Unconventional Reservoirs

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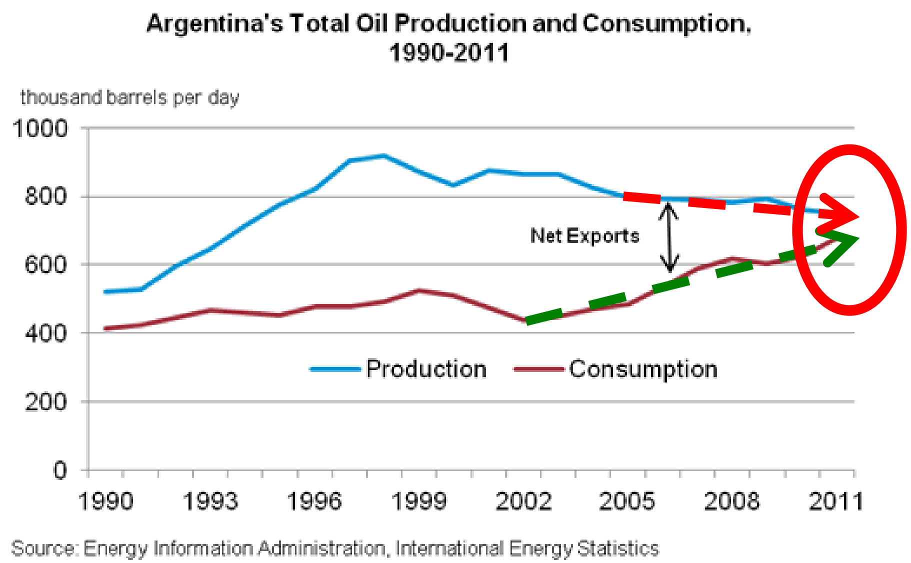
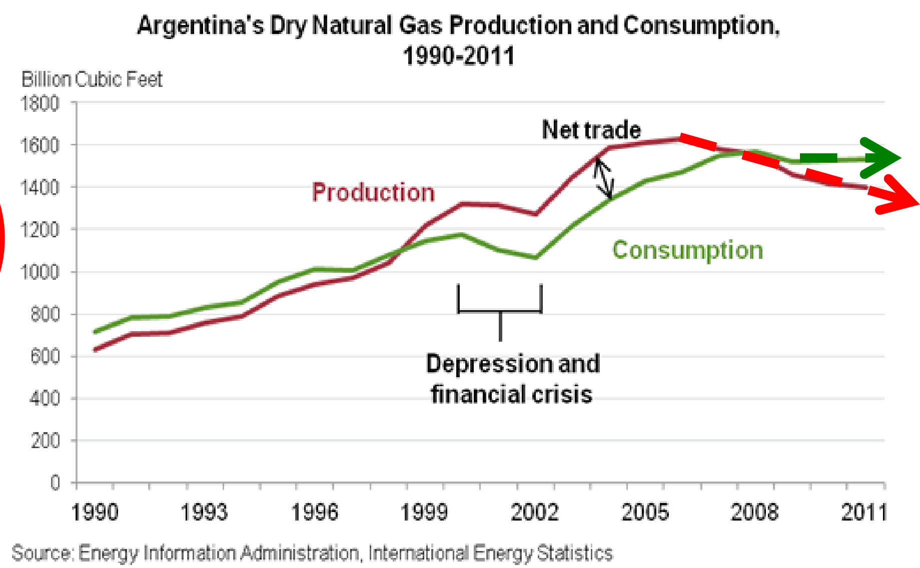
Why do we need Unconventional Reservoirs (UN)?

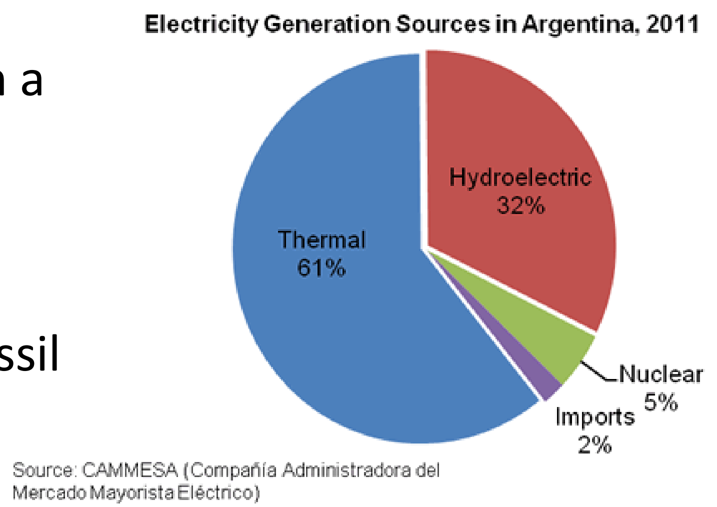
- World daily life is built on different types of energy
- Despite economy suffers ups and downs as a general trend energy demand goes up
  - Growing population and income per capita
  - BRICS conglomerate's economy is highly energy demanding
  - Modern life depends basically on electricity and/or natural gas
  - Globalization has incremented traveling around the globe, thus increasing different types of fuel demand for air, sea and ground transportation
- Conventional sources are running out
  - No more giants like Saudi Arabia
  - Large reserves in environmentally sensitive areas (Alaska, Florida, Pacific)
  - Subsalt discoveries in Brazil - expensive
  - Counterpart in Africa – expensive
  - Selfsufficiency is critical for certain countries under the world political scenario
- Renewables (Wind, Solar, Biodiesel, Biomass, Geothermal, Nuclear, Hydropower, Marine power, Anaerobic digestion/algae) are not enough to fill in the gap of total energy demand

Is Argentina an Exception?





- Demand trend of gas and oil goes up
- Oil and gas production decreases to reach a crossover point
  - Need to import energy
  - Lost of selfsufficiency
- 2/3 of the electricity is generated from fossil fuels basically natural gas and gas oil
  - Other sources can not meet demand gap



The Size of the Treasure – Worth it?

Top 10 countries with technically recoverable shale oil and gas resources

Rank	Country	Shale oil (billion barrels)	
1	Russia	75	
2	U.S.[1]	58	(48)
3	China	32	
4	Argentina	27	
5	Libya	26	
6	Venezuela	13	
7	Mexico	13	
8	Pakistan	9	
Top 10 countries with technically recoverable shale oil resources			
10	Indonesia	8	
	World Total	345	(335)

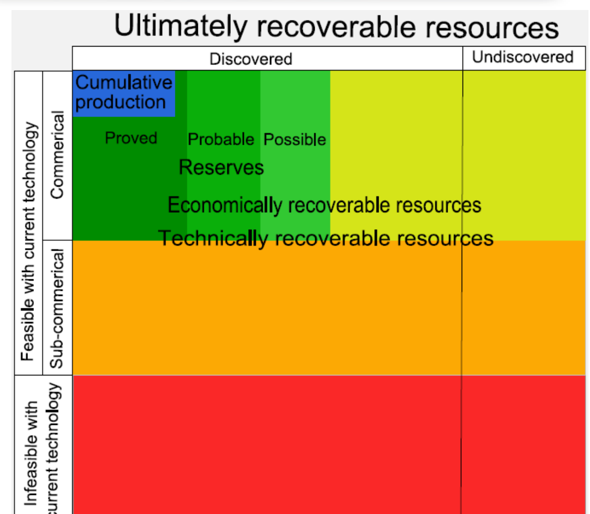
[1] EIA estimates used for ranking order. ARI estimates in parentheses.

Rank	Country	Shale gas (trillion cubic feet)	
1	China	1,115	
2	Argentina	802	
3	Algeria	707	
4	U.S.[1]	665	(1,161)
5	Canada	573	
6	Mexico	545	
7	Australia	437	
8	South Africa	390	
9	Russia	285	
10	Brazil	245	
	World Total	7,299	(7,795)

[1] EIA estimates used for ranking order. ARI estimates in parentheses.

Source: EIA, 2013

Formation
Vaca Muerta
Los Molles
Agrio
D-129
Los Monos
Lower Inoceramus
Cacheuta
Pre-Cuyo
Tobifera
Neocomiano
Yacoraite



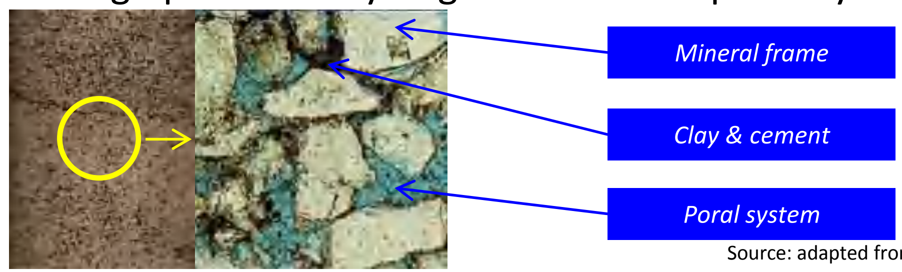
Source: ICEPT, 2012

What are Unconventional Reservoirs?

