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Distinguished Lecturer Program

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Acid Stimulation Challenges and Solutions in Deeper Limestone Reservoirs

Gino Di Lullo

Superior Energy

Society of Petroleum Engineers
Distinguished Lecturer Program
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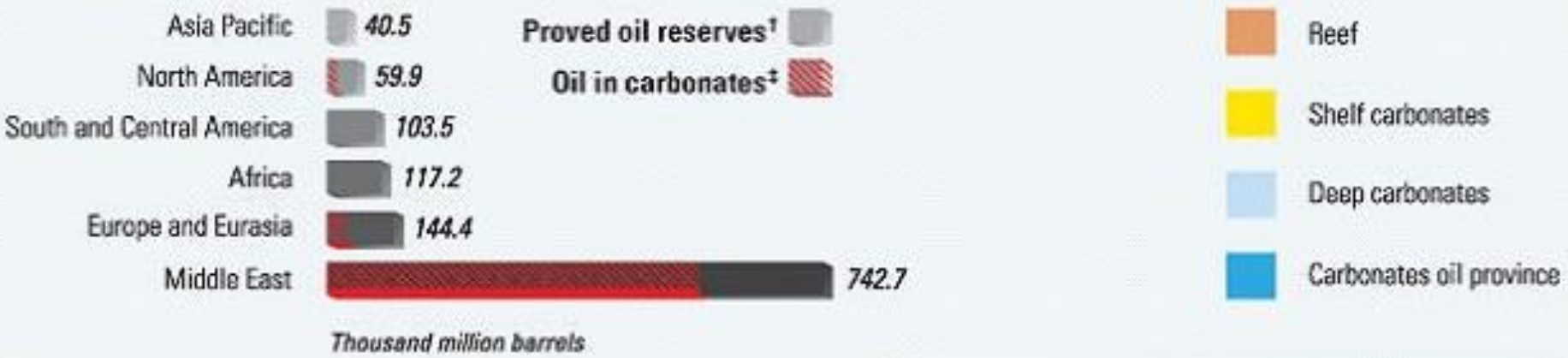
SUPERIOR ENERGY SERVICES

Overview

- Legacy
- Challenges
- Solutions
- Case History
- Conclusions



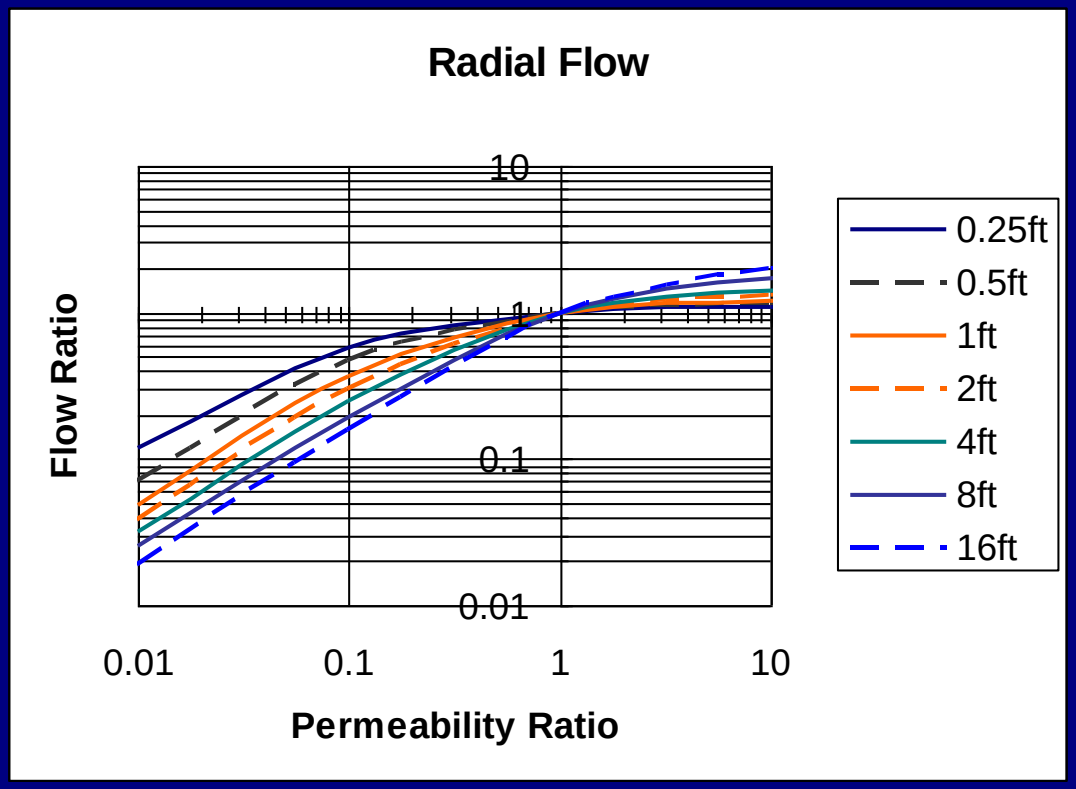
Legacy - Actual Stimulation Methods

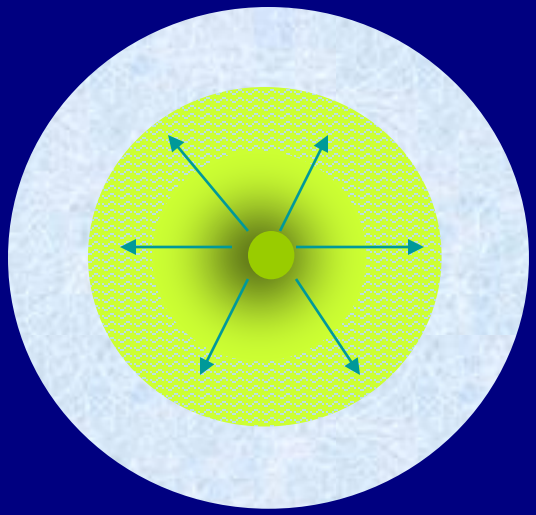
- **Matrix acidizing**
- **Fracture acidizing**
- **Closed fracture acidizing**
- **Competing technology: Horizontal wells**
- **CTU acidizing**
- **Acid Constructed Laterals**

All Acid Jobs in Carbonates are Successful !!!
But few were Optimally Designed !!!

Legacy - Carbonate Matrix Acidizing

- Radial injection of reactive fluids into the reservoir matrix at below fracturing pressure to dissolve the rock and or mud cake to improve production

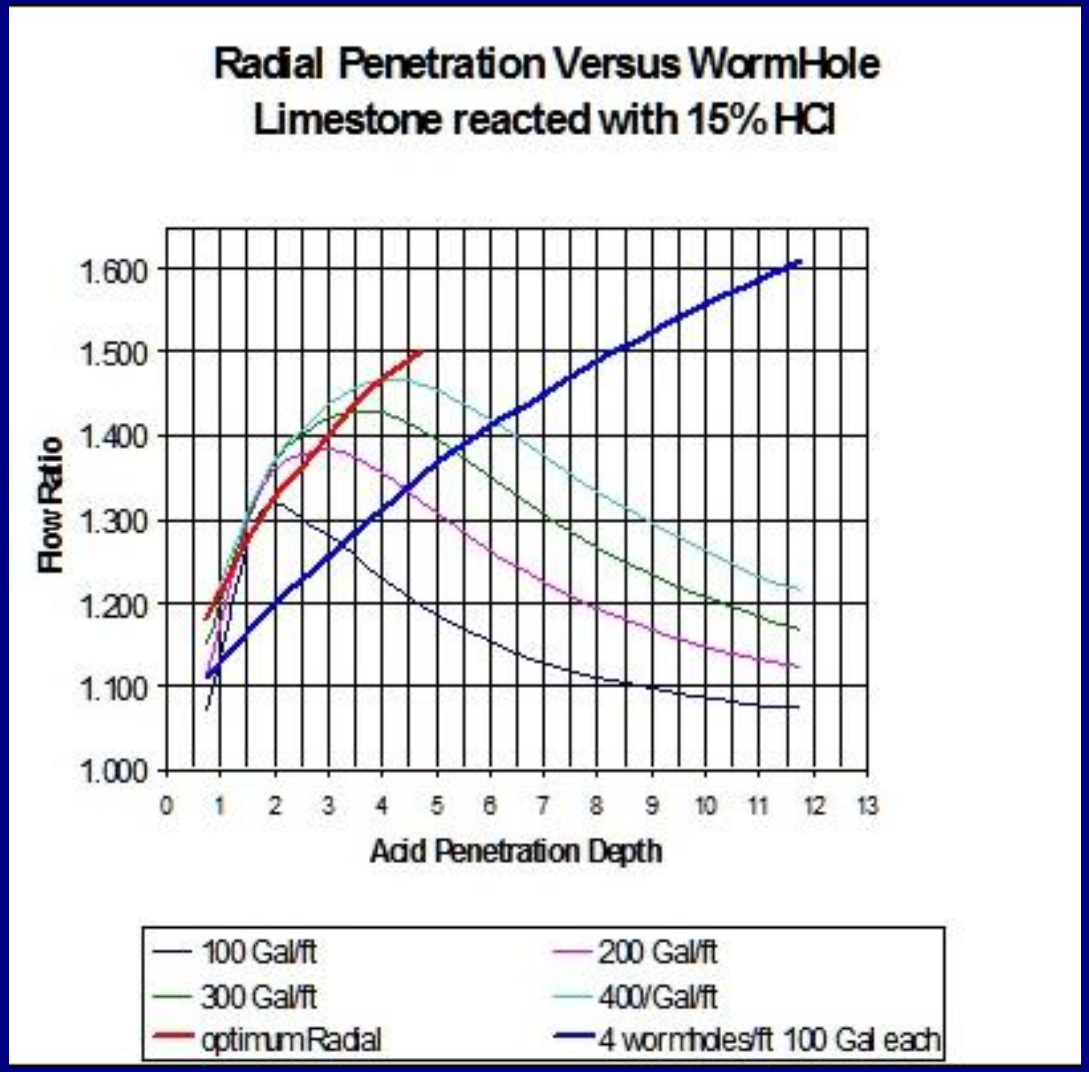


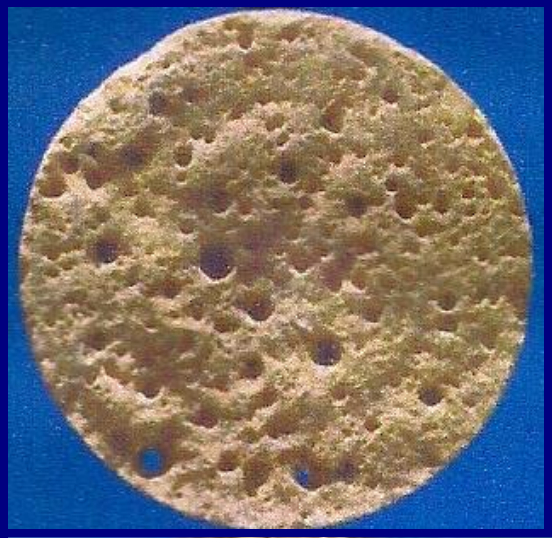


- Removing near wellbore damage
- Enlarging & interconnecting pores
- Increasing original permeability

Source SPE 82260

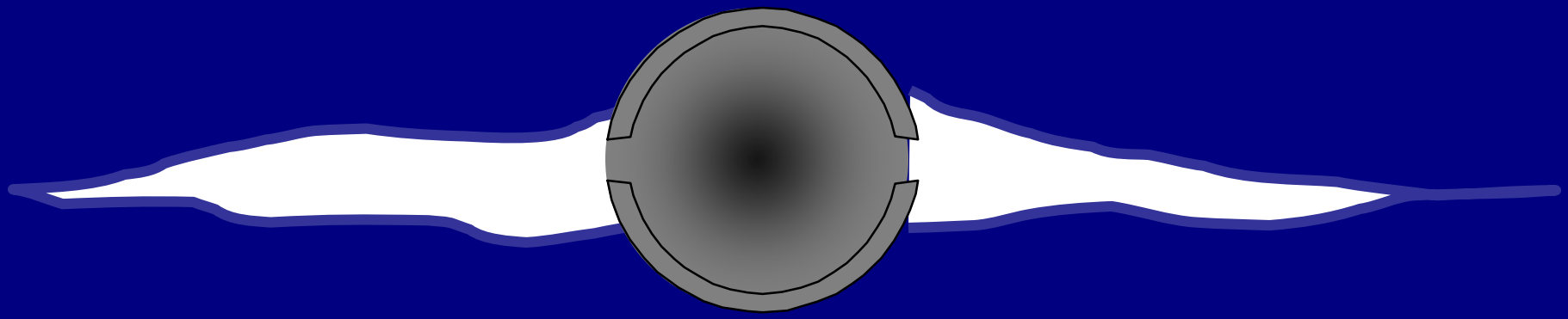
Legacy – Retarded versus Strong Acid – Radial versus Wormhole



