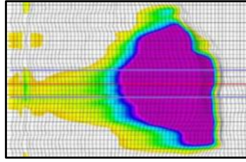
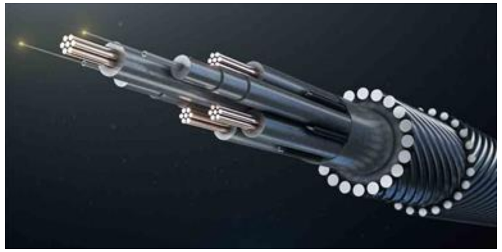
NORWEGIAN PETROLEUM DIRECTORATE
50 years

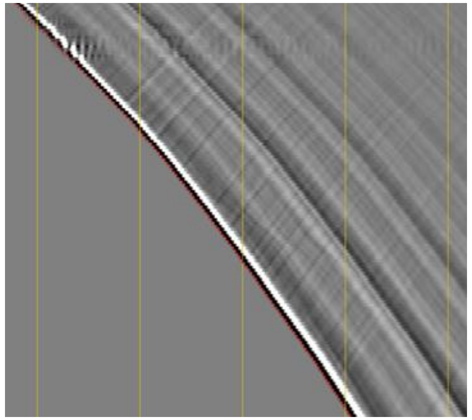
FORCE



NPD FORCE Geophysical Methods Group

Data acquisition technology on wireline & fiber optics





By: Rafael Guerra (Domain Center Geophysicist)

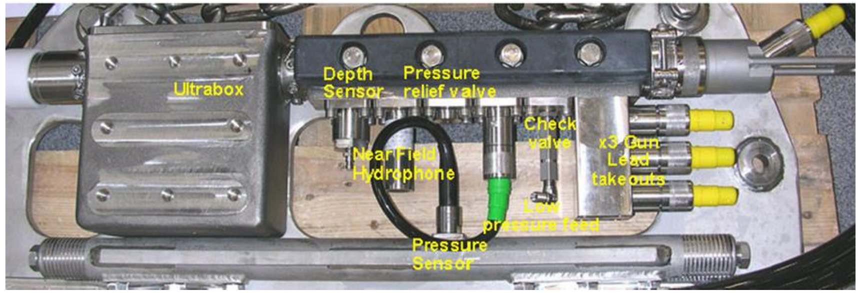
Schlumberger

Stavanger, 04-Oct-2022

Marine VSP Sources & In-sea gun controller

Airgun source controller

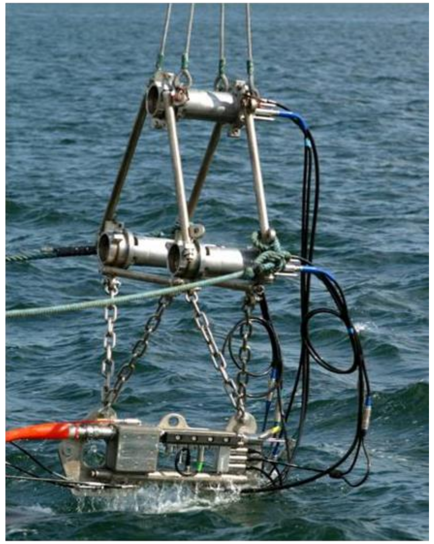
- In-sea, digital transmission
- Calibrated hydrophone
- Pressure sensor
- Remote monitoring & recording of source depth & pressure
- Depth sensor safety feature (shuts controller down < 2 m)

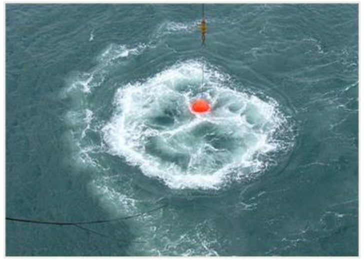


→ **+/- 0.5 ms tuning accuracy** → **Time-0 when guns fired**

→ **Near field hydro** *(far field sig estimation, source signature deconvolution)*