- Industry has defined long time ago that unconventional reservoirs are those that have permeability to gas lower than 0.1 mD, a better description is needed
  - Tax considerations
  - Not all UR types fit into this classification
- One common categorization (and very broad by the way) is:
  - Tight reservoirs
  - Organic rich shale reservoirs
  - Oil shale
  - CBM
  - Hydrates
  - Tar sands and heavy oil sandstones
- In order to understand the reservoir, need to consider:
  - Hydrocarbon generation
  - Migration if any
  - Hydrocarbon storage
  - Flow mechanism
  - Structural discontinuities
- Then complete and stimulate the well…

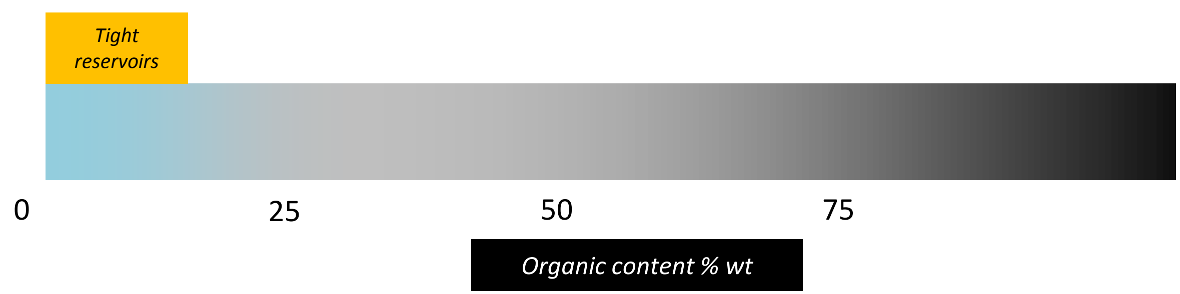
Tight Reservoirs (TR)

- By definition, reservoirs with permeability less than 0.1 mD to gas. Really ambiguous
  - Actually tight oil and tight gas reservoirs are being developed
- Hydrocarbons were generated at another source rock. Negligible organic material
- Migration occurs and hydrocarbons get trapped due to seals or extremely low permeability barriers
  - If hydrocarbons migrate there is enough permeability to gas to flow and porosity to store them, ergo:
  - Flow mechanism: Darcy´s flow
  - Storage: pore volume



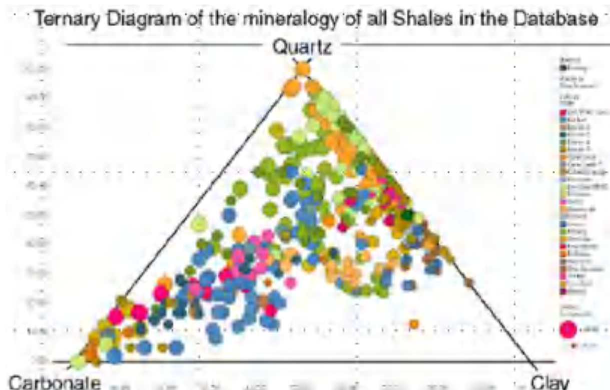
Source: adapted from Franco, 2011

- Rock types:
  - Sandstones: mostly quartz with clays and cementitious materials
  - Carbonates: low to very low permeability carbonates
  - Igneous and metamorphic rocks like basement
- Requires massive hydraulic fractures to get commercial rates

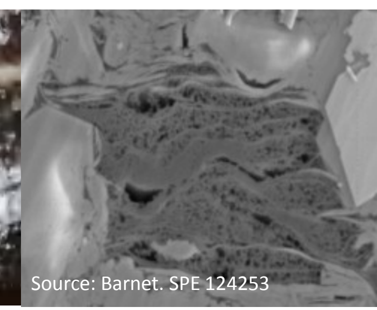


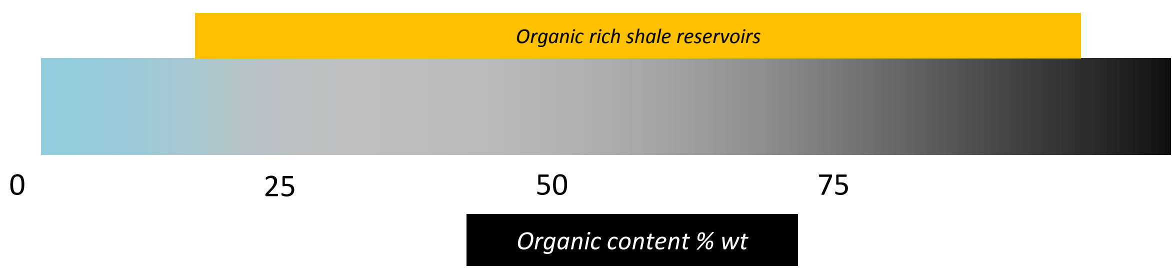
Organic Rich Shale Reservoirs (SR)

- Hydrocarbons are generated, stored and trapped in the same rock
- Definition of shale based on grain size rather than mineralogy composition
- Due to its extremely low permeability, hydrocarbons did not have enough time to migrate
  - As there is low permeability there is also low porosity
  - Presence of organic material not converted to hydrocarbon (kerogen)
  - Flow mechanism: Darcy´s flow in the matrix, Fick´s law in the organic portion
  - Storage: pore volume and adsorption in the organic material
- Rock types:
  - Siliceous
  - Carbonaceous
  - Argillaceous



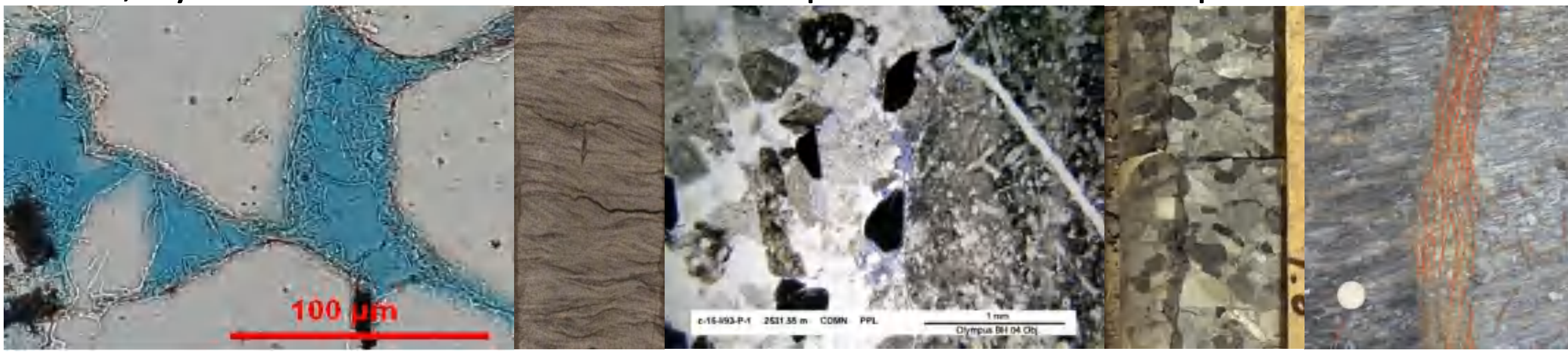
Source: SPE 115258





Hydrocarbons Storage

- In TR, hydrocarbons are stored in void space which include pores and fissures

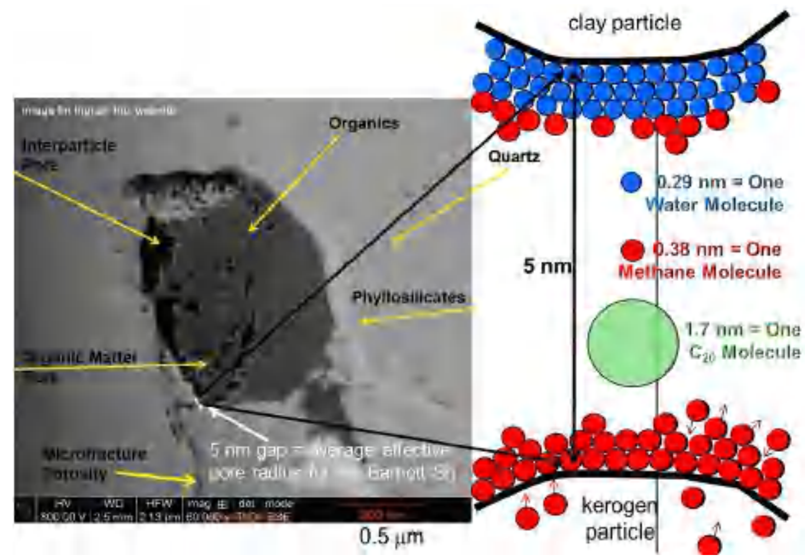


Source: Gale & Laubach

- In SR, total gas composed of three sources
  - Free gas
    - In matrix and kerogen pore space
    - Fractures and fissures (all scales)
  - Sorbed gas in kerogen and N.S. clays surface
  - Dissolved gas in liquid hydrocarbons and water