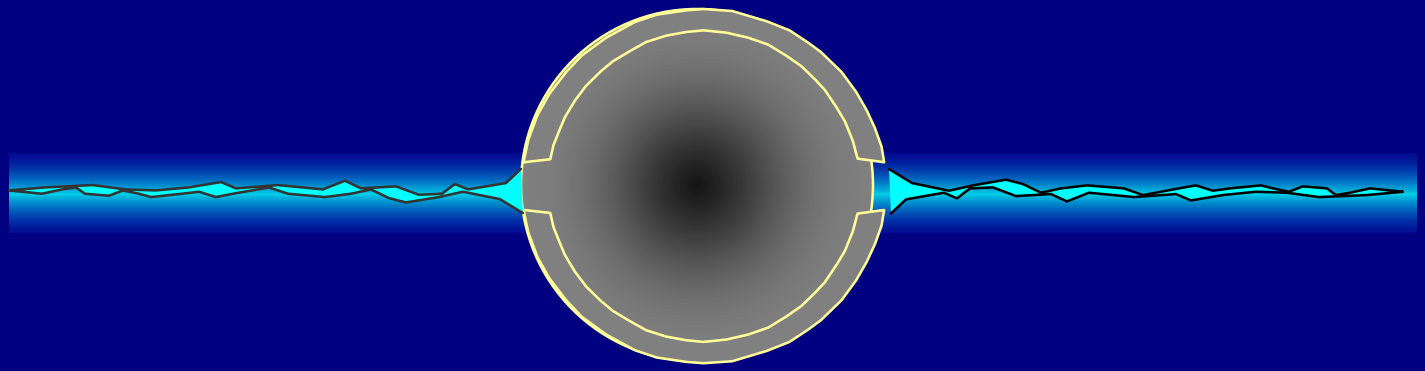


Source SPE 82260

Legacy - Acid Fracturing Carbonates

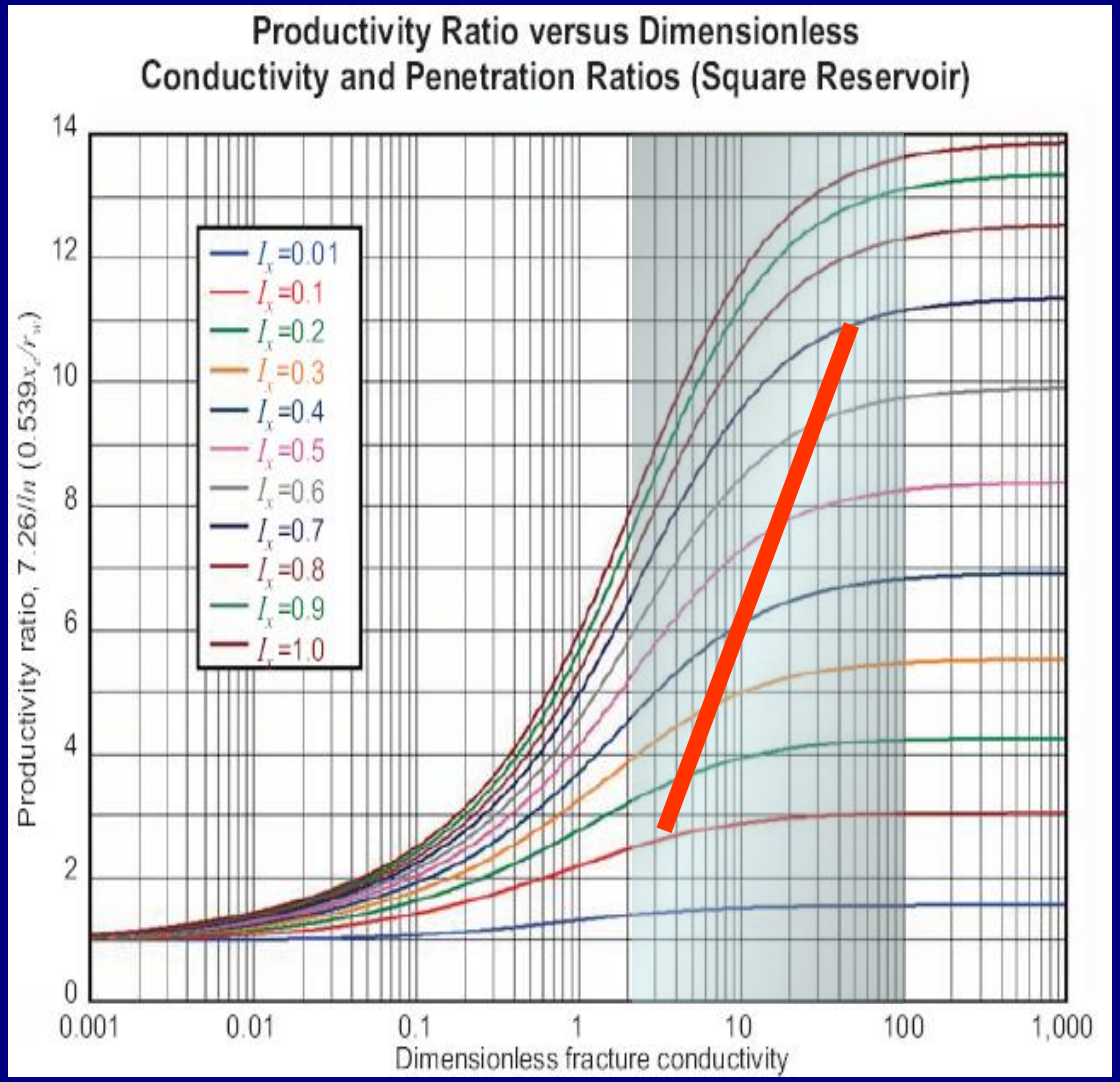


Pad Fluid Creates Fracture, Acid Dissolves Area Around Fracture Wall



Leaving Path of Increased Permeability-Conductivity After closure caused by differential etching

Legacy – Acid Fracture Design Criteria

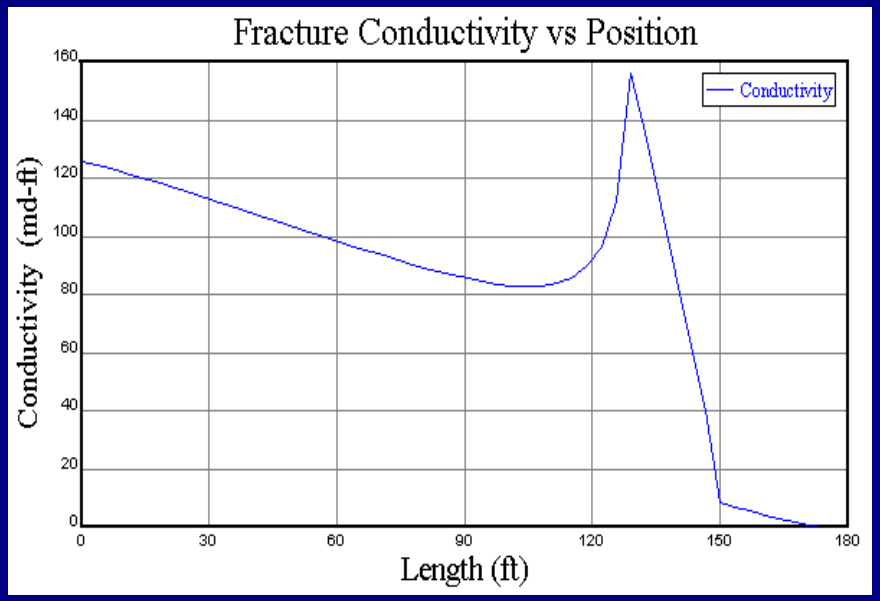


After Emulsified Acid- Most Retarded

After XL Acid-Best Leakoff Control -Cw

After Gelled – No retardation, Leakoff -Cv

Unrealistic Conductivity Prediction



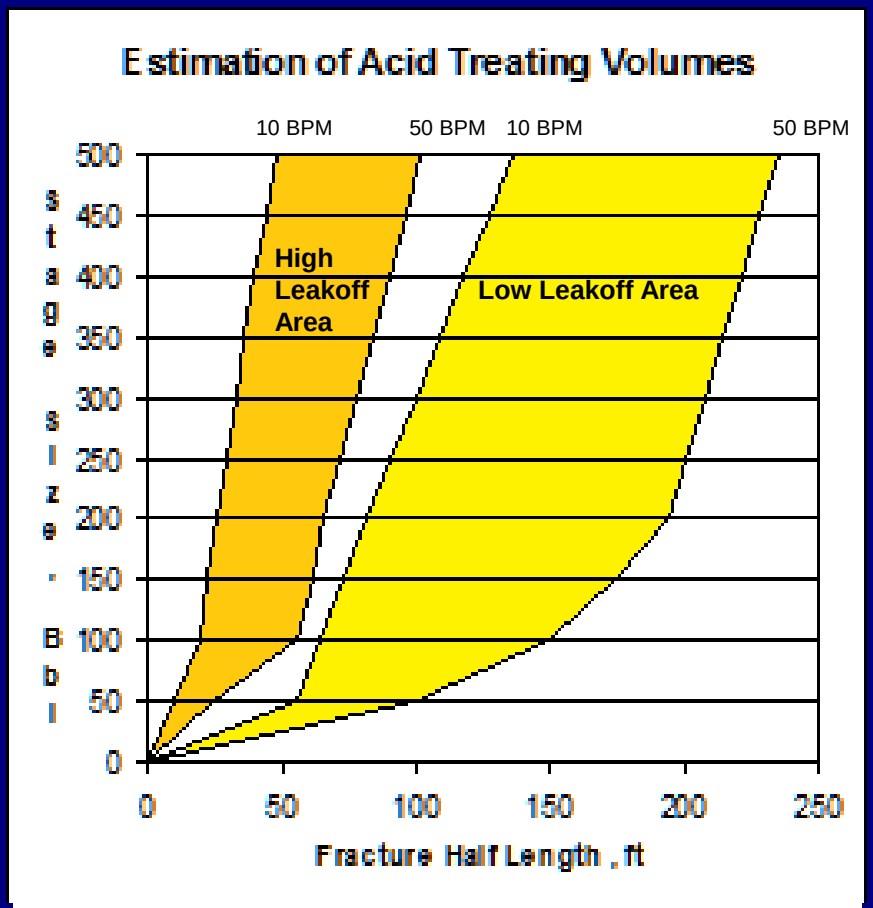
PRODUCTIVITY GAIN FOR FRACTURED WELL

Horizontal fracture

Fract. Length X_f' ft	Vert. fract. J_{Vf} / J_V	Skin S	J_{Vf} / J_V	r_{we}	$\frac{r_{we}}{X_f}$
50	2.07	-4.92	2.75	45.5	.90
100	2.54	-5.65	3.71	94	.94
200	3.28	-6.35	5.58	187	.945
400	4.66	-7.05	10.7	380	.95

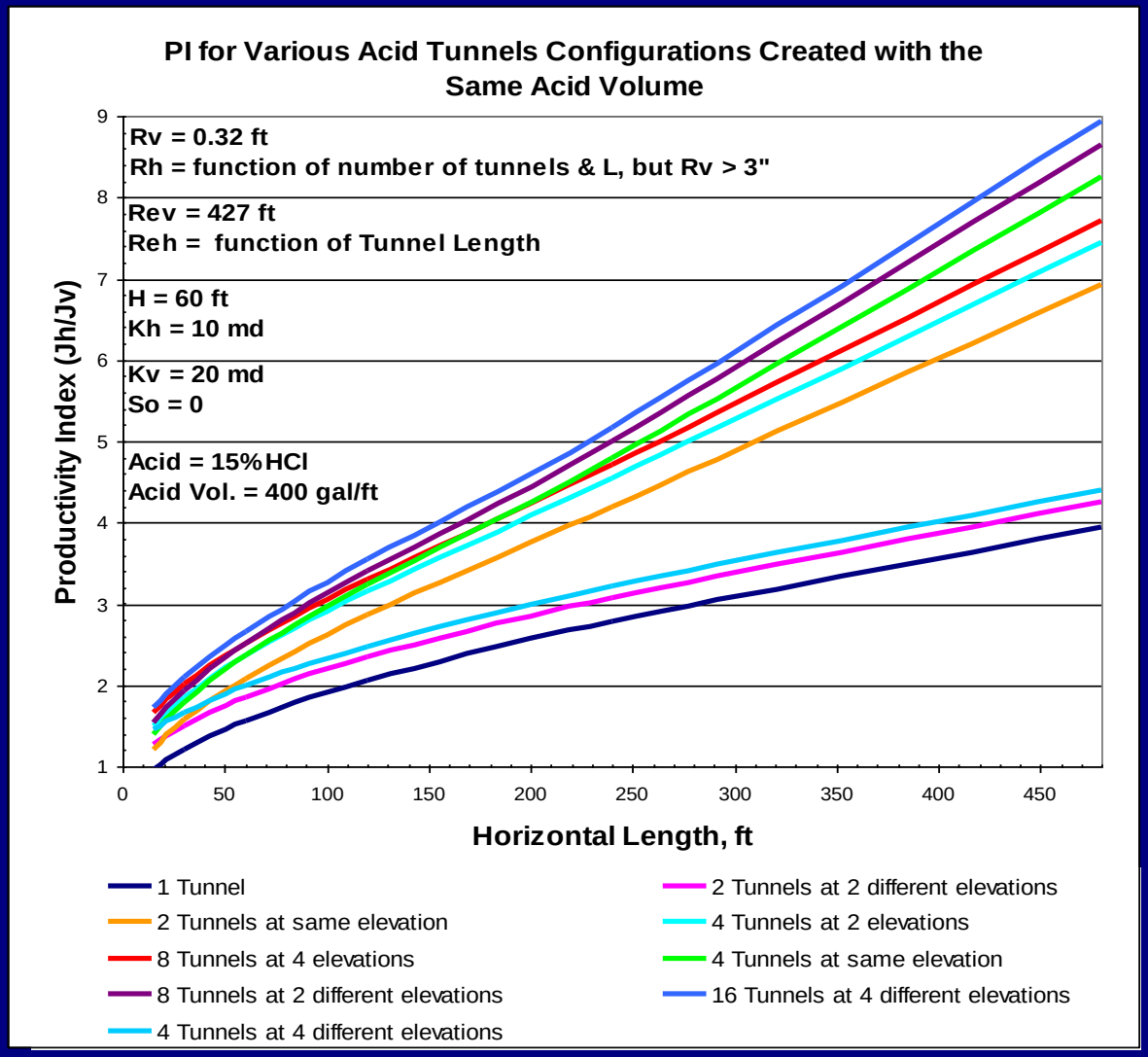
20 Acre spacing r_e = 527' r_w = 0.33'

