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Also thanks to Petrobras

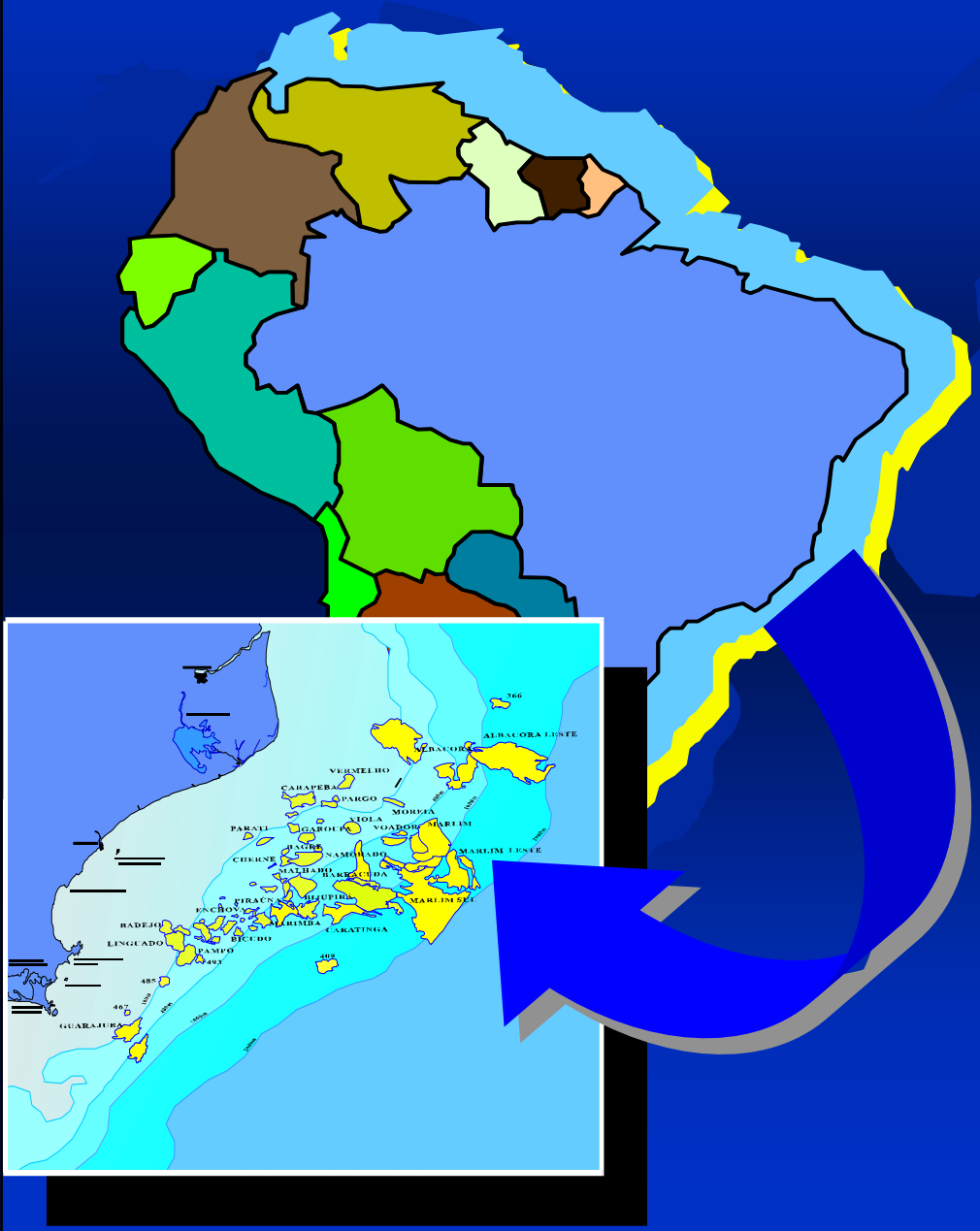
Frac-pack in Ultra Deep Water: Lessons Learned from a Hundred of Well Succeeded Operations

Carlos A. Pedroso

Outlines

- 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:

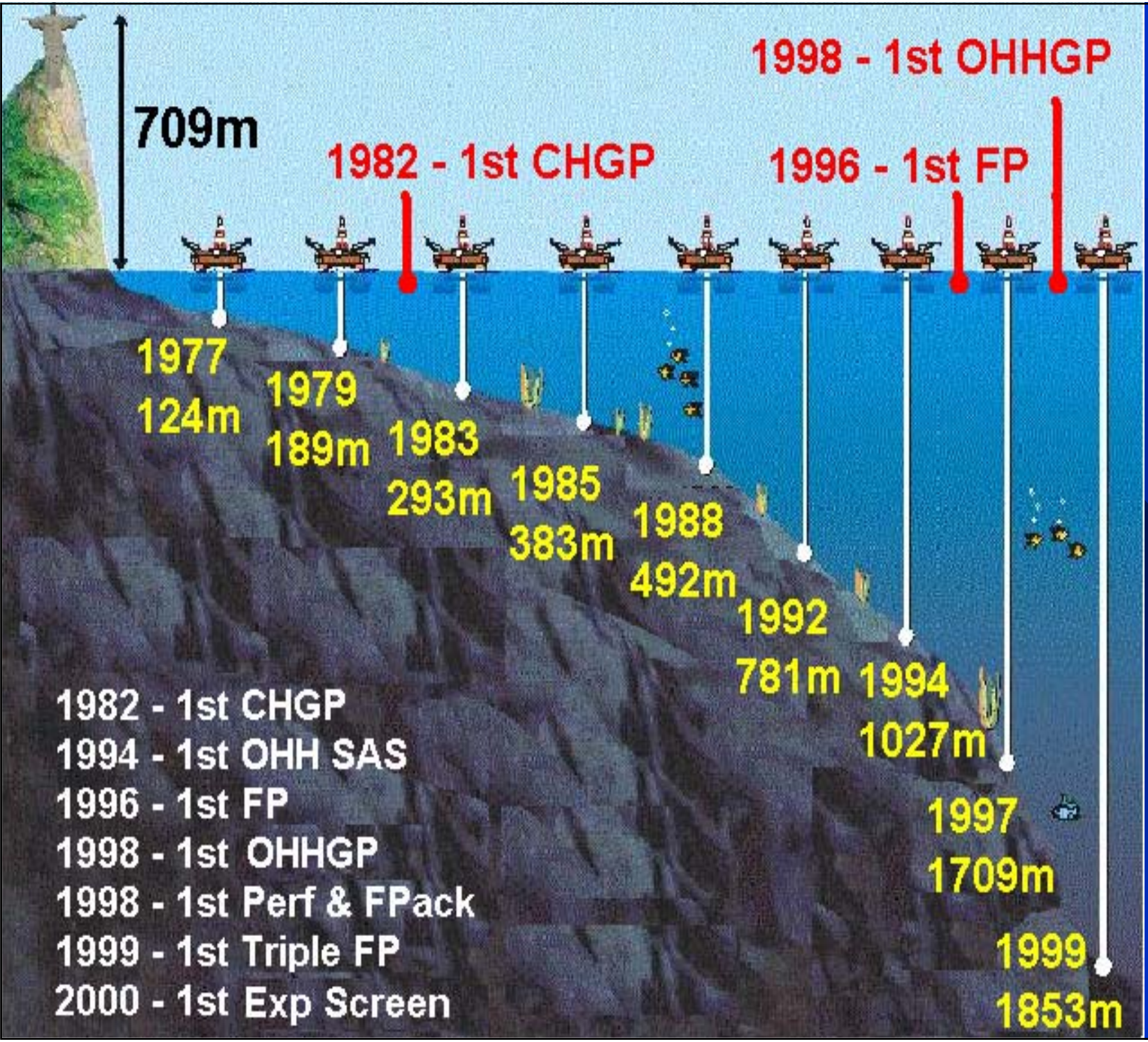
- Clean, high-permeability (300 to 14,000 mD) sandstones

- 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

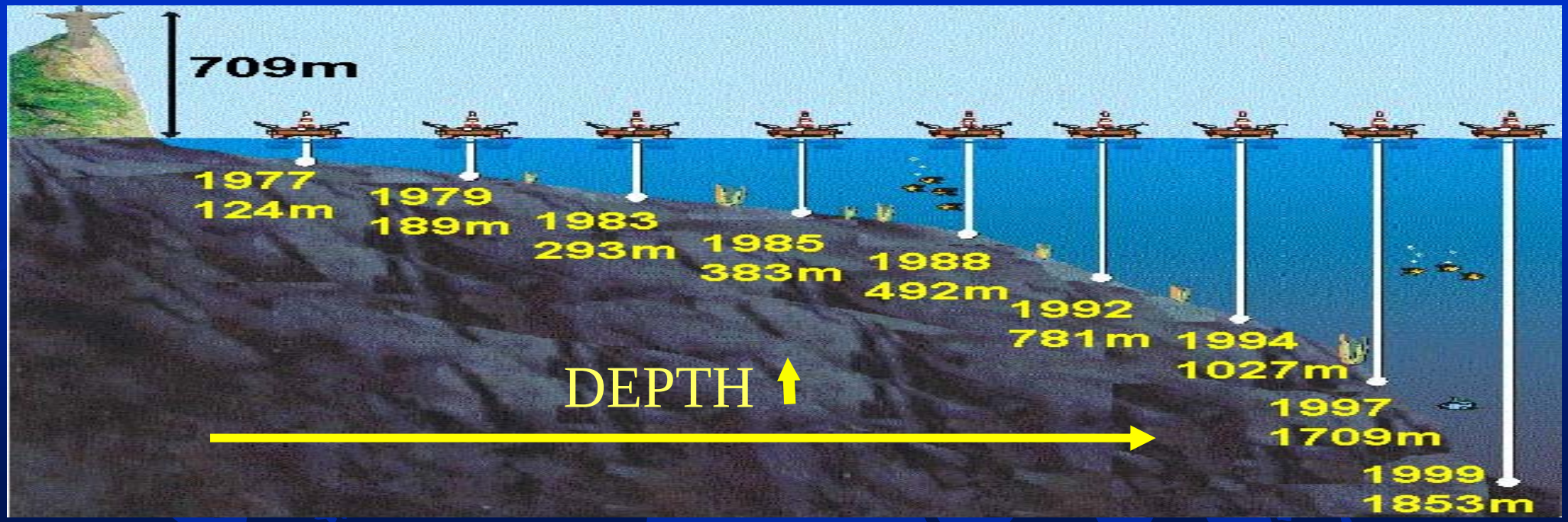
PROCAP "1000"

1993

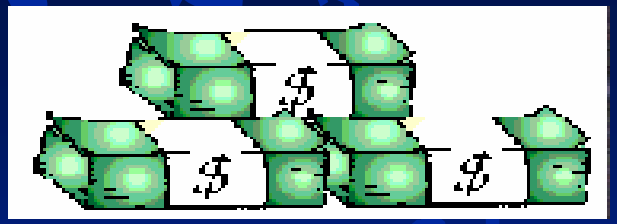
PROCAP 2000

2000

PROCAP 3000



COST



NEED FOR PRODUCTIVITY

Introduction

Deep water

High permeability

Unconsolidated Sands

Scenario

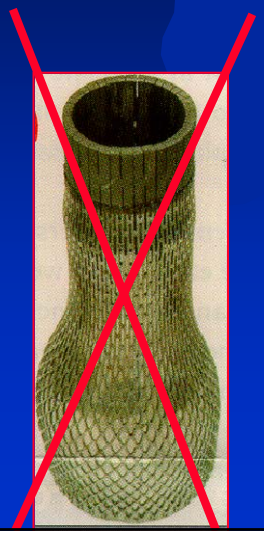
Possible Solutions

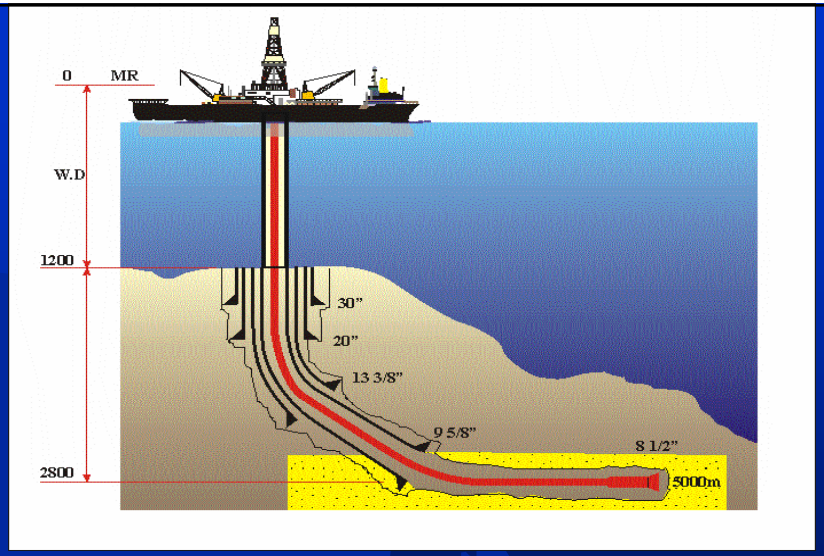
Sand Control

High Productivity

Durability

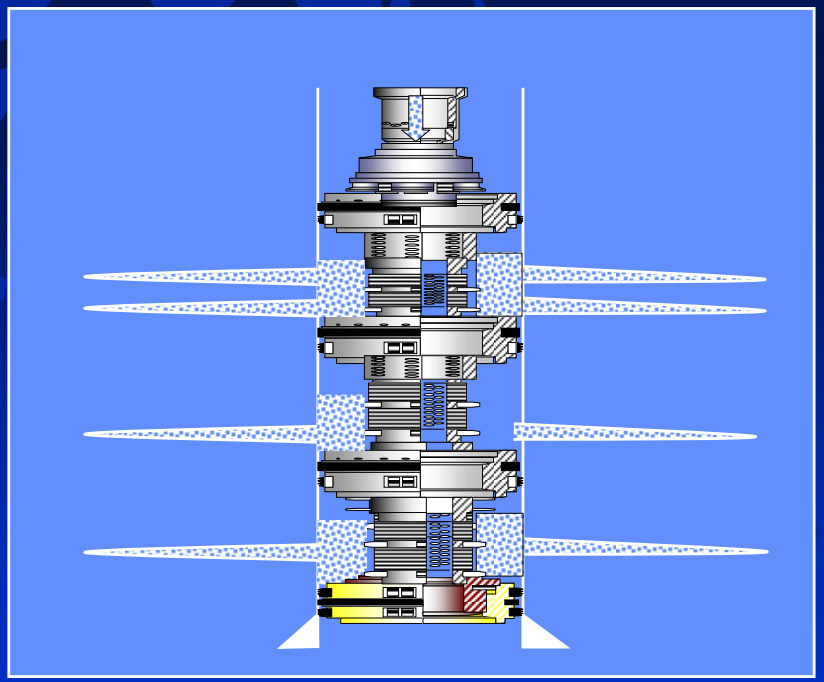
Needs





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

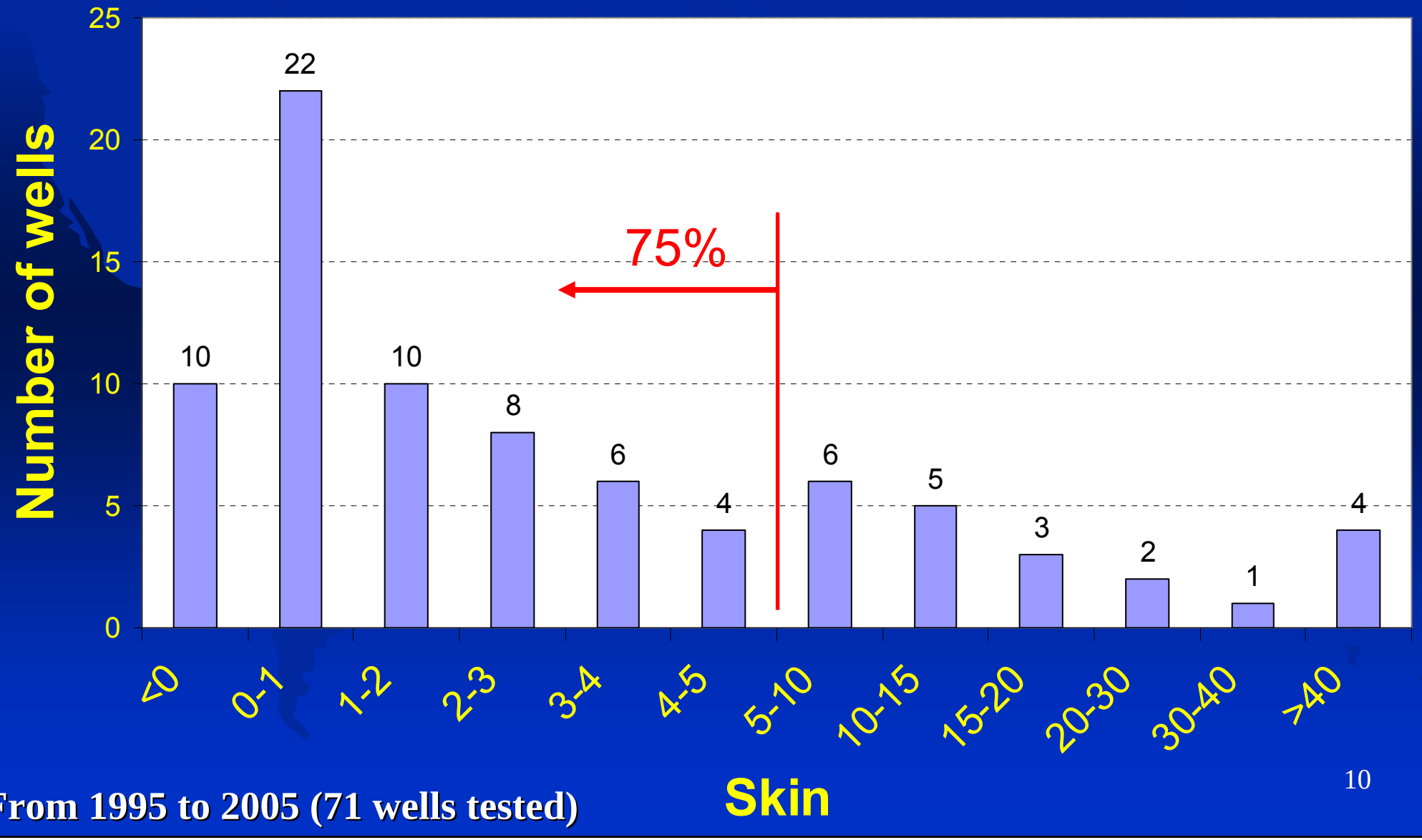
Well succeeded fracpack

(FRACPACK DEFINITION)

- Low skin → Best practices
- High conductivity fractures→ TSO as planned
- No remedial acid jobs → Both
- No sand production → Proper sand control design

Well succeeded fracpack

Skin (Buildup & Falloff Test)



From 1995 to 2005 (71 wells tested)

Best (good) practices

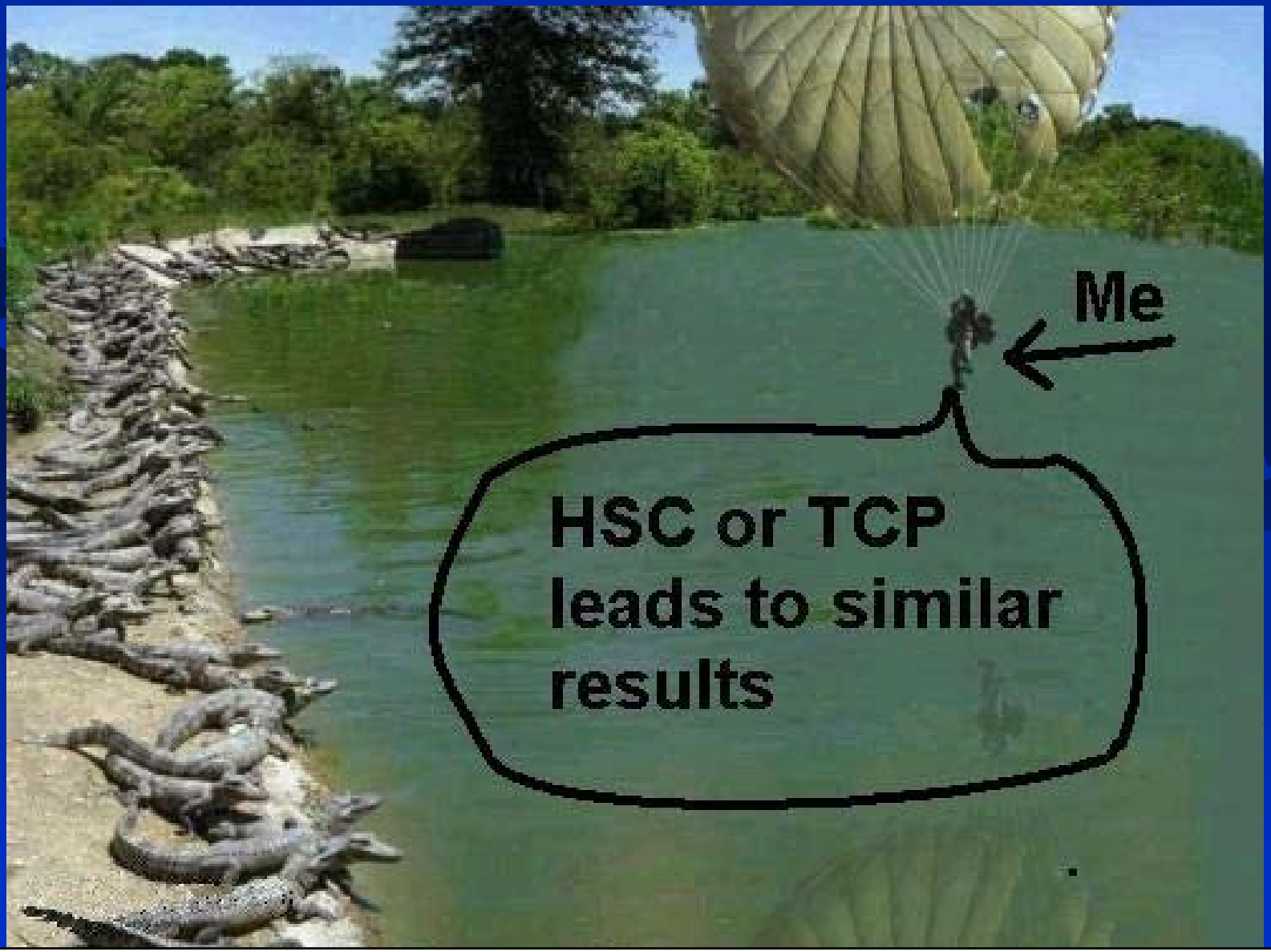
- HSC Overbalance x TCP Underbalance
- Clean up flow prior to fracturing
- Acidizing prior to fracturing
- Riser and casing cleaning
- Internal coated work string cleaning
- Brine Filtration
- Gel and proppant quality