Fuente: Pitman, 2011

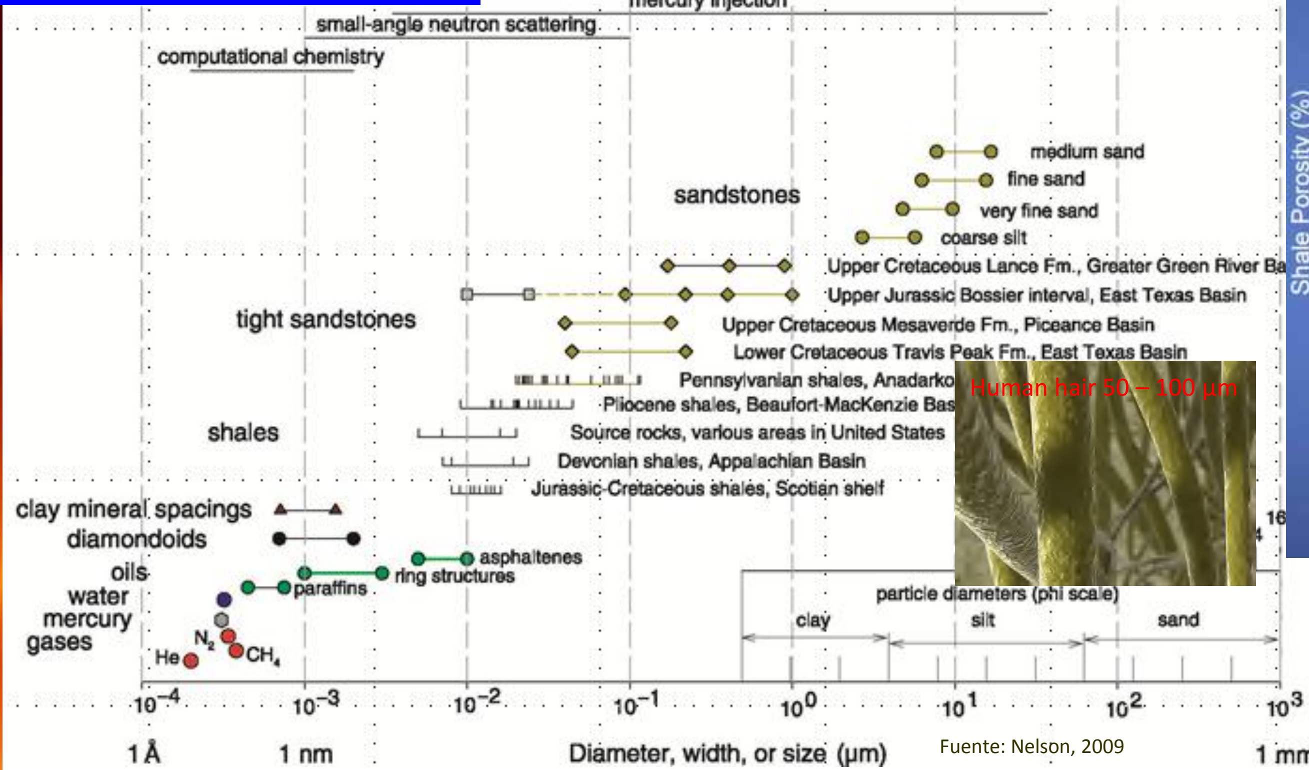
Source: Bustin, 2009



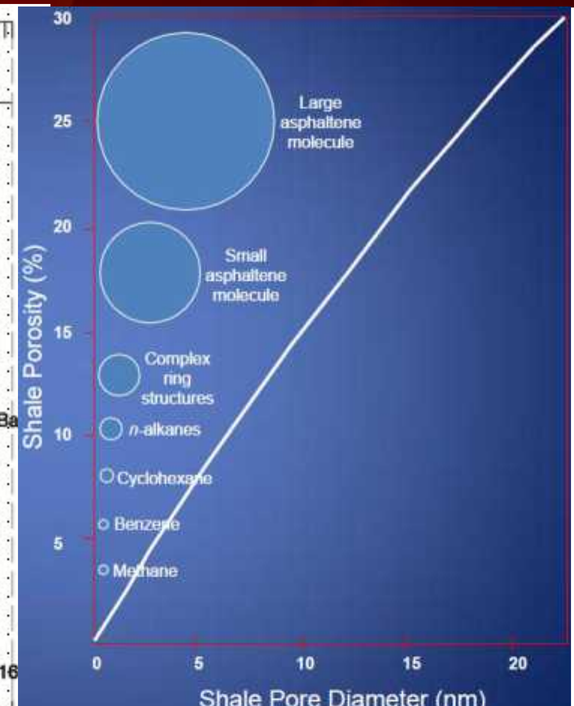
Fuente: Williams, 2012

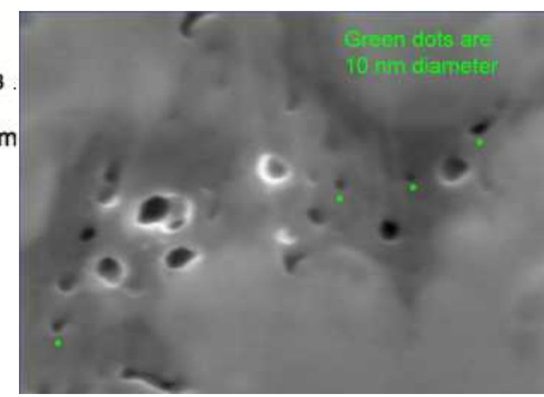
The "NANO" World in Perspective

1 µm = 1 E-06 m = 0.001 mm
1nm = 0.001 µm = 1E-09 m
1 Angstrom = 0.1 nm



Fuente: Nelson, 2009





Fuente: Jarvie, 2008

Conventional Oil & Gas

$D_{pore} \geq 1$ µm

$K \geq 1$ mD

Tight Reservoirs

1 µm $\geq D_{pore} \geq 10^{-3}$ µm

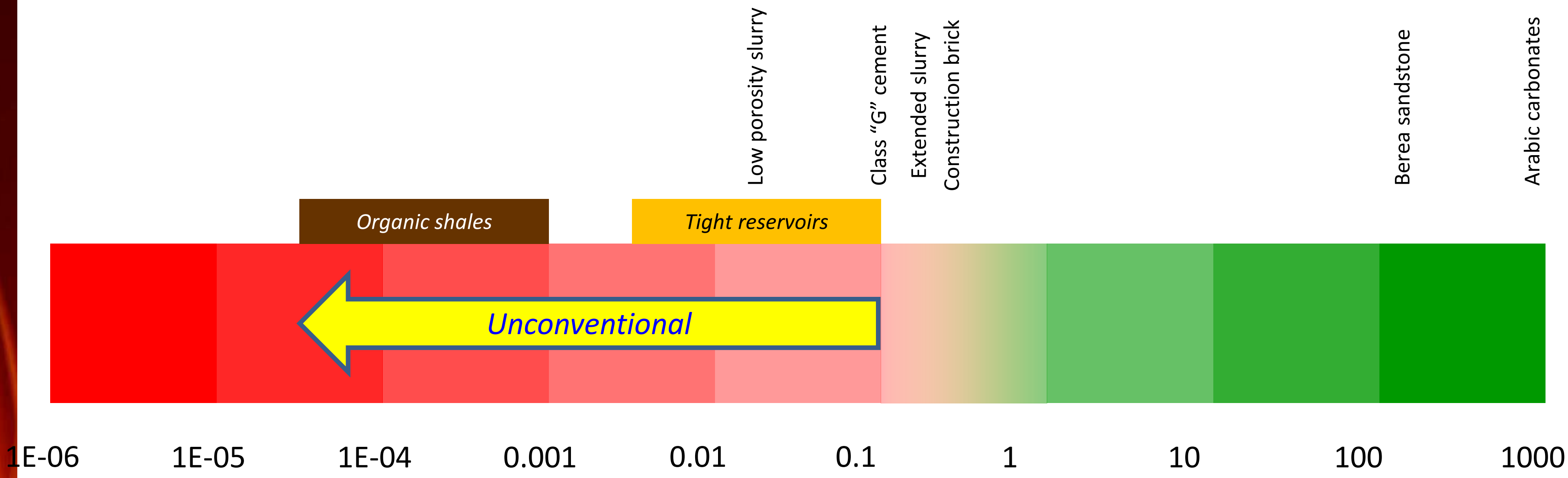
1 mD $\geq K \geq$ 1 µD

Shale Reservoirs

1 µm $\geq D_{pore} \geq 10^{-3}$ µm

10^{-9} mD $\geq K \geq 10^{-3}$ mD

Reservoir Permeability & Flow Capacity

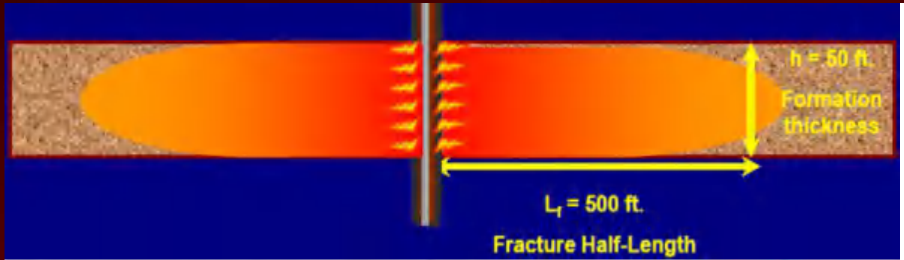


Dry Gas / Darcy Flow	
P_res	5500 psi
BHFP	1500 psi
BHT	200 ºF
SG_gas	0.65
Thickness	5 m

Qg \ K_gas	10 mD	1 mD	0.1 mD	0.01 mD
m^3gpd	924,000	92,400	9,240	924

- For dry gas, no commercial rates below 0.1 mD unless well is hydraulically fractured
- If multiphase flow exists, gas production is much lower
- In shales K<<0.1 mD, so matrix flow is extremely low. Need to have extremely large contact areas to get economical rates
- Presence of natural fissures and fractures enhance fluid flow tremendously

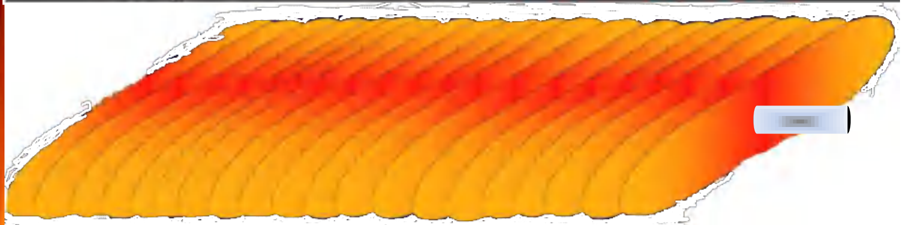
Contact Area and Fluid Properties Impact



Openhole completion: 8¾" hole diameter * 50 ft = 115 ft² of contact

Cased hole completion: 4 spf, with 2 ft. penetration beyond cement
200 perf tunnels, ½ inch diameter = 52 ft² of contact

Fracture Stimulated Completion: 500 ft half-length
2 wings * 2 faces * 500 ft * 50 ft = 100,000 ft² of contact



Openhole completion: 6" hole diameter * 50 ft = 7850 ft² of contact

Cased hole completion: 1 spf, with 2 ft. penetration beyond cement
5000 perf tunnels, ½ inch diameter = 1310 ft² of contact

Fracture Stimulated Completion: 500 ft half-length
20 Stages * 2 wings * 2 faces * 500 ft * 50 ft = 2,000,000 ft² of contact

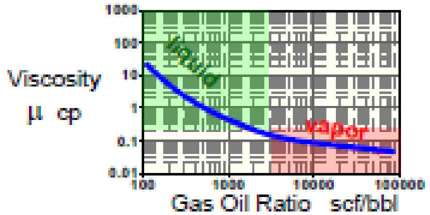
Source: Pearson, 2013

HF can increase reservoir contact in a vertical well ~1,000 fold!