Triple G-Guns 3x250 in^3





Six G-guns 3x250 + 3x150 in^3

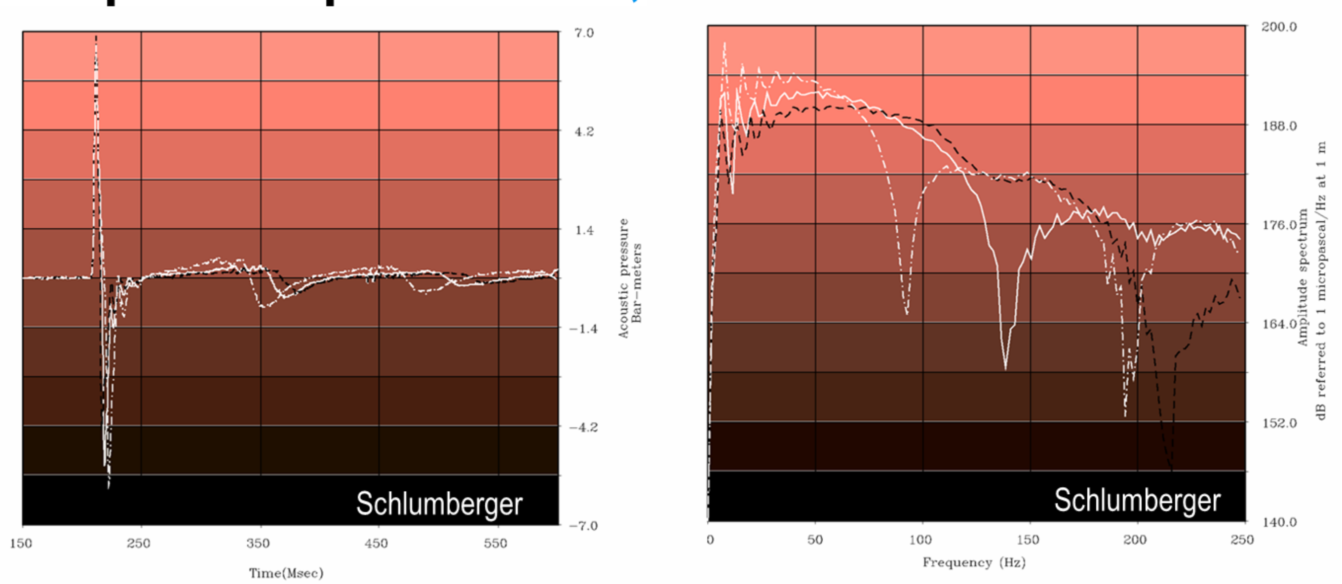
Airguns Strength or SNR

(simplified):

$$\approx \boldsymbol{N_{guns}} * P^{\frac{3}{4}} * V^{\frac{1}{3}} * \sqrt{\boldsymbol{N_{shots}}} * \boldsymbol{g(z)}$$

(*) The gun depth g(z) impacts energy level over seismic bandwidth

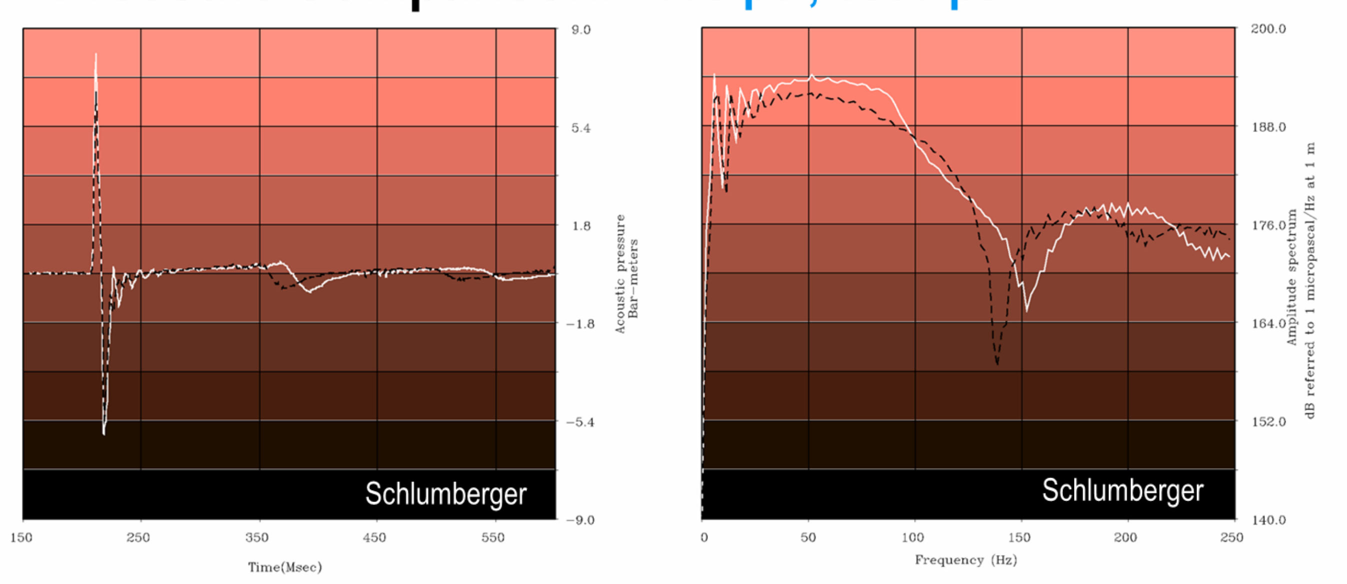
Depth Comparison: 3 m, 4.5 m, 7 m



Gun depth impacts:

- Low frequency amplitude
- Ghost notch frequency
- Bubble period

Pressure Comparison: 2000 psi, 3000 psi



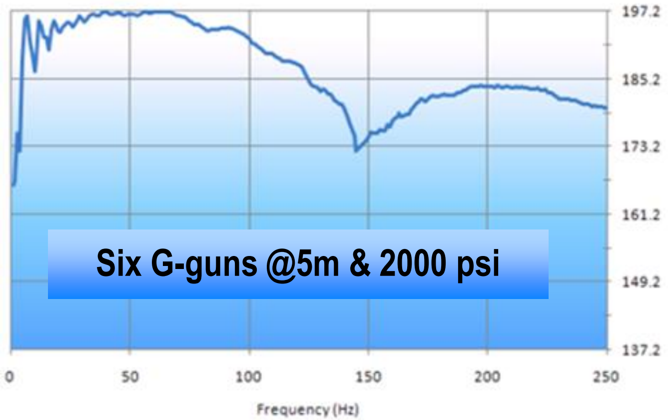
Gun pressure impacts:

- Amplitude
- Bubble period

***NB:** ghost notch frequency should not change but experiment in Norway's Fjord saw water velocity changing due to aeration effects*

Example of Walkaway/Walkabove VSP Equipment

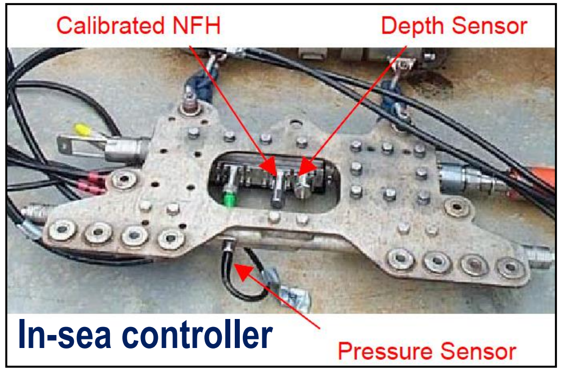
6 guns, 1200 in3



Peak-to-Peak Amplitude = *23 bar-m*

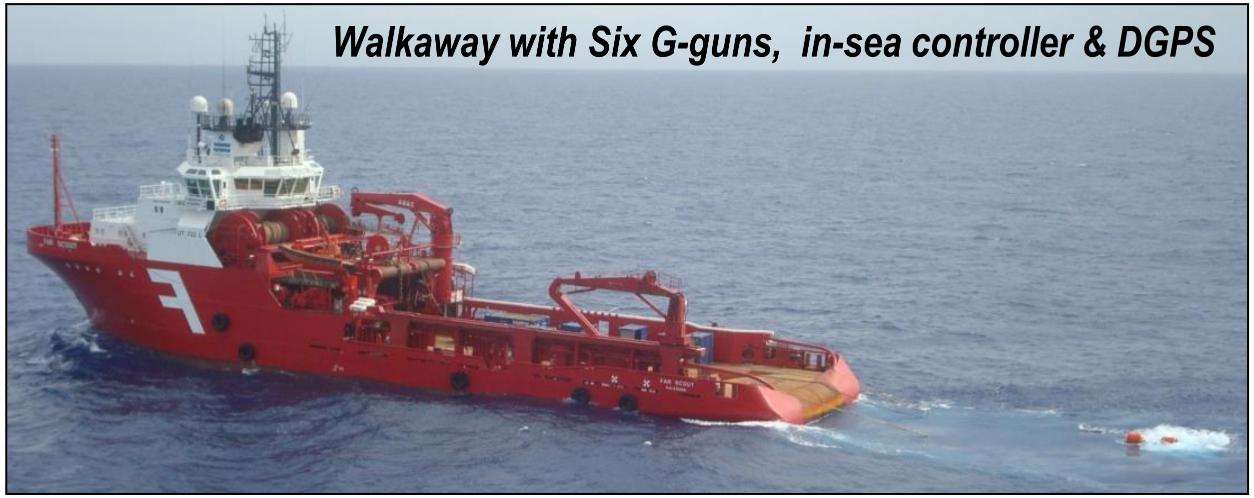
SEL = *220 dB re 1 μPa²s @1m*

0-Peak SPL = *238 dB re. 1 μPa @1m*



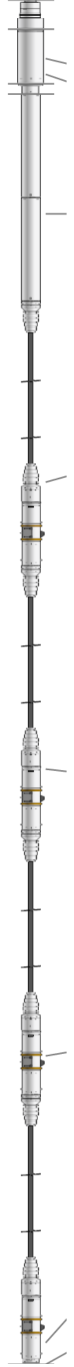
- *Synchronization +/- 0.5 ms*
- *Source signature (16 bits)*
- *Gun depth & pressure at every shot*