Well	k (mD)	*s*	*DR*	Perforating
A-1	354	1.9	1.3	Overbalanced
A-2	1516	1.6	1.1	Overbalanced
A-3	70	-1.5	0.8	Underbalanced
A-4	460	13.9	2.7	Underbalanced
A-5	860	3.9	1.6	Underbalanced
A-6	2795	10.2	6.7	Overbalanced
A-7	6600	45.2	7.0	Underbalanced

X

Perforations

HSC overbalance x TCP underbalance

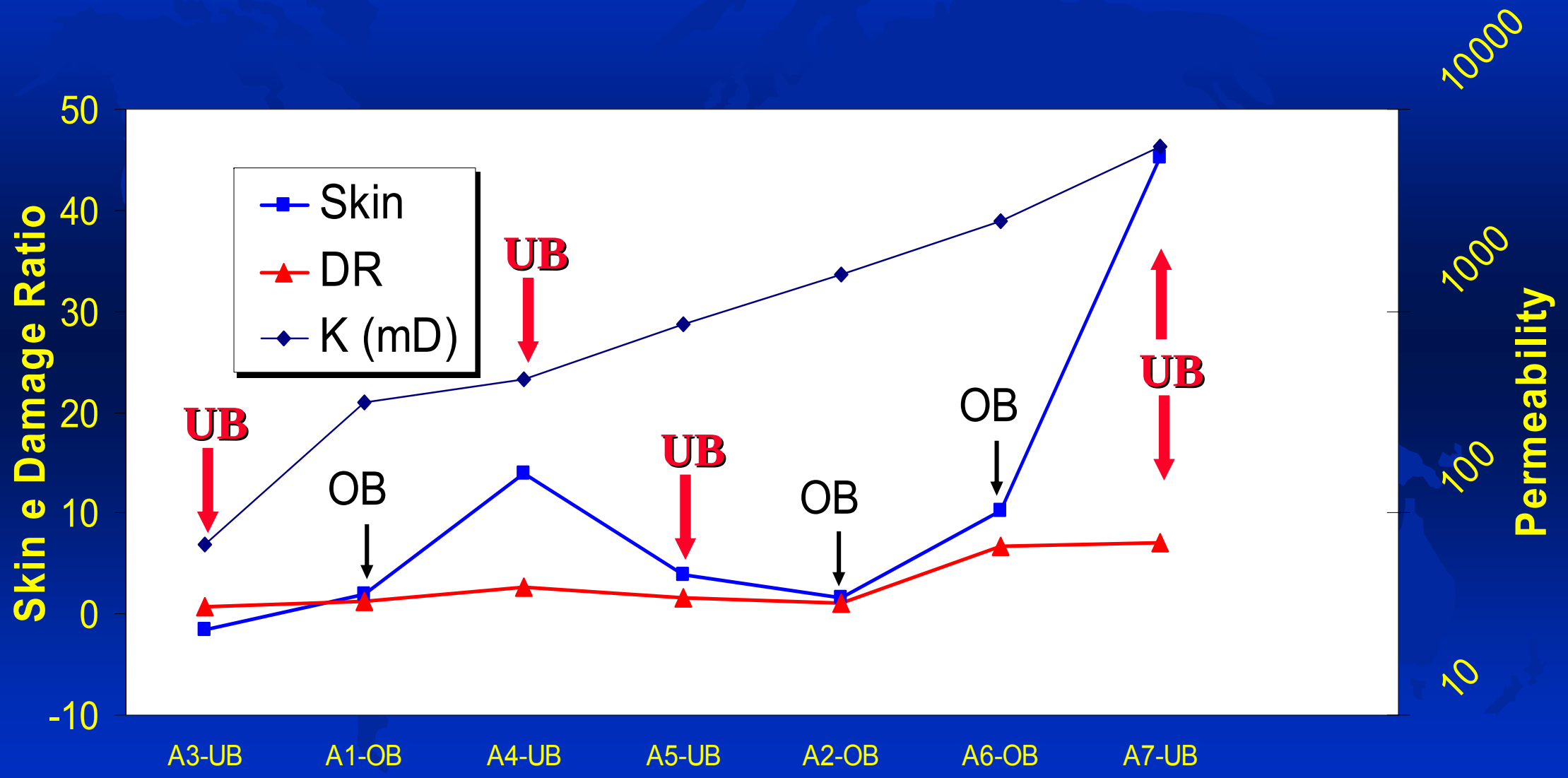


Perforations

Well	K (mD)	Skin	DR	Perforation
A3-UB	70	-1.5	0.8	Underbalance
A1-OB	354	1.9	1.3	Overbalance
A4-UB	460	13.9	2.7	Underbalance
A5-UB	860	3.9	1.6	Underbalance
A2-OB	1516	1.6	1.1	Overbalance
A6-OB	2795	10.2	6.7	Overbalance
A7-UB	6600	45.2	7	Underbalance

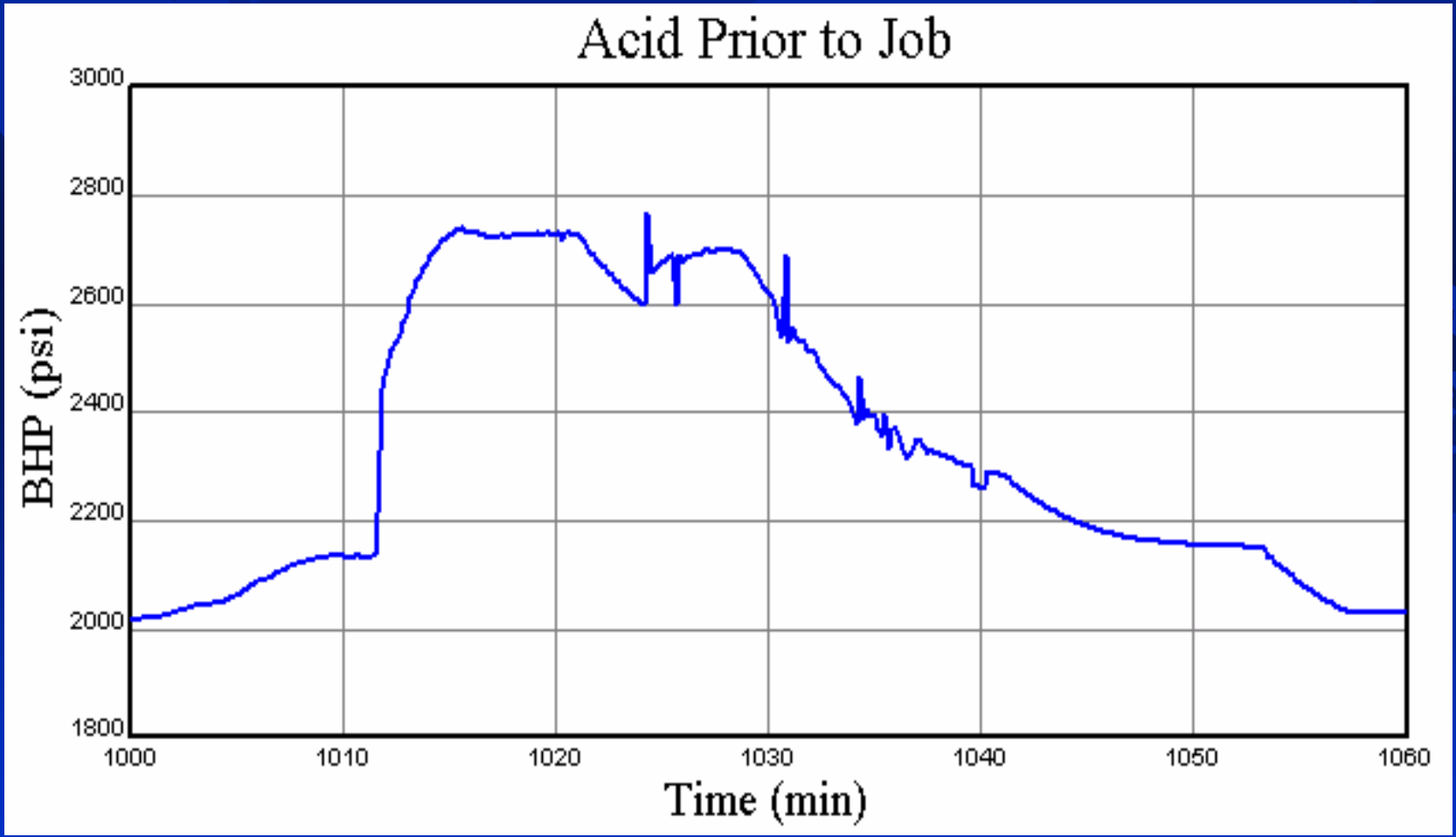
Field "A", same reservoir, equivalent operational conditions (1997 to 1999)

Perforating Type x Skin & Damage Ratio



Acidizing prior to fracturing

Main objective: clean perforations

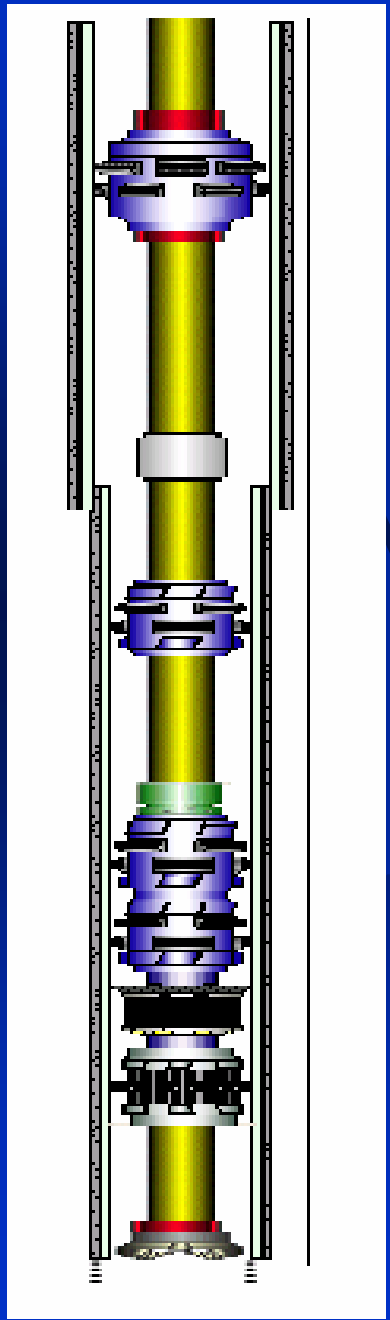


(BHP Data)

Workstring cleaning

Solvent and/or pickling

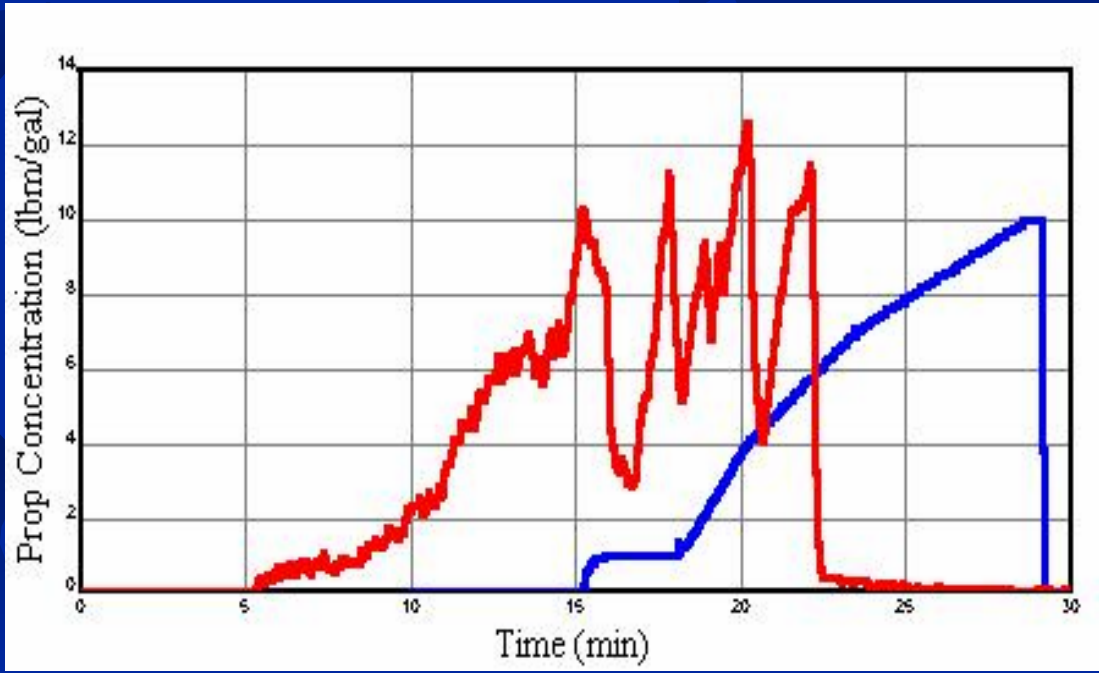
Casing and riser cleaning



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

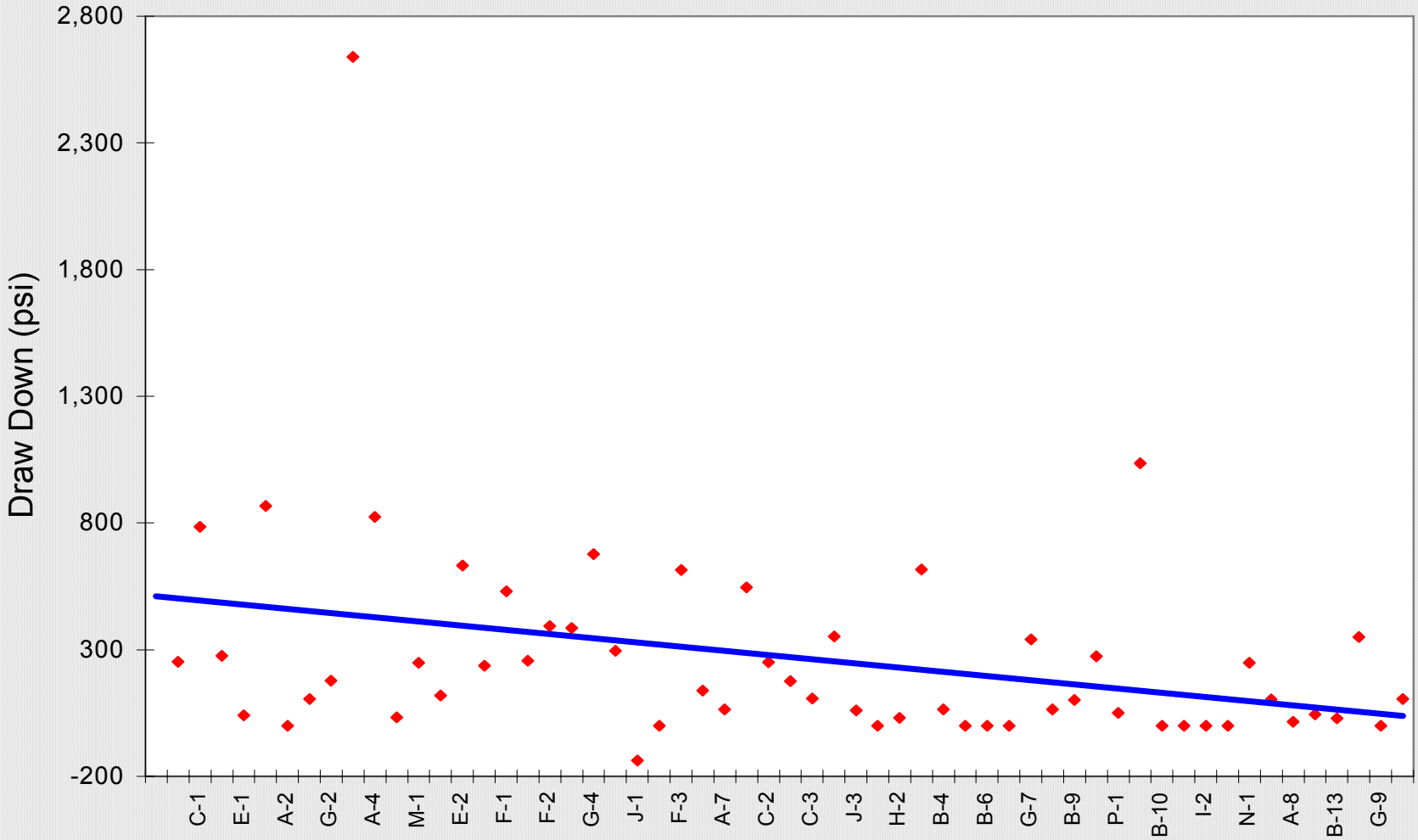


(SPE – 73722)

Good practice	Statistic	Cost
HSC Overbalance x TCP Underbalance	YES	HIGH (*)
Clean up flow prior to fracturing	YES	HIGH (*)
Acidizing prior to fracturing	NO	LOW
Riser and casing cleaning	NO	LOW
Internal coated work string cleaning	NO	LOW
Brine Filtration	NO	MEDIUM
Gel and proppant quality	YES	MEDIUM

(*) +US$ 1,500,000/well due to OB (HSC) perforation

BEST (GOOD) PRACTICES



SPE – 73722

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 -50F
- 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 ν)

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

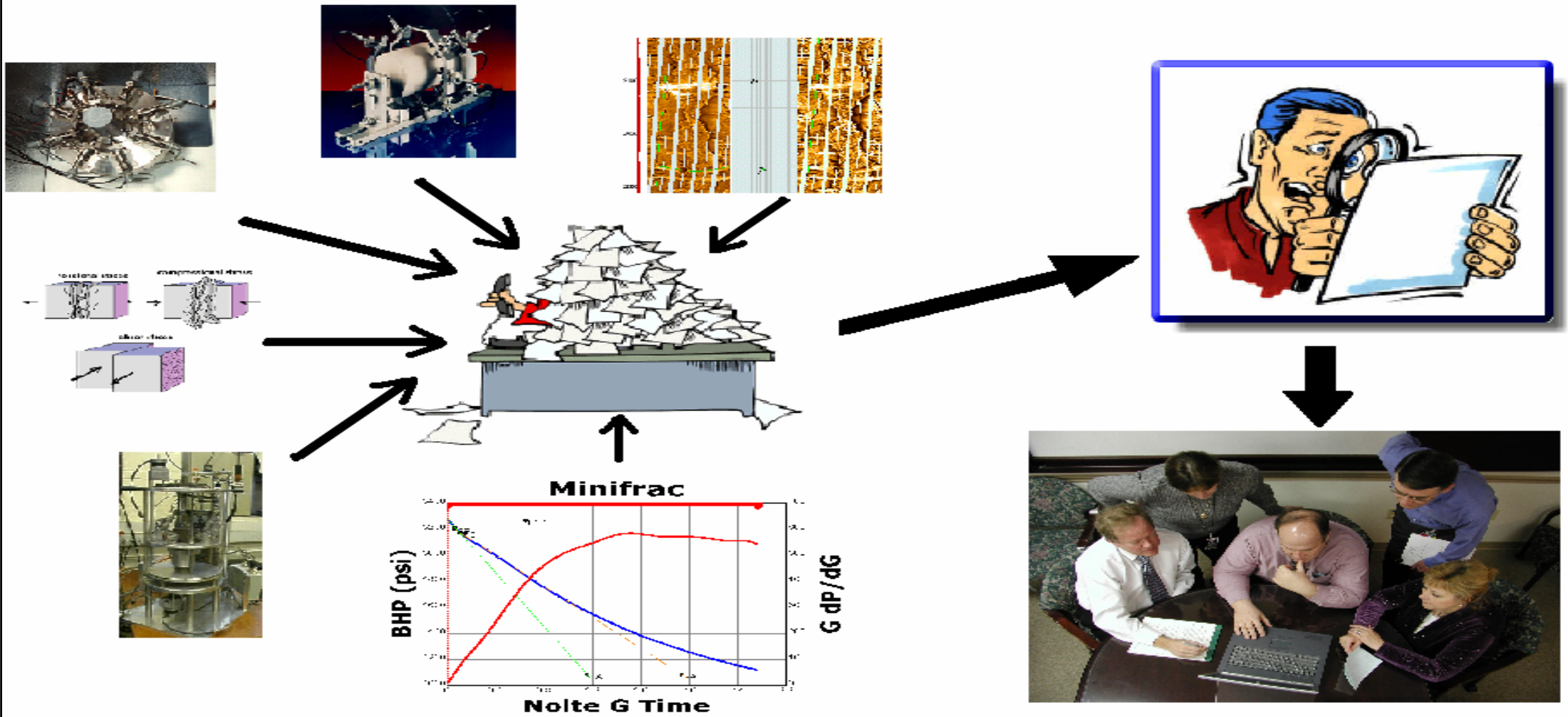
Well	TSO	ΔPnet (psi)	Prop (%)	Skin
A-1	Y	370	88	1.9
A-2	Y	1050	55	1.6
B-6	Y	300	100	-0.7
B-8	Y	450	20	4.2
G-1	Y	1100	29	4.8
B-4	N	Zero	67	21.9
B-5	N	Zero	100	18.0
C-3	N	Zero	100	26.0

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

$$W \propto \left(\frac{\mu QL}{E'}\right)^{1/4} \propto H\Delta p_{net}$$

TSO is the key factor…

Reliable data collection → **Correct** Analysis → **Skilled** planning



…but it's not easy !