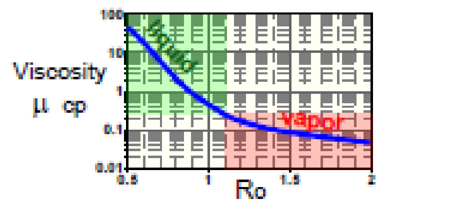
Multi-hyd fracs in HZ's increase reservoir contact area >10,000 fold over a vert well!

$$Q \approx \frac{k(Si) \ * H \ * \Delta P}{\mu}$$

Viscosity matters for fluid flow in shales… even for gases



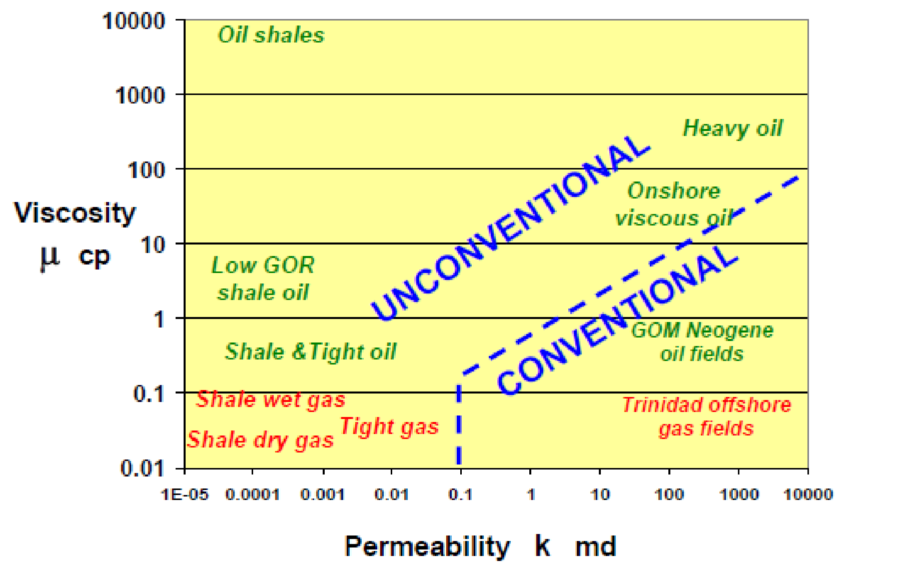
Viscosity of petroleum retained in shales is mostly a function of GOR…



…so μ correlates with Ro and continues to decrease even in the gas window

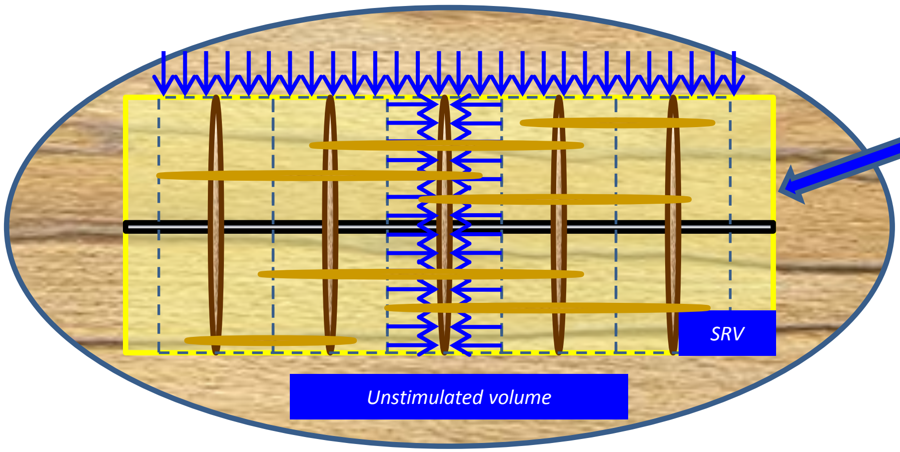
Source: Cander, 2012

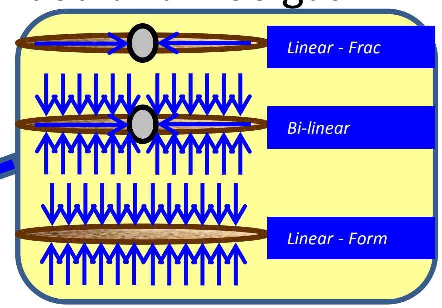
Unconventionals can be defined on a graph of viscosity (μ) vs. permeability (k)

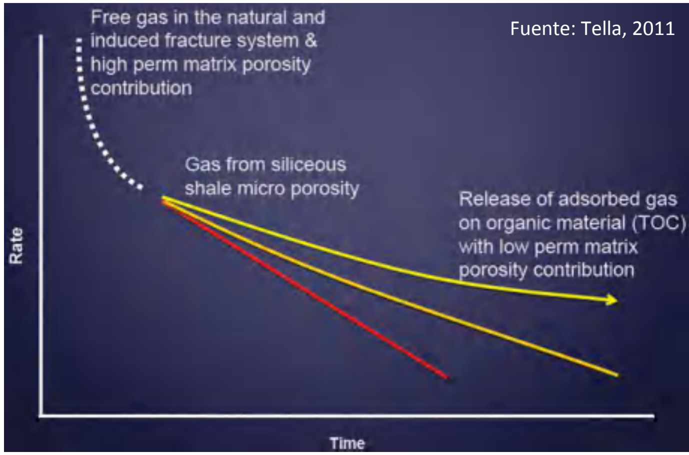


Production in Shale Reservoirs

- If permeability is less than 5E-5 mD gas only flows within the SRV to HF's
  - No flow beyond frac tip in 30 years. Effect is magnified when oil is produced
  - Linear and bilinear flow
  - Flow area is restricted in shales. The only thing we can do is try to activate part of the reservoir (SRV) if appropiate conditions are found. Frac interference
  - Darcy, Knudsen and diffusive flow. Adsorbed and free gas







k, mD	Xf, ft / m	t_int, hr	T_int, días	T_int, años
0.1	100 / 30.5	2.28	0.095	~
0.1	300 / 91.4	20.52	0.855	~
0.001	100 / 30.5	228	9.5	~
0.001	300 / 91.4	2052	85.5	0.2
0.00001	100 / 30.5	22800	950	2.6
0.00001	300 / 91.4	205200	8550	23.4

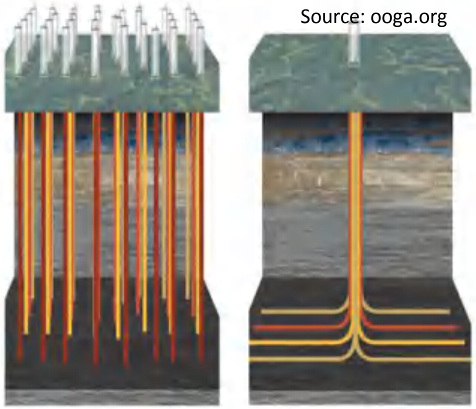
$$t \geq \frac{1.14 \times 10^4 \phi c_t \mu x_F^2}{k}$$

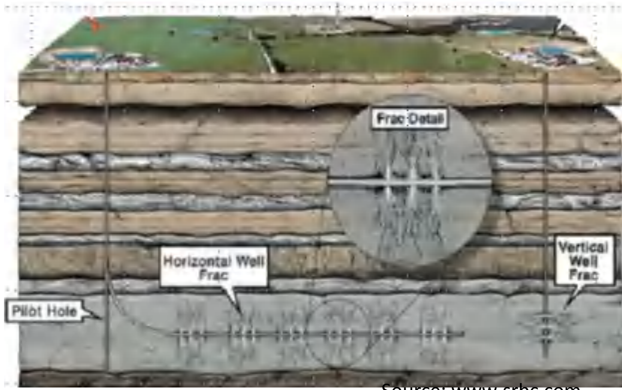
But Xf,eff= D/2 !

Why Multi-fractured Horizontal Wells?

- Mandatory state regulations
  - Requirement of minimum ground disturbance
  - Access to reservoirs under populated cities, farming areas, preserved lands, water resources
- Cheapest way to put in the ground several wells at the same time!
  - Closer well spacing. Drainage area is much smaller
  - Pad drilling and completion. Offshore approach
    - Centralized facilities. Smaller foot print
- Vertical wells
  - Field trials, pilot hole
  - Frac mapping monitor wells
  - Disposal wells

