VSP AND BOREHOLE GEOPHYSICS

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Outline

- Drilling a well
- Borehole geophysics (introduction)
- Vertical seismic profiling (VSP) basic concepts
- Vertical seismic profiling (VSP) examples

Drilling overview

- Drilling a well
- Borehole geophysics (introduction)
- Vertical seismic profiling (VSP) basic concepts
- Vertical seismic profiling (VSP) examples

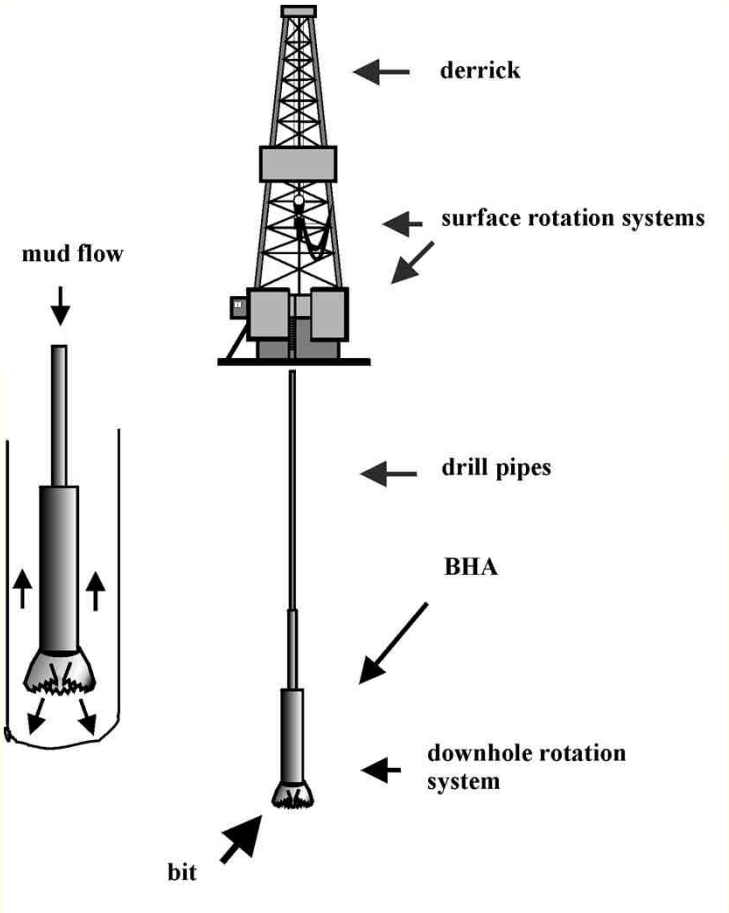
Drilling wells

Wells are positioned and planned on the basis of geophysical, geological and, where existing, nearby well information about reservoir or target area.

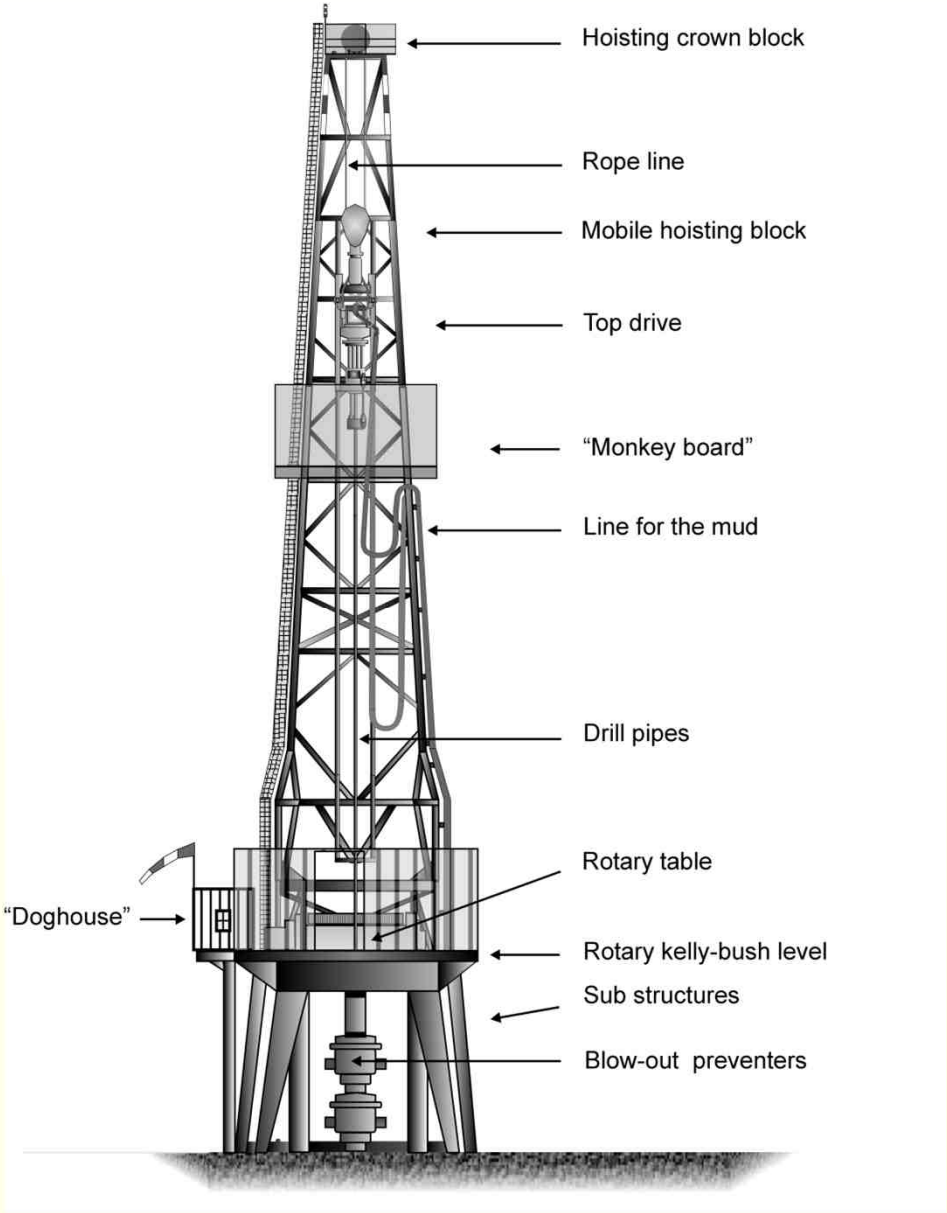
Type of wells:

- Exploration wells
- Appraisal
- Production
- Other (e. g., scientific research)

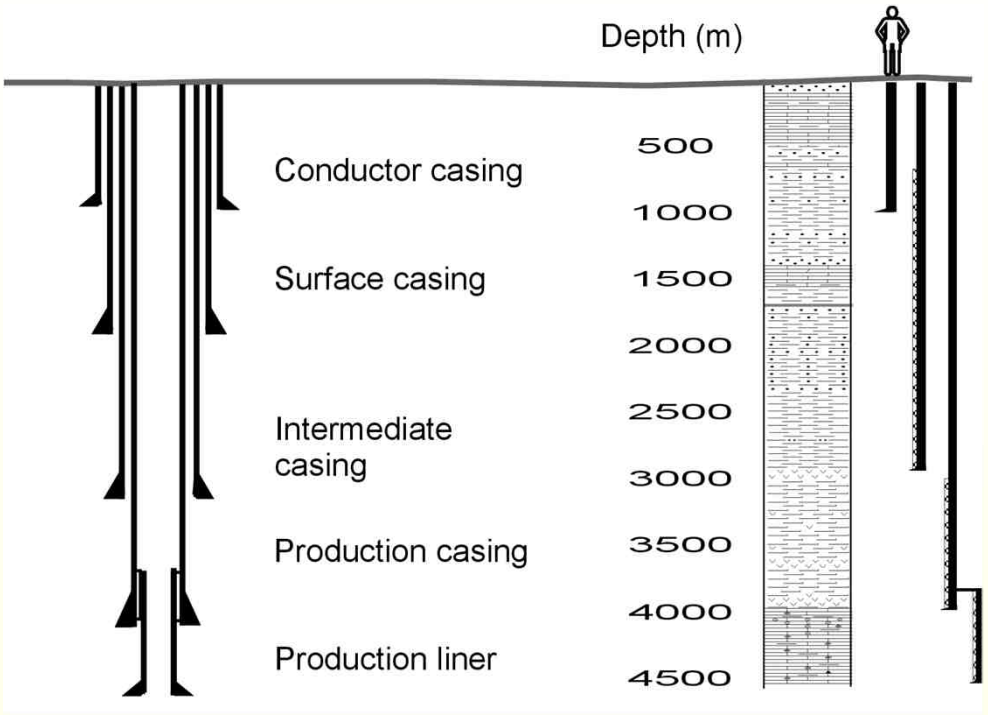
Drilling plant



Derrick system

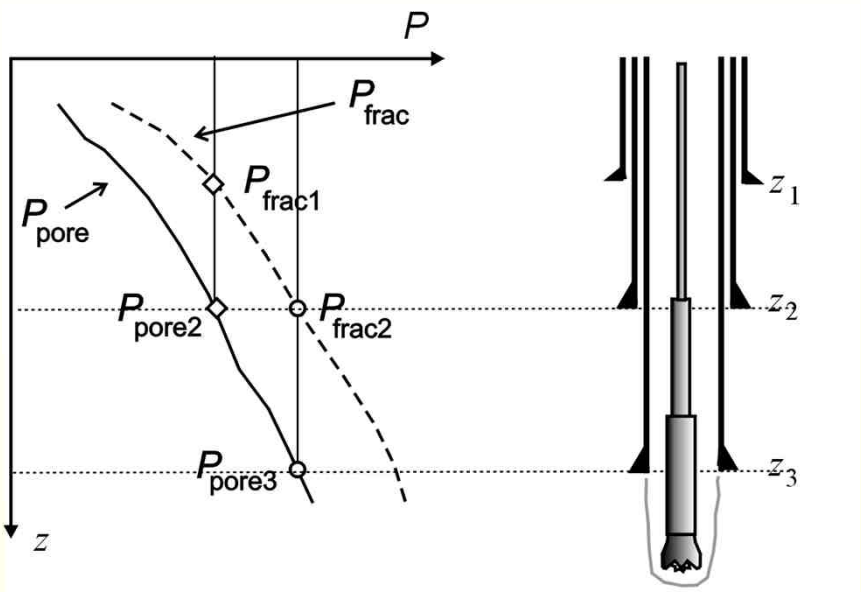


Drilling a well – casing plan

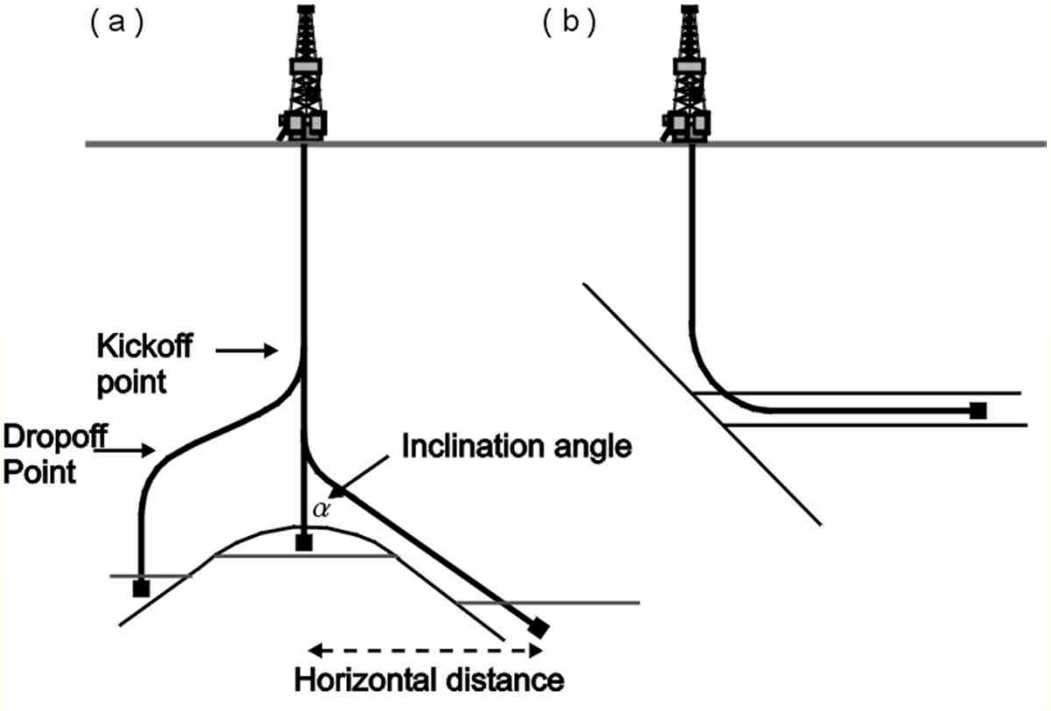


(After Poletto and Miranda, 2004)

