Introduction to Hydraulic Fracturing

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Society of Naval Architects and Marine Engineers

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Overview

- How do we construct wells?
- What is hydraulic fracturing?
- How do we know we are treating the correct zone?
- Where does the fluid and proppant go?
- How do we know if there is a problem?

Drilling & Completion Video

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Wellbore Construction

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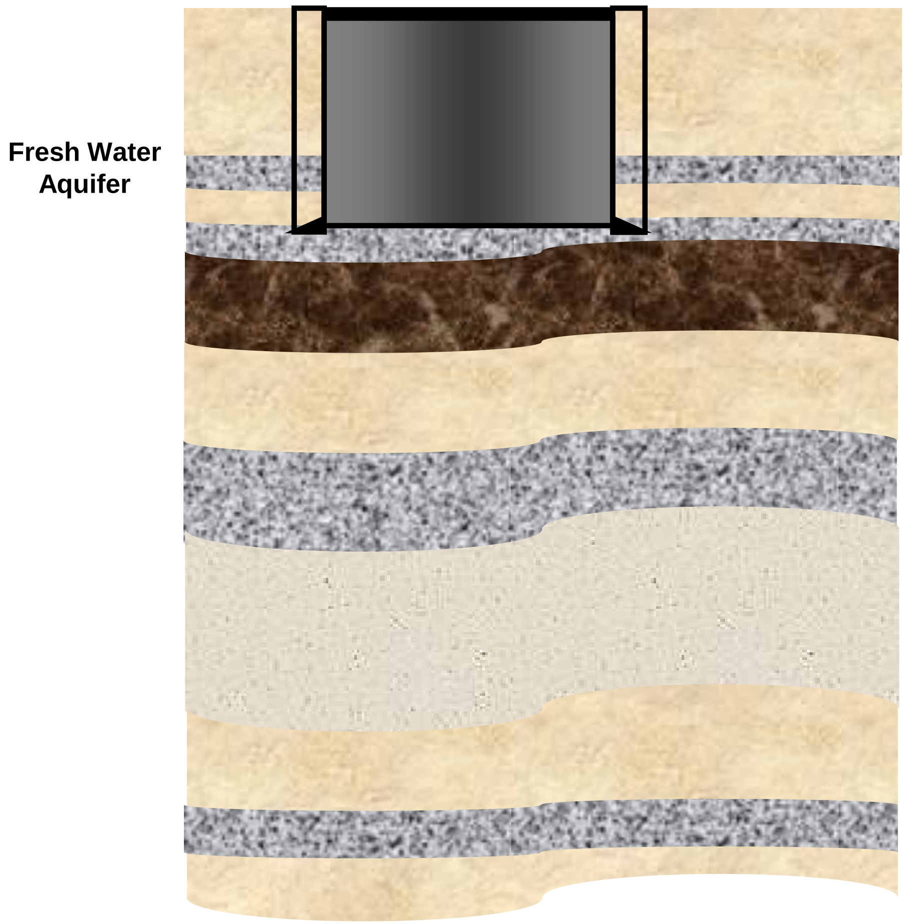
Wellbore Construction – Casing Design

- Casing design is dictated by the expected pressure conditions
- Three major design criteria
  - Burst due to internal pressure from pumping conditions
  - Collapse due to external pressure acting on an evacuated hole
  - Joint strength due to tension and weight of the pipe
- Based on the maximum pressure conditions
- Safety factors are applied to determine actual design

Wellbore Construction – Surface Casing

- Set conductor at 20’ to 80’ deep
- Auger used to drill hole
- Grouted in place
- Drill surface hole with fresh water
- Determine depth by the deepest known useable water
- Typical depths range from 500’ to 5000’
- Cement casing in place
- Pump a cement slurry down the casing
- Circulated the cement up between the wellbore and the casing
- Circulate cement back to surface
- Top surface casing and conductor annulus with cement

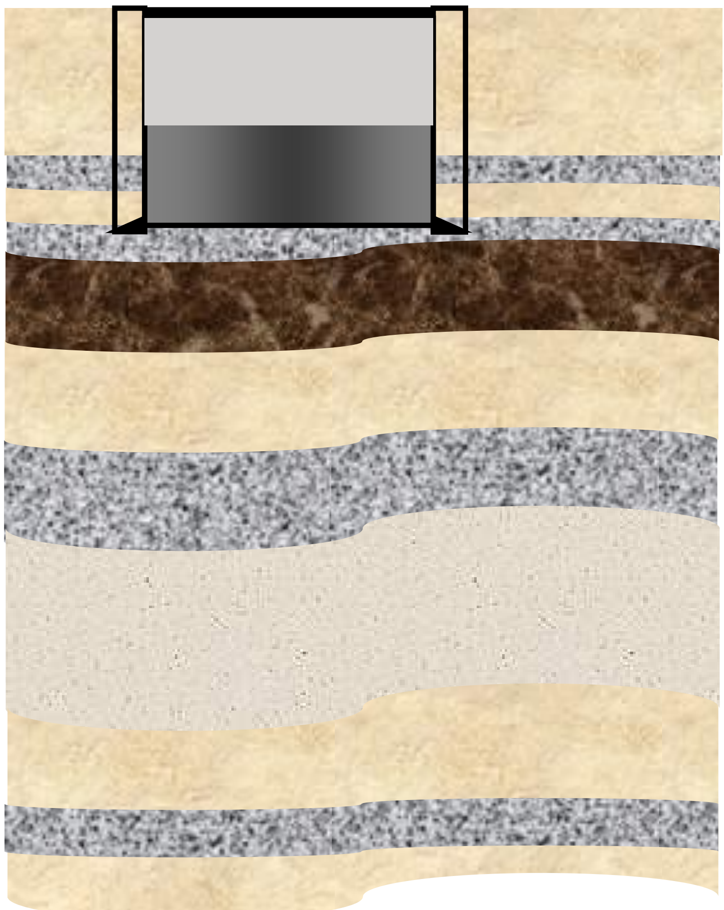
Surface Casing



- **Set surface casing at a depth adequate to protect groundwater**
- **Cement to surface**

Surface Casing

Fresh Water
Aquifer



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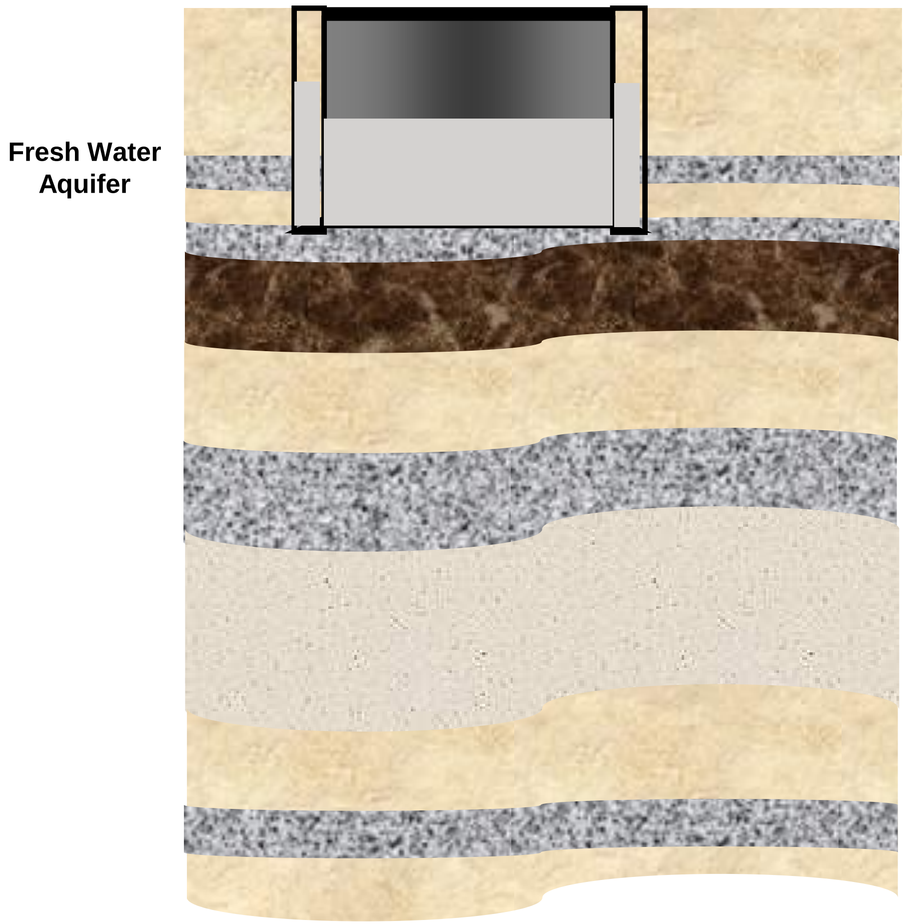
Surface Casing



- **Set surface casing at a depth adequate to protect groundwater**
- **Cement to surface**

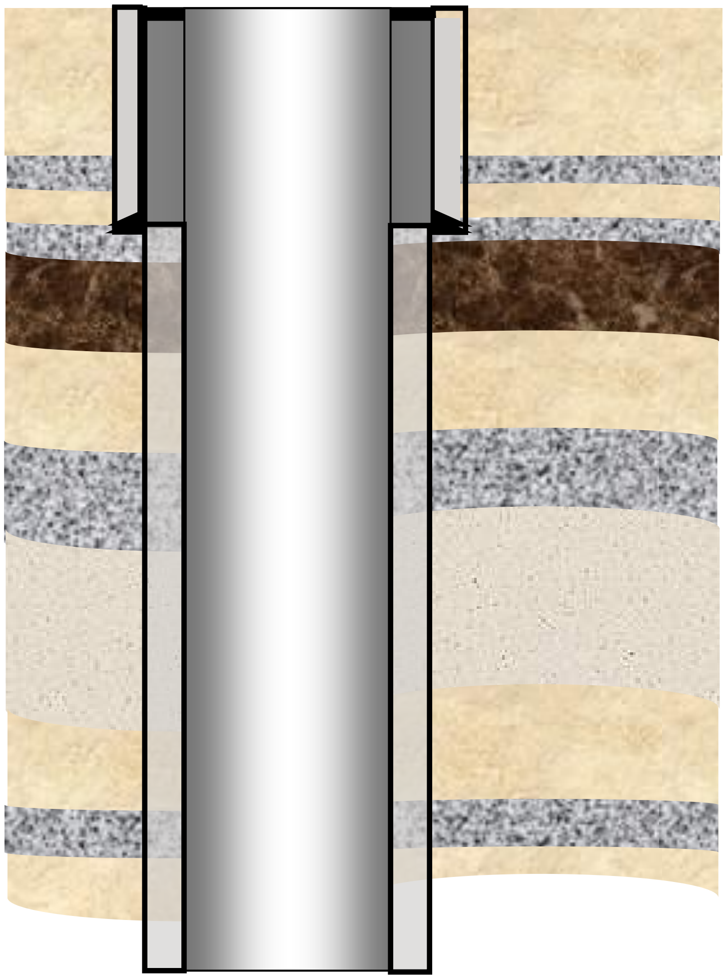
Surface Casing

- Set surface casing at a depth adequate to protect groundwater
- Cement to surface

Wellbore Construction – Production Casing

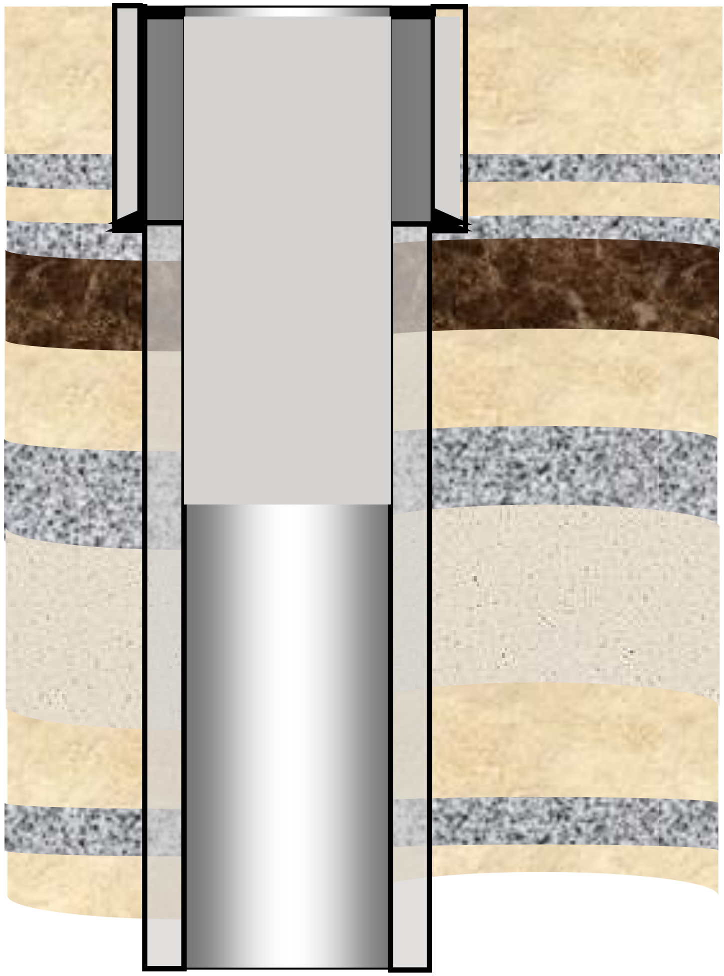
- Drill well to T.D. (total depth)
- Drill utilizing mud systems – bentonite, polymers and barite
- Typical mud weights = 9 to 14 ppg
- Run production casing in the well to T.D.
- Cement casing in place
- Pump cement slurry down casing
- Circulate slurry up the wellbore and casing annulus
- Design cement top to effectively isolate hydrocarbon bearing interval
- Typical cement tops range from 1000' over the pay interval to cement back into the surface casing

Production Casing



- **Set production casing at T.D.**
- **Cement to isolate productive interval**

Production Casing



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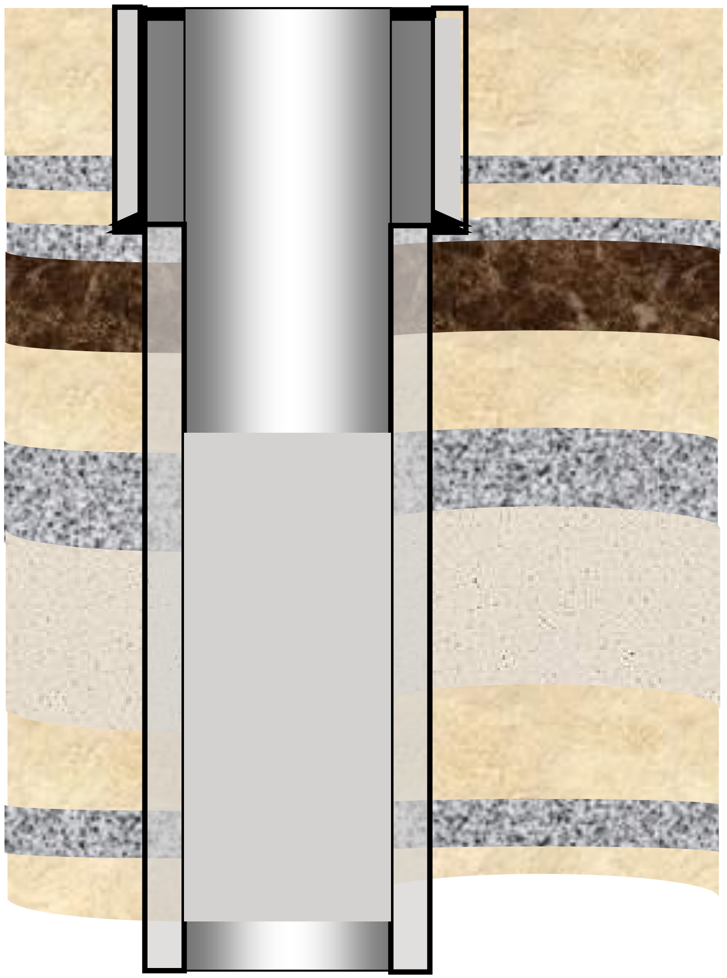
Production Casing



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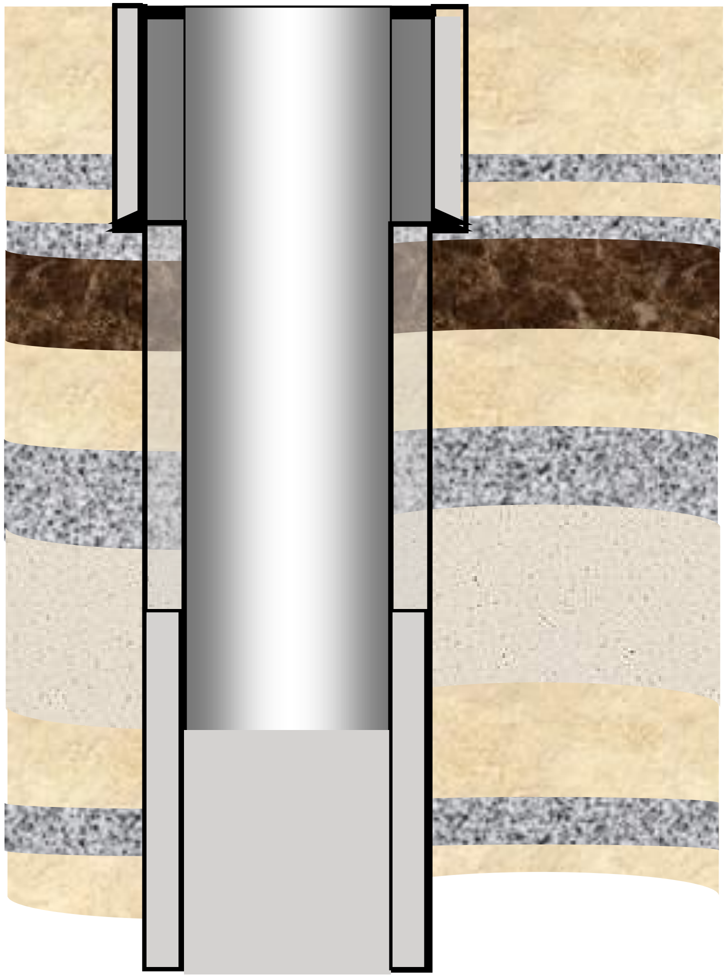
Production Casing



