Wireline Logging

Describes a suite of geophysical tools that are lowered into a well (often oil & gas; sometimes water, mining, or environmental monitoring) to record physical properties of the down-hole environment.

Much cheaper than coring (~$15–60 per m, plus transport); provides ***in situ*** information on medium that can't be gained from core & enables "ground-truthing" of physical properties imaged by surface geophysics.

Main types include:

- ***Electrical*** (resistivity, spontaneous potential)
- ***Nuclear*** (active and passive gamma, neutron)
- ***Seismic*** (sonic ⇒ acoustic (i.e. P-wave), velocity log)
- "***Other***" (caliper, temperature, camera, magnetic susceptibility, …)

Geology 5660/6660 Applied Geophysics

20 Apr 2018

Last Time: Wireline Logging

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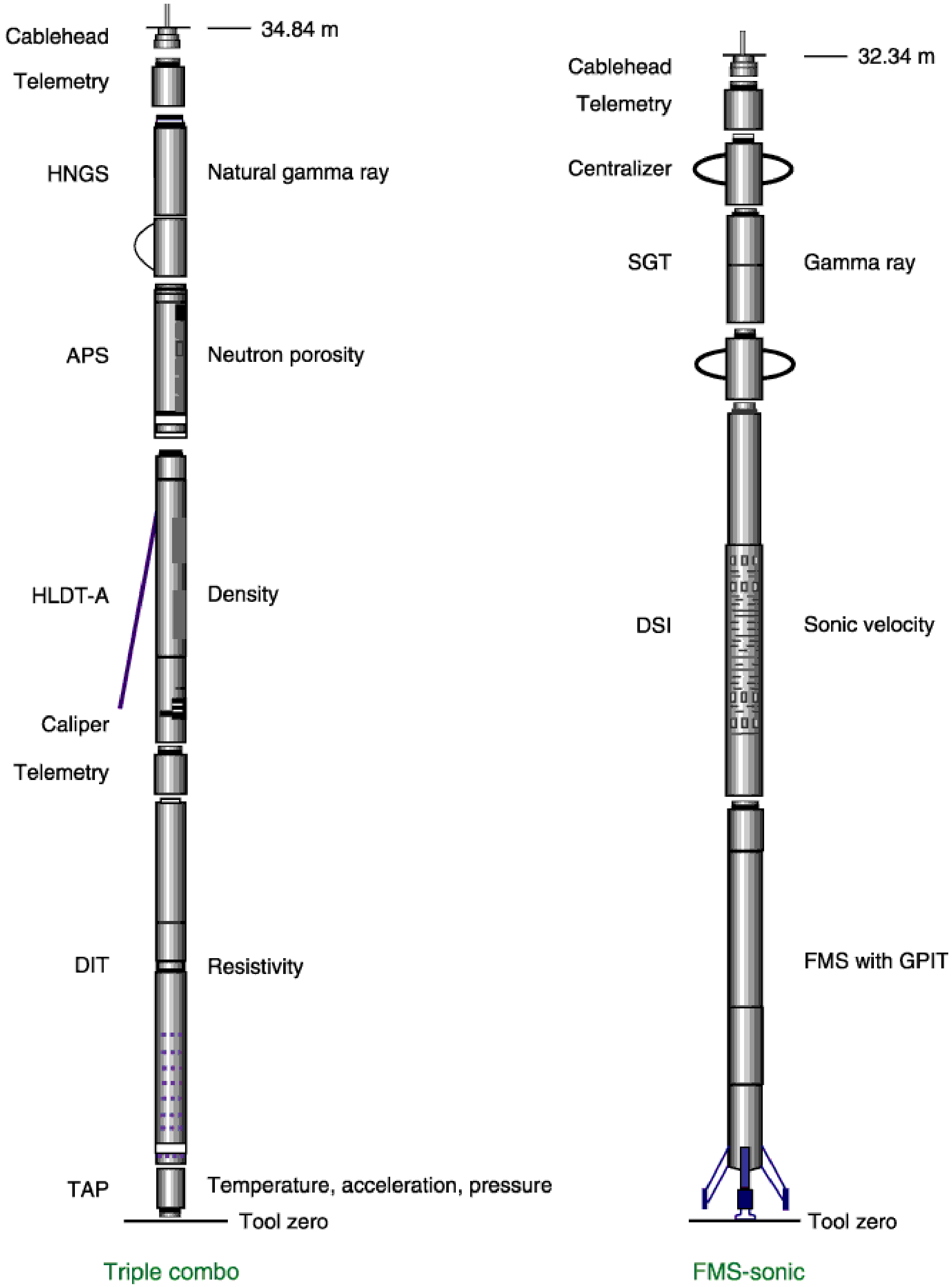
- ***Borehole televiewer*** (& caliper) give fracture properties, "dipmeter", log/core correlation
- ***Resistivity logs*** work on similar principles to surface DC resistivity method; low ρ implies shale, clay or briny fluid
- Low ***Spontaneous Potential (SP)*** indicates presence of high-porosity/permeability, brine-filled formations
- ***Natural Radioactivity ("Gamma") Log*** measures high energy EM (γ-freq) radiation; multi-spectral $\rightarrow$ concentrations of K, Th, U elements. Useful for shale content, cementation, some detrital minerals, strat correlation, paleosols...

Wireline Logging Applications matrix

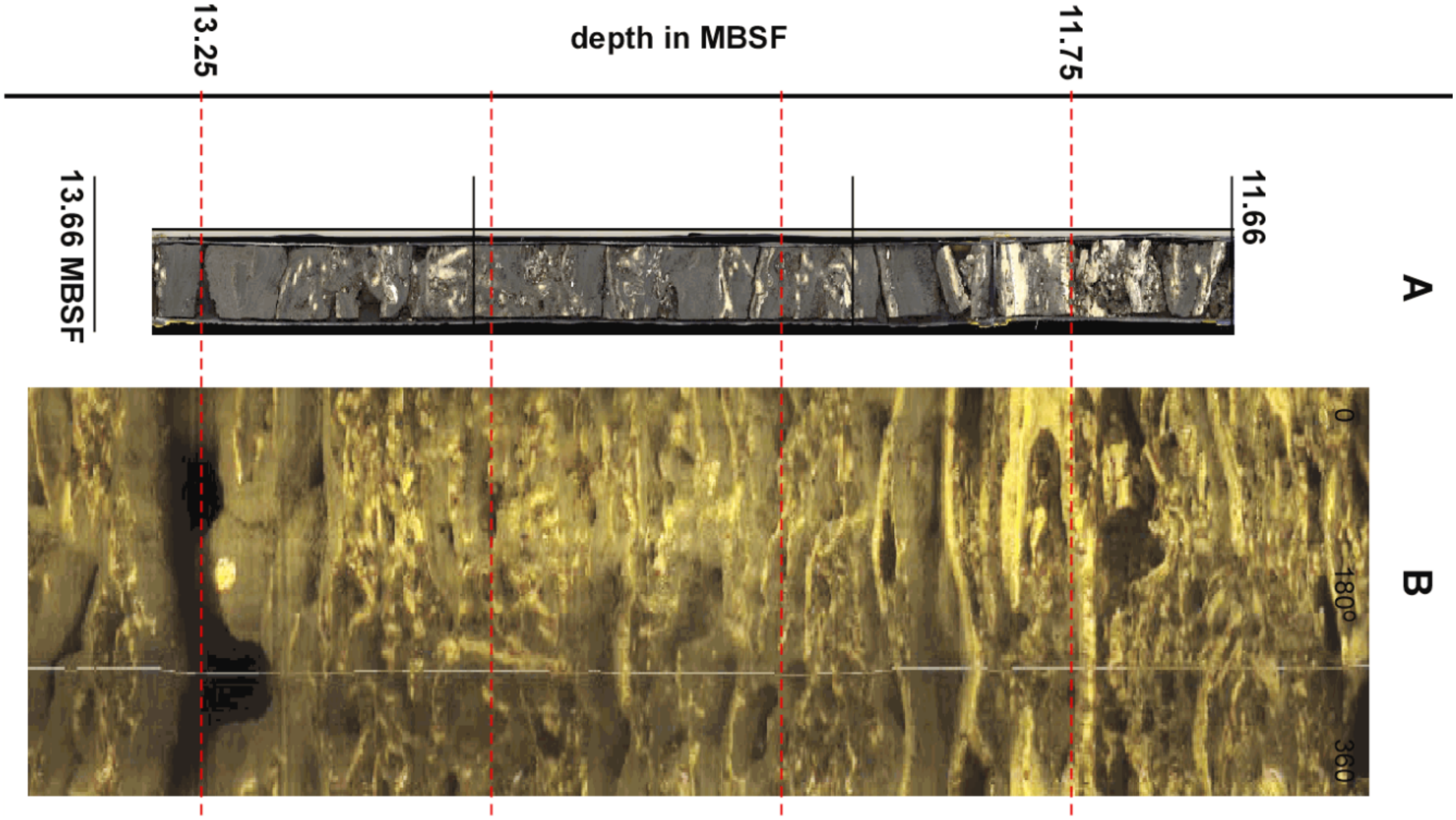
(IODP-USIO website at Lamont-Doherty: https://iodp.tamu.edu/tools/logging/selection.html)

	Principal Application	Resistivity	Velocity	Density	Porosity	Gamma Ray	Geochemistry	Imaging	Vertical Seismic Profile	Temperature/Pressure	Borehole/Drilling Parameters
Technical	Core-Log Integration	●	●	●	●	●	●	●	●	●	●
Technical	Log-Seismic Integration		●	●					●		
Technical	Drilling Operations									●	●
Technical	High Temperature Environments			●		●				●	●
Technical	Hole Stability Problems				●						●
Scientific	Hydrogeology	●			●			●		●	
Scientific	Paleoclimate, High Resolution	●	●	●	●	●					
Scientific	Stratigraphy/Sedimentology	●	●	●	●	●	●	●	●		●
Scientific	Structural Geology			●		●		●	●		
Scientific	Gas Hydrates	●	●	●	●		●	●	●	●	

Single logs are ambiguous; combine logs to get lithology, porosity, pore fluid type



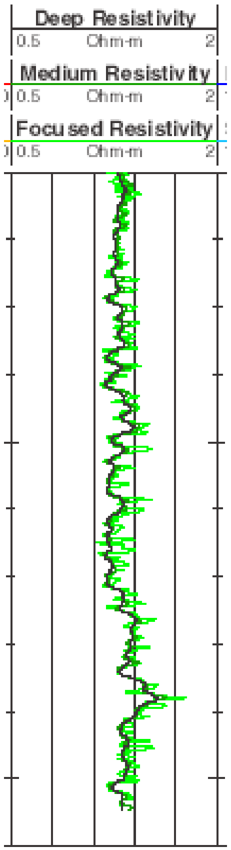
Typically a single wireline tool will include several different sources and sensors to maximize efficiency…



Borehole television or televiewer (acoustic reflection) is useful to get fracture orientations, breakouts & drilling-induced tension fractures (⇒ stress orientation; caliper also gives this). When compared to unrolled images of core, image correlation enables correction to true depth & orientation of the core.

Electrical Logging

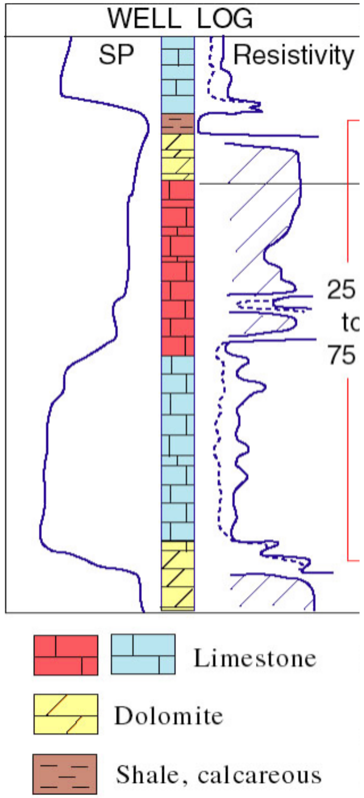
Resistivity logging uses four or more electrodes (two+ current, two+ voltage) to measure apparent resistivity of the well environment. Often use different spacings to image "shallow" and "deep"; may also measure ρ of borehole fluid.



Recall resistivity dependence:

	Low ρ_a	High ρ_a
Lithology	shale, clay	sandstone, limestone
Pore Fluid	brine	freshwater, hydrocarbon
Porosity	high	low

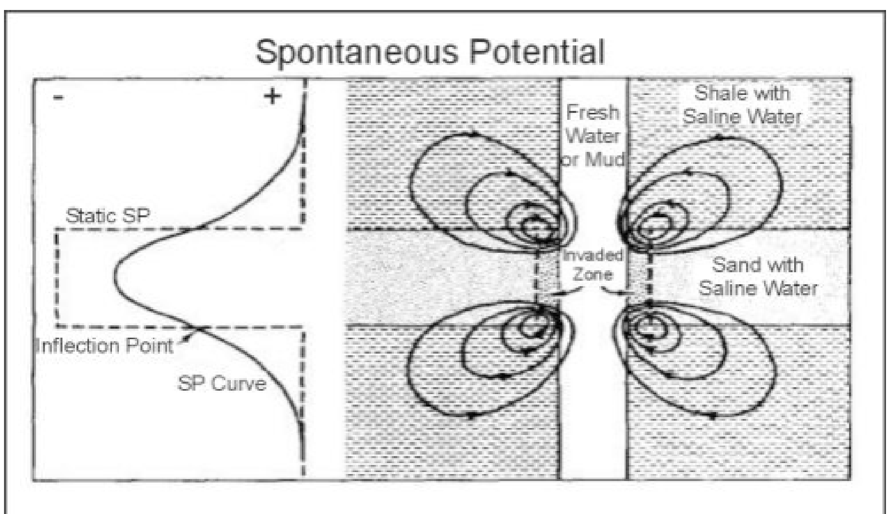
So resistivity is used ***in combination with other logs*** to infer lithology, porosity, pore fluids. FMS (formation microscanner; here "focused") also yields dip, structure, foliation & correlation to core...



