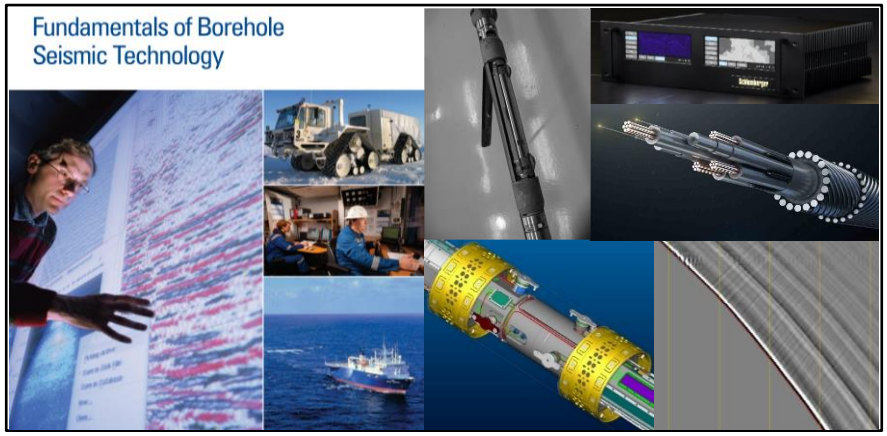
NPD FORCE Geophysical Methods Group

Fundamentals of Borehole Seismic Technology



By: *Neil Kelsall, Rogelio Rufino and Rafael Guerra*

Schlumberger

Stavanger, 04-Oct-2022

Agenda

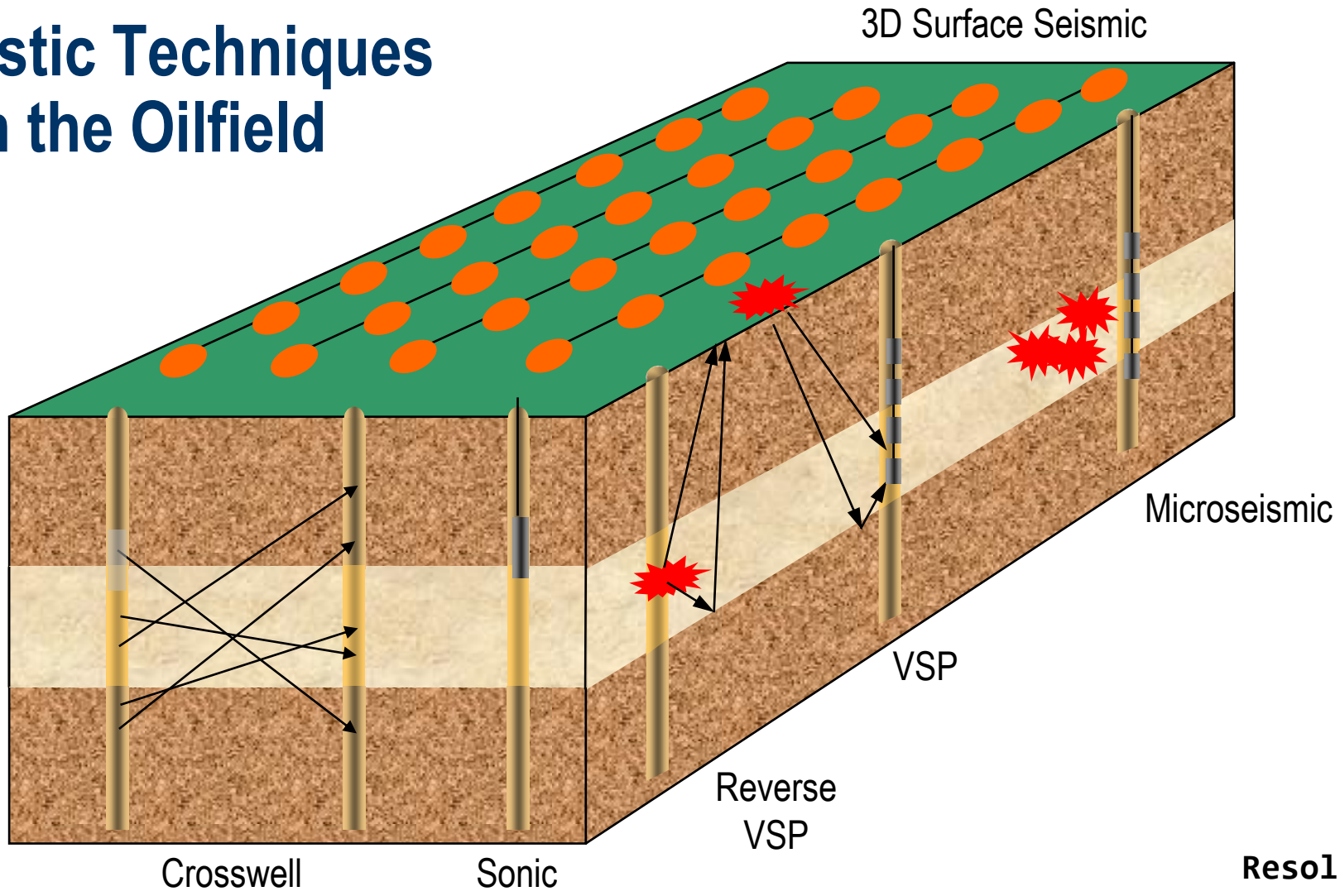
- **Borehole Seismic introduction** *(10 min) – R. Guerra*
- **Data acquisition technology on wireline & fiber optics** *(20 min) – R. Guerra*
- **LWD seismic while drilling technology** *(30 min) – N. Kelsall*

Lunch Break (60 min)

- **Survey design & modelling** *(10 min) – R. Guerra*
- **Data processing technology & case studies** *(35 min) – R. Rufino*

Final discussion & adjourn (15 min)

Acoustic Techniques in the Oilfield



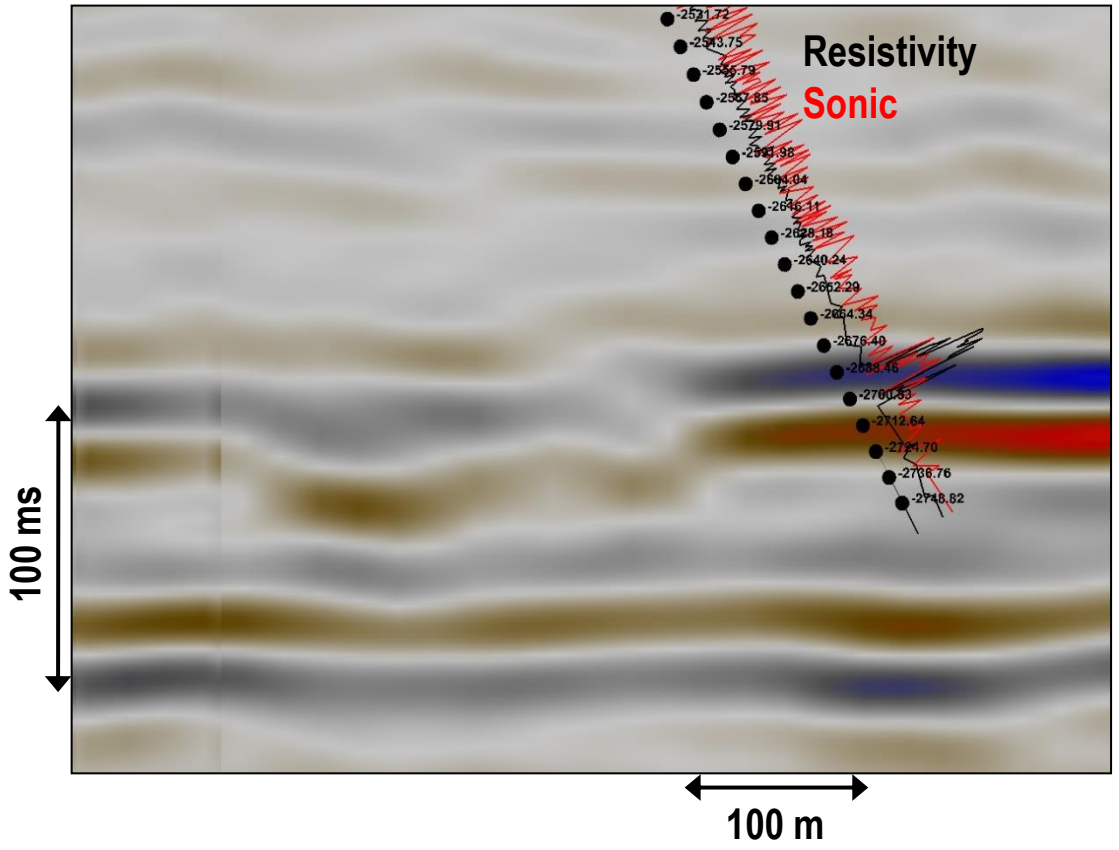
- Passive, impulsive or vibrational sources, temporary or permanent
- Geophones, hydrophones or fiber optics, temporary or permanent
- Recorded during drilling, OH/CH logging or during production