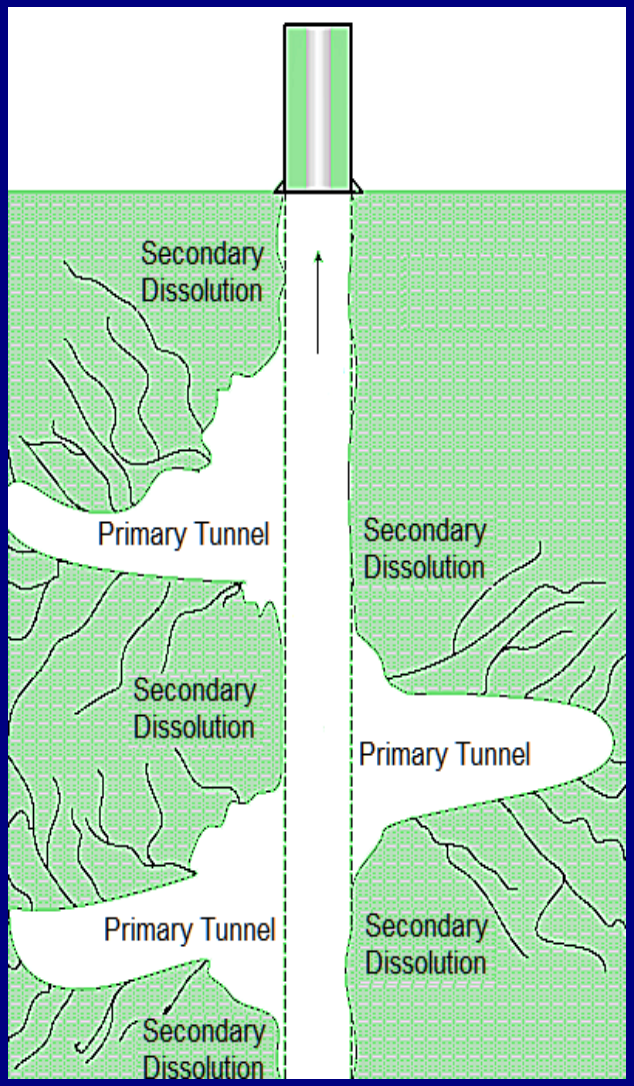
Formation thickness = 20'



High Rate Bullheaded Acid & Limited Entry - In a North Sea Field Transient Analyses indicated a 30 ft length average in high leak-off areas while 150 ft average Fracture length in low leak off areas for similar designs