Reliable data

Rock pproperties

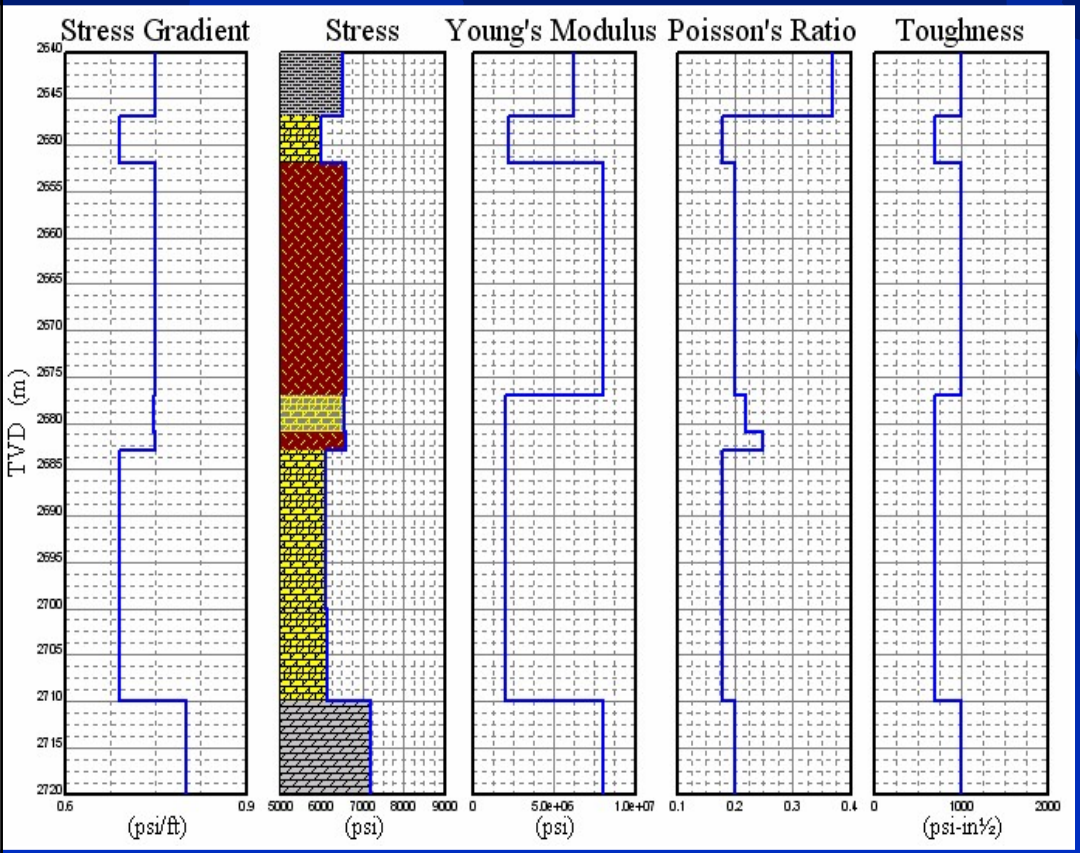
- Reliable elastic moduli
- Minimum stress direction
  - Imaging fracture
  - Oriented Cores
    - Velan
    - ASR

Leak off data

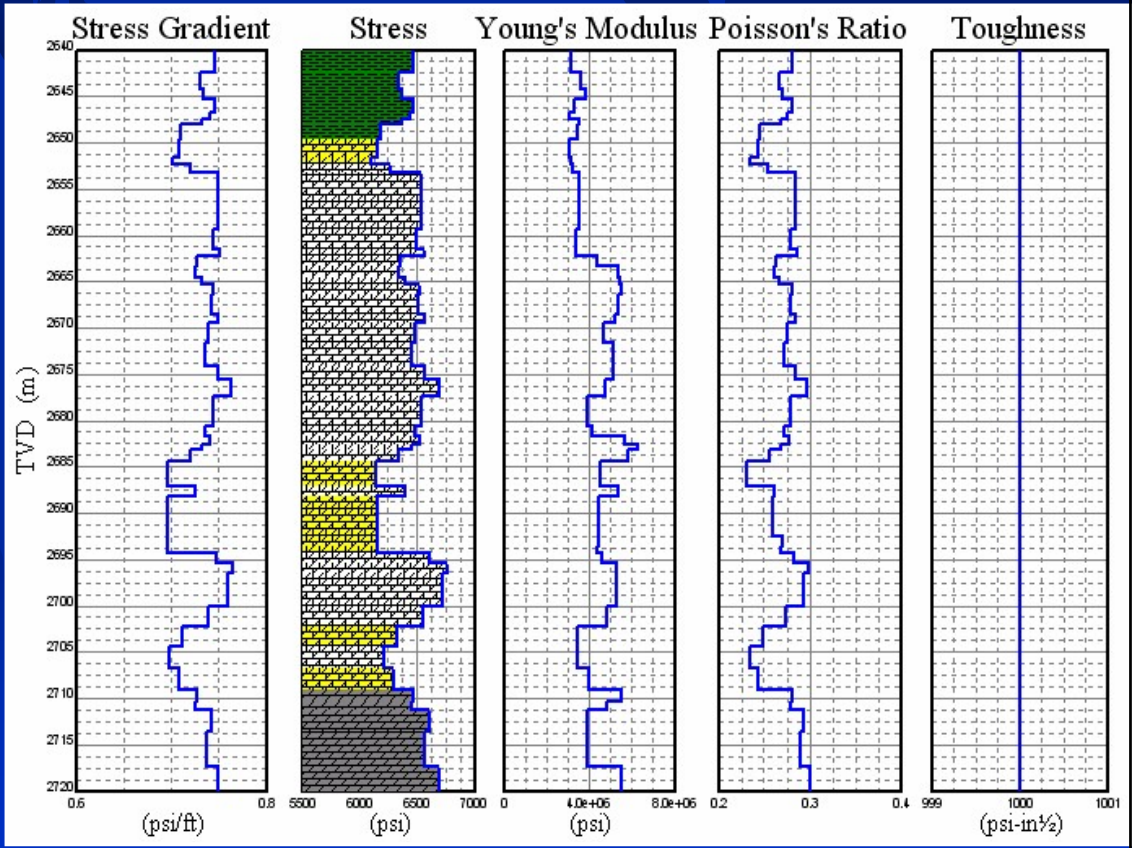
- Calibration test
  - Surface pressure x BHP
  - Live annulus pressure
  - On site analysis

Elastic Moduli

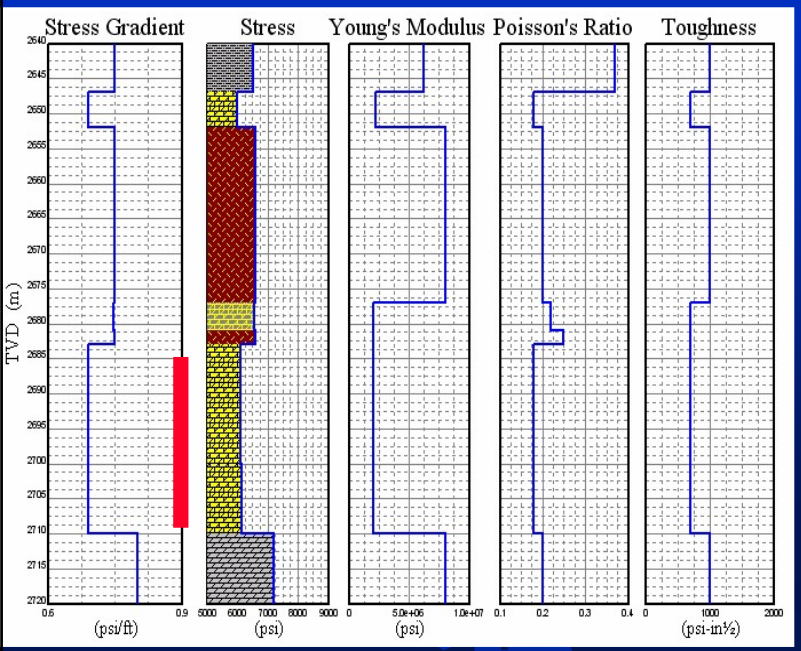
Simplified Model



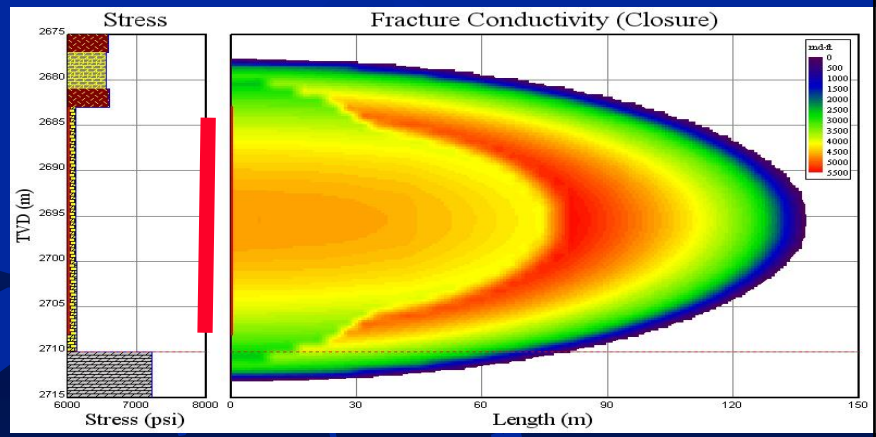
"More realistic" Model

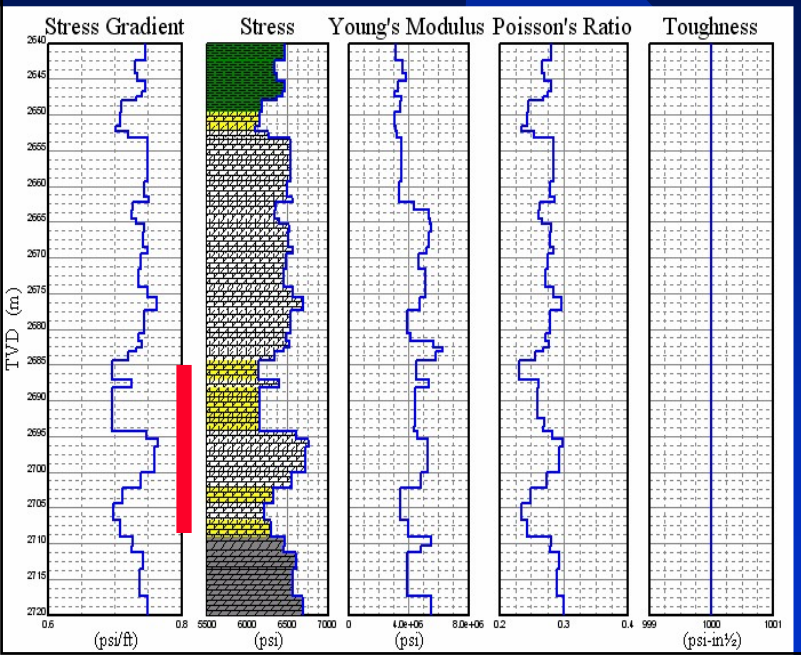


Usual simplifications → Probable results

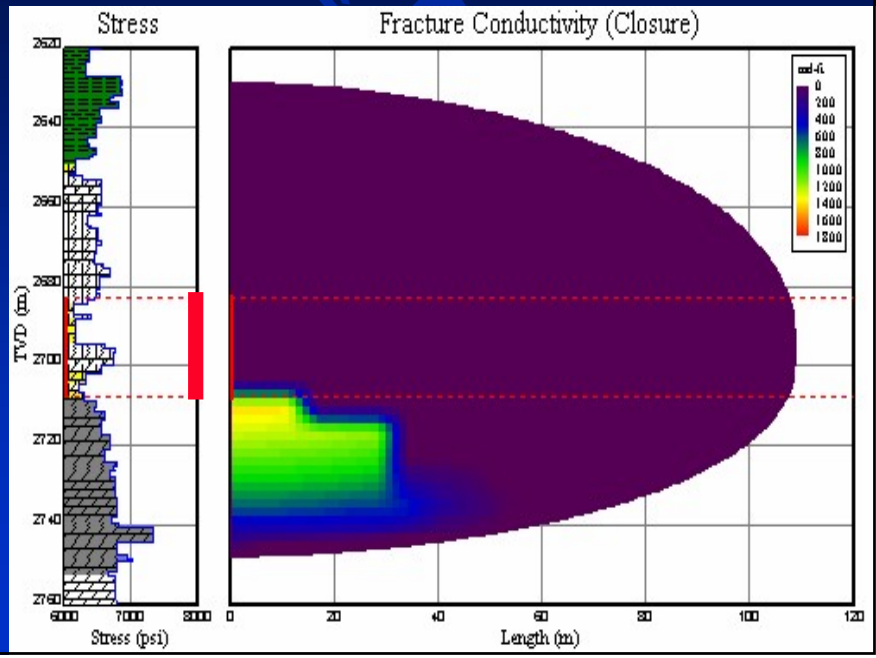


"Planned" Fracture



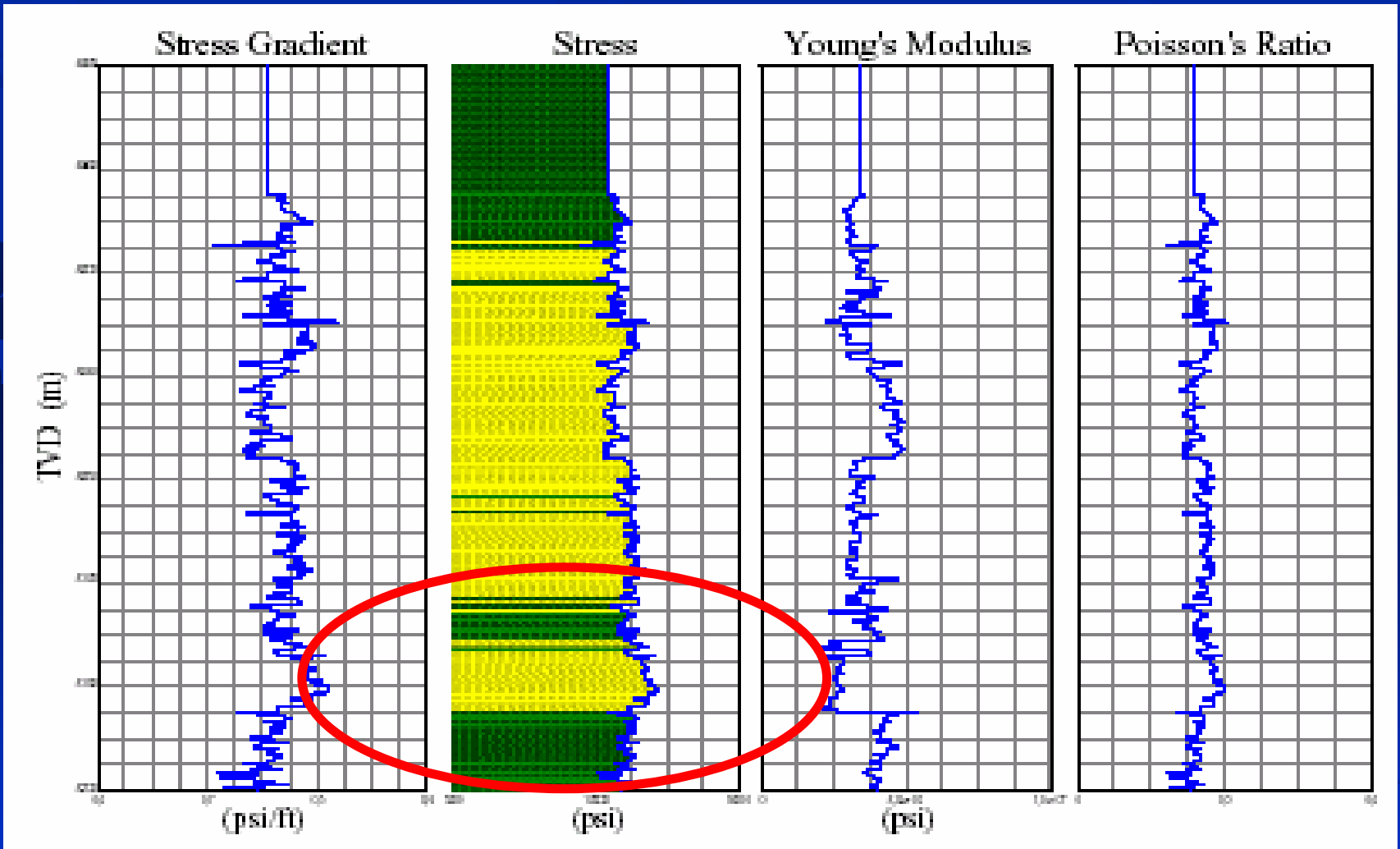


Obtained Fracture



Elastic properties With…Inverted stress

Good Data !!!



Reliable data

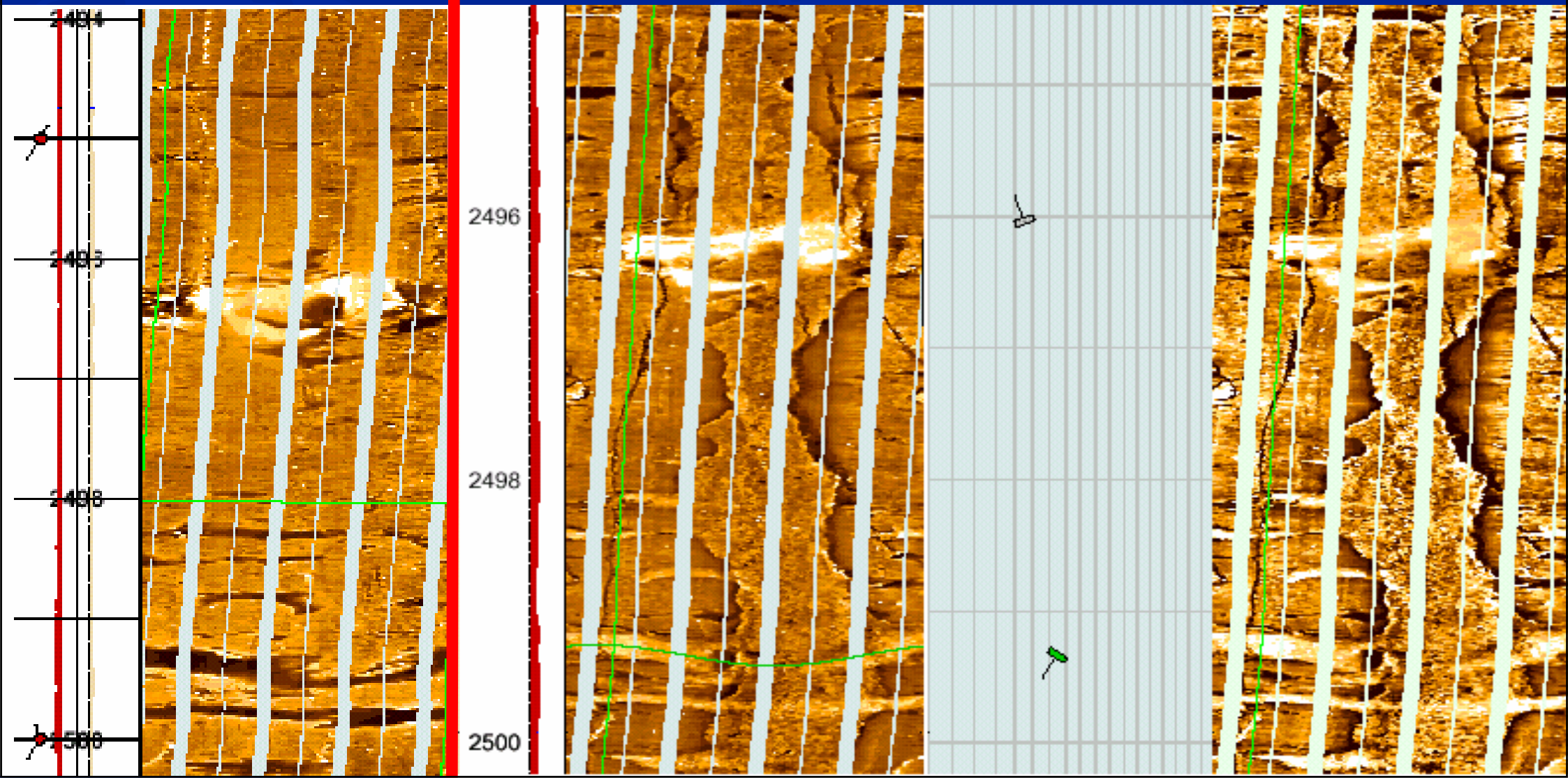
- **Reliable elastic moduli**
- Minimum stress direction
  - Imaging fracture
  - Oriented Cores
    - Velan
    - ASR
- Calibration test
  - Surface pressure x BHP
  - Live annulus pressure
  - On site analysis