Resolution

Logging	(~10^3 Hz)	**~ 0.3 m**
Xwell	(~10^2 Hz)	**~ 3 m**
VSP	(~ 50 Hz)	**~ 10 m**
Seismic	(~ 25 Hz)	**~ 20 m**

Surface Seismic Data

(Marques et al., 2011)



Vertical Resolution

(Rayleigh's criterion):

$$dz = \lambda_{dominant} / 4$$

$$= V / (4 * F_{dominant})$$

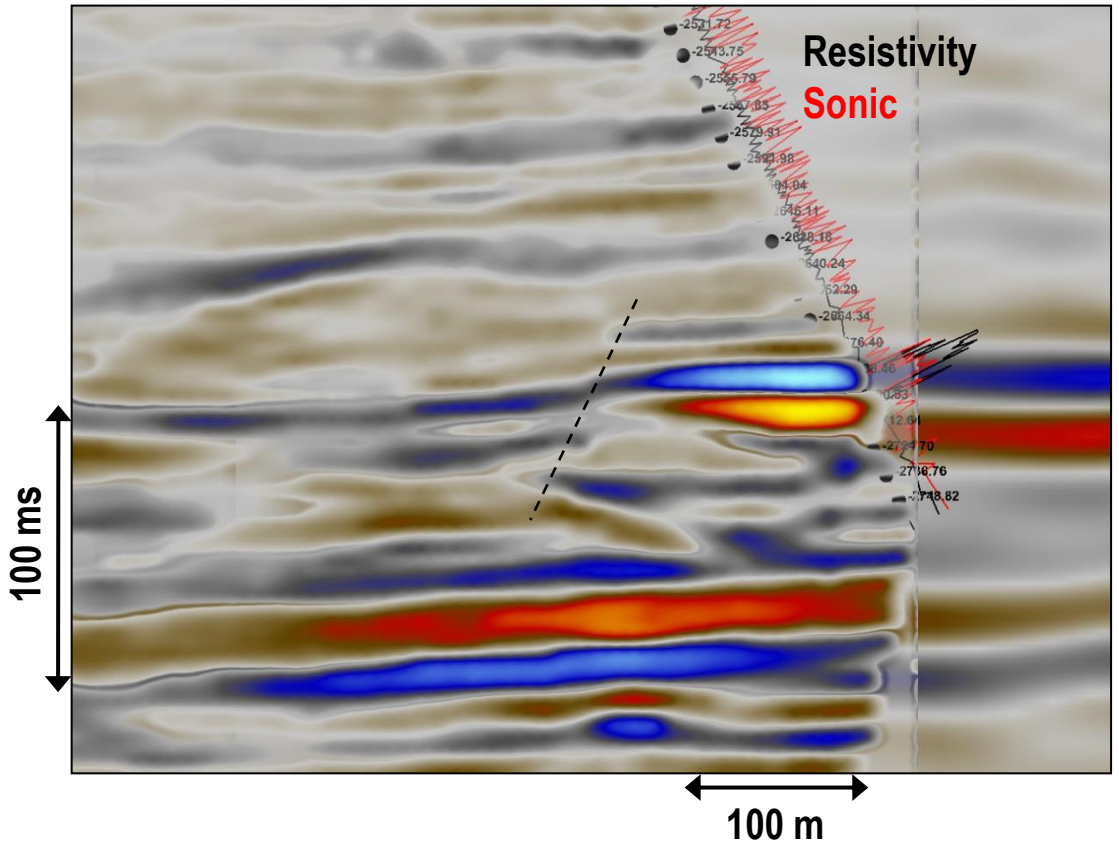
With V=2800 m/s at the reservoir:

Seismic *(8-45 Hz): dz = 26 m*

- **The surface seismic does not resolve the 15 m thick sand body drilled by the pilot-hole**

VSI image below well deviations

(Marques et al., 2011)



Vertical Resolution

(Rayleigh's criterion):

$dz = \lambda_{dominant} / 4$

$= V / (4 * F_{dominant})$

With V=2800 m/s at the reservoir:

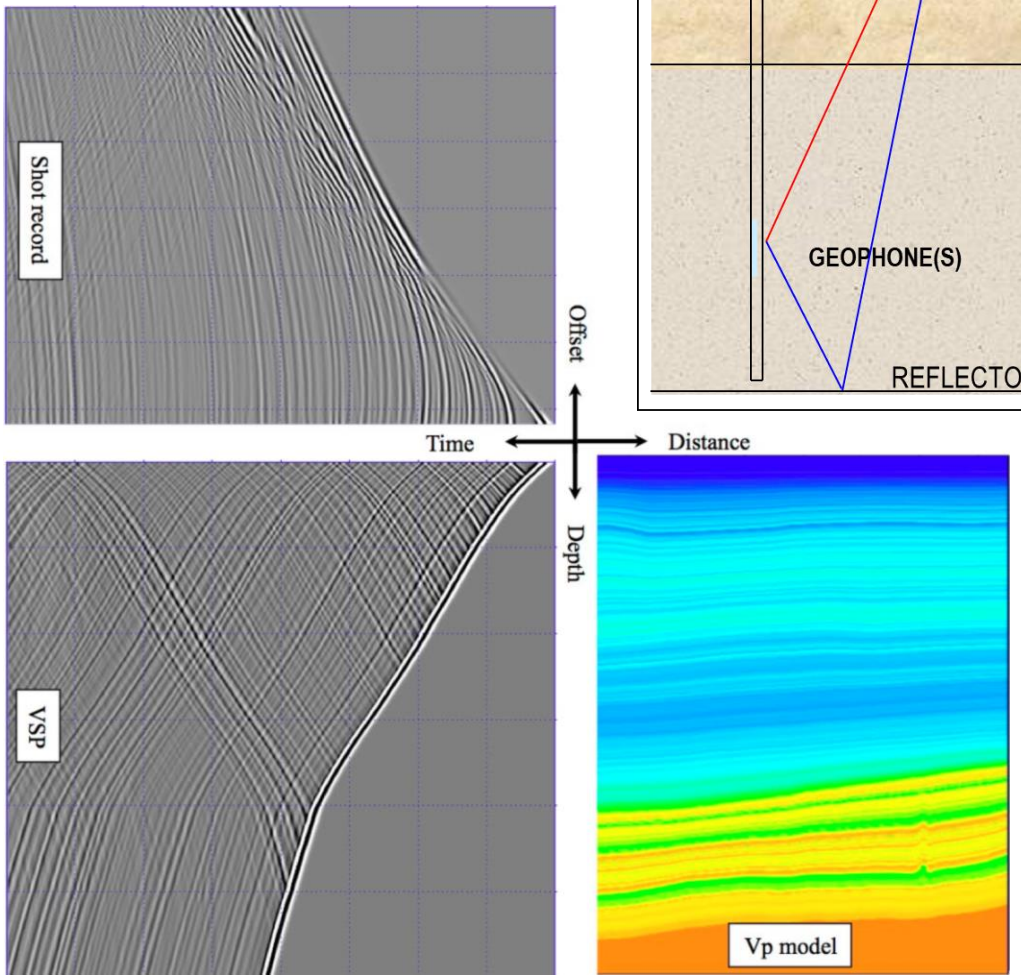
Seismic *(8-45 Hz): dz = 26 m*

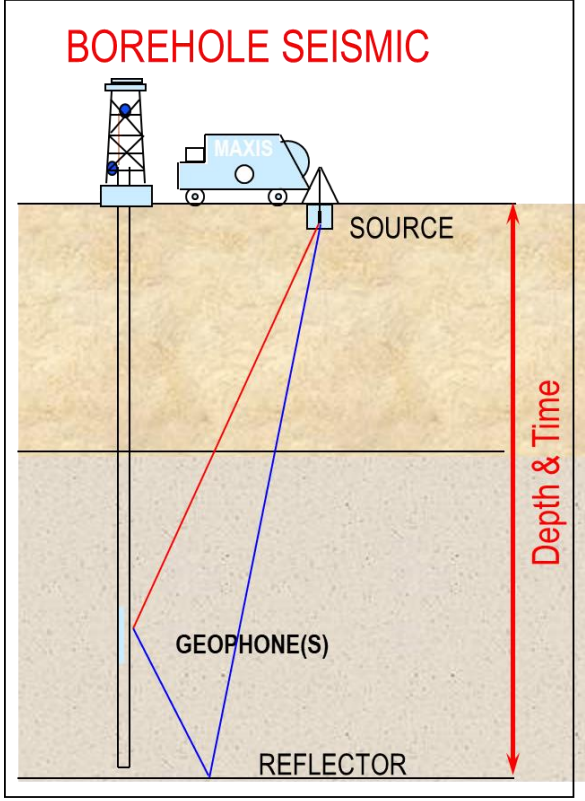
VSP *(5-96 Hz): dz = 14 m*

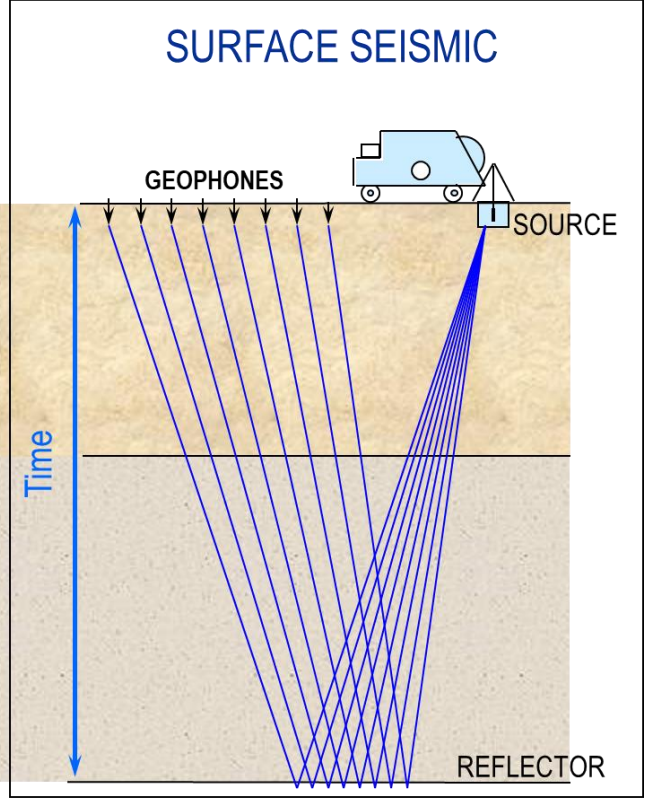
- **The high-resolution VSP image does resolve the 15 m thick sand body**

Borehole vs Surface Seismic

(Liner, 2010)

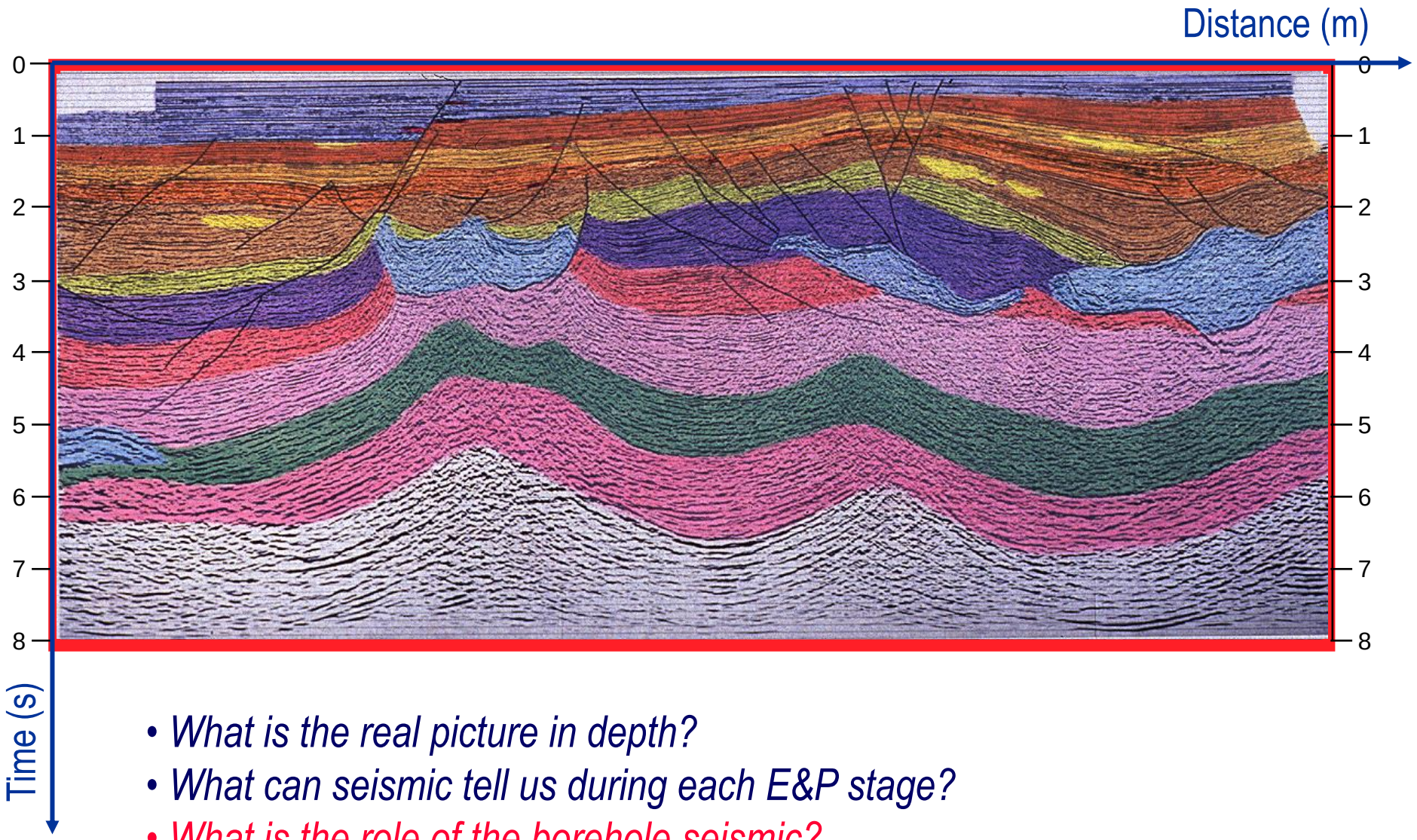






- Borehole seismic measurements are performed in time and in depth
- Nearly one-way seismic paths
- 3C or 4C are standard

Surface seismic section in Time

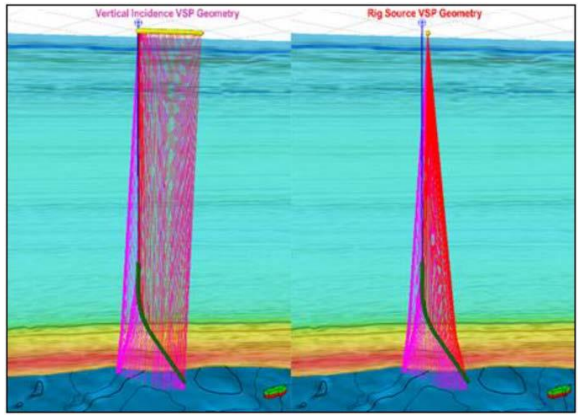


- *What is the real picture in depth?*
- *What can seismic tell us during each E&P stage?*
- *What is the role of the borehole seismic?*

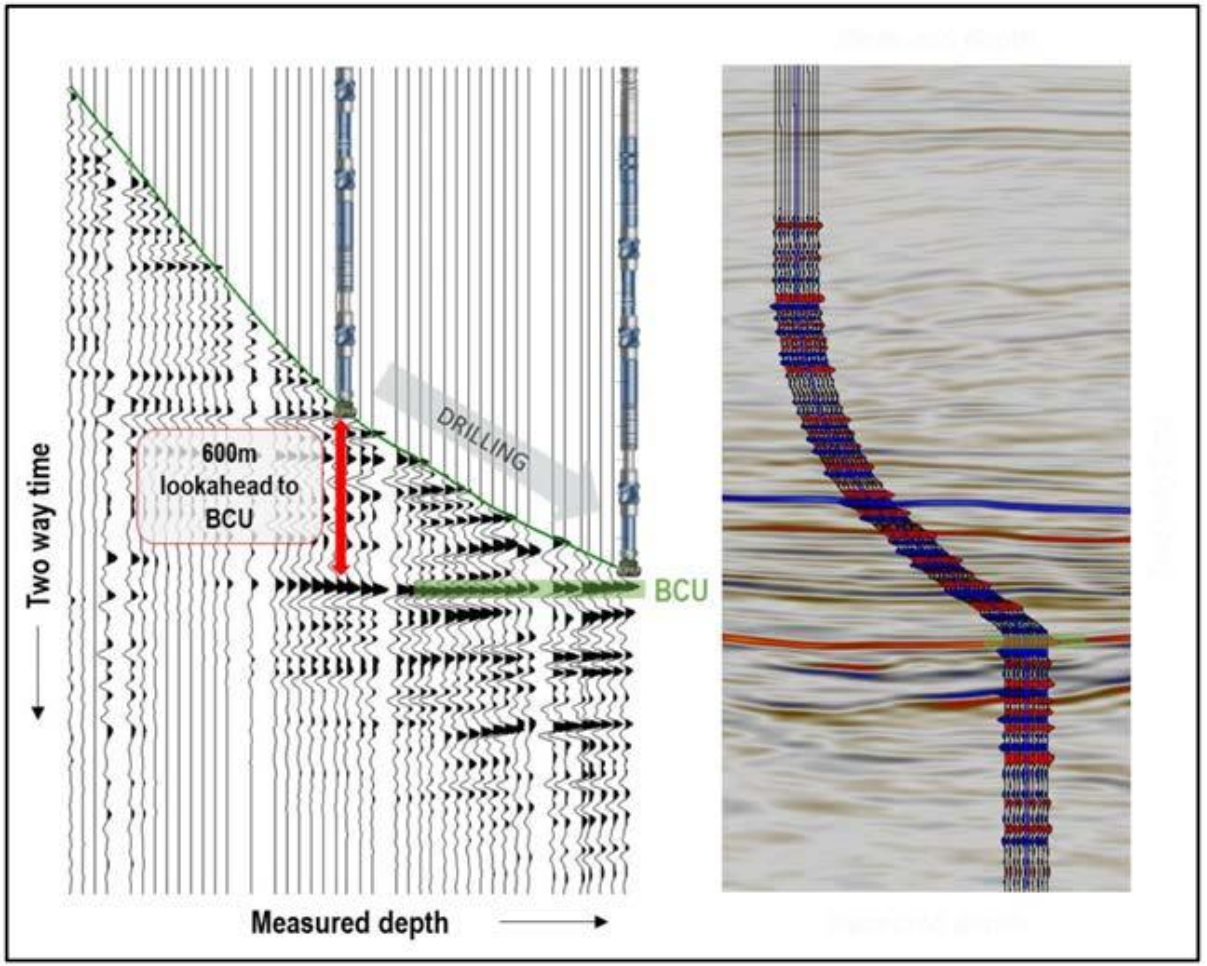
LWD Seismic while drilling & depth prediction ahead of the bit