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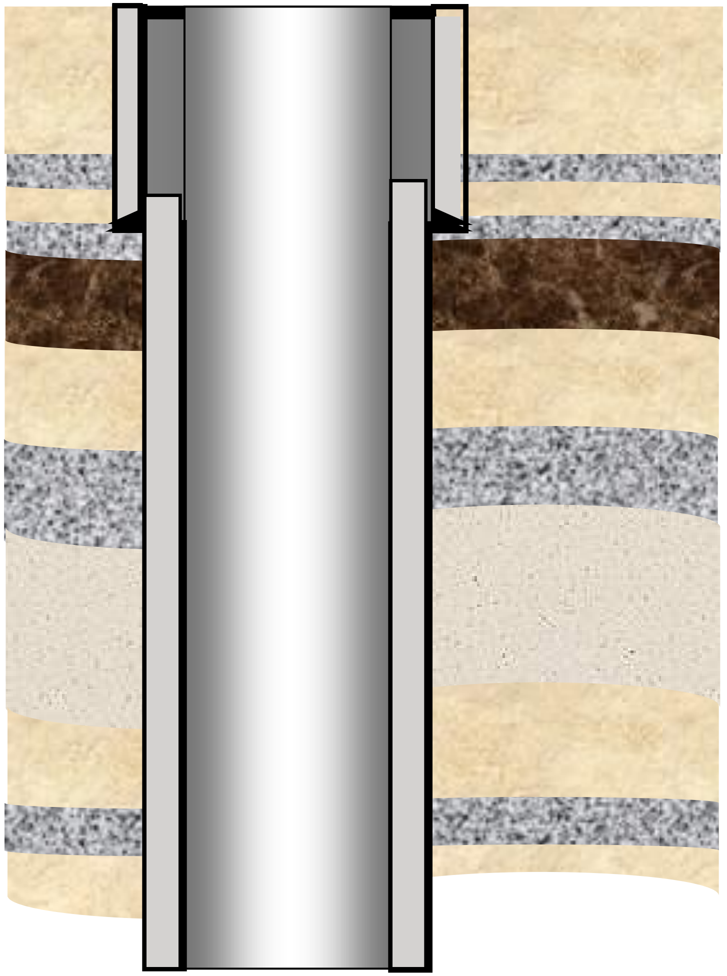
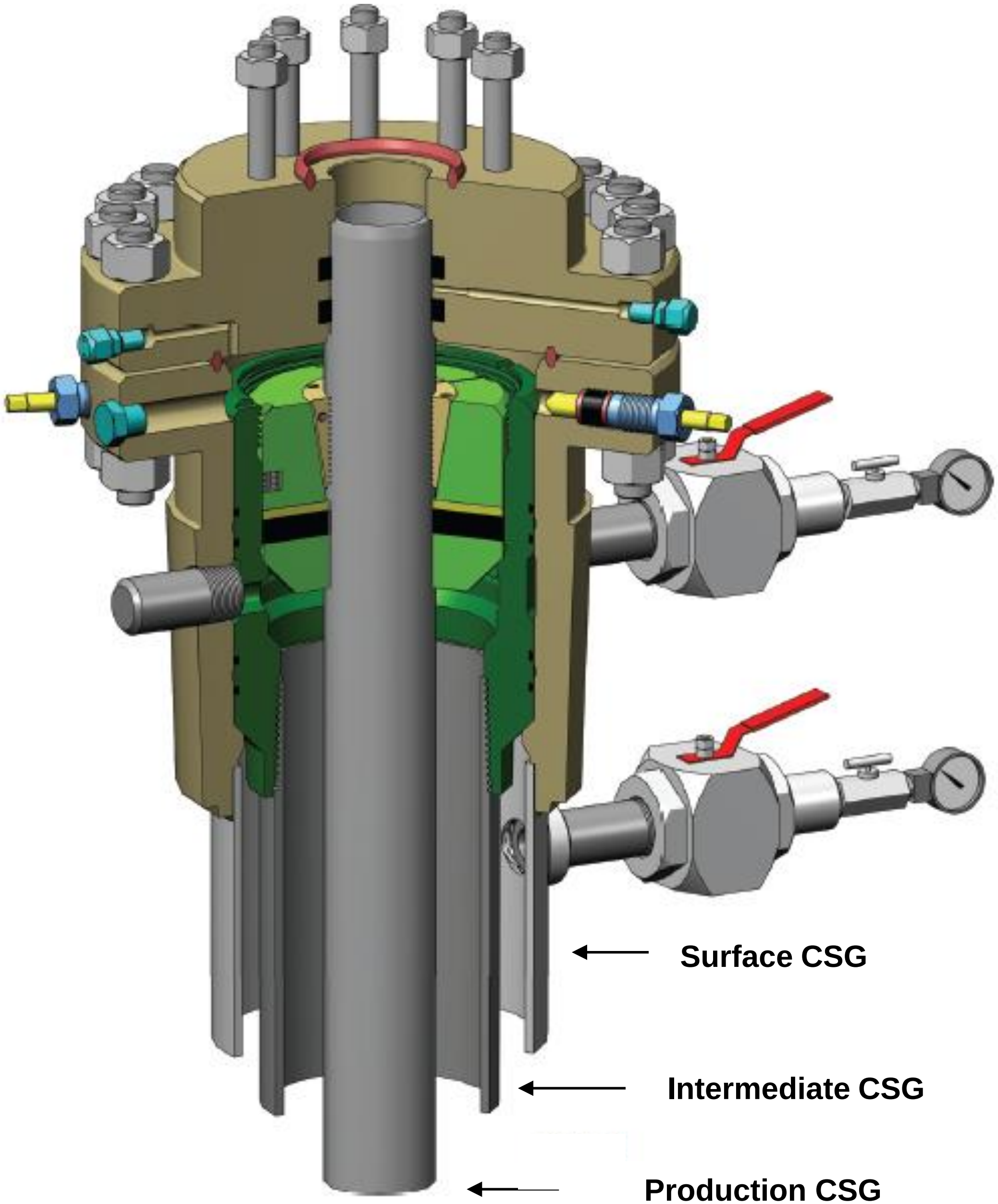
Production Casing

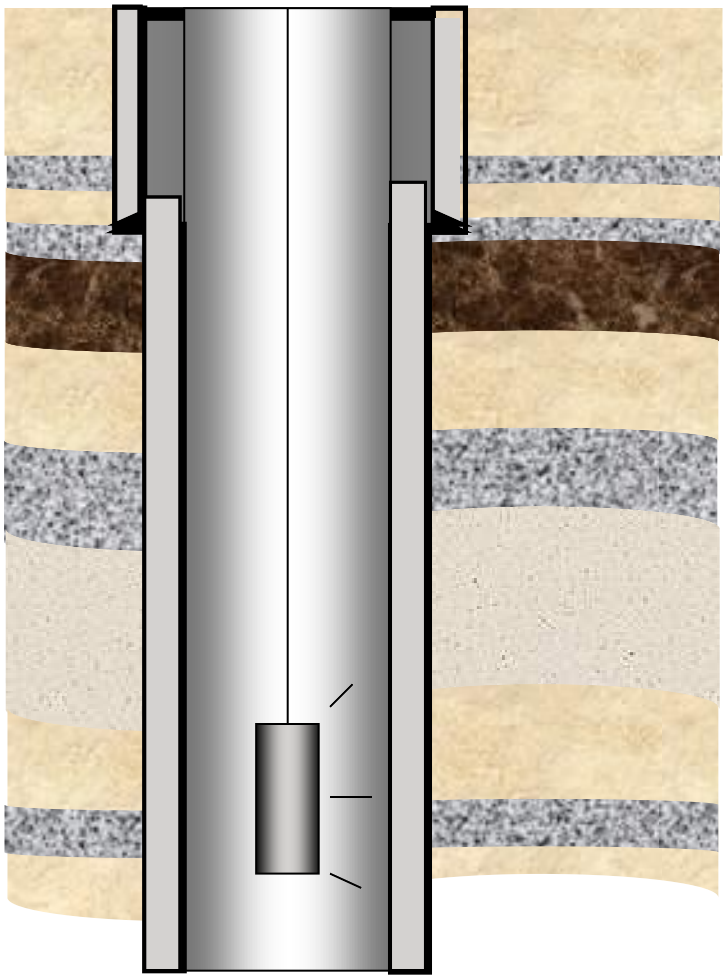


- **Set production casing at T.D.**
- **Cement to isolate productive interval**

Typical Casing Head



Cement Bond Log



- Use a Cement Bond Log tool to evaluate the cement top and quality of the cement bond.
- Temperature log is also used
- Use an acoustic signal
- Un-cemented pipe “rings”
- Attenuate acoustic reflection with cement bonding
- Pressure test casing to ensure integrity prior to commencing completion
- Hydro-test to a pressure greater than the maximum expected treating pressure (usually 80% of casing design)

Typical Cementing Equipment

Cement mixing and pumping equipment

Dry cement hopper

Oil Well Cement

- Not concrete – does not contain sand, gravel or rock
- Not construction grade cement
- Specially formulated for oil and gas well applications
- Small particle size
- Designed to build compressive strength quickly

History of Hydraulic Fracturing

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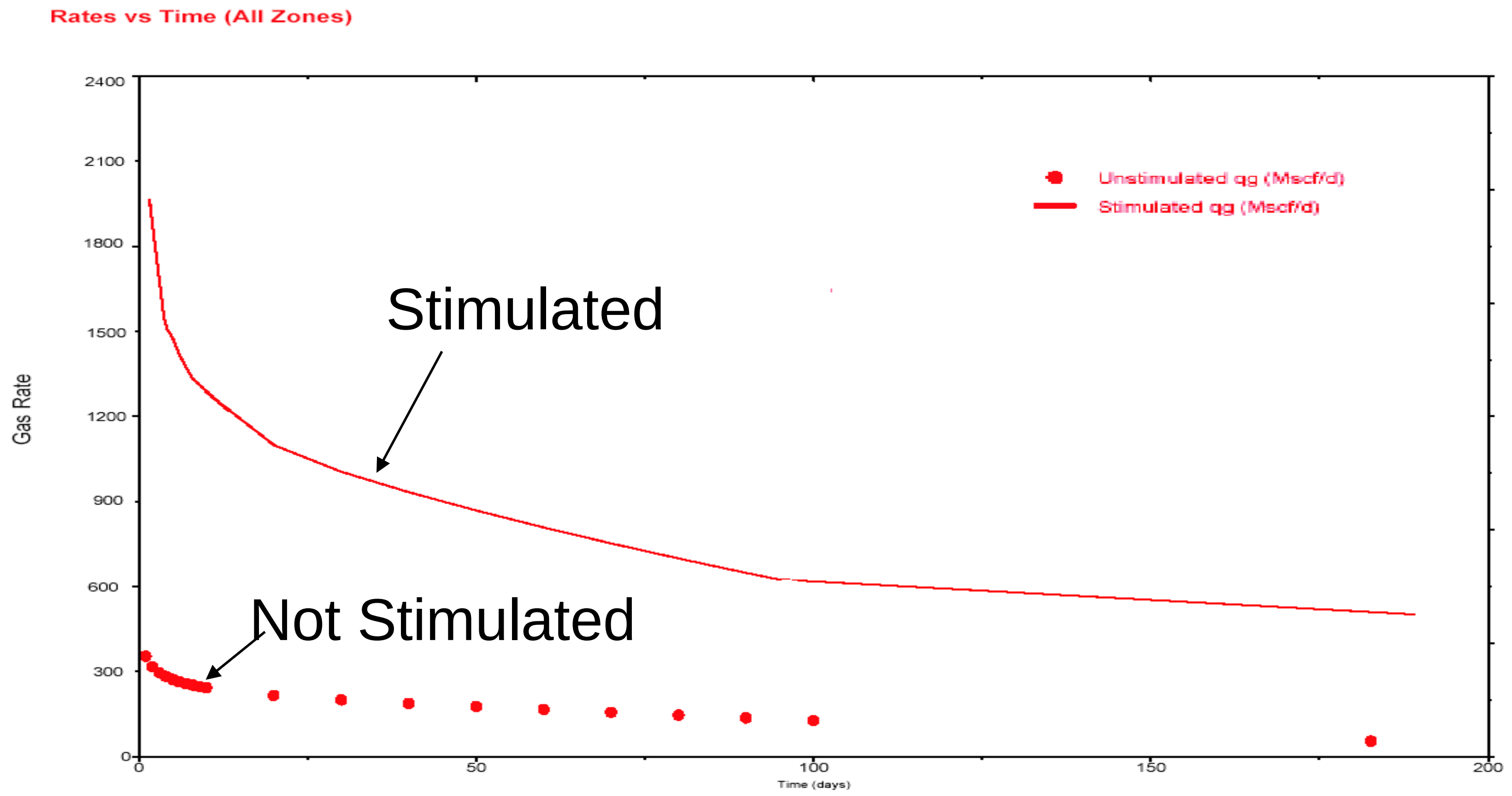
What is a frac job?
Oilfield stimulation history

- Acid and nitroglycerin (separately) until late 1940’s.
- 1947, the 1st frac job took place in Hugoton Field, Western Kansas.
- +60-year technique used worldwide.

Why Fracture a Well?
Reservoir Permeability too Small (<1 md)



Wells are not economic without fracturing

History of Hydraulic Stimulation

- Hydraulic fracturing used in various industries since 1903
- First hydraulic fracture in the oil and gas in 1947
- First commercial frac job in 1949 (by Halliburton)
- First fracturing fluids were oil based – using oil produced from the formation
- Developed water based systems with guar viscosifiers in the late 1950's = first "slickwater fracs"
- First water based crosslinked fluids systems developed to create thick, high viscosity fluids for proppant transport in 1969
- Modern "slickwater" frac fluids are the standard in unconventional tight gas sand projects

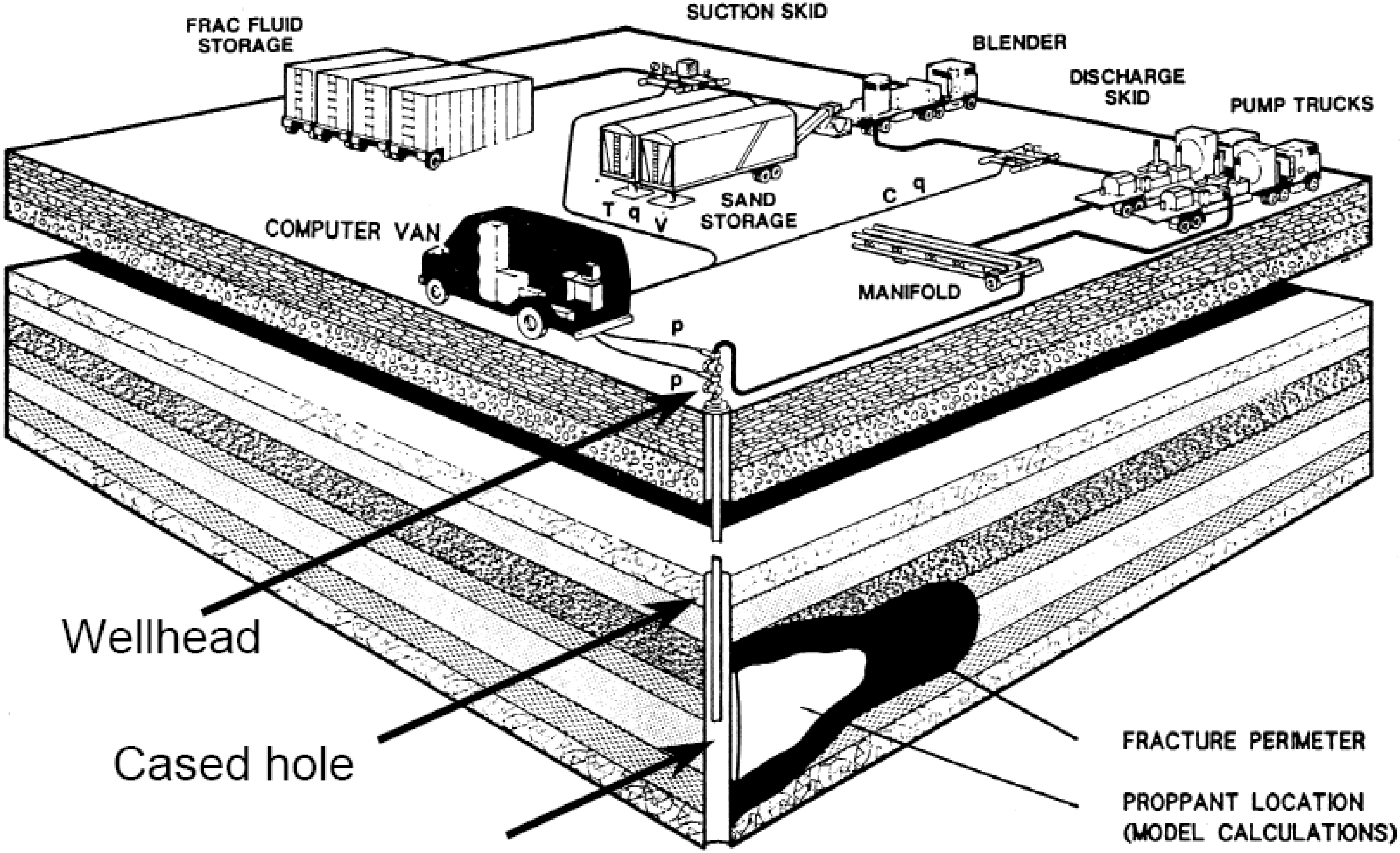
History of Hydraulic Stimulation

- Sand was the first proppant used
- Proppants used in the early years
  - Walnut hulls
  - Glass beads
  - Aluminum pellets
- Today's proppants consist of (in order of increasing crush resistance):
  - Sand
  - Resin coated sand
  - Intermediate strength ceramics
  - High strength - bauxite

What is a “Frac” job?
Sequence of operations

- Create holes (perforate) in casing
- Pump pad & slurry to create frac
- Shut down pumping & rig off well
- Flow back well to clean up fluids
- Produce the well.

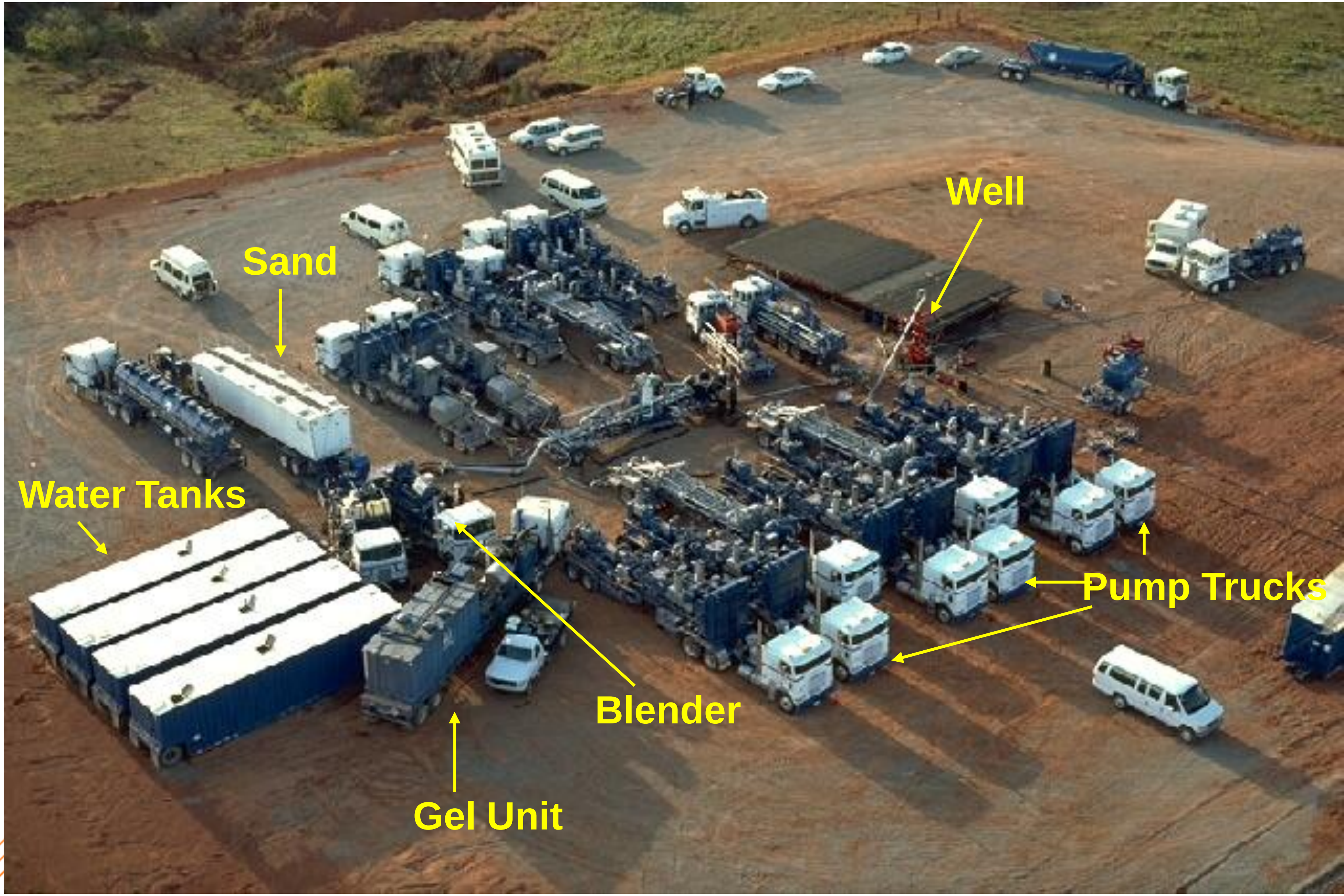
What is a frac job?
Frac site layout



What is a frac job?