Spontaneous Potential Logging

Low SP indicates interaction of brine fluids with drilling mud disturbance.

	Low SP	*High SP*
Low ρ_a	brine in porous limestone, sandstone	shale
High ρ_a	fresh water or hydrocarbon in porous limestone/sandstone;	tight limestone or sandstone



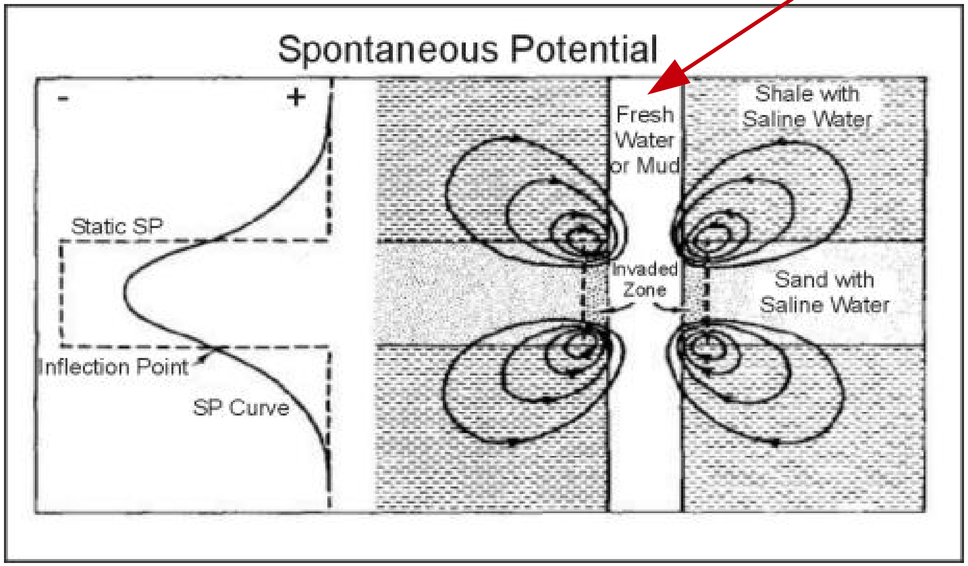
So SP is used ***in combination with other logs*** (especially resistivity) to infer lithology, pore fluid type, permeability

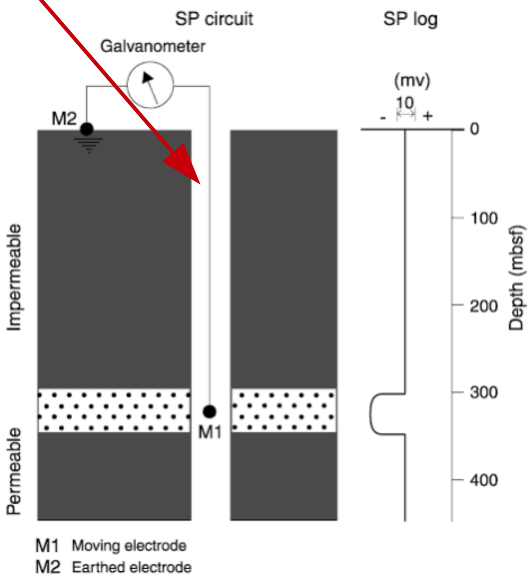
Spontaneous Potential (SP)

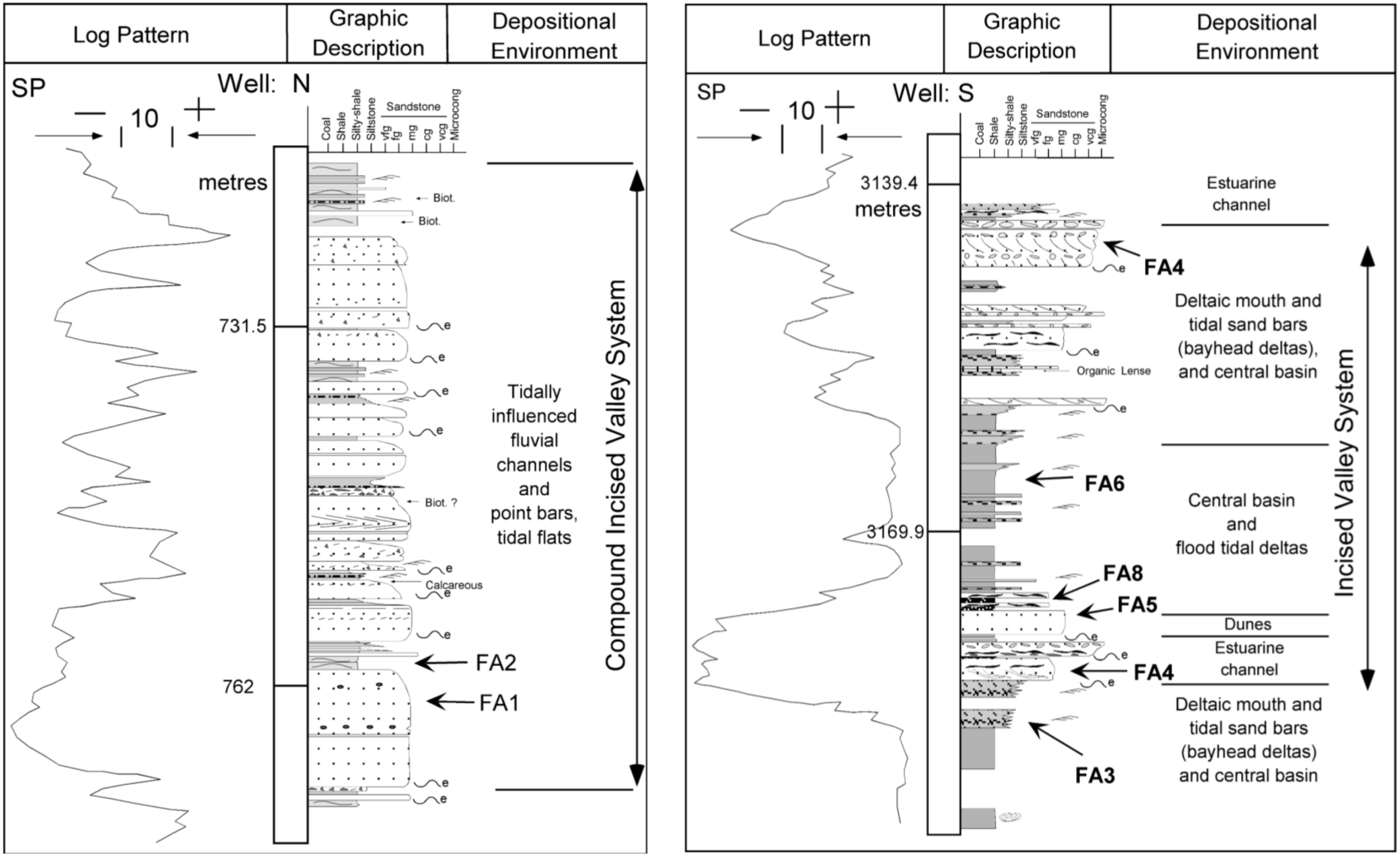
SP is an electrical potential that arises **"without"** an applied current (i.e., electrical current flow arising from natural processes or disturbances that are not initially electrical)

Three most common applications:

(i) ***Well-logging***: Electrochemical potential arises from differential diffusion of ions into drilling mud-cake from permeable formations ⇒ electrical current flow







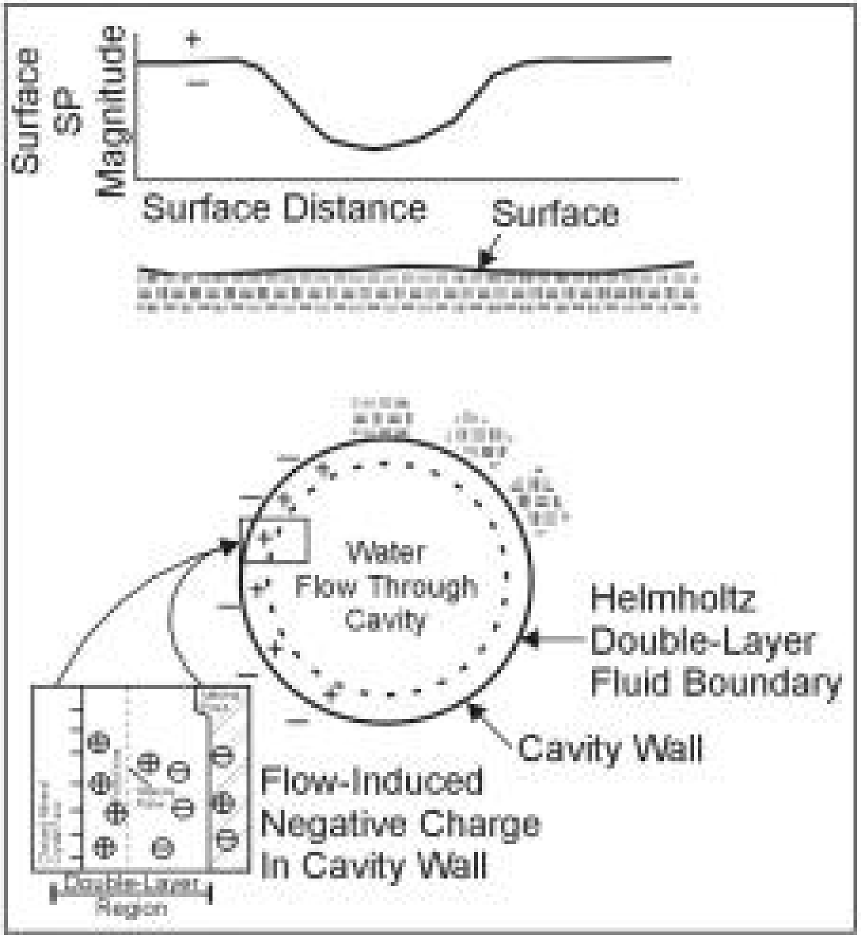
(Toro & Steel, 2020)

Note : More permeable formations $\Rightarrow$ More negative spontaneous potential

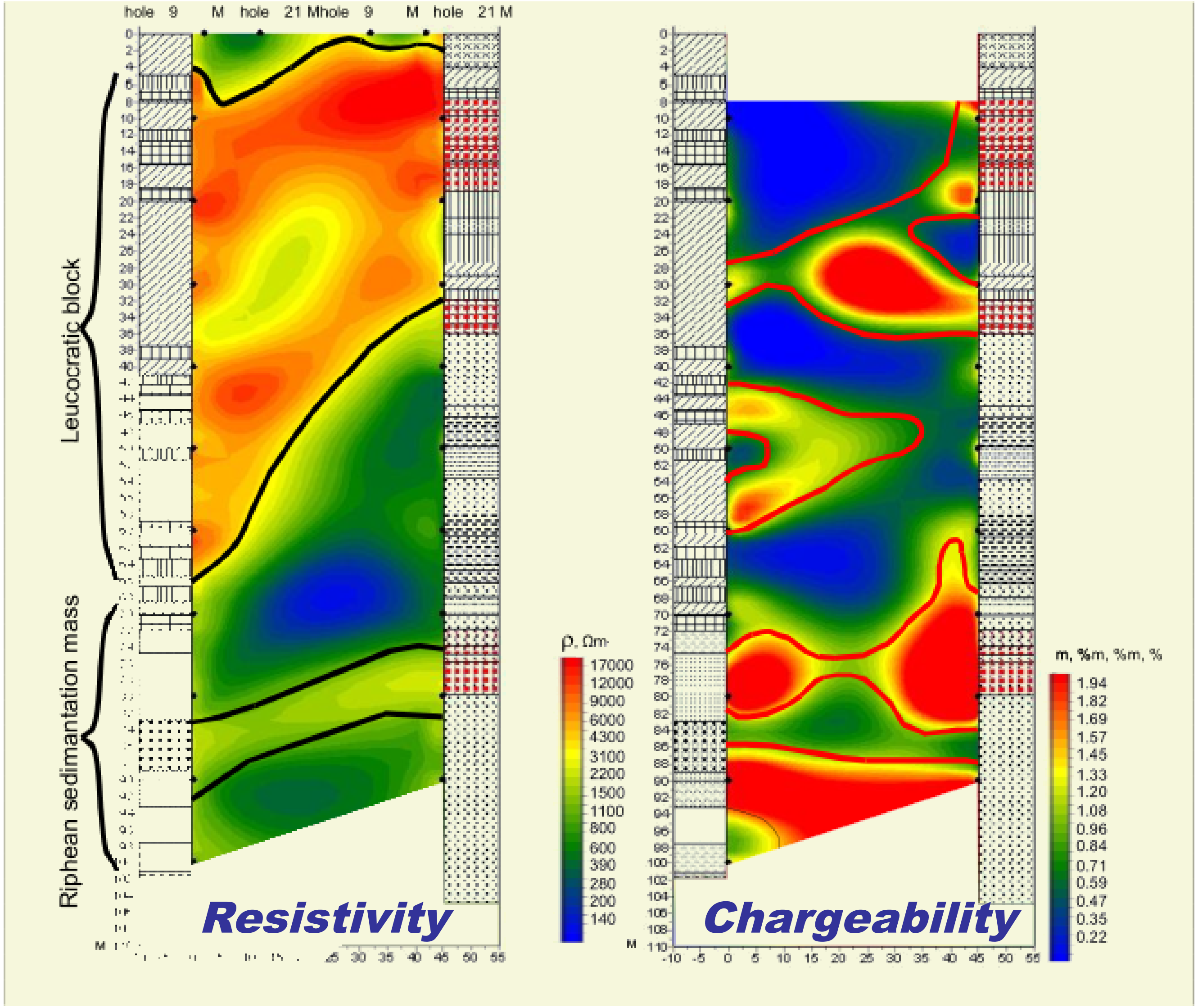
Besides well-logging, a couple of other common uses of SP include:

(ii) ***Mining***: Electrical potential differences also arise in ore bodies that are partly above the water table (oxidizing conditions) and partly below (reducing). Resulting differences in charge concentration produce electrical current.