Cross Dipolar Sonic Log

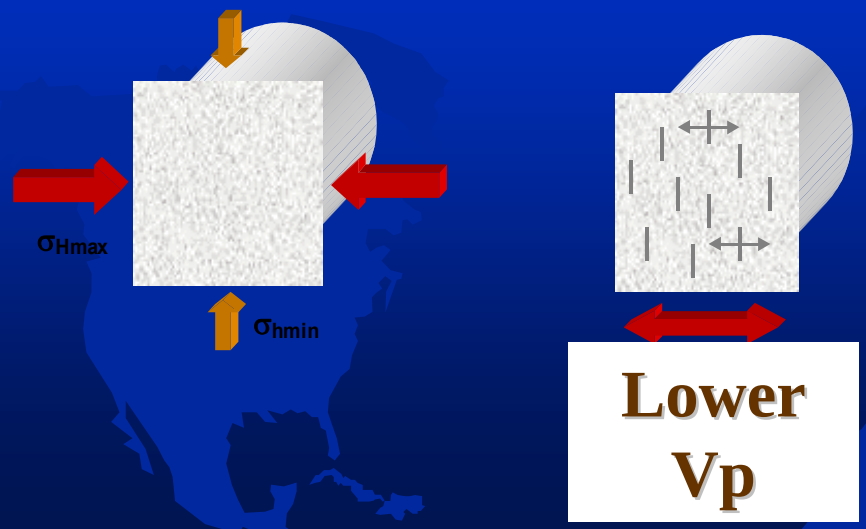
Minimum stress direction

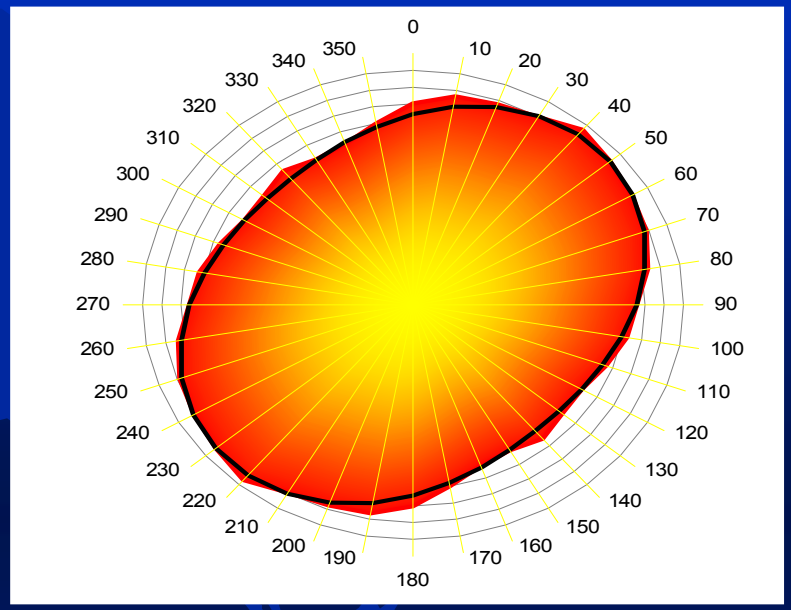
Before

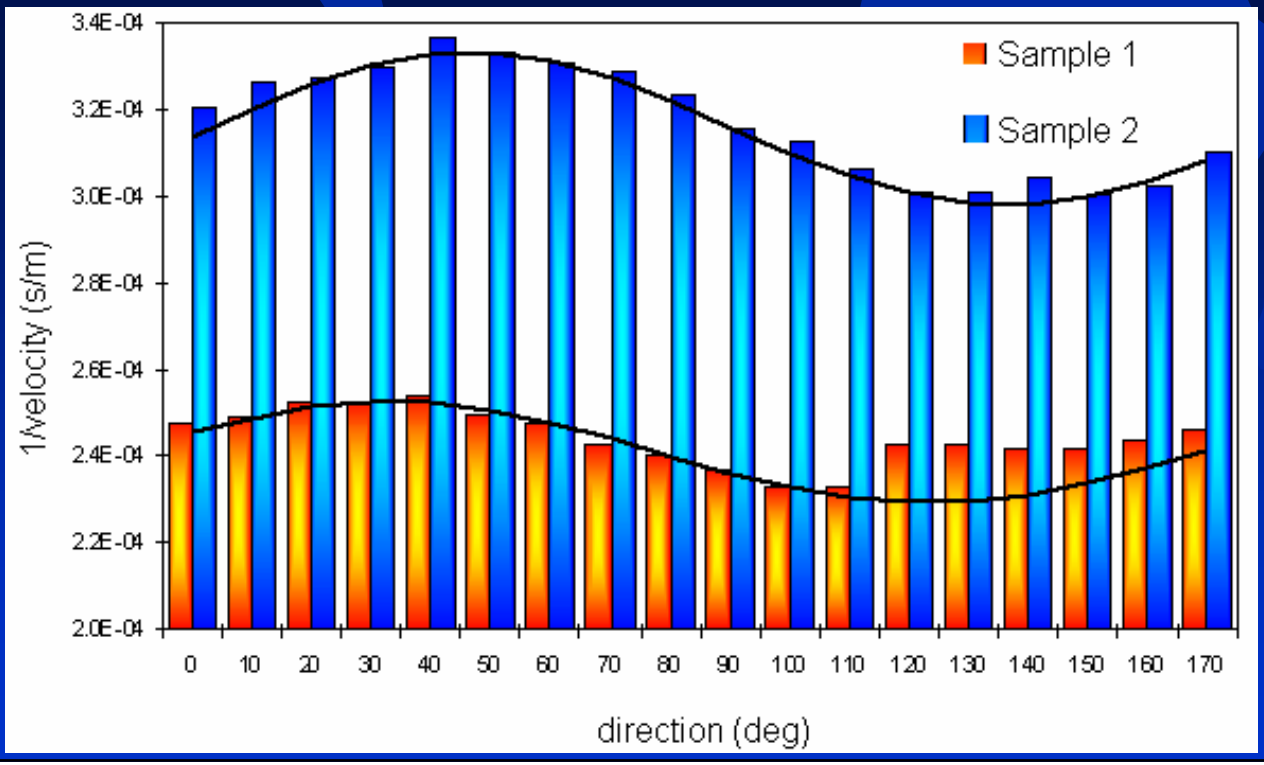
• Imaging after XLOT

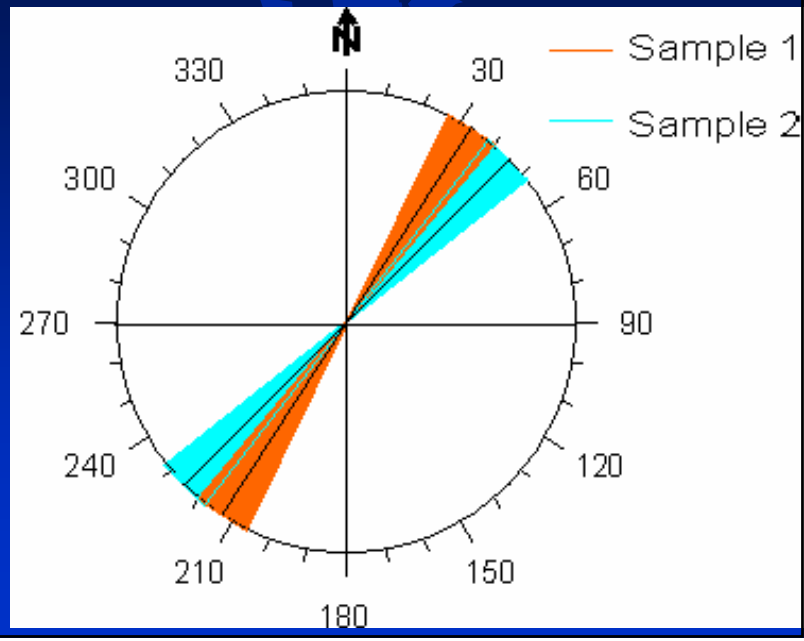


VELAN - Velocity Anisotropy

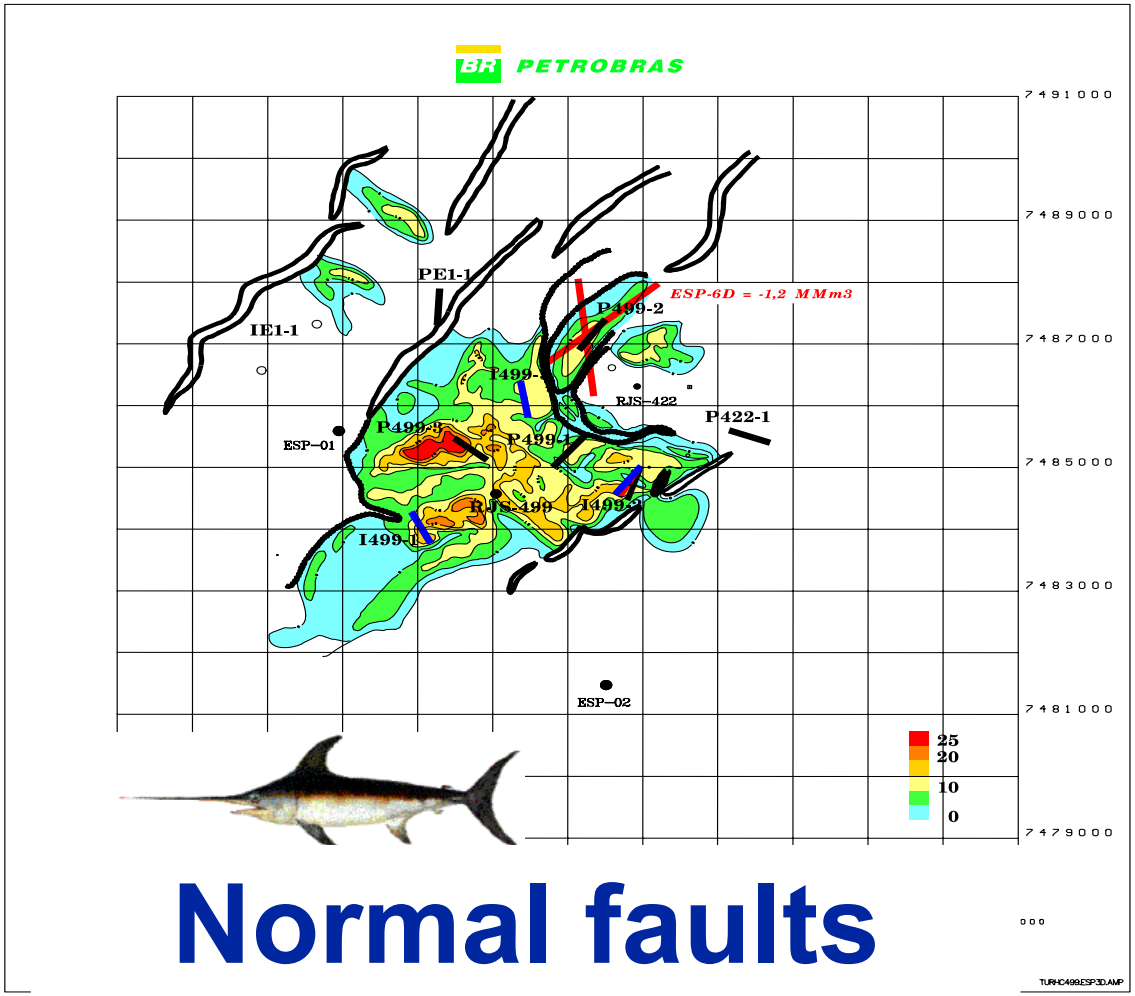






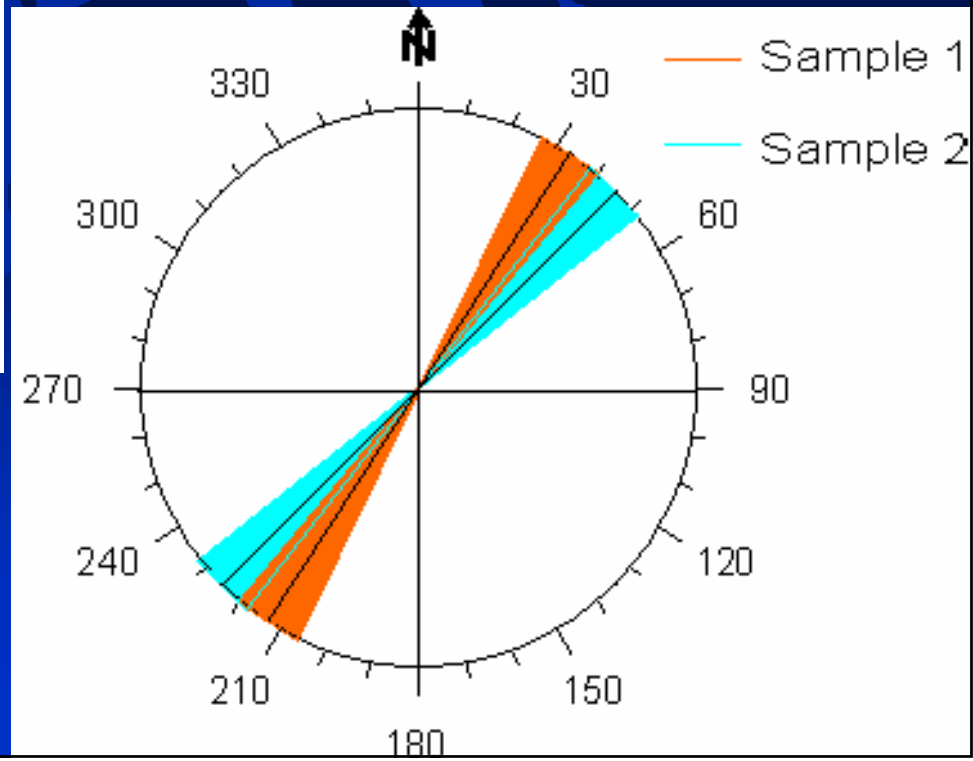


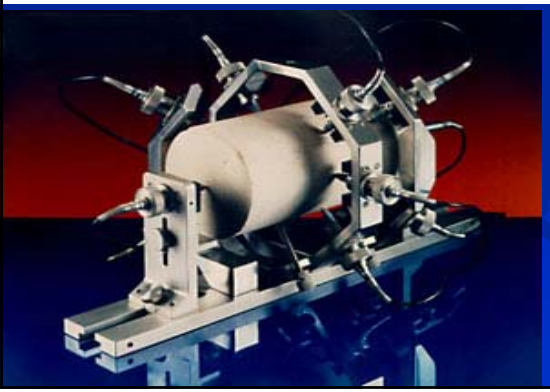
Minimum stress



Normal faults

Velan





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, <u>with BHP</u>, 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

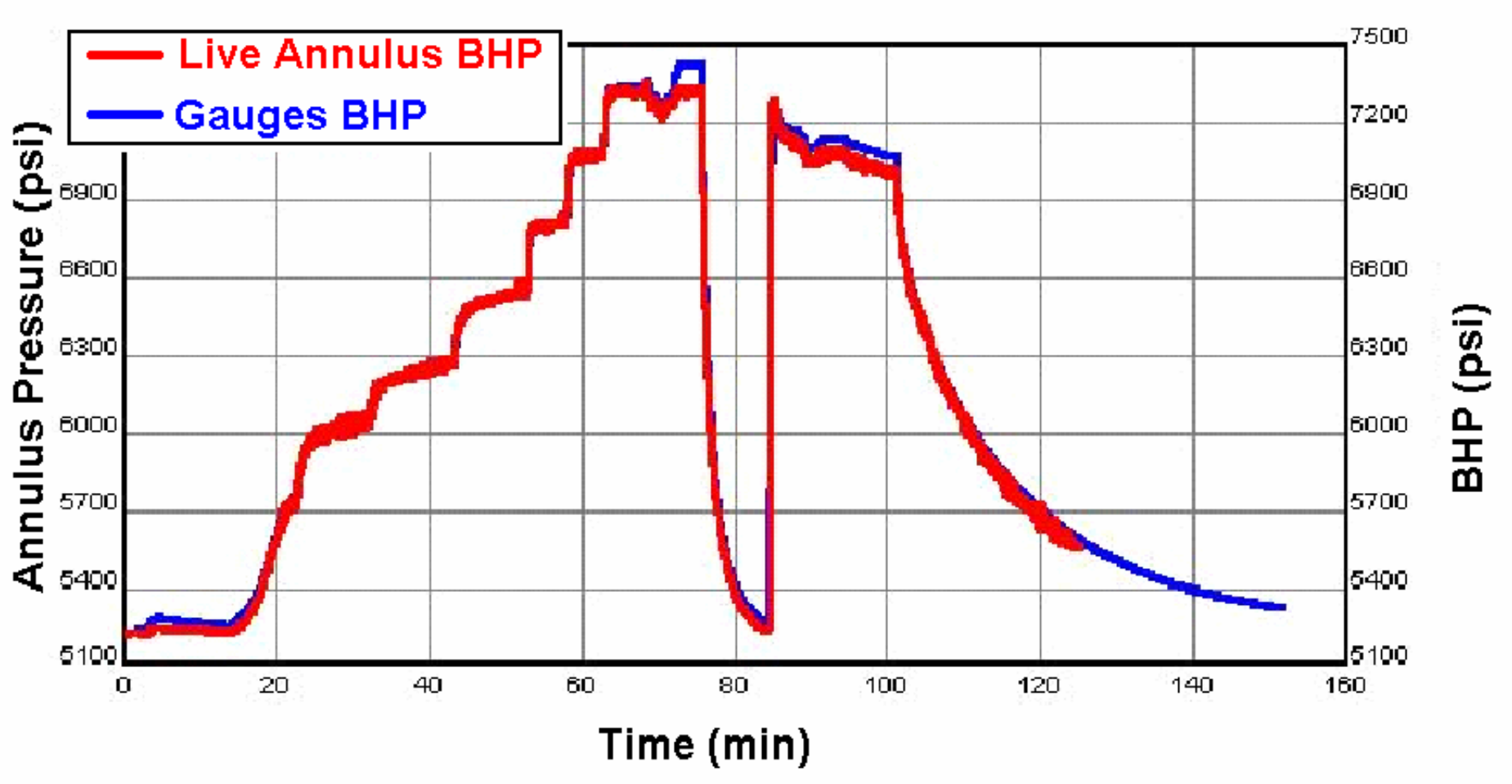
Analysis	Pc (psi)	Tc (min)	cw (*)	ef (%)
Minifrac	5118	2,05	0,0145	15,5
SRT	5113	4,61	0,0068	22,5

Minifrac Analysis
Importance of BHP for high permeability

Well	Surface data (DP) Tc (min)	Ct ft√min	Ef %	BH data Tc (min)	Ct ft√min	Ef %	Error %
A-2	0.90	0.048	6.6	0.26	0.091	2.7	**-59.1**
A-6	0.13	0.086	2.7	0.20	0.046	3.3	**22.2**
A-1	1.23	0.073	13.1	0.64	0.213	5.6	**-57.3**
A-7	0.12	0.093	1.7	0.56	0.062	6.8	**300.0**
A-5	0.43	0.018	7.0	1.18	0.025	8.1	**15.7**
A-4	5.06	0.004	22.7	5.92	0.002	24.4	**7.5**
A-3	13.42	0.003	38.9	13.54	0.004	40.1	**3.1**

Live Annulus Data

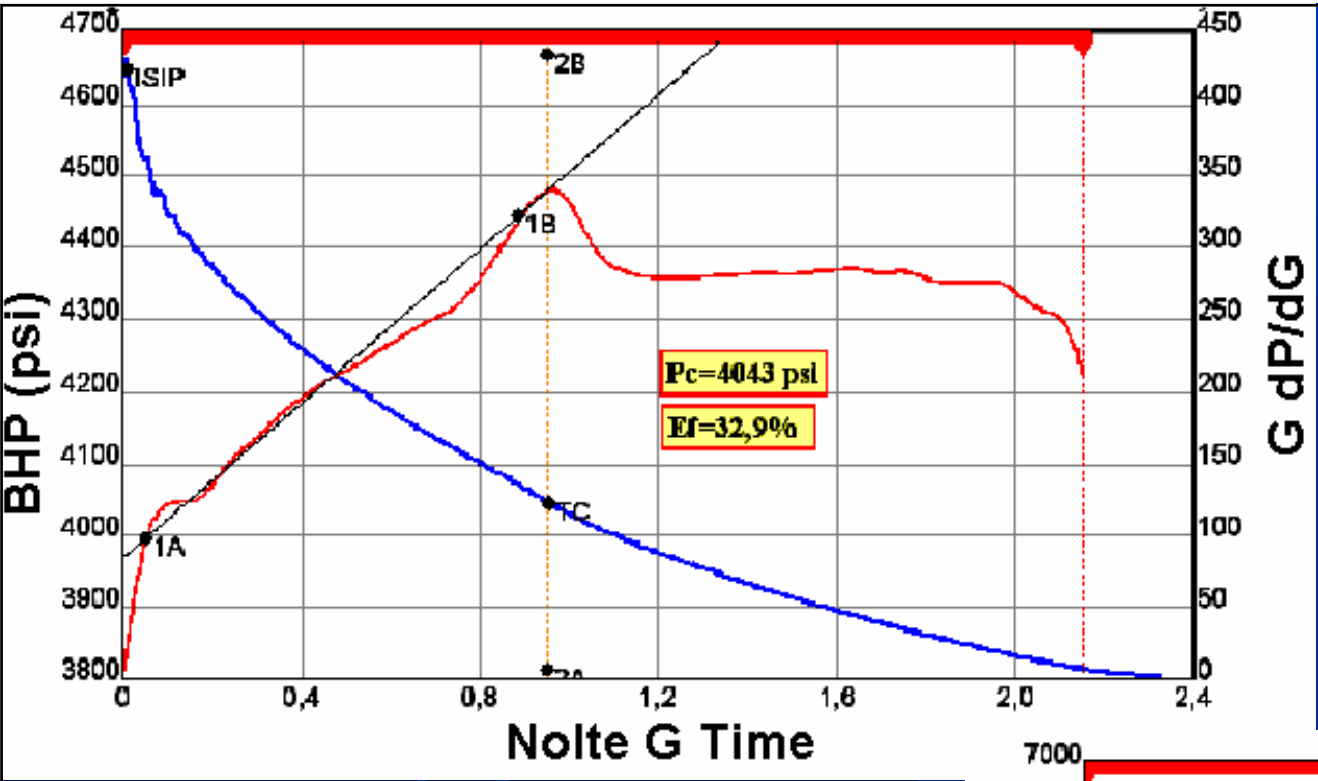
- **BHP data from live annulus is very close to BHP data from electronic gauges**