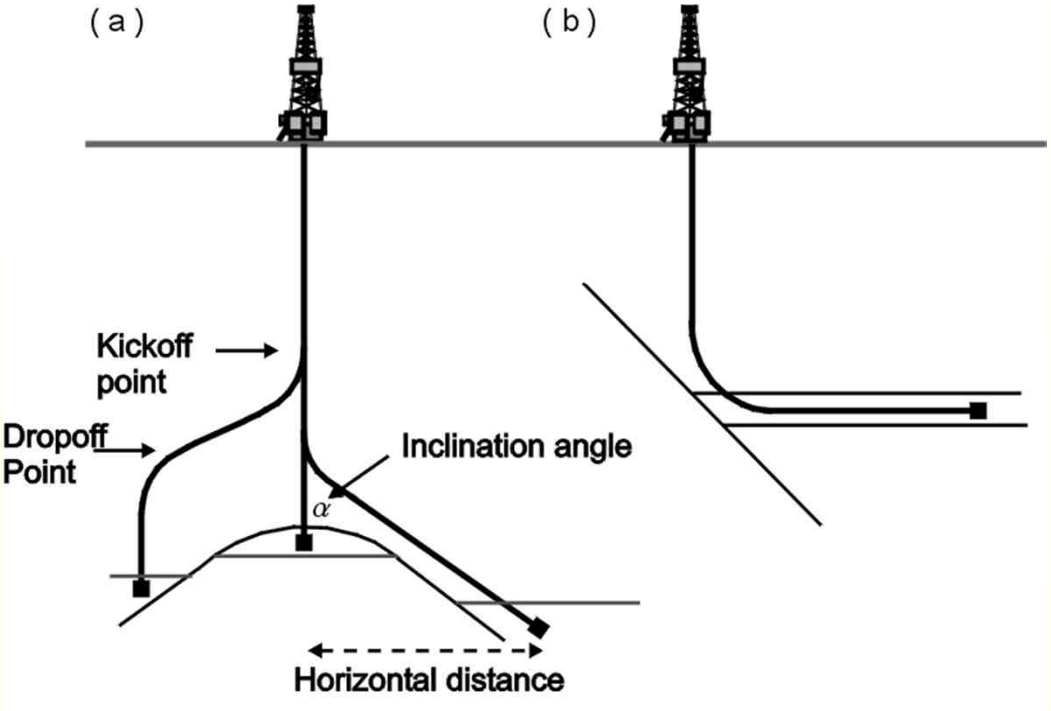
Mud weight and casing plan



Drilling a well - directional

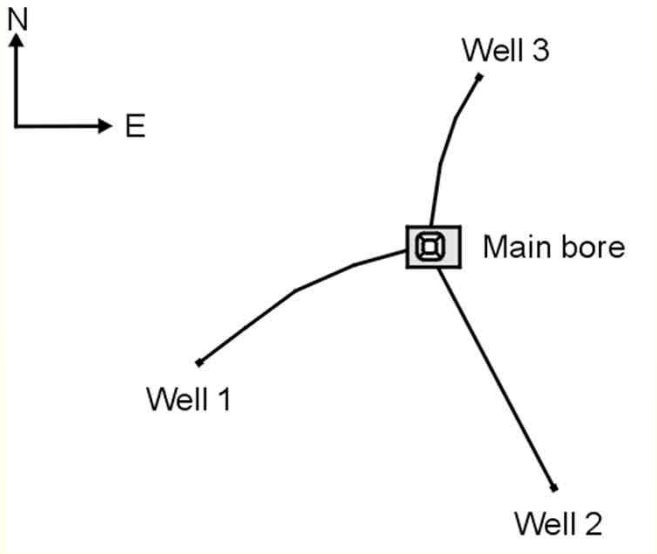


Drilling a well - directional

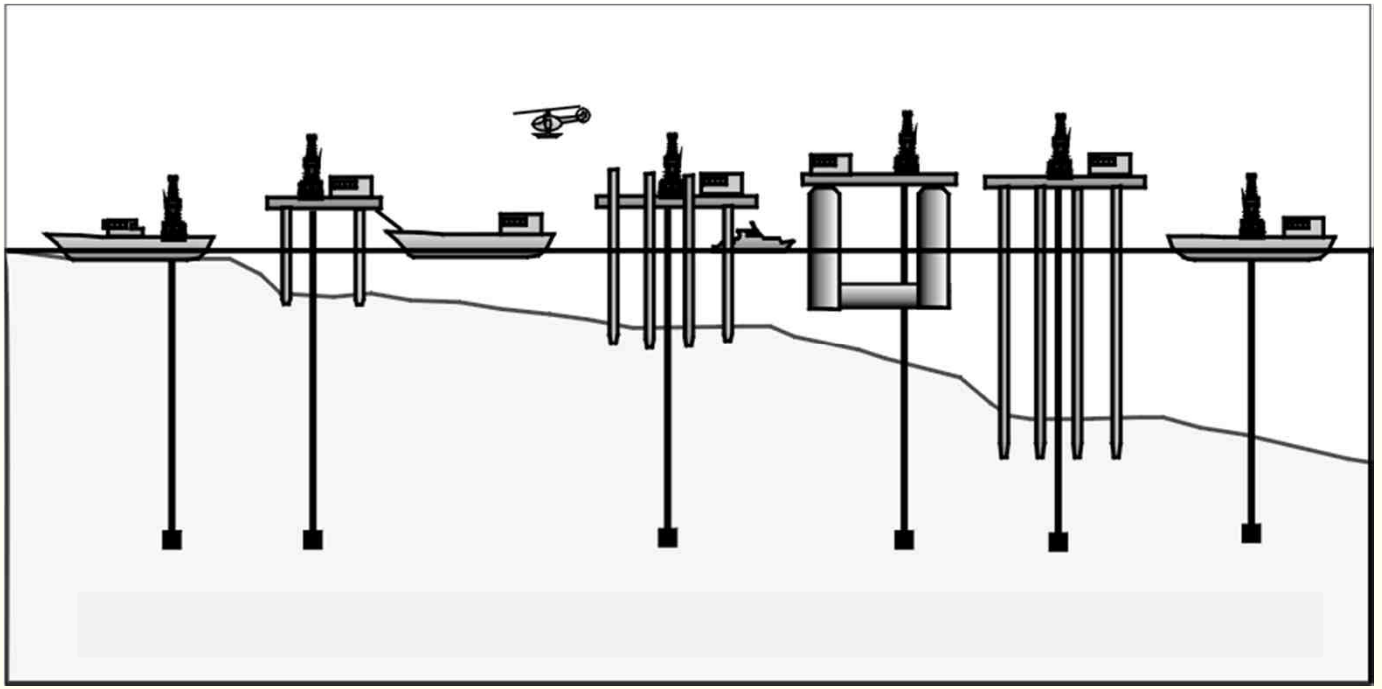


e. g., gas shales (unconventional)

Multilateral cluster – top view



Drilling a well – offshore



Borehole geophysics

- Drilling a well (just an introduction)
- Borehole geophysics (introduction)
- Vertical seismic profiling (VSP) basic concepts
- Vertical seismic profiling (VSP) examples

Borehole geophysics

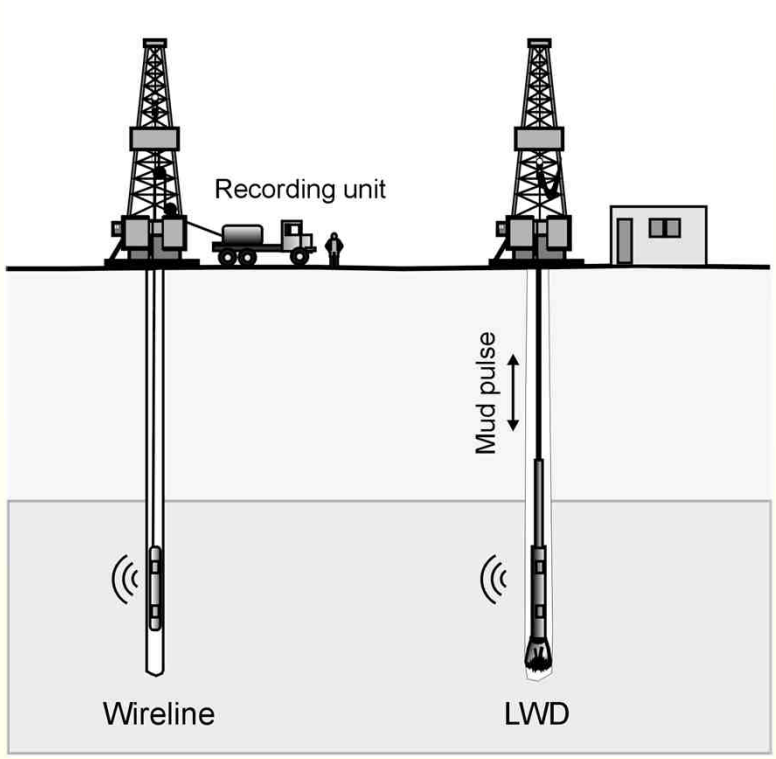
Direct measurements of physical quantities in borehole

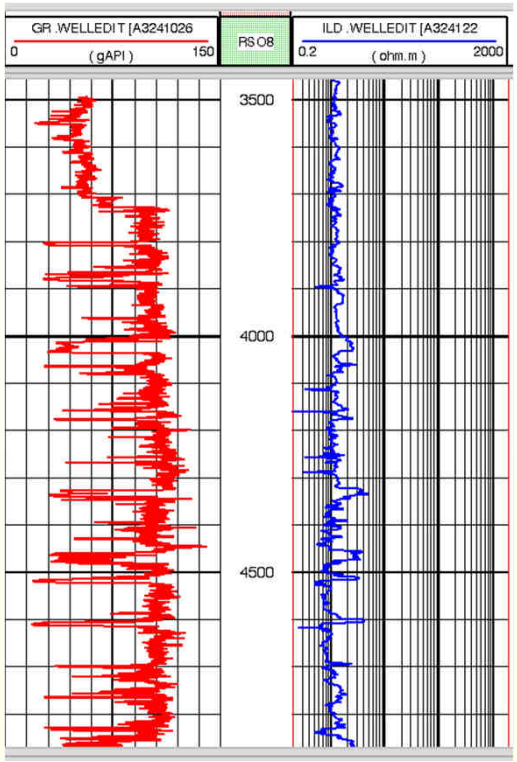
- Cased well section
- Open hole section
- After drilling
- While drilling

Borehole geophysics

- WIRELINE LOGS
- LWD
- MWD
- BOREHOLE SEISMICS
  - Vertical seismic profiling (VSP)
  - Crosswell

Logging While Drilling (LWD)





LWD

Logging While Drilling (LWD) methods

LWD uses mud-pulse telemetry to perform MWD downhole communication in the status of the Art, in substitution of wireline logs

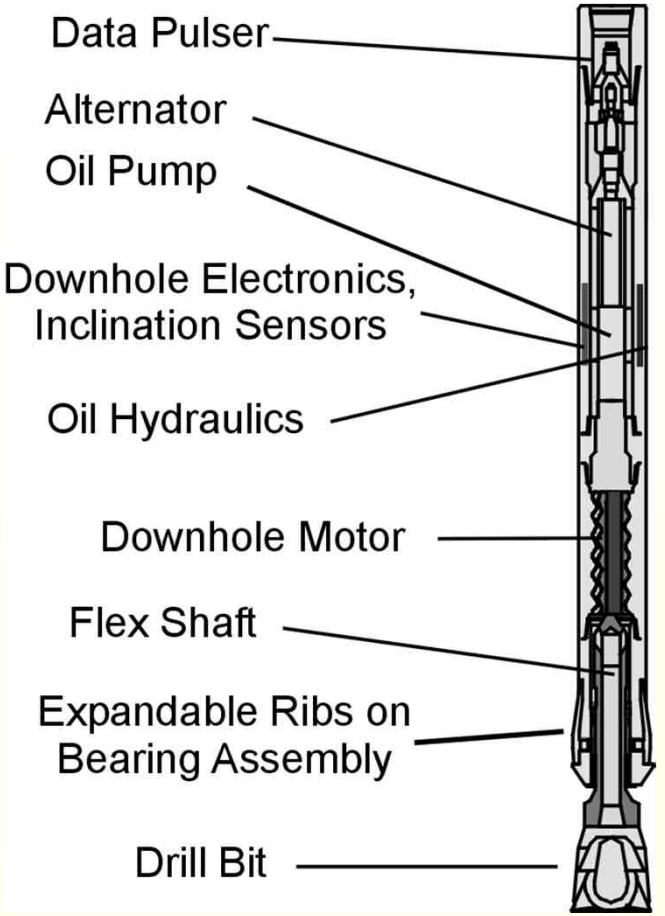
- Gamma ray
- Resistivity
- Neutron
- Density
- Sonic
- Nuclear magnetic resonance
- Formation pressure test
- EM dielectric
- Directional gyro

Other (not while drilling), e.g., temperature, SP, CBIL, cliper

Measurements While Drilling (MWD)

Rotary steerable systems to steer drilling, e.g., commercial tools of main contractors.

Directional systems steered by MWD are used in combo with LWD (EM, directional, gamma ray)



Vertical seismic profiling (VSP)

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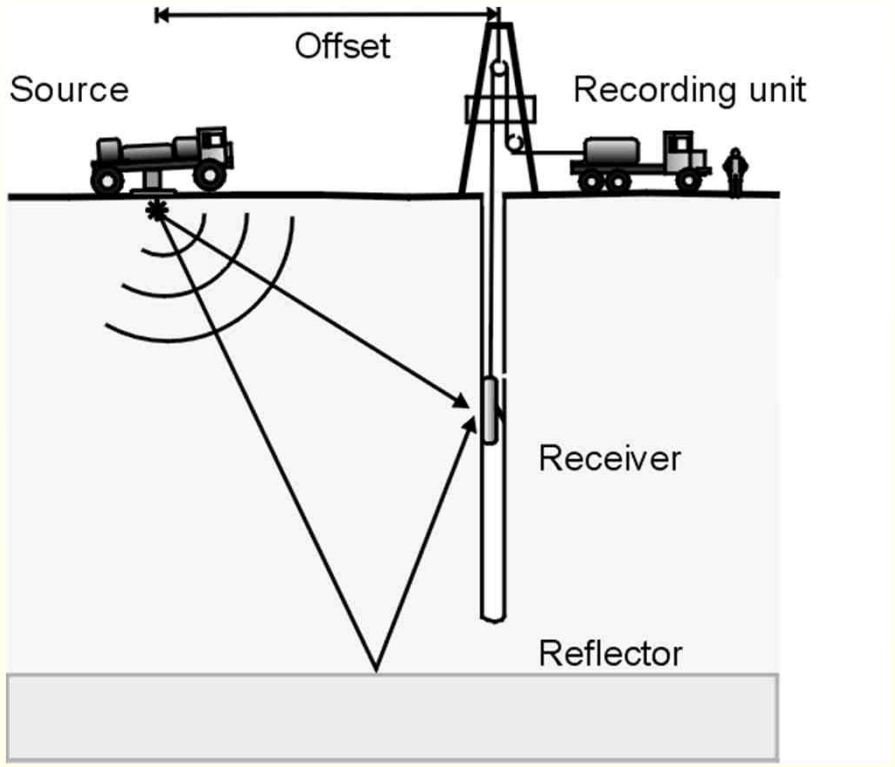
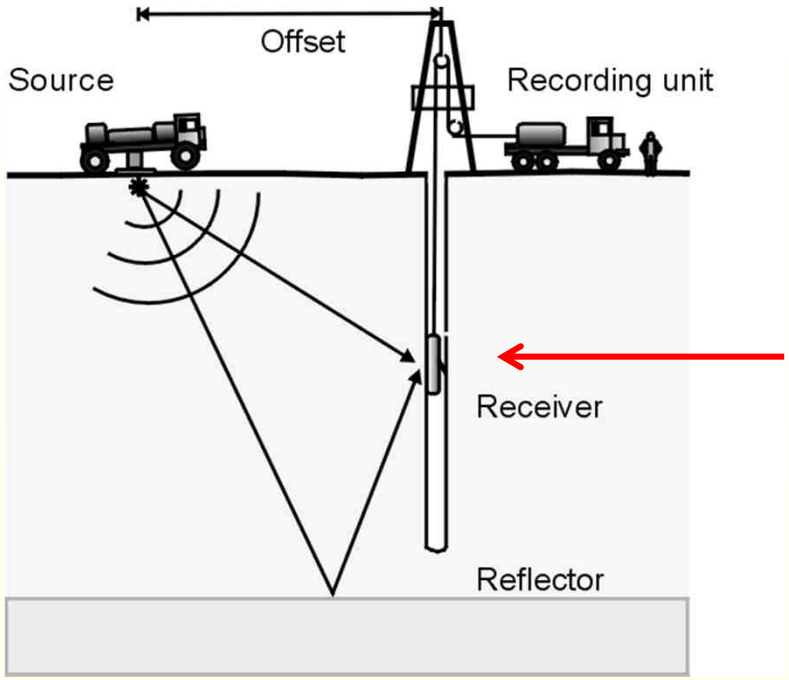
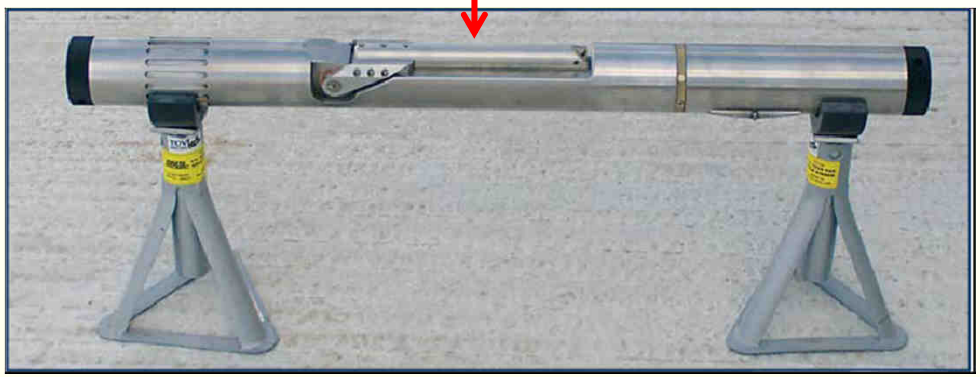
Wireline VSP layout