(iii) ***Karst investigation***:
Water flowing through a cavity can build up a charge as well ("***streaming***" or ***electrokinetic potential***)



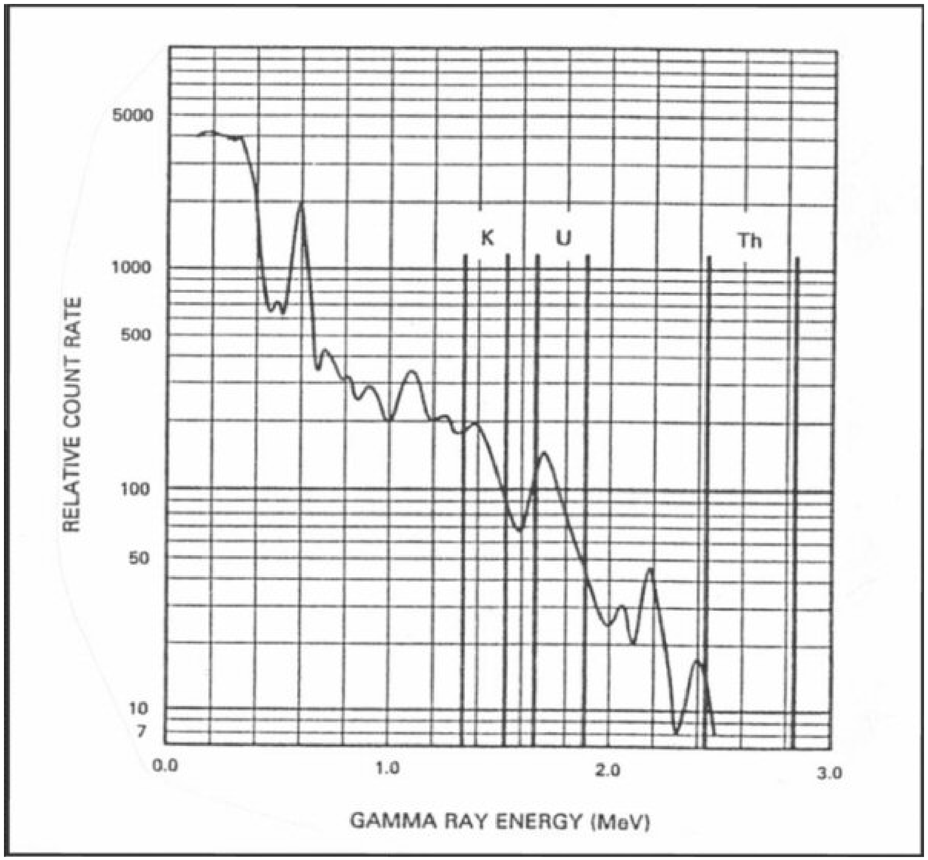
Induced Potential (IP) also gets used in a borehole context, But as in the case of surface surveys, it is used primarily for mining and environmental monitoring applications.



Here, cross-borehole imaging shows high resistivity associated with a metasomatic granite; high chargeability with sulfides accompanying trace deposits of gold.

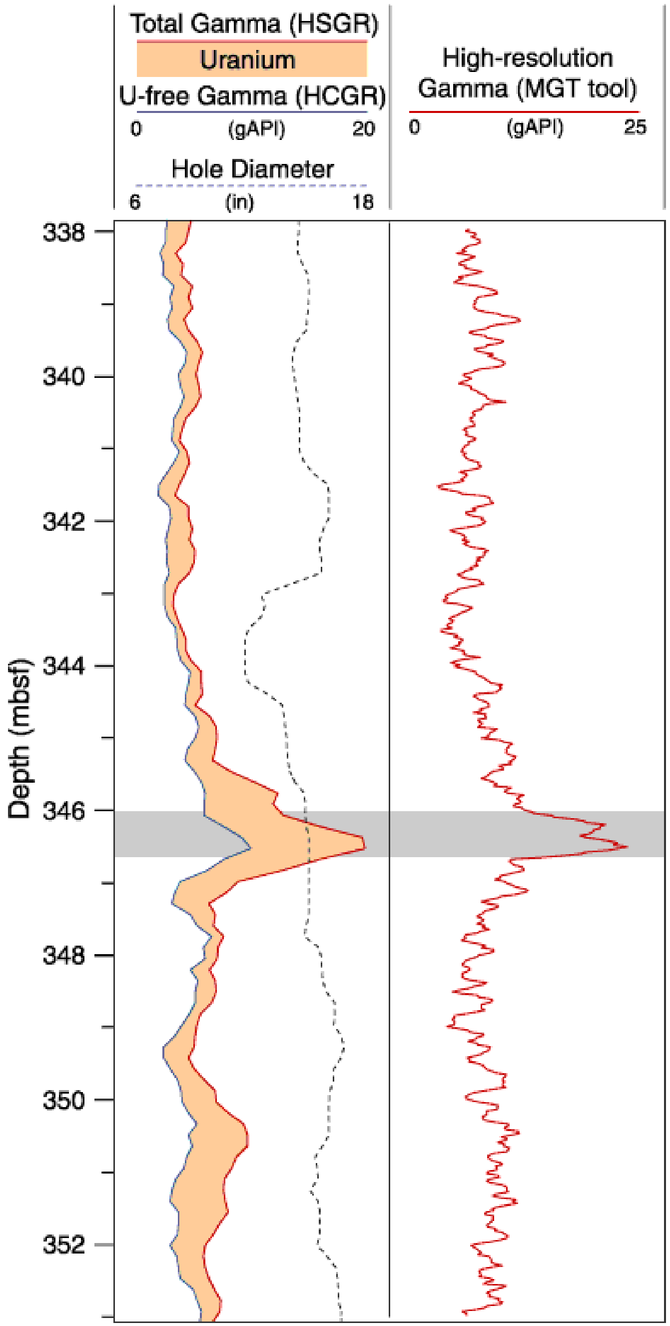
Nuclear Borehole Logging

Uses either passive or active recording of radioactive (nuclear fission) emissions.



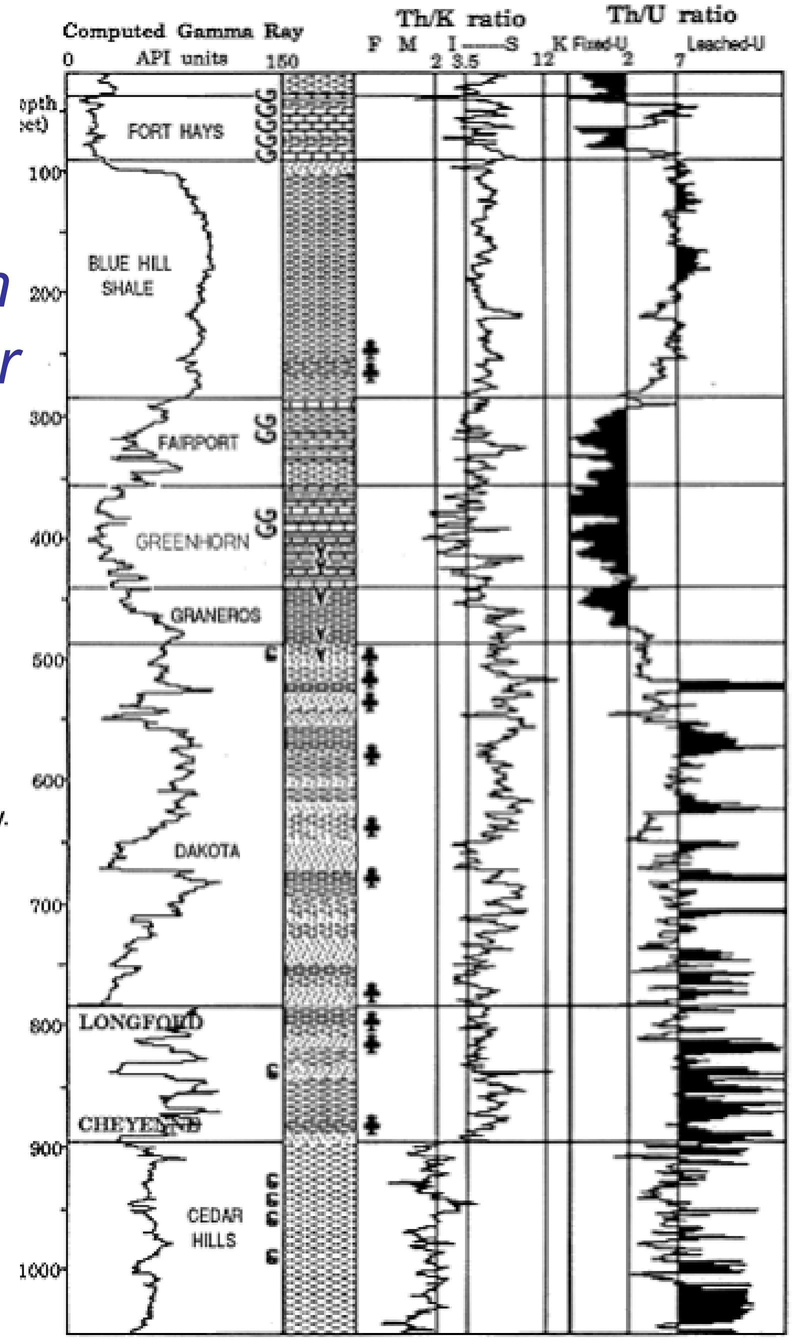
Natural Radioactivity logging records spectral content of passively-sensed gamma rays produced by fission. Spectra are different for different radioactive elements so measure concentrations of K, U, Th in the formation.

Radioactivity in sediments generally means weathered by-products of feldspar, so mostly used to infer lithology (although it also has implications for cementation, permeability, strat-correlation).

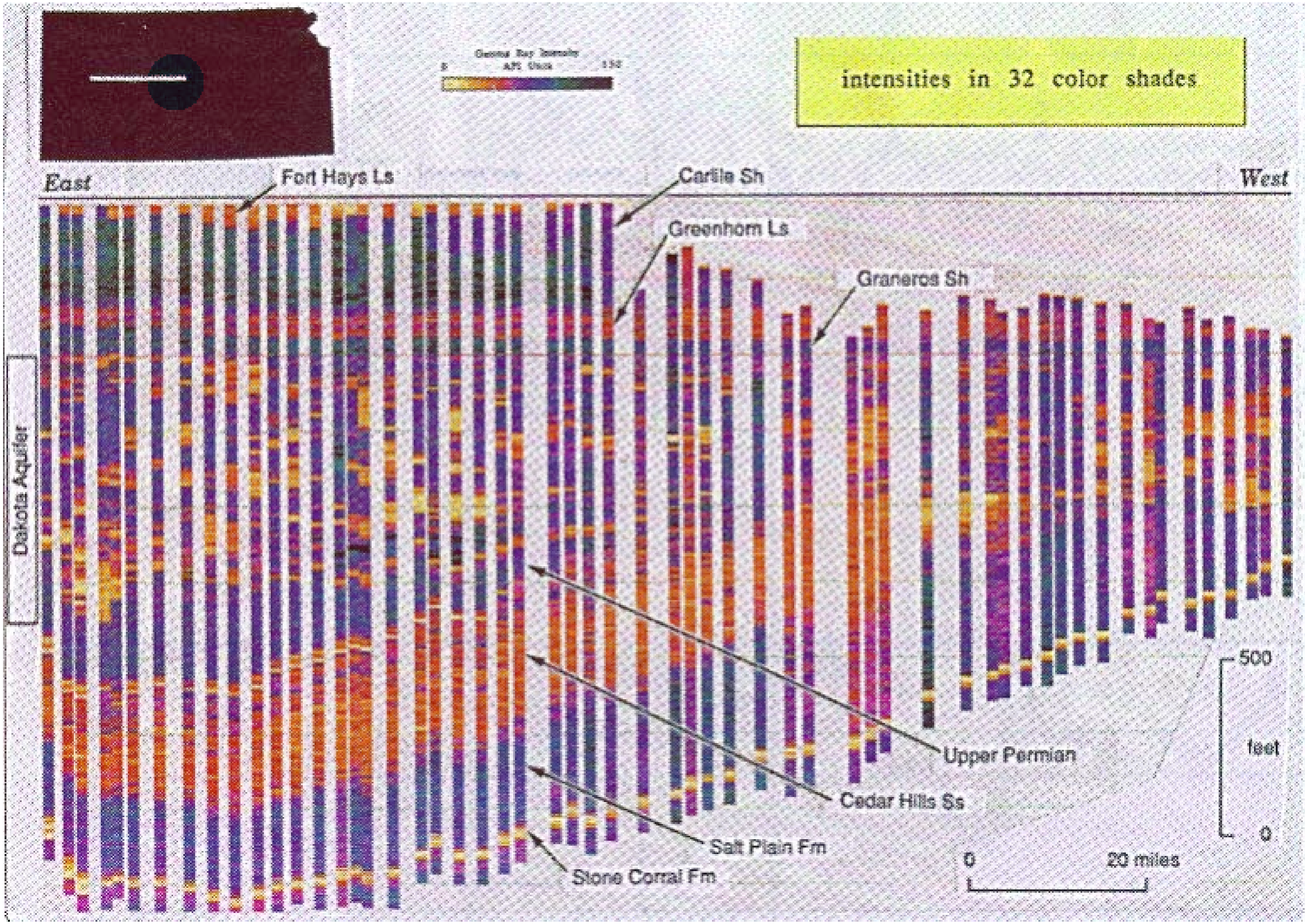


Generally speaking, low gamma means clean sandstone or limestone; high gamma indicates presence of shale.