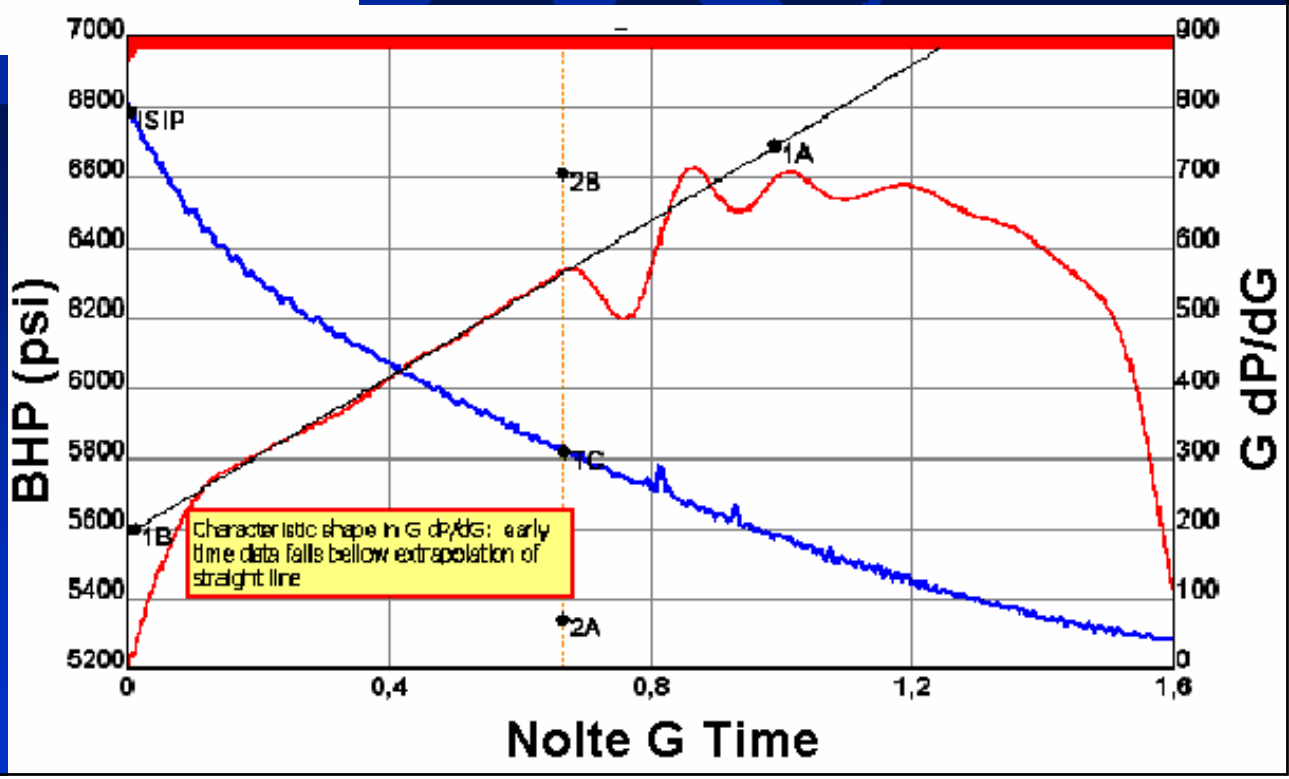


Non ideal pressure decline in soft rock

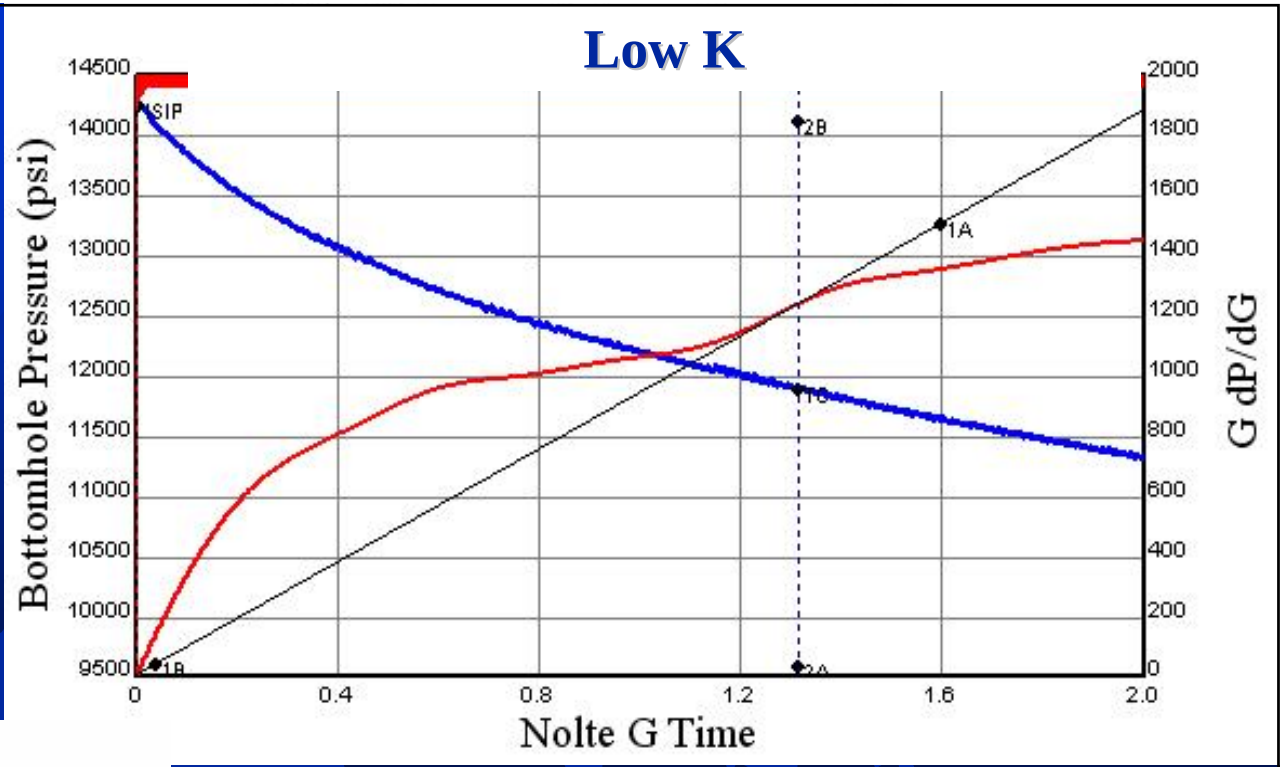
- Tip extension
- Pressure dependent leak off
- Height recession