Legacy - Vertical Well with Acid built Laterals

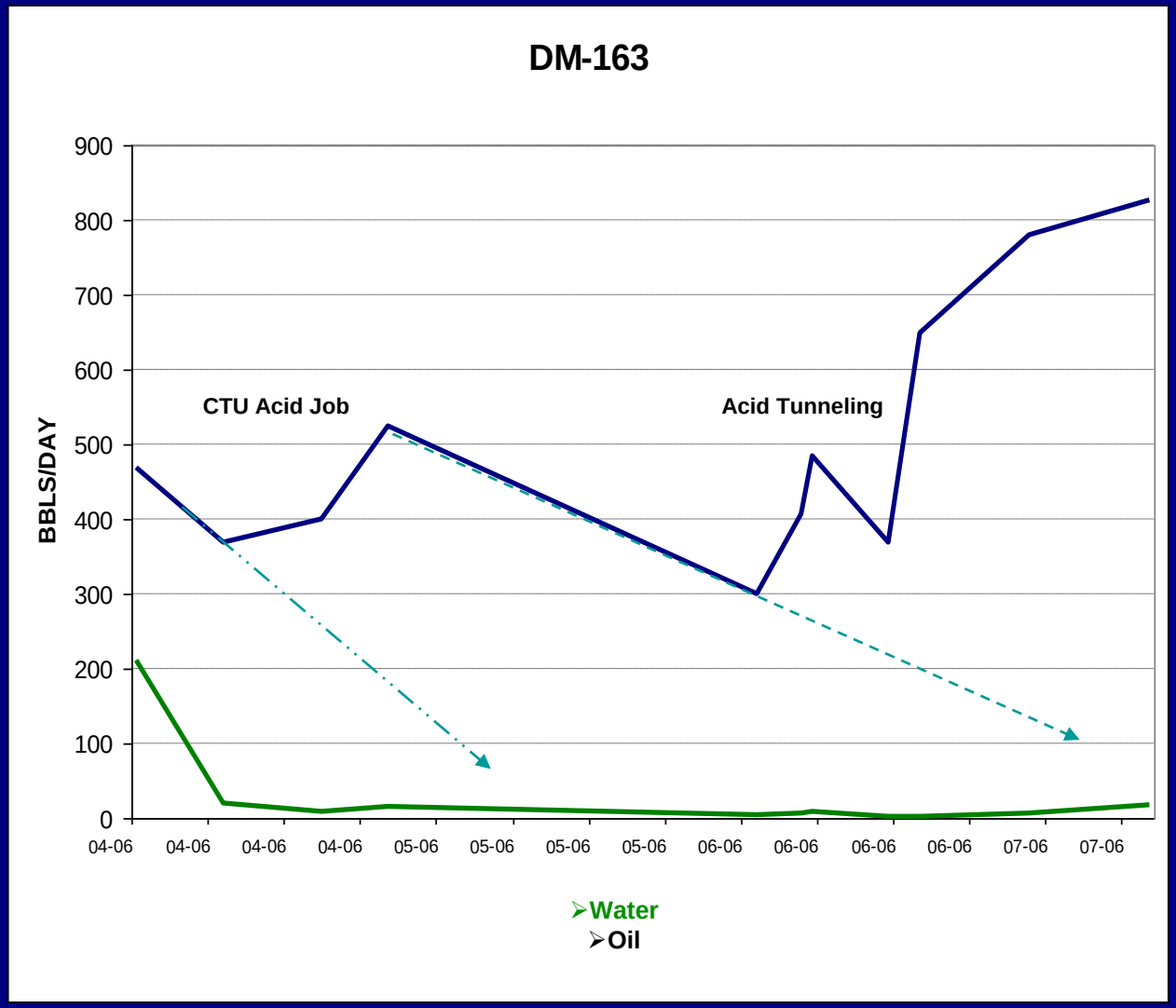


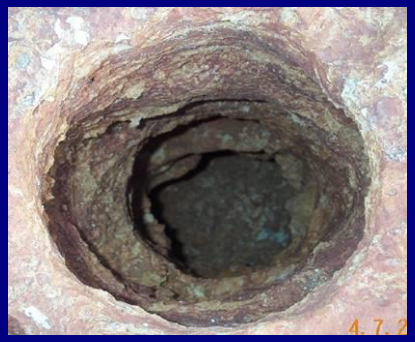


Guaranteed Penetration, total accumulated Length the longer the better

Source SPE 103333

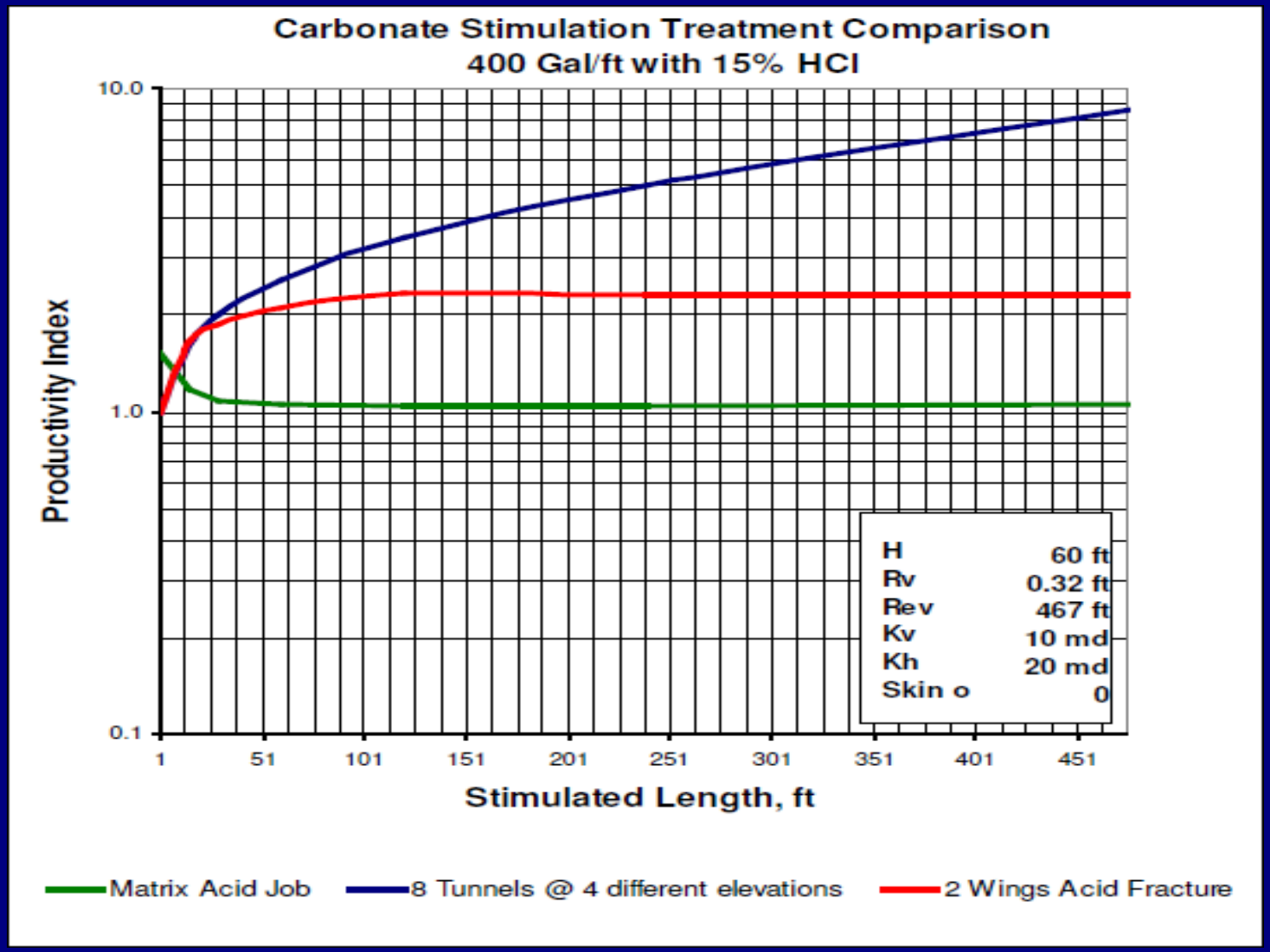
Legacy- Multiple Laterals Mara Field





Source SPE 103333

Legacy- Treatment Comparison

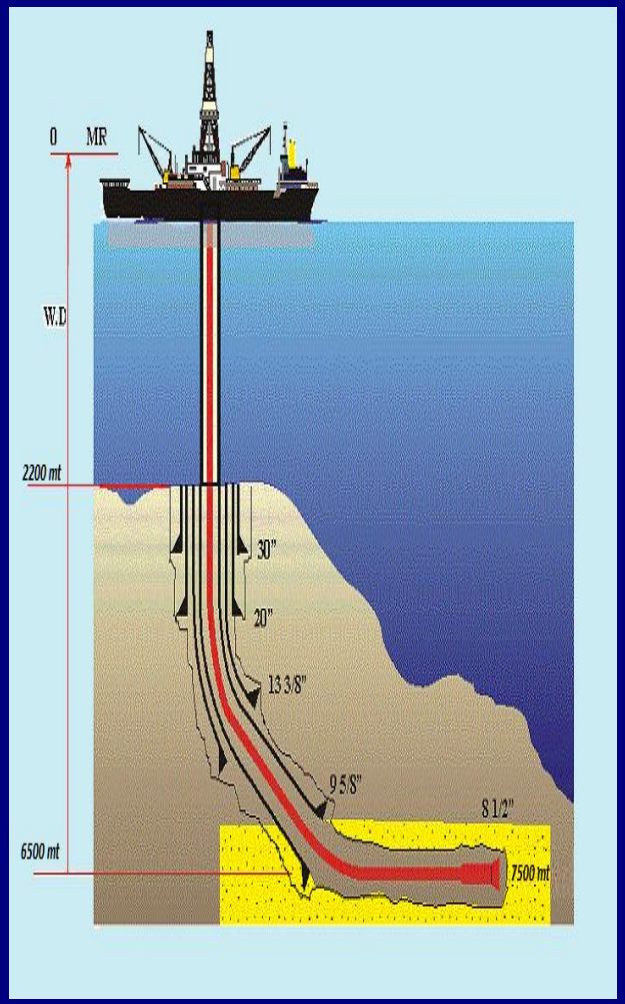


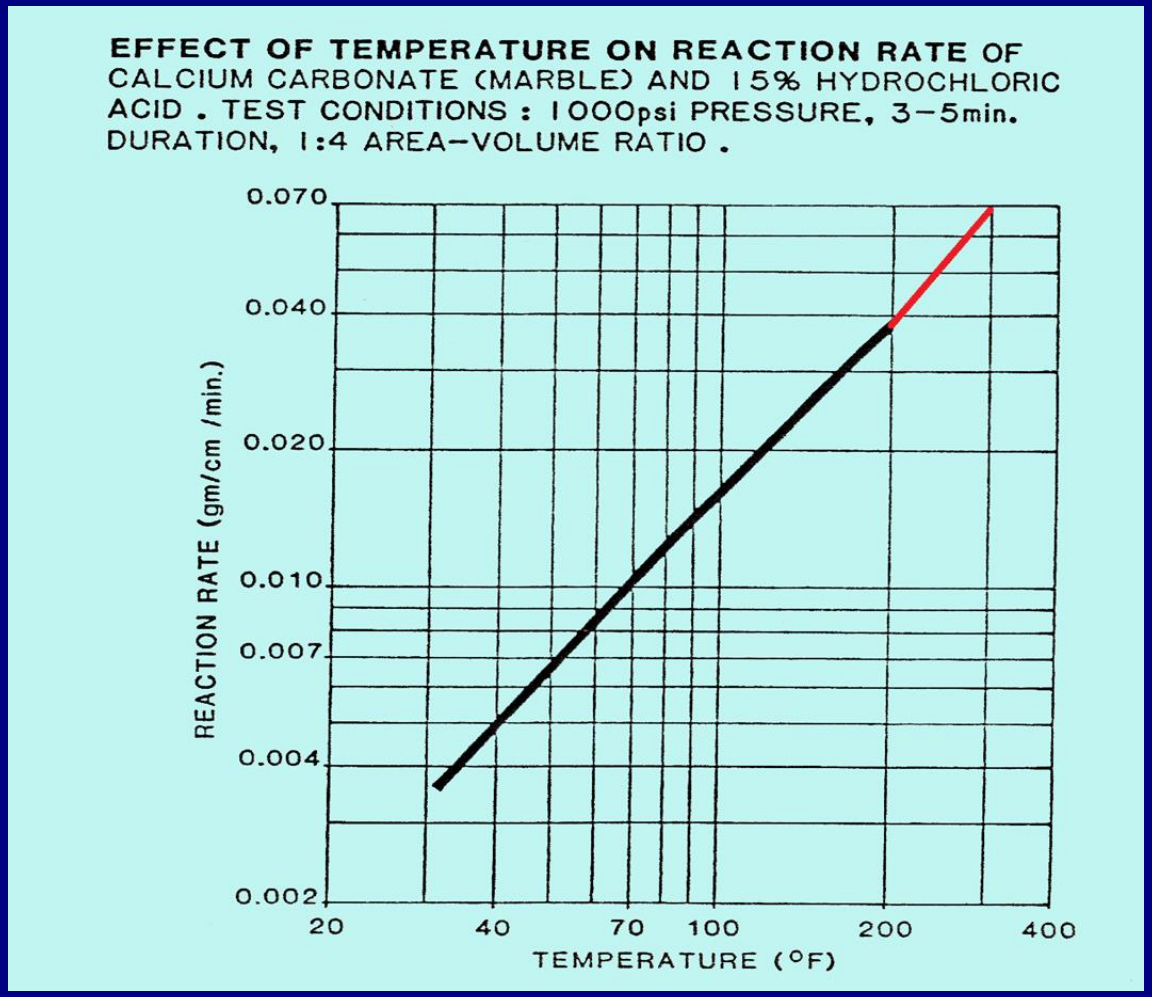
Source SPE 103333

Legacy – Design based on History

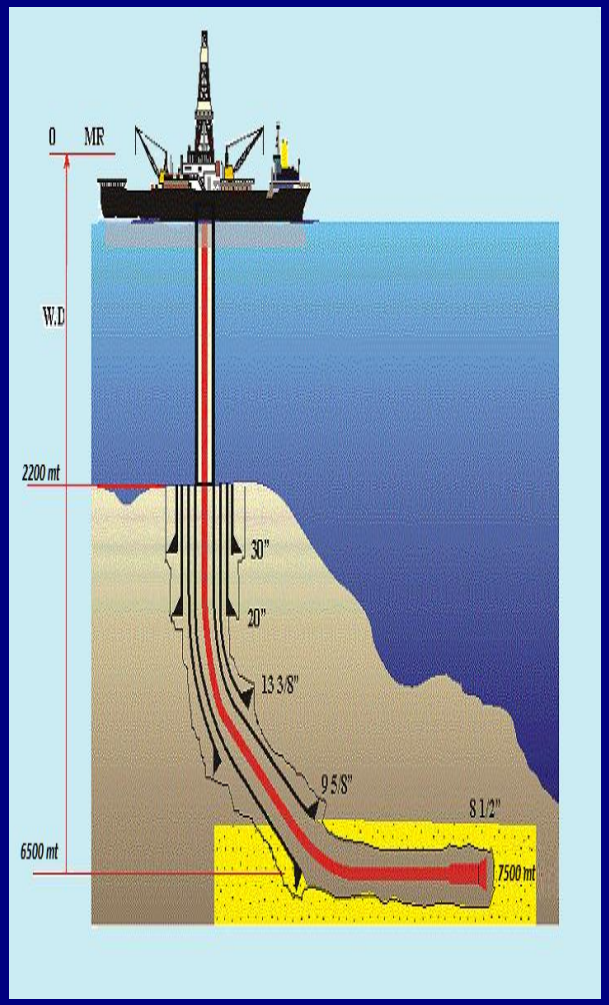
Caution : What works for one well ... doesn't necessarily work for all wells!!!

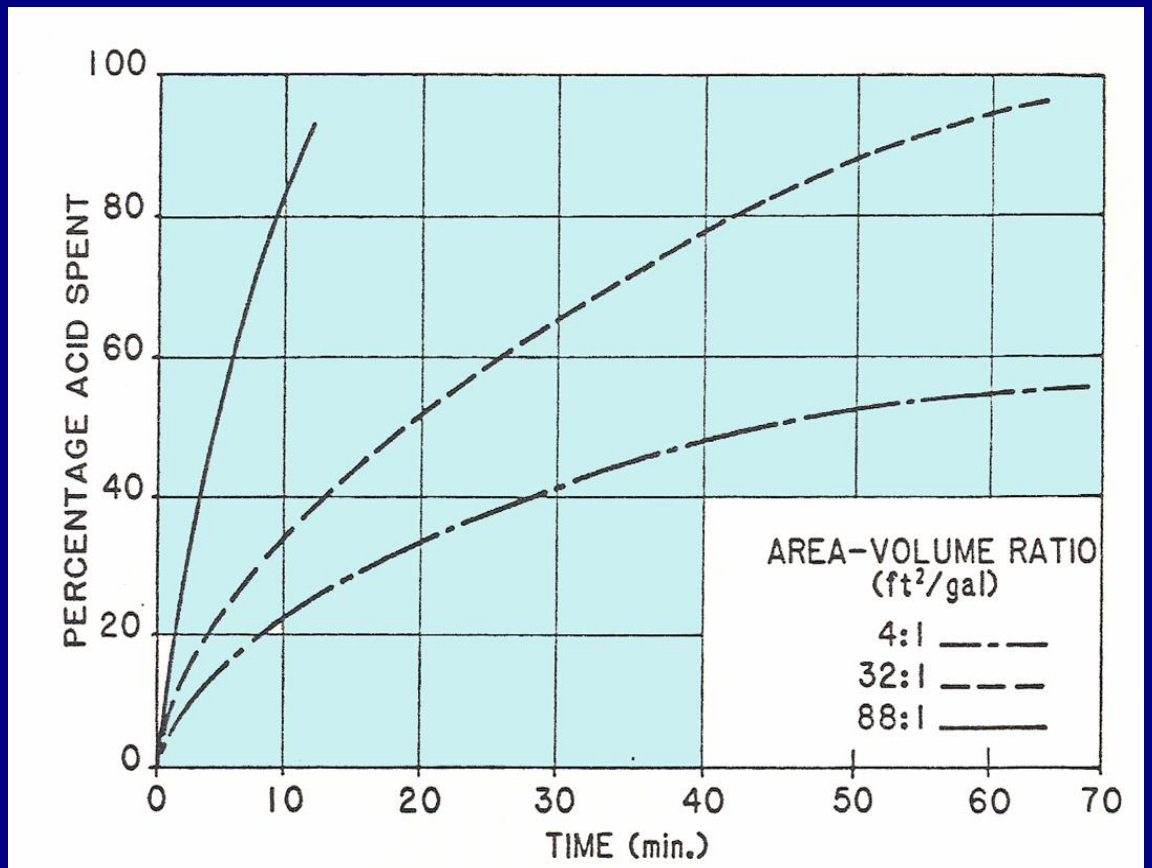
Challenge in Deeper Carbonate Stimulation





Challenge in Deeper Carbonate Stimulation

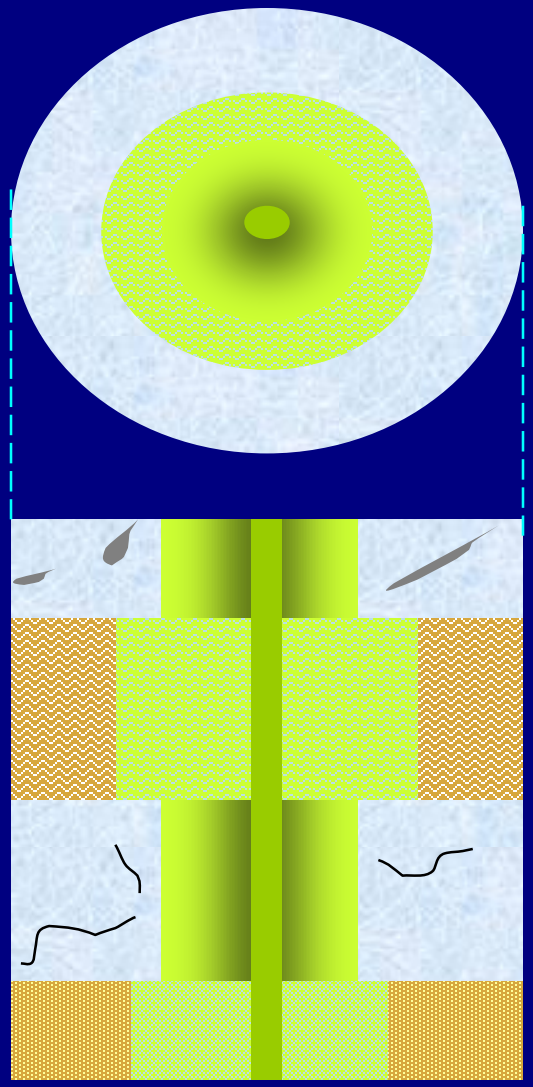




Graph showing the rate of 15% H Cl spending for varying area-volume ratios (80°F, 1000psi)