Present day frac site

Typical Fracturing Equipment Layout



Fracturing Equipment

- Sand storage and delivery

- Sand conveyed to blender

Fracturing Equipment

- Blender
  - Mixes sand, water, frac gels and additives
  - Delivers slurry to frac pumps

- Frac Pump
  - Pump frac slurry from low pressure to fracture treating pressure
  - Up to 15,000 psi

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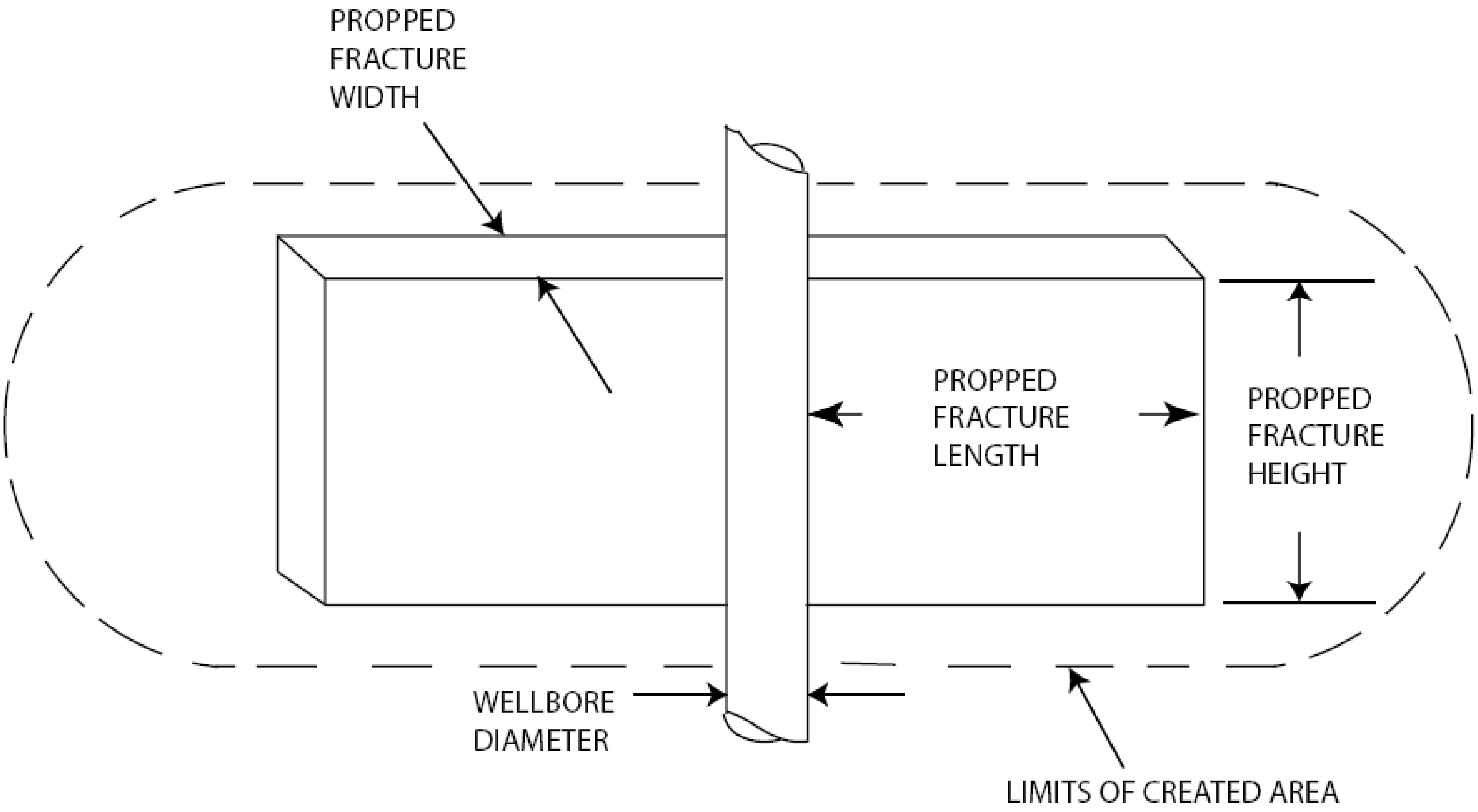
What is a frac job?

General info on fracing

- Critical technique in low permeability formations.
- In certain areas, +95% of wells are fractured.
- Over a million wells have been hydraulically fraced worldwide.
- Needed for tight gas or shale reservoirs.

What is a frac job?

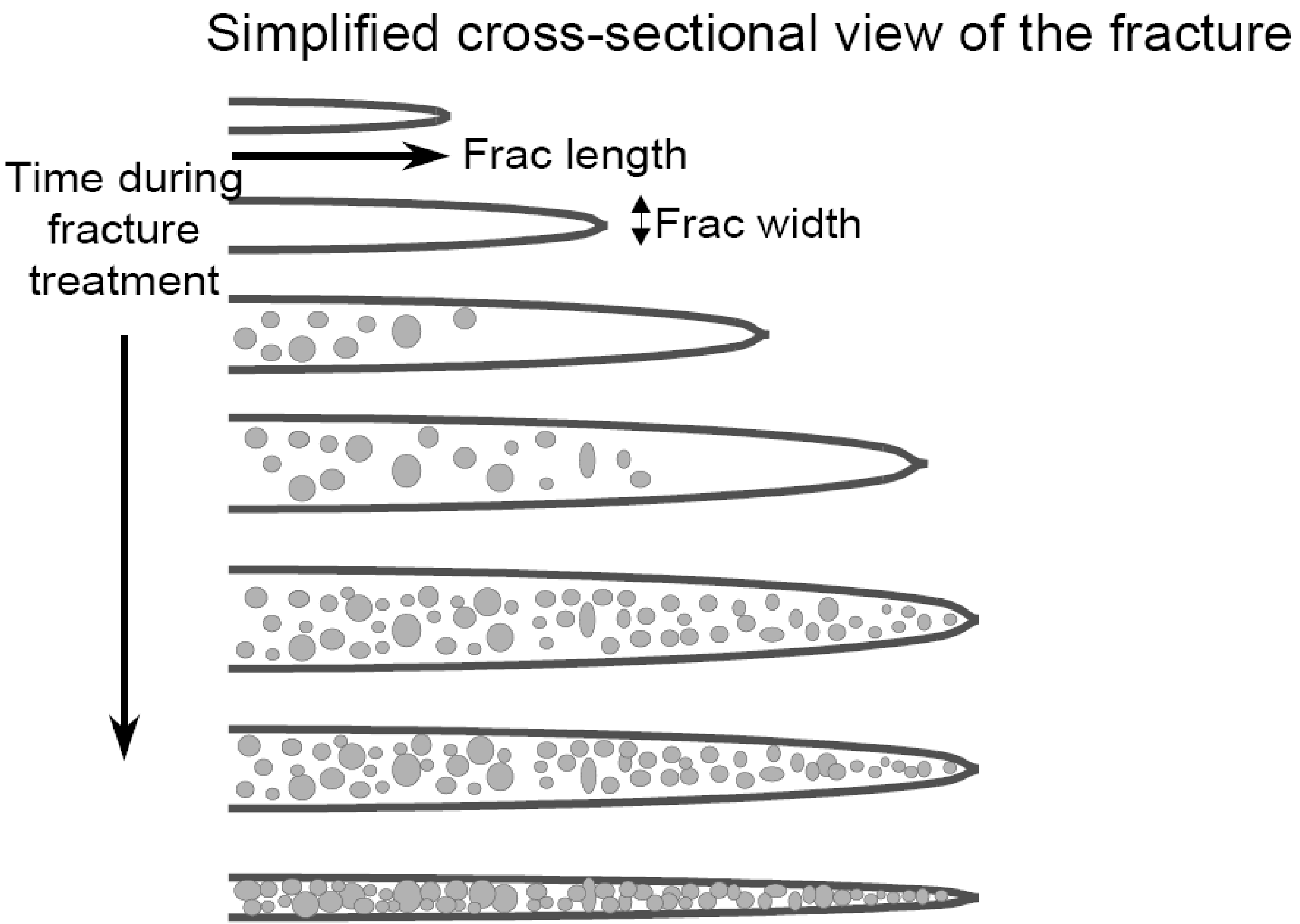
Simple fracture geometry



NOT TO SCALE

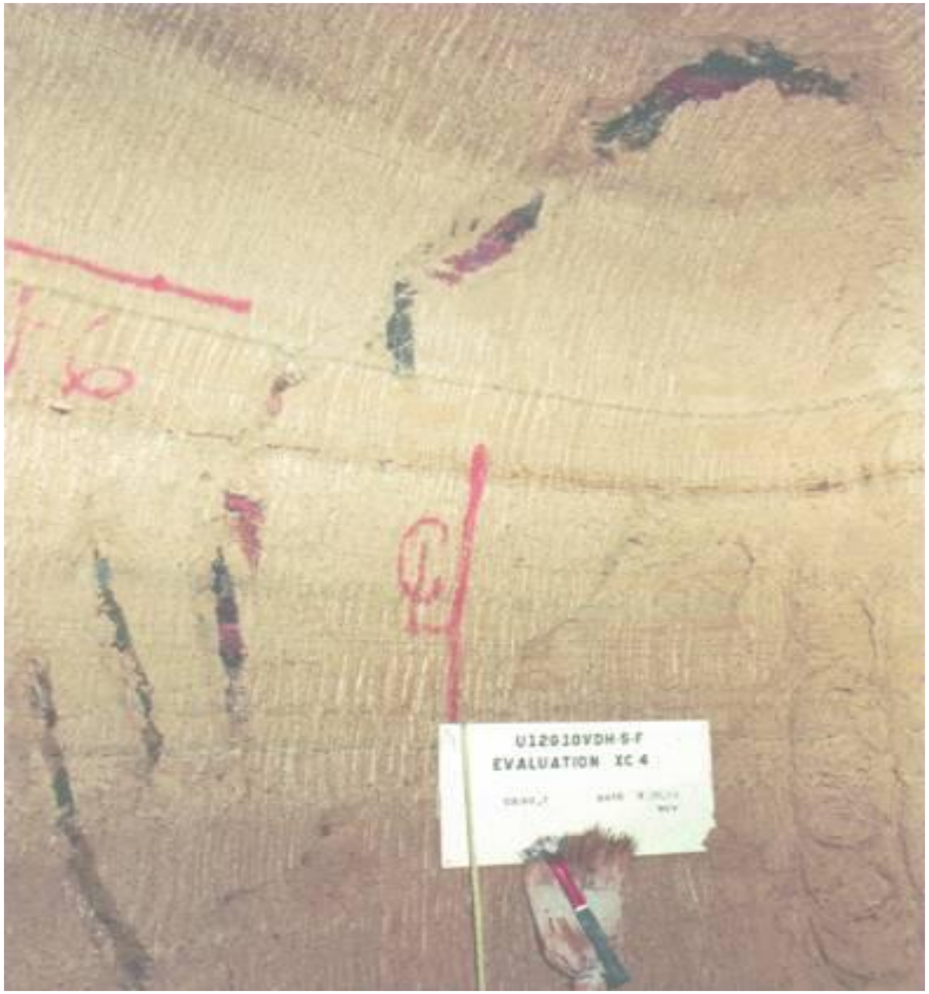
What is a frac job?

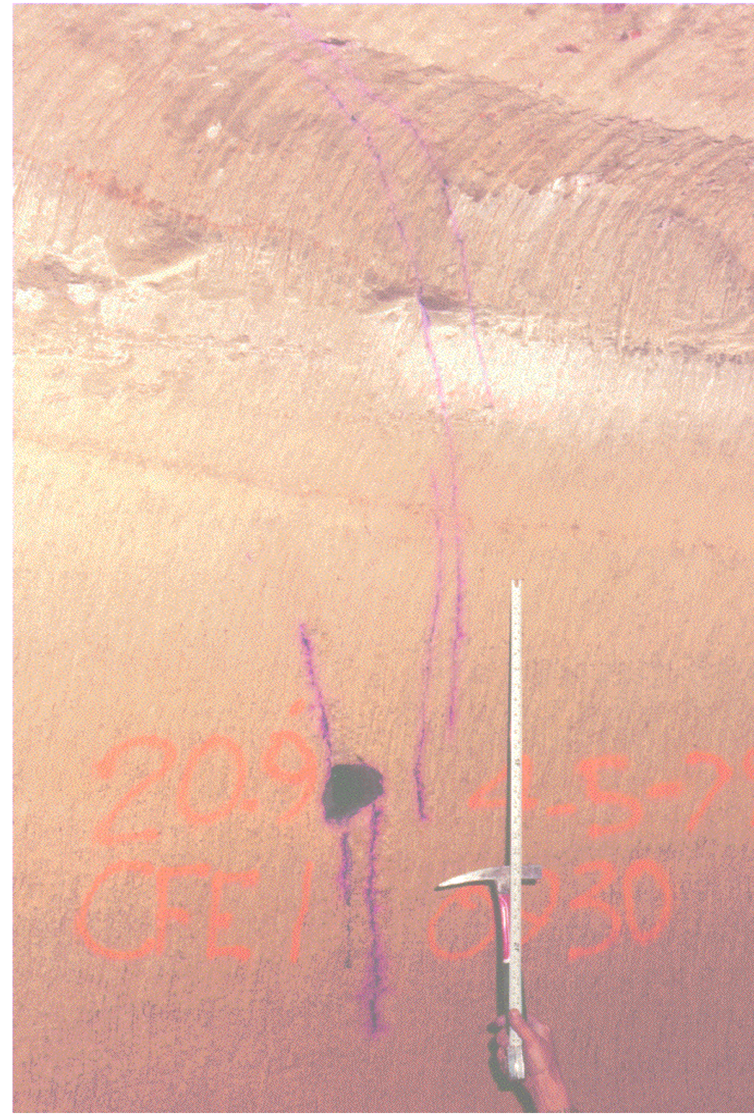
Frac initiation & growth



What is a frac job?

Multiple strands in a propped fracture





NEVADA TEST SITE MINEBACK

Courtesy: N.R. Warpinski, Sandia Labs

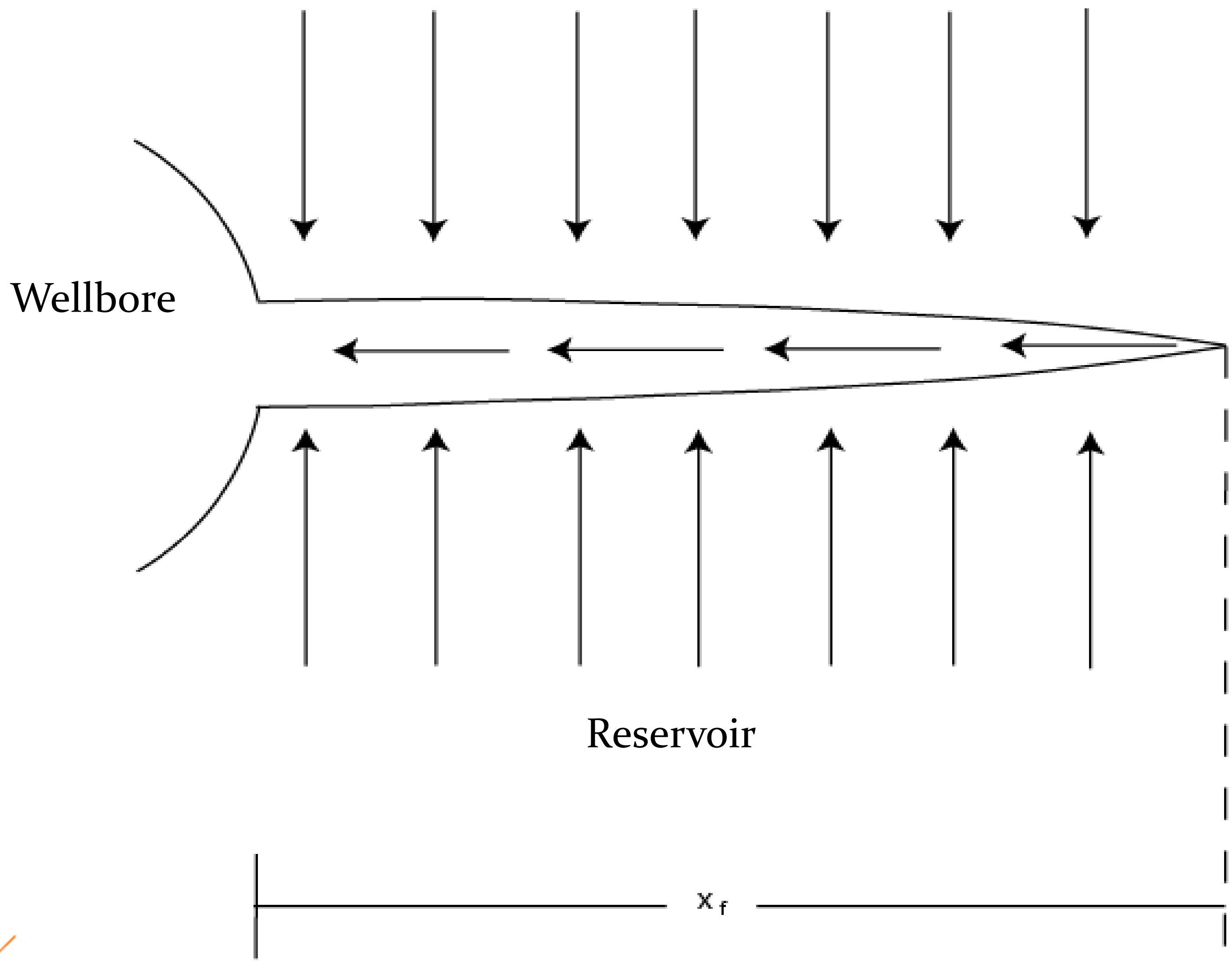
What is a frac job?