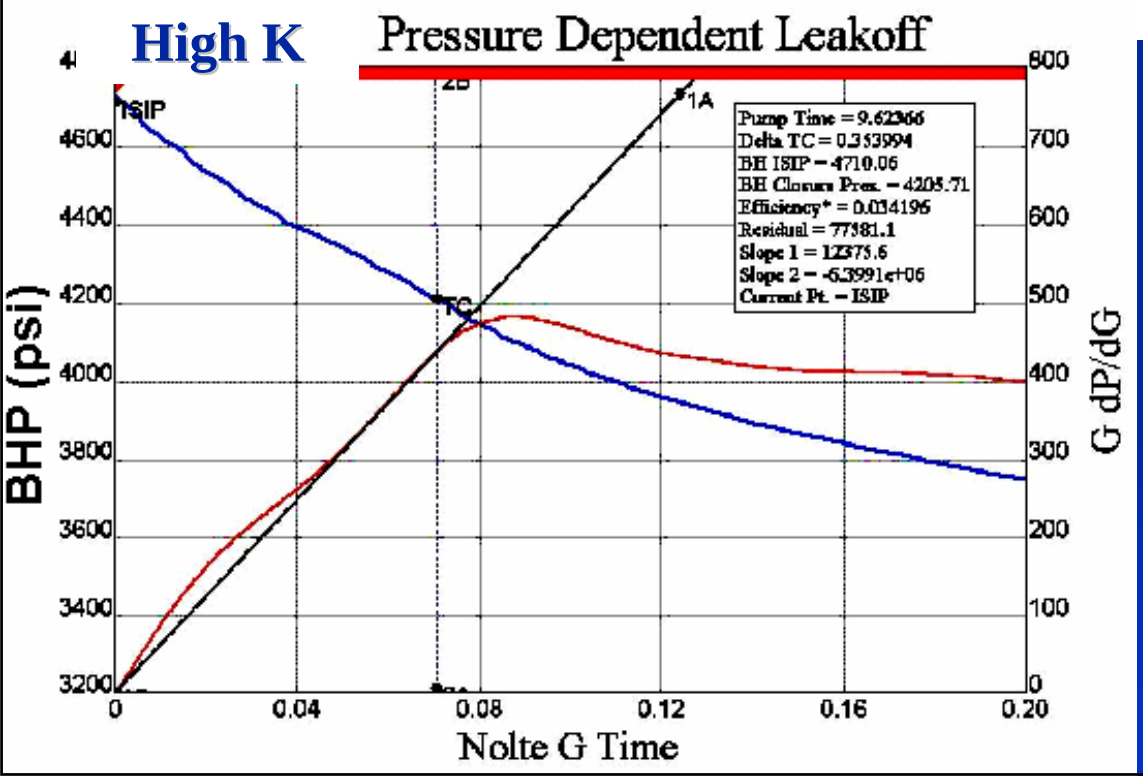
Tip Extension





Pressure Dependent Leakoff

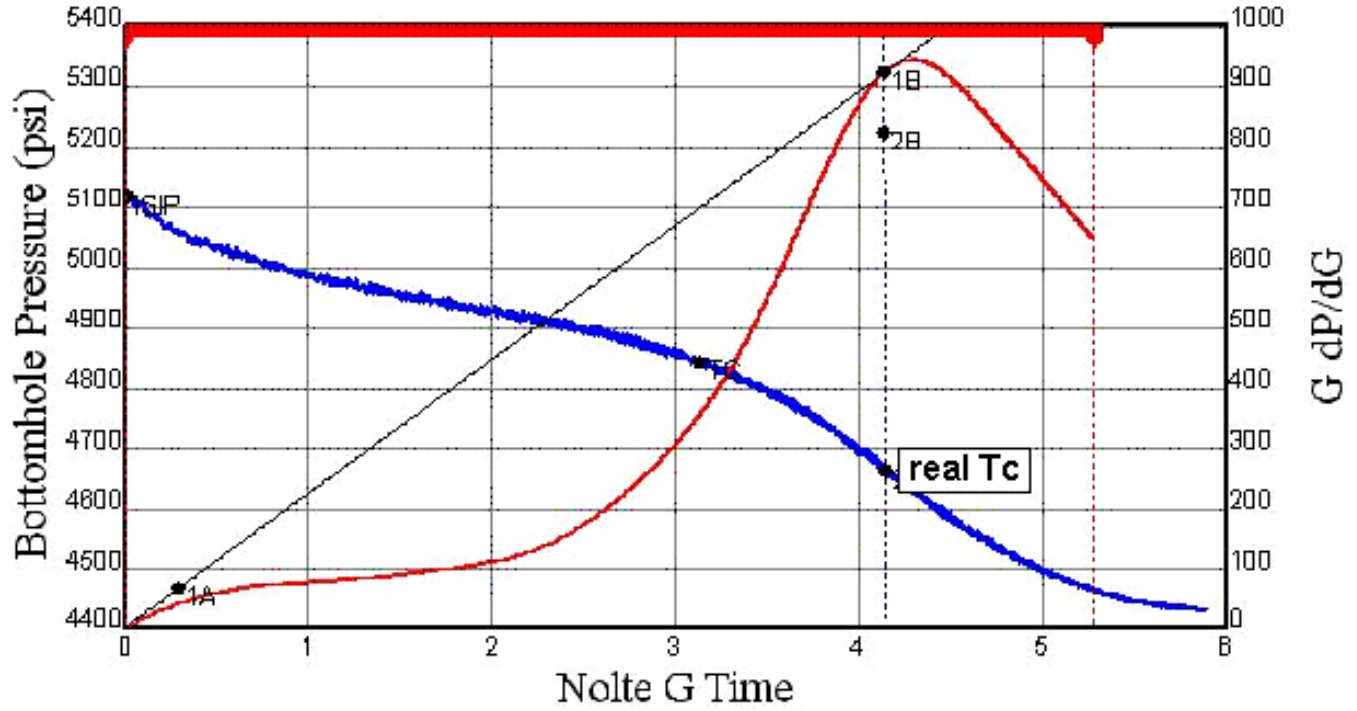


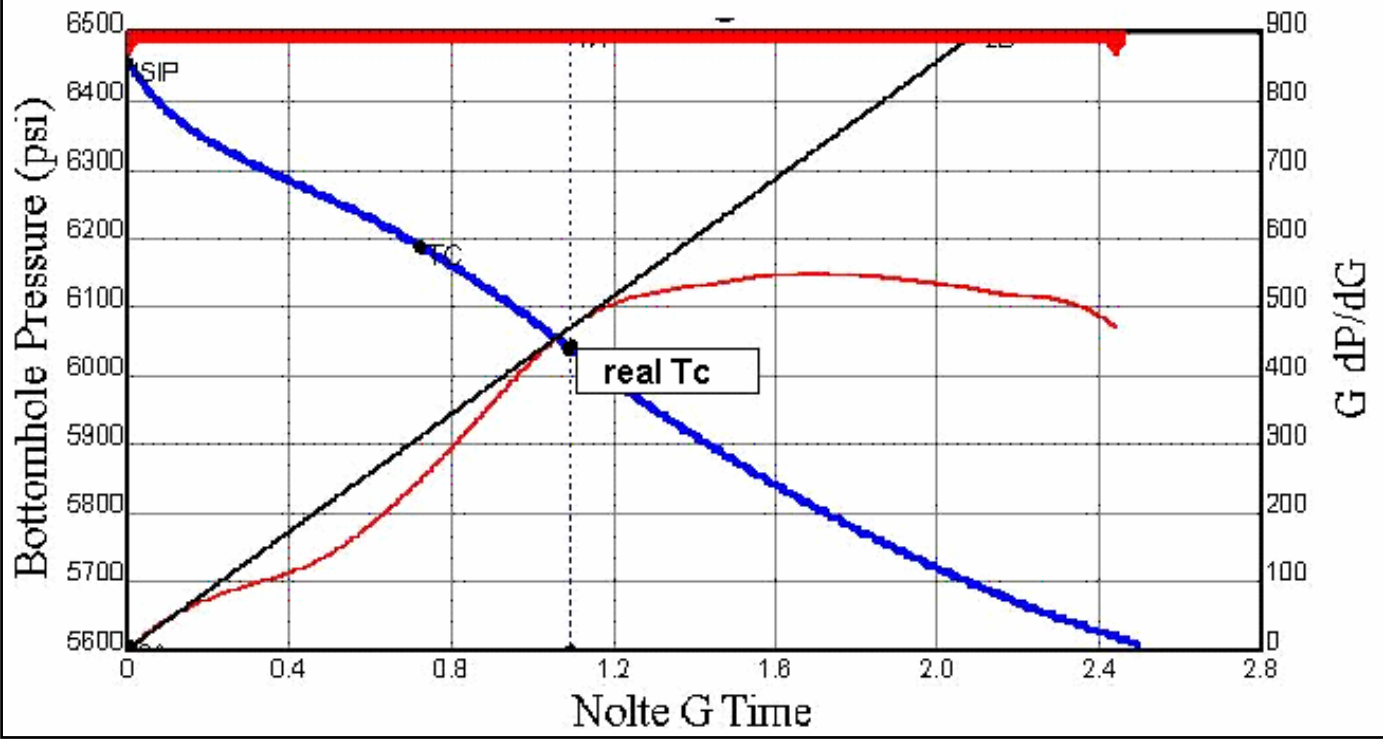


Low K

High K

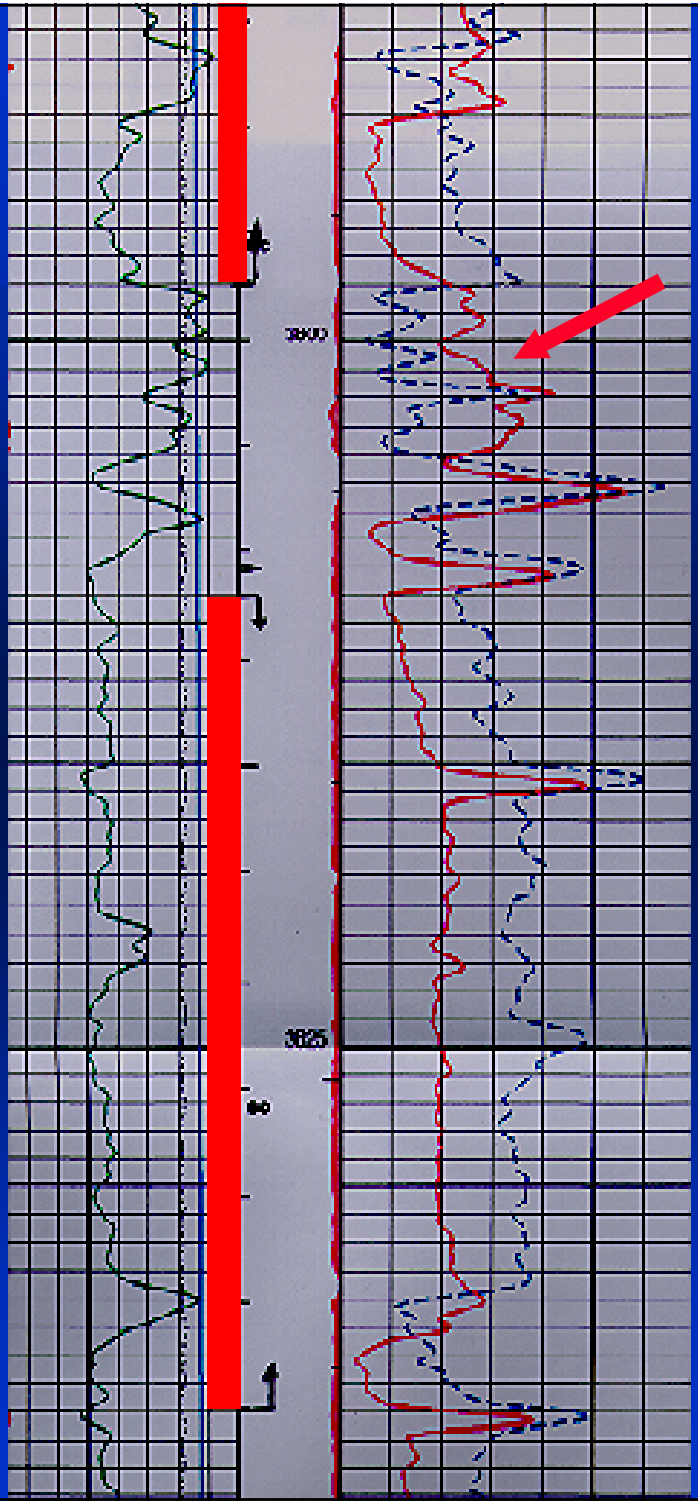
Height Recession

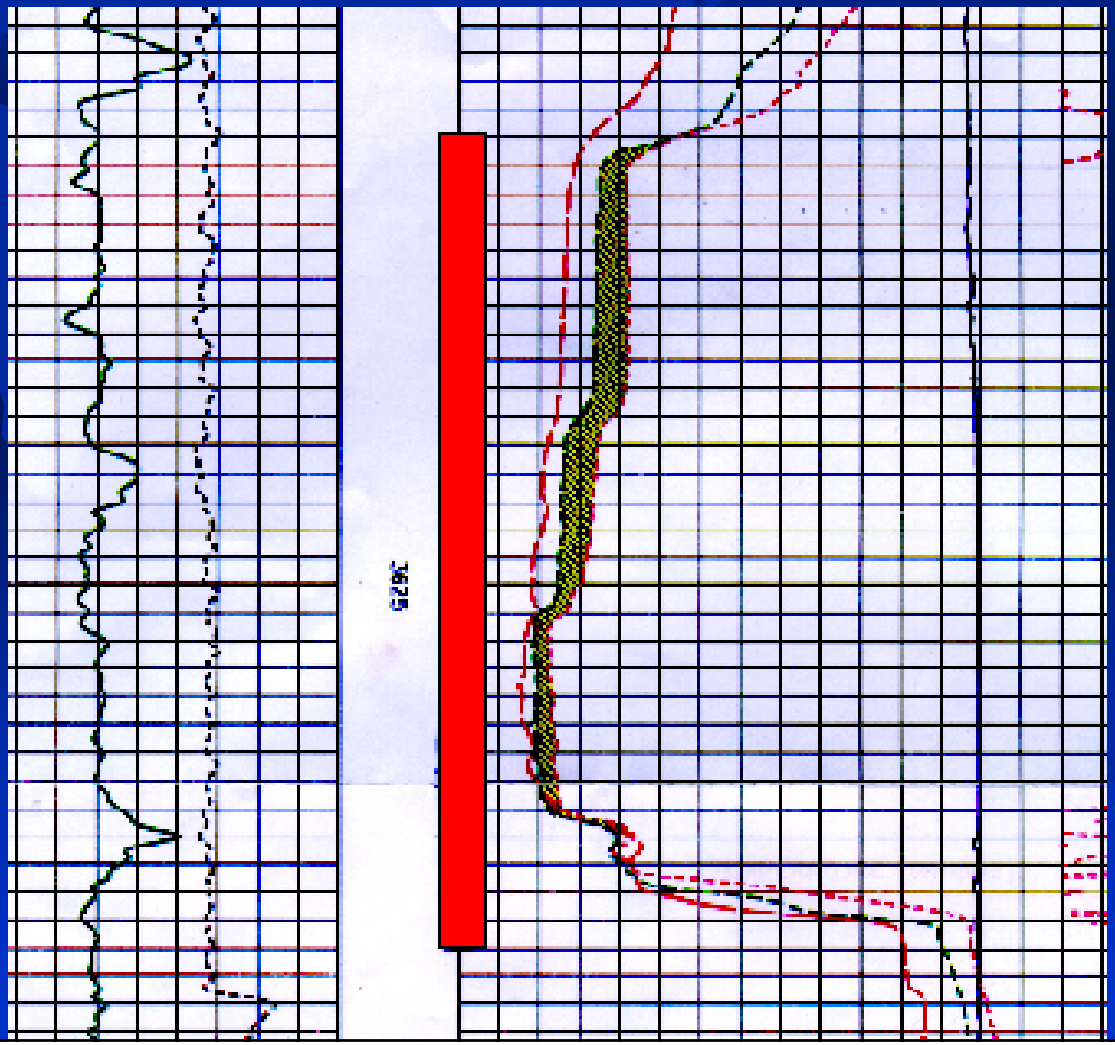




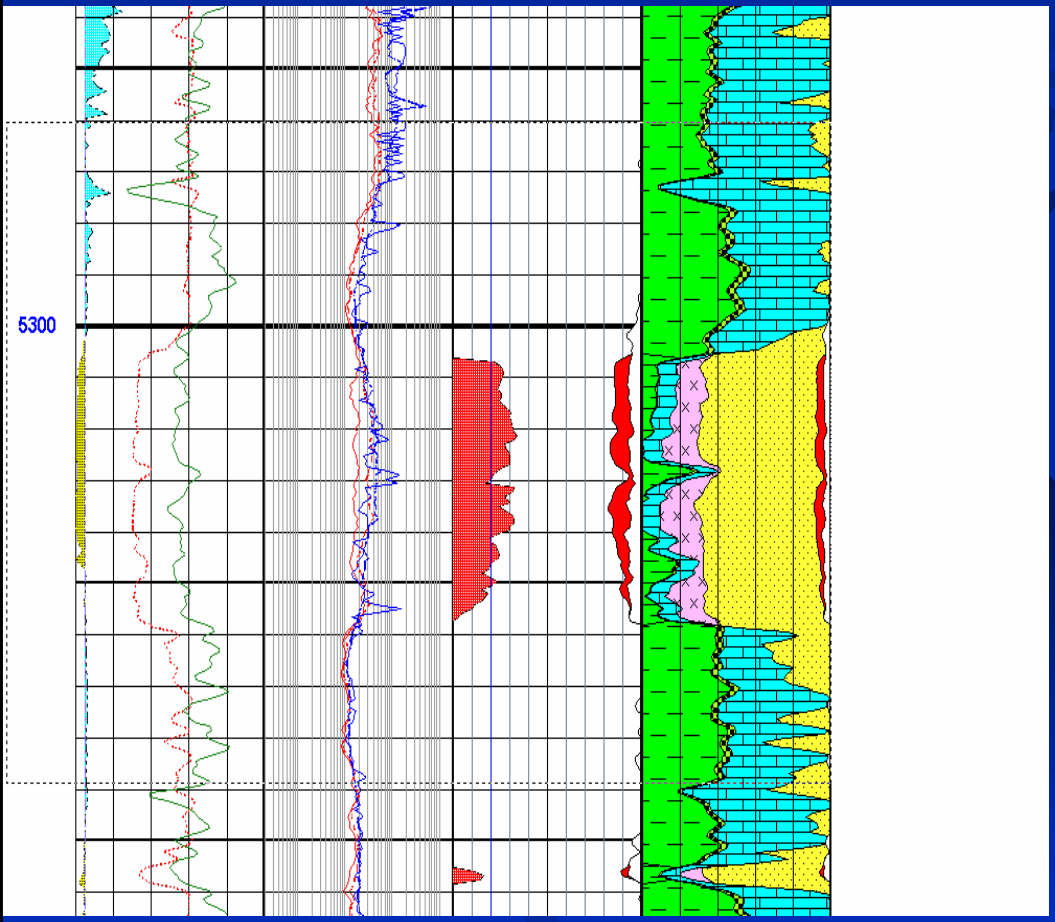
Height grow

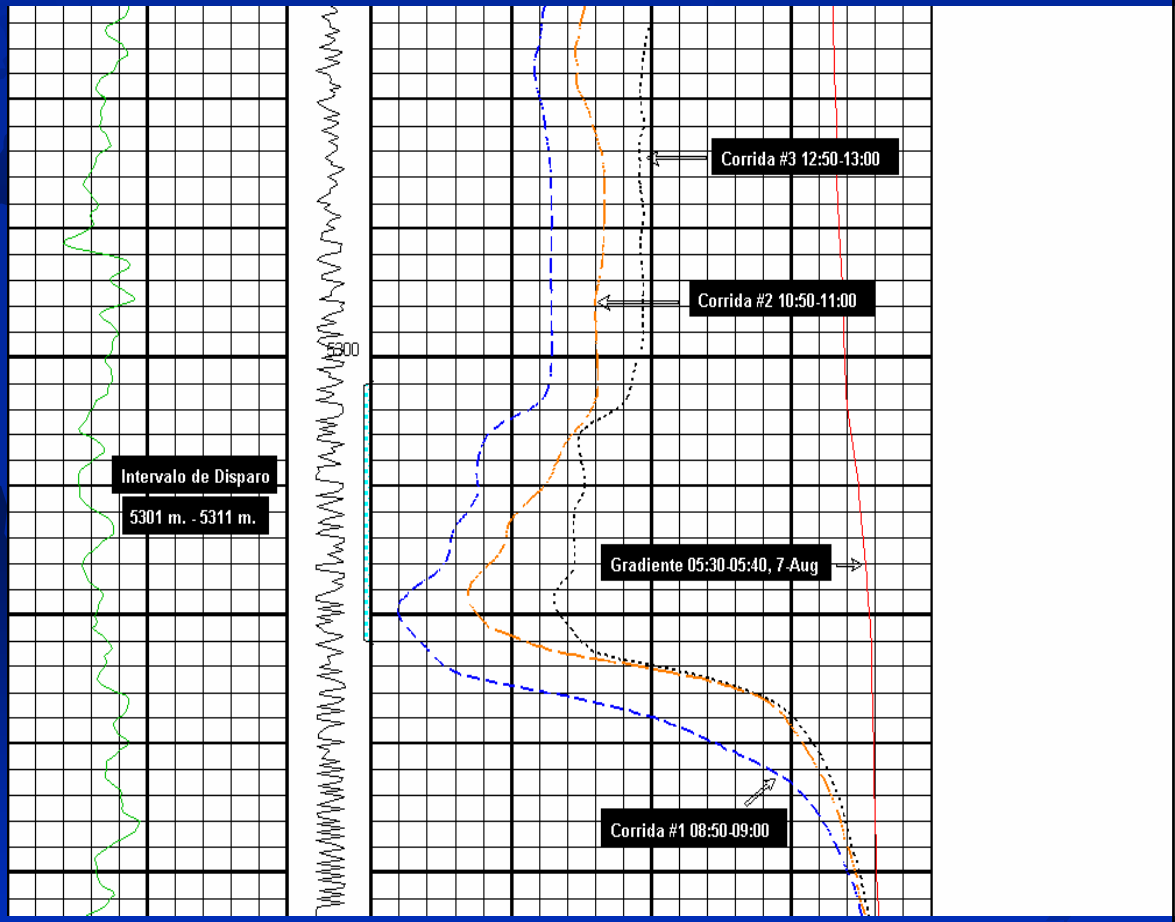
Temperature logs





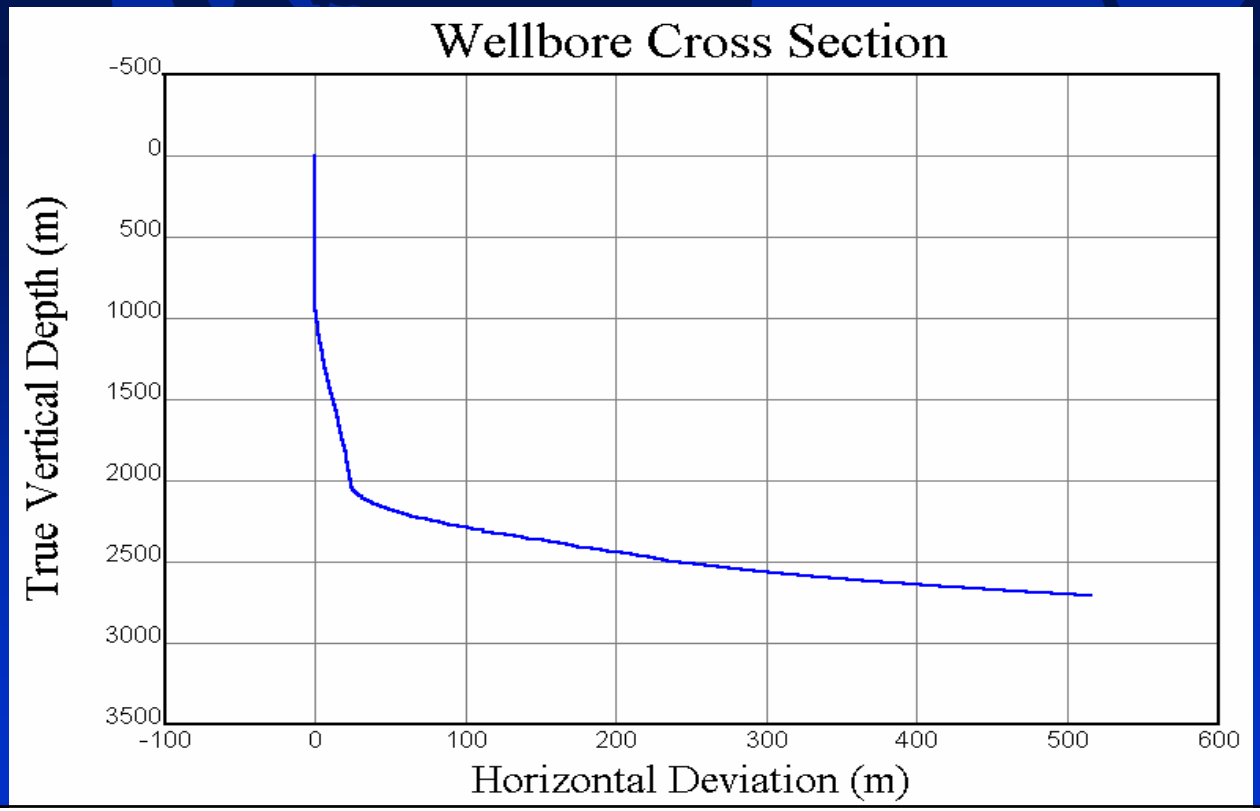
Temperature Logs

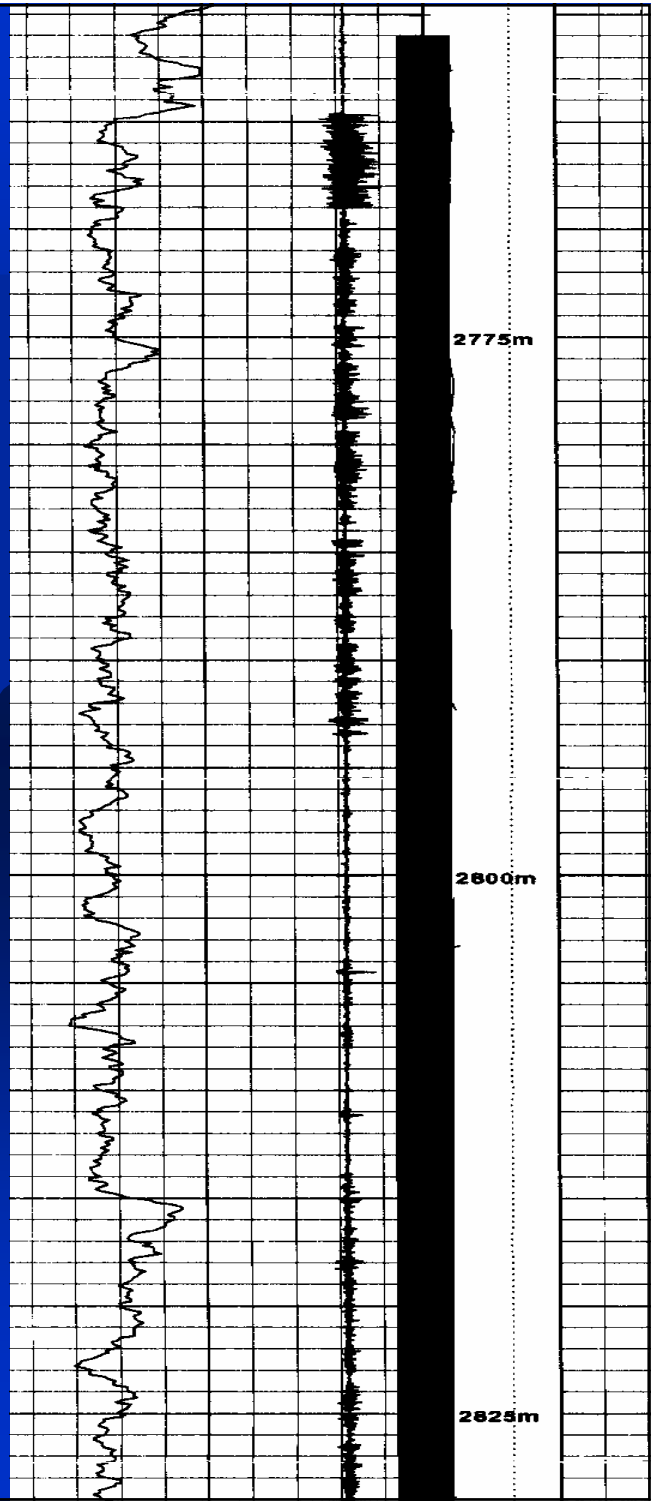




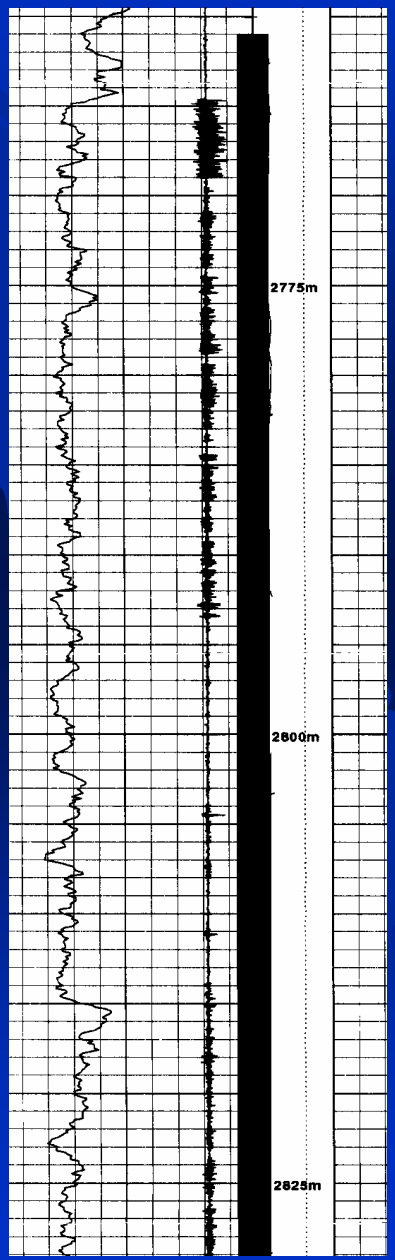
Thick, deviated interval

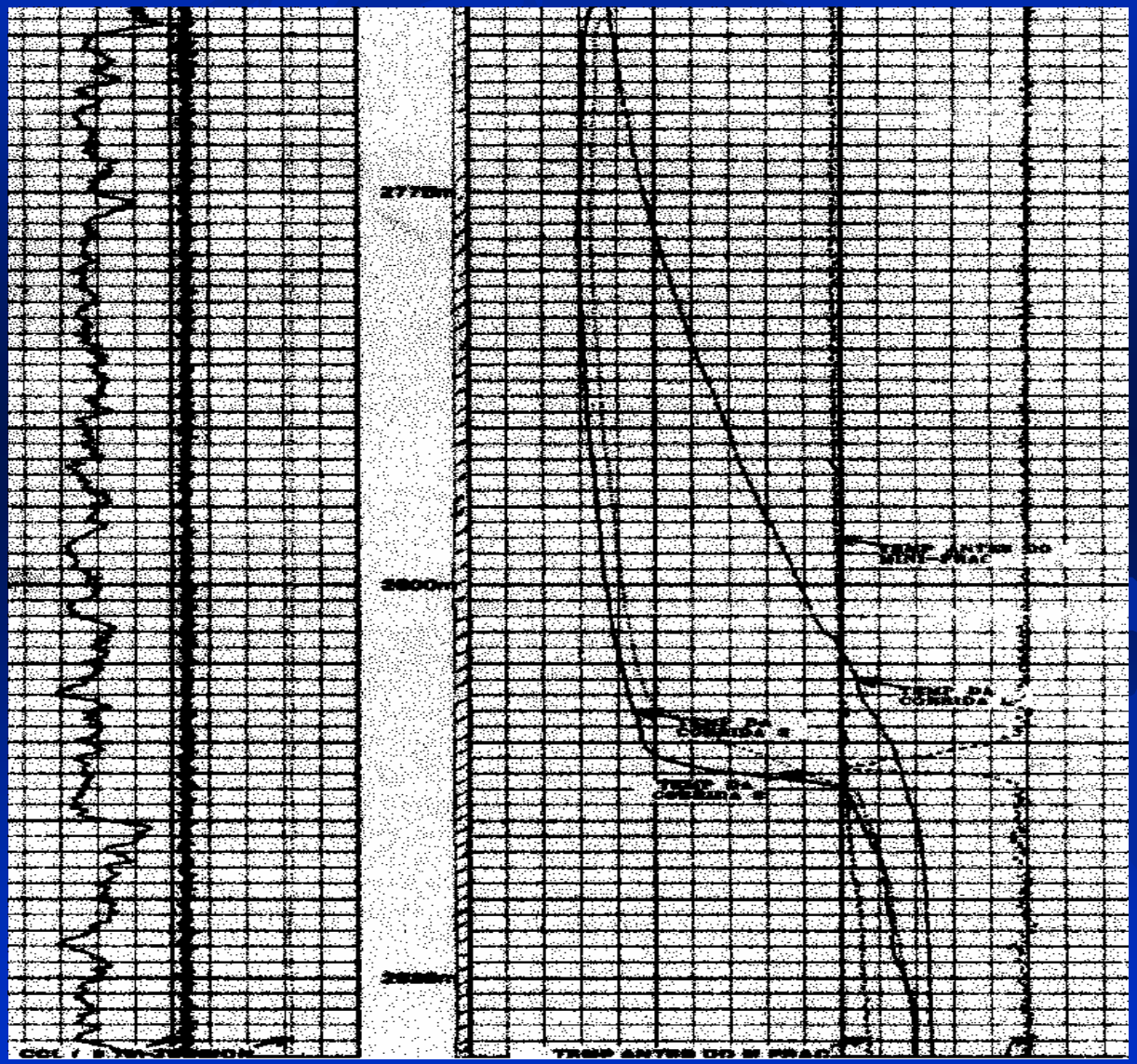
- Perforation: 2761-2830 (69m)
- Inclination: 64º
- Net pay: 30.5m
- Limited entry perforation prior to mf
- Minifrac: 25 bpm





