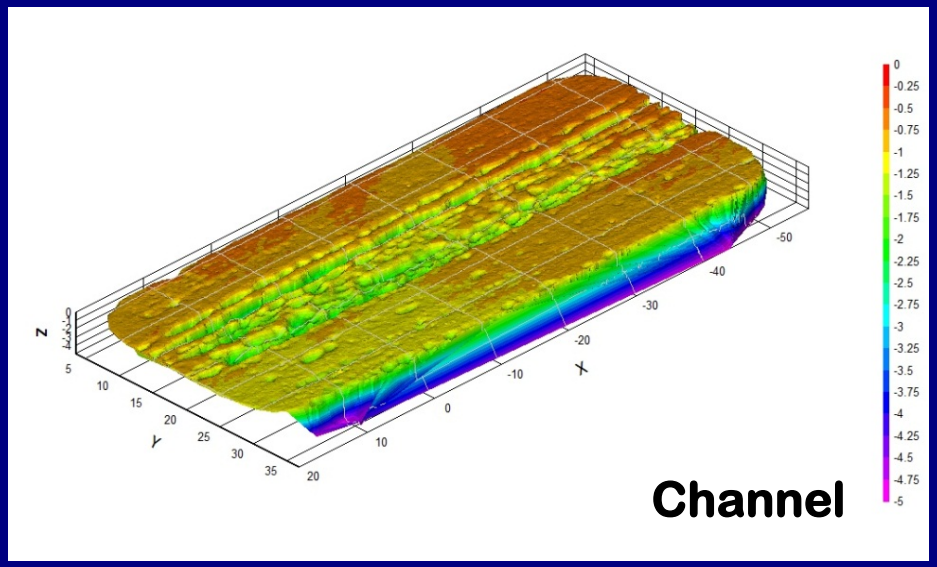


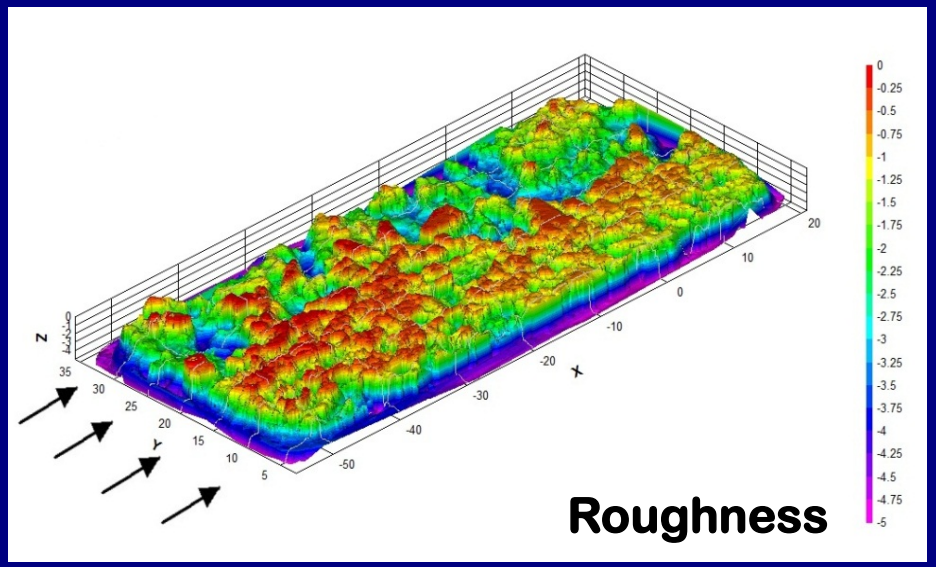
Experimental investigation II

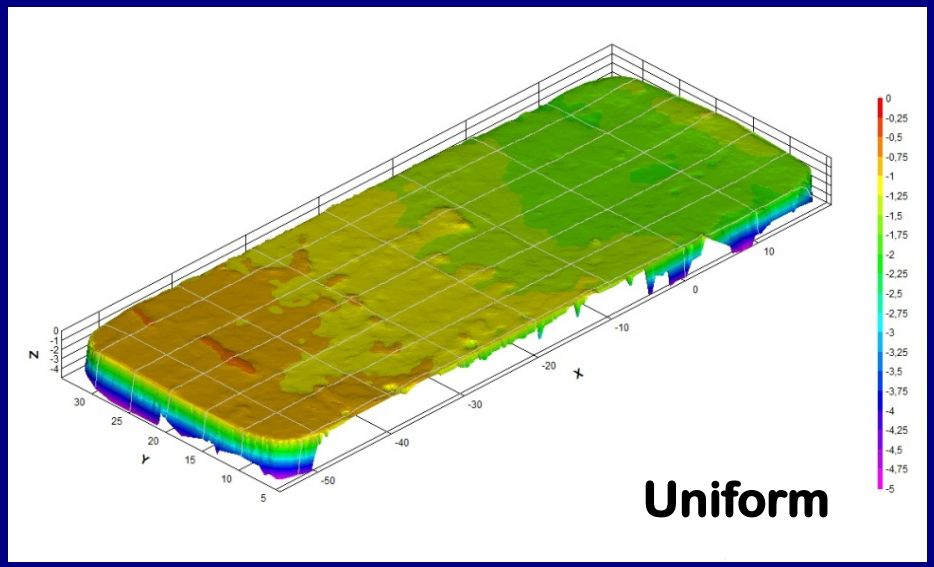
tensile fractures vs saw cut smoothed fractures