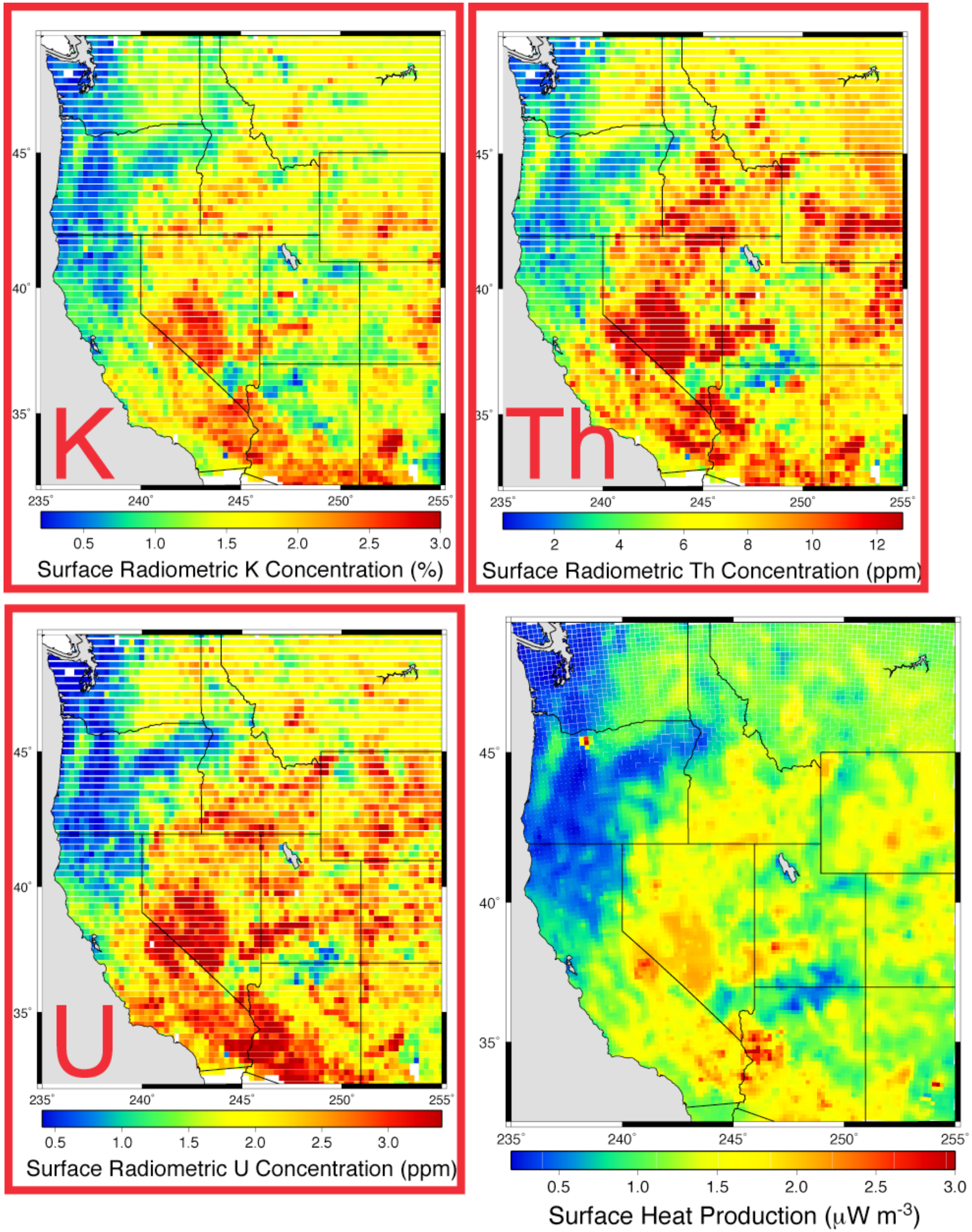
Cenomanian/Turonian boundary.
Possibly a minor black shale
or a hardground (unconformity).



(Proc Oc Drill Prog v198, 2001)

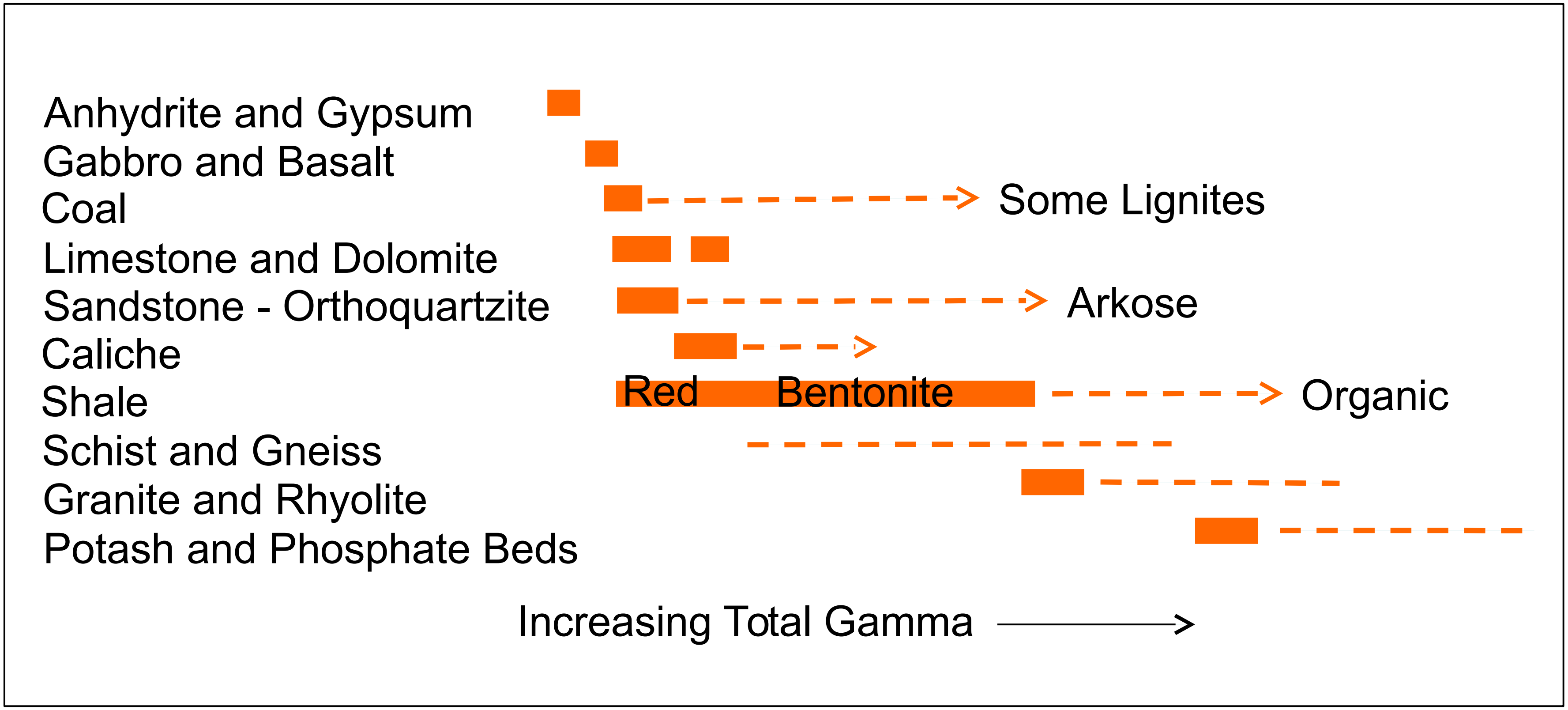


Profile of Permian to Upper Cretaceous γ-logs for a basin in western Kansas

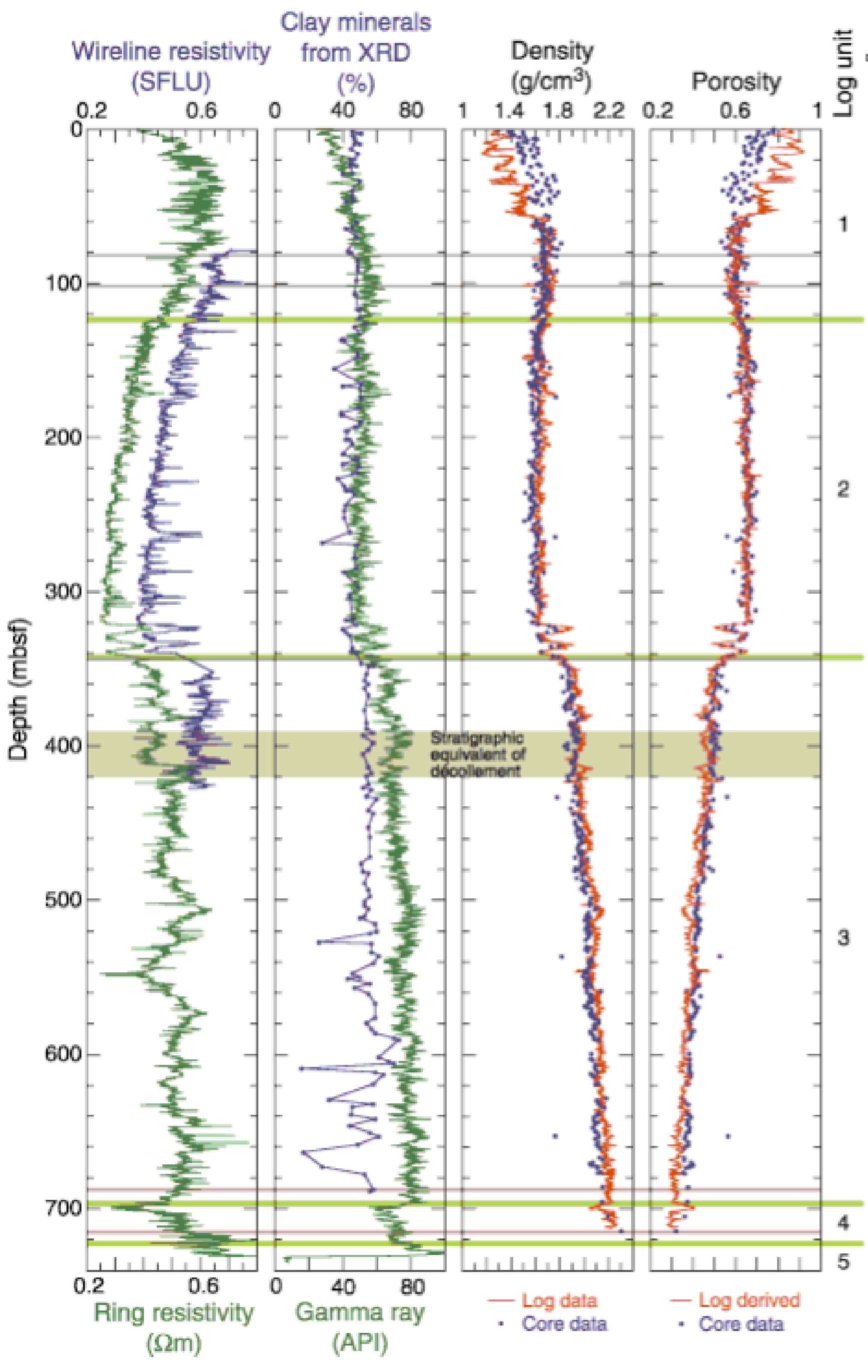


Aside:
Aero-spectral gamma also has applications in mining industry and other exploration problems

Nuclear Logging:

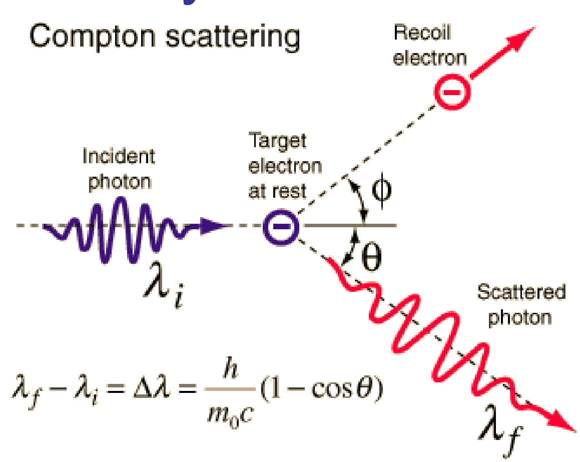


Total "γ" natural radioactivity of various rocks

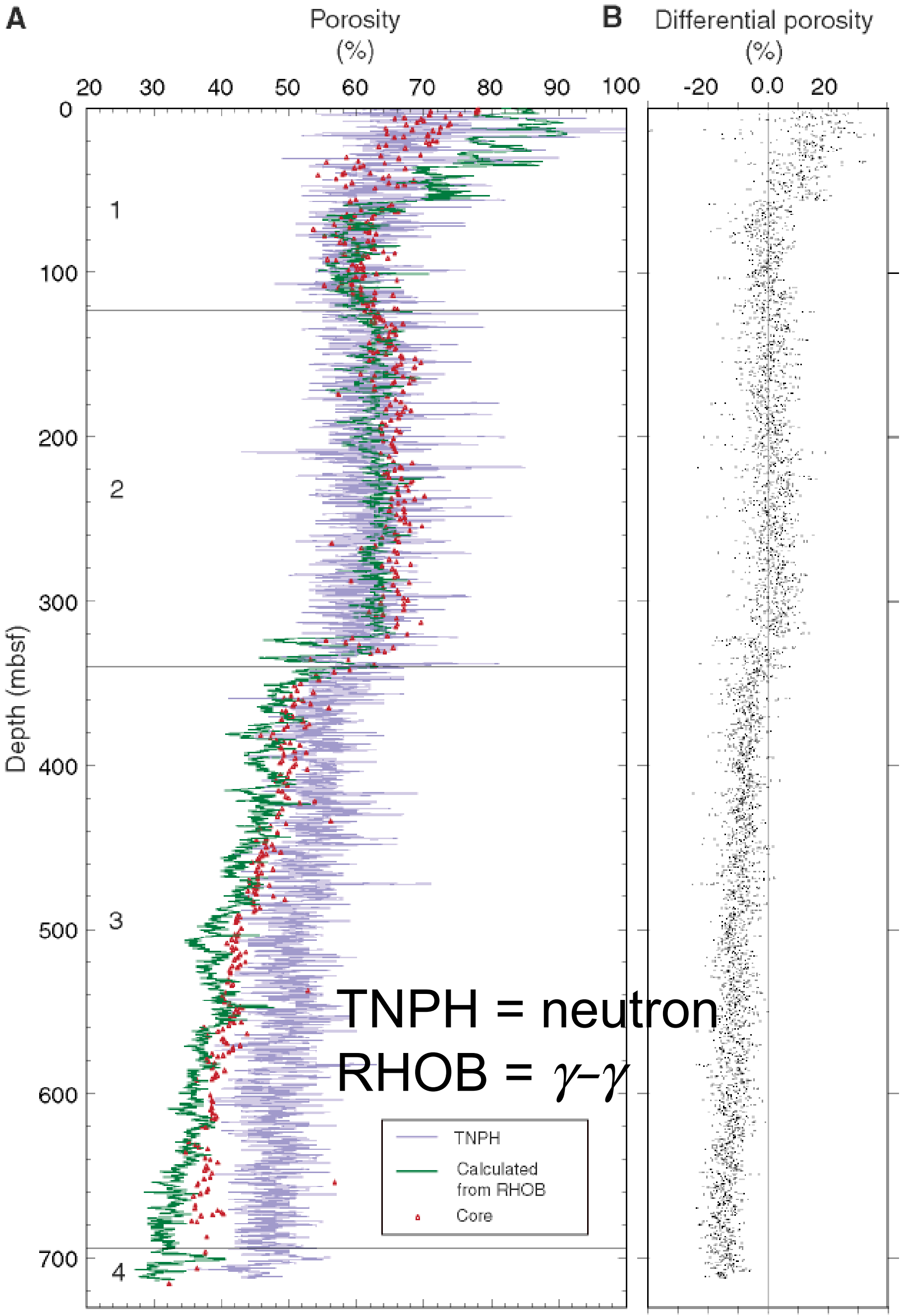


"Formation Density" (γ-γ) logs

estimate density of electrons in the ***total formation*** (rock matrix plus pore fluids) by measuring Compton scattering of gamma rays (generated by a radioactive Cesium source on the wireline tool). Gamma rays detected relate directly to electron density in the medium. Porosity can be determined ***IF*** the rock lithology and pore fluid type are independently known!