125 SCFM Compressor and/or gas quads



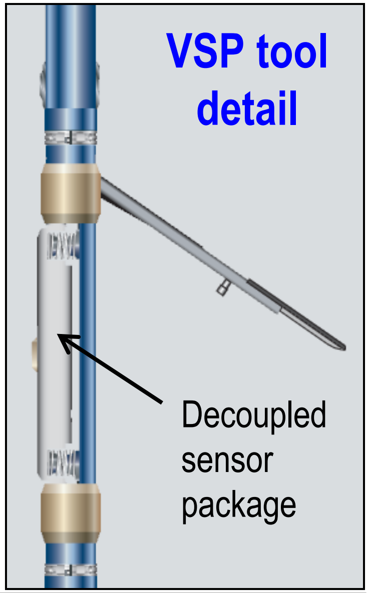
DGPS positioning

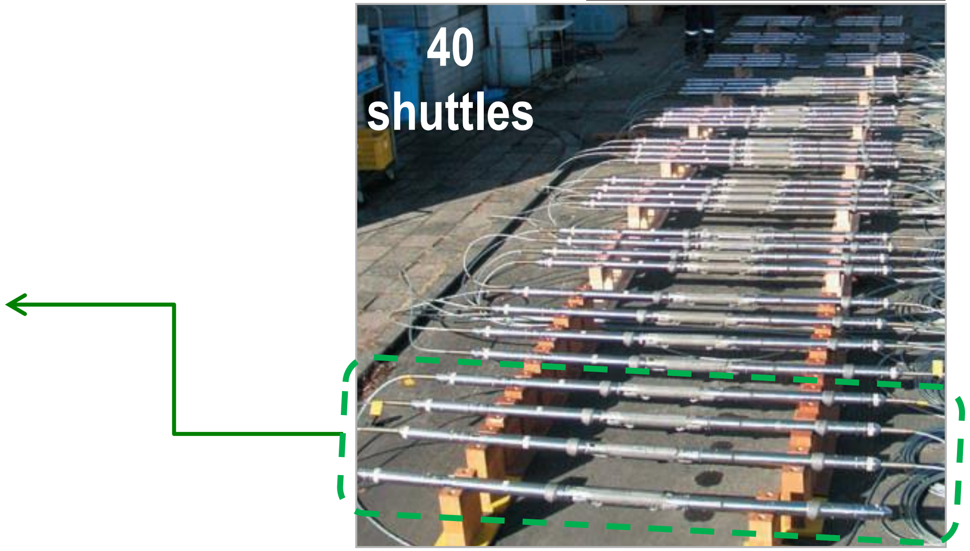
VSP tools

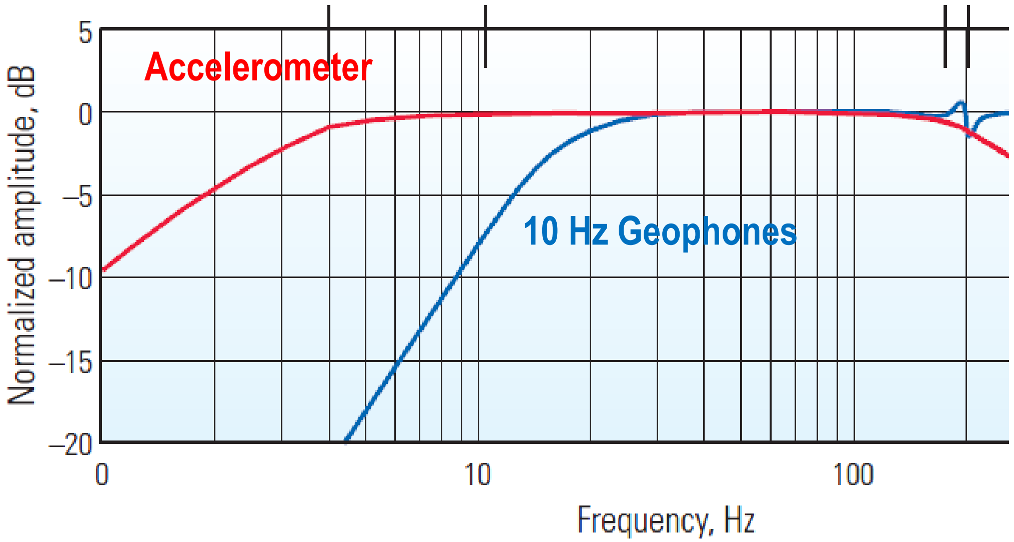


Standard spacing = 15 m

But 7.5 m spacing
sometimes requested

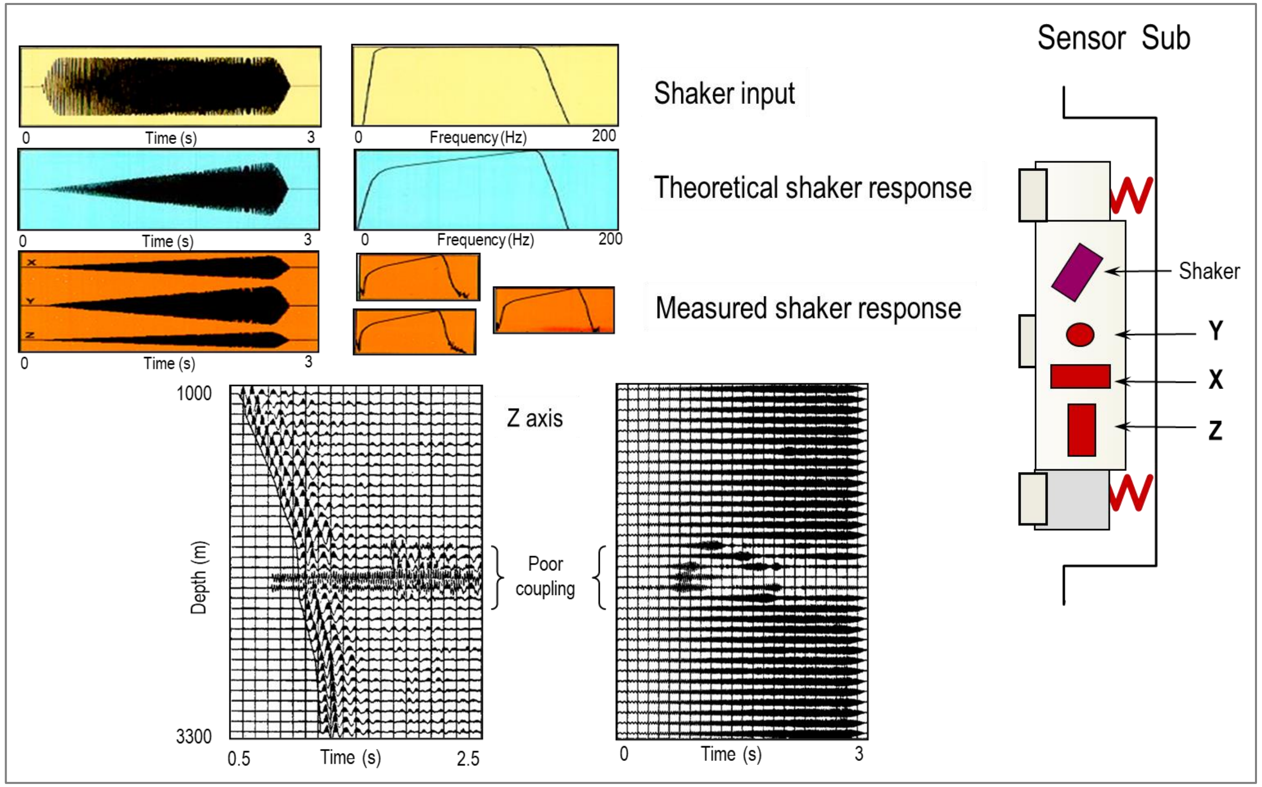