Why we do it?

- Bypass near-wellbore damage
- Put “pipeline” into reservoir
- Reservoir management

What is a frac job?

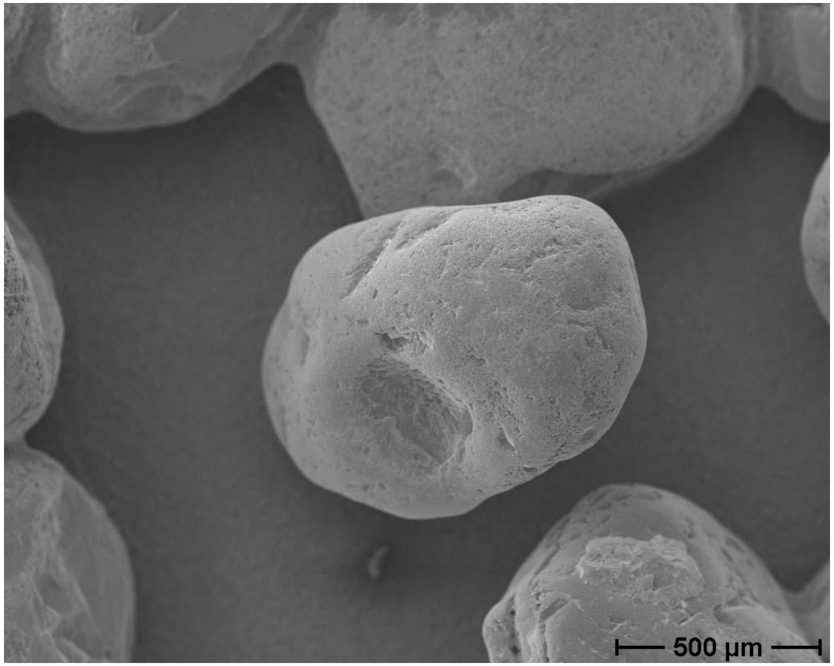
Creates pipeline to wellbore

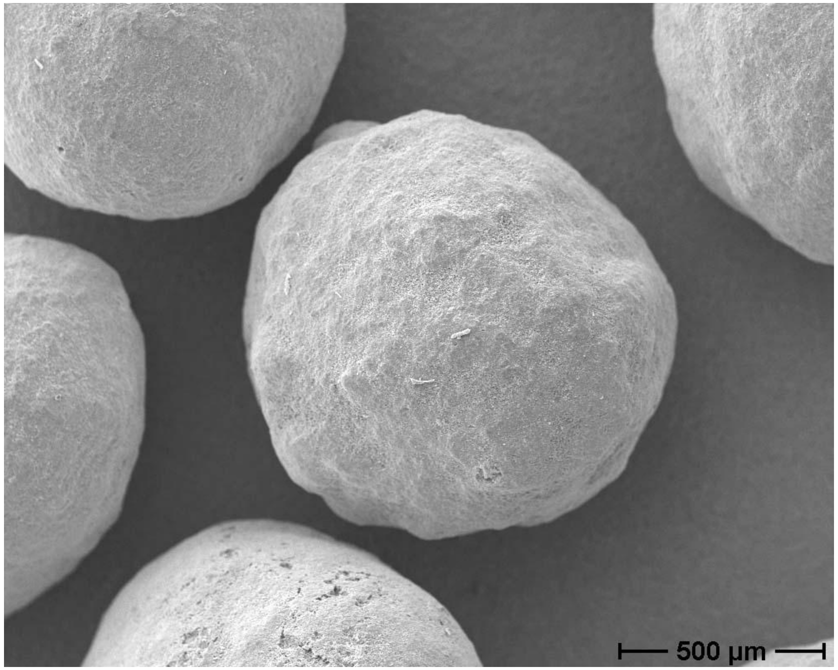


Materials Used

Generic Proppant Types

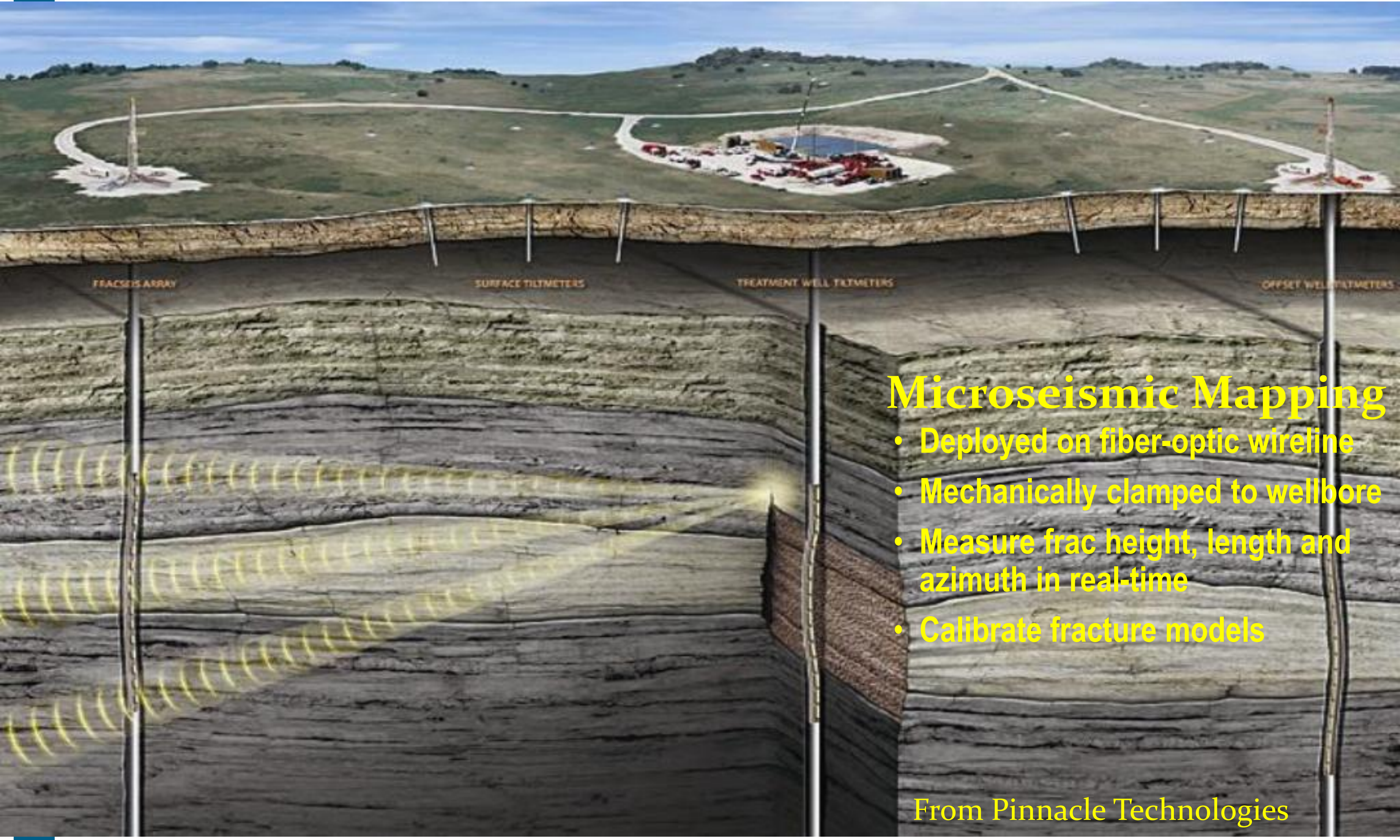
- Sand
- Artificial or ceramics





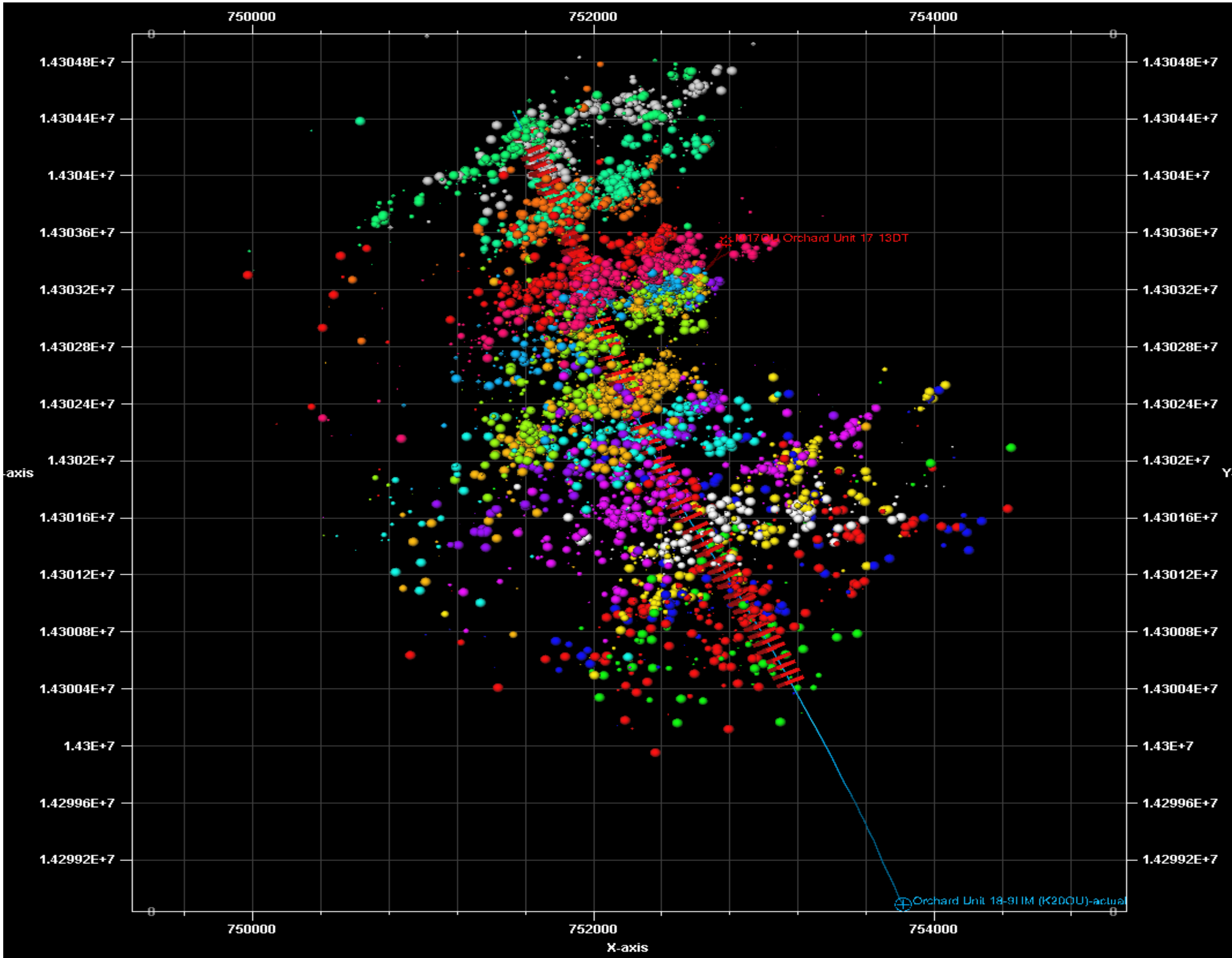
Tech advancements

Frac monitoring



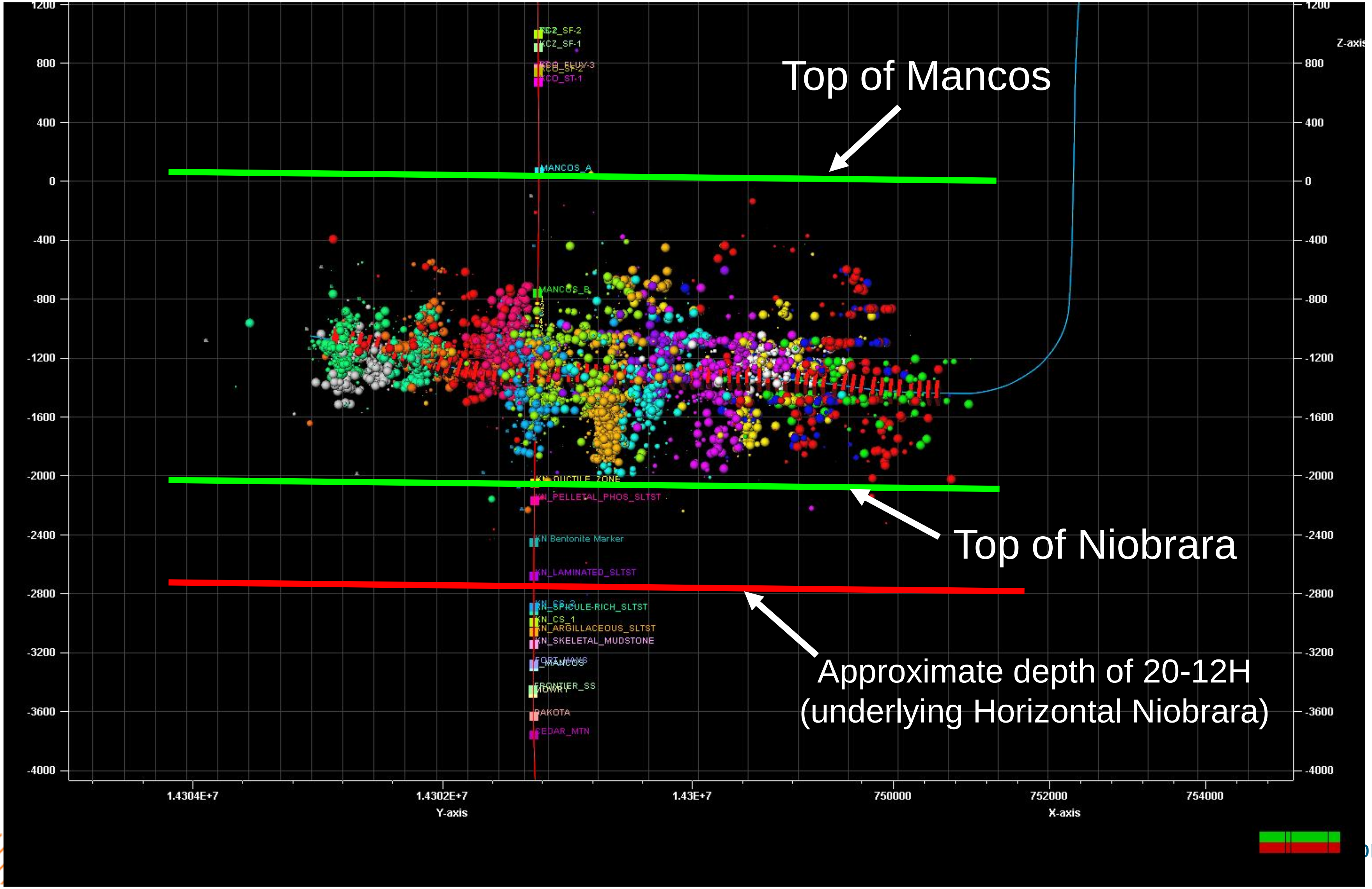
Tech advancements

Frac monitoring, map view



Tech advancements

Frac monitoring, transverse (side) view

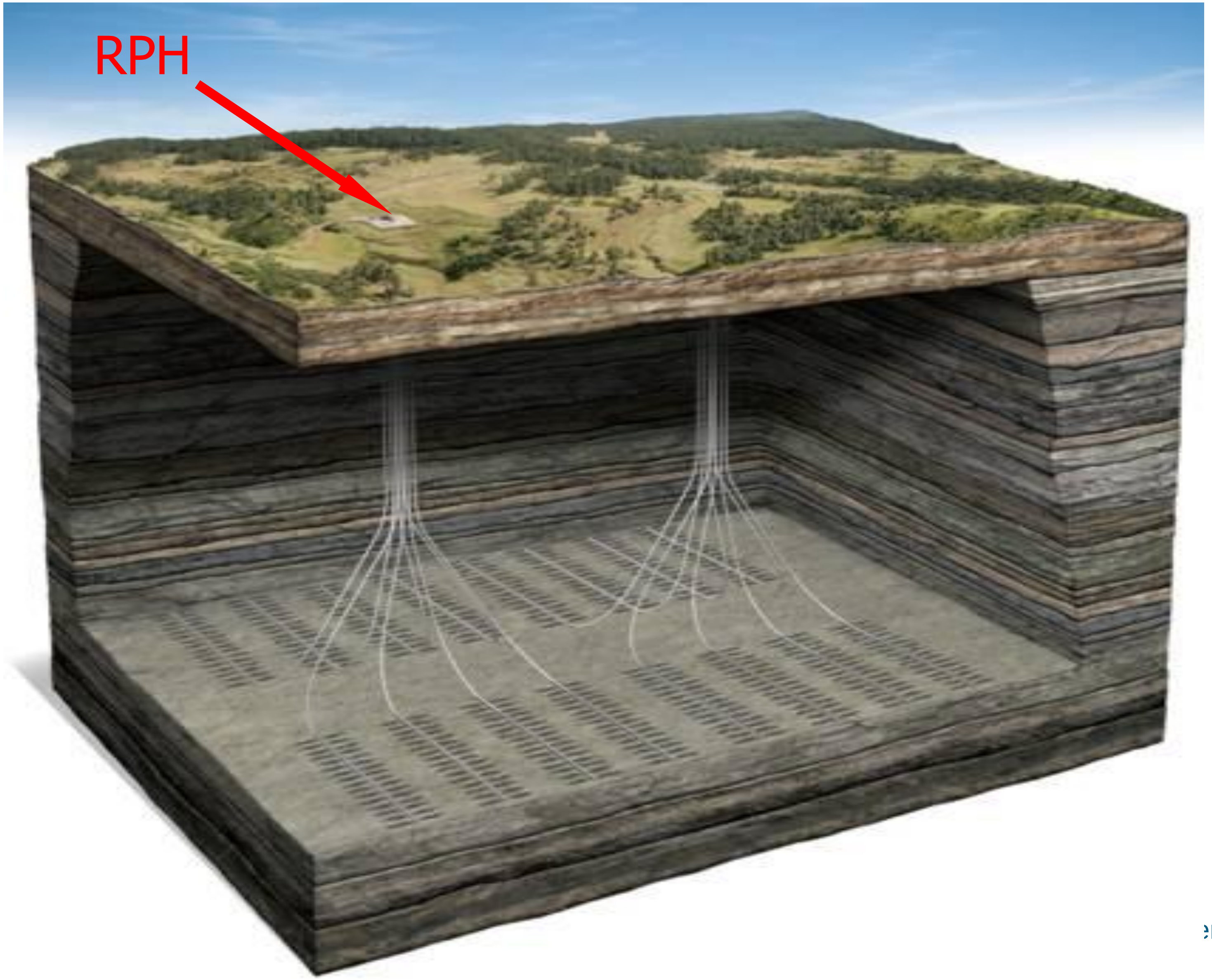


Tech advancements

Vertical well – multiple wells on 1 pad

Tech advancements

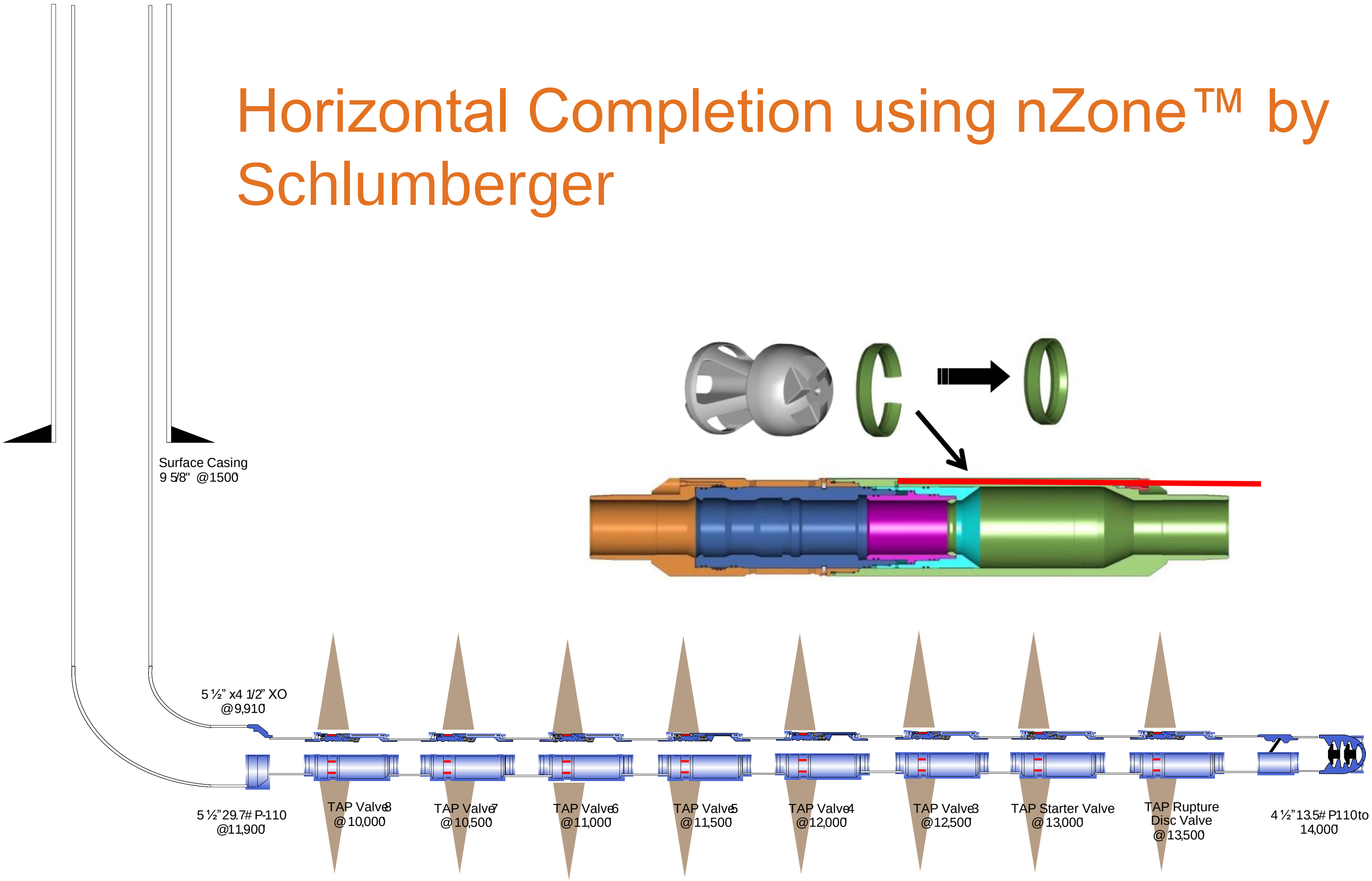
Resource Play Hub (RPH) – multiple laterals from 1 pad



Tech advancements

Horizontal completion using nZone® by Schlumberger

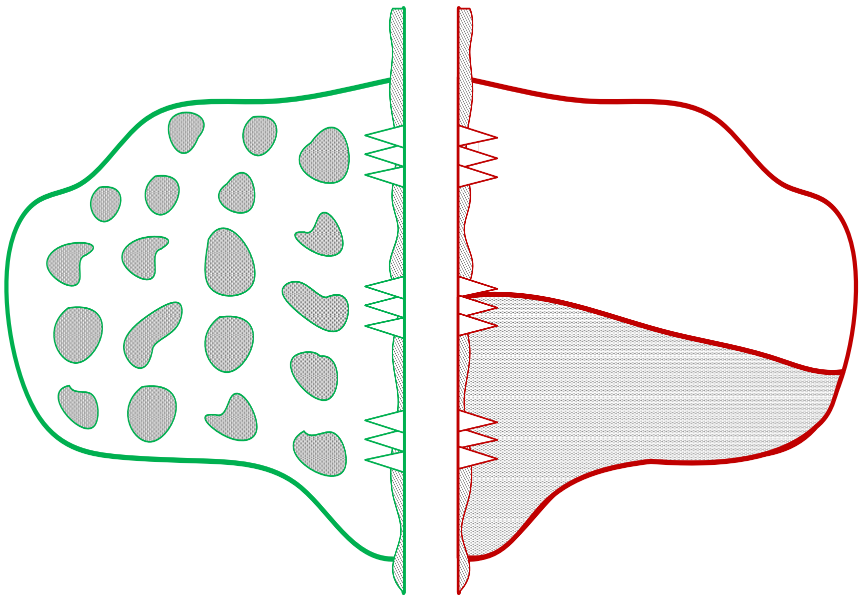
Horizontal Completion using nZone™ by Schlumberger



Tech advancements

HiWAY® system by Schlumberger

- Previously
  - Porous media of limited permeability
- Now
  - Preferential flow thru channels



Tech advancements

Other concepts out there

- Packer & sleeves in horizontal wells
- Tractor devices in horizontal wells
- Neural networks
- LEAN concepts
- DAS/DTS, down-hole pressure and temperature

Fracturing Fluids

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Fracturing Fluid Design