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$



Proc Oc Drill Prog v196, 2001

Neutron Log: Radioactive source (Am-Be or Pu-Be) emits fast neutrons; these interact with/lose energy to hydrogen atoms until they slow to energies where they scatter or are absorbed, releasing a γ-ray.

Hence provides a measure of concentration of H atoms… After correcting for borehole muds, P-T-salinity, formation lithology, & pore fluid type (using other logs), can use to estimate porosity.

Sonic Log:

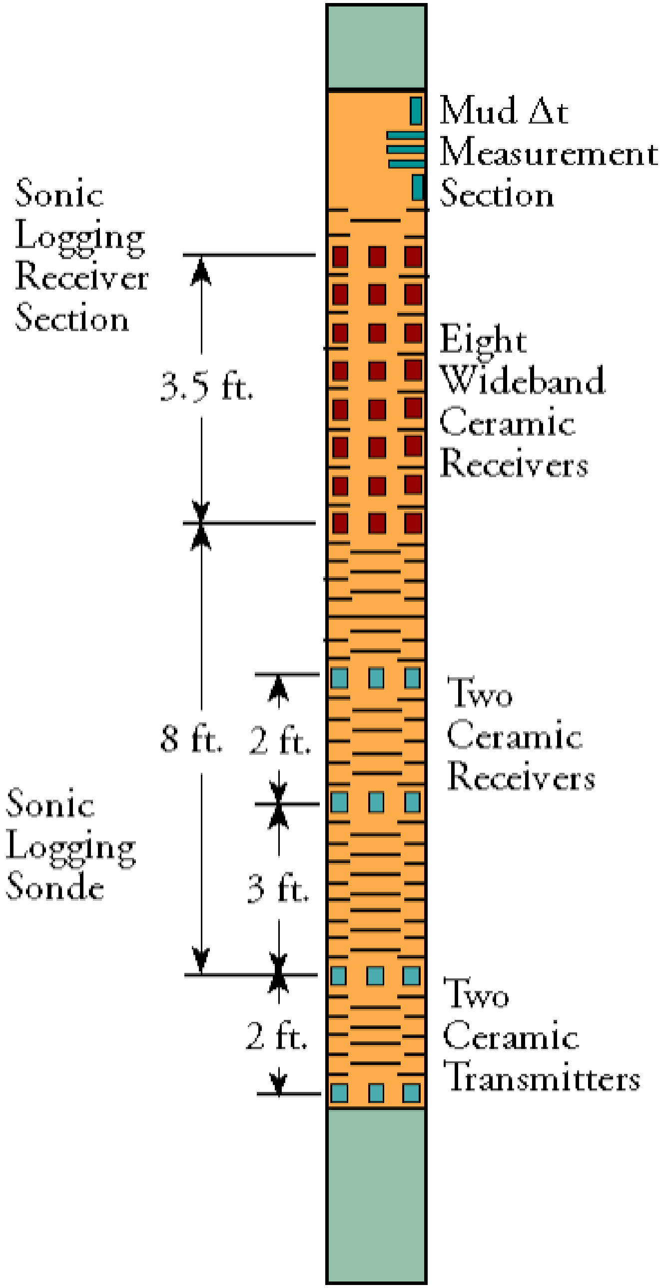
Measures acoustic (P-wave) travel times at very high frequencies

Array sonde like the one shown here can measure mud velocity, formation P-wave and Stoneley wave (like a surface Rayleigh wave: interference pattern of P & S near a free surface). In combination can give both v_P and v_S velocities.

Used to measure velocities for well-correlation with seismic ("synthetic seismograms") and for porosity ϕ: Empirically,

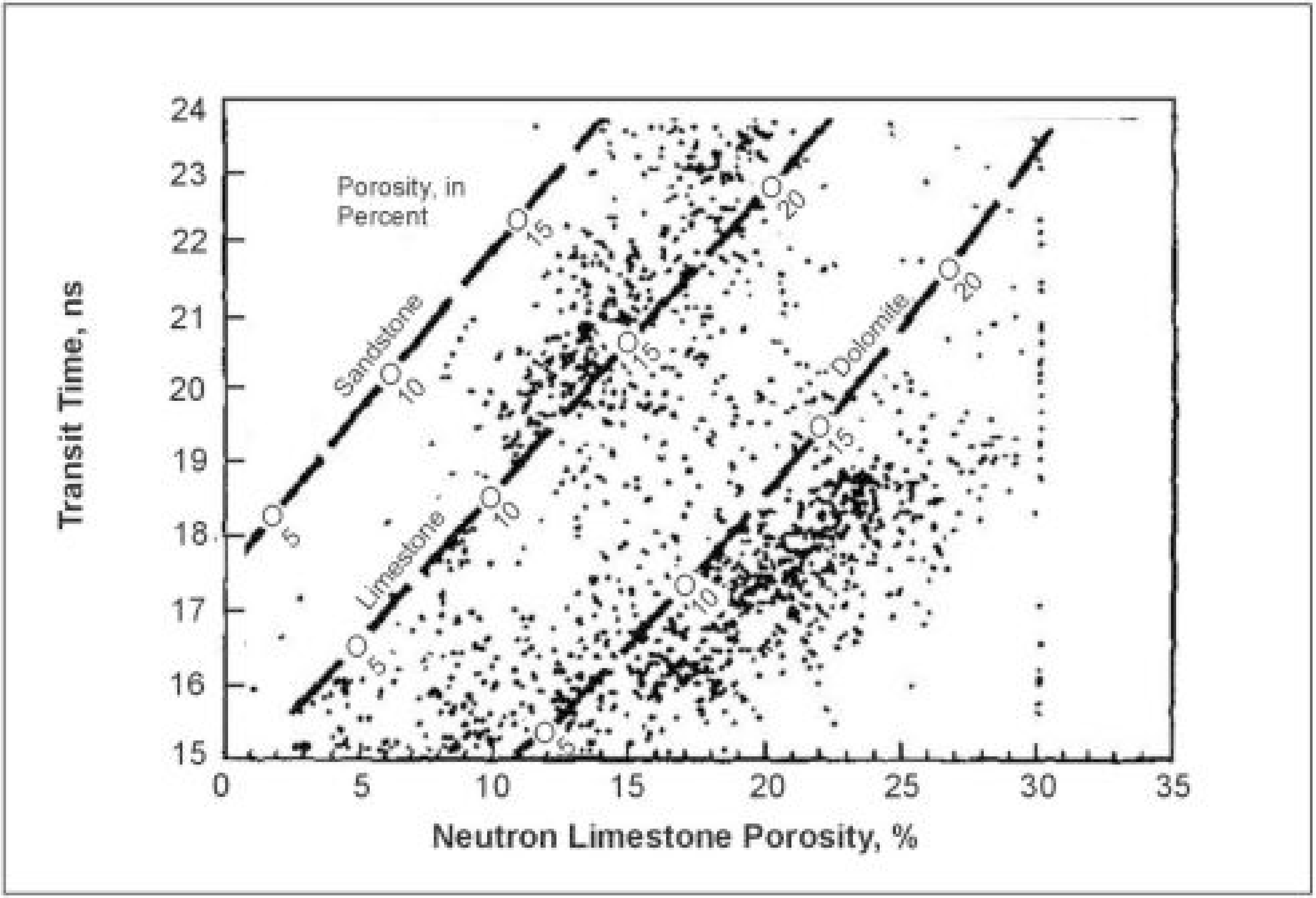
$$\phi = \frac{\Delta t - \Delta t_m}{\Delta t_f - \Delta t_m}$$

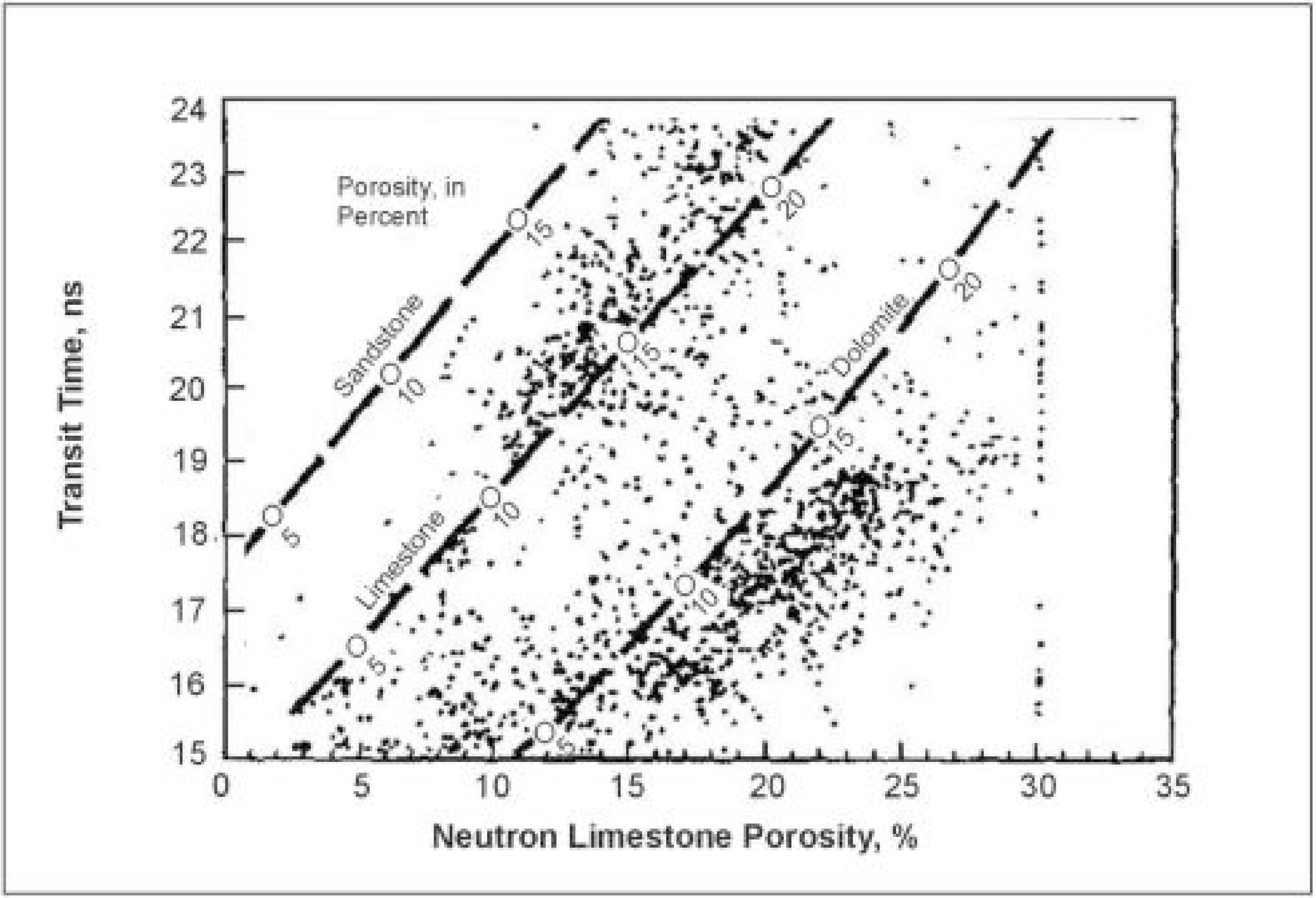
(& get lithology– i.e., Matrix Δt_m– from other)



Example: Array Sonic Sonde

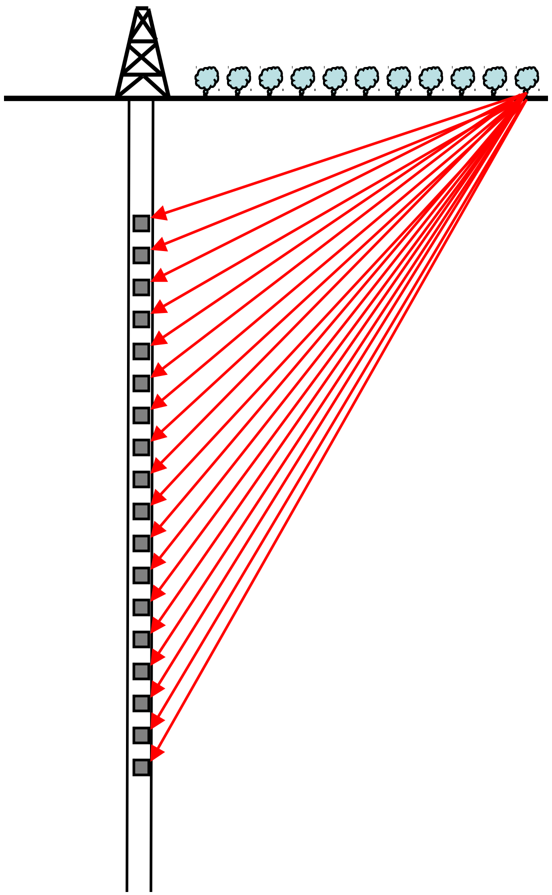
Many applications of well-logging involve a combination of simple physics and empirical observations (e.g., “crossplots”) to sort out contributions from lithology, porosity, & pore fluids in the formation… These days done with automated software.