Challenges in Matrix – Stimulation

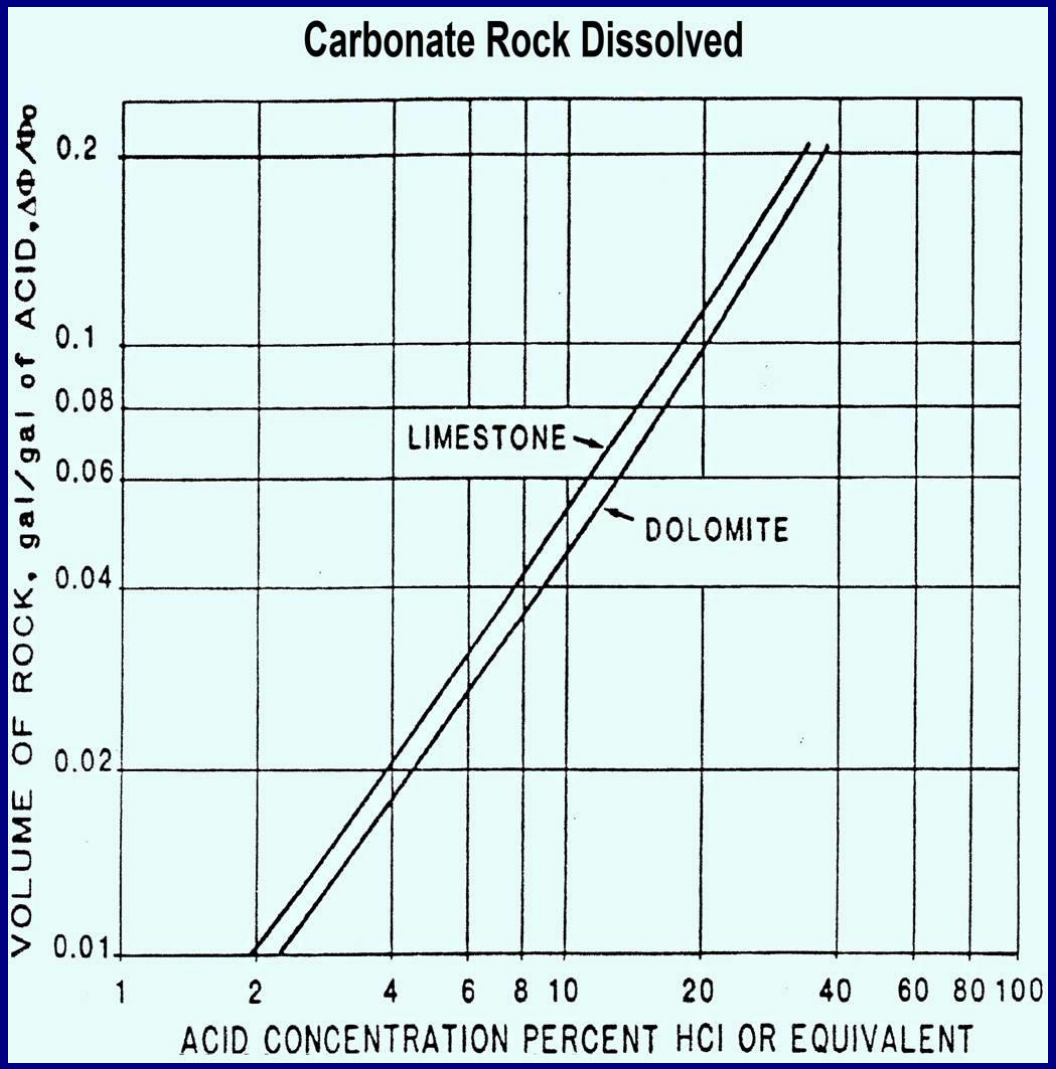
- **Divert & Penetrate**
  - **Treating the complete zone interval equally**
  - **Limiting-Retarding acid enough to overcome higher temperature & Area : Volume ratio**
- **Obtaining designed radial penetration or optimized long wormholes**



Challenges in Fracture-Stimulation

- Obtain Long Fractures with Reactive Fluids
- Formation Collapse after Closure
- Poor differential-etching
- Lack of fracture Conductivity

Challenge - Replace HCl in Deep Hot Wells



- HCl a Gas not an Acid
  - Volatile, Fumes
- Availability at ~38%
  - Transport, storage
- Carbonate Solubility
  - Chlorides by product
- Corrosive
  - Expensive Inhibition
- Cheap
- Forms Precipitates
  - Sludge
  - Iron precipitates

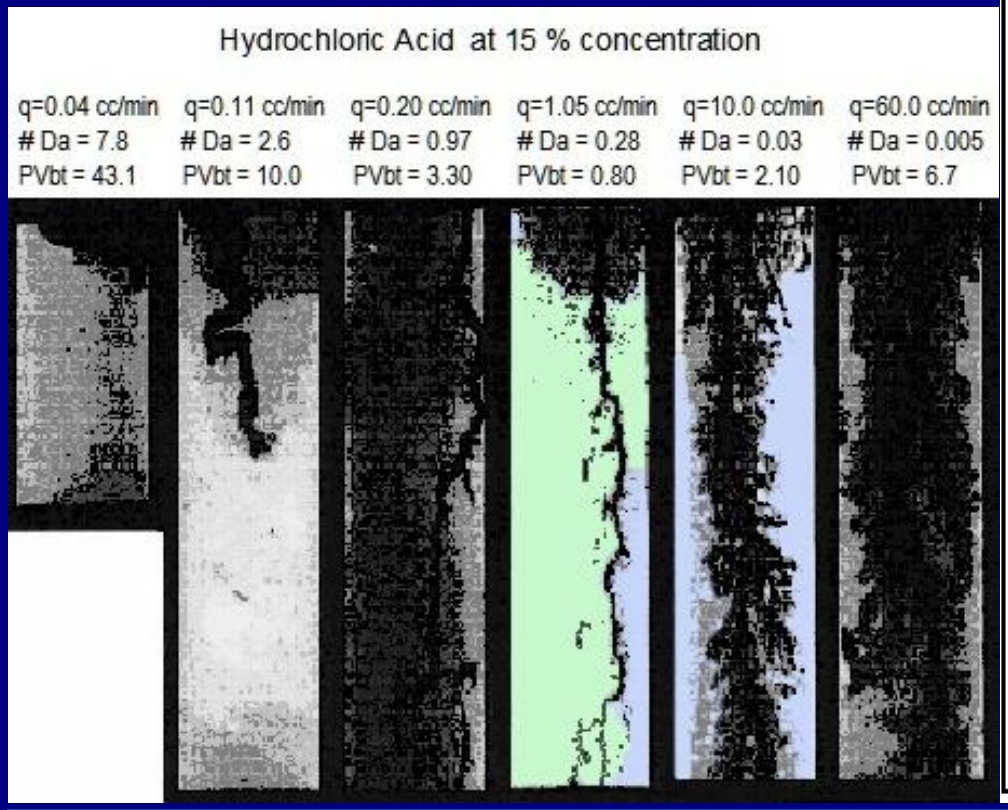
1 Barrel 15% HCl dissolves only 1 Gallon of Carbonate

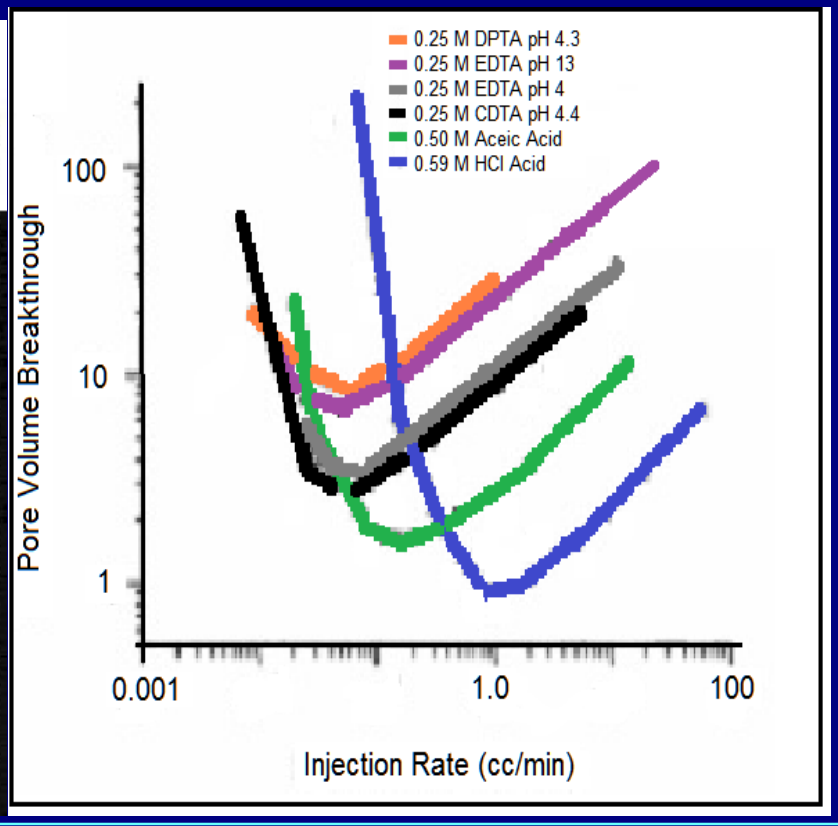
Challenge - Replacing HCl

Acid	pK5	pk4	pK3	pK2	pk1	Log K 1:1 Complex
HCl					-3	
MSA					-1.92	
NTA		9.7	2.5	1.8	1.0	6.40
DPTA	10.5	8.5	4.3	2.6	1.8	10.80
EDTA	10.2	6.2	2.7	2.0	1.5	10.70
Phosphoric			12.3	7.2	2.2	
HEDTA			9.8	5.4	2.6	8.40
HEIDA				8.7	2.2	4.80
Citric			5.7	4.4	2.9	3.50
Acetic					4.8	0.53
Carbonic					6.4	

Acid-Carbonate Effervescent Reaction & Hard to Control

Challenge - Increasing rate to obtain Penetration



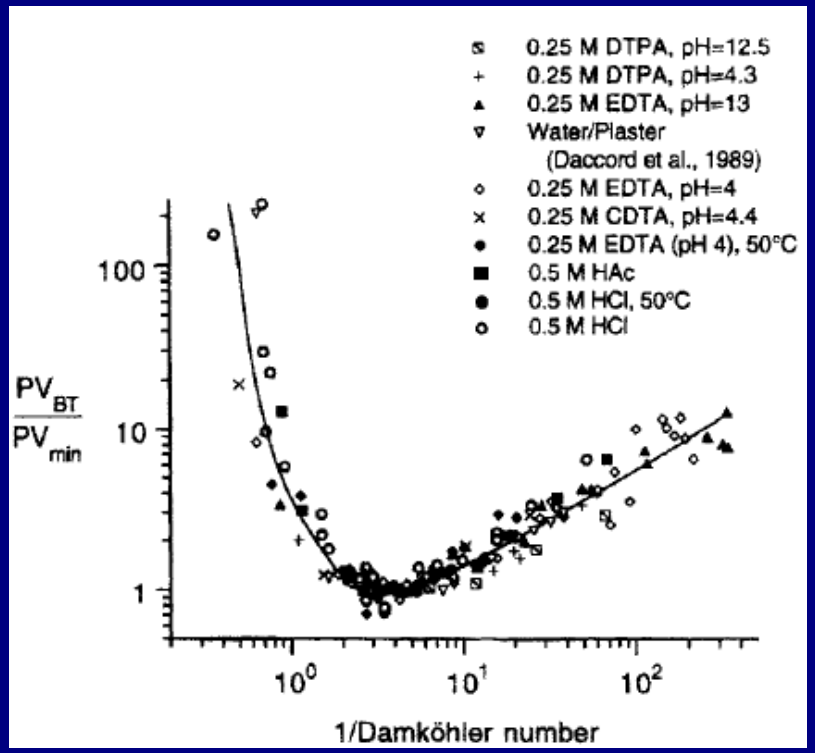


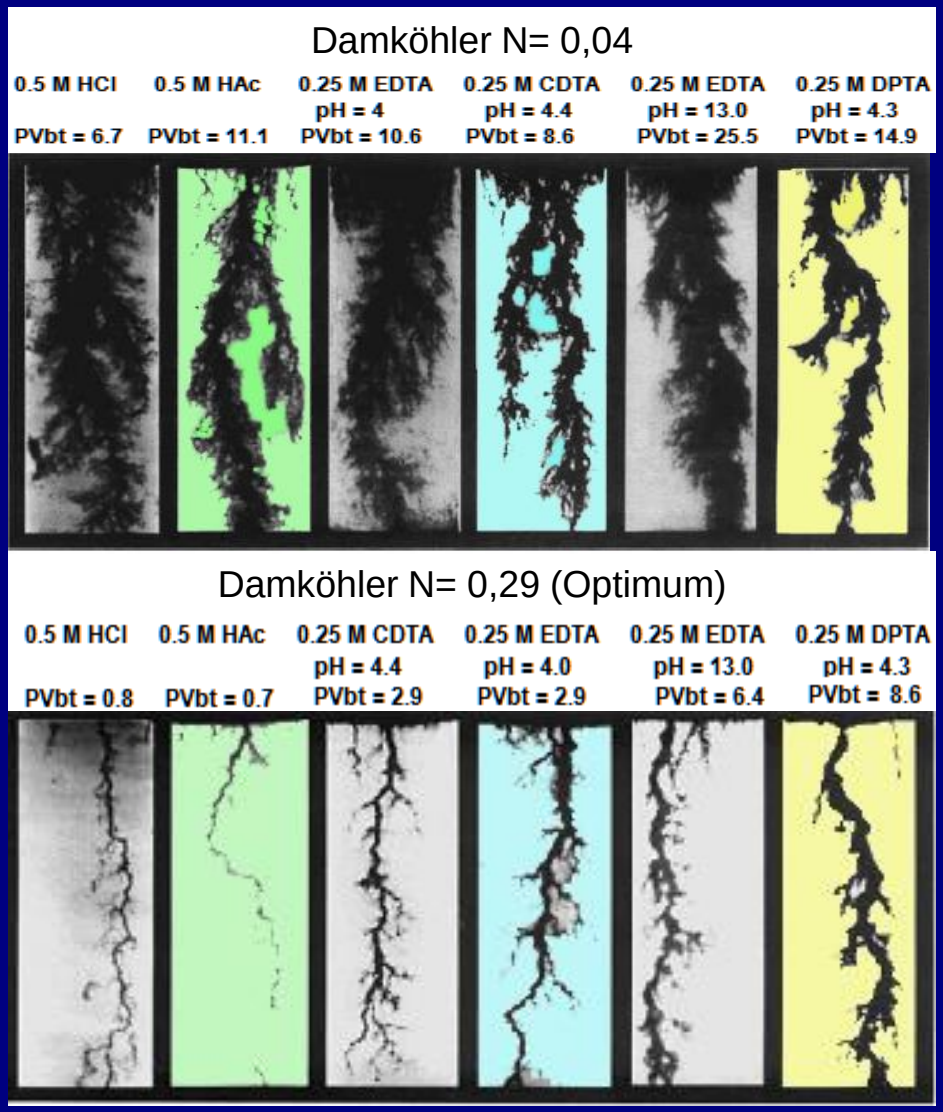
- **Matrix jobs ; increasing the rate help in getting deeper in the formation up to a point**
- **Fracture jobs ; increasing the rate improve leak-off , also increase acid diffusivity but not necessarily differential etching**