Source: ooga.org





Source: www.srbc.com

Source: epmag.com

Jonah field, 40 acres well spacing

Marcellus, 40 acres well spacing in pads

Source: Griffin, 2007

Well Construction – Factory Mode

Pad Drilling

Source: Griffin, 2007

Frac Head

Source: SA Express News

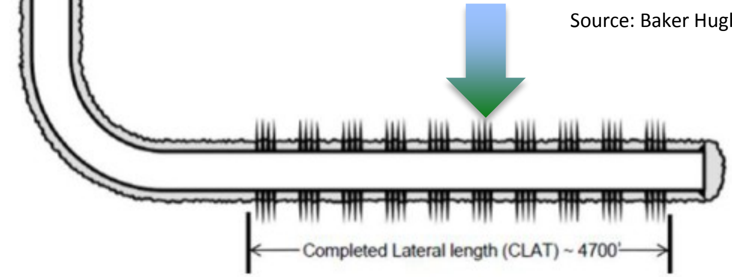
Casing & Cementing

Source: EXCO, 2012

Hydraulic Fracturing Operations at Pad Site

Perforating

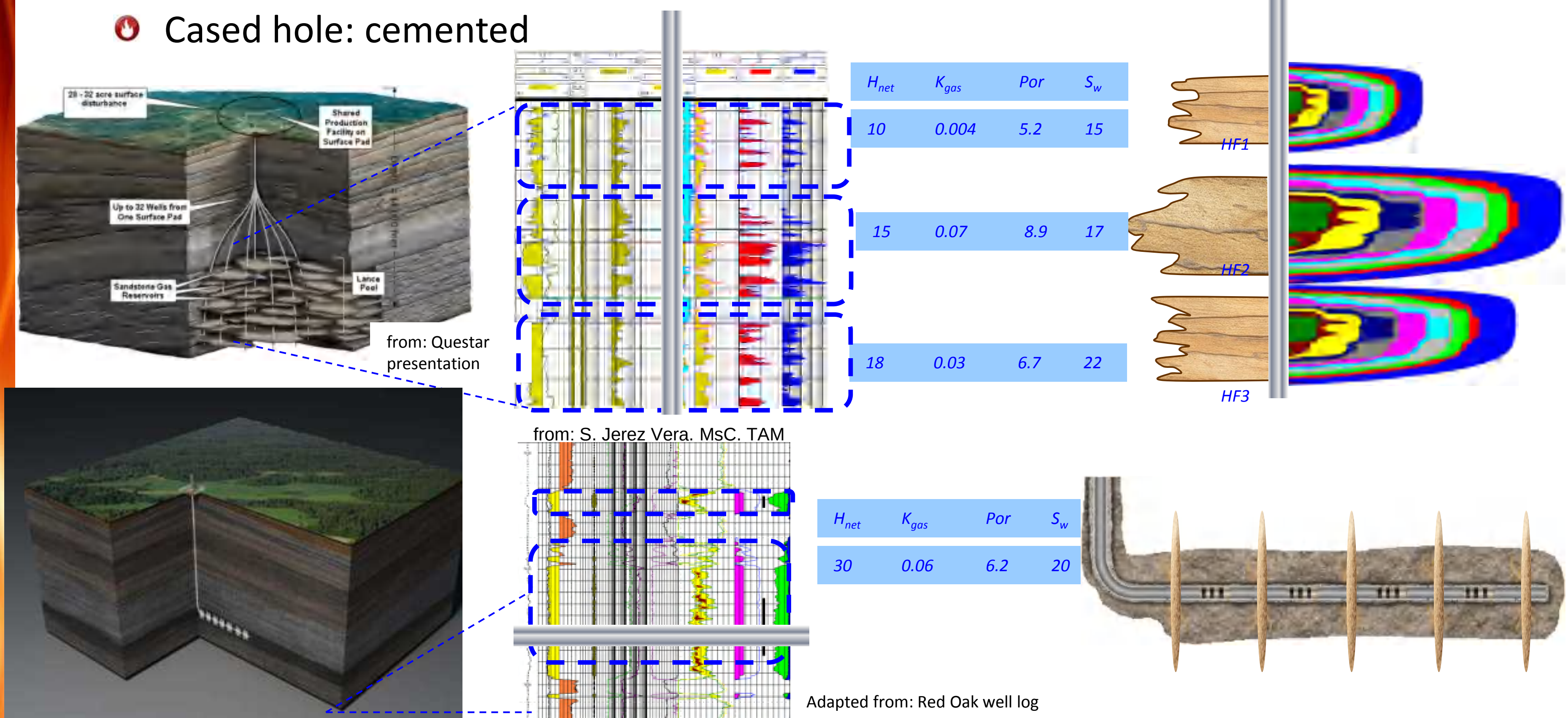
Source: Baker Hughes



Source: Thomson, 2012

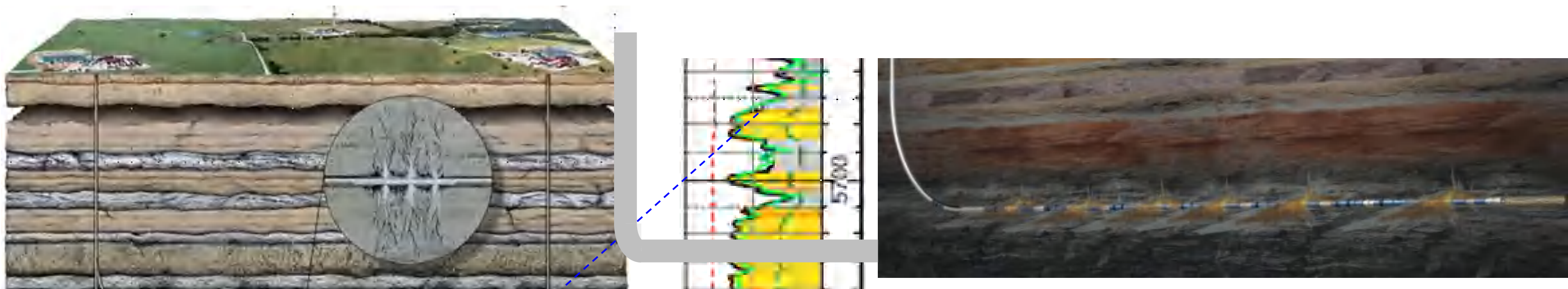
TR Completion and Stimulation

- By reservoir type
  - Multiple stacked layers: multi hydraulically fractured vertical wells.
  - Single or double individual reservoirs: mostly horizontal wells. First wells must be vertical for gathering information. Multiple hydraulic fractures
- By completion type
  - Cased and un-cemented completions. Packers for zonal or compartment isolation
  - Cased hole: cemented



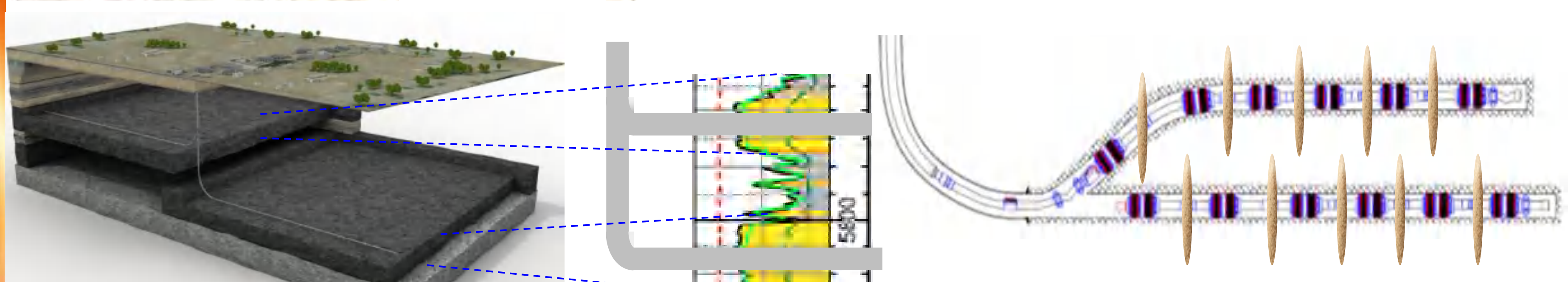
SR Completion and Stimulation

- By reservoir type
  - Single reservoir: multi hydraulically fractured horizontal wells. Few verticals at beginning for gathering information
  - Double individual reservoirs: dual horizontal wells with multiple hydraulic fractures
- By completion type
  - Cased and un-cemented completions. Packers for zonal or compartment isolation



from: www.srbc.net

Source: PackersPlus



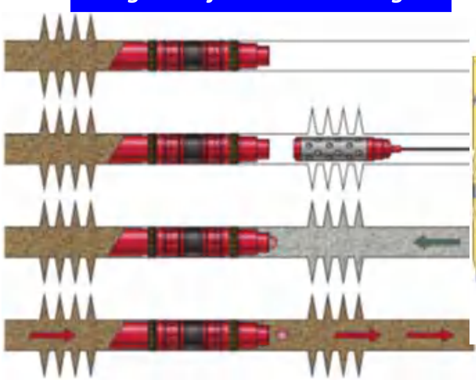
Source: PackersPlus

Adapted from: PackersPlus

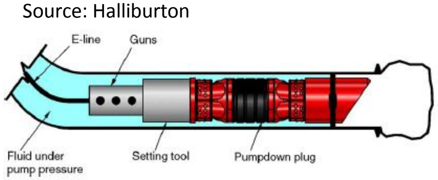
Multi Stage Completions

- Multiples technolgies are available but market dominated by three technologies:
  - Plug & Perf. 70 – 75 % of wells are completed using this technology
  - Ball operated frac ports. 20 – 25 % of wells. Sometimes this and previous method are combined to get more stages
  - CT based techniques. Less than 5 % of wells uses this technology
    - Abrassive jet perforating. Sand or composite plugs to isolate stages
    - Pumping mainly donw thru annulus but also possible thru tbg if diameter is big enough
    - Packer and anchor
    - CT activated frac sleeves