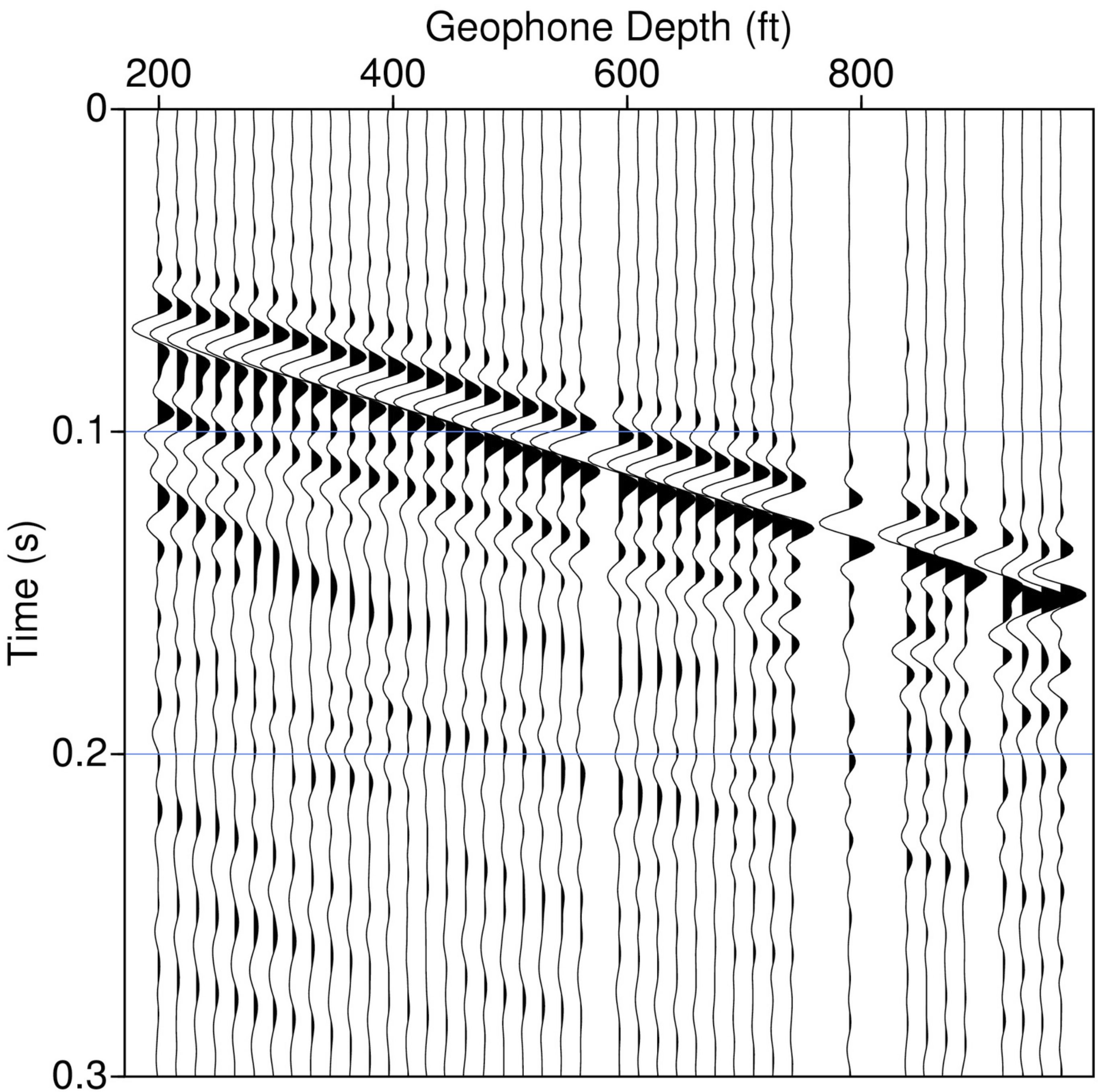


Worth noting that much of the characterization of wireline log response was done long ago, using a limited range of formation environments… Today's drilling targets are often more challenging, and may require further look at petrophysics!

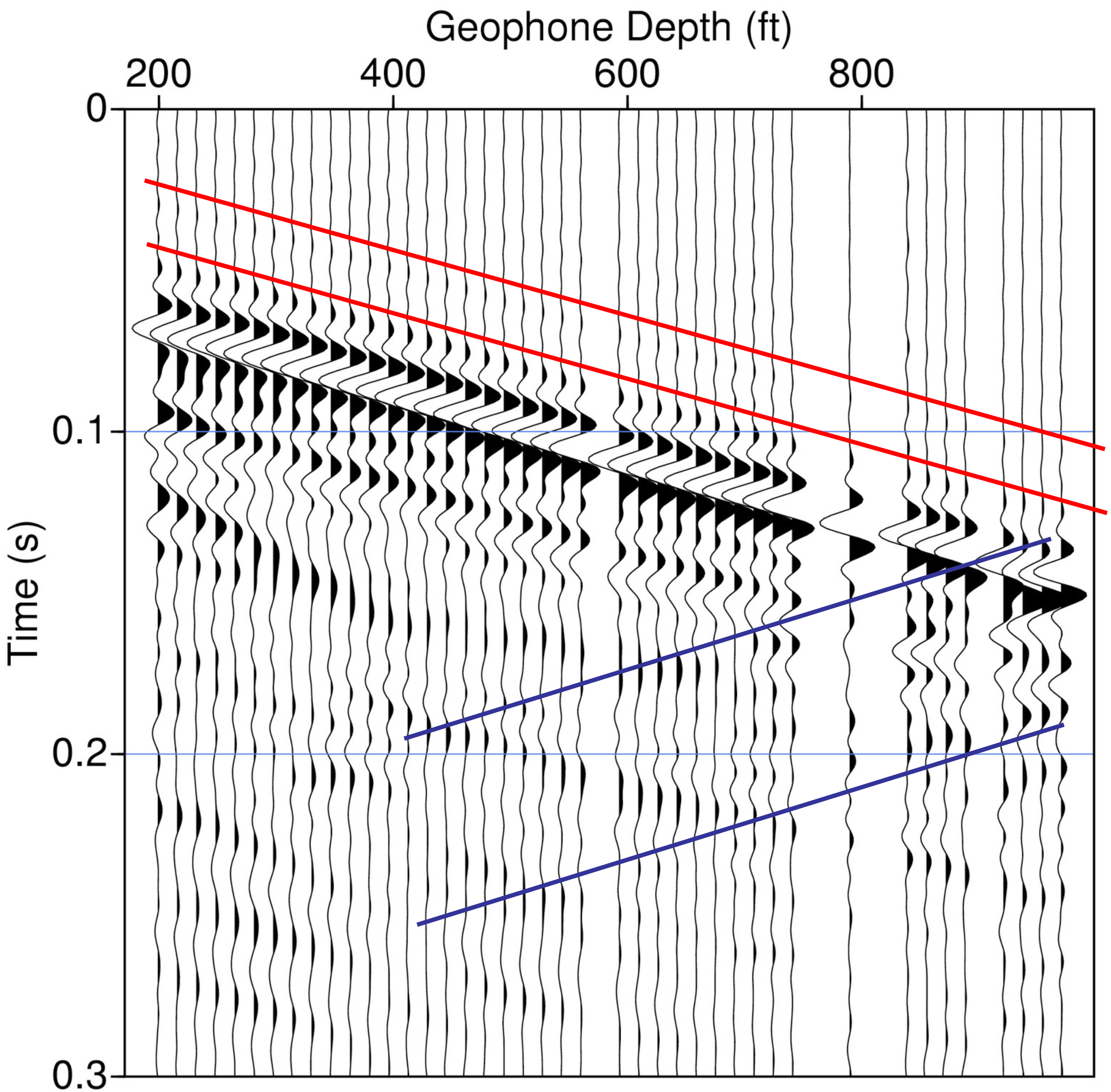
Vertical Seismic Profiling uses geophones (or sources!) in the borehole and sources (or geophones!) arranged along the ground surface to better characterize seismic properties in the near-well environment



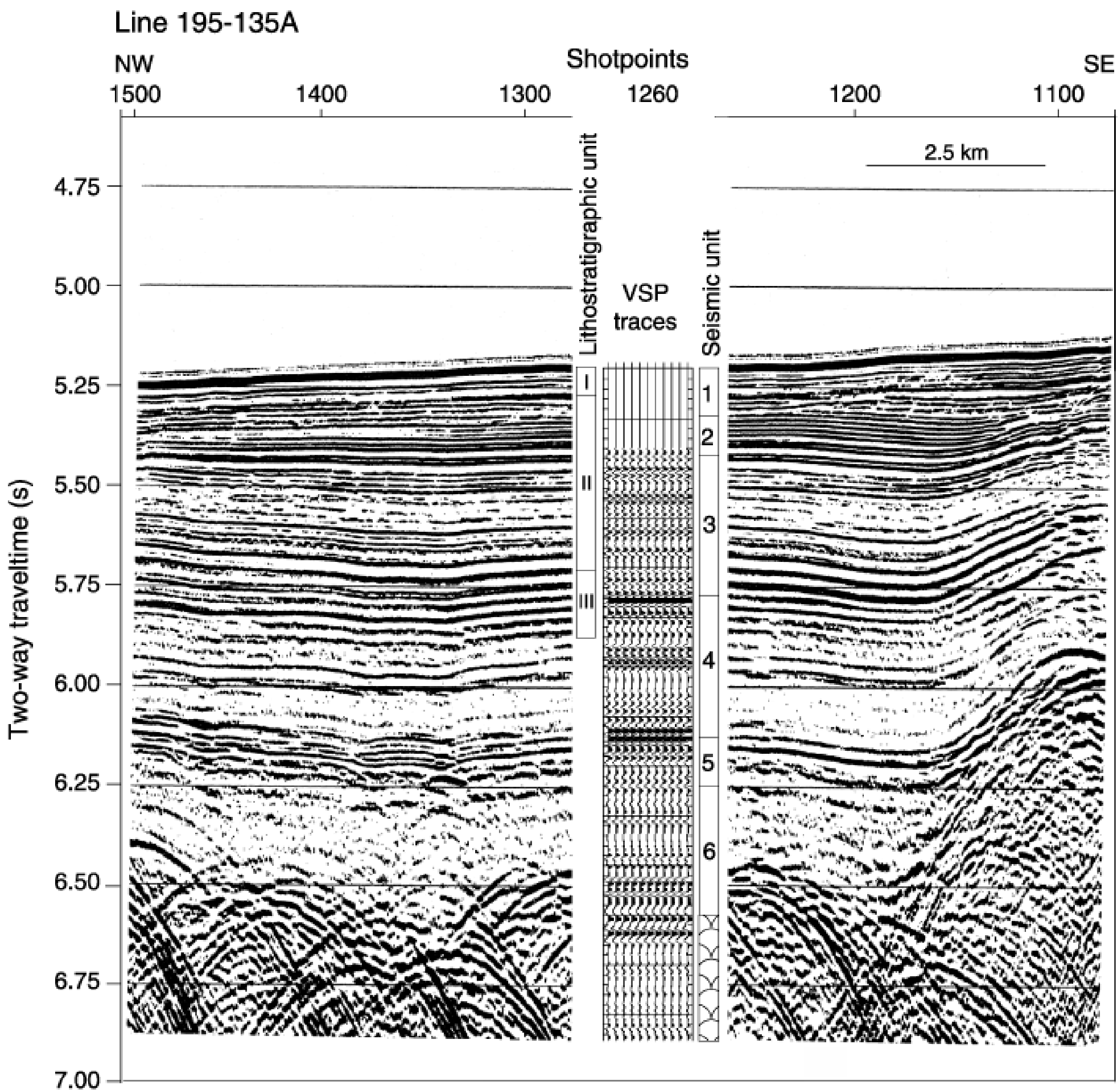
"Seismic while drilling" uses noise generated by the drill bit as a source for geophones at the surface…



One primary advantage of ***VSP*** over e.g. sonic log is that frequency content (& thus spatial averaging, amplitude response) is more similar to that of surface seismic (so provides better depth migration constraint, AVO constraint)



Can isolate the down-going wave-field for averaging of interval velocities for migration constraint; & the up-going (reflected) wave-field for correlation & AVO analysis…



Volpi et al., Proc ODP Leg 178

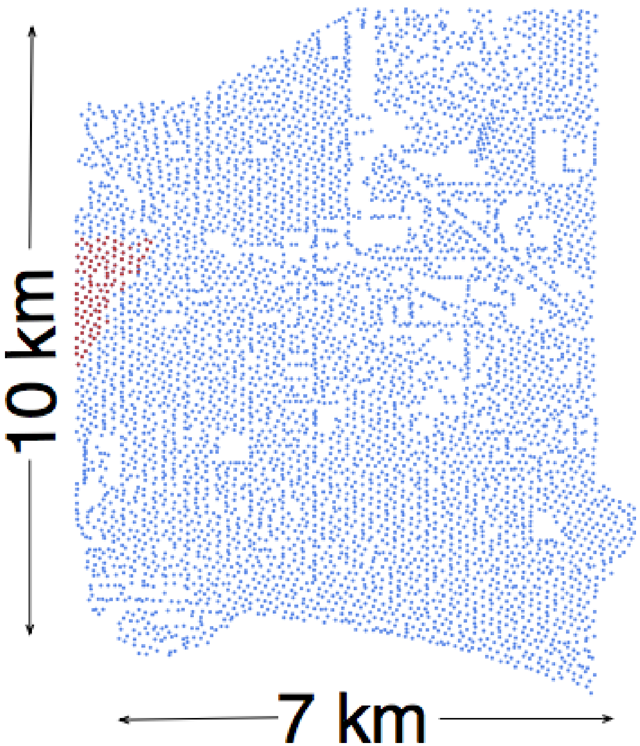
Example using stacking of the up-going wavefield from a zero-offset source to generate VSP traces for well-seismic stratigraphic correlation.