Wireline VSP

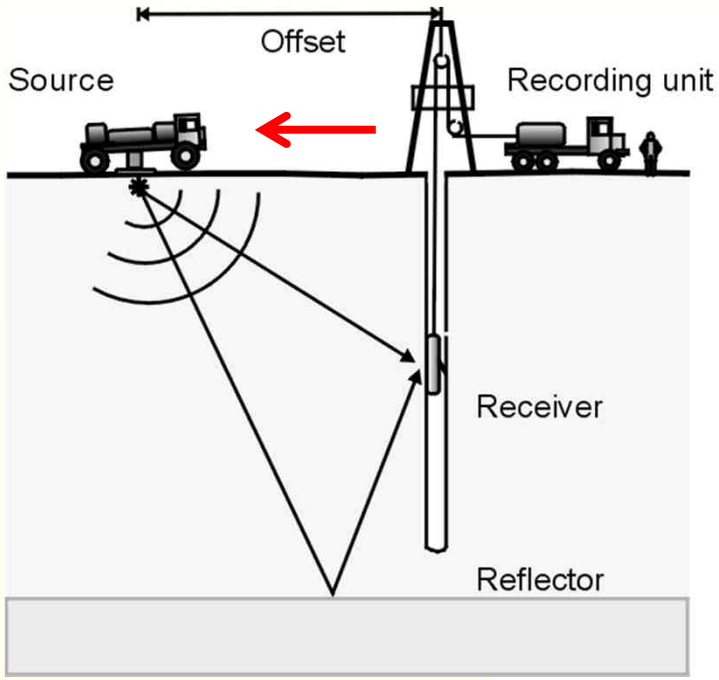


Clamping arm



3C borehole geophone

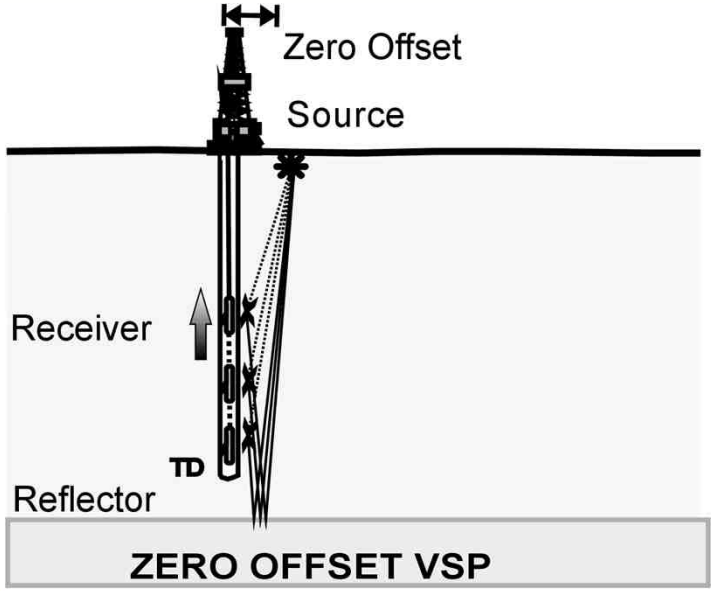
Wireline VSP

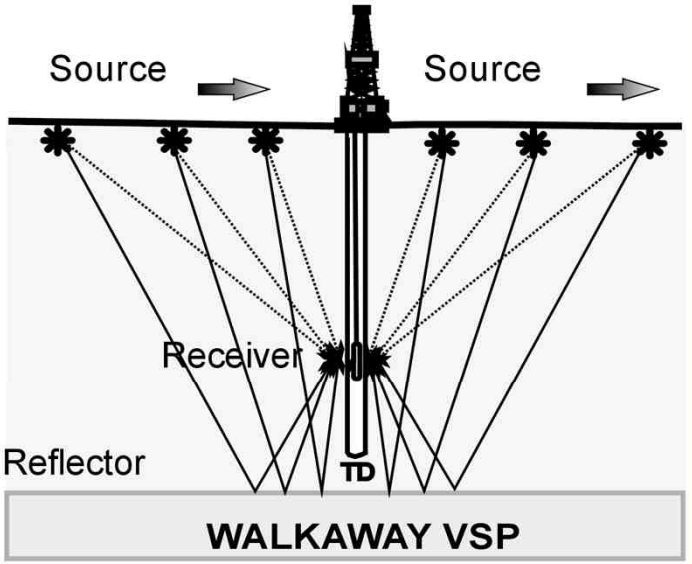


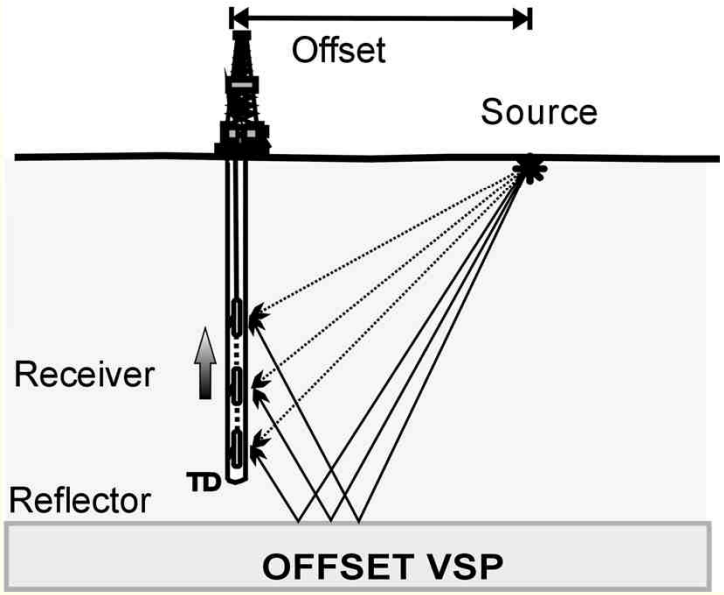
Vibrator source

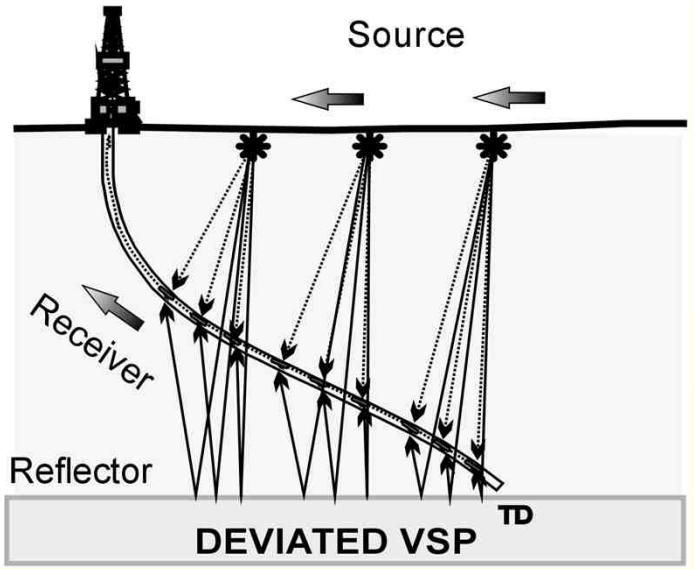
Impulsive source

VSP geometries

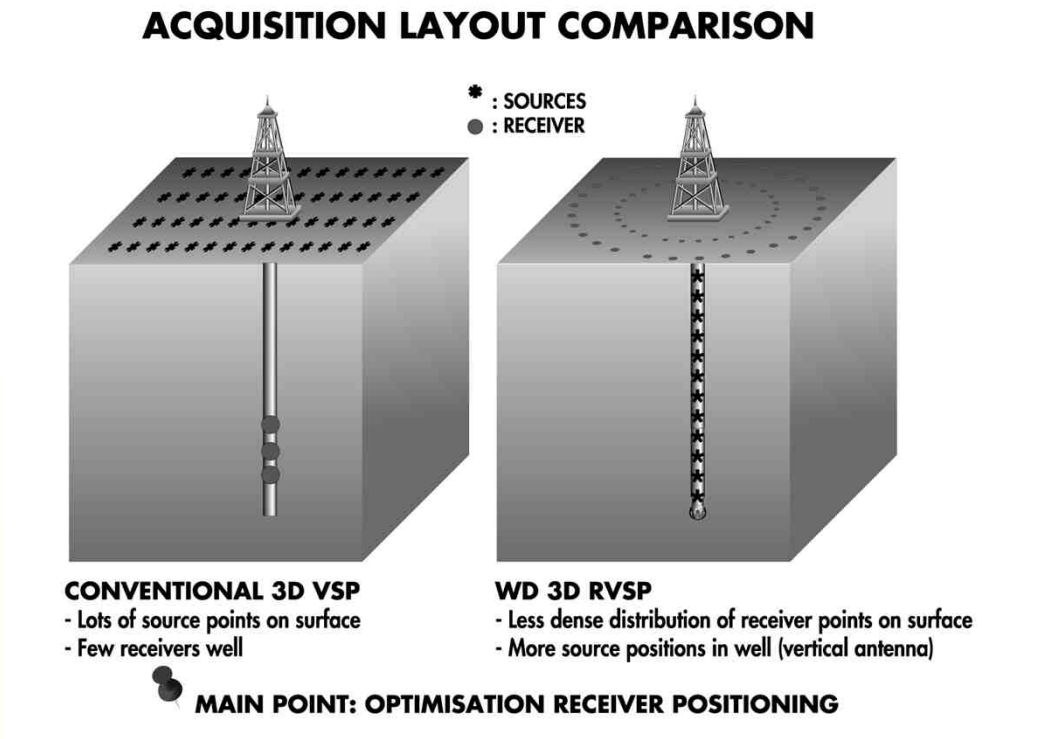




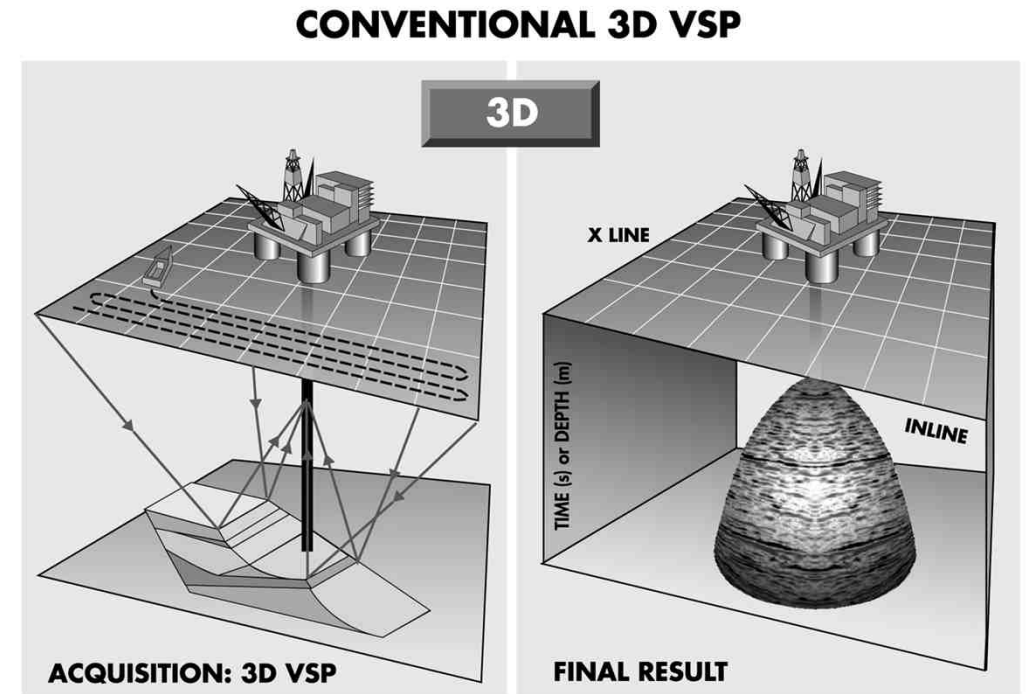




3D VSP


ACQUISITION LAYOUT COMPARISON
: SOURCES
: RECEIVER
CONVENTIONAL 3D VSP
- Lots of source points on surface
- Few receivers well
WD 3D RVSP
- Less dense distribution of receiver points on surface
- More source positions in well (vertical antenna)
MAIN POINT: OPTIMISATION RECEIVER POSITIONING

3D – 3C VSP


CONVENTIONAL 3D VSP
3D
X LINE
TIME (s) or DEPTH (m)
INLINE
ACQUISITION: 3D VSP
FINAL RESULT

VSP advantages

- Shorter reflection travelpaths with respect to surface seismics (approximately one way)
- Improved time and space resolution with respect to surface seismics
- Provides time-depth correspondence for calibration of seismic and log signals in depth
- Observe separately upgoing and downgoing waves in well
- Improved signal processing

VSP advantages

- Receivers closer to reflectors, shorter reflection travel paths with respect to surface seismics
- Improved time and space resolution with respect to surface seismics
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Attenuation

$$A = e^{-\alpha z}$$

$$\alpha = \frac{\pi}{\lambda Q}$$

$$\frac{1}{\lambda} = \frac{f}{V}$$

A signal amplitude, α attenuation factor, z propagation distance

λ wavelenght, f frequency, Q quality factor

VSP advantages

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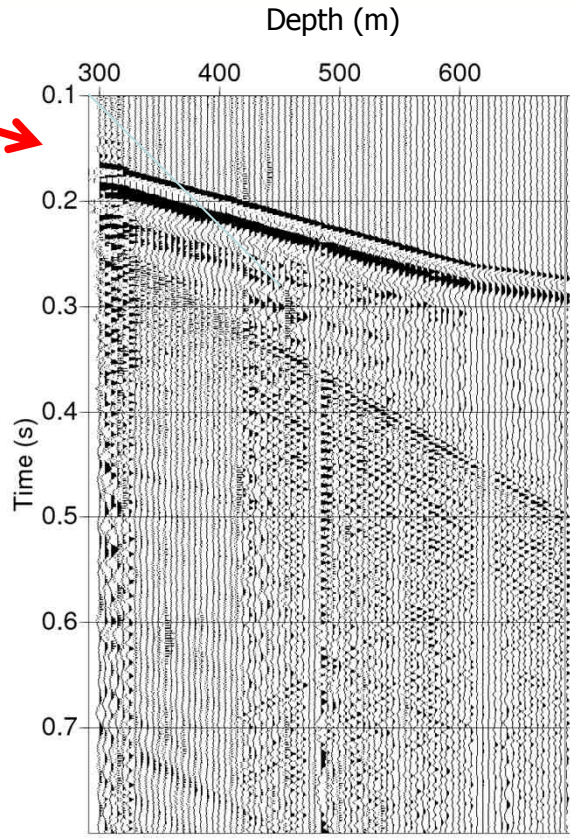
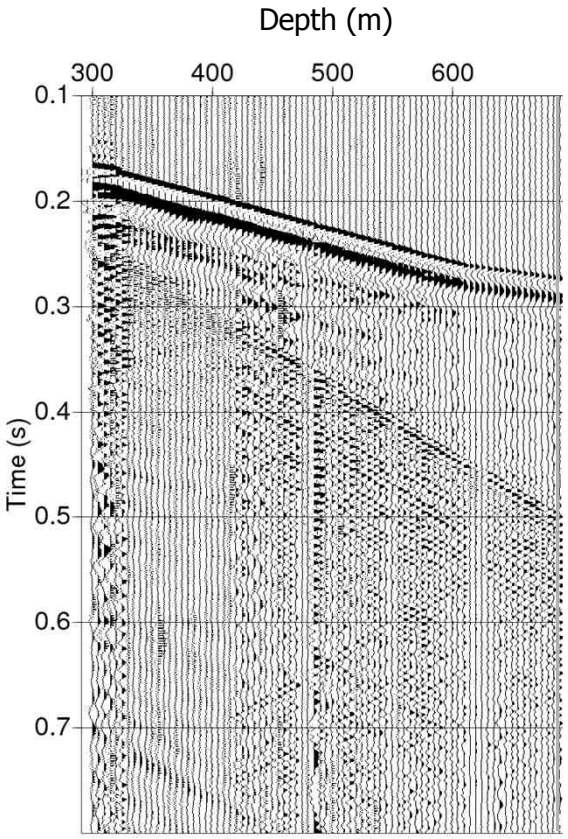
Near-offset VSP total field