Etching patterns from saw cut surfaces



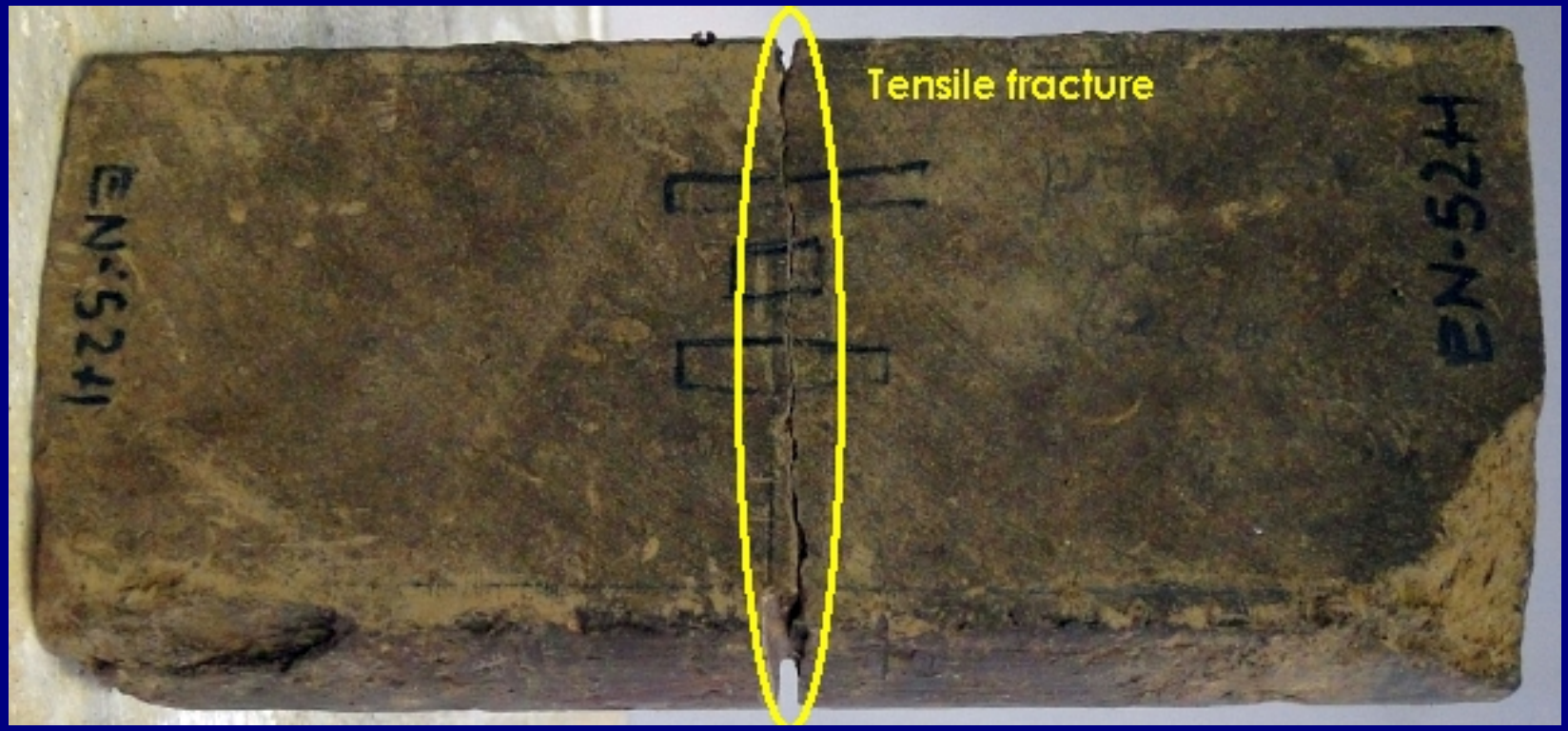






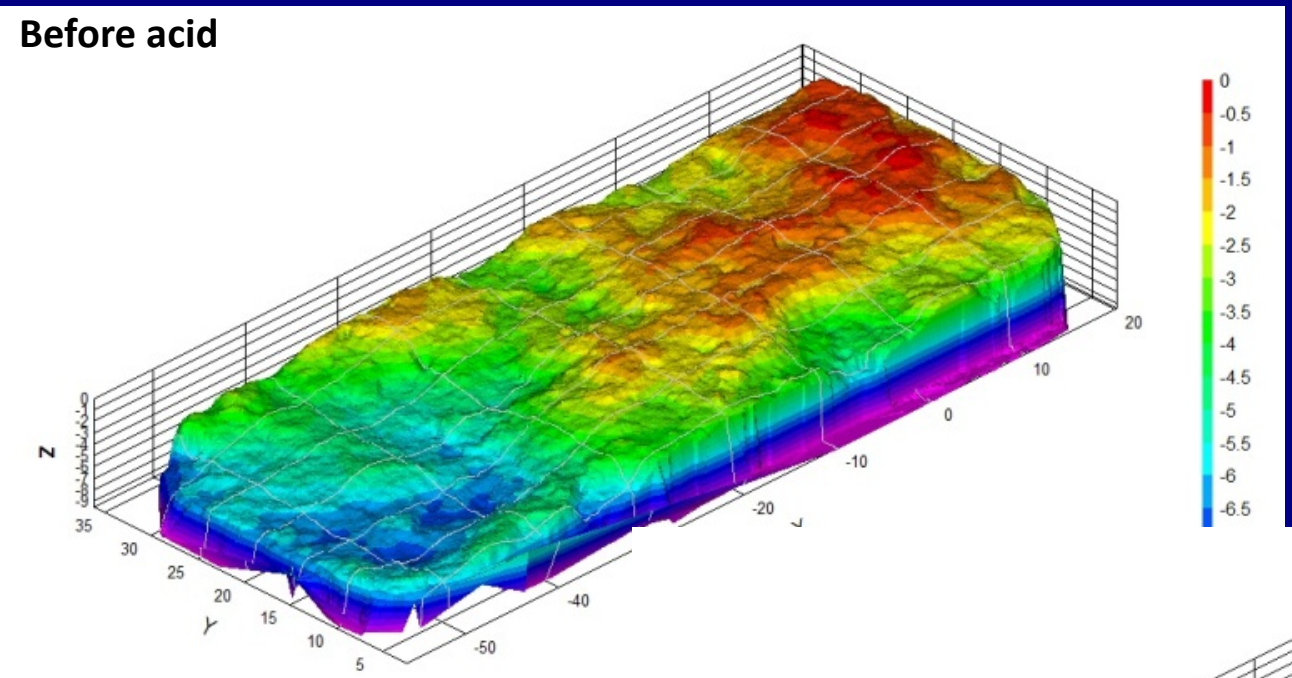
Note: dimensions in millimeters, same color scale