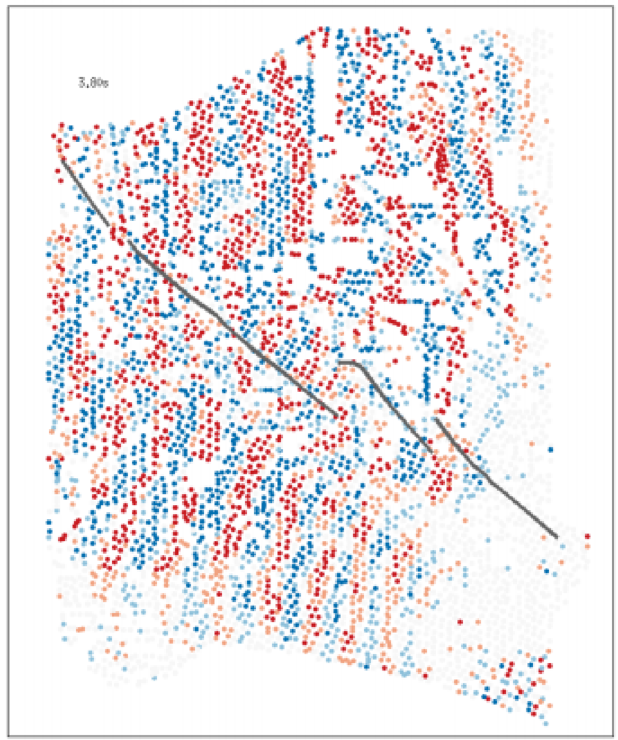
Some speculation on future directions in industry-oriented geophysics…

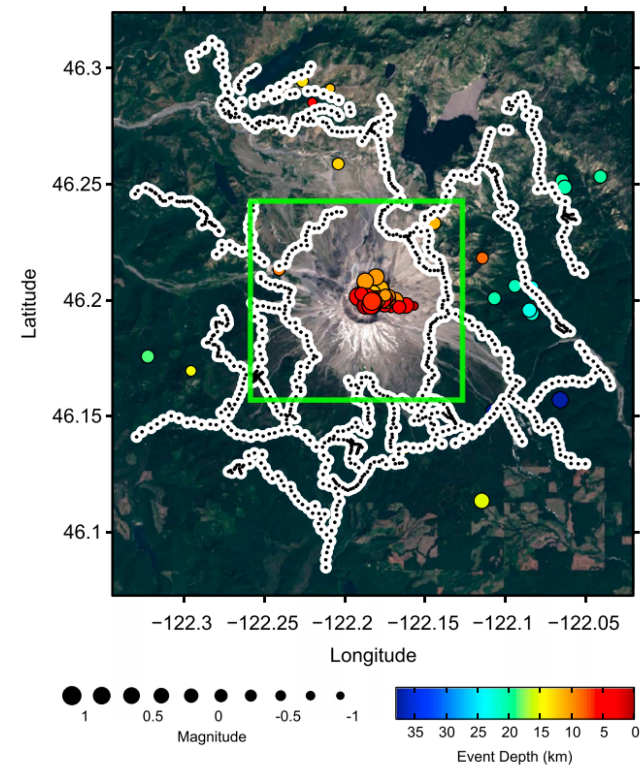
Current "buzz" includes:

- "Full wavefield" seismic imaging of large-N array data (But!): Requires low-cost development prospects (i.e., onshore)
- "Integrated imaging", especially joint inversion of EM & seismic data

"Full-wavefield" imaging goes a step beyond "full waveform"– inverting for velocity structure from amplitudes as a function of time– by using a large number of densely-spaced instruments that fully sample spatial wavelengths of the data



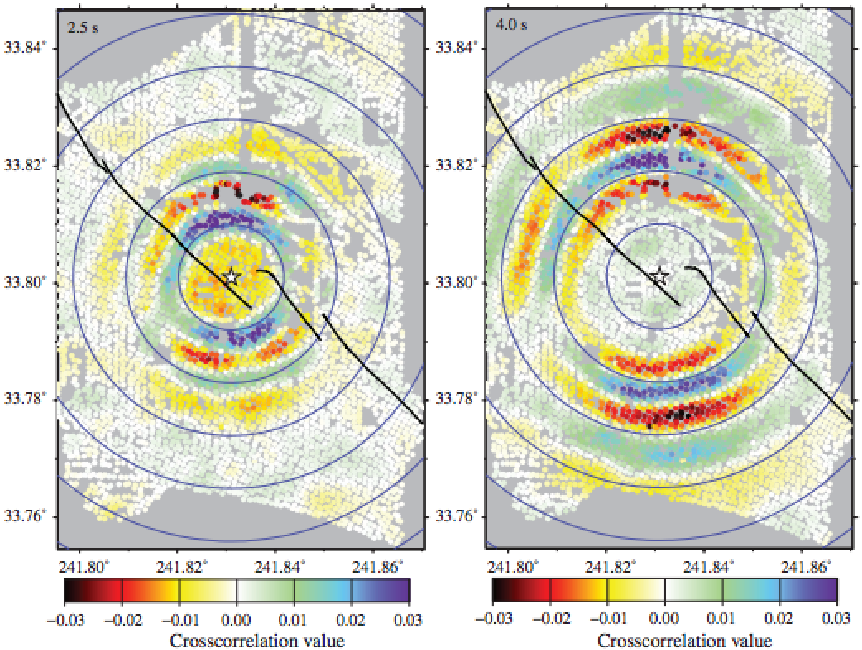


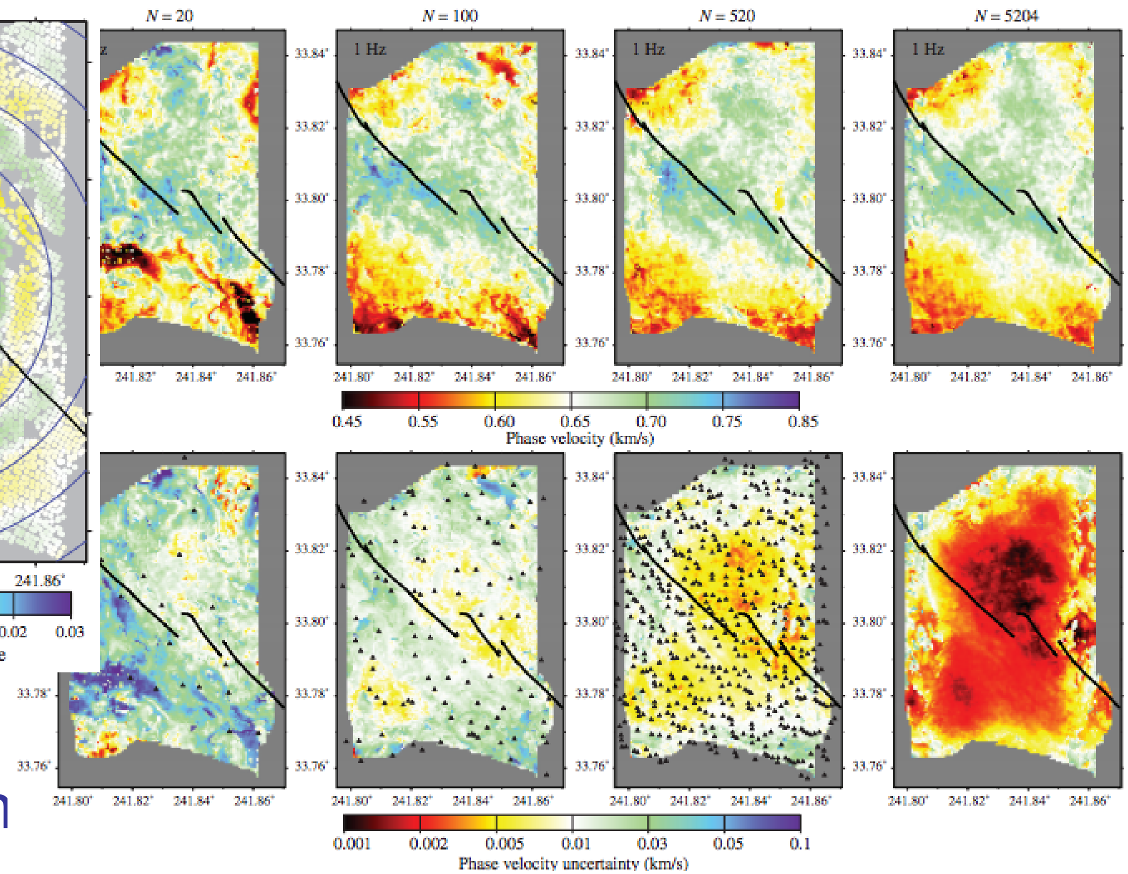


NodalSeismic deployment in Long Beach, 5200 sites *(Li et al., SEG Ann Mtg, 2015)*

Mt St Helens experim't 904 stations *(Hansen & Schmandt, Geophys. Res. Lett., 2015)*

"Full-wavefield" imaging



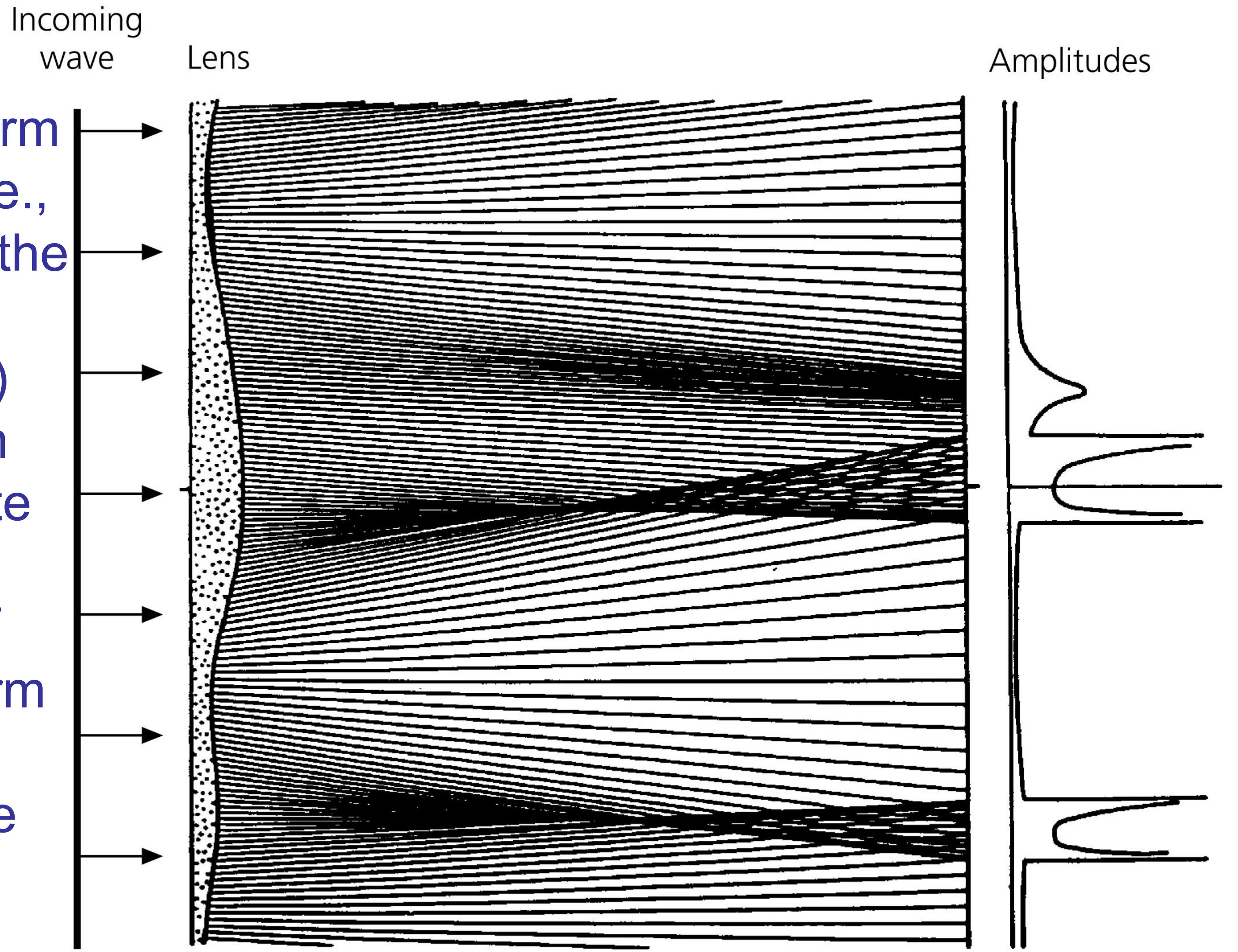


An important approach involves cross-correlation of "ambient noise" to get virtual source-receiver information

NodalSeismic deployment in Long Beach, 5200 sites *(Lin et al., Geophysics, 2013)*

Multipathing:

Figure 3.7-5: Example of velocity heterogeneities affecting wave amplitudes.