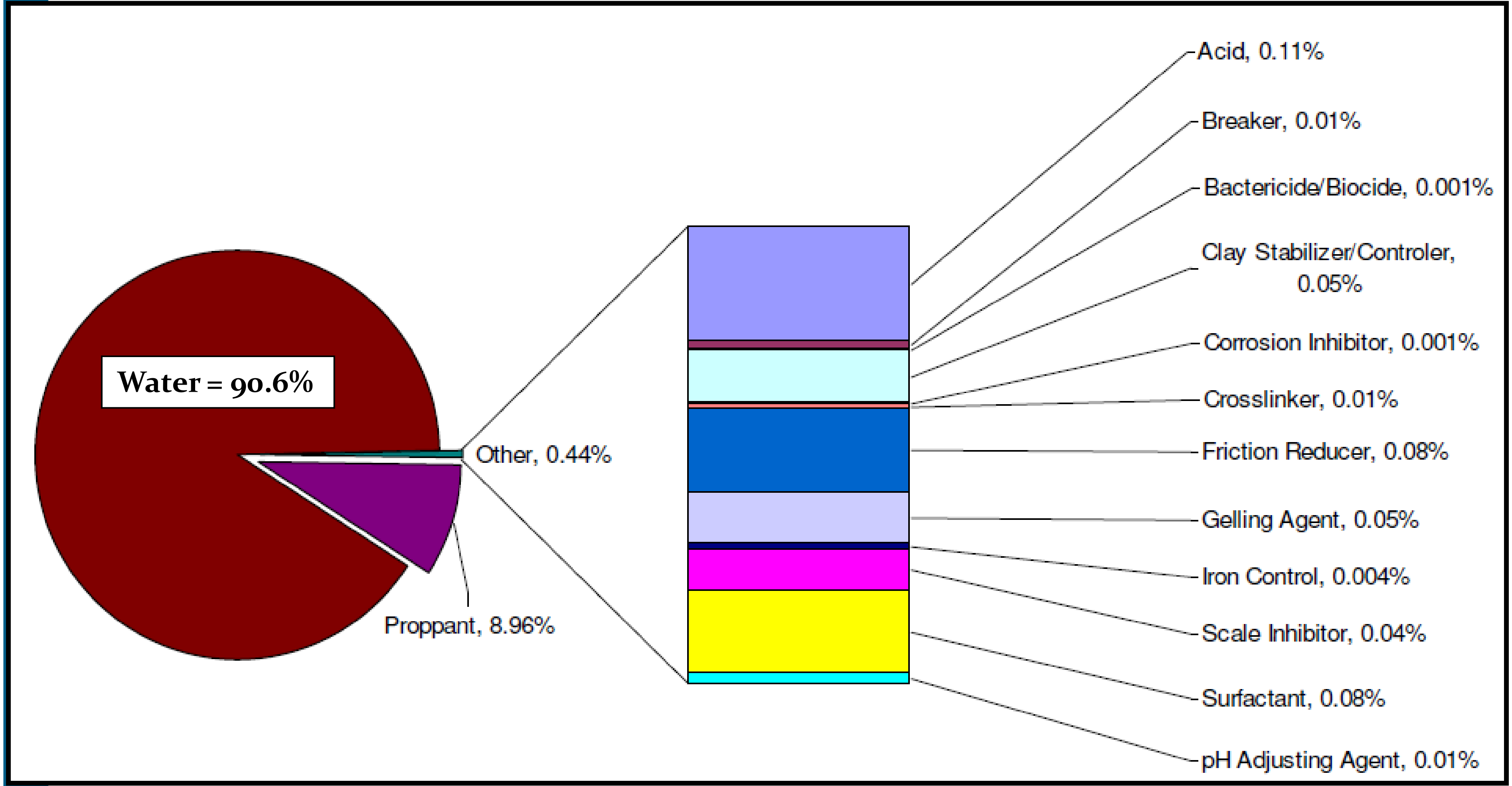
- Fracturing fluids are designed to:
  - Create a hydraulically induced fracture
  - Preserve the reservoir’s flow capacity
  - Create viscosity to transport and place proppant in the created fracture
  - Reduce to lowest possible viscosity to flowback out of the well and leave the proppant in place
  - Leave a clean proppant pack in place

Slickwater Frac Fluid Design

- Slickwater systems:
  - Are simpler designs
  - Consist of water, sand, and friction reducer
  - Rely on fluid velocity to transport sand
- Friction reducer to help maximize pumping rate
- Surfactants, clay stabilizer, and scale inhibitors can be used as required

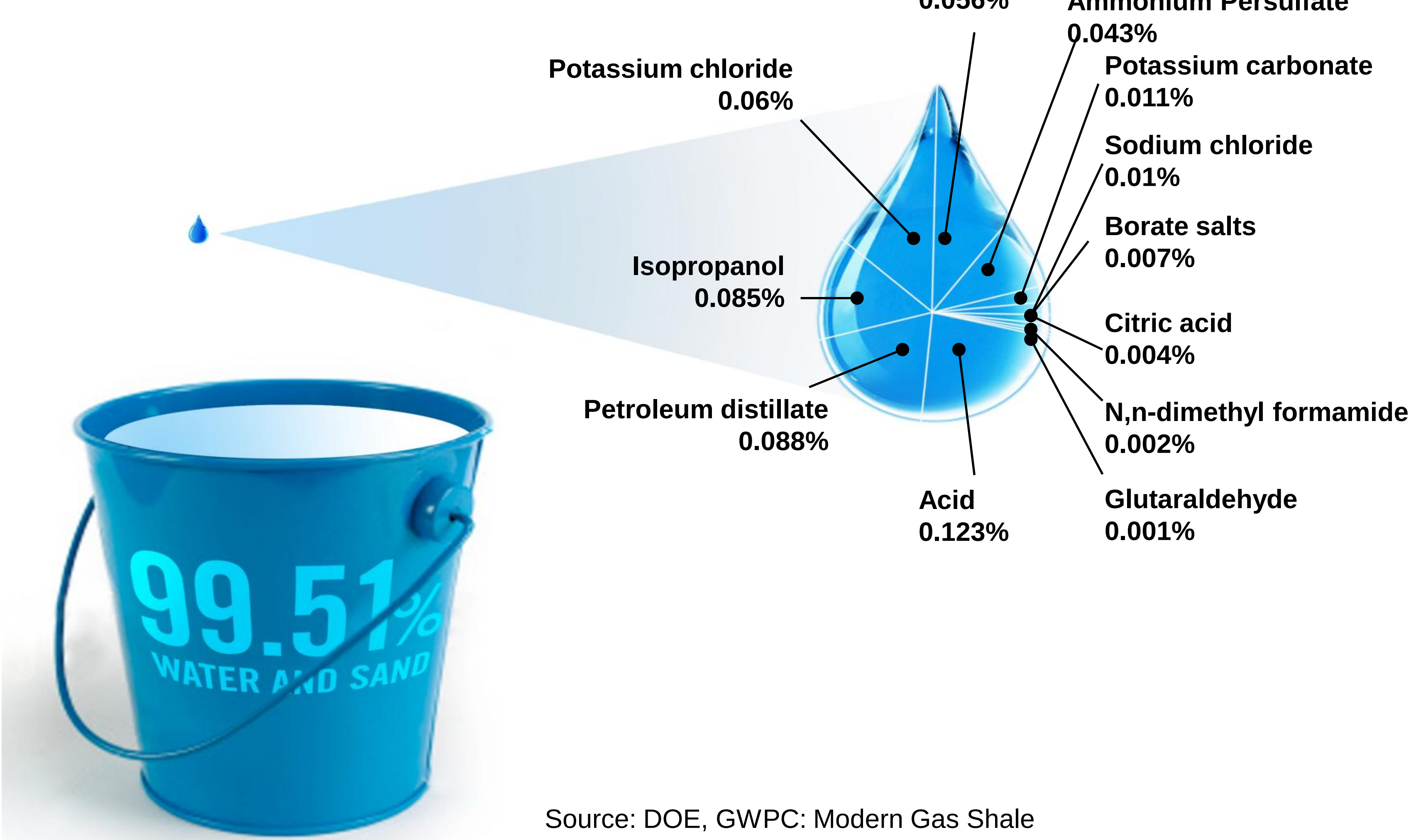
Materials Used

Hydraulic Frac Water Composition



NYSERDA - 2009

0.49% ADDITIVES



Source: DOE, GWPC: Modern Gas Shale Development In the United States: A Primer (2009)

Materials Used

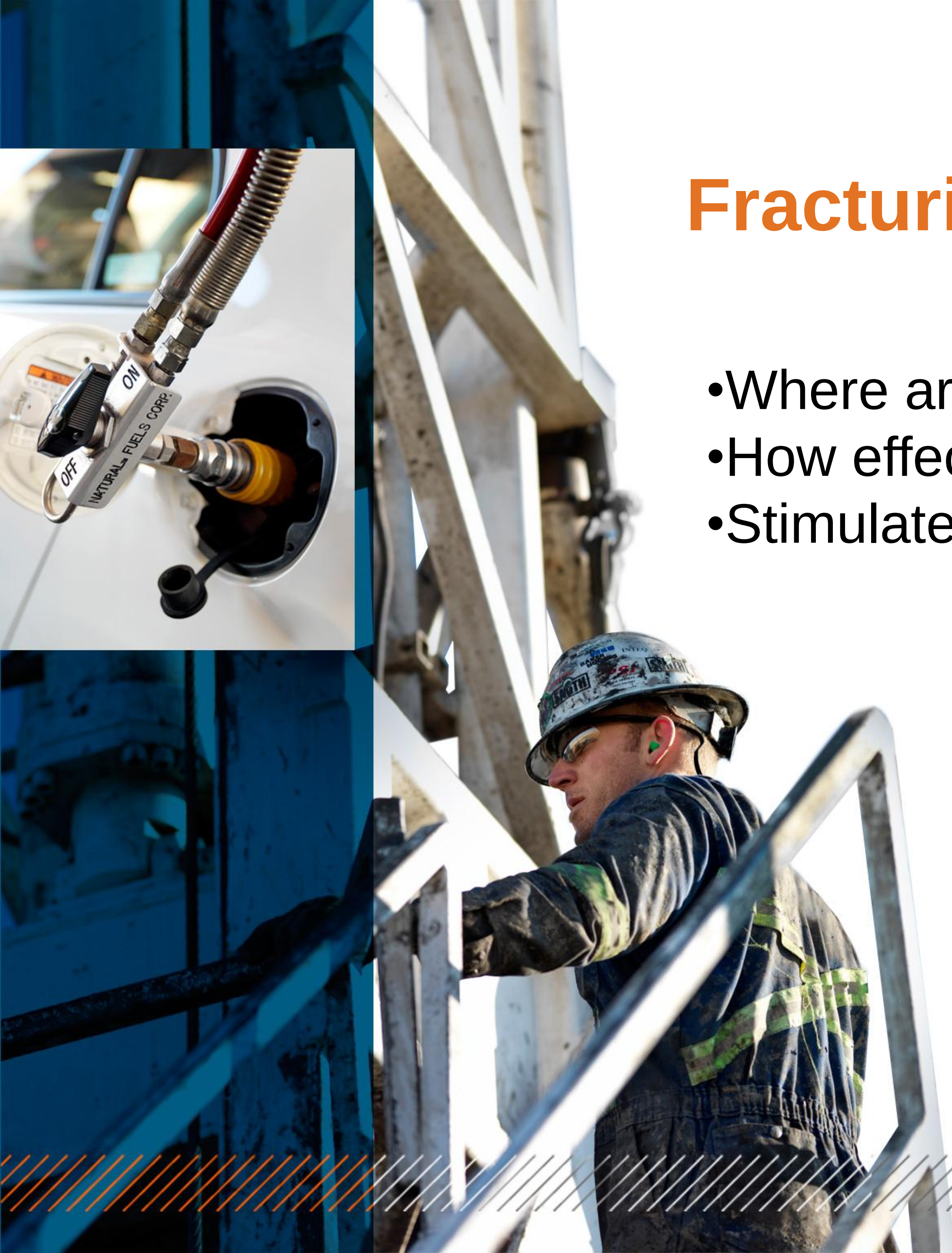
Frac fluids additives and common usage

Additive	Main Compound	Common Use
Diluted Acid	Hydrochloric or Muriatic Acid	Swimming Pools
Biocide	Glutaraldehyde	Dental Disinfectant
Breaker	Ammonium Persulfate	Bleaching Hair
Crosslinker	Borate Salts	Laundry Detergents
Iron Control	Citric Acid	Food Additive
Gelling Agent	Guar Gum	Biscuits
Scale Inhibitor	Ethylene Glycol	Antifreeze
Surfactant	Isopropanol	Glass Cleaner
Friction Reducer	Polyacrylamide	Water and Soil Treatment