Source SPE Journal March 98

Challenge - Picking up the right Acid

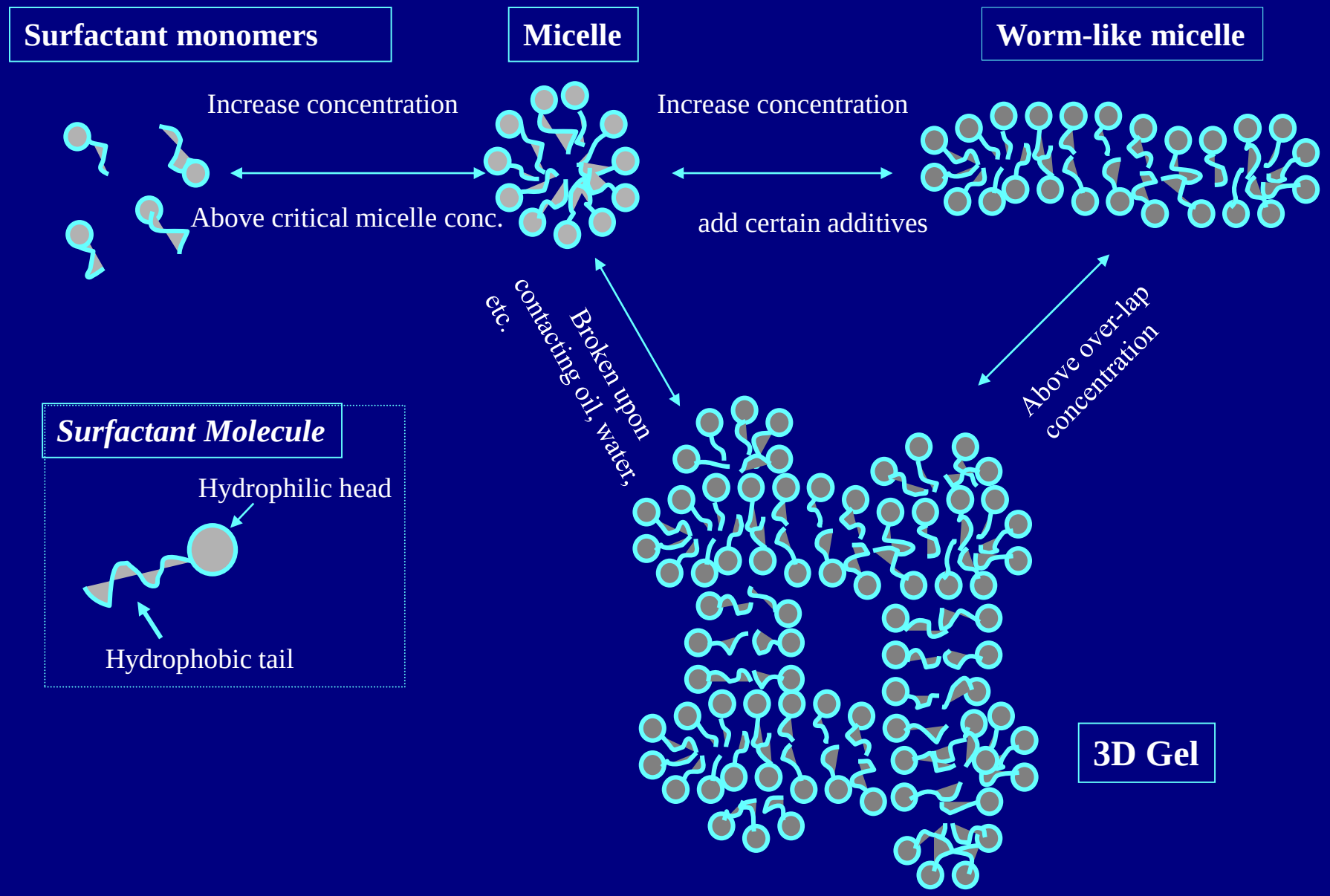
$$Da = \frac{\pi dlk}{Q}$$





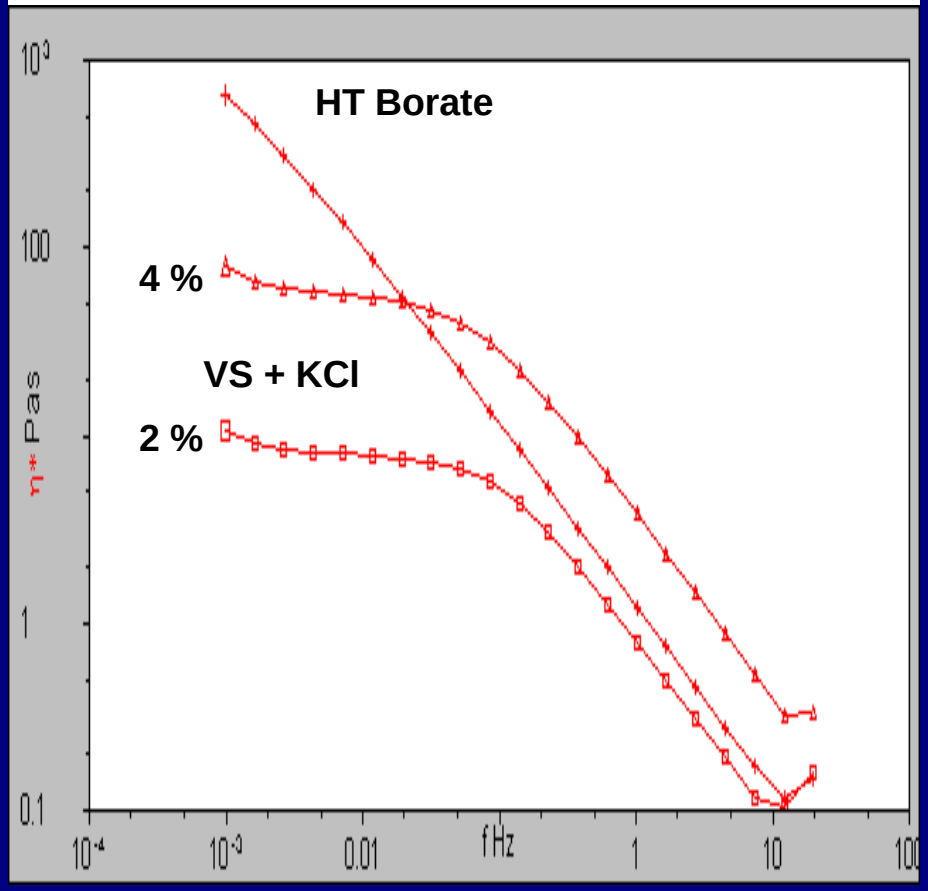
Source SPE Journal March 98

Solution - Viscous-elastic Surfactants

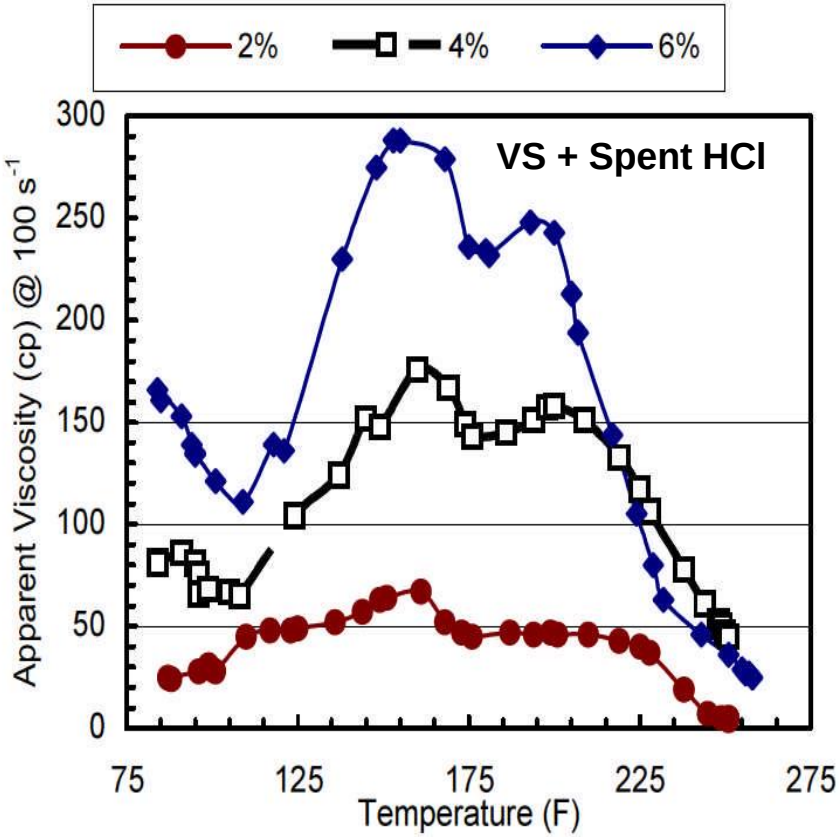


Solution - Viscous-elastic Surfactants

Viscosity Comparison - Oscillatory Frequency

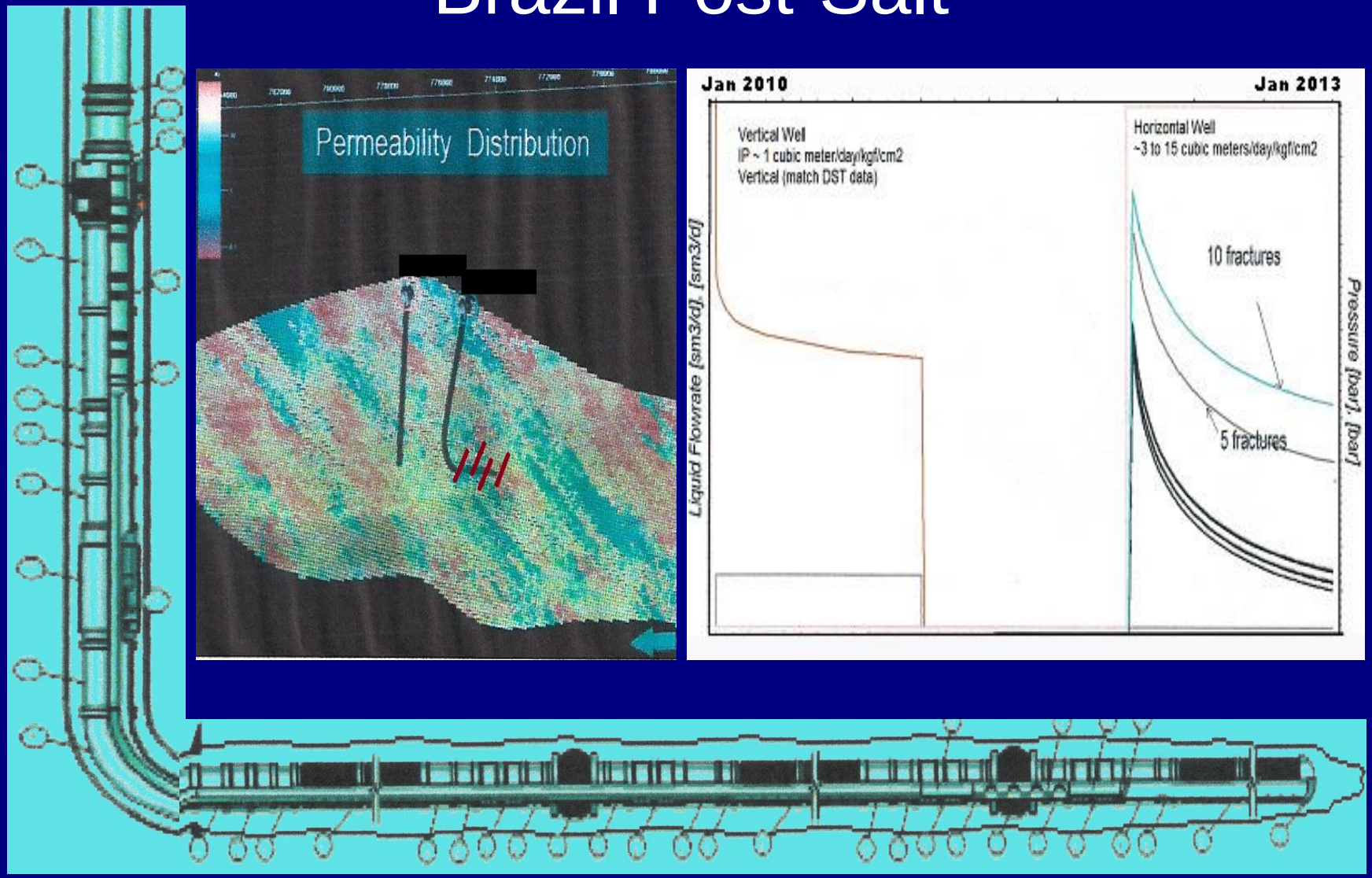


Viscosity Comparison – Spending Acid



LEAKOFF ACID VISCOSITY INCREASE AS CALCIUM CHLORIDE IS FORMED DURING CARBONATE DISSOLUTION

Case History – Typical Treatment Brazil Post-Salt

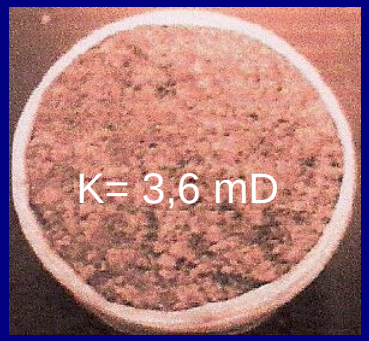


Source OTC 22417

Case History –Typical Treatment

Each Stage Per zone 170 Bbl	Rate BPM	Fluid	Acid
Pre-flush	0,5	HCl-Solvent	15%
Treatment	0,5	HCl	15%
Diverter	0,5	Viscoelastic Pill	15%
Treatment	0,5	HCl	15%
OverFlush	0,5	Solvent	0
Flush	0,5	Brine	0