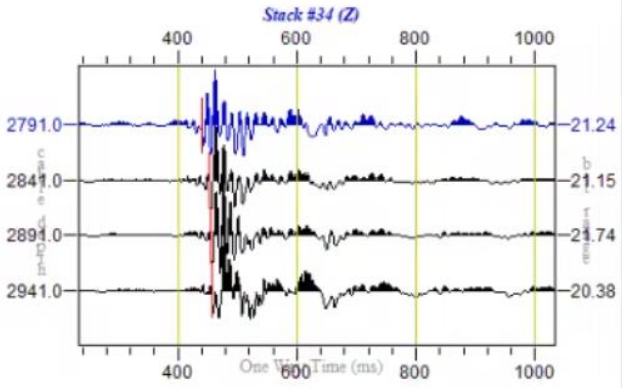


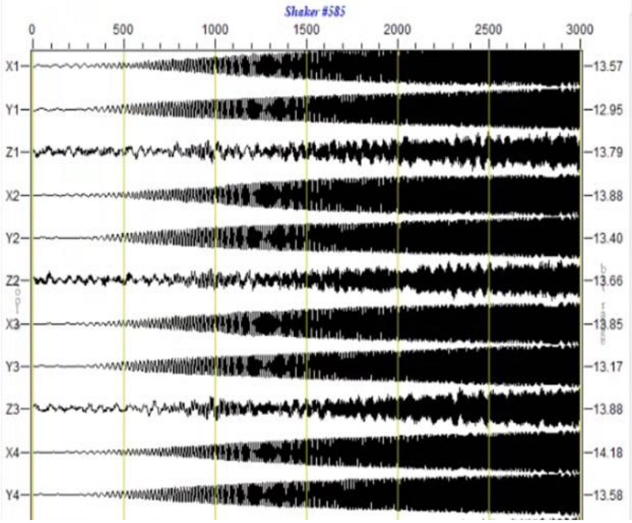
- *1 to 40 shuttles (anchors by sets of 4)*
- *4 shuttles record about 40 levels per hour*
- *3-Component GAC accelerometers (2-200Hz)*
- *24-bit downhole ADC*
- *Tmax = 175°C, Pmax= 20,000 psi, 2.9” to 30” hole sizes*