Perry, GTI – 2010

Fracturing Fluid Components

Product Category	Active Ingredient	Purpose	Other Common Uses
Fluid and Proppant	99.50%		
Water	H20	Create fracture and deliver sand	
Sand (Proppant)	Silica	Prop fractures open to enable gas production	Drinking water filtration, glass, foundry casting, concrete, brick mortar
Other	0.50%		
Gel	Guar Gum	Thickens water to suspend the sand	Cosmetics, baked goods, ice cream, toothpaste, sauces, salad dressings
Friction Reducer	Polyacrylamide	Minimize friction between fluid & pipe	Water treatment, soil conditioners
Crosslinker	Borate Salts or Zirconium	Greatly increases base gel viscosity	Laundry detergents, hand soaps, cosmetics
Anti-Bacterial Agents	Glutaraldehyde	Eliminates bacteria in water that produces corrosive by-products	Disinfectant, sterilizer for medical and dental equipment
Breaker	Ammonium or Sodium Persulfate	Breaks gel to lower viscosity	Hair coloring, disinfectant, food preservation, dyes
Corrosion Inhibitor	n,n-dimethyl Formamide	Preventscorrosion of the pipe	Pharmaceuticals, acrylic fibers, plastics
Iron Control	Citric Acid	Prevents metal oxides precipitation	Food additive, food and beverages, lemon juice ~7% citric acid
Clay Stabilizer	Potassium or Quarternary Chloride	Creates a brine carrier fluid	Road de-icer, low-sodium table salt substitute, medicines, IV fluids
pH Adjusting Agent	Sodium Hydroxide or Potassium Carbonate	Maintains desired pH for crosslinker effectiveness	Laundry detergents, soap, water softener, dish washer detergents
Surfactant	Isopropanol	Used for water recovery and preventing emulsions	Rubbing alcohol, glass cleaner, multi-surface cleanser, antiperspirant, deodorants, hair-color



Fracturing Diagnostics

- Where are my stimulations going?
- How effective are they?
- Stimulated Reservoir Volume- SRV

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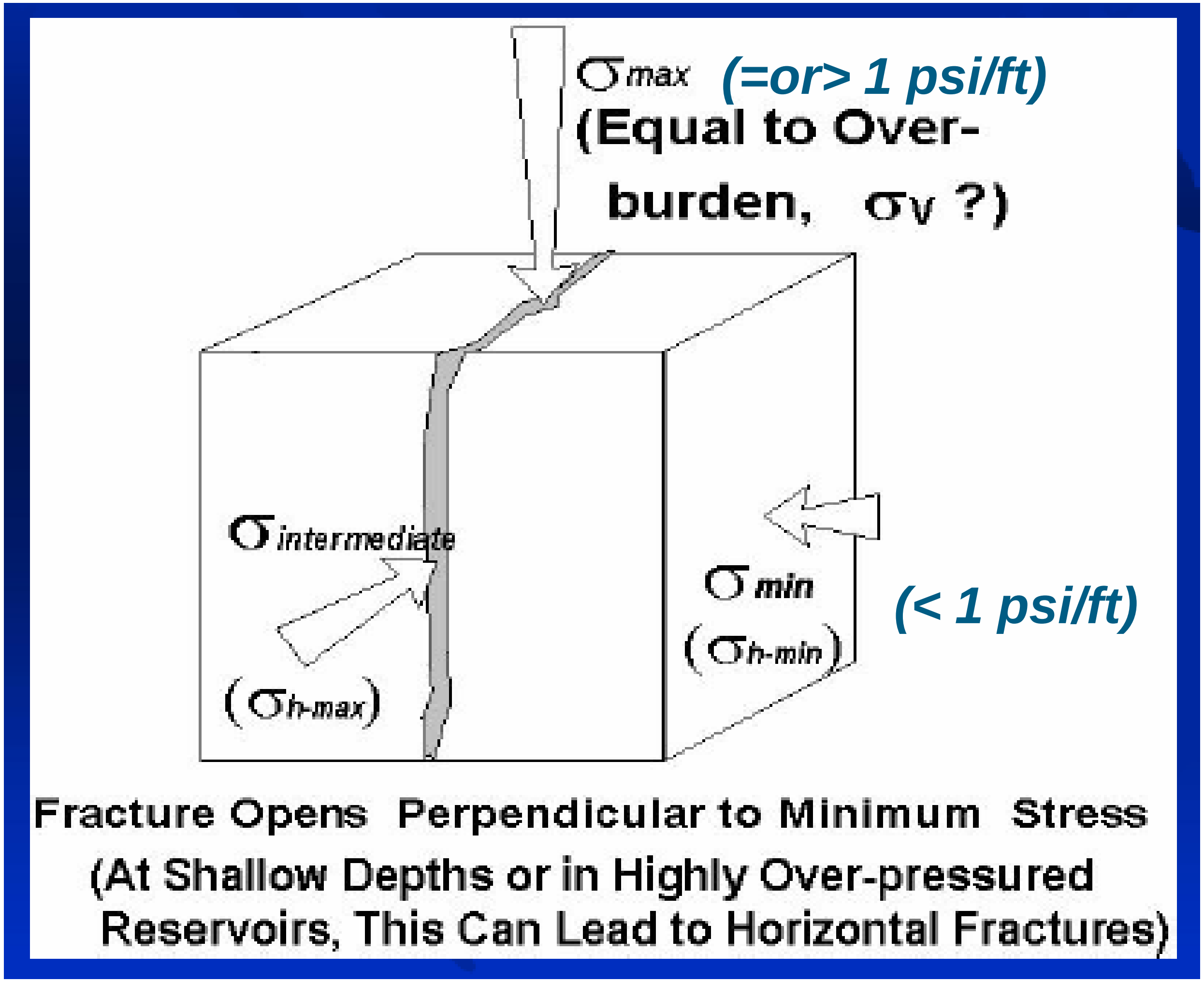
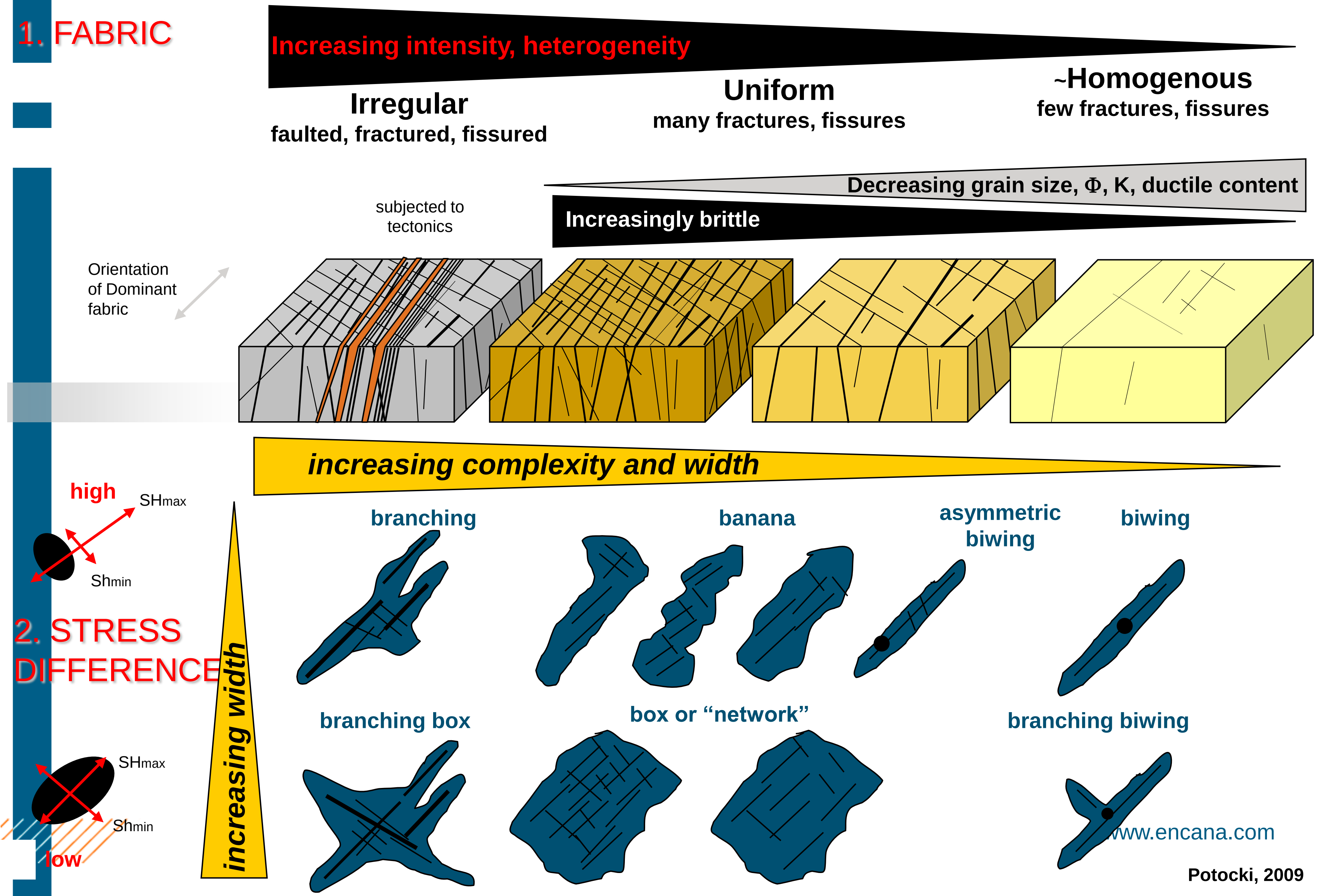
Fracture Orientation Dictated by Rock Stresses



- Acoustic logs
- Core analysis
- Image logs
- Regional stress

Two Main Controls on Stimulated Area



Microseismic

Fracture Seismic is the latest technology to determine fracture geometry

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Fracture Seismic

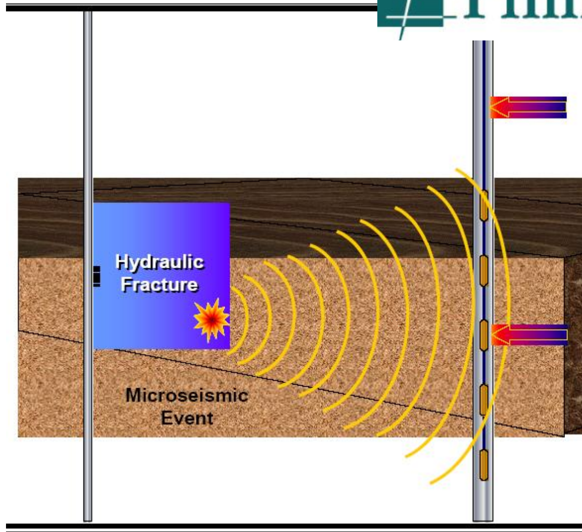
- Seismic phones are lowered into nearby non-producing well
- Seismic tools “hear” tiny shear slippages caused by fracturing
- Triangulates position of seismic activity
- All geologic basins have a preferred stress direction
- Tool for early exploration

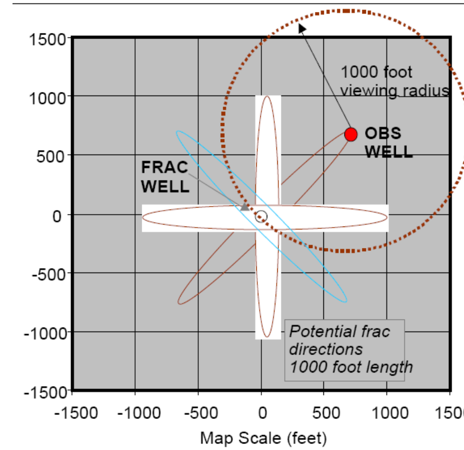
Wireline Method

Limits

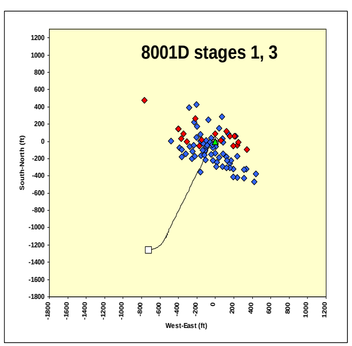
- Distance 1000-3000’
- Temp
  - Pinnacle fiber optic – 270F
  - Other tools 345F over long (frac) time
- PS wave pickers
- Pad noise
- Far wing ambiguity

Pinnacle



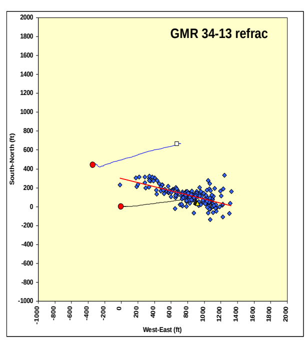


Piceance Data



ON PAD

RECORDING



OFF PAD

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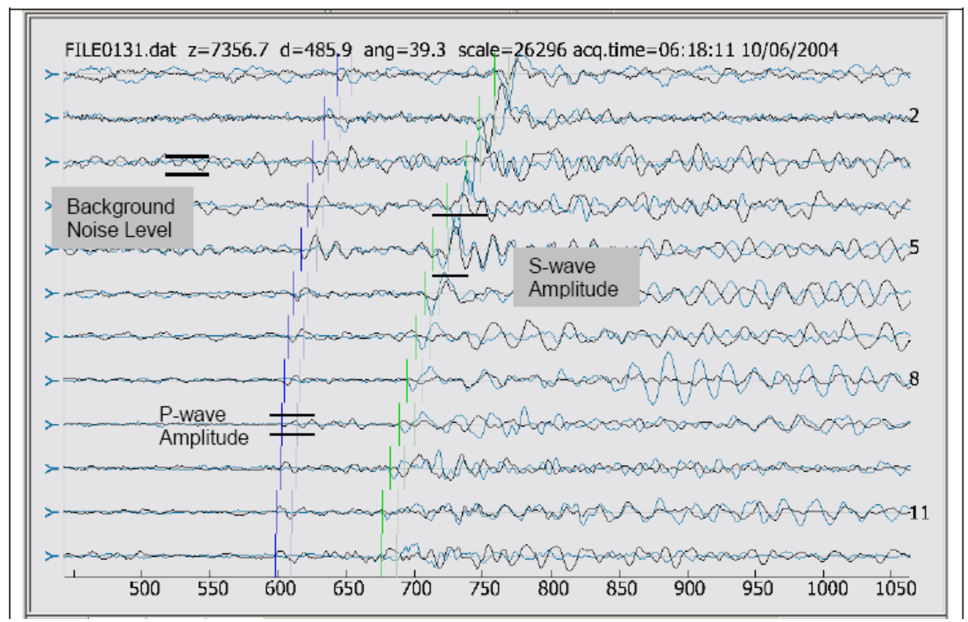
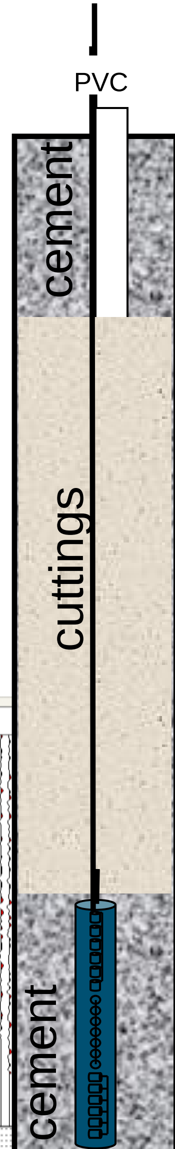
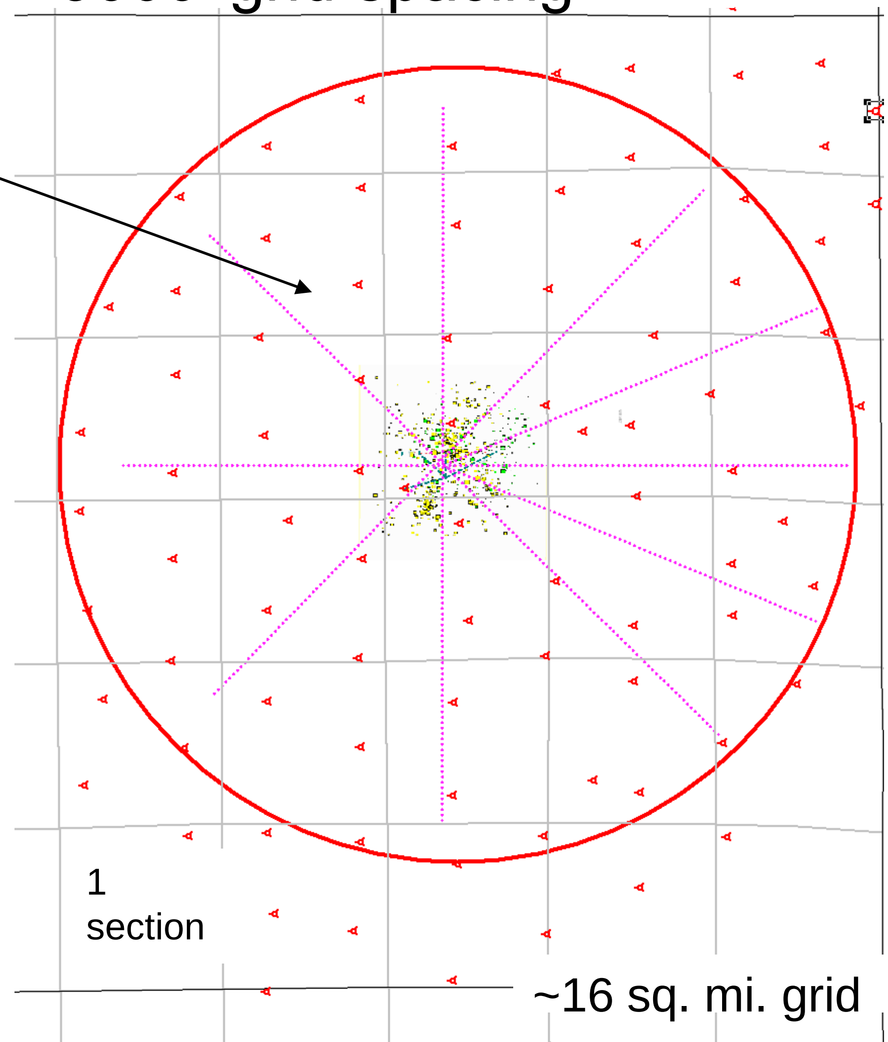


Buried Array

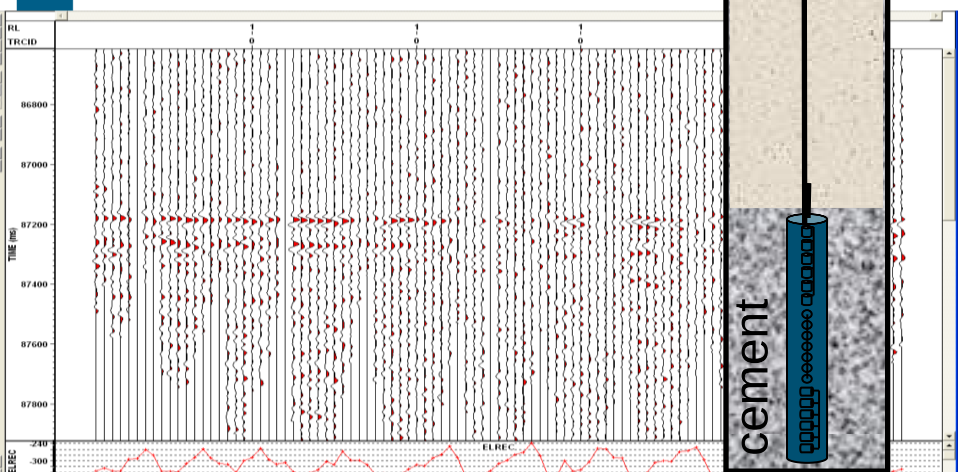


250' hole

- 100 stations
- 3000' grid spacing



~16 sq. mi. grid



Typical Record

"Micro" or Very Small Seismic Events

Moment Mag	Comments	Recording Range (feet)	Moment (MNm)	Slip and Area	Equivalent Explosive Charge
-4	Smallest we can record	<100'	001	10 µm .003 m^2	1 mg
-3		~1500'	.04	40 µm .03 m^2	30 mg
-2	Big for Barnett	~2500'	1	.1 mm .3 m^2	1 g (blasting cap)
-1	Biggest in Barnett	~5000'	40	.4 mm 3 m^2	30 mg
0	Limit of "microseismic" Biggest at Ekofisk	>10000'	1,000	1 mm 30 m^2	1 kg stick of explosive
1	Largest event Habanero geothermal		40,000	4 mm 300 m^2	30 kg
2			1,000,000	1 cm 3,000 m^2	1 ton
3	Felt earthquake		40,000,000	4 cm .03 km^2	30 ton