Direct arrivals



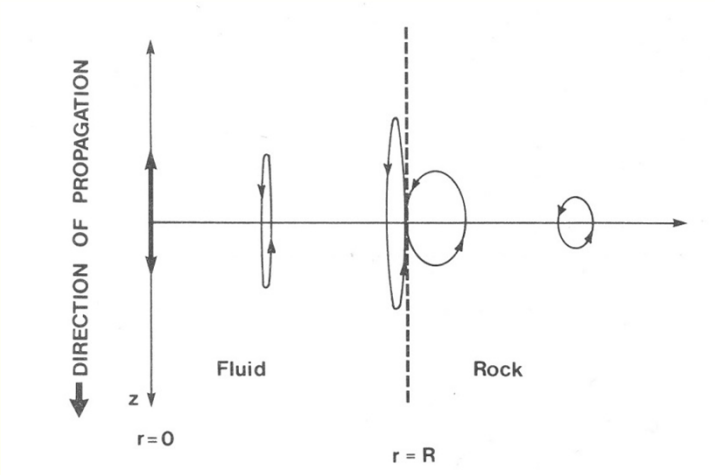
VSP noise components



Tube waves

VSP noise components

Tube waves: low-frequency dispersive Stoneley guided waves



$$V_{T0} = \frac{V_f}{\left(1 + \frac{\rho_f V_f^2}{\rho V_S^2}\right)^{1/2}}$$

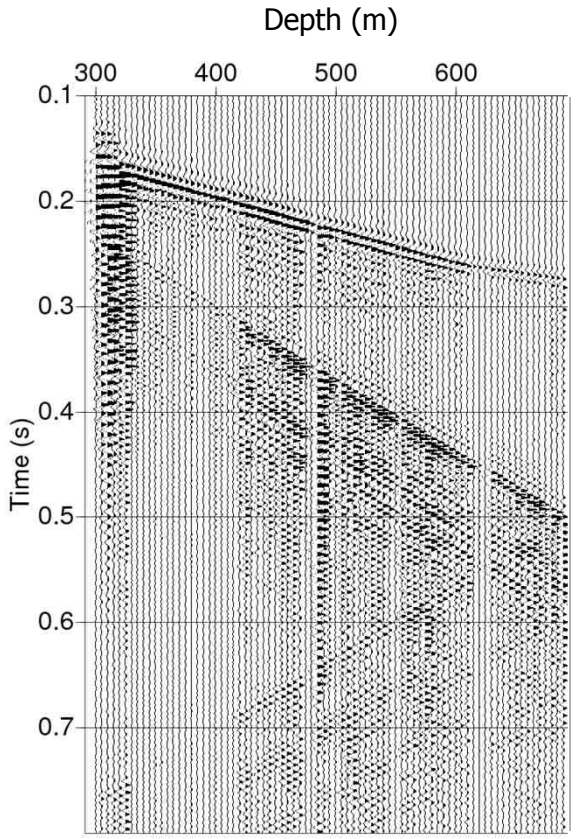
V wave velocity (speed), ρ mass density, f denotes fluid, and S shear wave

VSP sampling in depth (Nyquist)

$$\Delta z < \frac{V_{min}}{2f_{max}}$$

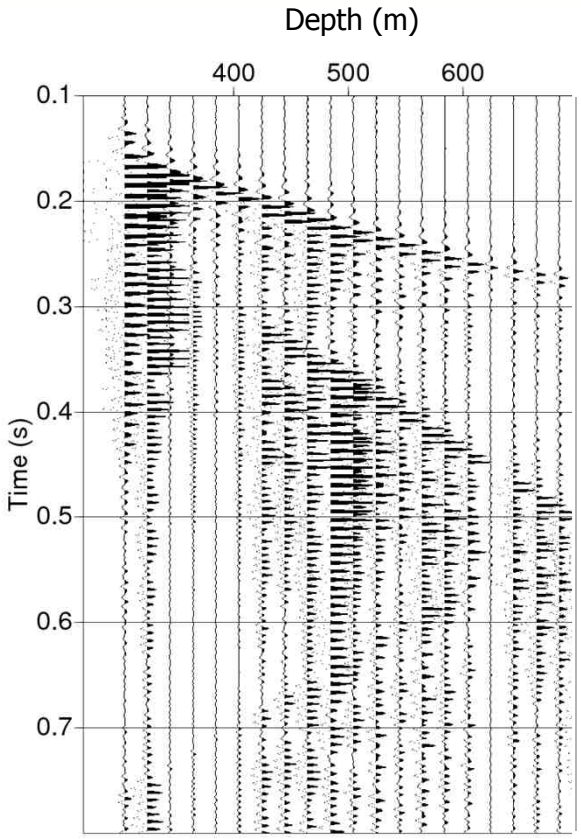
Δz depth interval, V wave velocity, f frequency

VSP sampling in depth



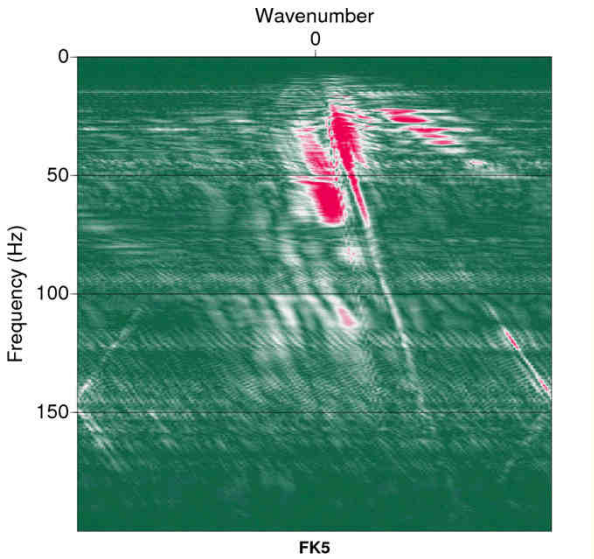
5 m BP 100-200 Hz

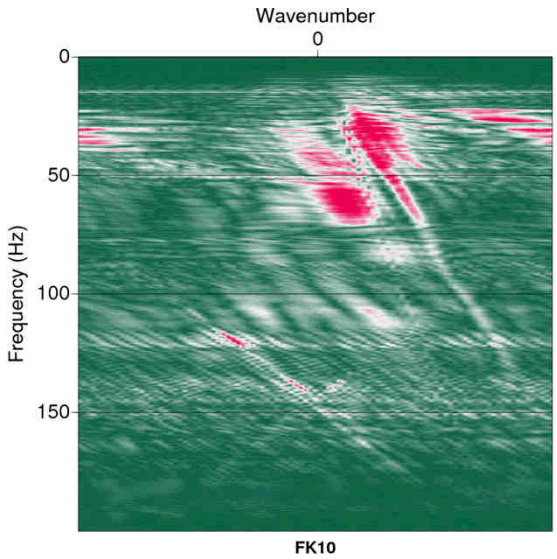
VSP sampling in depth

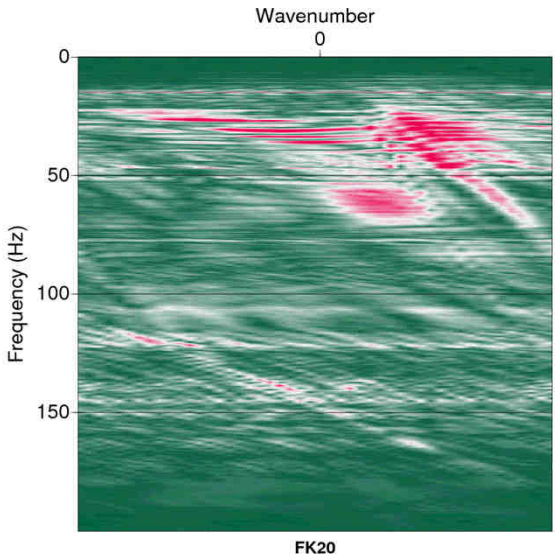


20 m BP 100-200 Hz

VSP *f-k* spectra and aliasing







5 m

10 m

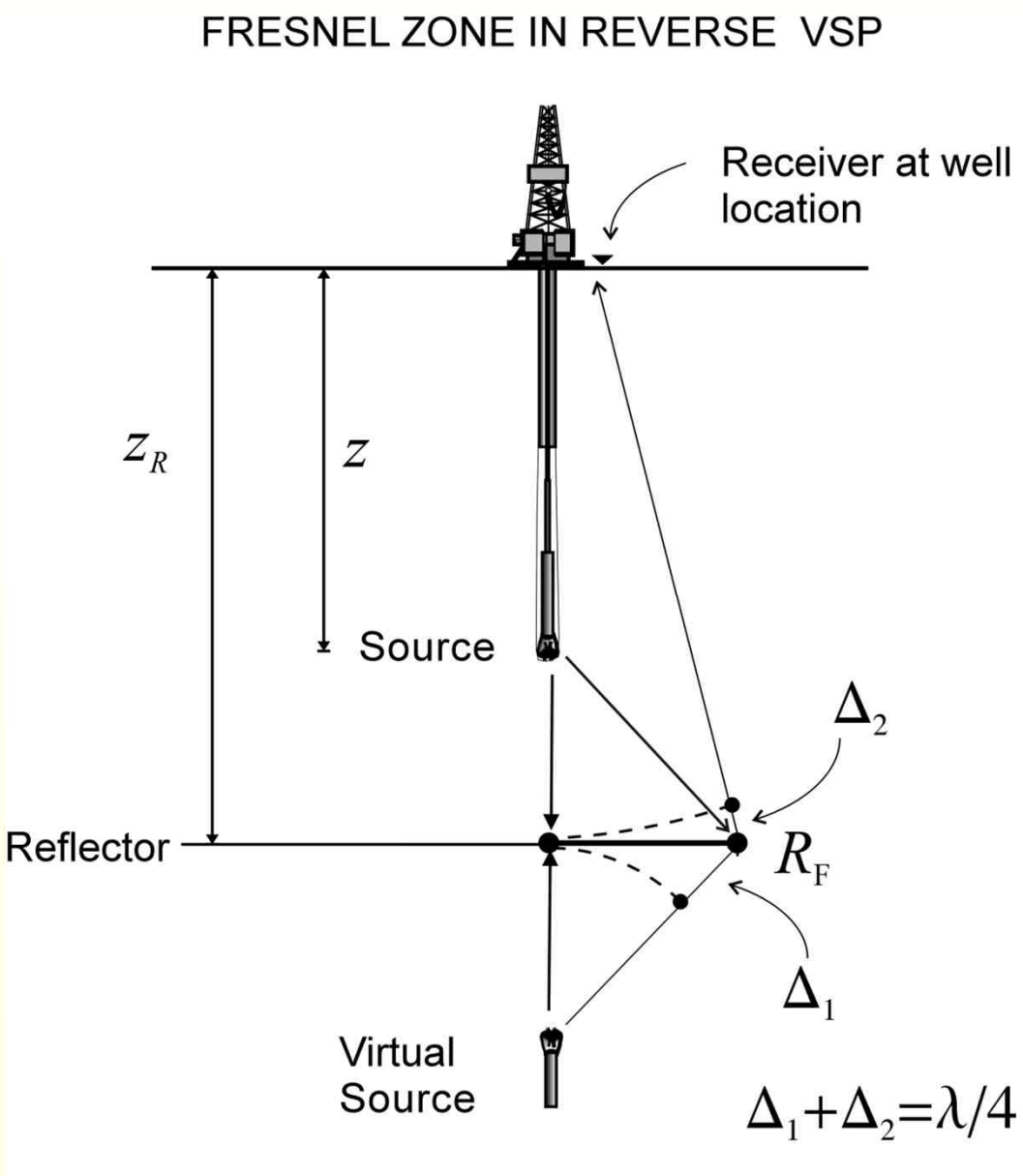
20 m

where $k = \frac{\omega}{V}$ is the wavenumber

VSP advantages

- Receivers closer to reflectors, shorter reflection travel paths with respect to surface seismics
- Improved space resolution with respect to surface seismics
- Provides time-depth correspondence for calibration of seismic and log signals in depth
- Observe separately upgoing and downgoing waves
- Improved signal processing

VSP spatial resolution



(After Poletto and Miranda, 2004)

VSP spatial resolution

$$r^2 = \lambda \frac{ab}{a+b}$$

$$a = z_R - z$$

$$b = z_R$$

VSP spatial resolution

$$r^2 = \lambda \frac{ab}{a+b}$$

- Es. 1: Surface, a=b=2000 m, λ=20 m, r=140
- Es. 2: Well, a=200 m, b=2000 m, λ=20 m, r=60

VSP advantages

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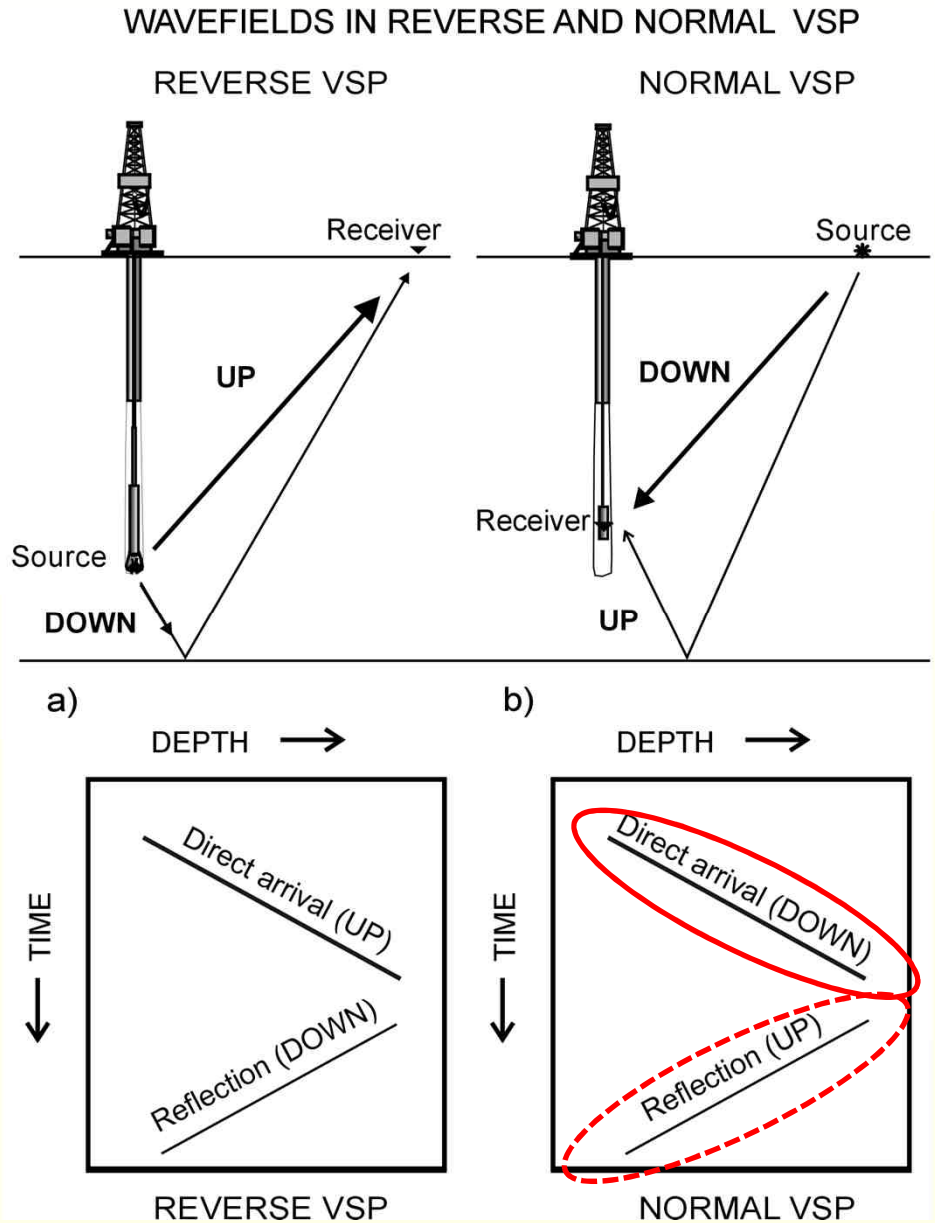
VSP wavefields