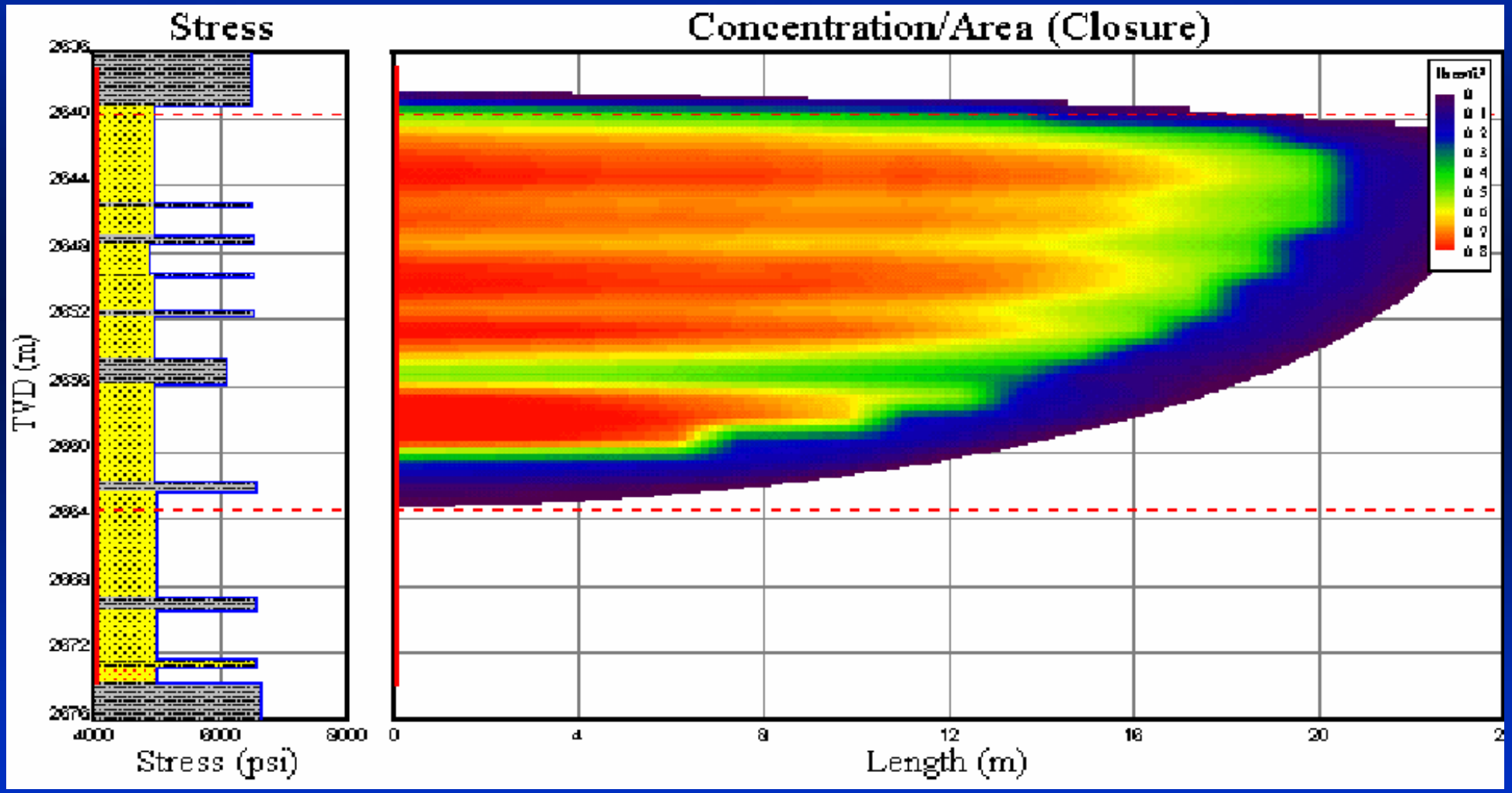
Thick, deviated interval





Correct analysis helped by temperature log

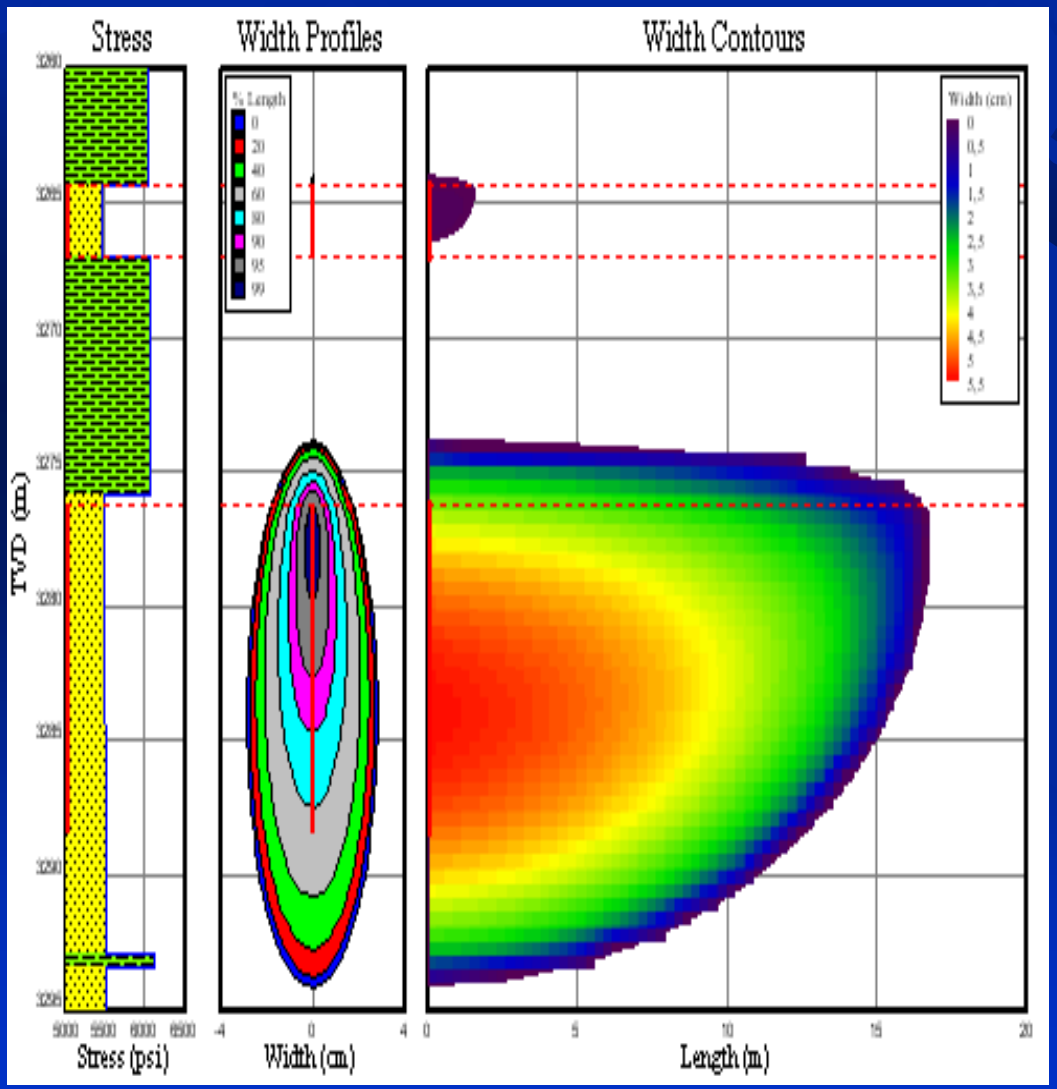
Thick, deviated interval

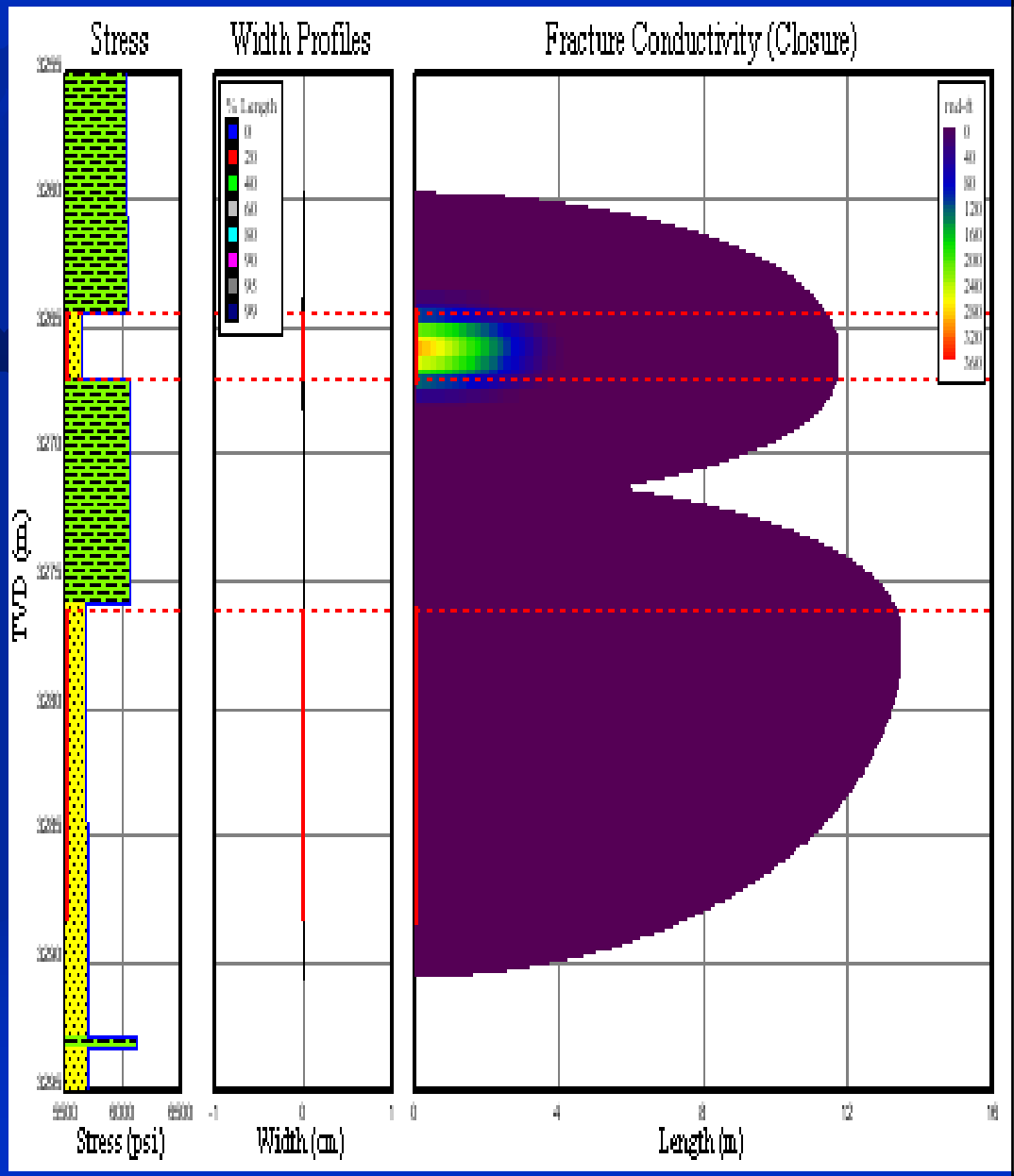


Skilled design

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

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

Well	TVD (ft)	Fluid	DR	[Prop]
I-1	16.4	Gel	3.3	10
G-12	17.7	Water	1.5	1
G-13	10.5	Water	1.2	1-2
J-5	16.4	Water	1.3	1-2
M-3	19.7	Water	1.7	1-2

Stress anisotropy

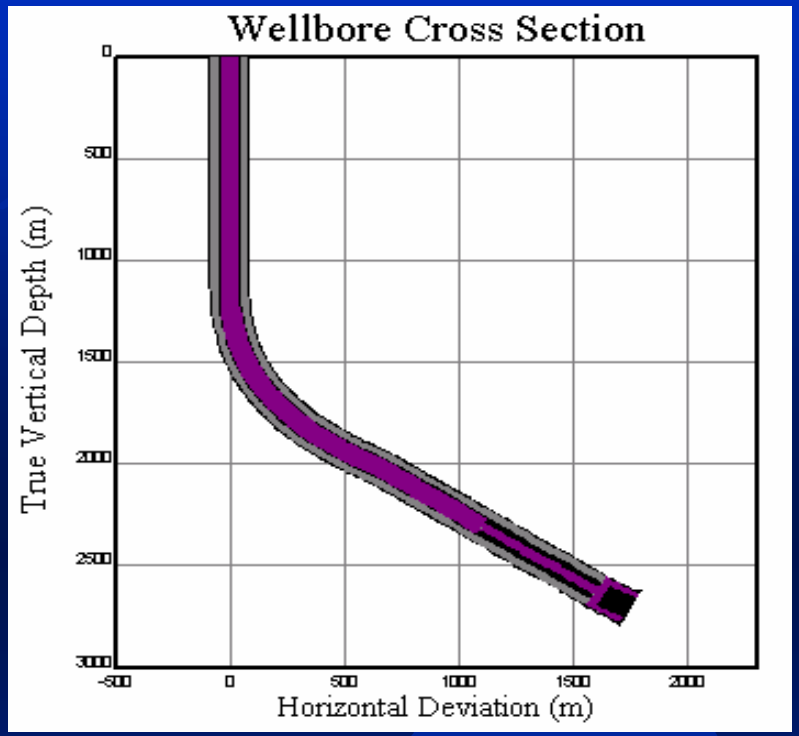
Field M-2

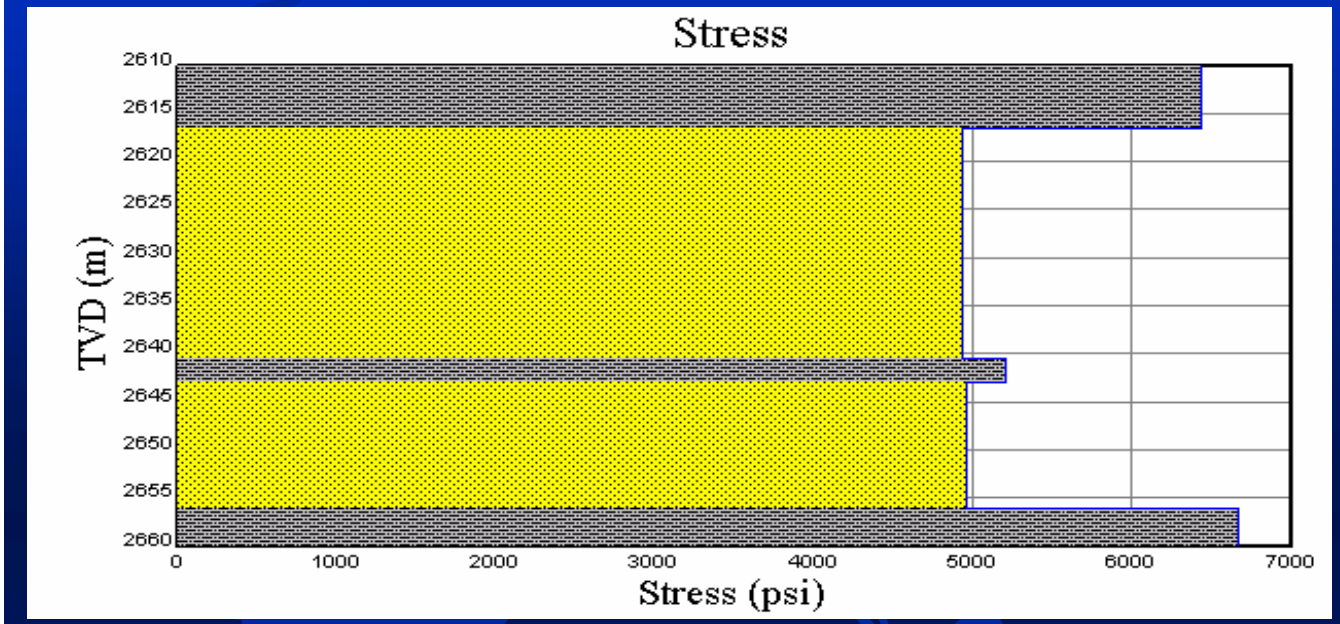
- **Completely unconsolidated**
- **Permeability > 2,000 mD**
- **UCS < 200 psi**
- **E < 400,000 psi**

→

Stress Isotropy Expected

Deviated well – 58 Grades





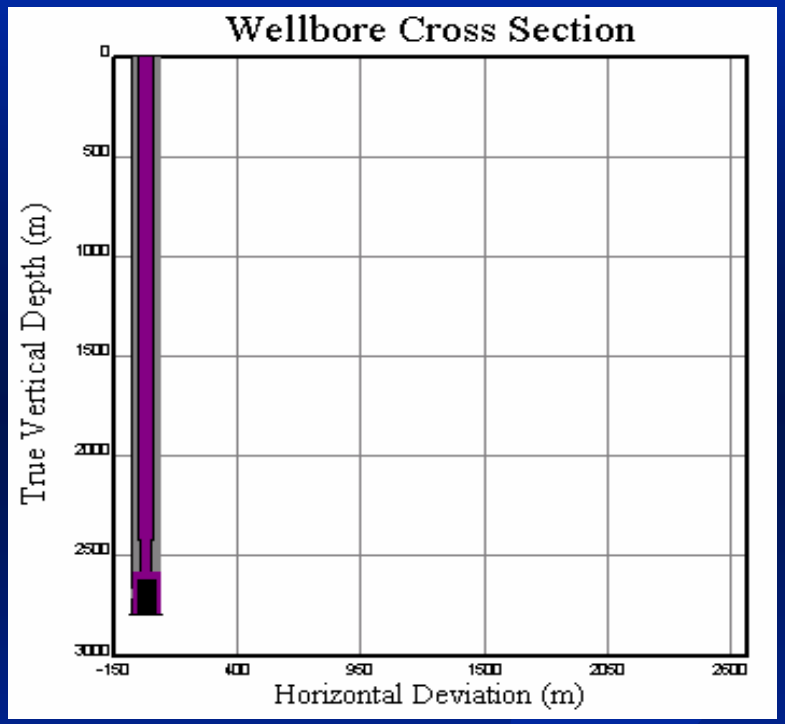
5 m shale (MD) - 2.6 m TVD

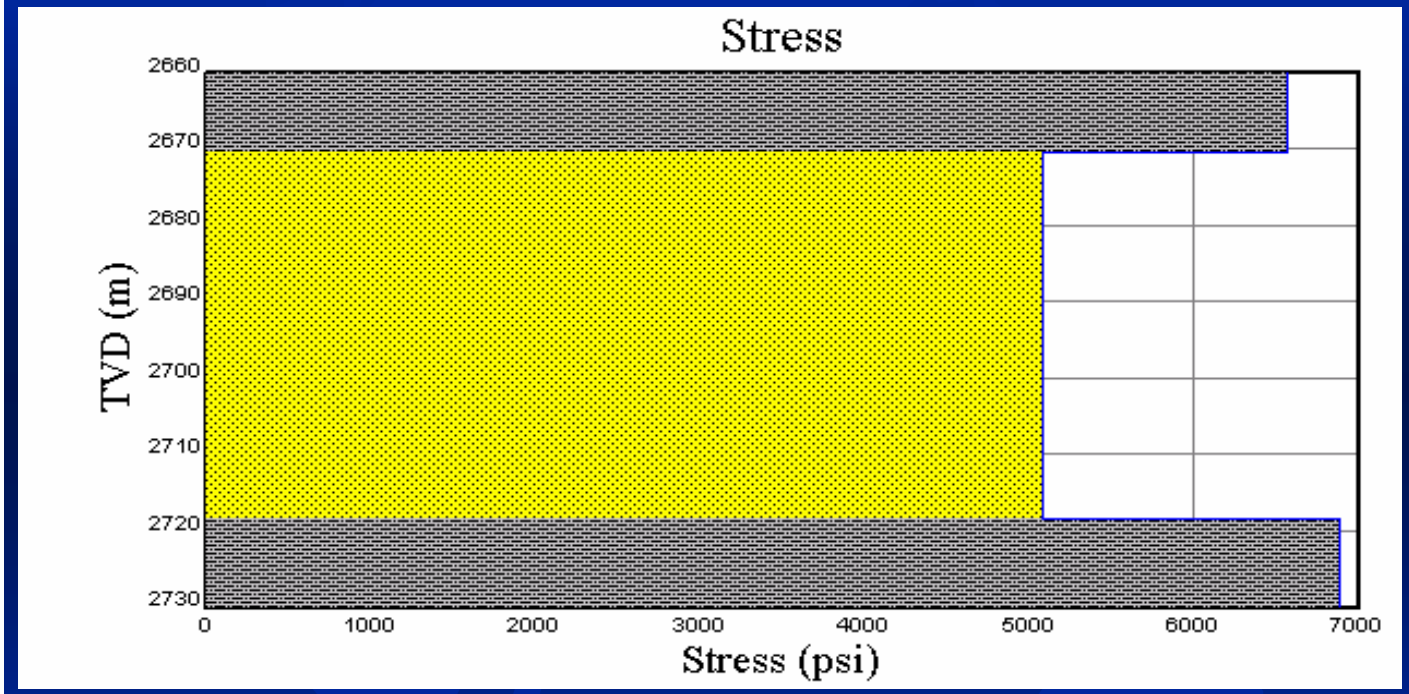
- **2 stacked fracpacks – 3470/3490 m (TVD – 2645/2656 m)**

  3435/3455 m (TVD – 2627/2637 m)