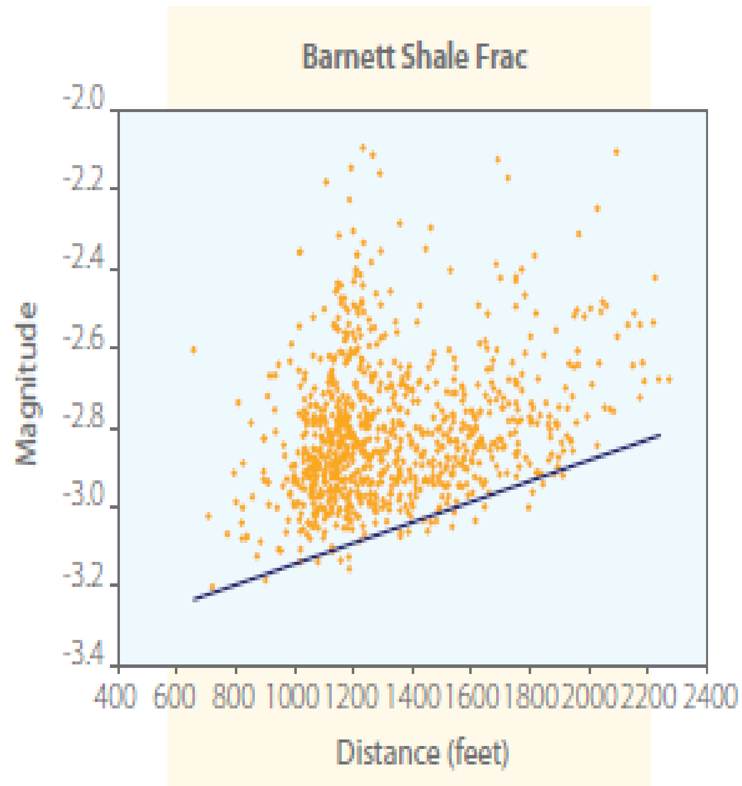
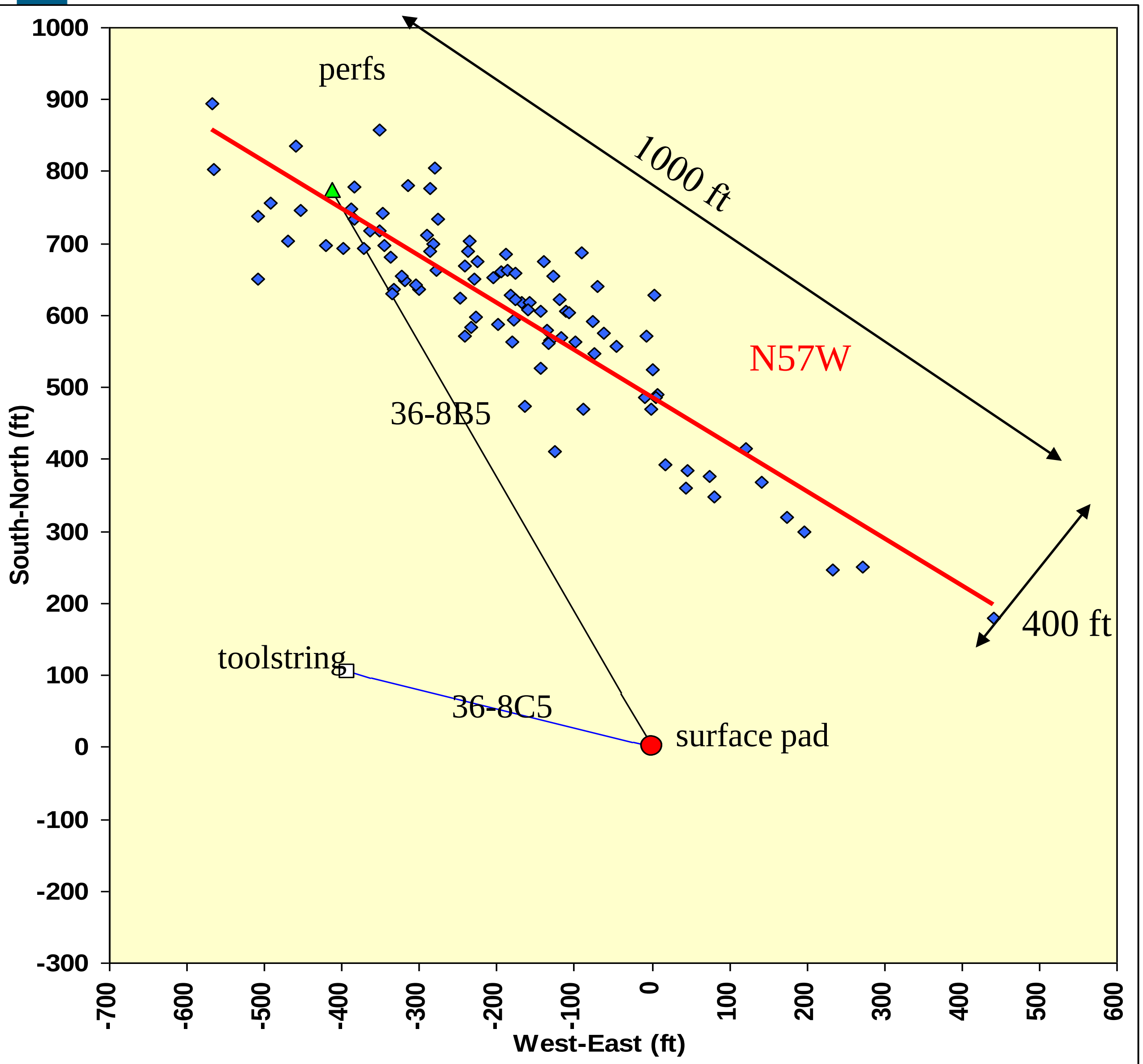


Figure 1. Magnitude versus distance plot indicating complete detection.

Plan View Micro-Seismic



Azimuth: N57W

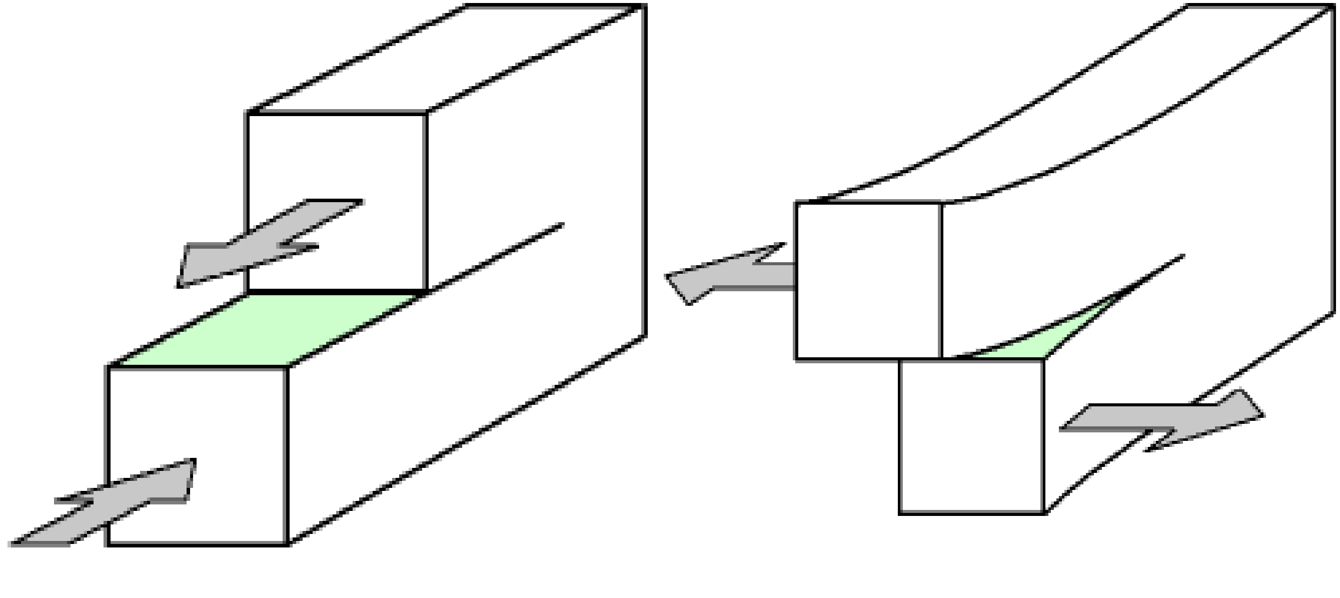
Length: 1040'SE, 200'NW

95 micro-seismic events used for analysis. Several hundred detected

Fracture assumed symmetrical

Apparent asymmetry since southeast fracture wing is closer to observation well

Modes of Fracture



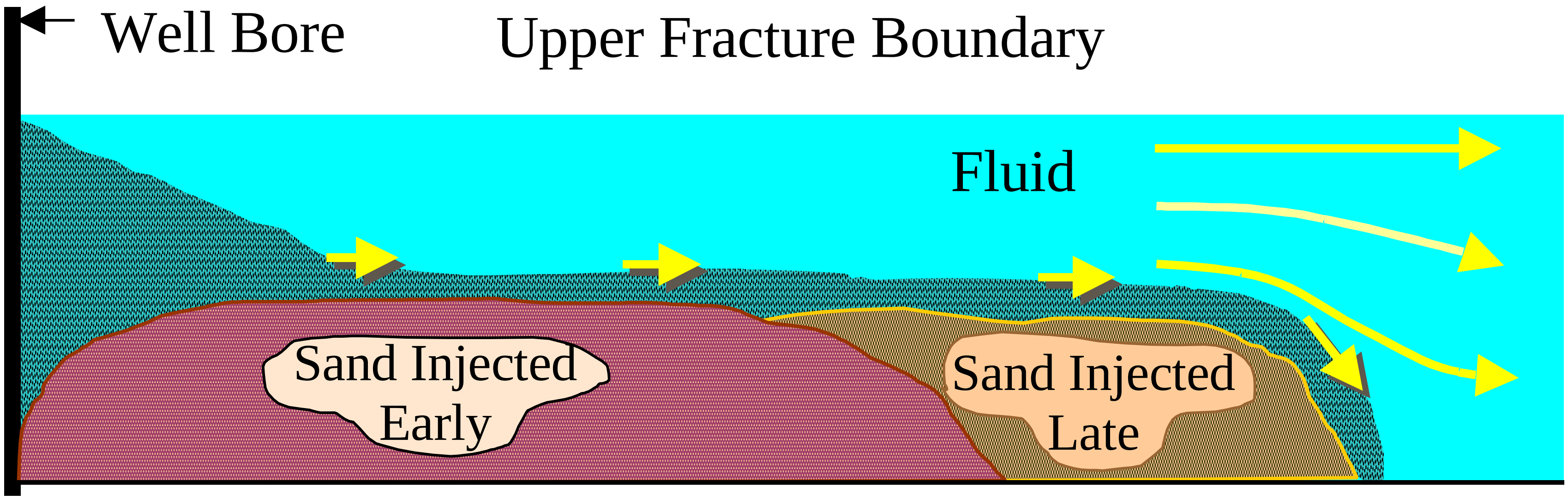
Mode I: Tension | Mode II: Sliding Shear | Mode III: Tearing Shear

Conventional frac models only assume Mode I

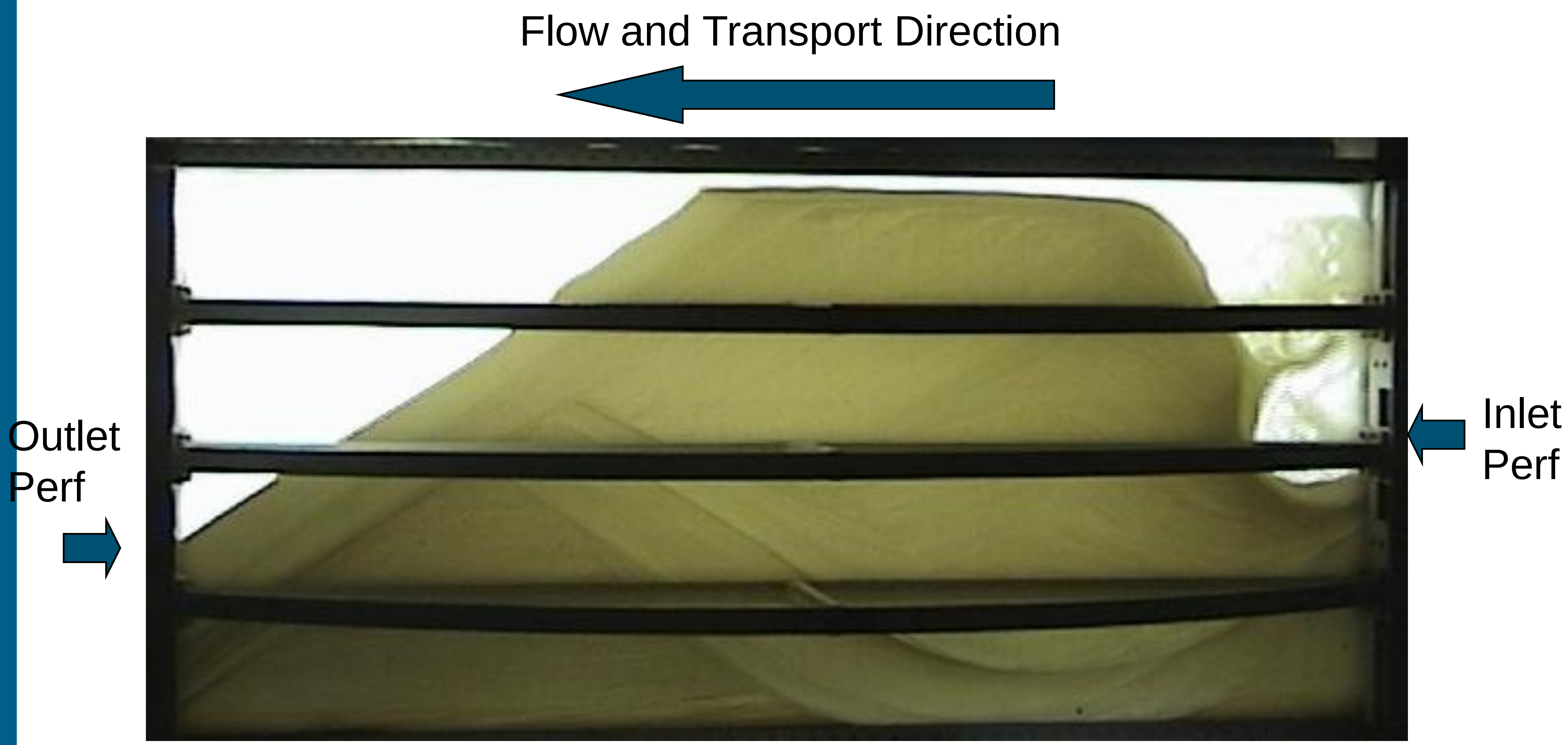
Available Frac Models

- 2D Models
  - Perkins-Kern Nordgren (PKN)
  - Khristianovich-Geertsma-DeKlerk (KGD)
  - Penny-Frac
- Pseudo-3D Models
  - MFRAC
  - StimPlan, e-StimPlan
  - FracCade
- Lumped Parameter Models
  - FracPro
  - FracPro-PT
- 3D Models
  - GOHFER
  - N-StimPlan
  - Terra-Frac

Schematic of Sand Transport in Low-Visc Fluid



Sand Transport in Thin Fluids: 4 ft Tall Slot Model



Equilibrium bed height is formed by high velocity flow across top of sand bank. Fracture is filled with immobile sand.

Fracture Modeling Conclusions

- Significant (and continuing) improvements in understanding and modeling over the last 50 years
- Current beliefs tend toward well contained fracture heights driven by shear, formation anisotropy, and heterogeneity rather than just stress profiles
- New proppant transport models give a more realistic view of placement and treating pressure behavior (cause and effects of problems in pumping and performance)
- Improved diagnostics have enhanced model development

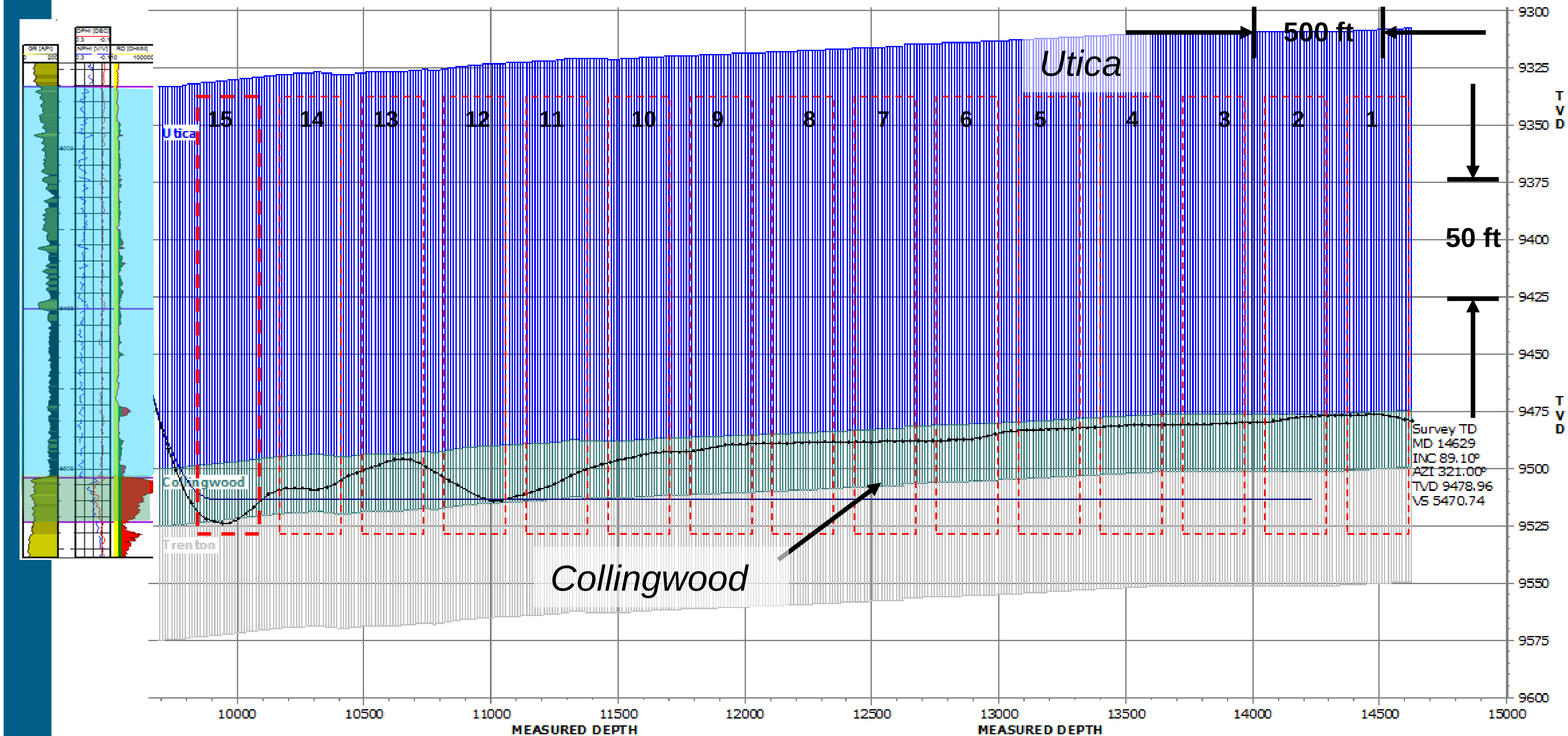
State Oil & Gas Regulations

- Permitting
  - Locating, wellbore design, drilling, completion, operation
- Well Construction
  - Surface and intermediate casing
  - Cementing ~ isolate production zone from groundwater zones
    - Cement standards
    - Cement integrity testing
    - Cement bond logs
- TA Wells
  - Integrity testing
  - Bridge plugs
- Well Plugging – Final Abandonment
  - Cement producing formation
- Orphan Well Programs

2012 Michigan Utica/Collingwood Shale Completions Technical Review

State Pioneer 1-3HD1.