Pre Acid Entrance Face



Post Acid Entrance Face

Post Acid Exit Face

- Expected Production 5 to 6 folds
- Equivalent to 12 gpt (gallons per foot)
- Post Job DST transient result (– 5.9) skin
- Stabilized Production ~ 2 folds

Source OTC 22417

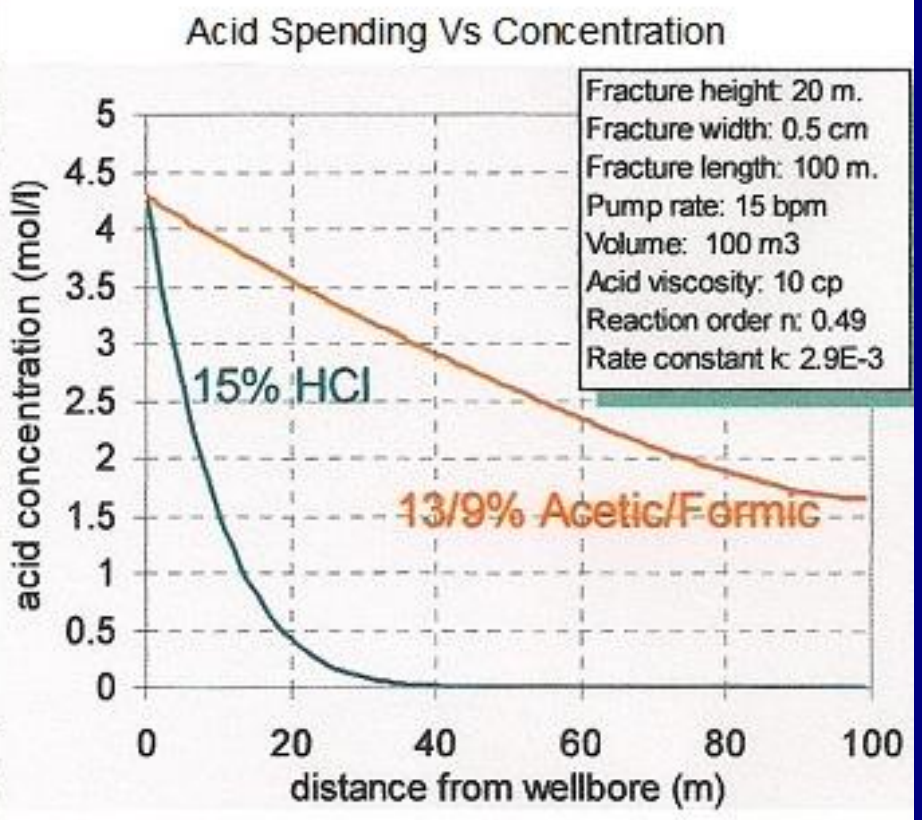
Case History –Typical Frac with Organic Acid in Venezuela

Acid Fracture Treatment

Stage	Fluid	Volume bbl	Rate bpm
1	Organic acid	5	2
2	Gelled water	145	2-18
3	Crosslinked PAD	200	18
4	Gelled Organic Acid	220	18
5	Crosslinked PAD	100	18
6	Gelled Organic Acid	220	18
7	Crosslinked PAD	100	18
8	Gelled Organic Acid	220	18
9	Gelled water	200	18-20
10	Organic Acid (CFA)	170	20-4
11	Organic Acid (CFA)	40	4
12	Water w/methanol	50	4
13	Water	161	4

Organic Acid Vs HCl concentration

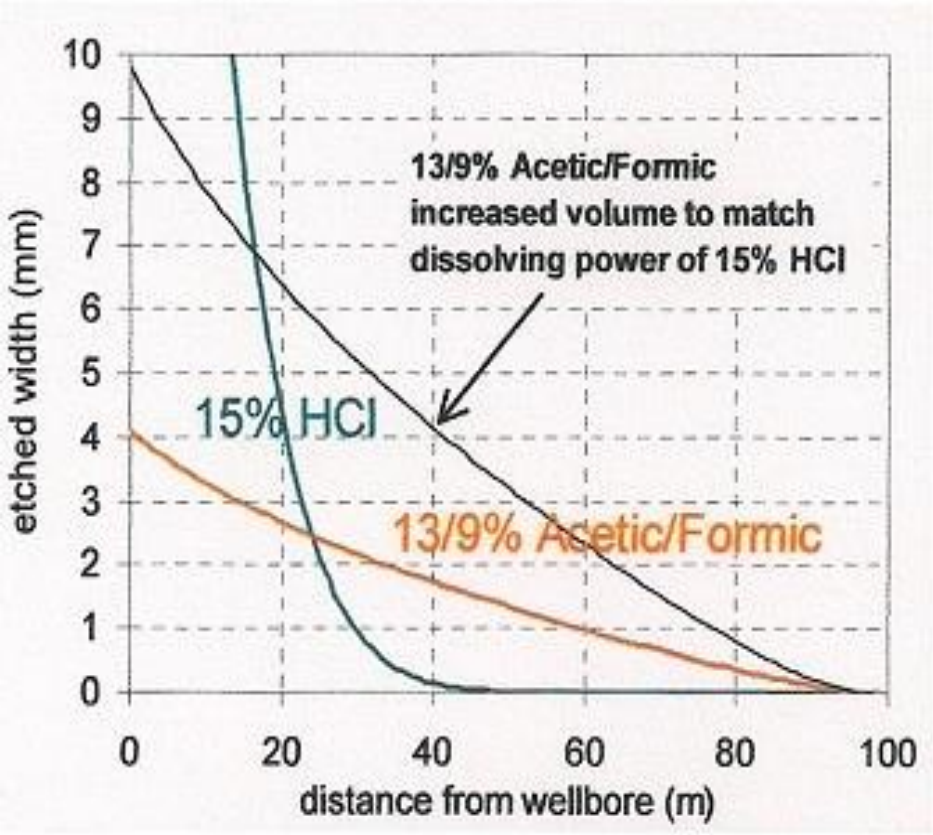
acid mix	% of acid component spend			equiv. HCl %
	HCl	Acetic	Formic	
10% Acetic	-	54	-	3.4
10% Formic	-	-	85	6.8
13/9% Ac/Fo	-	31	82	8.5
7/11% HCl/Fo	100	-	78	14.1
15/10% HCl/Ac	100	24	-	16.5



Source SPE 82211

Case History –Typical Frac with Organic Acid in Venezuela

Etched width Vs Frac Length



Acid Dissociation constant and strength

acid type	diss. constant K_A (mol/l)	strength of 1 mol/l pH	strength of 1 mol/l $[H^+]$ mol/l
HCl	>>1	0	1.0
Formic	1.8E-4	1.8	0.016
Acetic	1.8E-5	2.3	0.005

Pre & Post Job Production Results

Well	Net Pay ft	Prod. Before bopd	Prod. After bopd
A	14	0	1252
B	22	350	1717
C	17	0	1940
D	26	1000	3152
E	47	1525	4290
F	22	0	260
G	16	450	2005
H	9	0	350
I	45	0	2485
J	25	0	882
K	28	294	2162
Total		3619	20495

~ 700 gal/ft of acid

Source SPE 82211

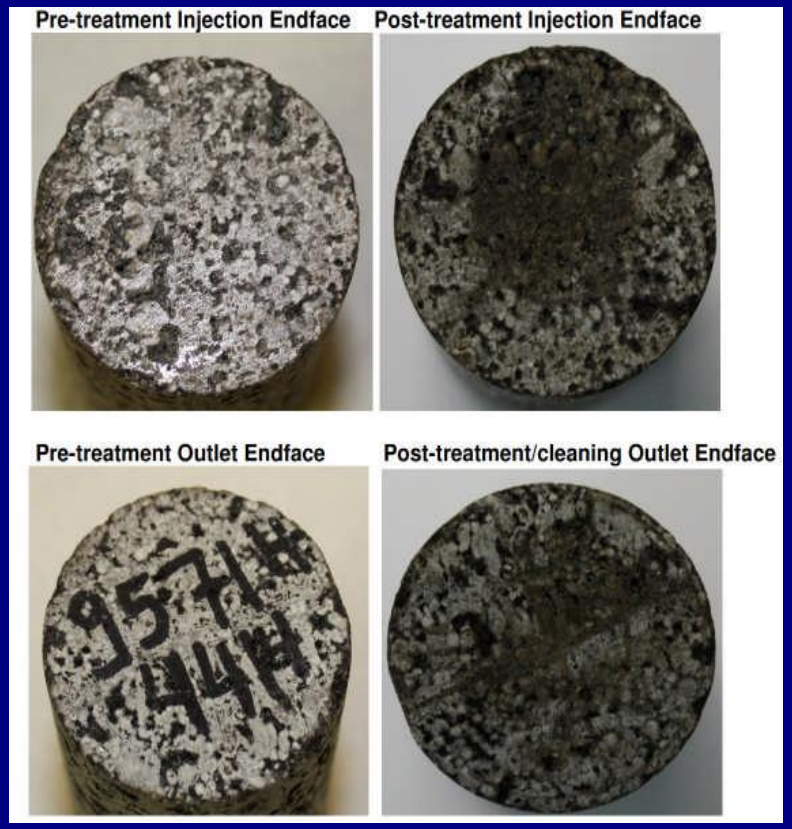
Alternative Solution – Treating Acid Gelled with Viscoelastic Surfactant

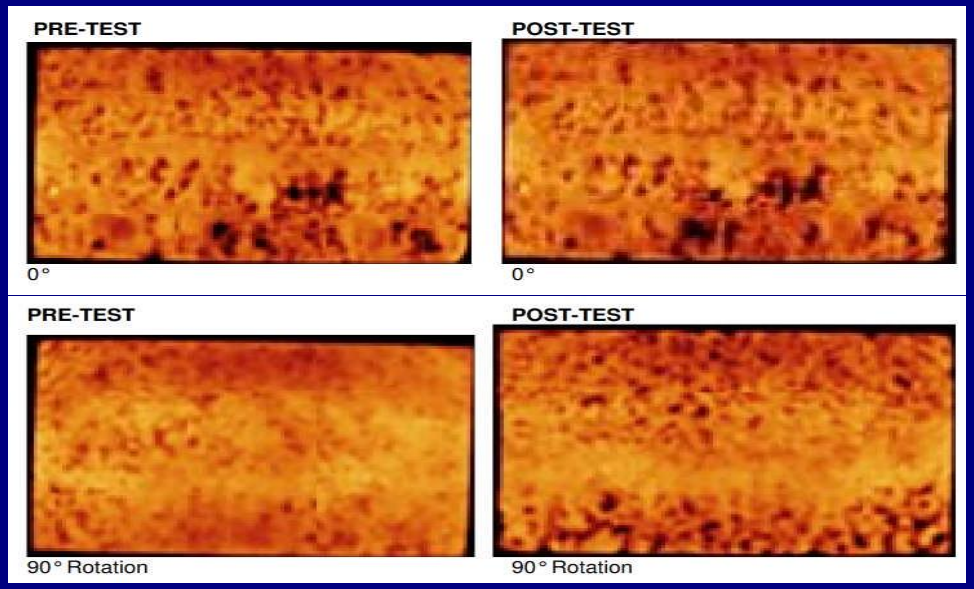
- Bullheaded Acid Treatment

- Continuous use of VS in HCl instead of Diverter Stage
  - Better Diversion , complete zone treatment
  - Better Fluid Loss Control , Longer Fractures
  - Etching pending on Formation's nature

- No Chemical Acid retardation
- VS Works with HCl, not optimized for other acids
- Still not Optimum !!