- **PI – 31 ($m^3/d/kg/cm^2$)**
- **DR – 2.9**

Vertical well



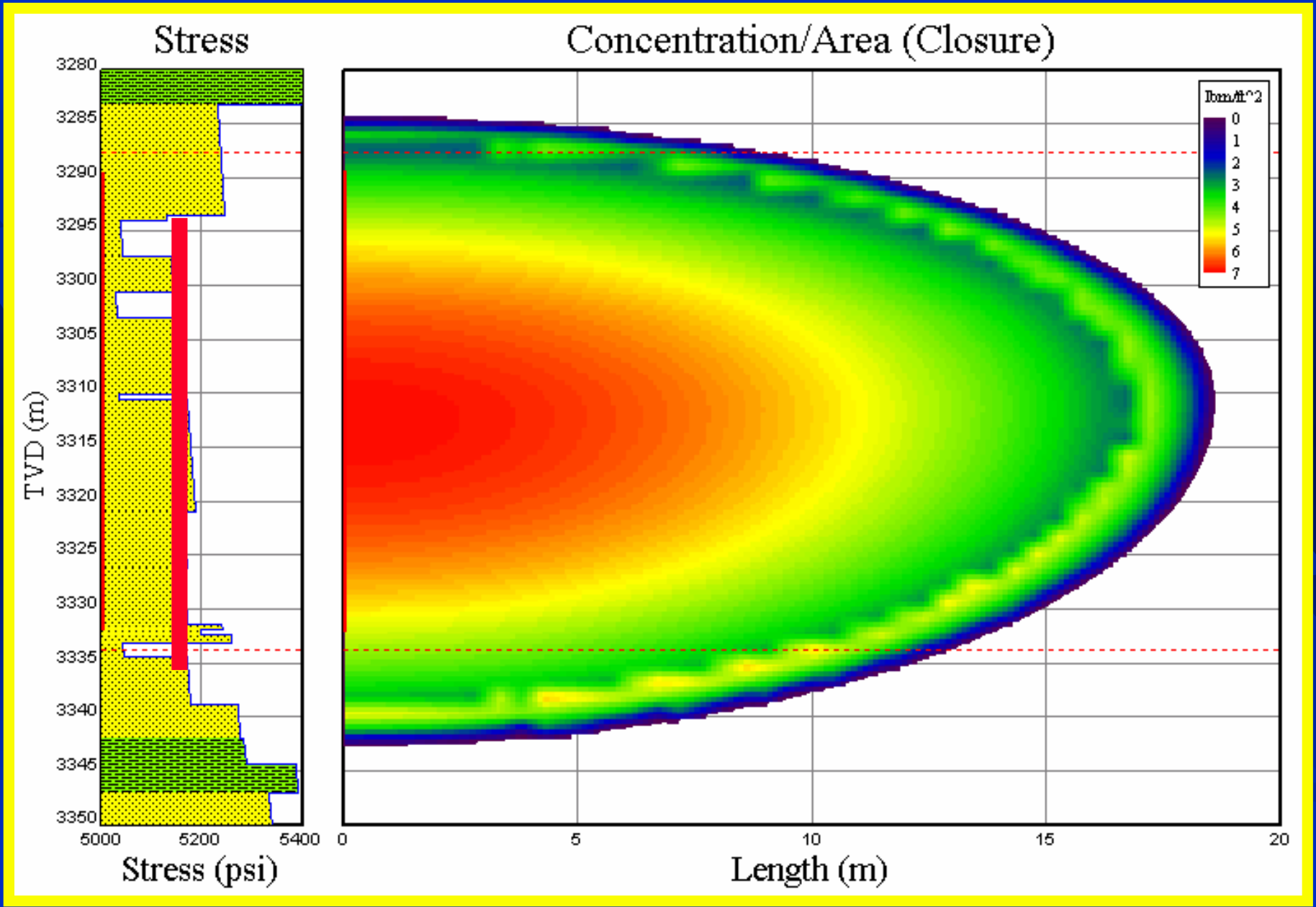


- **Interval -2671/2718 m**
- **PI – 133 ($m^3/d/kg/cm^2$)**
- **DR – 1.1**

Highly deviated well

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

Restricted Perforation



Aug/2006 → 12 operations well suceeded

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

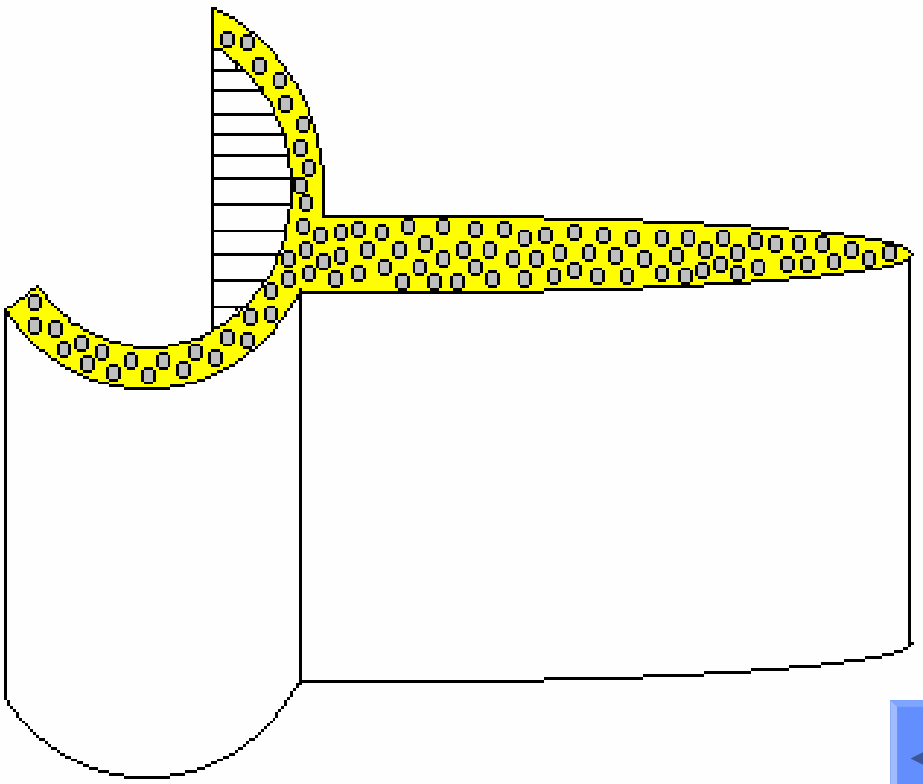
carlos.pedroso@petrobras.com.br

Phone: 55 22 99862010

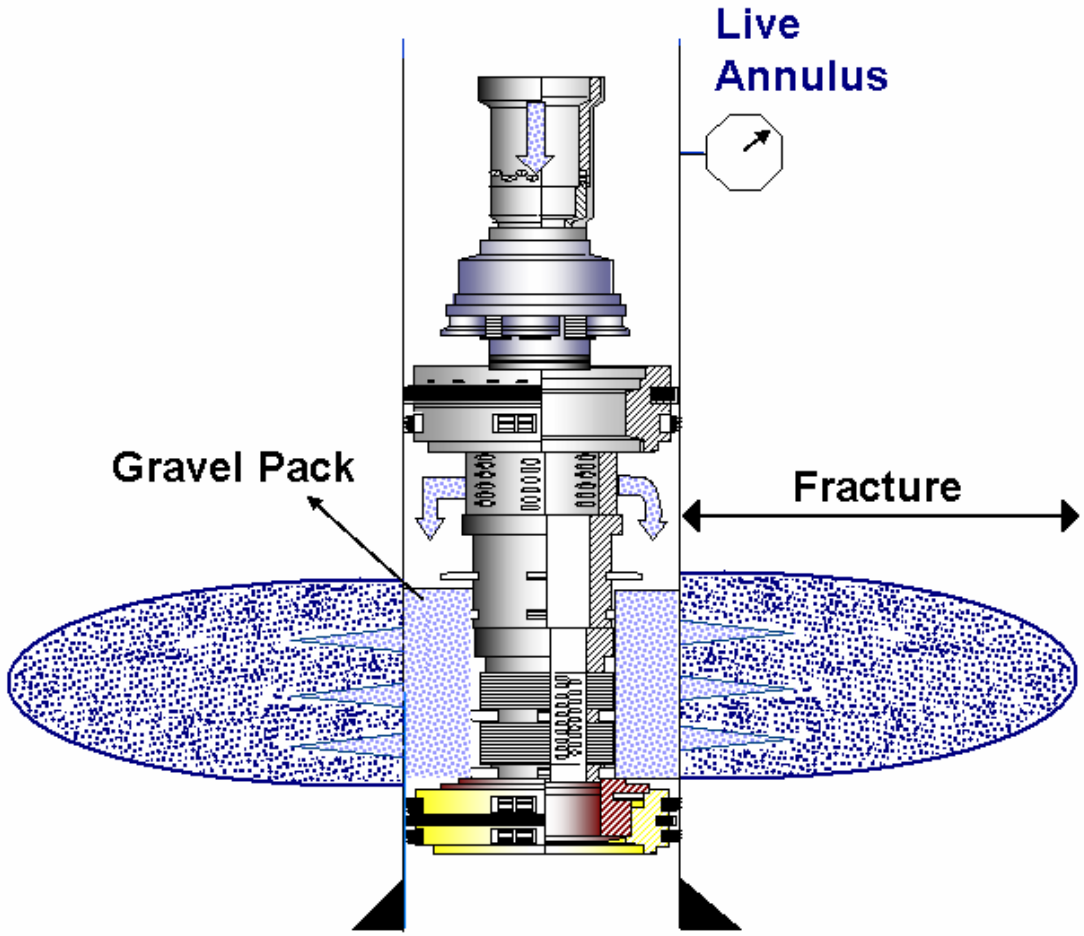
Back up & Complementation

FRACPACK – Definition

Combination of the fracturing with gravel pack



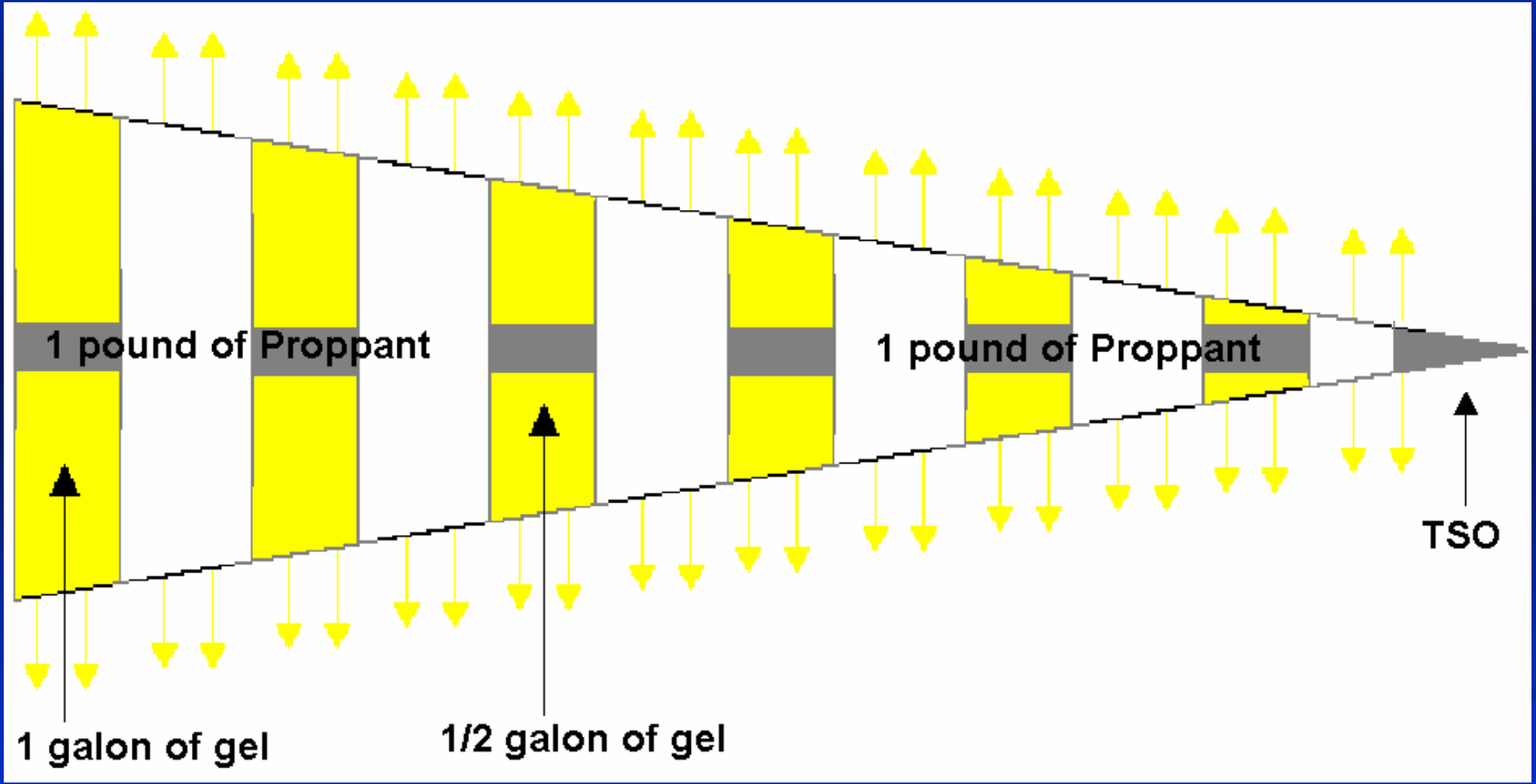
High permeability fracturing job pumped with screens (GP assembly) installed



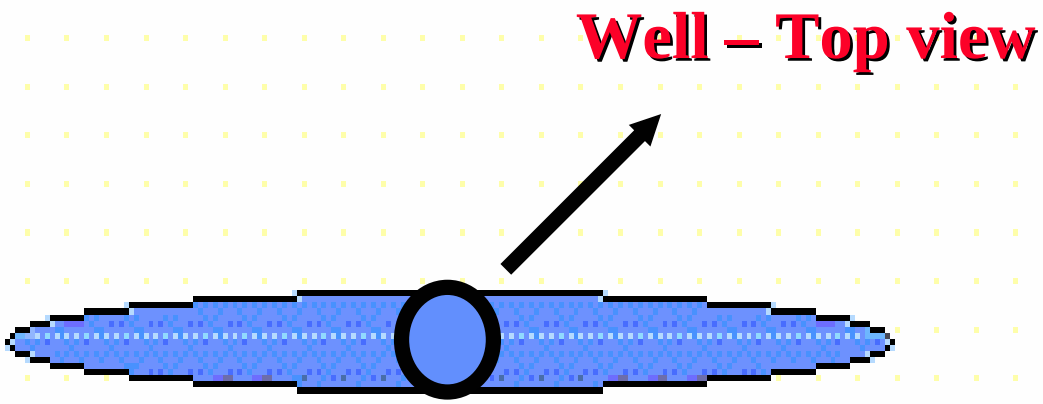
Tip screen out (TSO)

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

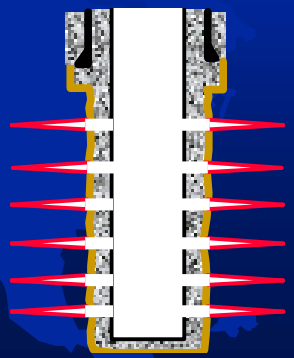


Tip Screen Out

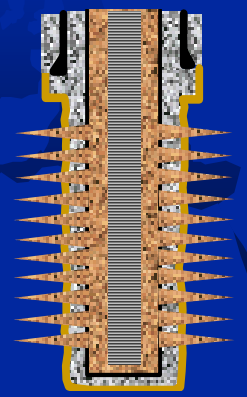


Sand Control Options

Cased & Perforated

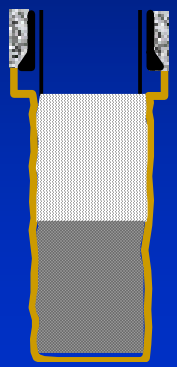


Cased Hole Gravel Pack



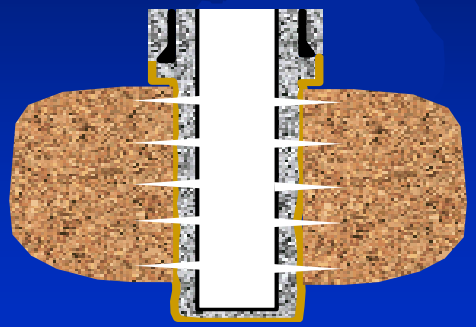
Slotted Liner / Screen in Open Hole

Expandable Screen



Open Hole Gravel Pack

Cased Hole Frac Pack



After Darell Wood

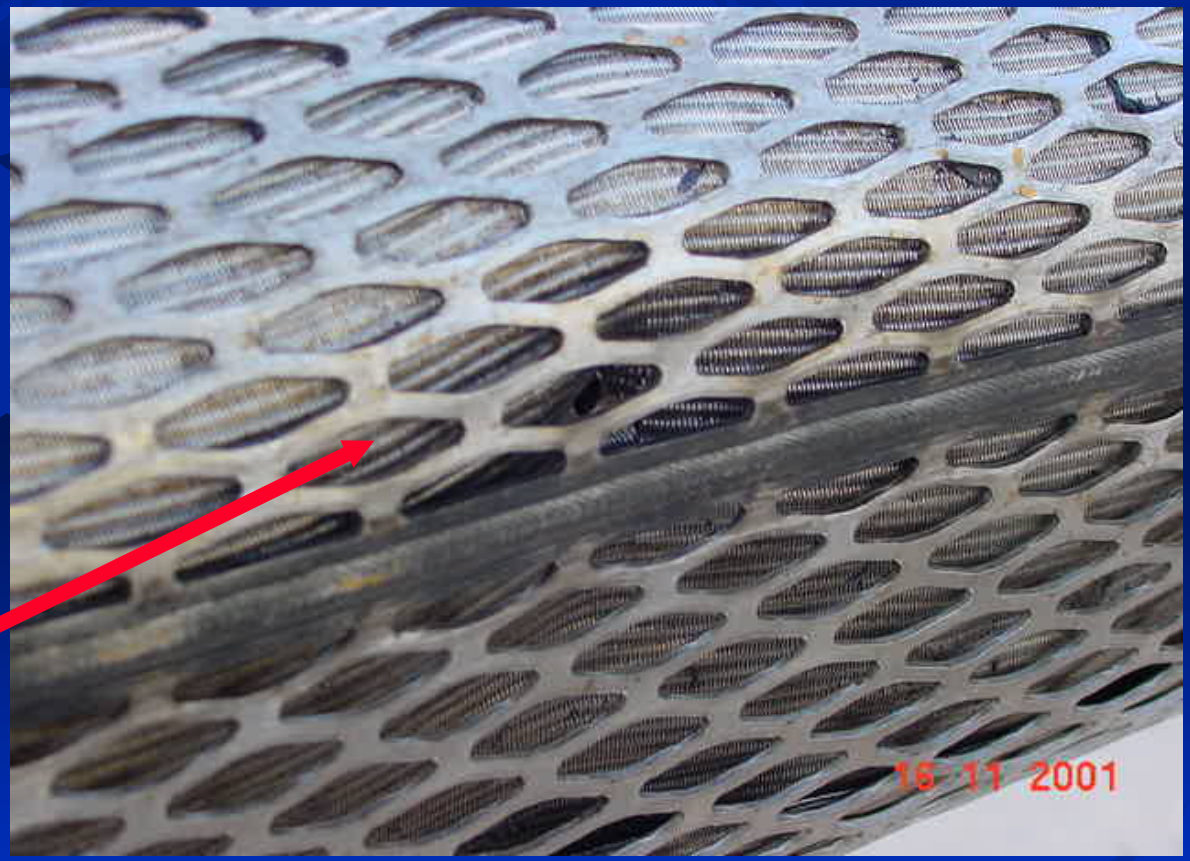
Expandable Screen

Cased & perforated

O.L. Field Venezuela

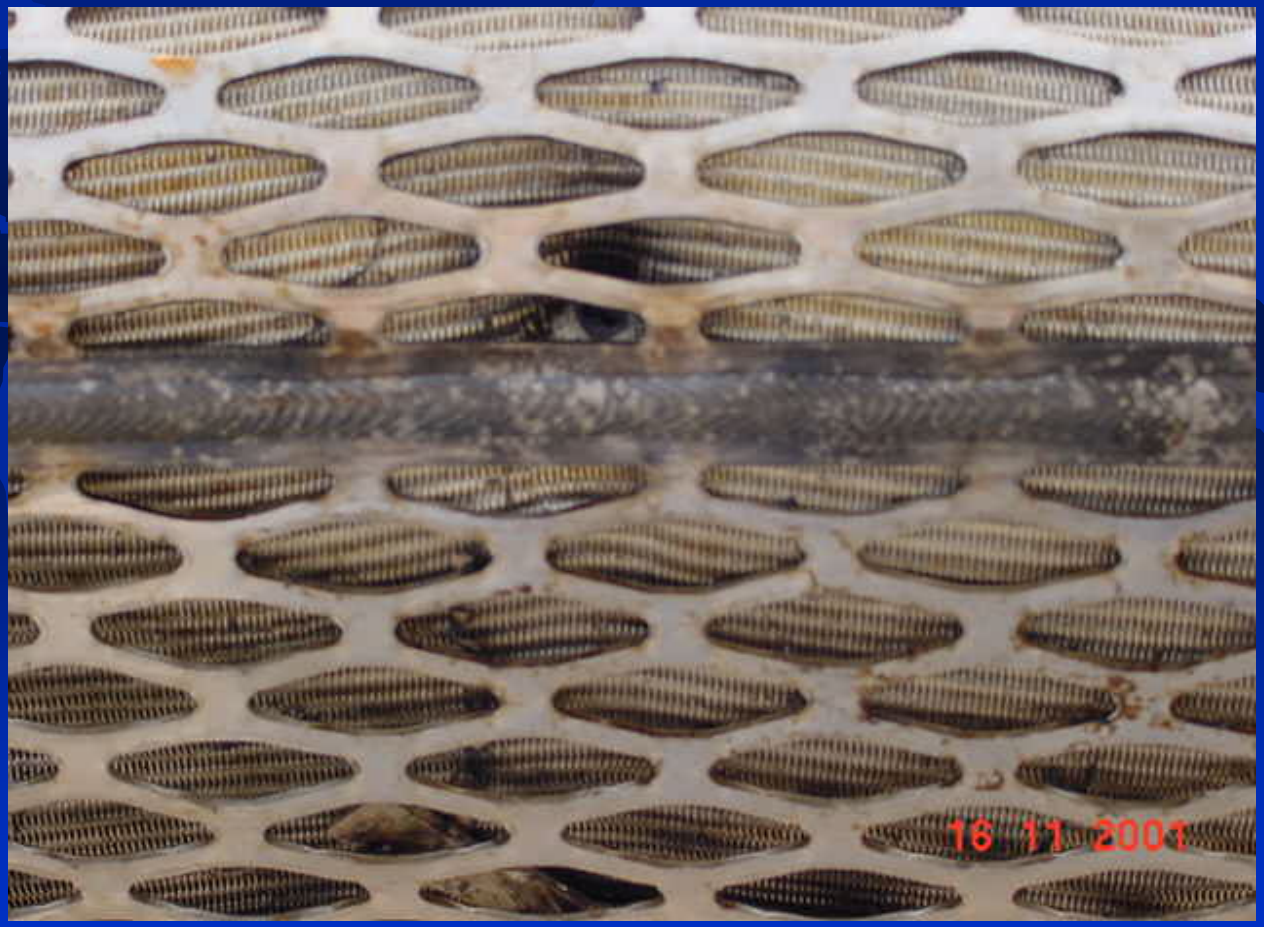
- Cased & perforated
- Heavy oil
- Swabbing for 4 hrs for testing → sanding
- Decided to remove Expadable Screens

- Hot spots



Expandable Screen

Hot-Spots



Expandable Screen

Cased & Perforated

Expandable Screen

Partial Expansion

Expandable Screen

Cased & perforated

Conclusions from Service Company

Fail occurred due to heavy oil flowing through "restricted" perforations

Indication: Do not run expandable screens into cased producers wells

Expandables in Off-Shore Open Hole Horizontal Well

Well	Type	L (m)	Screen	# (μm)	Q (bbl/d)
M-1	In	115	Compliant	150	23200
M-3	In	1138	Compliant	250	39700
M-4	In	1008	Compliant	250	> 40000
M-2	Pr	390	Compliant	150	22200
MS-1	Pr	507	Compliant	250	Fail
MS-2	Pr	620	Compliant	250	Fail
V-1	Pr	274	Non Compliant	250	Fail