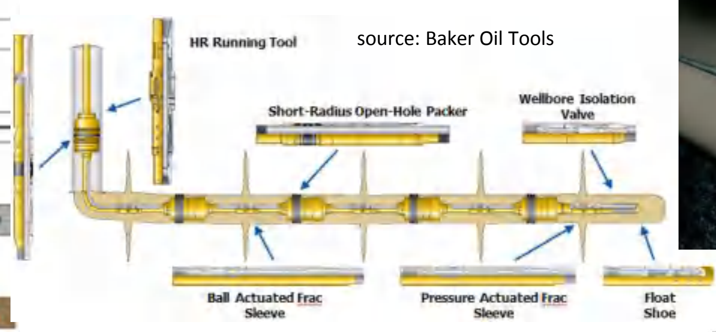
Plug & Perf – Unlimited stages



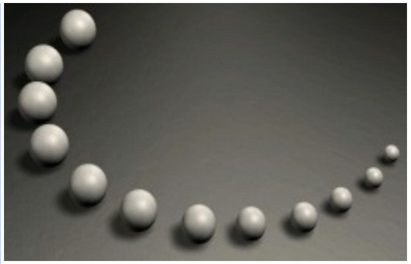
Source: Halliburton



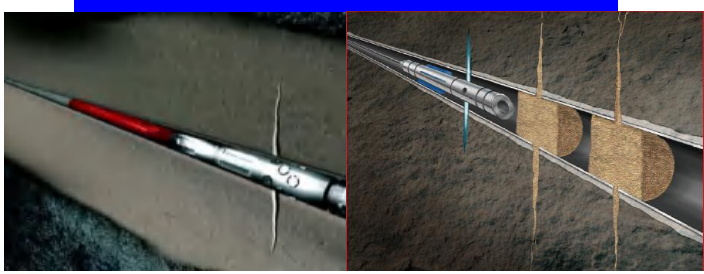
Frac Ports – 40 stages max

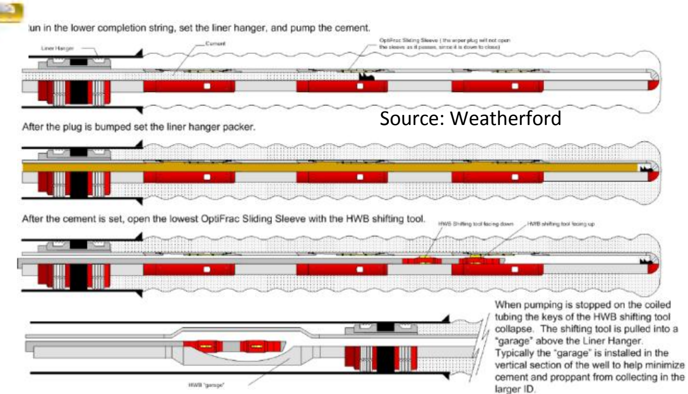


source: Baker Oil Tools



CT based techniques – Unlimited stages

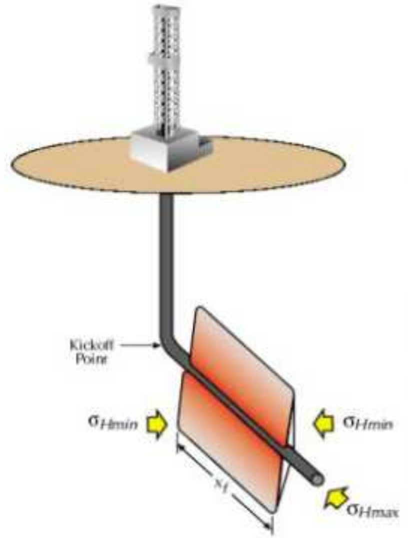


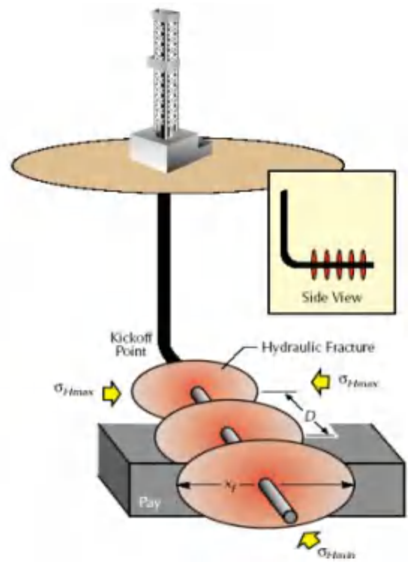


Source: Weatherford

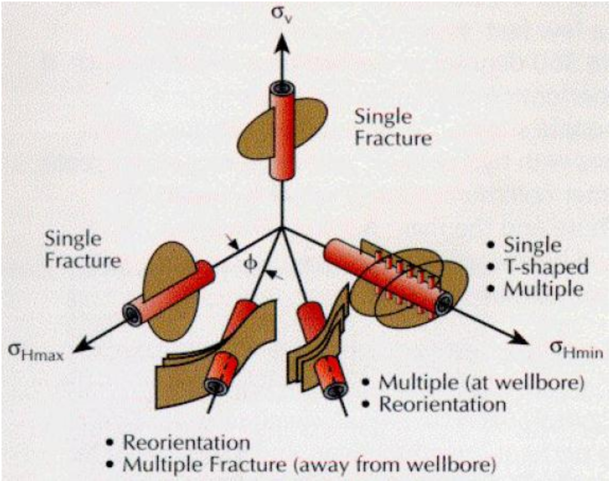
Geomechanics, Well and Frac Orientation

- In vertical wells there are no issues as fracture can initiate anywhere around the wellbore. Unless deviation exists most of the HF will be connected to wellbore
- As HF grows in the same plane of the two principal stresses, the direction of the horizontal wellbore axis will dictate the orientation of the HF to the well
  - Longitudinal fractures: no impact on well productivity if permeability is less than 0.1 mD. In addition, no assurance entire fracture will be connected to wellbore
  - Transverse fractures: best option for reservoirs with permeability less than 0.5 mD. As contact point with wellbore is reduced, choked flow is observed
  - Fractures at any other angle: hard to initiate. Fracture tends to start growing parallel to wellbore axis, until it leaves local stress effects and turns to align to field stress. High breakdown and treatment pressures. High tortuosity. High probability of early screen outs





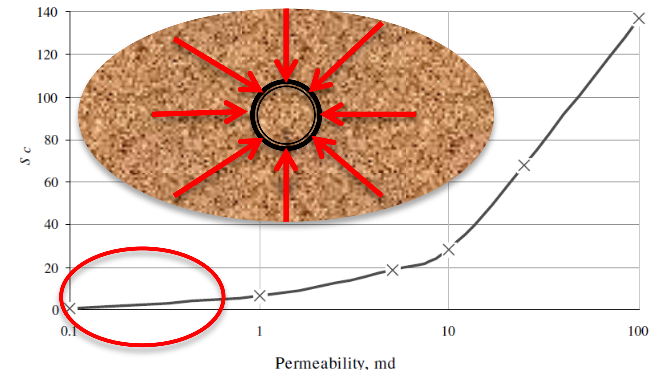
Source: Halliburton



Source: Halliburton

Why Transverse Fractures?

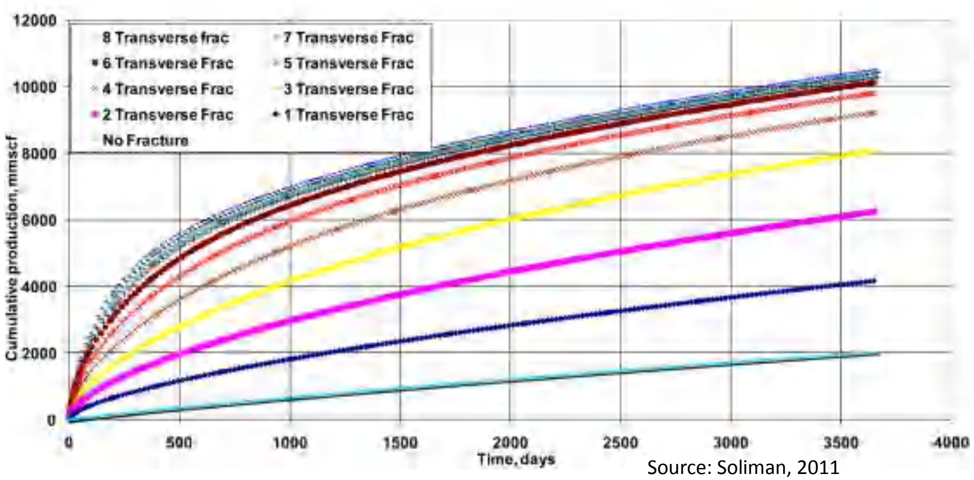
- Transverse HF is only attractive from productivity perspective as permeability decreases
  - Best option for k < 0.5 mD. The lower the K the better the option is
  - Basically choke flow at perfs is the limiting factor
- Multi-fractured horizontal wells provides highest productivity index
  - No other combination can surpass it
  - High number of fractures provides large IP and cumulative production
    - Incremental production diminishes with number of frac stages. Reservoir issues
    - Economical considerations



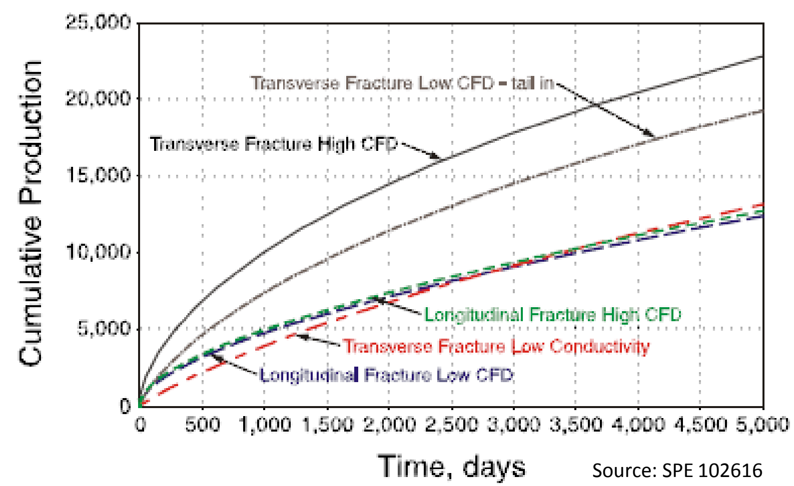
Source: Wang, 2009

$$s_c = \frac{kh}{k_j w}\left[\ln\left(\frac{h}{2r_w}\right) - \frac{\pi}{2}\right]$$

$$J_{DTH} = \frac{1}{(1/J_{DV}) + s_c}$$



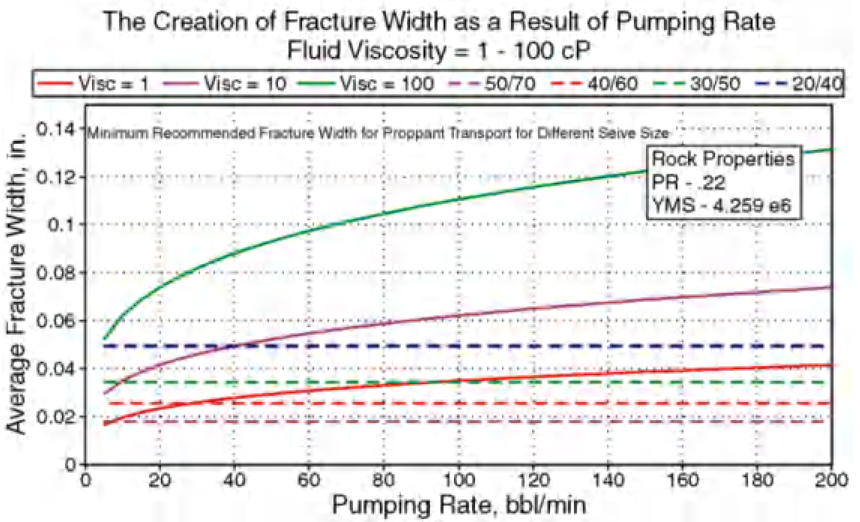
Source: Soliman, 2011



Source: SPE 102616

Frac Design – General Guidelines

- Frac fluid system depends mainly on reservoir type and density of fissures
  - TR: linear, X-linked or hybrid designs
  - SR: mainly slick water
- Fracturing rate dictated by reservoir type
  - TR: proppant transport governed by viscosity
  - SR: velocity is the transport mechanism
- Frac volume
  - TR: contacted area is the main factor
  - SR: SRV is the key factor. Larger is better
- Proppant concentration
  - TR: low to medium. Generally 4 - 5 ppg maximum
  - SR: low. No more than 2 ppg as final conc in gas, for oil higher concentartions
- Proppant mesh size
  - TR: governed by frac width
  - SR: governed by frac width and proppant transport capability of frac fluid



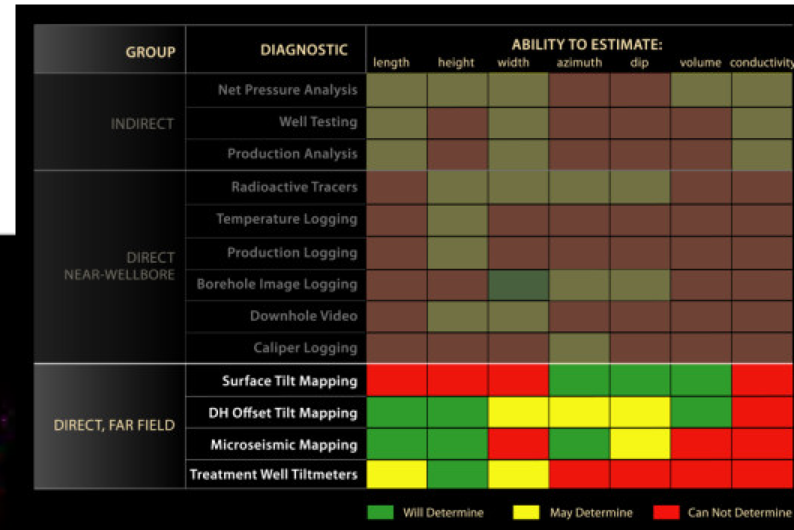
from: SPE 115258

Brittleness	Fluid system	Fluid viscosity	Natural fractures	Frac rate	Proppant conc	Frac fluid volume	Proppant volume	Fracture geometry	Frac width
Brittle	SWF	Low	Severe	High	Low	High	Low	Network	Very narrow
	SWF	Low							
	Hybrid	Low/medium							
	Linear	Medium							
	Foam	Medium							
	X-Linked	High							
Ductile	X-Linked	High	No fracs	Low	High	Low	High	Two-wing	Narrow