Carbonate sample with tensile fracture



CP-38 Etching pattern: tensile

Before acid



Before

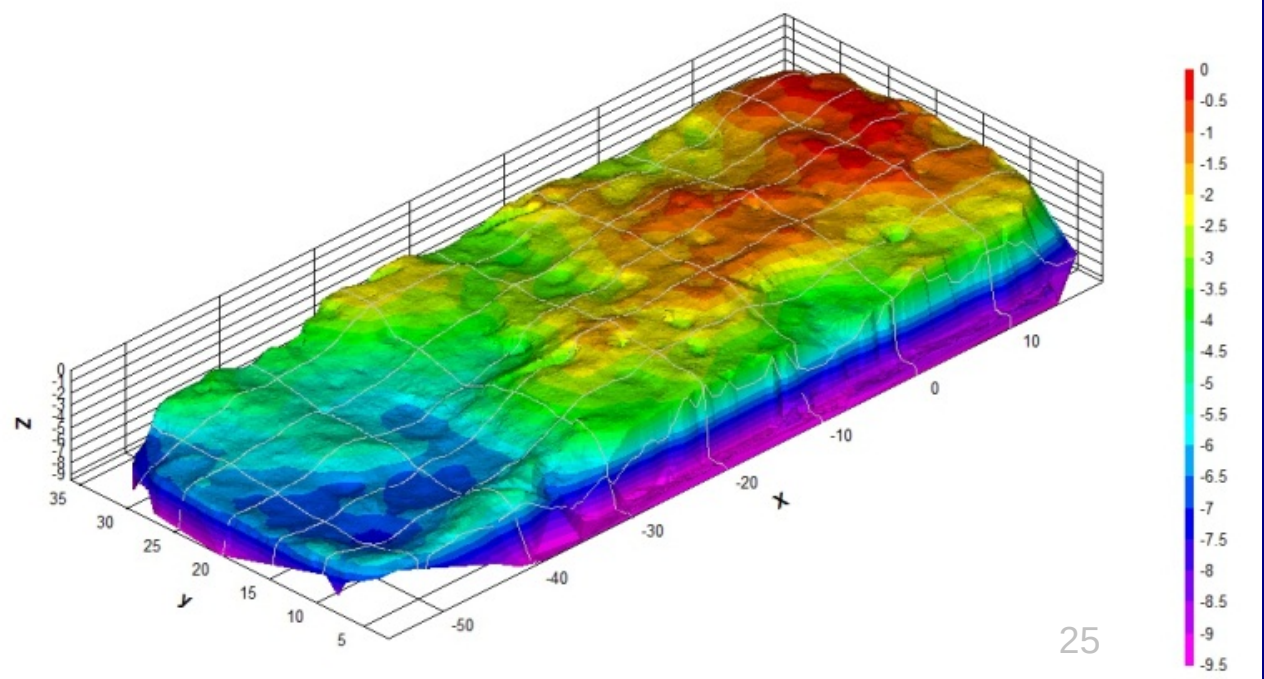
$$r_L = \frac{2149}{1937} = 1.107$$

After

$$r_L = \frac{2151}{1937} = 1.110$$

$$\Delta m = 0.76g$$

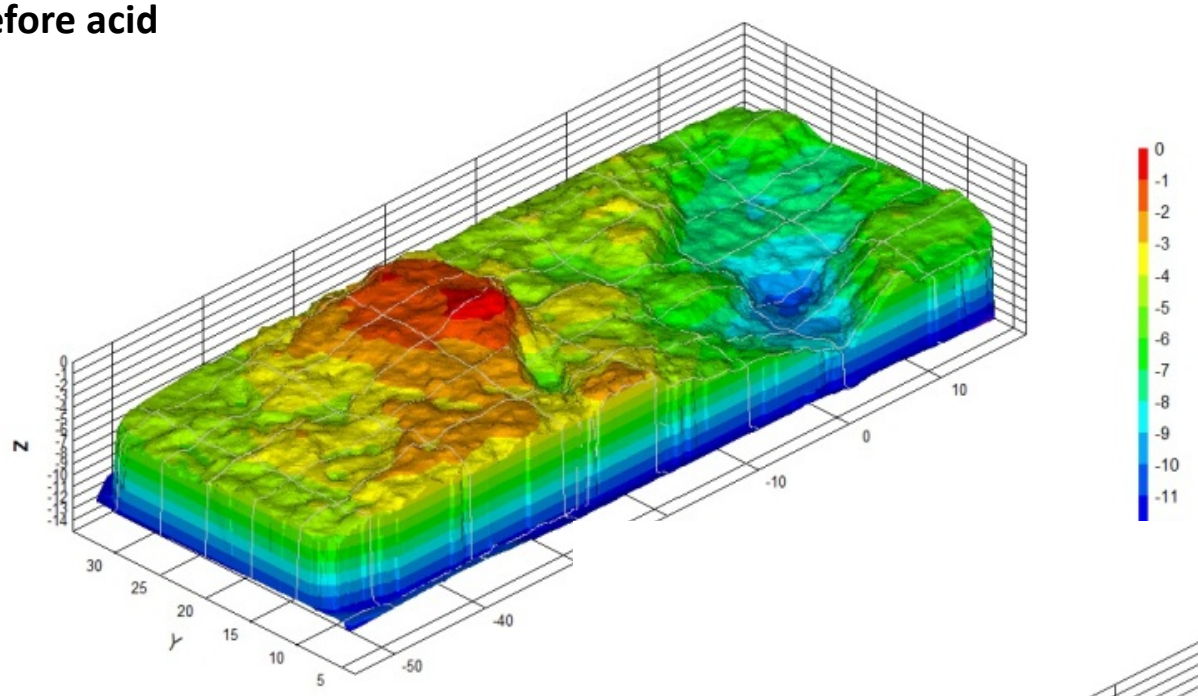
C_1 = 7290 mD-ft



After acid

CP-55 Etching pattern: tensile

Before acid



Before

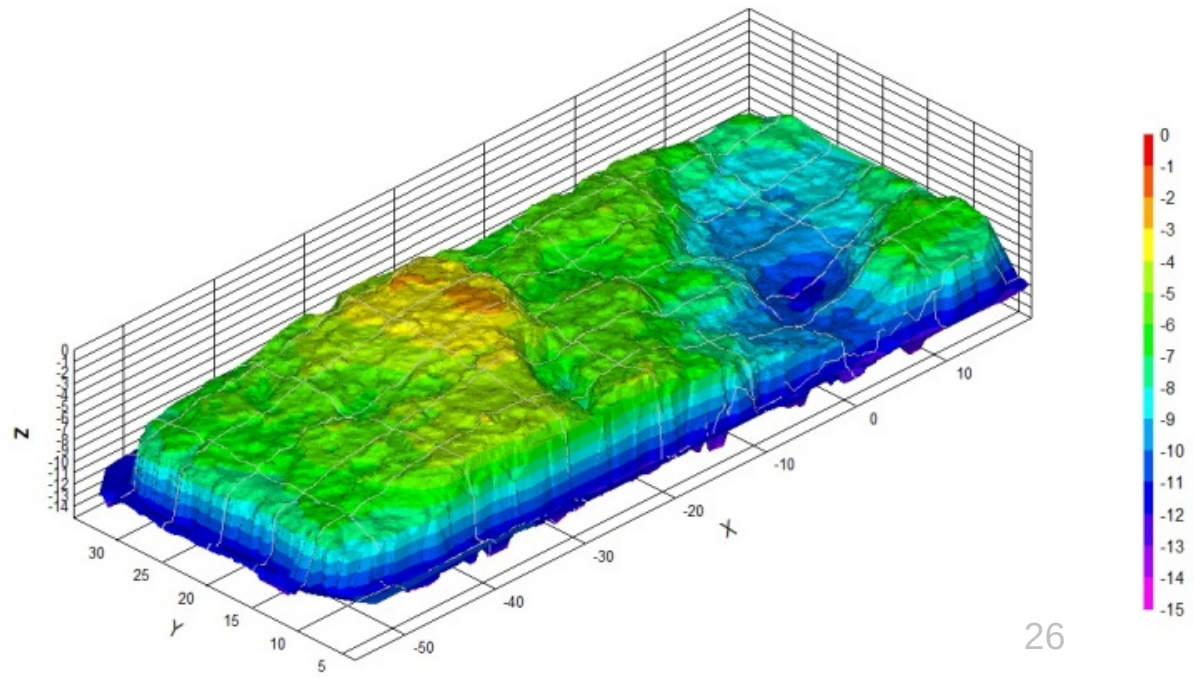
$$r_L = \frac{2558}{1937} = 1.320$$

After