LWD Seismic tool & Six airgun array

Ray-tracing modelling: *rig source vs VIVSP*

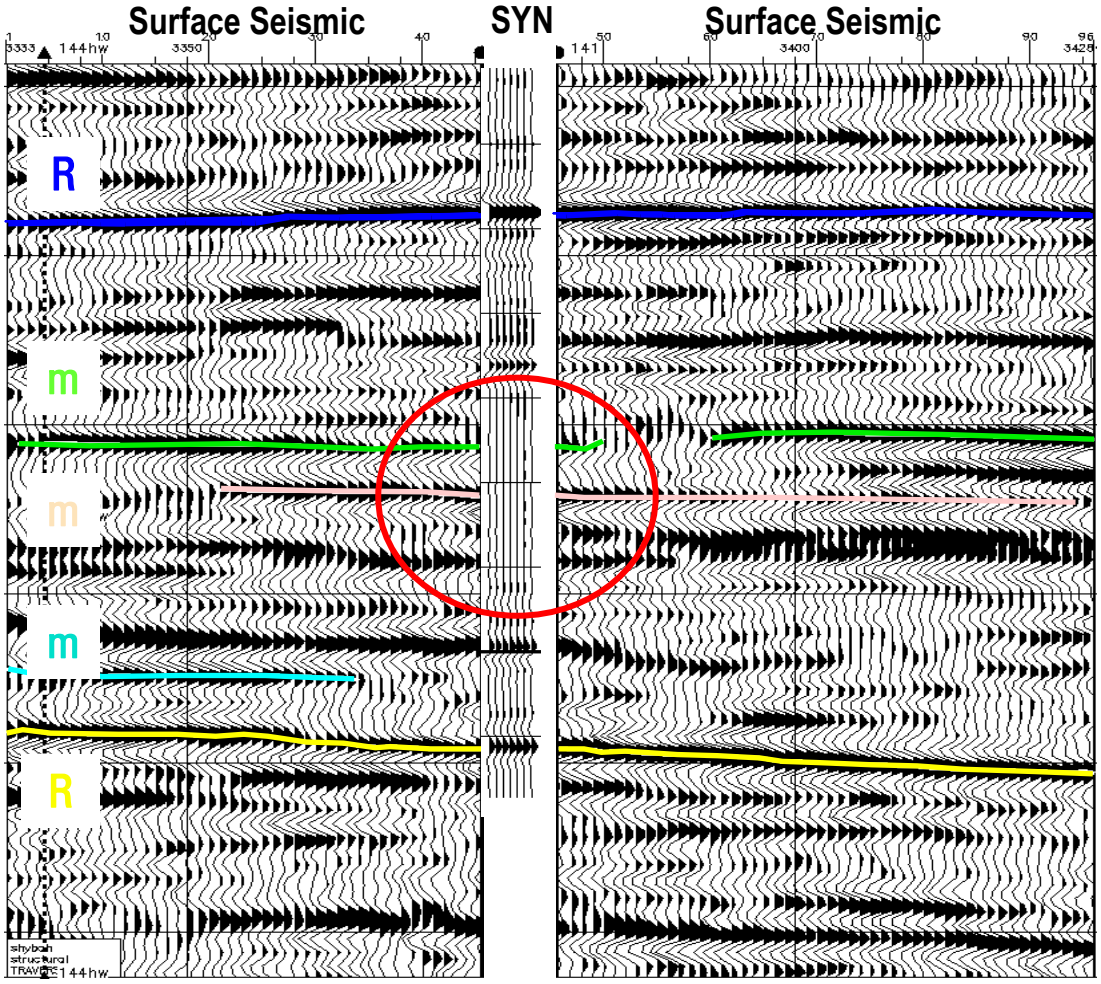


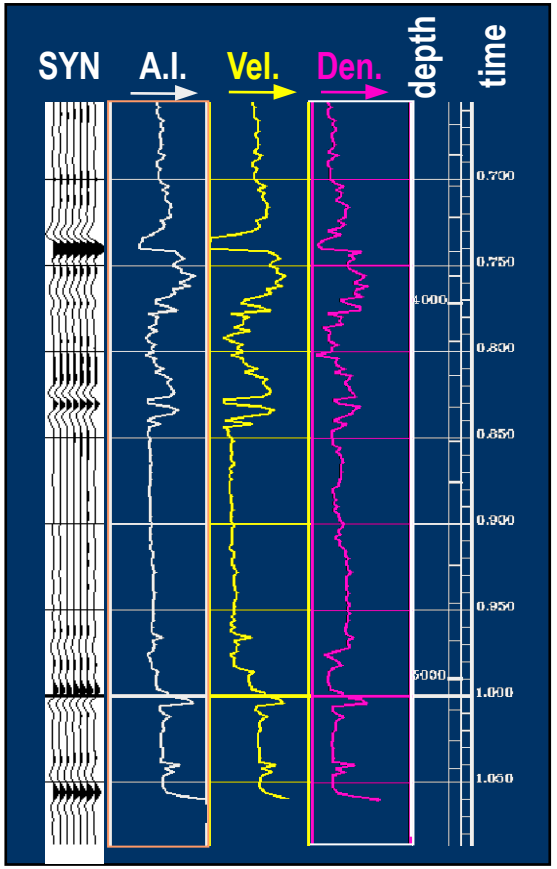
Final lookahead update during drilling



(Kelsall et al., 2020)