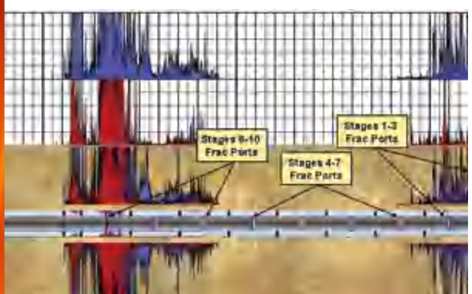
Stimulation Success and Optimization

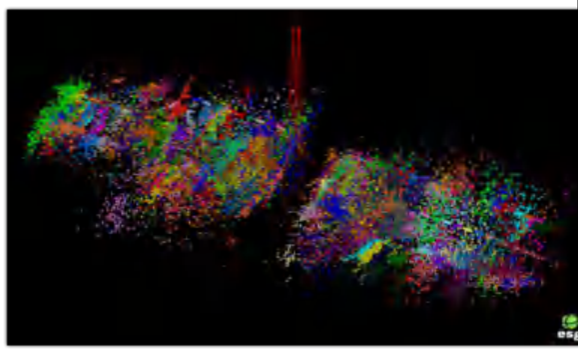
- The only way of being successful and continue improving the development of UR is to push the limits of existing technologies and apply new ones. Cost driven development!
- Verify if what you planned is what you got. Evaluate new technologies. Check assumptions, calibrate and test changes. Currently four major technologies are used:
  - Microseismic
  - Tracers (chemicals and radioactive)
  - Production logs
  - Production transient and decline analyses

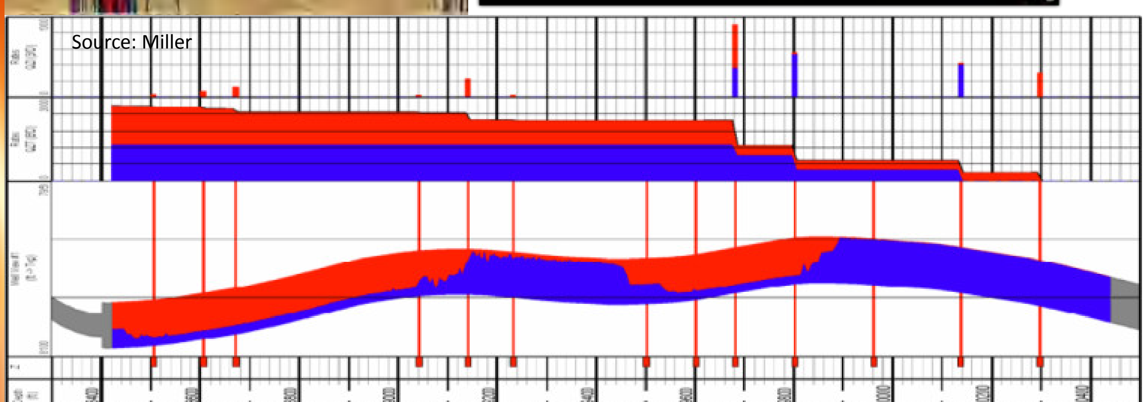
Source: SLB

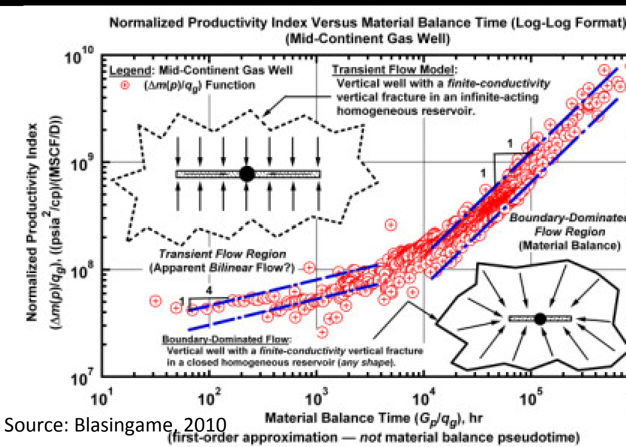


Source: epmag.com







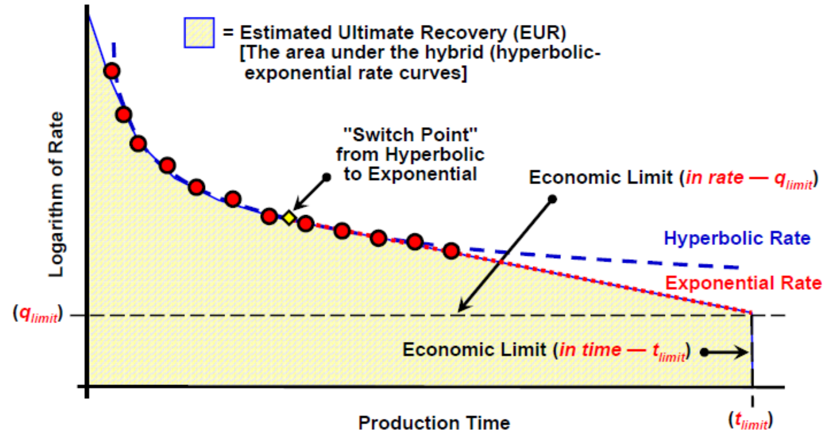


Source: Blasingame, 2010

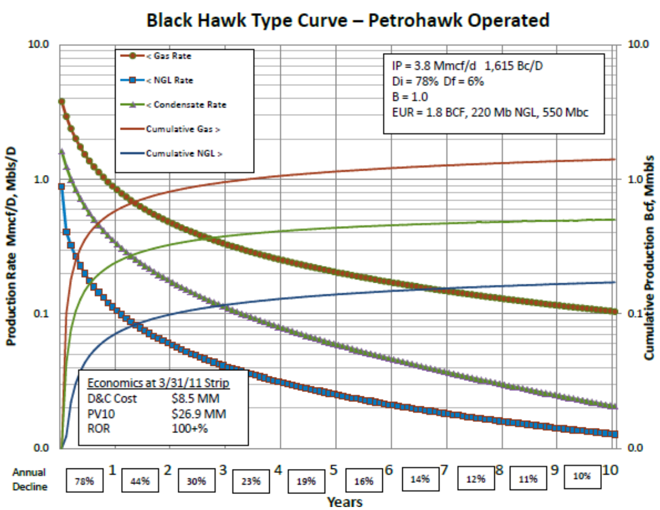
Production Forecasting and Reserves Estimation

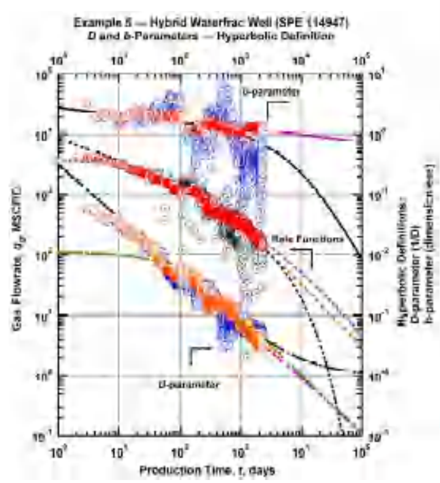
- Production decline analysis
  - Base relations: Arps's eq
  - Only valid for pseudosteady state (boundary limits were reached!!!)
  - In practice most of the time actual b>1
- Physical vs mathematical problem
  - b> 1 just indication of transient flow
  - No limits reached = not possible to apply the methodology. Use better methods!
  - If b>1 at t= long enough, reserves are infinite!
- Decline behavior
  - Strong decline during first years

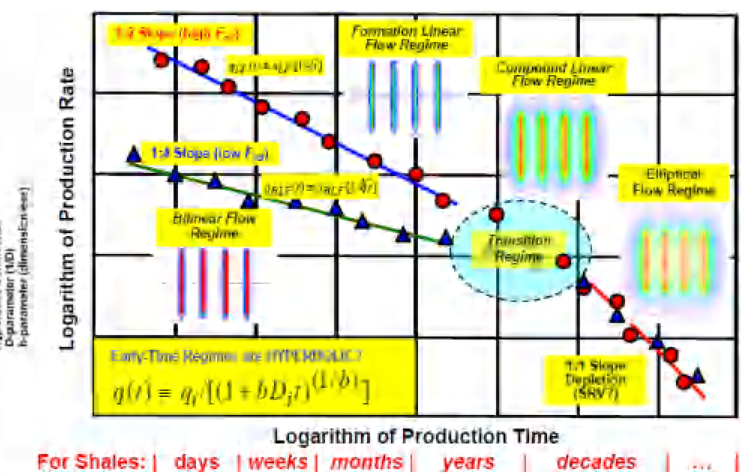
Case	Rate-Time Relation	Cumulative-Time Relation
Exponential: (b=0)	$q_g = q_{gi}\exp[-D_i t]$	$G_p = \frac{q_{gi}}{D_i}[1-\exp[-D_i t]]$
Hyperbolic: (0<b<1)	$q_g = \frac{q_{gi}}{(1+bD_i t)^{(1/b)}}$	$G_p = \frac{q_{gi}}{(1-b)D_i}[1-(1+bD_i t)^{1-(1/b)}]$
Harmonic: (b=1)	$q_g = \frac{q_{gi}}{(1+D_i t)}$	$G_p = \frac{q_{gi}}{D_i}\ln(1+D_i t)$