$$r_L = \frac{2916}{1937} = 1.505$$

$$\Delta m = 10.12g$$

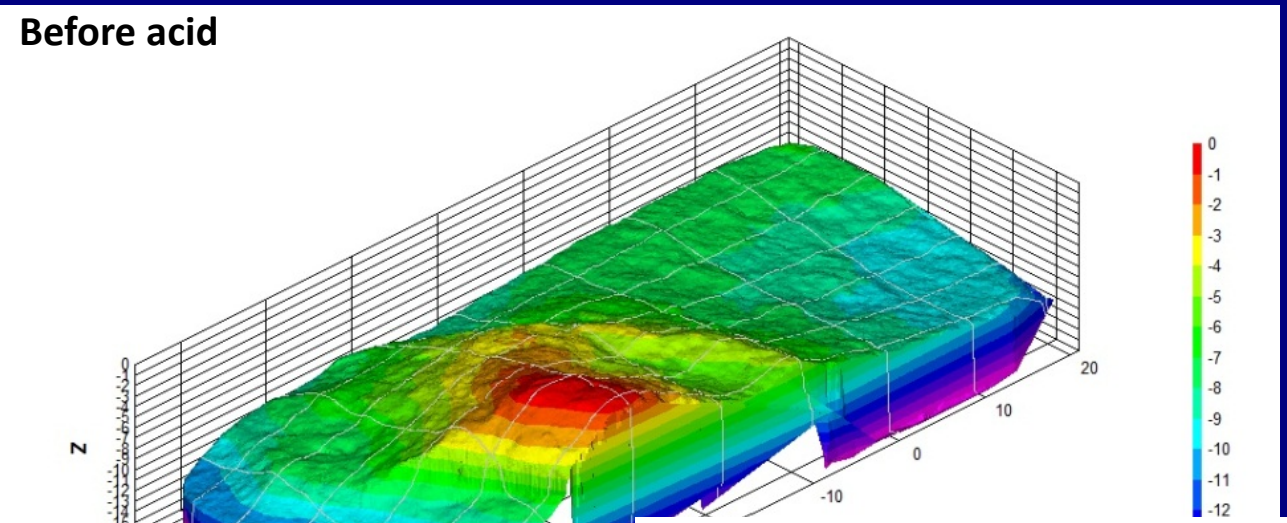
C_1 = 61420 mD-ft



After acid

CP-40 Etching pattern: tensile

Before acid



Before

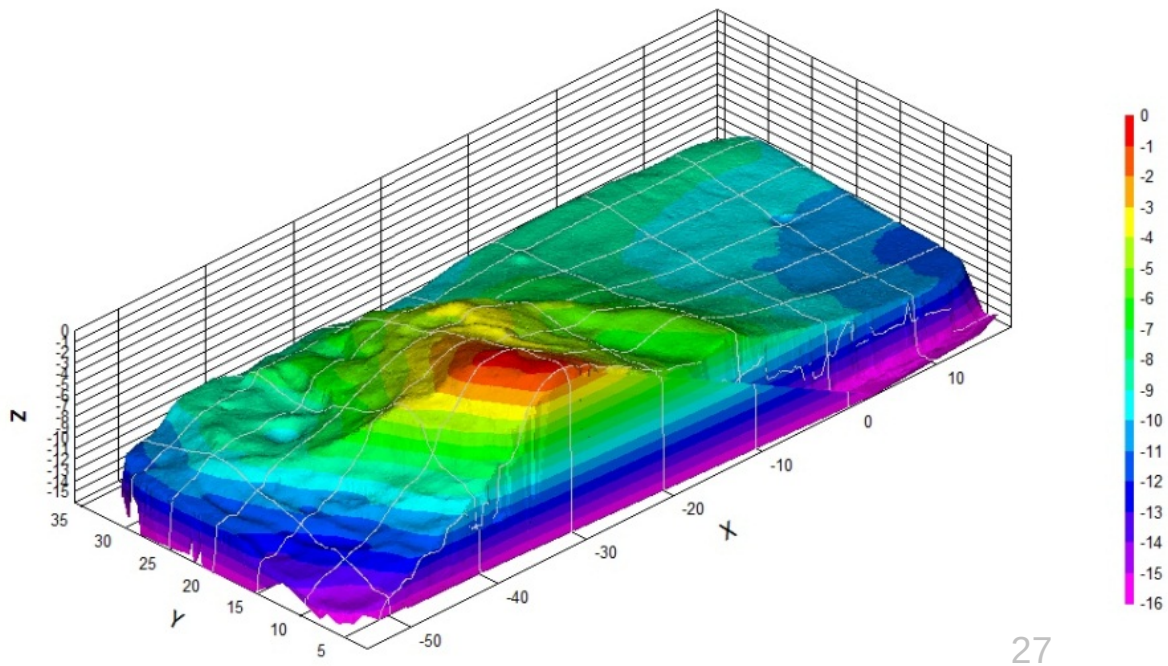
$$r_L = \frac{2145}{1937} = 1.107$$

After

$$r_L = \frac{2214}{1937} = 1.143$$

$$\Delta m = 6.44g$$

C_1 = 199150 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

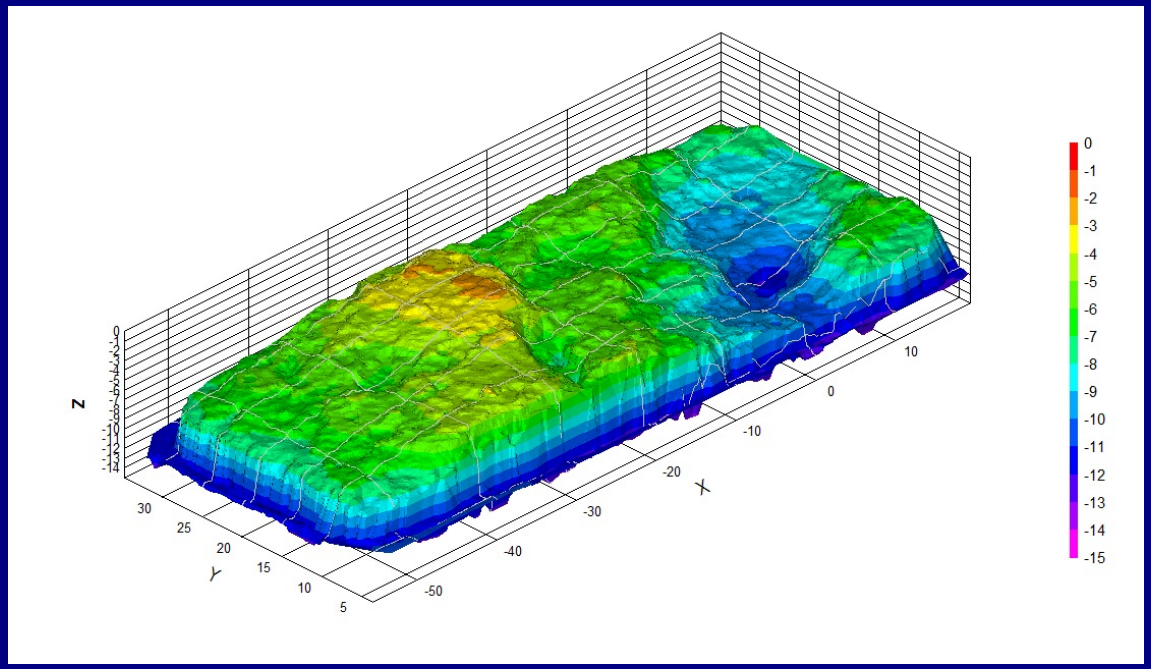
	Area (mm^2)		r_L		r_{LT}		Area (mm^2)		r_L		r_{LT}
	Before	After	Before	After			Before	After	Before	After	
CP-37	2138	2127	1.104	1.098	0.995	Ctr-1*	481	441	1.202	1.103	0.917
CP-38	2149	2151	1.109	1.110	1.001	Ctr-2	477	445	1.193	1.113	0.933
CP-39	2149	2365	1.109	1.221	1.101	Ctr-3	518	491	1.295	1.228	0.948
CP-40	2145	2214	1.107	1.143	1.032	Ctr-4	495	...	1.238	...	...
CP-55	2558	2916	1.320	1.505	1.140						
CP-56	2534	2978	1.308	1.537	1.175						
CP-59	2483	...	1.287	...	...						
CP-60	2161	...	1.115	...	...						