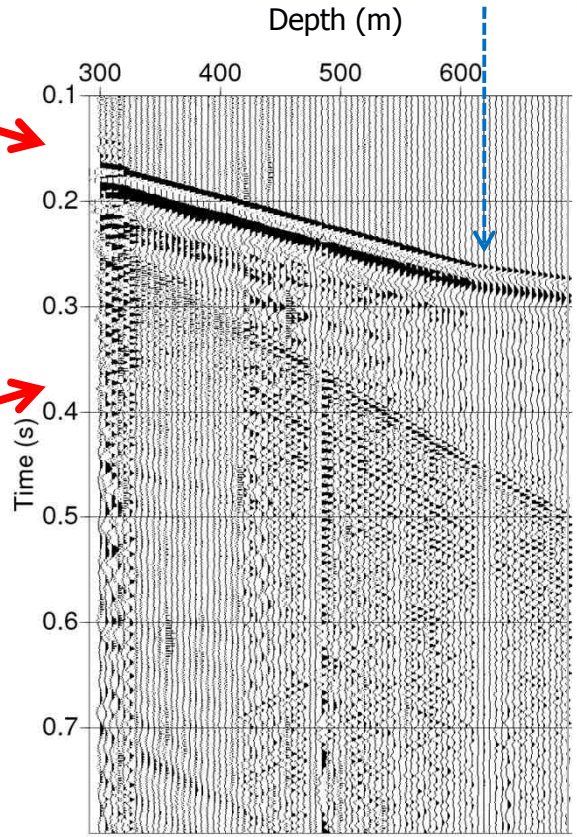


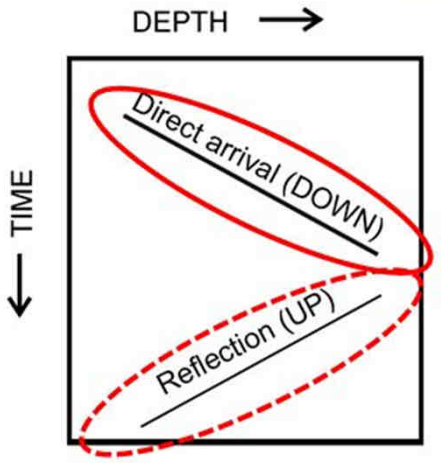
VSP total field

Reflector depth

Direct arrivals

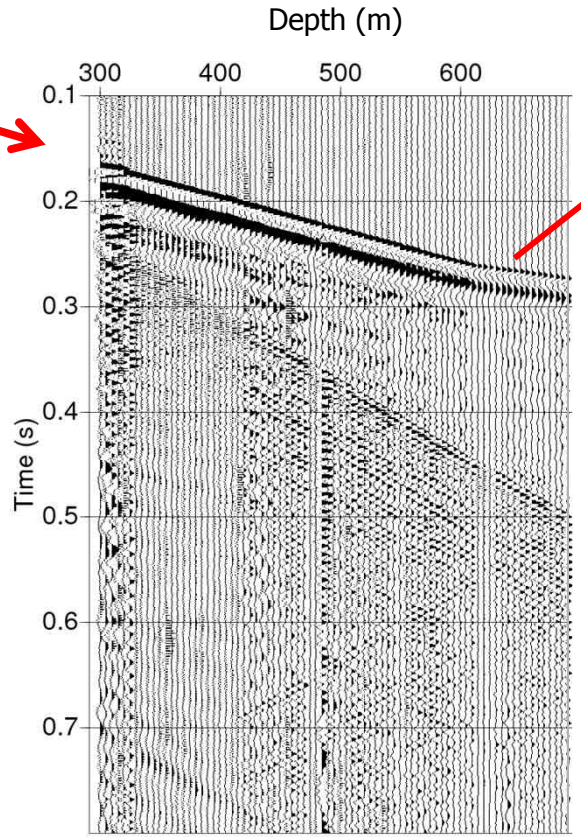
Reflection

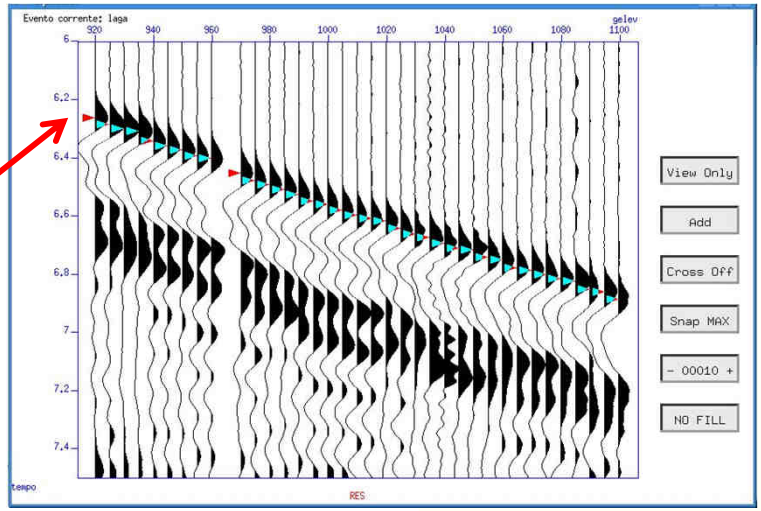




VSP total field

Direct arrivals

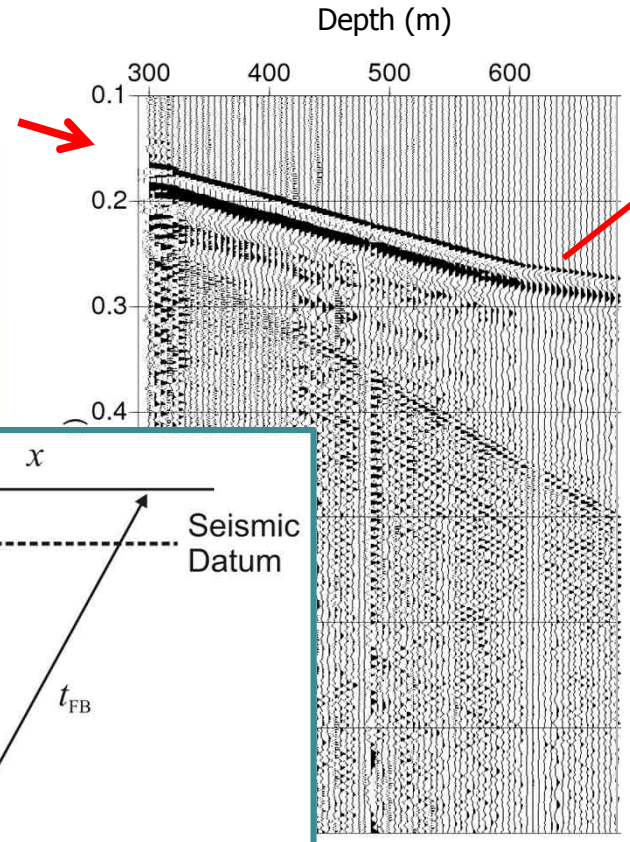


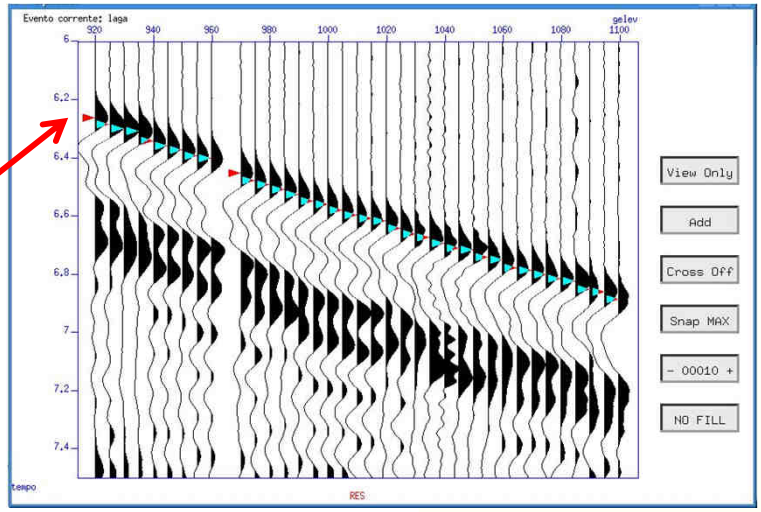


FB time picking

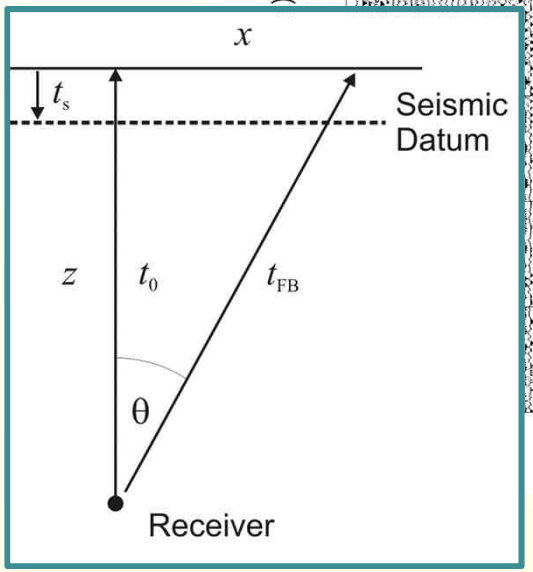
VSP total field

Direct arrivals



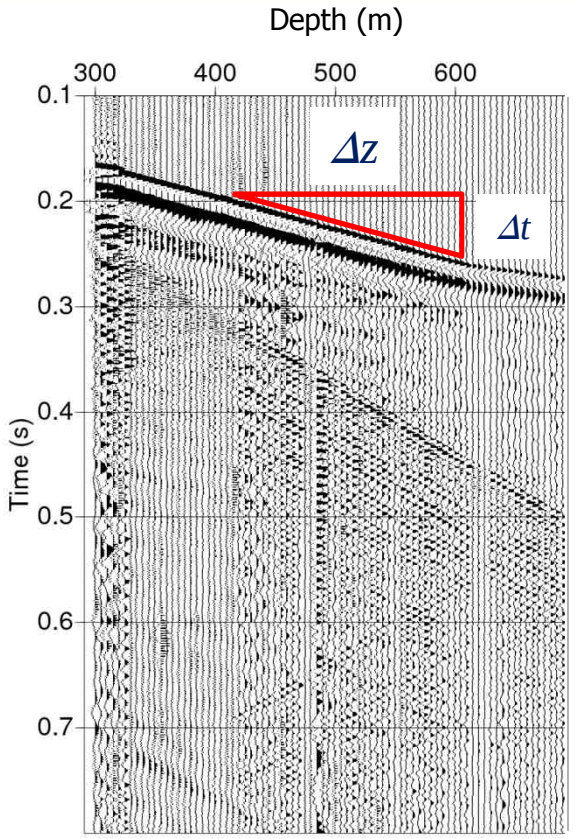


FB time picking



Verticalization

VSP interval velocity



Interval velocity $V_{int} = \frac{\Delta z}{\Delta t}$

VSP wavefield separation

Multidimensional (t-z) processing approaches:

- Median filters (preserve steps, not linear!)
- f-k dip filters (regular sampling), τ-p processing
- Parametric separation (3C multicomponent)

VSP wavefield separation

Multidimensional (t-z) processing approaches:

- Median filters (preserve steps, not linear!)

  (12, 5, 33, 31, 1)

VSP wavefield separation

Multidimensional (t-z) processing approaches:

- Median filters (preserve steps, not linear!)

(12, 5, 33, 31, 1) → (1, 5, 12, 31, 33)

VSP wavefield separation

Multidimensional (t-z) processing approaches:

- Median filters (preserve steps, not linear!)

(12, 5, 33, 31, 1) → (1, 5, 12, 31, 33)

VSP wavefield separation

Multidimensional (t-z) processing approaches:

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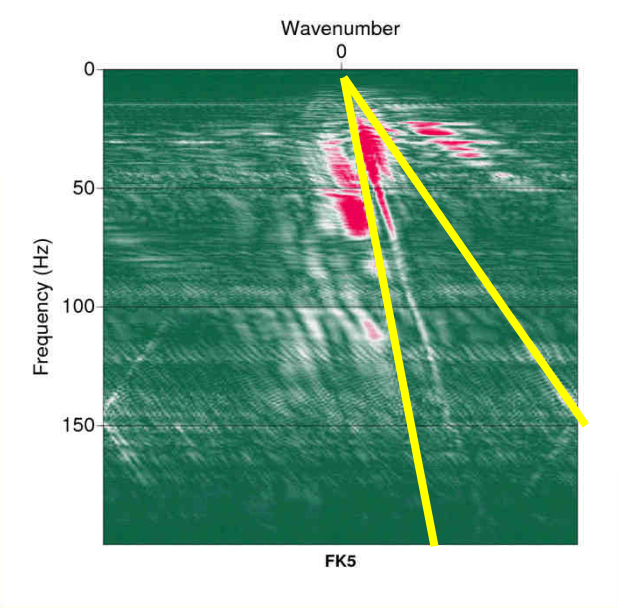
VSP wavefield separation

Multidimensional (t-z) processing approaches:

- f-k dip filters (regular sampling)

$$2\pi f = Vk$$



VSP wavefield separation

Multicomponent (dual fields v, p) processing approach:

Displacement $$u = De^{i(\omega t - kz)} + Ue^{i(\omega t + kz)}$$

Particle velocity $$v = \frac{\partial u}{\partial t}$$

Pressure $$p = \rho V^2 \frac{\partial u}{\partial z}$$

VSP wavefield separation

Multicomponent (dual fields v, p) processing approach:

Displacement $$u = De^{i(\omega t - kz)} + Ue^{i(\omega t + kz)}$$

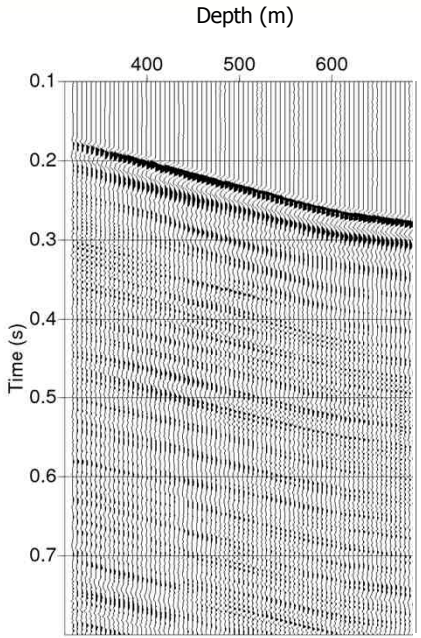
Particle velocity ($z=0$) $$v = \frac{\partial u}{\partial t} = i\omega(D + U)$$

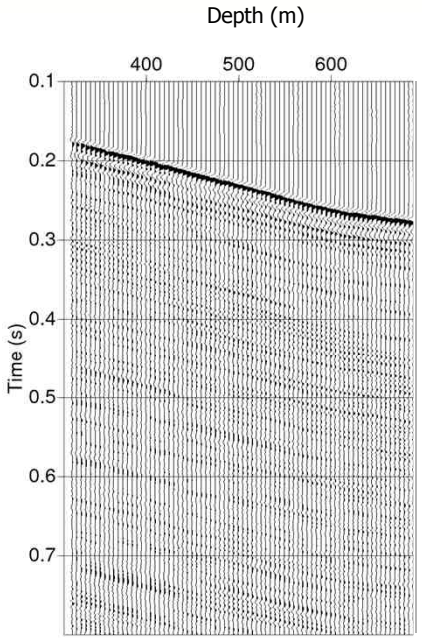
Pressure ($z=0$) $$p = \rho V^2 \frac{\partial u}{\partial z} = i\omega\rho V(-D + U)$$

$$D = \frac{v - p/(\rho V)}{2i\omega} \qquad U = \frac{v + p/(\rho V)}{2i\omega}$$