Alternative Solution – Treatment Brazil Pre & Post Salt Reservoirs

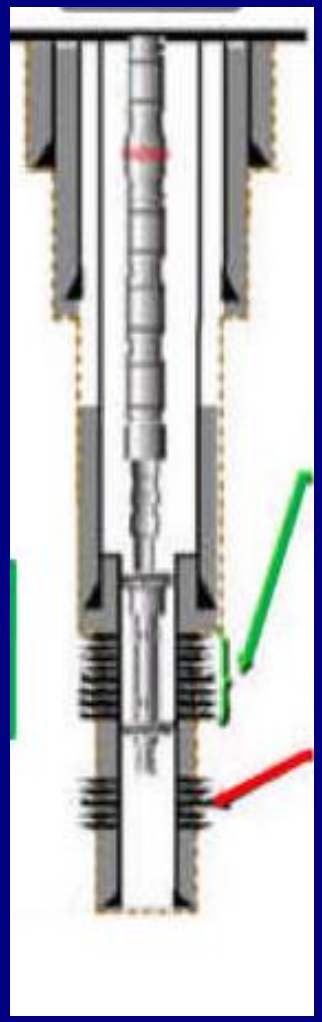


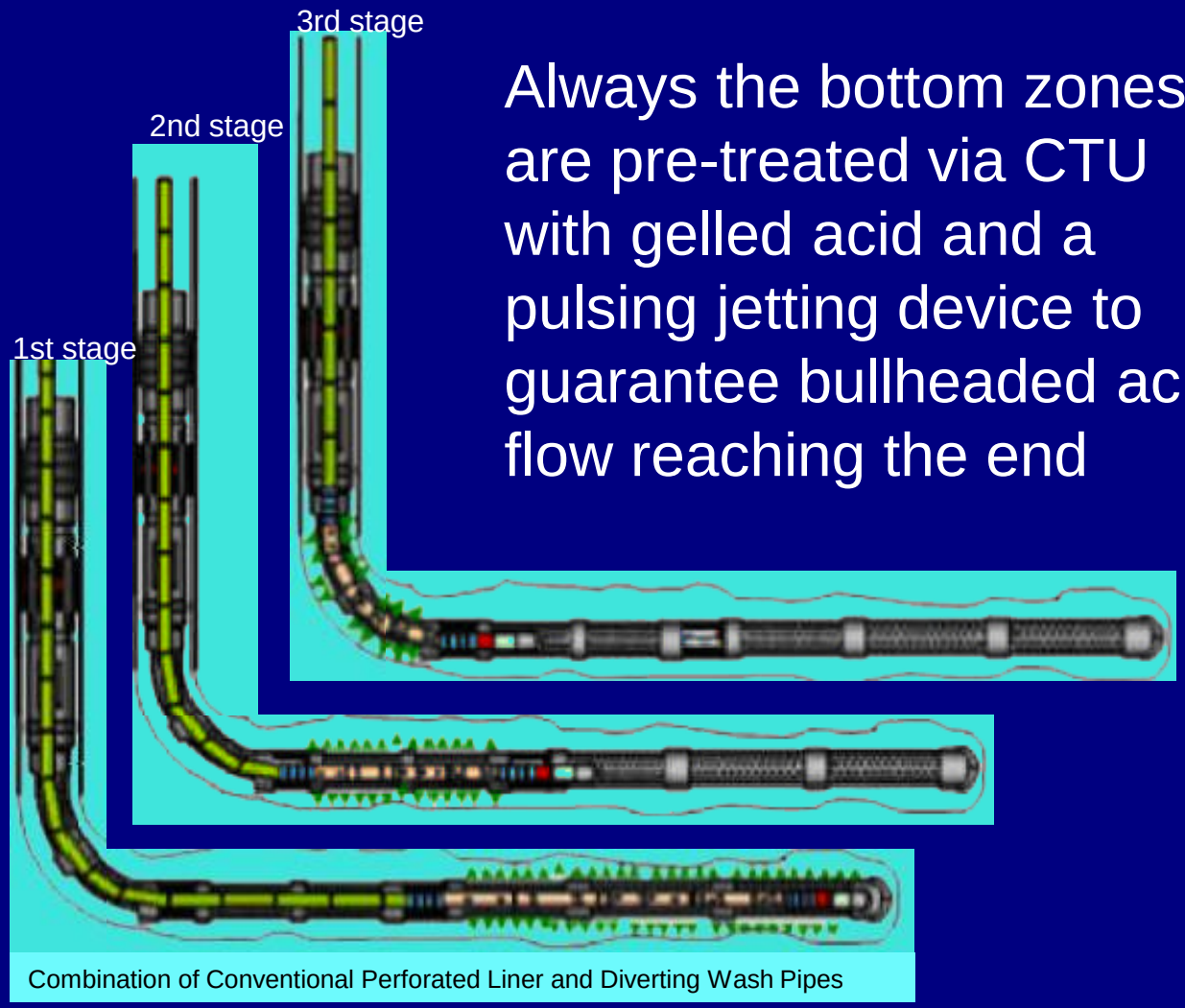


- Core Flow Test indicate
  - No worm holes
  - Pore enlargement
  - Homogeneous acid distribution
  - Oil Permeability increased 500 times
  - Acid 10% HCl with 6% VE surfactant

Source SPE 165089

Alternative Solution –Treatment Brazil Pre & Post Salt Reservoirs



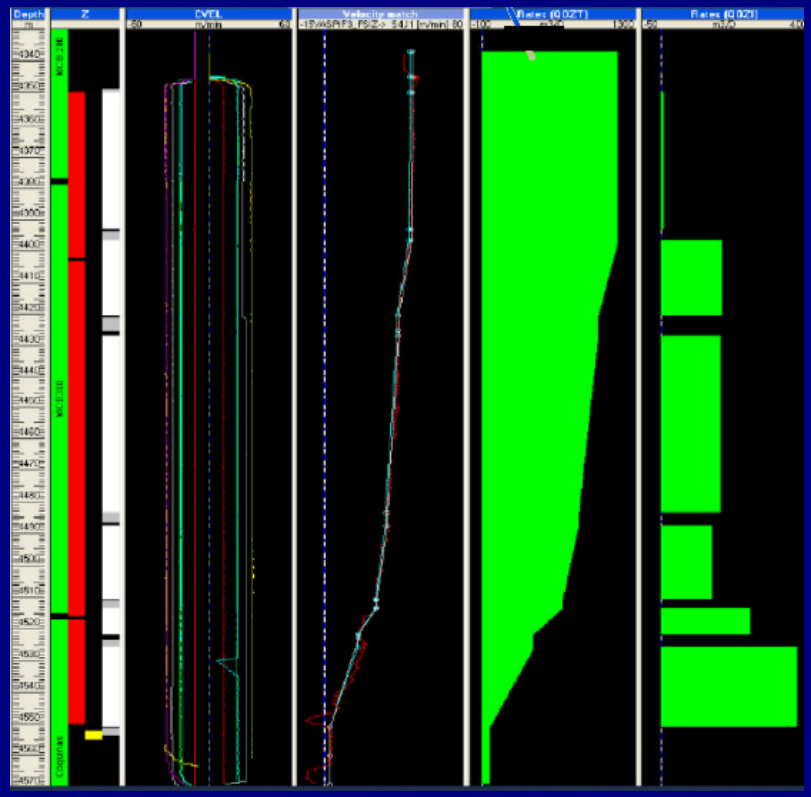


Always the bottom zones are pre-treated via CTU with gelled acid and a pulsing jetting device to guarantee bullheaded acid flow reaching the end

Source SPE 165089

Case History 1 - Vertical Well

Well Type	Oil Producer
Well Inclination	Vertical
Rig Type	Semi-Submersible
Water Depth	4,690 ft
Last Casing	7”- 32 lbm/ft
Perforated Interval	14,268 – 14,924 ft
Perforation Length,	656 ft
Formation	Pre-Salt Carbonate
Reservoir Permeability	23 mD (14,268 – 14,439 ft) 35 mD (14,439 – 14,816 ft) 83 mD (14,816 – 14,924 ft)
Reservoir Pressure	6854 psi
Reservoir Temperature	255 ^{o}F @ 14,353 ft
Oil Viscosity	0.7 cP
Oil Grade	31° API
Workstring	Production String



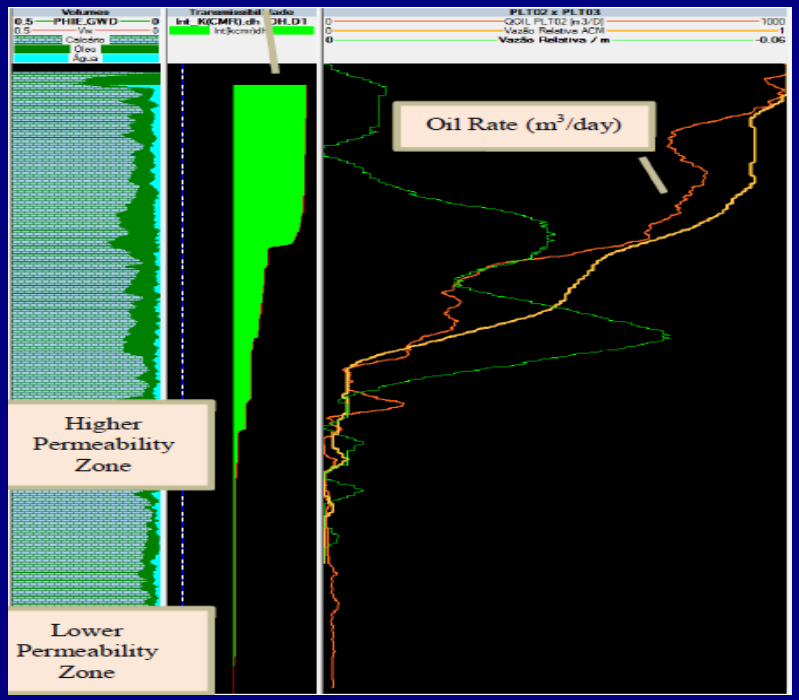
- 2450 Bbl 15% Acid with 6% Surfactant
- Equivalent to ~156 Gal/ft
- 1400 Bio Ball Sealers after 490 Bbl
- Pump rate increased to 20 BPM

	PRODUCTIVITY (bbl/day/psi)	DAMAGE RATIO (%)	SKIN
WELL C	34	0.57	-3.4

Source SPE 165089

Case History 2 - Vertical Well

Well Type	Oil Producer
Well Inclination	Vertical
Rig Type	Semi-Submersible
Water Depth	6,947 ft
Last Casing	7”- 32 lbm/ft @ 18,043 ft
Perforated Interval	16,072 – 16,384 ft
Horizontal Length,	312 ft
Formation	Pre-Salt Carbonate
Reservoir Permeability	6 – 20 mD – offset well
Reservoir Porosity	14 %
Reservoir Temperature	144 °F
Oil Viscosity	1.3 cP – offset well
Oil Grade	27 API
Workstring	5 1/2” Production String @ 15,801 ft



- 2000 Bbl 15% Acid with 6% Surfactant
- Equivalent to ~ 270 Gal/ft
- 1800 Bio Ball Sealers after 200 Bbl
- Pump rate increased to 15 Bpm
- Average Production 6 months test - 12578 BOPD

	ProductionTest Before Acidizing	Production Test After Acidizing
Skin	27.8	-3.71
Permeability (mD)	205	334
Conductivity (mD.m)	18600	30400
Productivity (bbl/day/psi)	4.3	40.2
Damage Ratio	4.8	0.7

Source SPE 165089

Case History 3 - Horizontal Well

Well Type	Oil Producer
Well Inclination	Horizontal
Rig Type	Semi-Submersible
Water Depth	3,857 ft
Last Casing	9 5/8"- 47 lbm/ft @ 13,737 ft
Horizontal Well Interval	13,737 – 18,697 ft
Horizontal Length,	4,959 ft
Horizontal Well Casing	7" Slotted Liner – not cemented
Formation	Calcarenite – Albian Carbonate
Reservoir Permeability	1 – 100 mD
Reservoir Porosity	12 %
Reservoir Temperature	226 ^{o}F – offset well
Oil Viscosity	1.2 – 1.6 cP
Natural Faults	yes
Workstring	5" – 19.5 lbm/ft

WELL A	PRODUCTIVITY (bbl/day/psi)	DAMAGE RATIO (%)	SKIN
	14.96	0.49	-3.4

- 2335 Bbl 17% HCl with 6% Surfactant
- Equivalent to ~ 20 Gal/ft
- Pump rate oscillated from 12 to 17 BPM

Source SPE 165089

Conclusions – Deeper Limestone Acidizing
Quantum Steps & or Evolution

- Dissolve Rock with acids - higher concentration, organic Acids, Sequestering agents
  - GLDA, Citric Acid
- Alternating pad-acid stages - Use Viscoelastic Surfactants
- Cleaner X-Link Acids - less damaging polymers
- Gelled Organic acids-
  - (Acetic, Formic, EDTA, HEDTA, etc ..)

Conclusions - Everything is Better But we still need to improve!

- Matrix Treatments
  - Acid concentration & retardation should be Ramped inversely proportional to radial flow area
  - Acid must be stronger , in situ gelled and retarded
  - Using Ester as pre-flushes is an interesting alternative

- Acid Fracturing Treatments
  - Spearhead or Pads should be highly retarded In Situ Acids
  - Avoid Acid dilution - Water, Oils, Gases (Foams & Emulsions)
  - Ramp Acid Retardation

- Lateral Tunneling
  - Increase Laterals per elevation
  - Increase Length & Optimize Lateral dissolved diameter
  - New Tool , faster and also applicable in Cased Wells

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