Tie Geological Markers

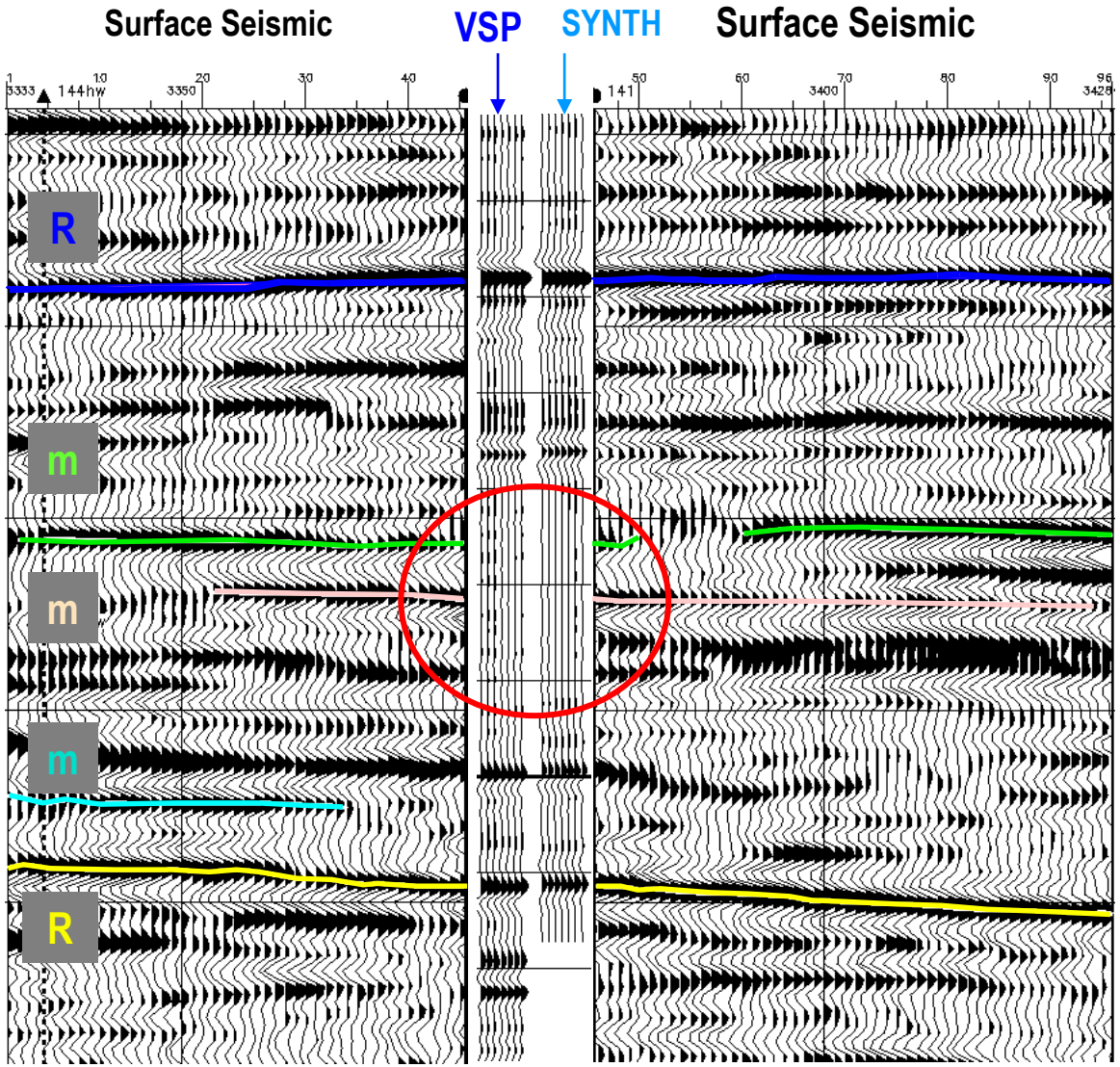




The synthetic does not match. Problem with logs or with seismic?

A successful synthetic match clearly establishes the relationship between the formations drilled and the surface seismic data. The time-to-depth relation has to be established, and the seismic response of the formations has to be determined.

Tie Geological Markers



What does the VSP corridor stack show?

The surface seismic may have multiple contamination problems and in this case, the borehole measurements are correct

Sonic [kHz] vs Seismic [Hz]

Borehole effect on sonic

- Dipole flexural dispersion
- Mud filtrate invasion
- Formation alteration
- Near-wellbore stresses
- Hole shape, caves, etc.

Different ray paths

- Sonic usually travels along the borehole
- VSP/Seismic depends on S-R geometry

Rock frequency dispersion

- Effect of layering (Backus averaging)
- Partially saturated rocks
- Attenuation anelasticity

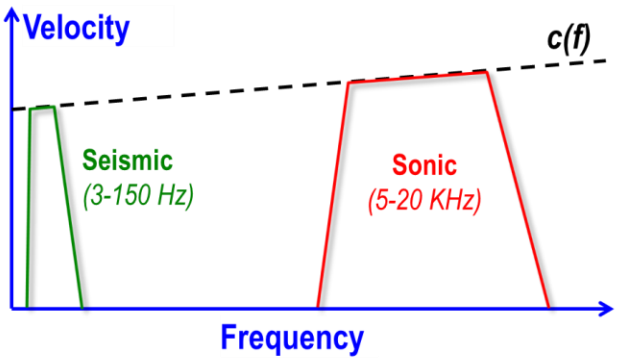
Different resolution

- Different depths of investigation and different resolutions (~ 2 ft vs ~10 m)

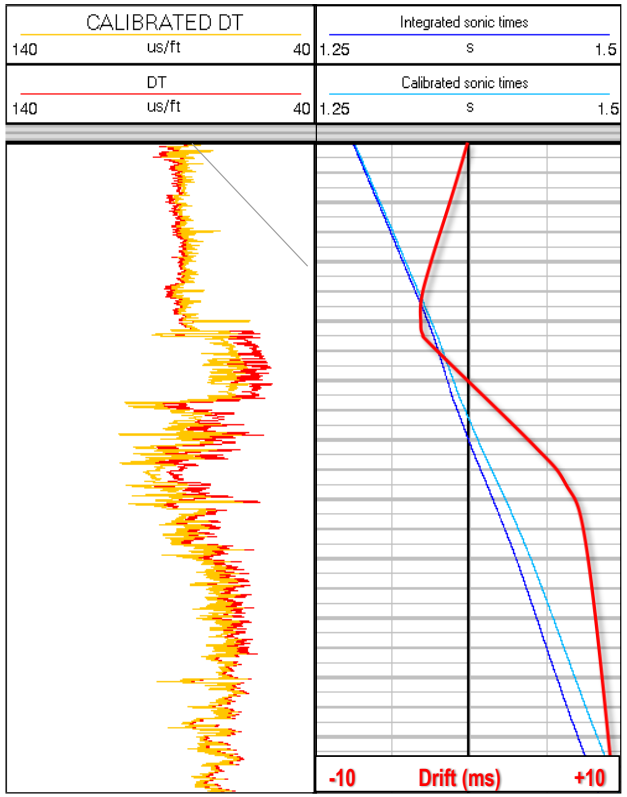
Frequency differences: *sonic vs seismic*

1) Velocity dispersion

$$c(f_2) = c(f_1)\left[1 + \frac{1}{\pi Q}\ln\left(\frac{f_2}{f_1}\right)\right]$$ ***Kolsky-Futterman (KF) model****



Sonic calibrated with VSP



Numerical examples:

f1 = 40Hz; f2 = 8000 Hz

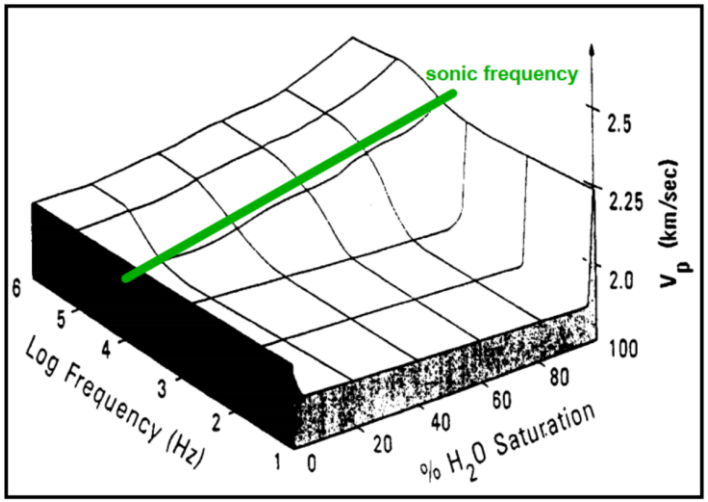
Q=30: $C_2 = C_1 * 1.056$ **(+6%)**

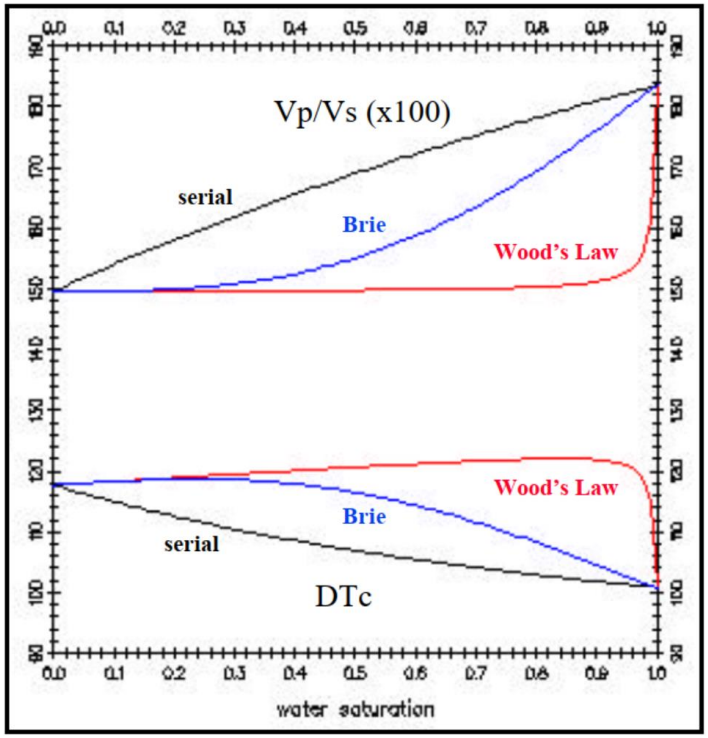
Q=50: $C_2 = C_1 * 1.034$ **(+3%)**

Q=100: $C_2 = C_1 * 1.017$ **(+2%)**

Q=150: $C_2 = C_1 * 1.011$ **(+1%)**

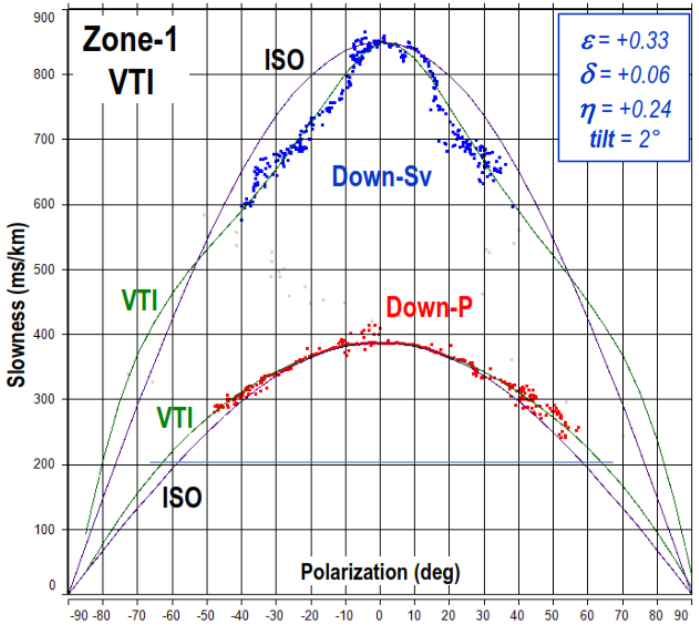
2) Partial gas saturation

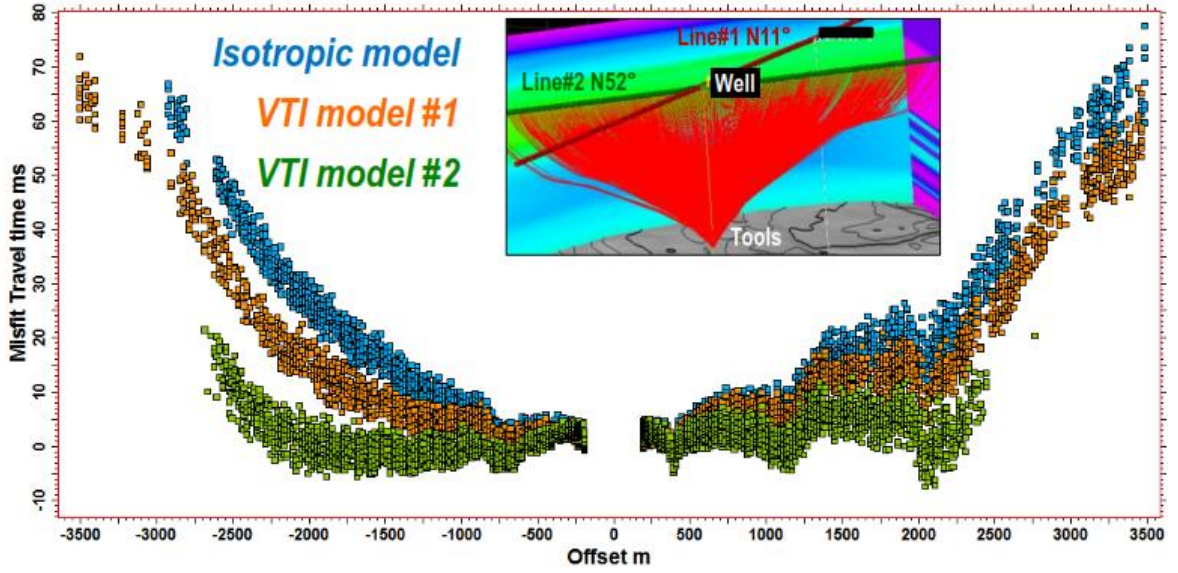


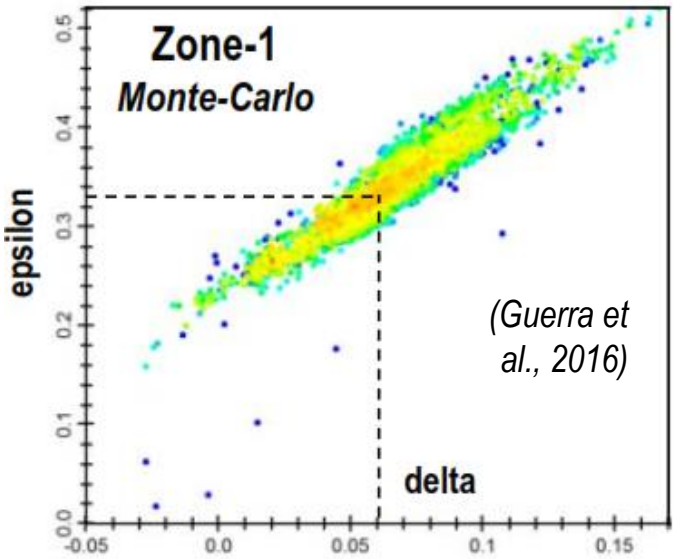


(Murphy et al., 1993)

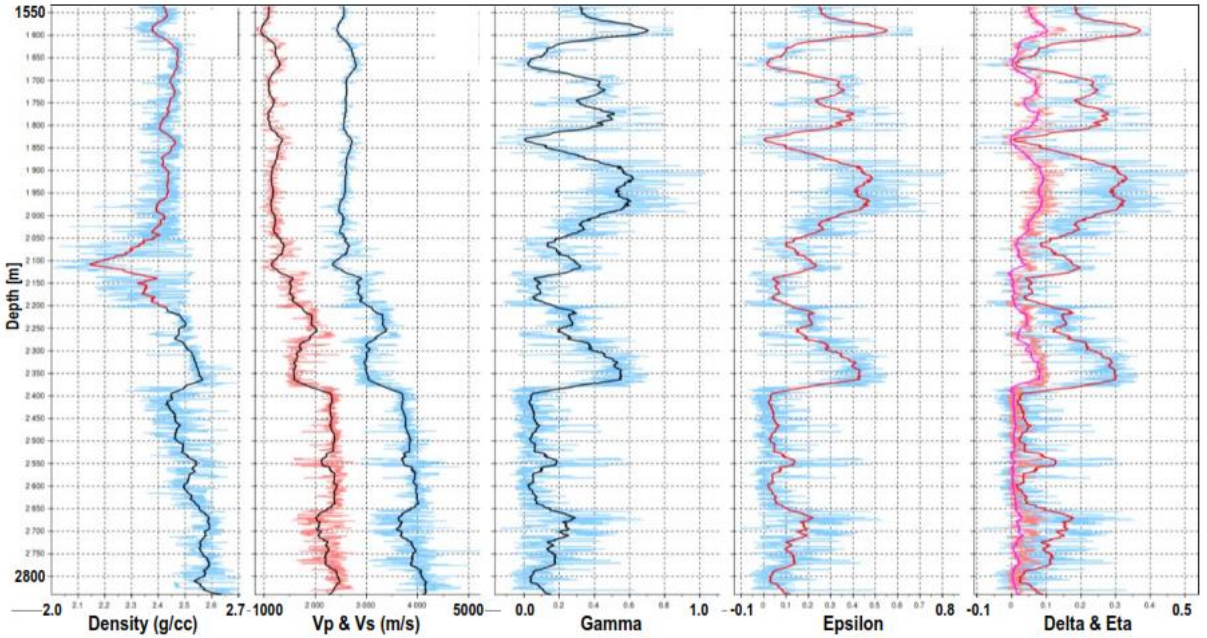
Advanced Sonic & Walkaway VSP for TTI anisotropy





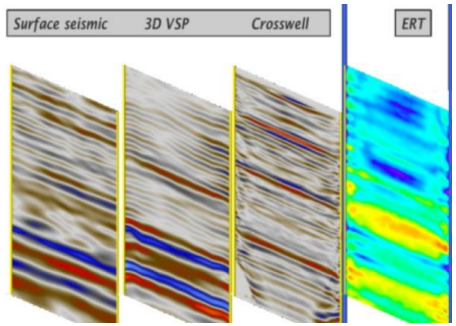


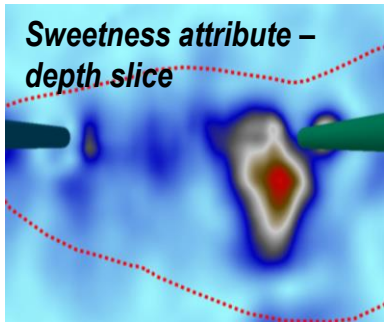
(Guerra et al., 2016)



Downhole acoustic monitoring

(Tøndel et al., 2013)