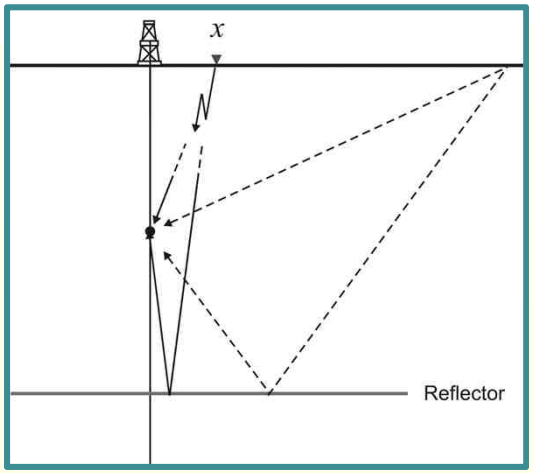
VSP separated wavefields

DW

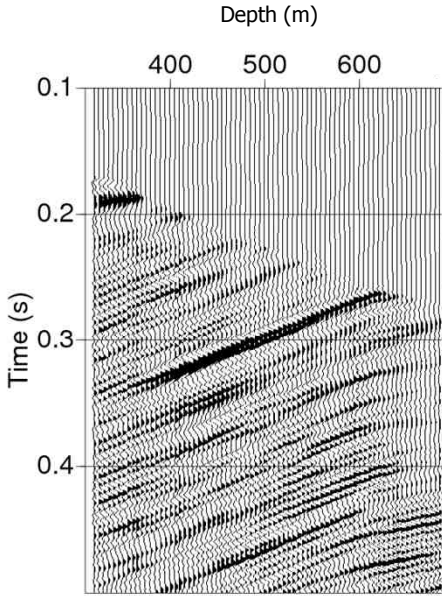




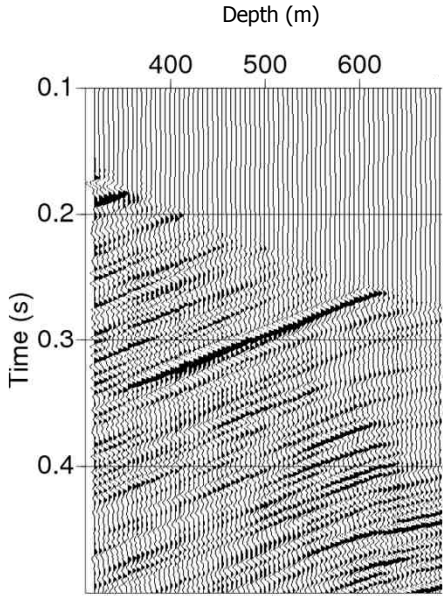
DW DEC



VSP separated wavefields

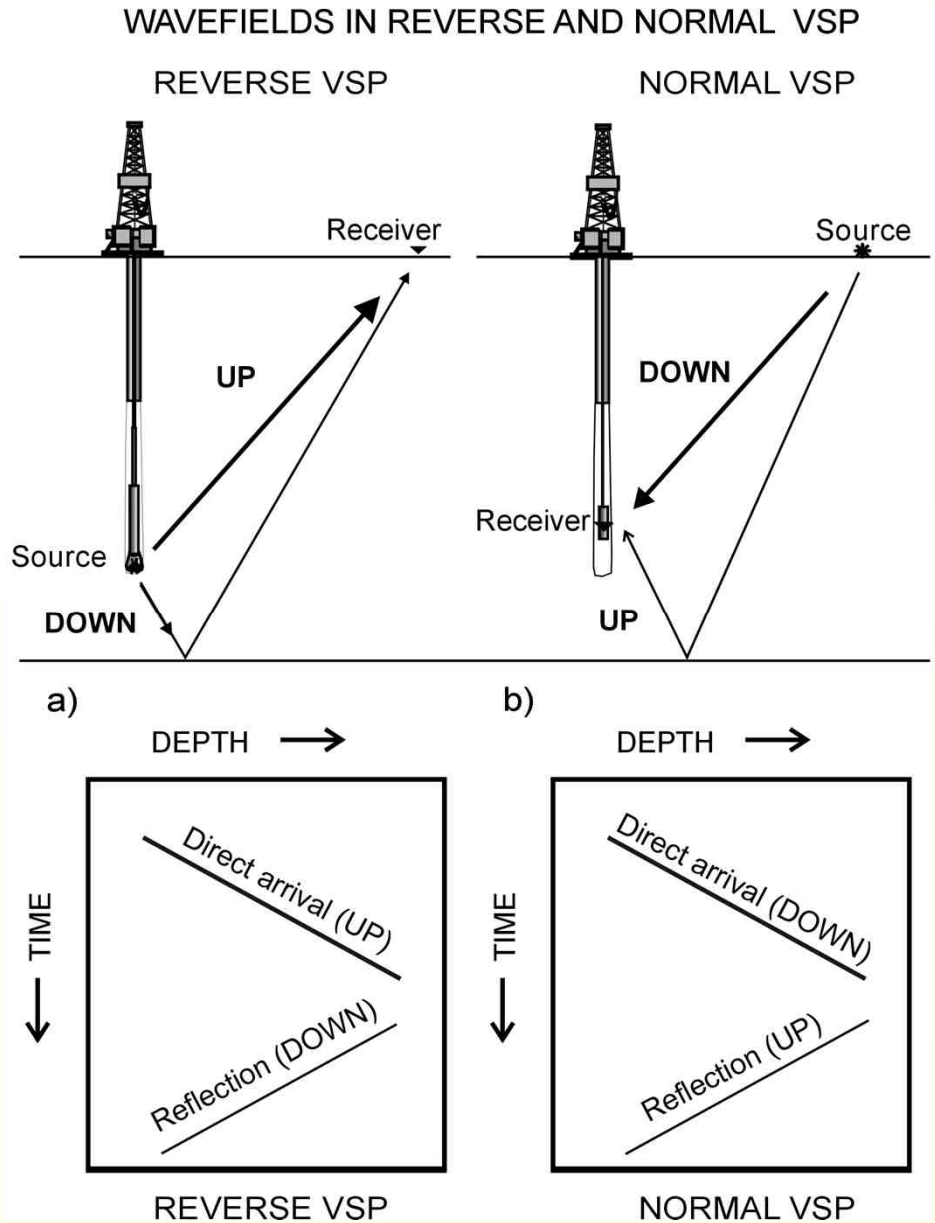


UP

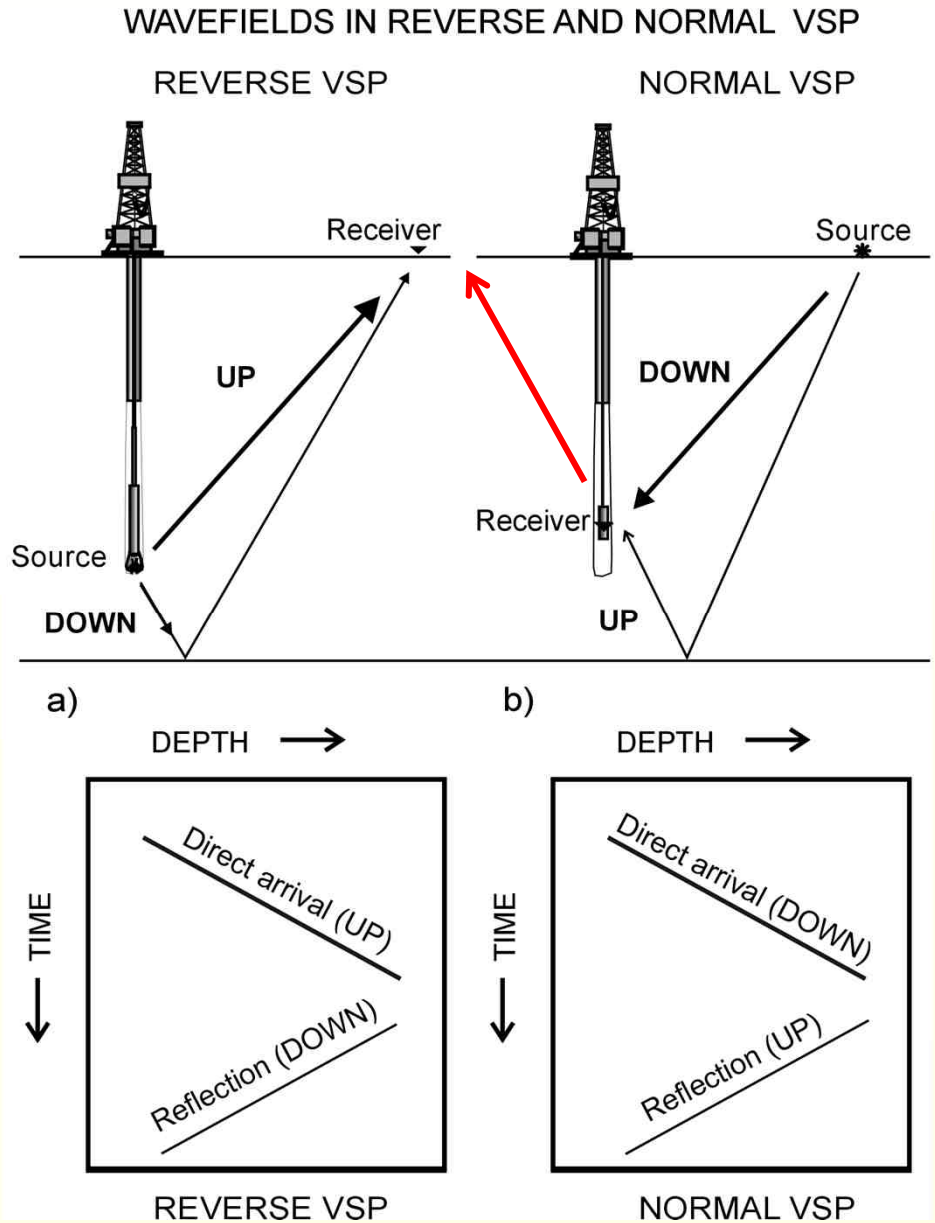


UP DEC

VSP wavefields

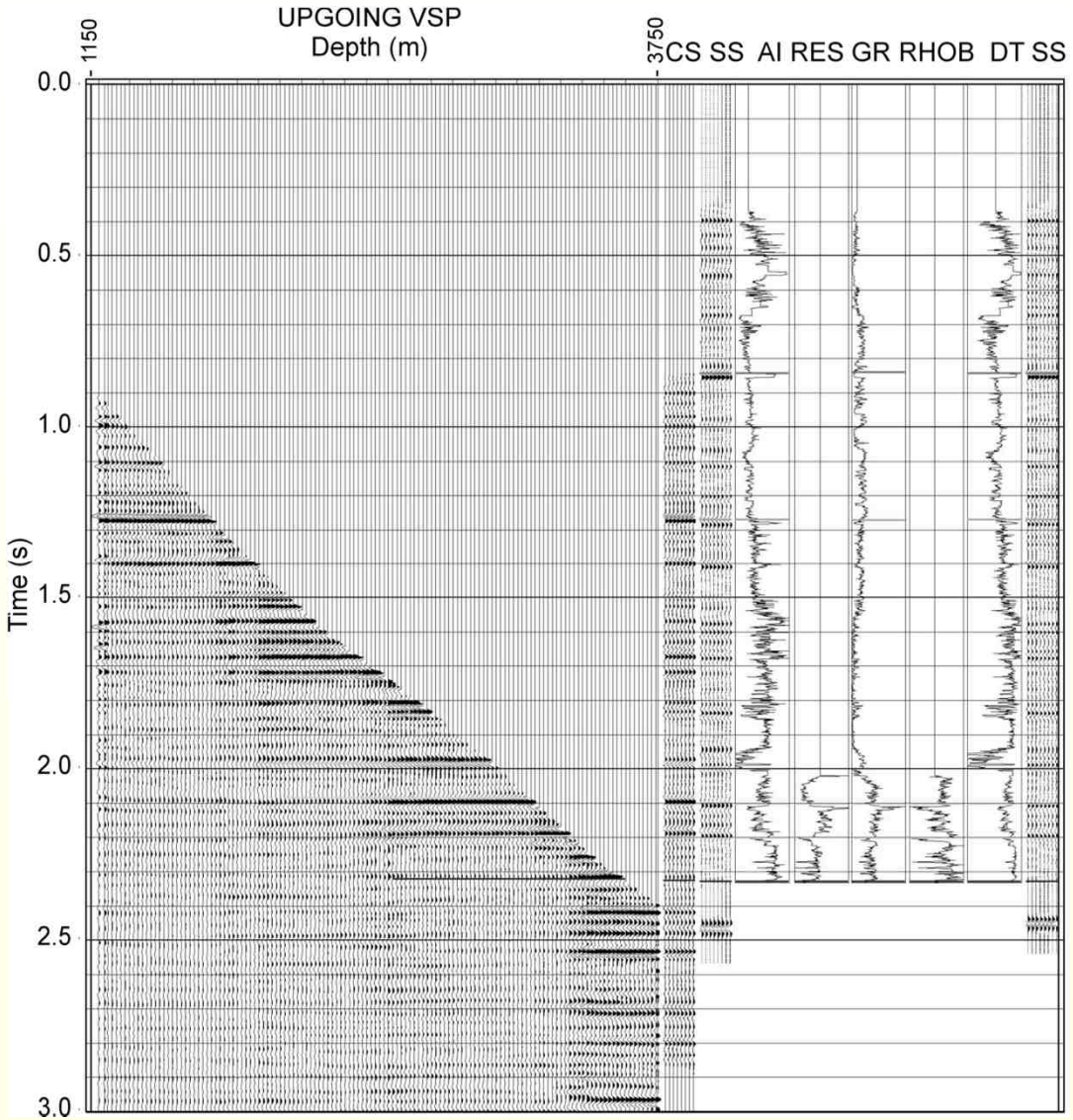


VSP vs surface seismic wavefields

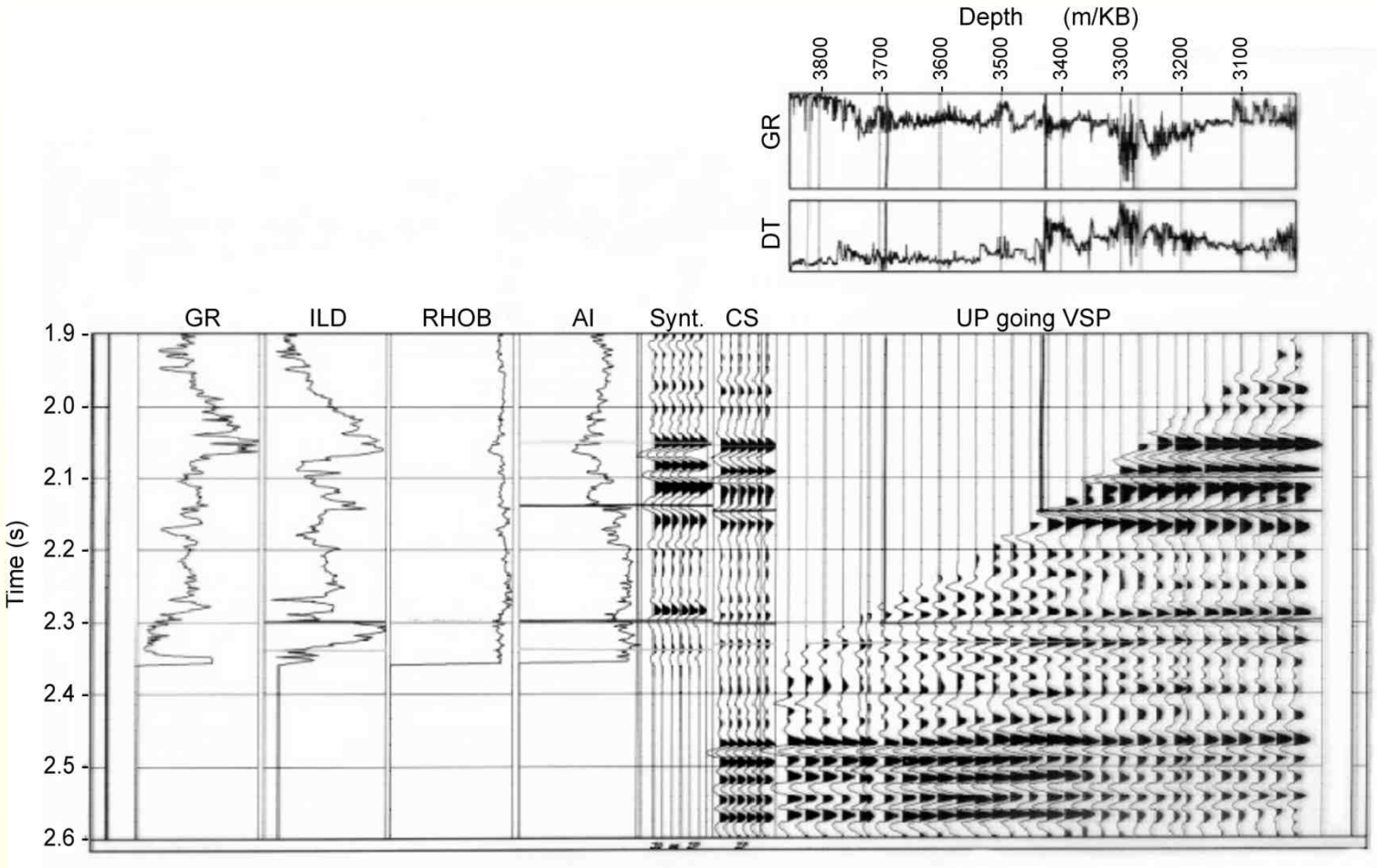


TWT

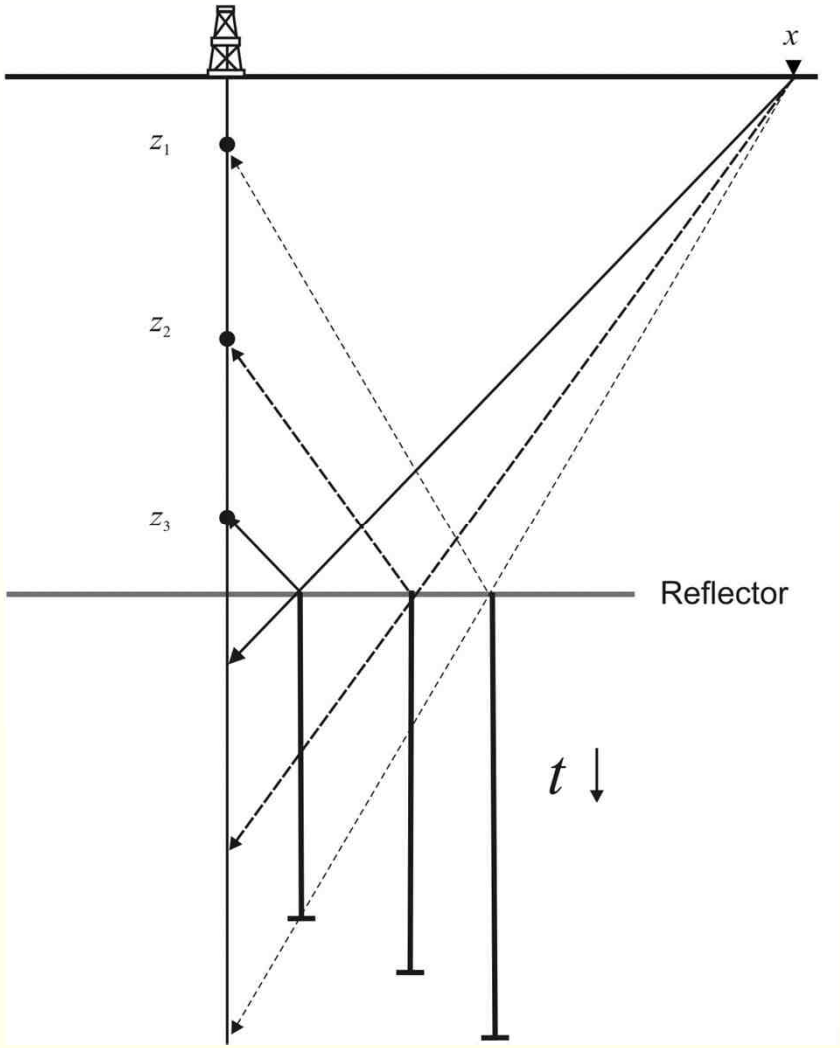
VSP near offset



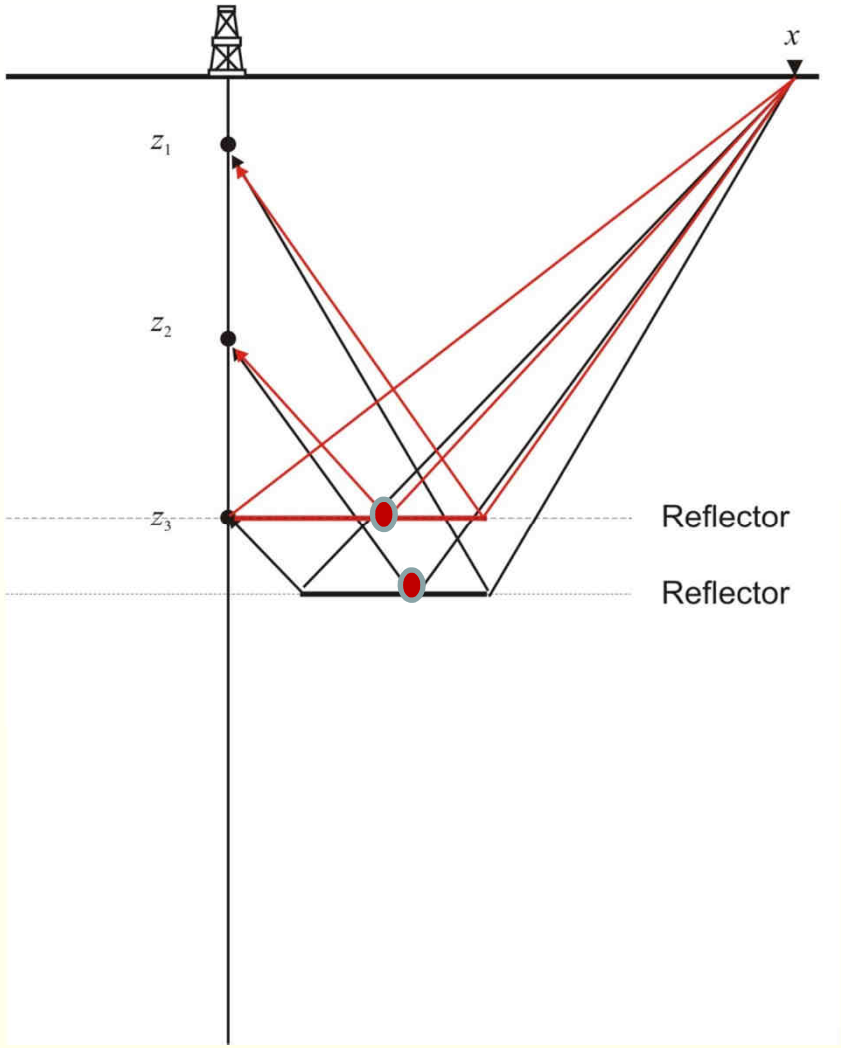
VSP and logs in time and in depth



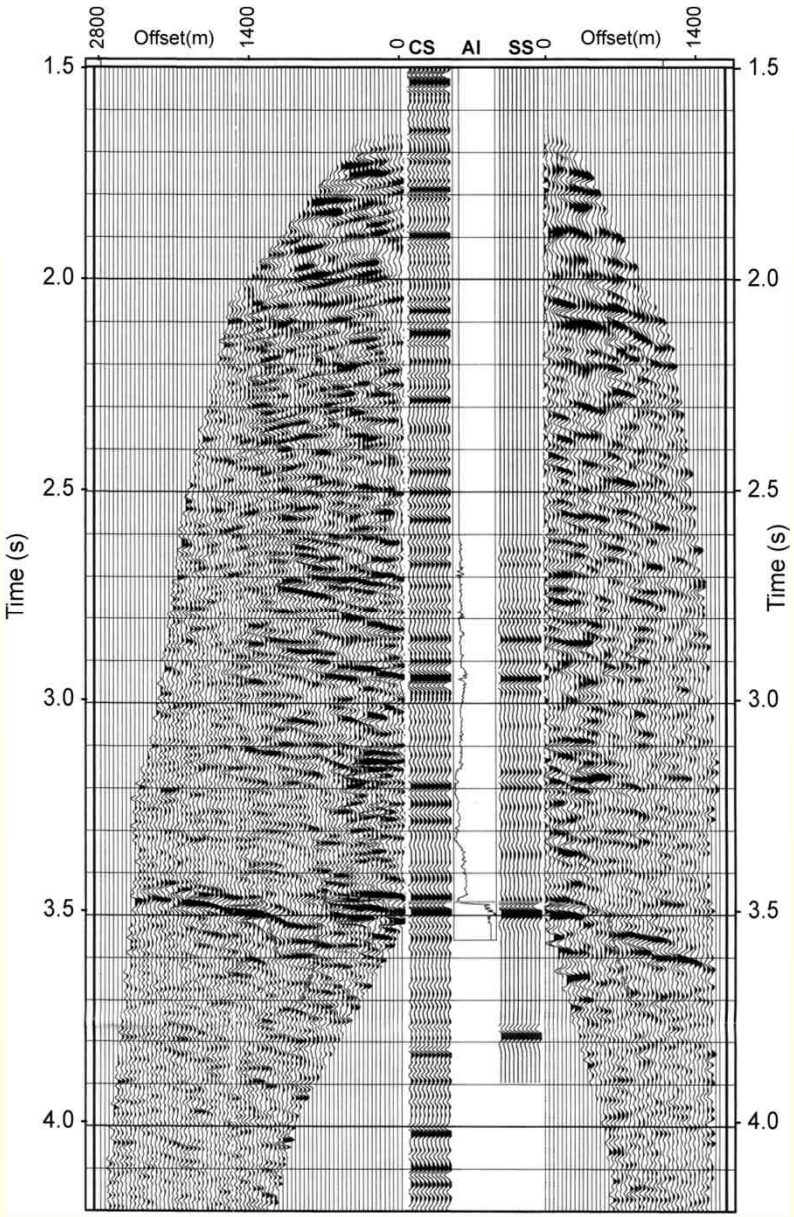
VSP offset



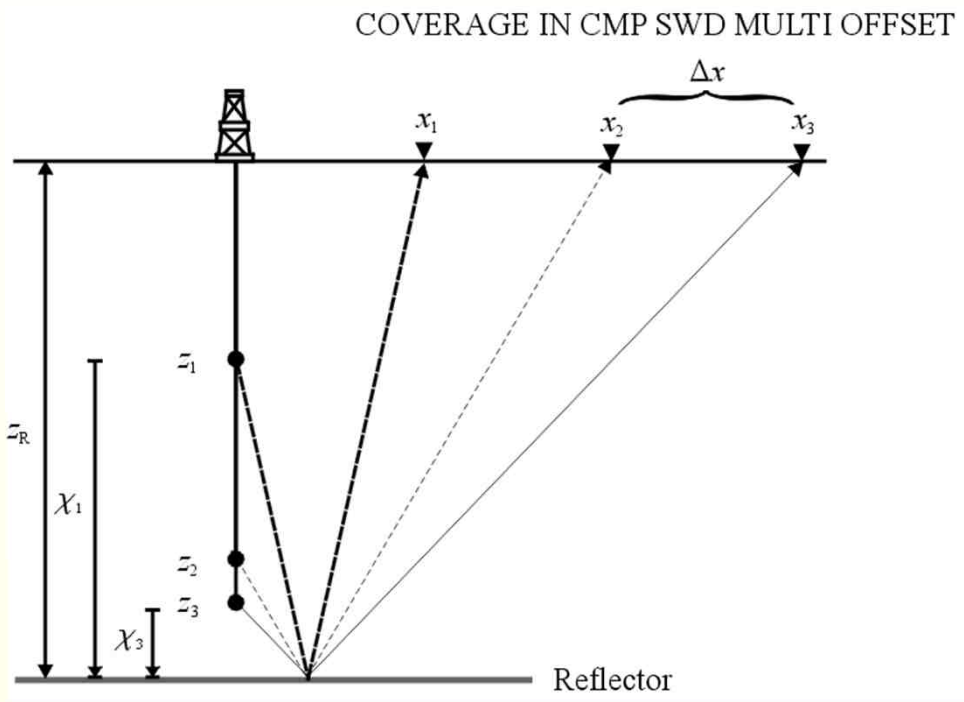
VSP offset



VSP offset


2800
Offset(m)
1400
0
CS
AI
SS
0
Offset(m)
1400
1.5
2.0
2.5
3.0
3.5
4.0
Time (s)
Time (s)

VSP multioffset



Examples: attenuation and 3C analysis