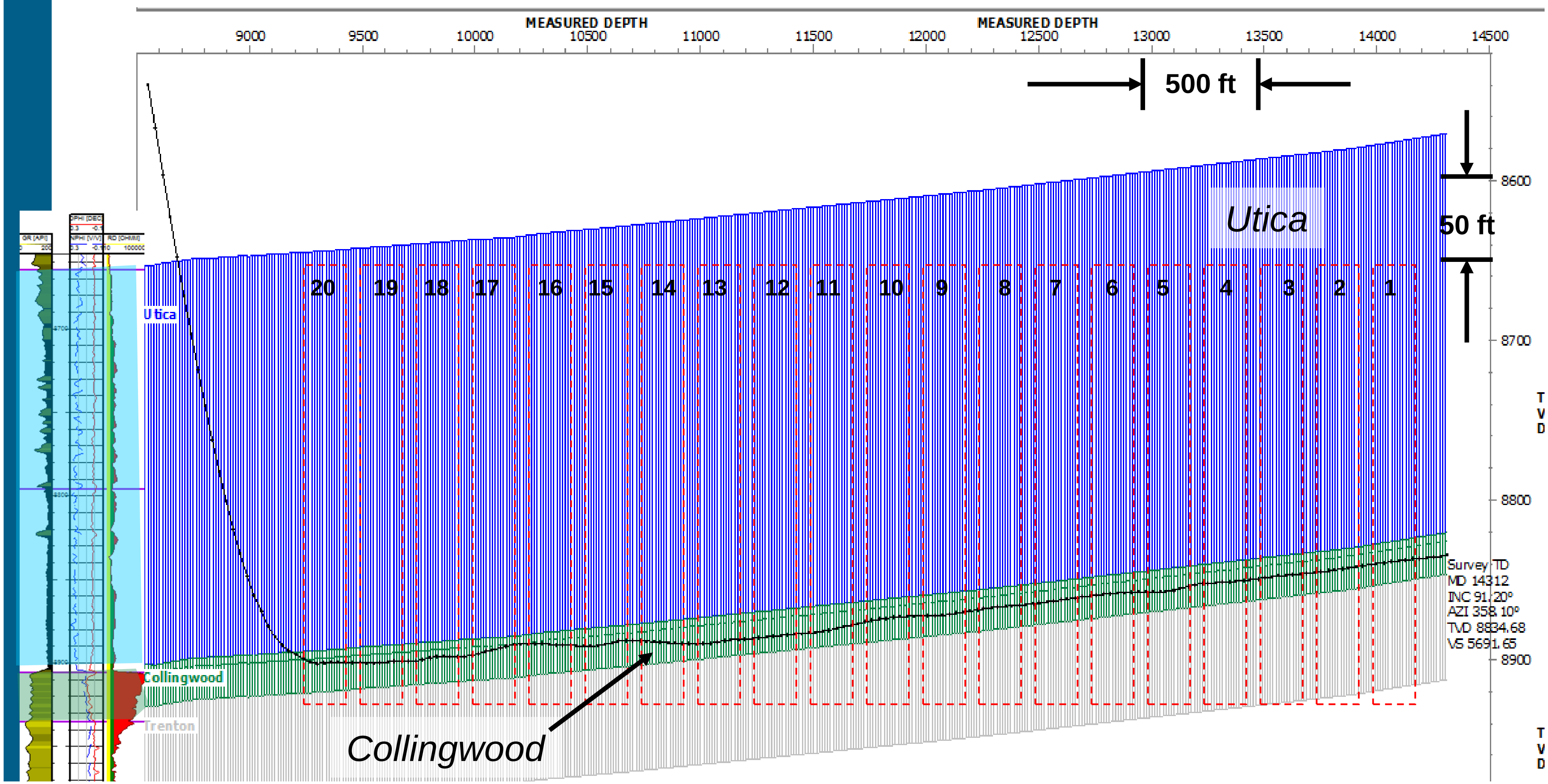
Frac Spacing & Completion Information



Stage	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Ave Treating Pressure (psi)	7,842	8,917	8,513	8,698	8,625	8,659	9,108	9,120	8,993	9,038	8,987	8,991	9,350	8,766	8,983
Frac Gradient (psi/ft)	1.12	1.12	1.12	1.12	1.12	1.12	1.16	1.12	1.01	1.11	1.08	1.08	1.04	0.93	1.04
Total Proppant (Klbs)	220	265	264	268	274	275	256	250	259	268	258	252	273	252	252
Total Fluid (bbls)	8,804	8,474	8,524	8,195	8,961	9,519	9,409	9,219	9,258	9,419	9,664	9,586	9,826	9,752	11,404

State Excelsior 1-13HD1

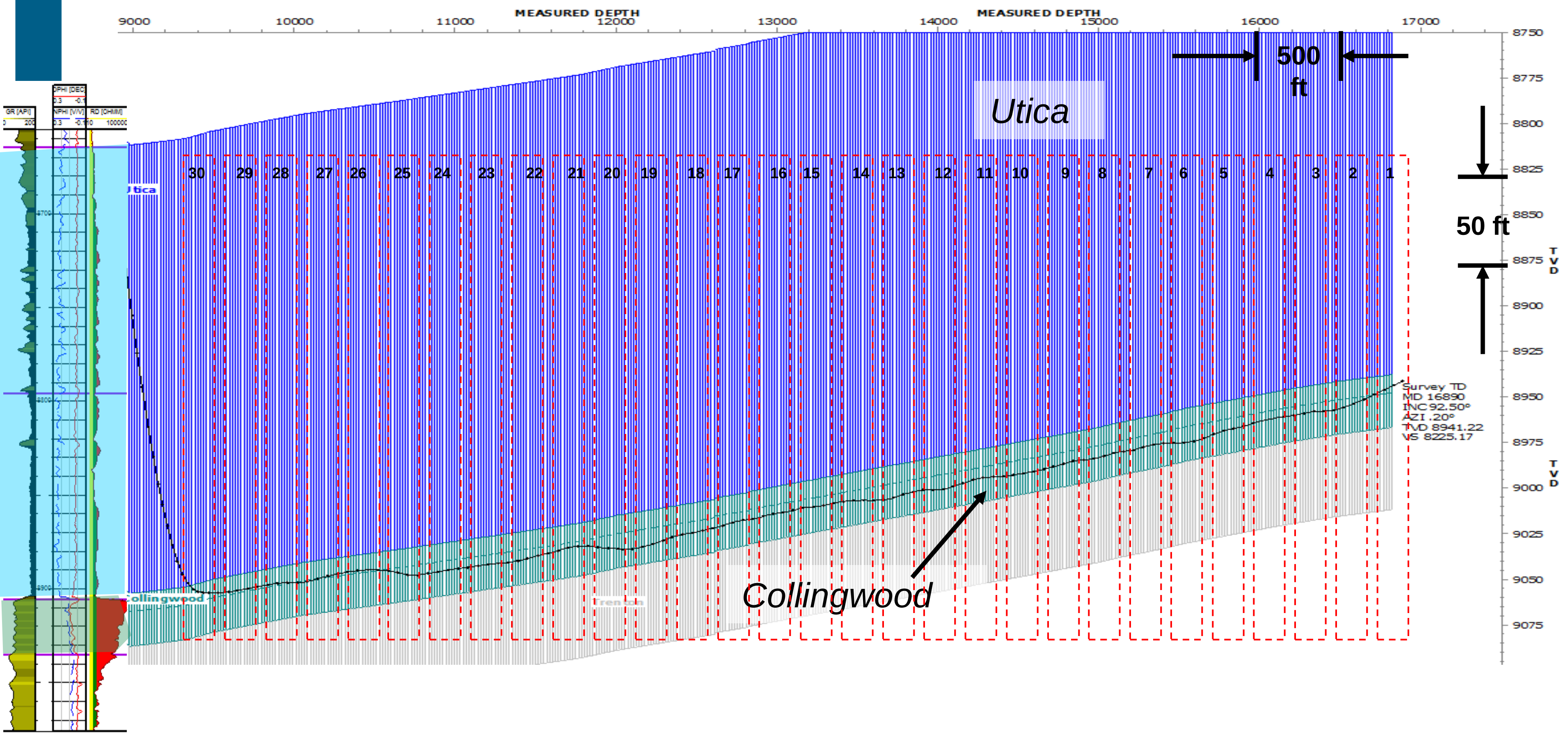
Frac Spacing & Completion Information



Stage	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Ave Treating Pressure (psi)	8,009	7,245	7,553	7,577	7,858	7,513	7,670	7,780	8,060	7,766	7,814	7,775	8,070	8,104	8,327	8,156	8,380	8,622	8,607	8,926
Frac Gradient (psi/ft)	1.18	1.12	1.13	1.11	1.14	1.13	1.14	1.11	1.12	1.12	1.12	1.12	1.10	1.12	1.13	1.12	1.16	1.12	1.09	1.42
Total Proppant (Klbs)	185	190	195	187	186	187	180	181	182	194	185	172	171	175	182	173	178	182	184	204
Total Fluid (bbls)	7,810	7,120	6,905	6,875	6,828	6,503	6,364	6,481	6,999	6,441	6,834	6,437	6,513	7,725	7,462	6,891	6,302	6,615	10,323	6,117

State Excelsior 1-25HD1

Frac Spacing & Completion Information



Stage	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Ave Treating Pressure (psi)	7,775	8,103	7,991	7,972	8,056	7,988	8,041	8,166	8,273	8,034	8,216	8,250	8,300	8,377	8,314	8,275	8,430	8,515	8,514	8,545	8,539	8,489	8,606	8,394	8,616	8,808	8,735	8,694	8,760	8,879
Frac Gradient (psi/ft)	1.09	1.11	1.10	1.09	1.09	1.10	1.10	1.09	1.10	1.10	1.10	1.09	1.10	1.12	1.10	1.11	1.13	1.12	1.10	1.11	1.12	1.12	1.11	1.12	1.12	1.12	1.12	1.14	1.14	1.13
Total Proppant (Klbs)	187	189	240	196	192	196	188	184	191	189	187	188	186	186	187	180	183	191	189	184	192	193	145	181	156	113	155	151	96	119
Total Fluid (bbls)	6,536	7,288	6,439	6,763	6,647	6,605	6,530	6,646	6,612	6,586	6,567	6,534	6,362	6,835	7,128	6,919	6,435	6,856	6,573	6,852	6,927	7,261	5,904	6,837	6,450	6,905	6,585	7,025	5,993	7,868

Encana Collingwood/Utica Completion Evolution

Well Averages & Immediate Future Well Design

	Actual			Proposed	
	Pioneer 1-3HD1	St. Excelsior 1-13HD1	St. Excelsior 1-25HD1	St. Excelsior 2-25HD1	St. Excelsior 3-25HD1
Lateral Length (ft)	5,029	5,200	7,500	7,500	10,000
Stage Number	15	20	30	30	40
Stage Length (ft)	350	250	250	250	250
Cluster Spacing (ft)	70	50	50	50	50
Clusters / Stage	4	4	4	4	4
Perfs / Stage	48	48	40	32	32
Perfs / Cluster	12	12	10	8	8
Pump Rate (bpm)	69	65	64	65	65
Rate / Hole (bpm)	1.46	1.35	1.60	2.03	2.03
Rate / Cluster (bpm)	17.4	16.2	16.0	16.3	16.3
Perforation Phasing	60°	60°	180°	180°	180°
Proppant / Cluster (lbs)	64,745	45,925	44,271	50,000	50,000
Proppant / Stage (lbs)	258,980	183,700	177,083	200,000	200,000
100 mesh (lbs)	*86,887*				
40/70 (lbs)	*172,093*	*54,860*	*62,460*		
30/50 (lbs)				*50,000*	*50,000*
20/40 (lbs)		*128,840*	*114,623*	*150,000*	*150,000*
Total Proppant (lbs)	3,884,700	3,674,000	5,312,500	6,000,000	8,000,000
Fluid / Stage (bbls)	9,334	6,977	6,716	10,000	10,000
Fluid / Cluster (gals)	98,010	73,260	70,513	105,000	105,000
Total Fluid (bbls)	140,014	139,542	201,467	300,000	400,000
Fluid Type	Slickwater	Slickwater	Slickwater	Slickwater	Slickwater

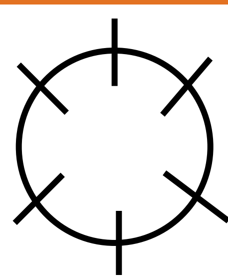
Improve

Completions Design Modifications

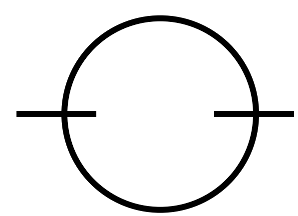
Existing South Wells

- Changes from Pioneer 1-3 completion
  - Larger proppant size
  - Shorter stage spacing
  - Pump acid for break down
  - Different drilled azimuth
- Modifications for Excelsior 1-25 (extended lateral)
  - Reduced friction
    - Higher concentration acid breakdown procedure
    - Perf phasing & number/stage

Pioneer 1-3 & Excelsior 1-13
60 degree phasing



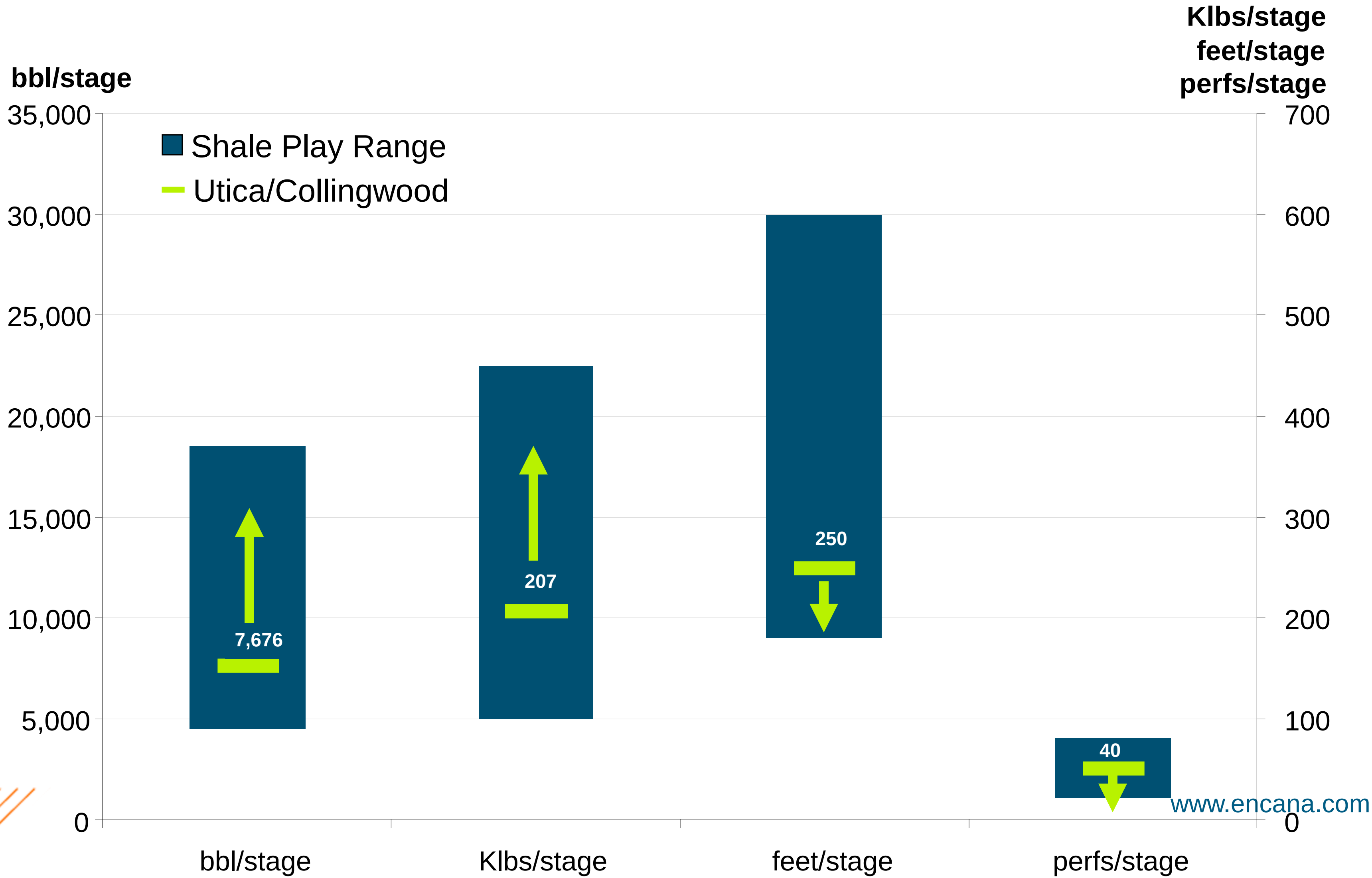
Excelsior 1-25
180 degree phasing



Michigan Utica/Collingwood

Completions Comparison to other Shale Developments

Multiple opportunities for completion optimization



Michigan Utica/Collingwood

Completions Summary

- Successfully completed all wells to date
- Minimal design changes to date
- Multiple opportunities for completion optimization and EUR improvement
  - Utilize LEAN methodology and Design of Experiments (DOE)
  - Encana track record of completion optimization and productivity improvement.

Future Ideas for Completion Optimization

Performance Improvements

- Stimulation Optimization
  - Fluid and Proppant
    - Volume
    - Type
  - Perforation Strategy
    - Spacing
    - Orientation
    - # Clusters
    - Rate/cluster
    - Fluid/cluster
    - # shots
    - Perf size
- Execution Changes
  - Pump-down plug and perf
  - Sliding sleeves
  - Non-cemented
  - Expandable casing packers (ECP)
  - Open-Hole Packers

Questions?