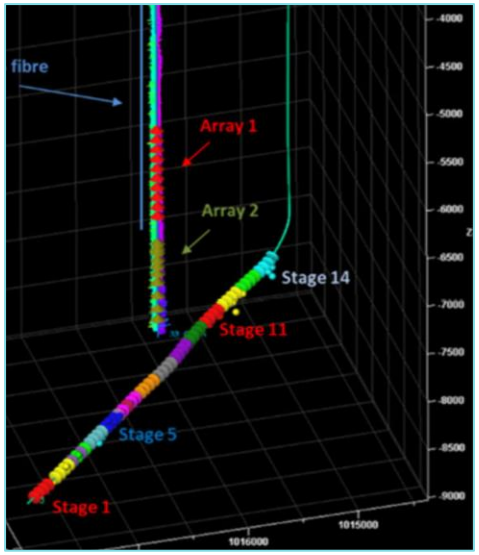


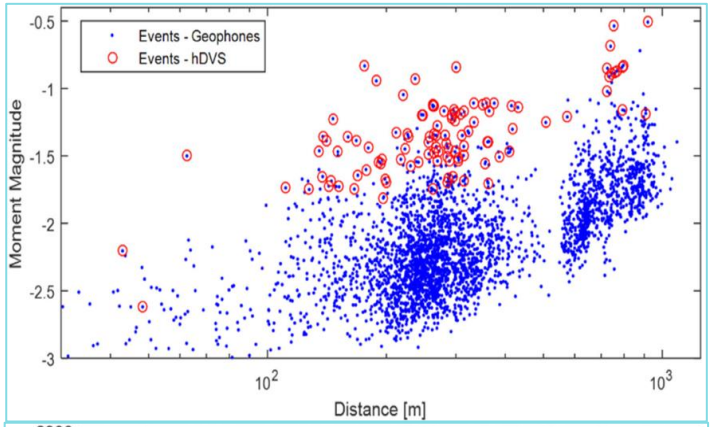


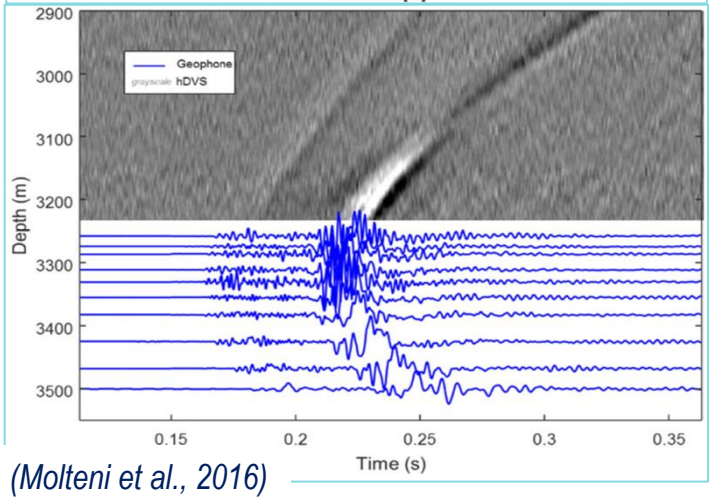
SAGD project

Time-lapse 3DVSP using cemented geophones

Cemented DAS fiber vs 3C-geophones µseismic

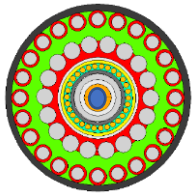




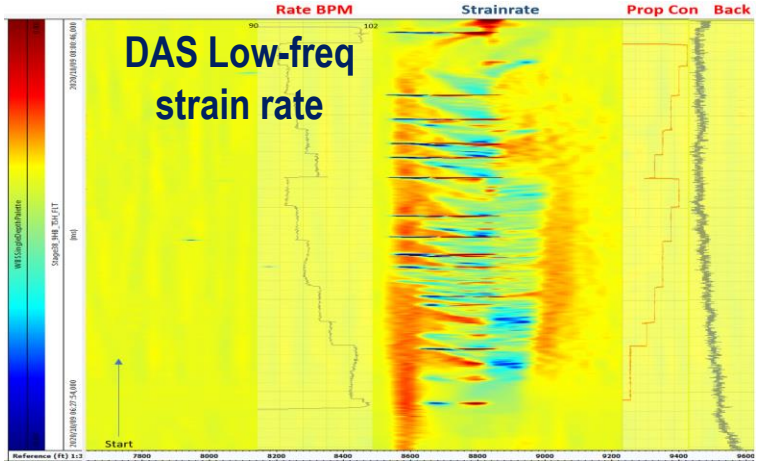


(Molteni et al., 2016)

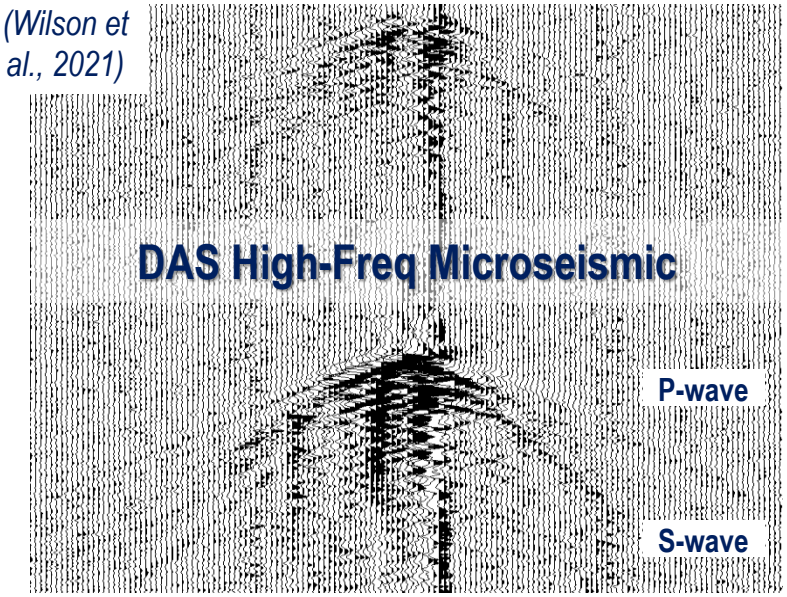
Coaxial hybrid cable



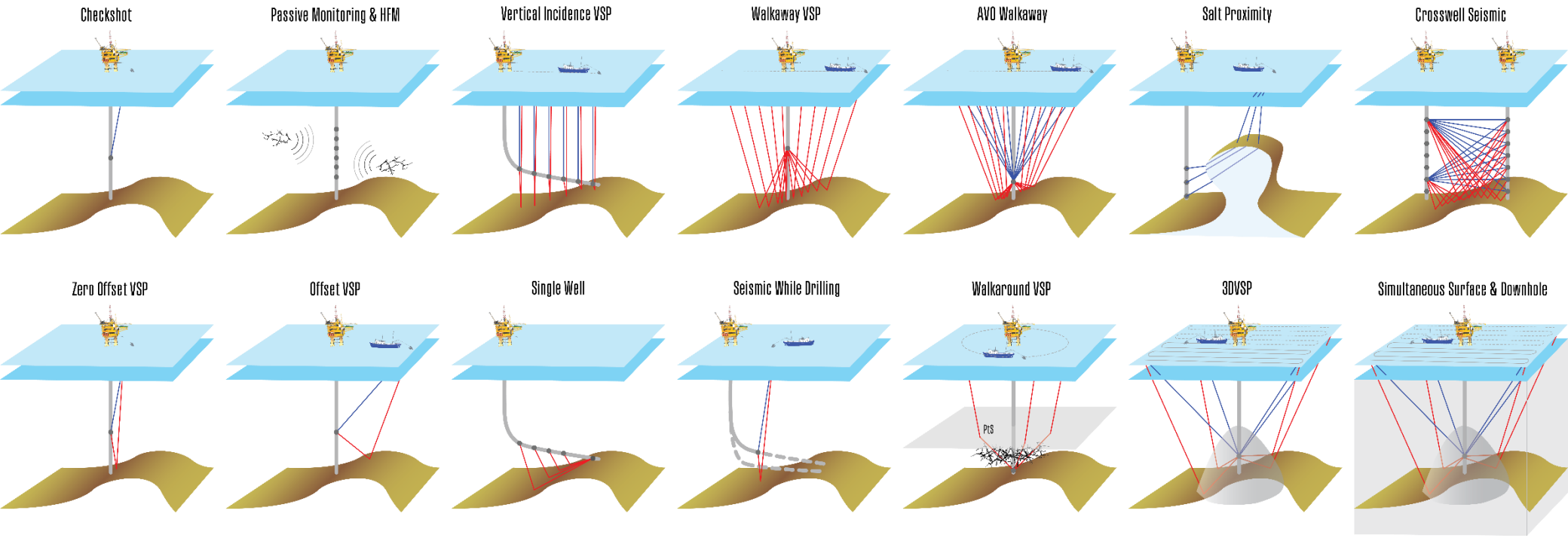
Cable pumped down in horizontal well
Fracking occurring in neighbor well