- Drilling a well (just an introduction)
- Borehole geophysics (introduction)
- Vertical seismic profiling (VSP) basic concepts
- Vertical seismic profiling (VSP) example 1

VSP attenuation

$$A = e^{-\alpha z} = e^{-\alpha V t} = e^{-\frac{\pi f t}{Q}}$$

$$\alpha = \frac{\pi}{\lambda Q} = \frac{\pi f}{QV}$$

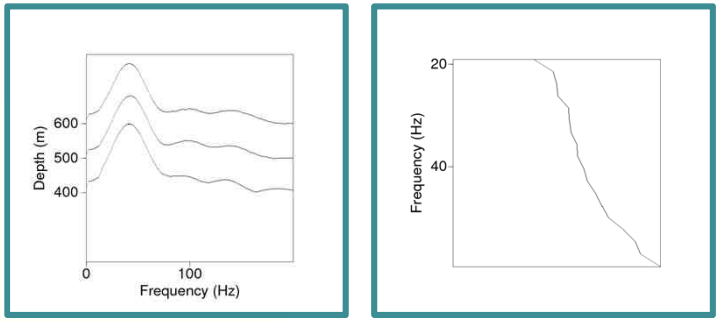
$$A_1 = e^{-\alpha z_1}, \qquad A_2 = e^{-\alpha z_2}$$

$$\ln \frac{A_2}{A_1} = -\alpha (z_2 - z_1) = -\frac{\pi}{V} \frac{(z_2 - z_1)}{Q} f$$

A signal amplitude, α attenuation factor, z propagation distance

λ wavelenght, f frequency, V velocity, t time, Q quality factor

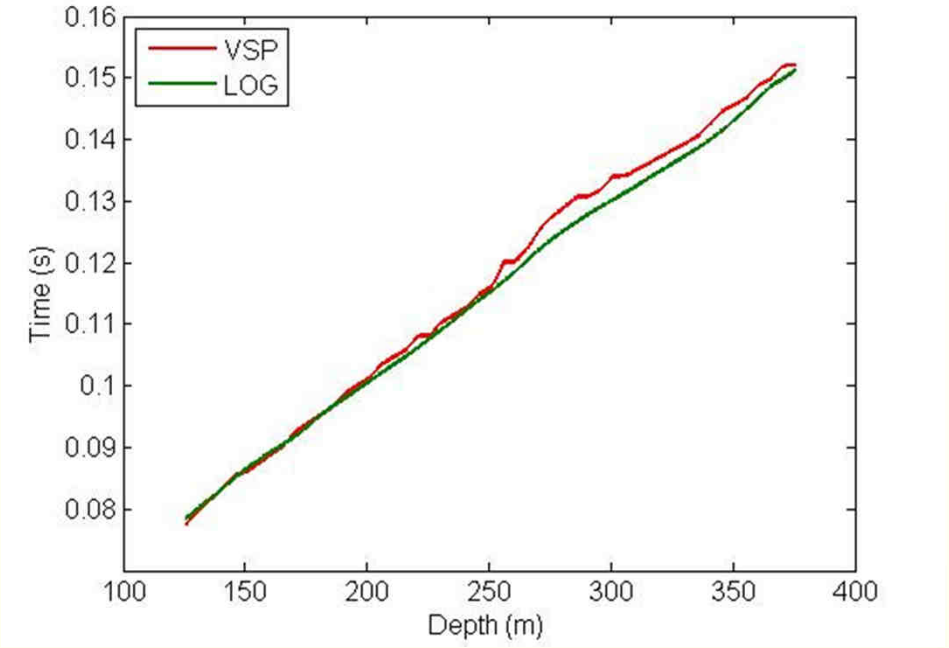
VSP attenuation



Cumulative attenuation B_z

$$\left[\ln\frac{A_z(f)}{A_0(f)}\right] = -B_z f + \ln G_z \qquad k_z = B_z/(z - z_0) \qquad \alpha_z = V_z k_z$$