Source: Petrohawk, 2011



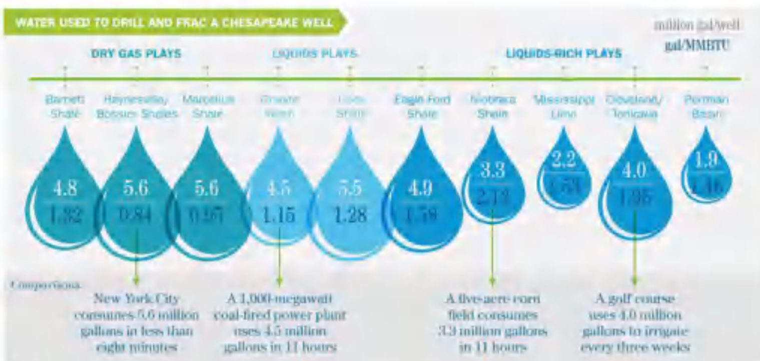


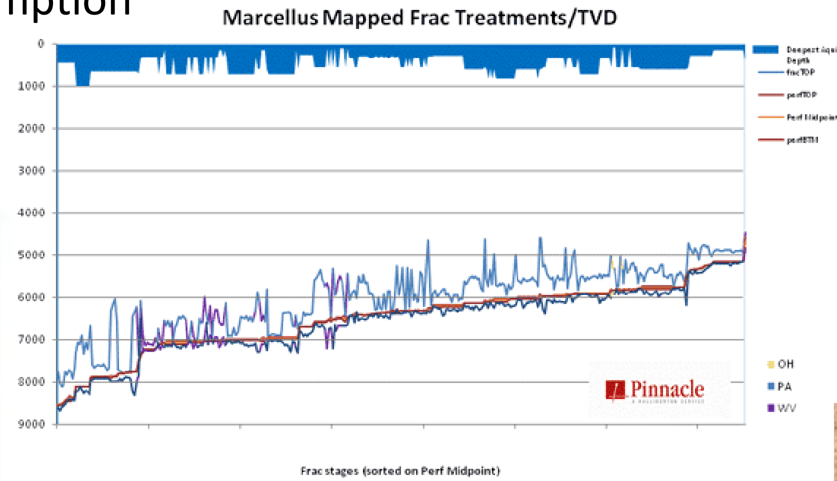


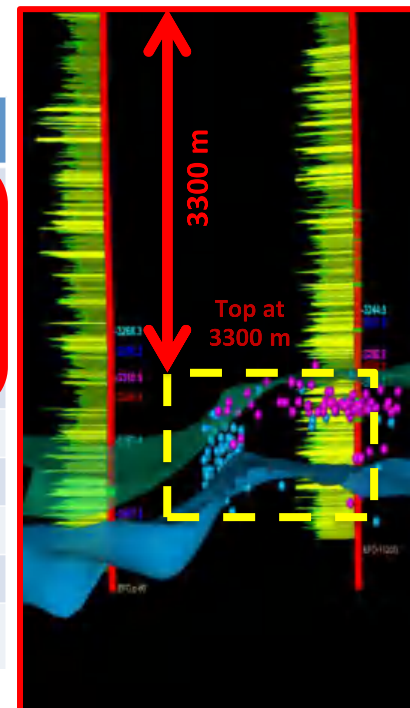
Source: Blasingame, 2013

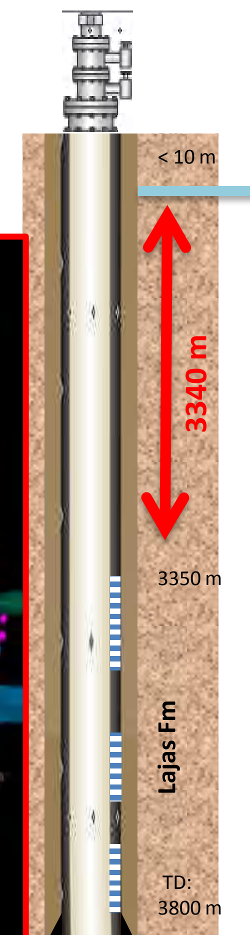
Environmental Concerns

- Fresh water contamination / consumption
  - Surface waters
  - Shallow aquifers
- Earthquakes









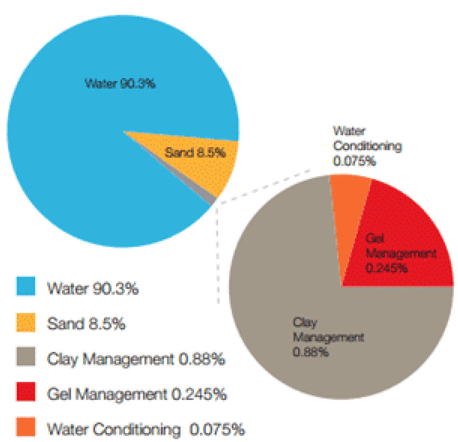
Moment Magnitude	Moment (MNm)	Detectablilty Range (m)	Slip (mm)	Radius (m)	Explosive Charge	Comments
-4	0.001	<30	0.01	0.03	1mg	Smallest recordable
-3	0.04	500	0.04	0.1	30mg	
-2	1.2	800	0.12	0.3	1g	Typical HF
-1	40	1,500	0.4	1	30g	
0	1,200	3,000	1.2	3	1kg	Big for HF
1	40,000	-	4	10	30kg	Big for geothermal
2	1,200,000	-	12	30	1 ton	Felt earthquake
3	40,000,000	-	40	100	30 ton	Minor earthquake
4	1,200,000,000	-	120	300	100 ton	Light earthquake
5	40,000,000,000	-	400	1000	300 ton	Moderate earthquake

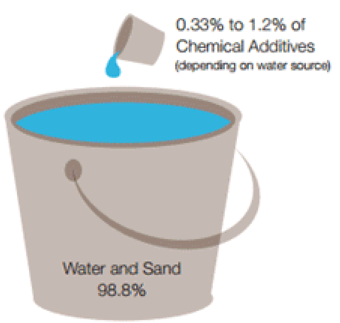
Source: Verdon, 2012

Environmental Concerns – Cont´d

- Strong complaints that frac additives are highly contaminating
  - Same products used fo medicines, foods, cosmetics, home cleaning products, etc

Composition of gel frac fluid





				Common Use	Range of Volumes in Frac Fluid	
Group/Function	CAS Number	Chemical type or name	Commonly found/used in household products	% volume of chemical in household items	Group % by volume (average)	% volume range of chemical in frac fluid
Sand (Proppant)/ Water	7732-18-5	Water	Irrigation, Drinking , bathing, cooking	1% to 100%	98.79% to 99.9%	88% to 97.6%
	14808-60-7	Silicon Dioxide (quartz / sand)	Hand Cleaner, arts & crafts, glass	1% to 100%		2.3% to 12%
Water Conditioning (Microbial / pH Control)	7681-52-9	Sodium hypochlorite	Disinfectant, bleaching agent, cleaners, cleaning of milking equipment, water treatment, medical use, mildew remover, anti- bacterial cleanser	0.1% to 20%	0.075% to 0.1%	0.01% to 0.02%
	1310-73-2	Sodium hydroxide (caustic soda)	Food preparation, soaps, detergents, toothpaste, aftershave, face mask, teeth whitening strips, eau de cologne, body wash, face cleaning pad, Hair remover, cocoa processing,	0.1% to 5%		0.002% to 0.1%
	497-19-8	Sodium Carbonate	household and laundry / dishwasher cleaners, toothpaste, fish aquarium, hair care, spa water clarifier	0.5% to 85%		0.0% to 0.025%
	144-55-8	Sodium Bicarbonate	Baking powder, Cakes, household cleaners, vegetable cleaner, toothpaste, fish aquarium, baby powder, deodorizer	1 % to 100%		0.0% to 0.006%
	64-19-7	Acetic Acid	Vinegar, food preparation and manufacturing, Salad dressings, Pickled Onions, relishes and spreads, household cleaning products	1% to 5%		0% to 0.1%
Clay Management	7447-40-7	Potassium chloride	Table salt substitute, medical use, hair products pet supplements, african violet food	0.5% to 40%	0.0% to 0.91%	0.0% to 0.91%
Gel / Viscosity Management	6410-41-9	CI Pigment Red 5	Food colouring, colour pigment in cosmetics, soaps ink, paint	0.01% to 30%	0.0% to 0.25%	0.0% to 0.00009%
	100-43-52-4	Calcium chloride	Detergents, cosmetics, deodorant, pet products, desiccant , food additive, sports drinks, pickles	0.1% to 90%		0.0% to 0.0002%
	Natural Mixture	Walnut Husk	Hair Dye, Polishing Material, Exfoliate in Facial and Body Scrubs, Aquarium and Aquaculture	3% to 50%		0.0% to 0.006%
	9000-30-0	Guar gum	Cosmetics, baked goods, ice cream, toothpaste, sauces, salad dressing, Substitute for wheat intolerant people to use instead of flour, cattle food, and medical use	0.5% to 20%		0.0% to 0.2%
	14808-60-7	Silica	Hand Cleaner, arts & crafts, glass	1% to 100%		0.0% to 002%
	9025-56-3	Hemicellulase Enzyme	Wine Additive, Soybean Paste, Fibre Additive, Commercial Baking and Food Processing, Farm feed additive	0.1% to 25%		0.0% to 0.0005%
	26038-87-9	MEA borate	Cosmetics, hair texturizer, hairspray, antiseptic, laundry detergent	0.1% to 5%		0.0% to 0.1%
	proprietary information	Acrylic Resin	Disinfectant Cleaner, FDA Approved Colorant, paint, food packaging, medicinal chemistry.	< 0.01% to 2%		0.0% to 0.002
	7647-14-5	Sodium chloride	Food production, table salt, food additive, detergents, hair products, water softener and medical saline drips.	0.03% to 99%		0.0% to 0.004%
	proprietary information	Enzyme	Laundry detergent, laundry stain remover, silverware cleaner, agricultural feeds, instant coffee production	~ 0.1%		0.0% to 0.0002%
	7772-98-7	Sodium thiosulfate	Personal care, food production, home aquarium health / commercial aquaculture, medical use for over 100yrs.	0.1% to 30%		0.0% to 0.04%

Source: www.aplng.com.au

What are the Next Frontiers?


1947 – First hydraulic fracture

Source: Smith, 2010

Thanks for your attention !


2008 – First three simo-frac

Source: Schein, 2008

Contact: jorgeenriqueponce@gmail.com