(Wilson et al., 2021)

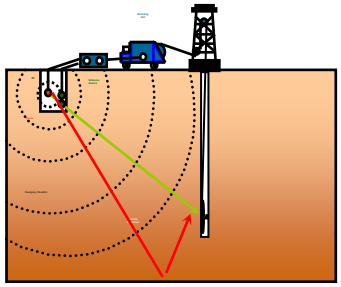


Borehole Seismic Survey Types

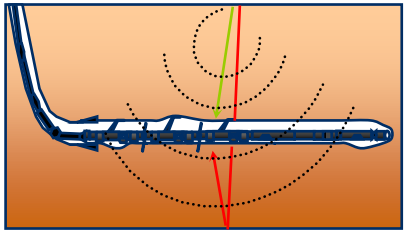


(Bettinelli, 2020)

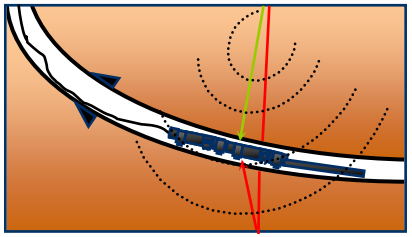
Borehole Seismic Conveyance



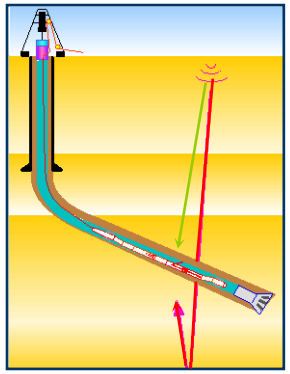
Conventional wireline



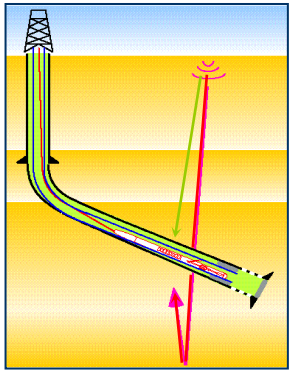
Drill-pipe conveyed (TLC)



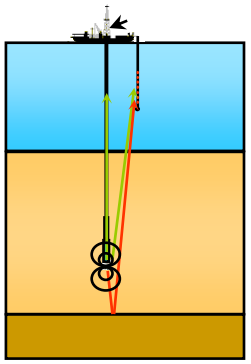
Well tractor



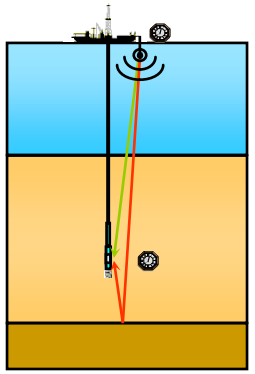
Thru-drillpipe seismic



Thru-tubing



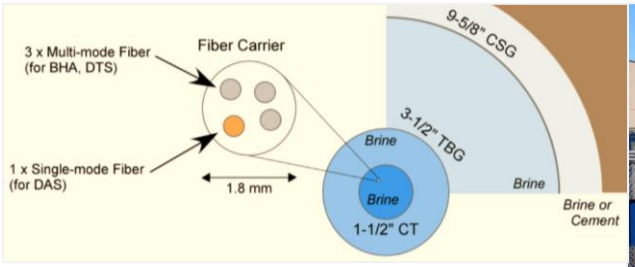
Drillbit seismic



LWD Seismic

DAS acquisition

Fibers strapped to tubing or cemented behind casing

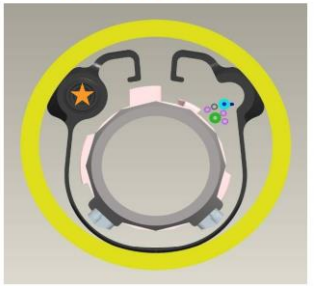


Coiled tubing

Perment

4C sensors, Analog, Part of tubing completion

Released state

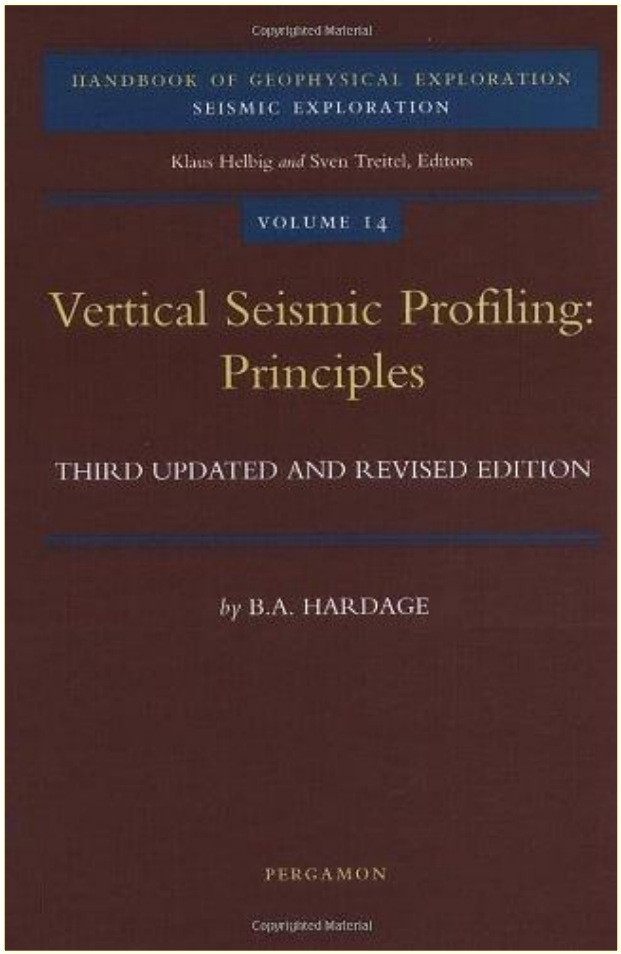


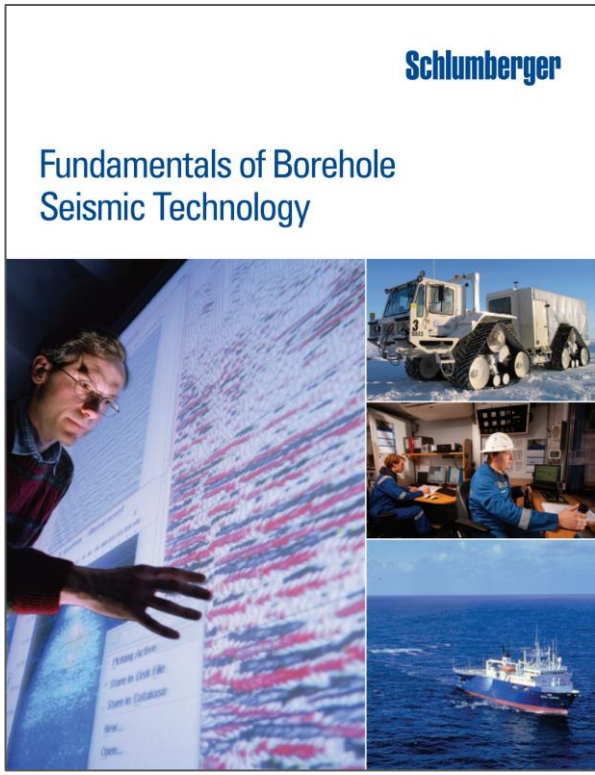
Borehole Seismic Advantages – *Summary*

- **Measurement in time & depth** → *tie well depths to seismic times*
- **Quite downhole environment** → *very high SNR datasets*
- **Shorter travel paths** → *less attenuation / wider bandwidth (resolution)*
- **True amplitude, phase and multiples free** → *advanced seismic calibration*
- **Identification of key seismic multiples generators** → *multiples studies*
- **Insitu property measurements** → *Vp/Vs, Q-factor, anisotropy*
- **Unique geometry** → *illuminate steep surfaces/faults, overhangs, etc.*
- **3C/4C measurements** → *rich wavefields (P & S); S-wave processing is standard*
- **S-wave birefringence** → *fractures direction and density*
- **Lookahead/Lookaround** → *sole log capable of looking ahead or around 100's of meters*
- **Real-time LWD VSPs** → *drilling assistance*
- **Fast fibre optics** → *efficiently record large datasets (1C DAS and/or 3C optical point sensors)*

Borehole Seismic Books

- Two references on borehole seismic principles and applications but not covering DAS yet - *Distributed Acoustic Sensing*
- Schlumberger book available as PDF (free). Printed book can be ordered





https://www.slb.com/resource-library/book/fundamentals-of-borehole-seismic-technology-overview

Acknowledgments

- Thanks to Thor Allan Garden (Equinor) for suggesting that we present this course at NPD FORCE.

- Thanks to the NPD FORCE Geophysical Methods Group and Schlumberger for the opportunity to present this course.