  *→ **HPHT version up to 4 tools** : 260°C and 30,000 psi*
- *Decoupled sensor package → less tube wave sensitivity, TLC, etc.*

Coupling quality assessed with Shaker Test

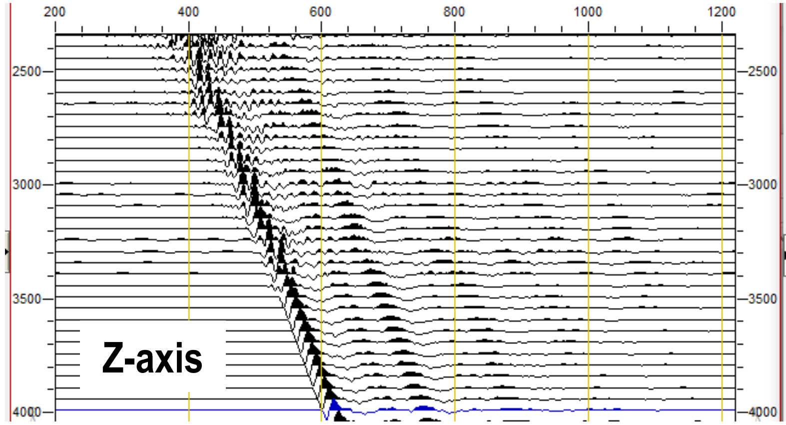


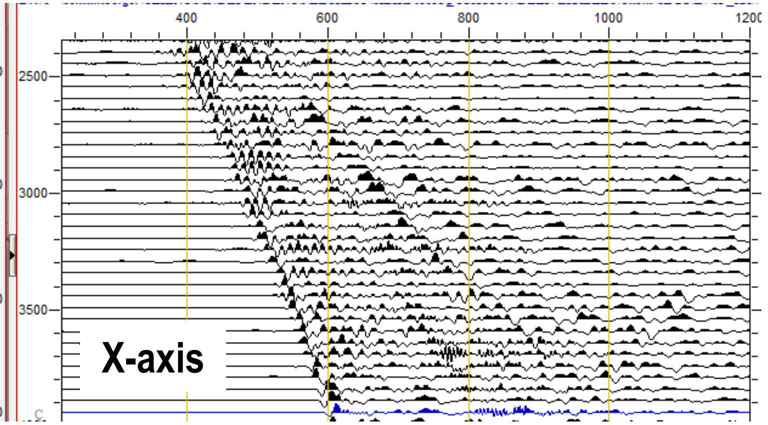
Example-1:





→ A QC tool for non-cemented/casing ringing intervals or rugous/caved intervals

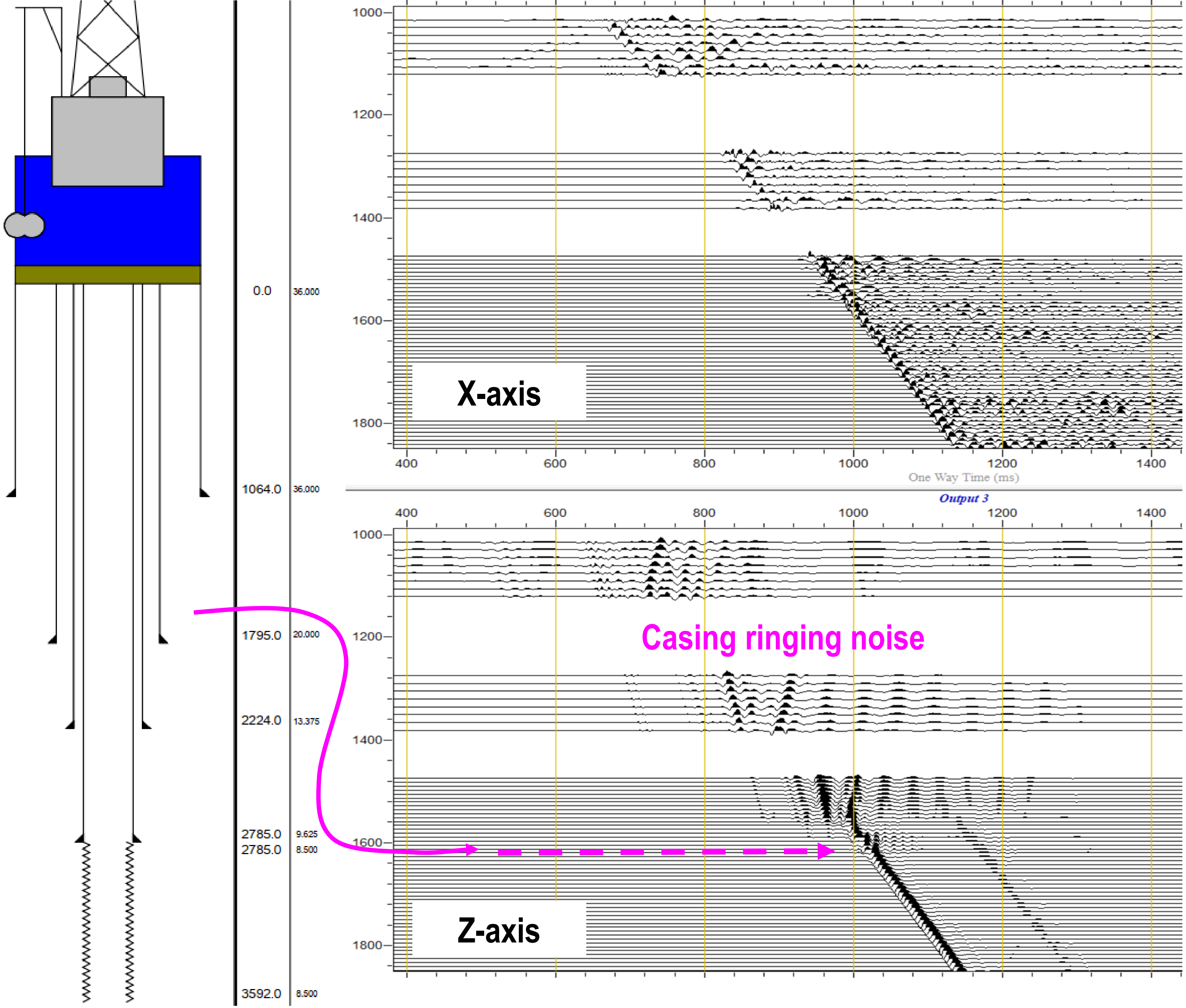