VSP attenuation and logs

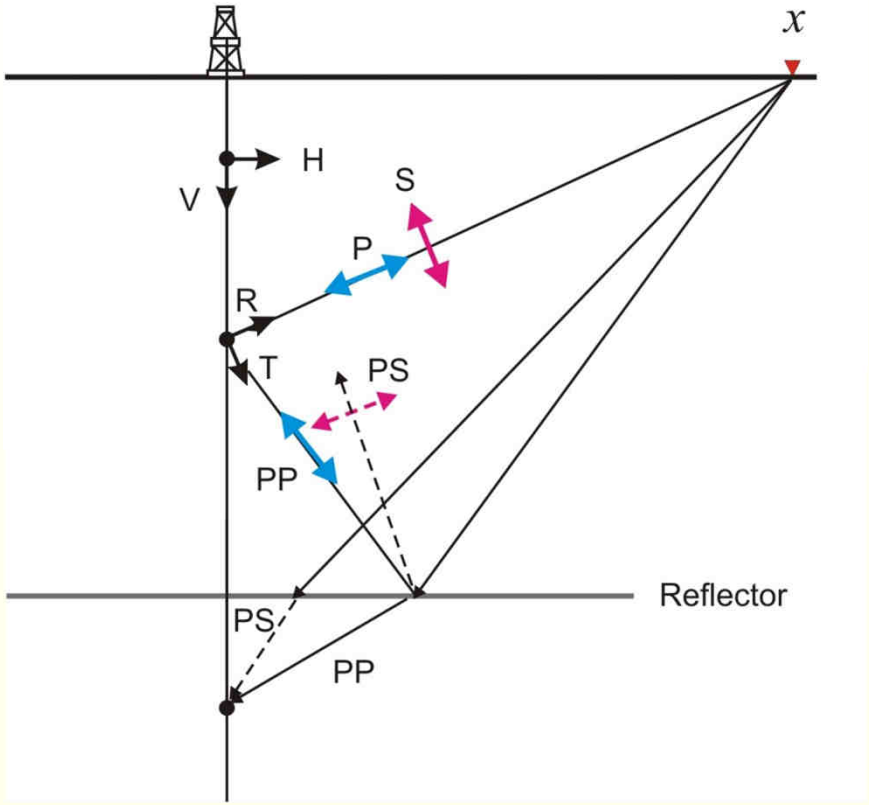


$$Q \approx 30$$

$$\frac{V(f_2)}{V(f_1)} = 1 + \frac{1}{\pi Q} \ln\left(\frac{f_2}{f_1}\right)$$

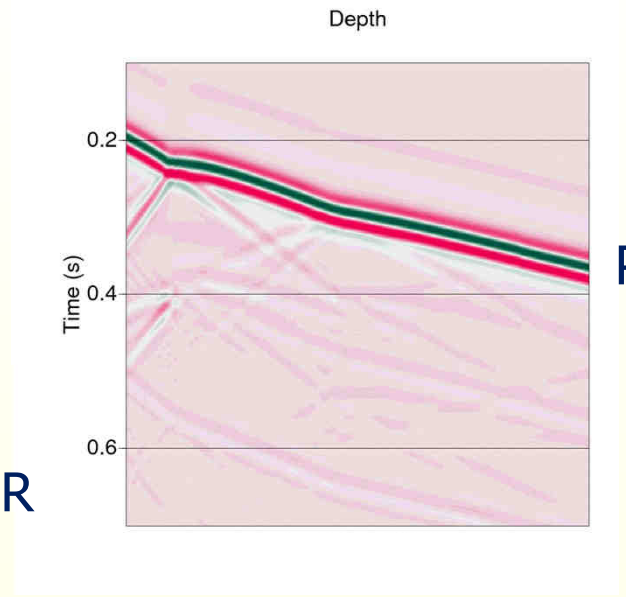
Kramers –Krönig relation

VSP 3C orientation analysis

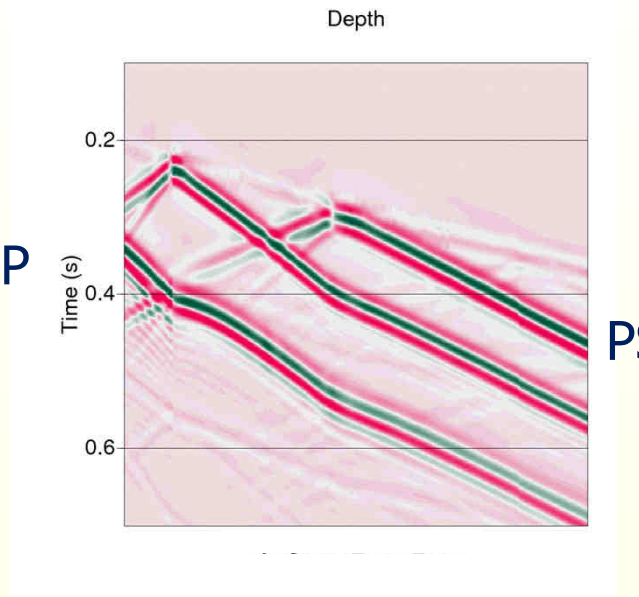


VSP multicomponent signal analysis

Synthetic R



PP



PS

Synthetic T

Seismic emission characterization

- Drilling a well (just an introduction)
- Borehole geophysics (introduction)
- Vertical seismic profiling (VSP) basic concepts
- Vertical seismic profiling (VSP) example 2

Basic concepts for seismic emission by vibrators

Radiation from a surface vibrating source (e. g., vertically pulsating plate) exposed to harmonic force $F_S e^{i\omega t}$:

- Particle velocity below the pulsating plate $v_{PL} = F_S Y_{PL}$
- Ground admittance Y (impedance Z) $Y = Y_1 + iY_2 \quad (Z = 1/Y)$
- Near-field term in Y, relative to far-field decay $\approx \frac{1}{rk}$

  (r radial distance, k wavenumber)
- Far-field condition $rk >> 1$
- Far-field particle velocity proportional to $(F_S e^{i\omega t})'$ $v_{FAR} \propto i\omega F_S$

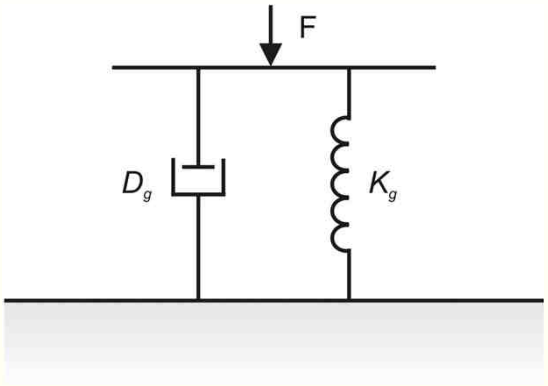
References: Miller and Purshey, 1954, 1955; Bycroft, 1956; Cassand and Lavergne, 1971; Ziolkowsky, 1980; Lerwill, 1981, 1982; Sallas and Weber, 1982; Sallas, 1984; Baeten, Fokkema and Ziolkowsi, 1988; Baeten and Ziolkowski, 1990.

Basic concepts for seismic emission by vibrators

- Particle velocity below the pulsating plate $v_{PL} = v_1 + iv_2 = F_S(Y_1 + iY_2)$

- Mechanical ground model analogy

  (after Sallas, 1984)

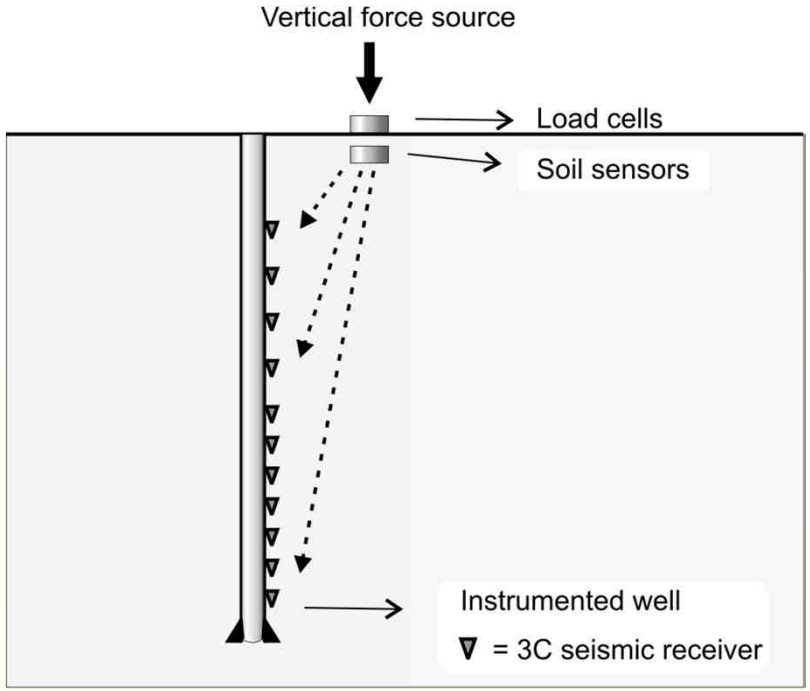


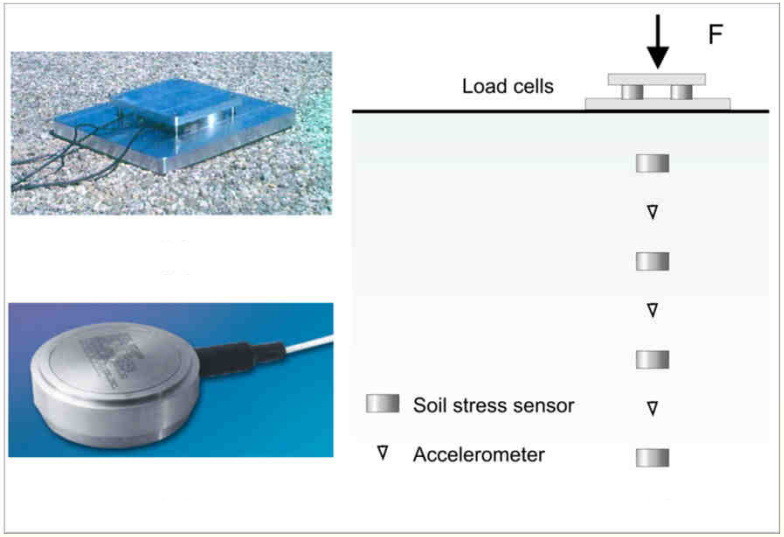
- Average power $W = \frac{1}{2}\mathrm{Re}\left[F_S v_{PL}^*\right]$

- Radiated power given by the in-phase term $W_S = \frac{1}{2}F_S^2 Y_1$

Poletto et al (2011), SEG, S. Antonio

Seismic emission characterization



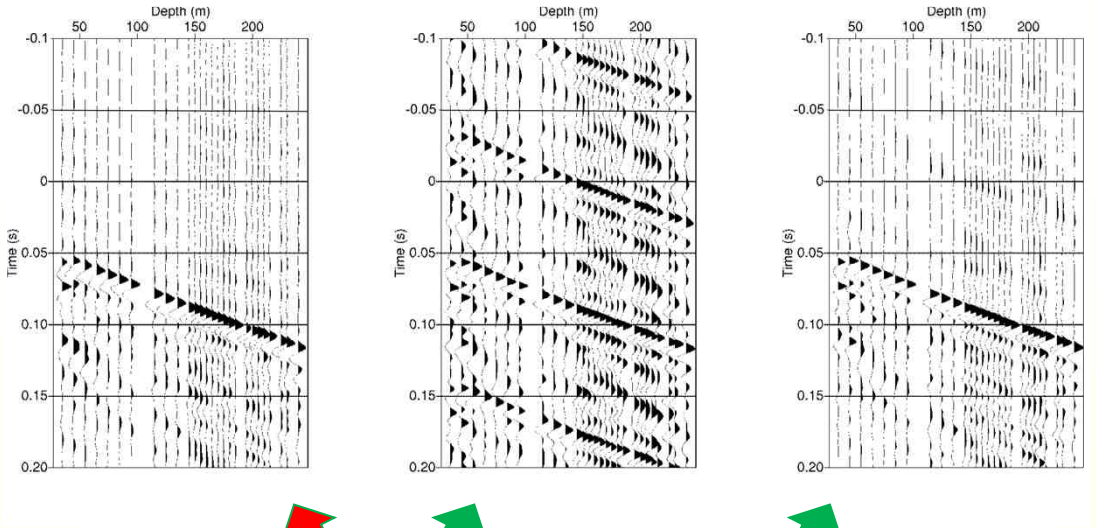


Layout of the experiment performed at the instrumented-well test site to measure the downgoing waves (far-field approximation) and the near-field vibrations produced by a vertical source at surface

Poletto et al (2011), SEG, S. Antonio

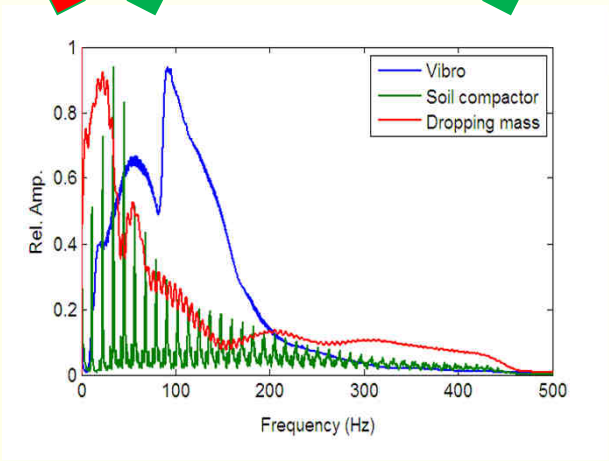
- Ground-force sensors located at 28 m offset from wellhead
- Permanent casing array of 3C geo-phones installed from 35 to 240 m depth, with 10 and 5 m interval

Seismic source repeatability

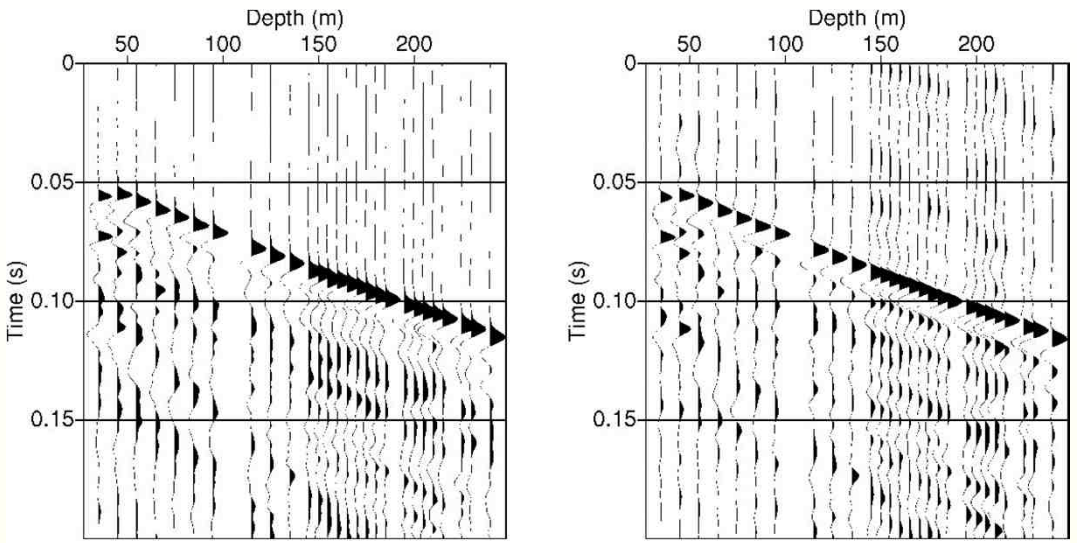


Corr

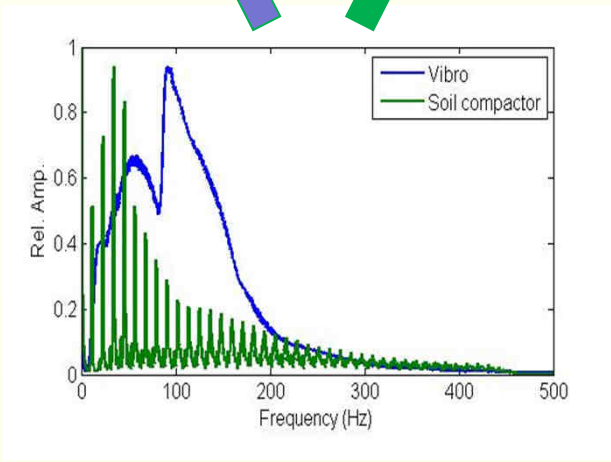
Decon



Seismic source repeatability



Decon Decon



Seismic source repeatability

$$NRMS = \frac{200 \times RMS(s_{VIB} - s_{CO})}{RMS(s_{VIB}) + RMS(s_{CO})} \approx 12 \div 27\%$$