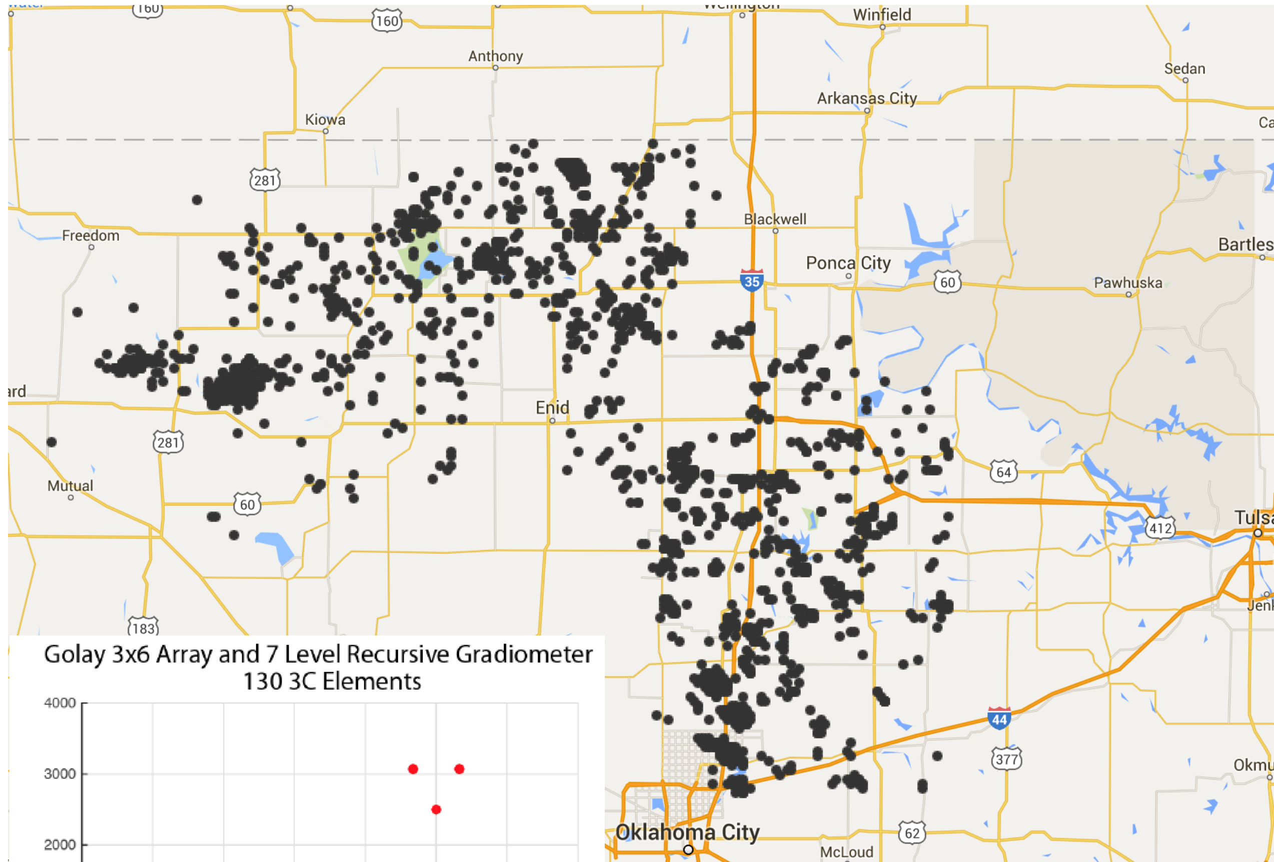


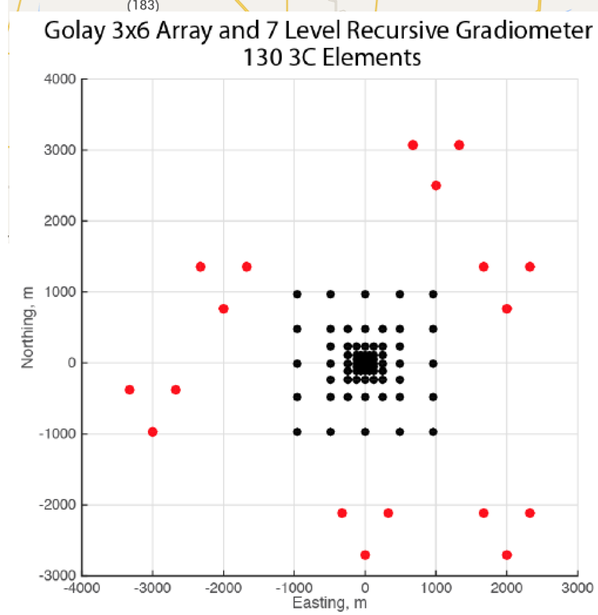
Full-waveform methods (i.e., using all of the amplitude information) benefit from the complete spatial sampling of the waveform afforded by these dense arrays.

RESOLUTION **WAVEFIELDS** NOT JUST WAVEFORMS — NO SPATIAL ALIASING

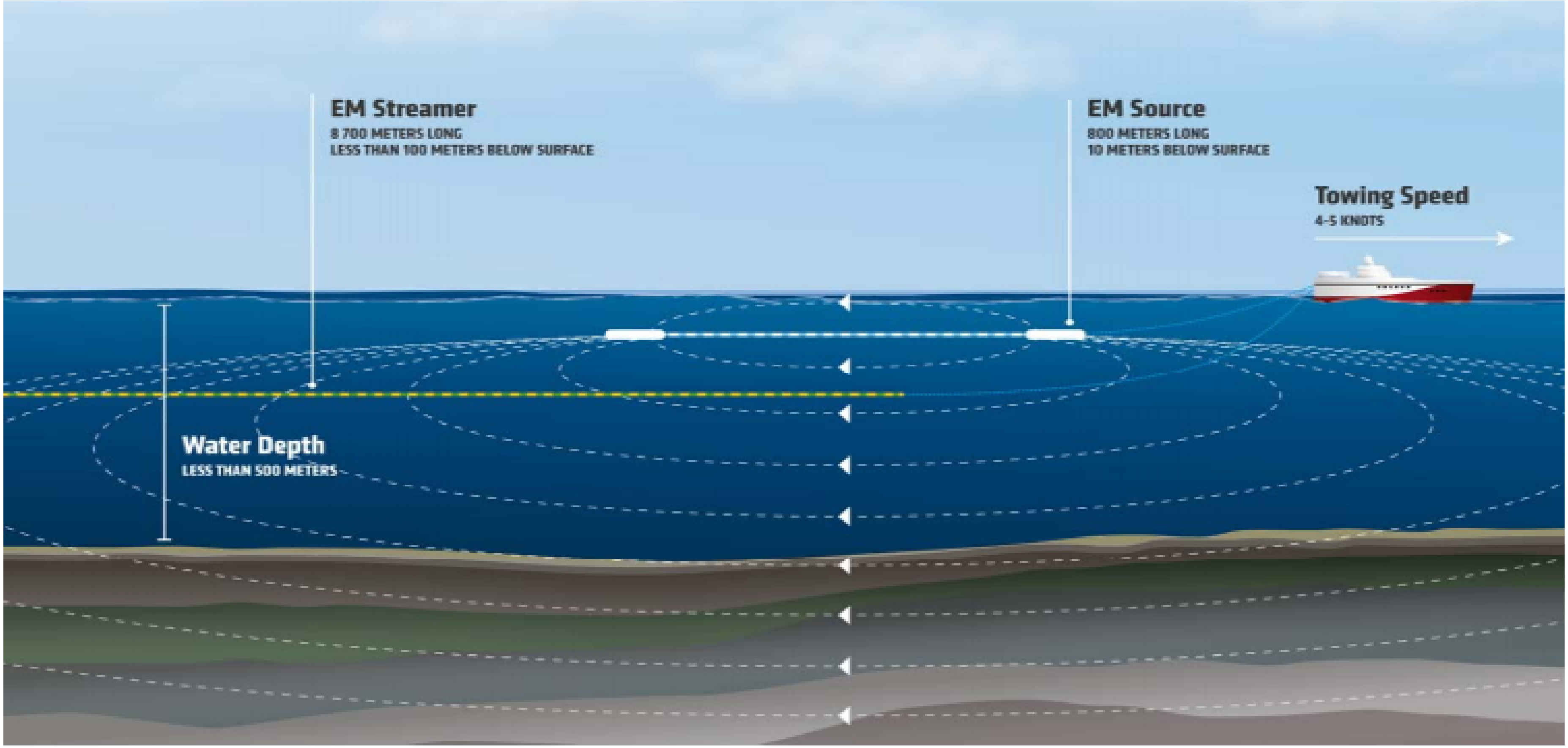
Full-wavefield imaging:

Experiment in 2016 utilized >1000 three-component broadband sensors in the region of wastewater injection induced seismicity in Oklahoma…



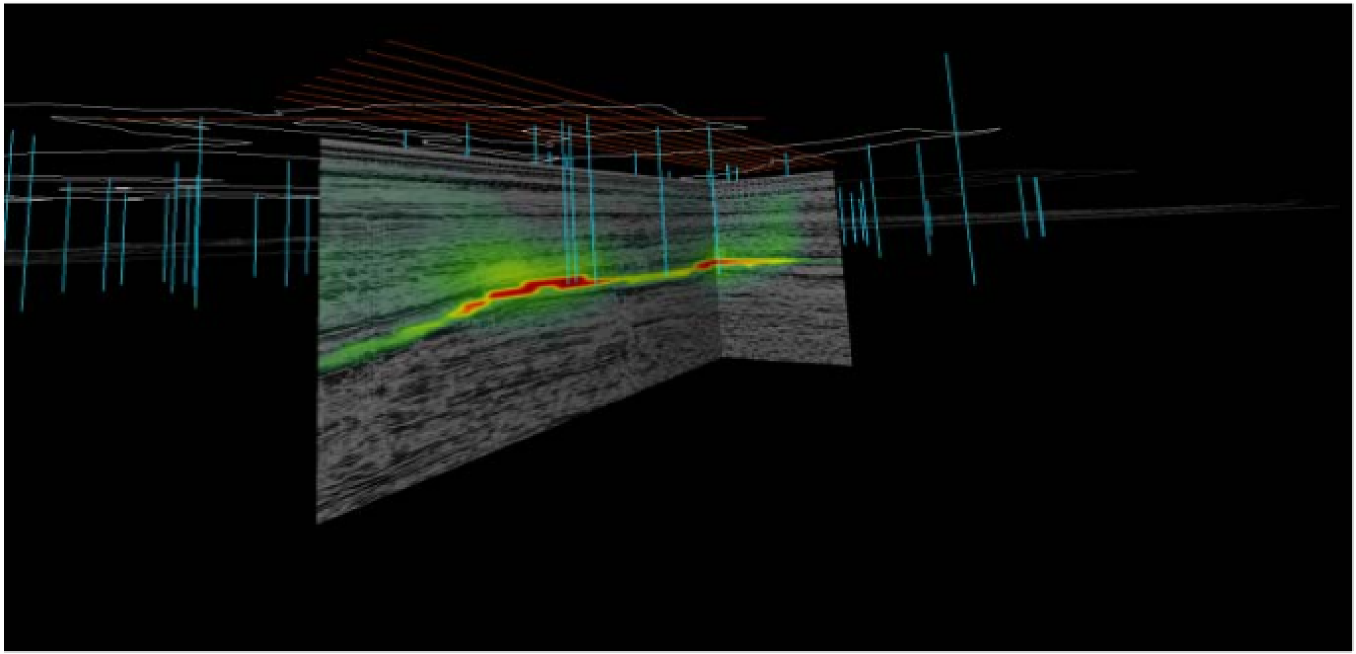


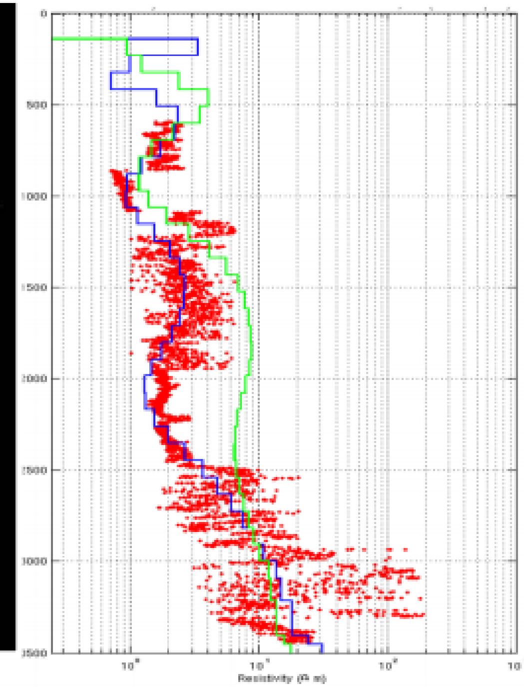
Controlled-Source Electromagnetic Imaging



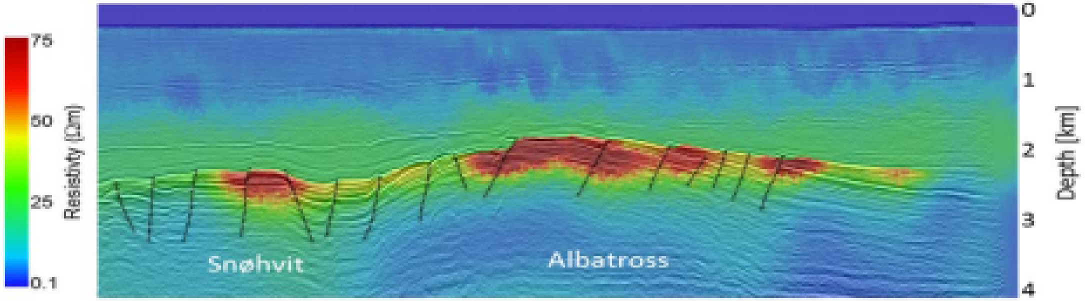
in marine environments, involves towing both EM sources and receivers behind a vessel (similar to marine seismic)

Controlled-Source Electromagnetic Imaging





Like (passive-sourced) magnetotelluric method, solves the diffusion equation for electrical resistivity (/conductivity) and therefore has lower resolution than seismic. Here, 1D structure is over-parameterized (introducing ambiguity)… But in near-well locations can resolve by tying to wireline resistivity!


75
50
25
0.1
Resistivity (Ωm)
0
1
2
3
4
Depth (km)
Snøhvit
Albatross