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.

Proposed acid fracture definition

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

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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

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

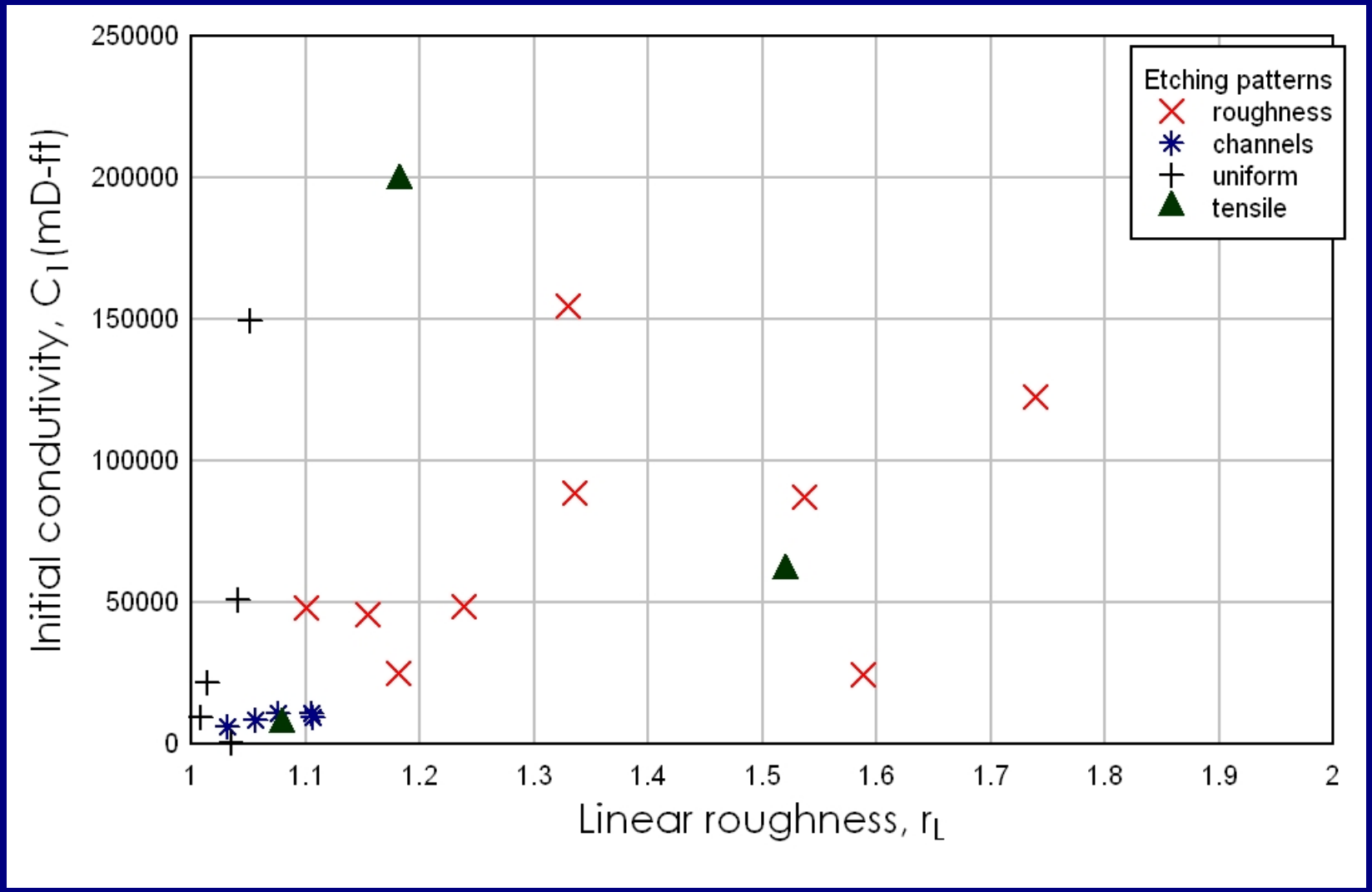
- Microbial Carbonates (RIDING, 2000; AHR, 2009)
  - stromatolite
  - oncolite
  - thrombolite
  - leiolite
- Outcrops and actual reservoir samples, Aptian and Albian age

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 cm^3/min
  - μ = 1 cP
- L = 6 cm, $H_{lab} \approx$ 3.1 cm
- ΔP measured
- $k_f w$ calculated

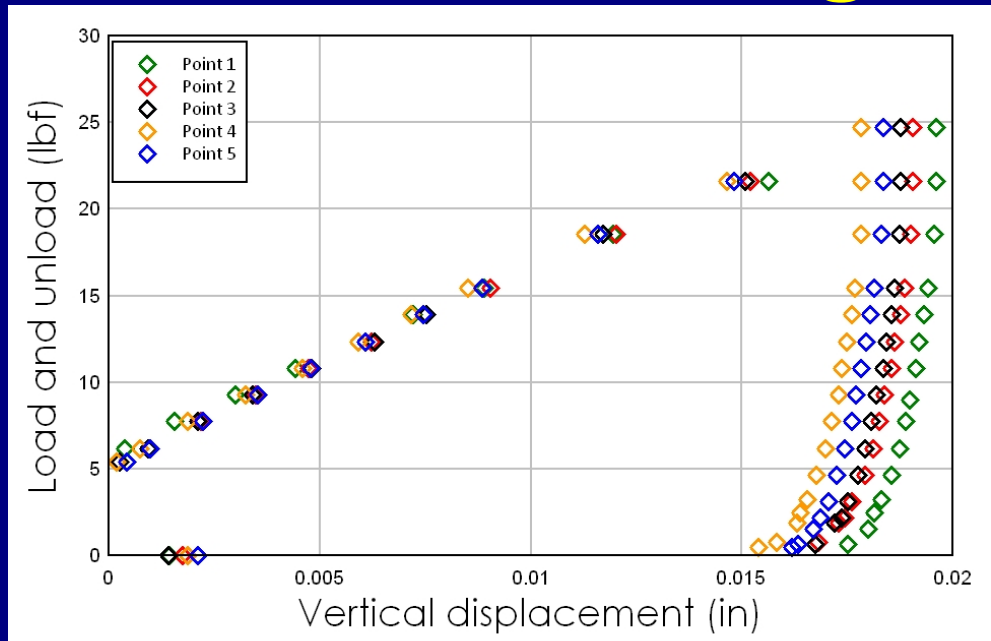
$$k_f w = \frac{\mu q L}{H_{lab} \Delta P}$$

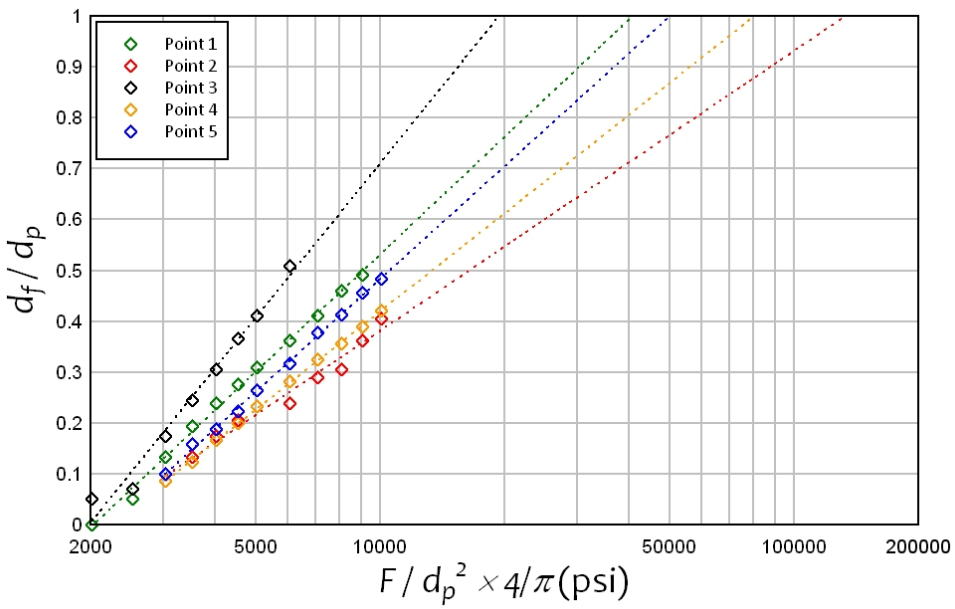
Initial conductivity, linear roughness and etching pattern



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 HUITT, 1966), divided by its projected area (NIERODE and KRUK, 1973)

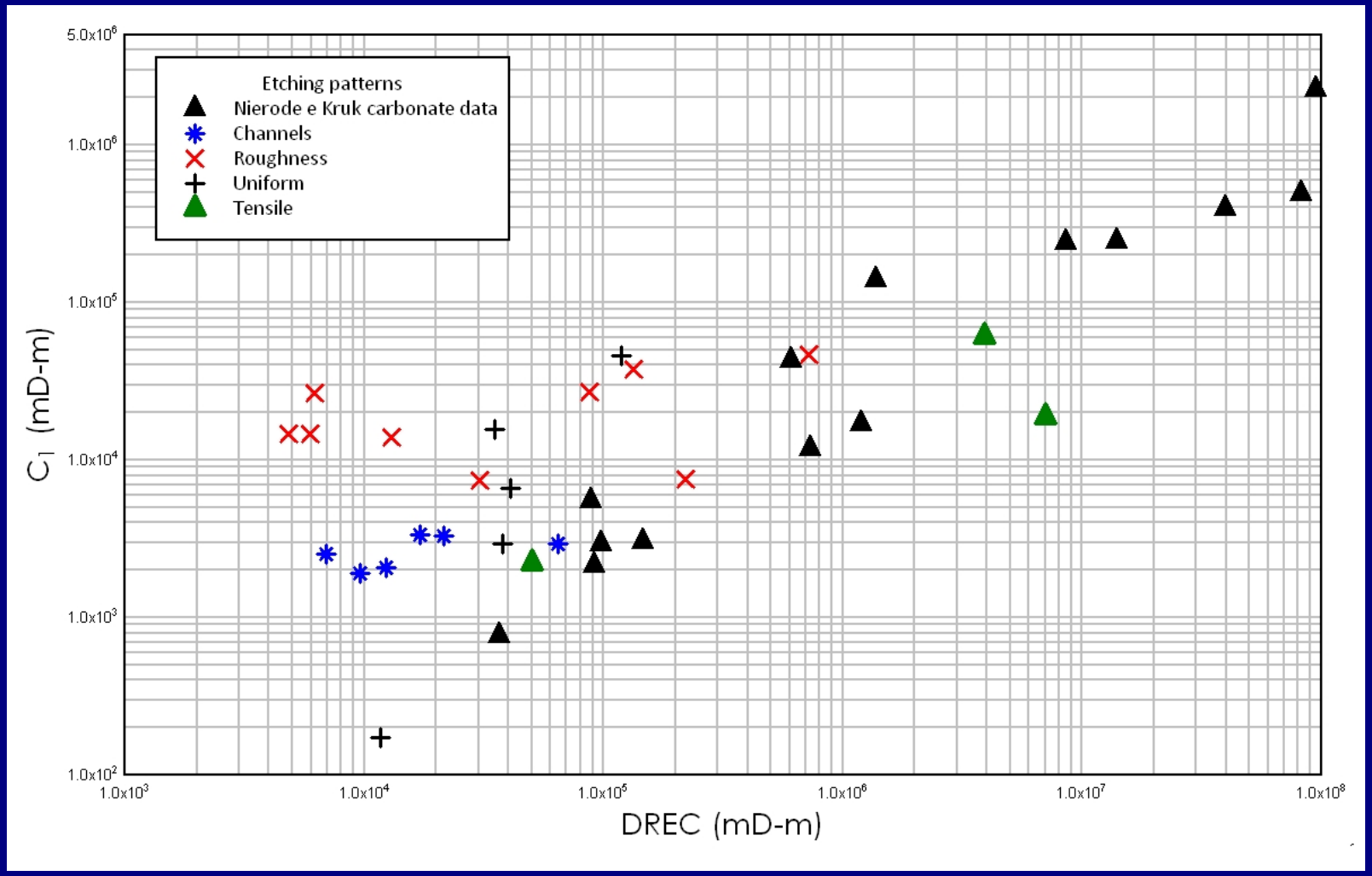




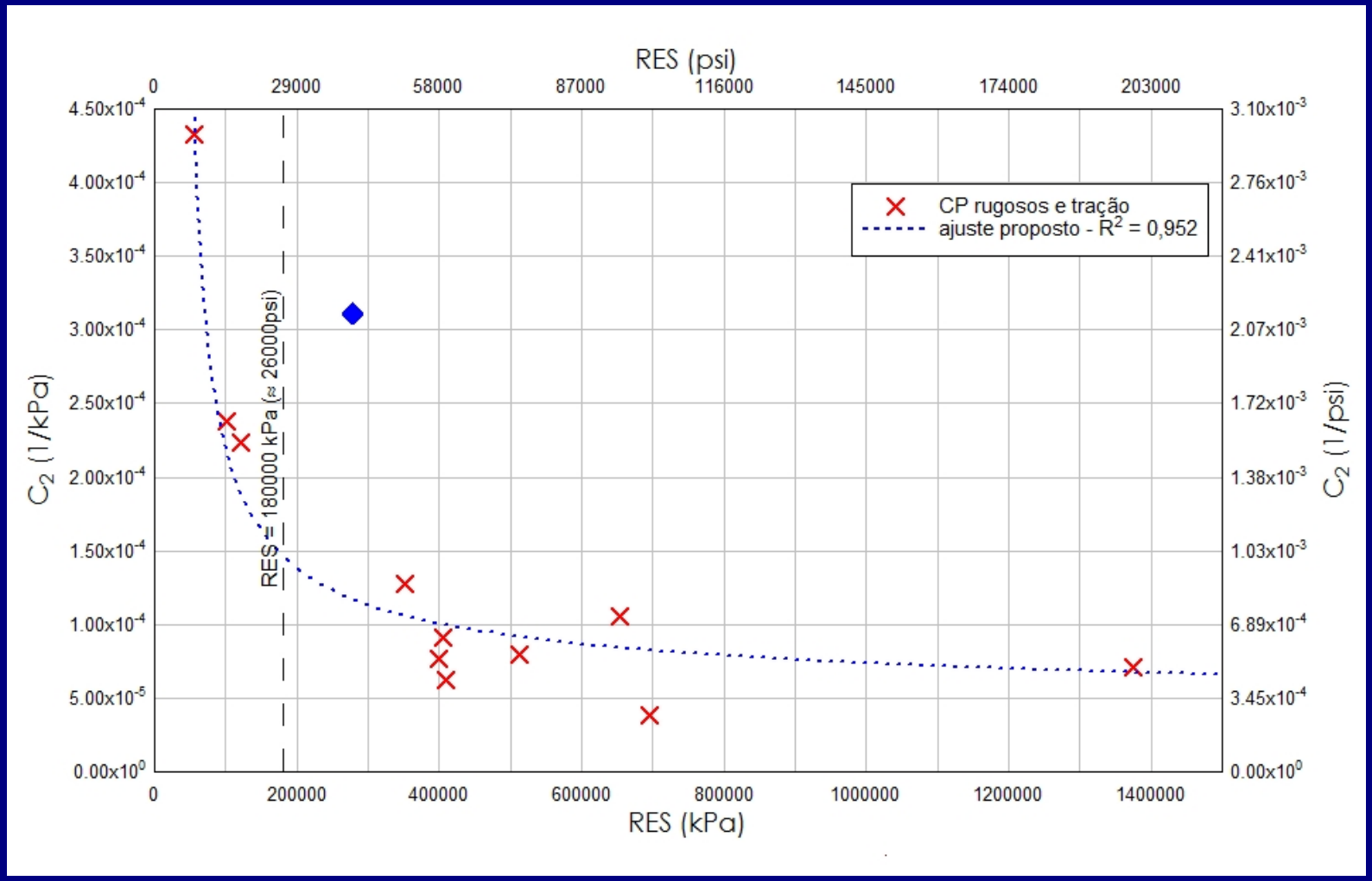
Loading: RES measurements
Unloading: Young´s Modulus estimate

Source: NEUMANN, 2011

Initial conductivity, DREC and etching pattern



RES correlation – NEUMANN 2011



The Argonauts, the patron saint of acid fracturing

[…] 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

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