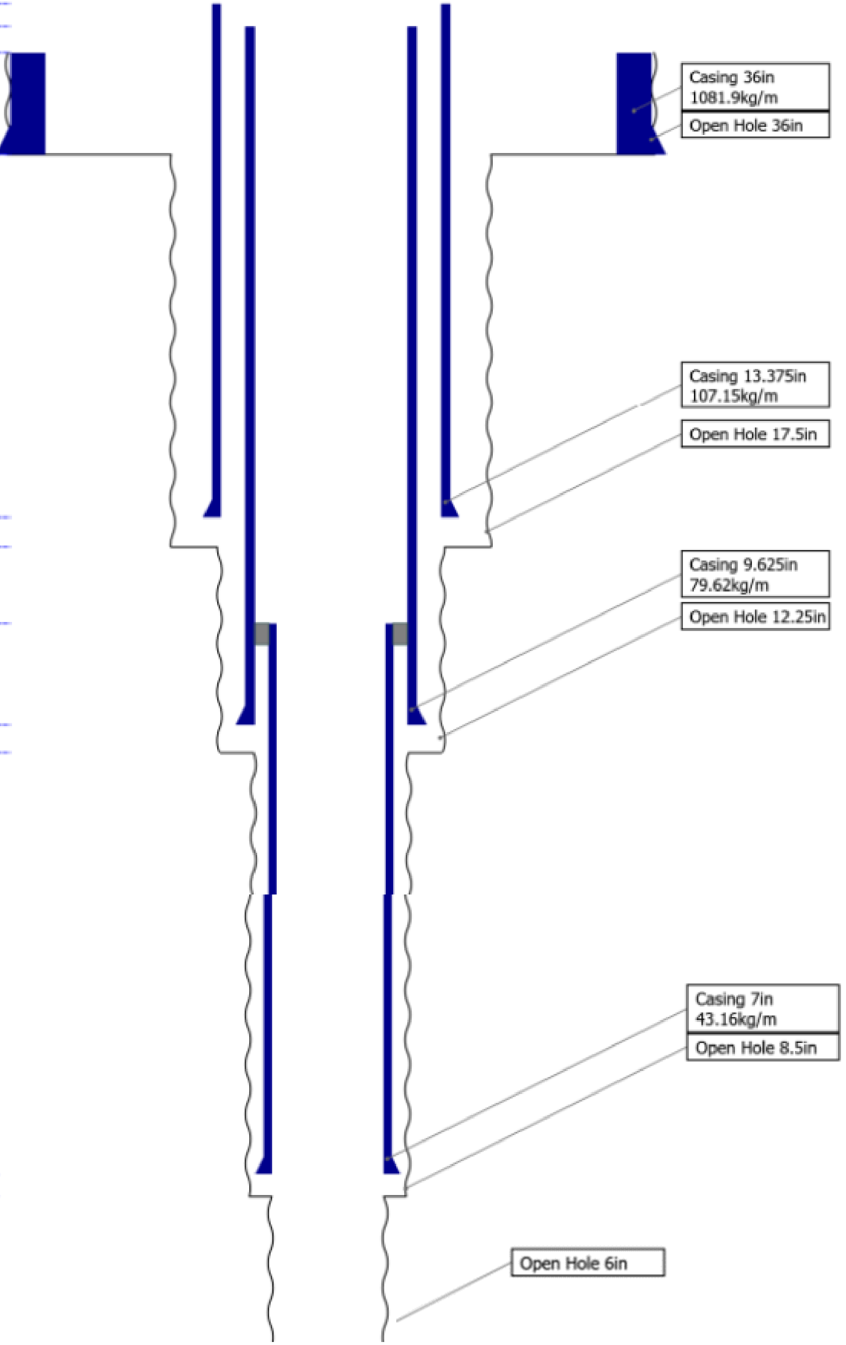
ZVSP with 8 shuttles

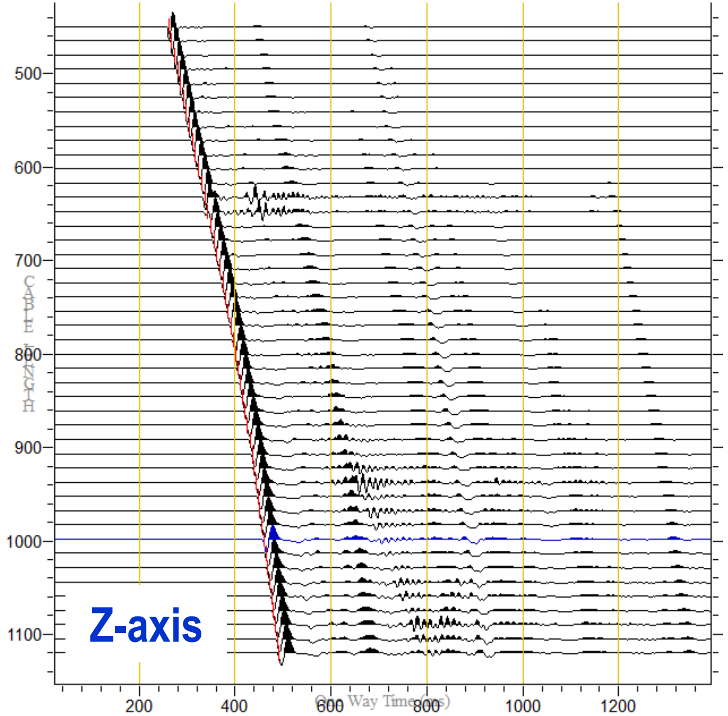
Vertical well

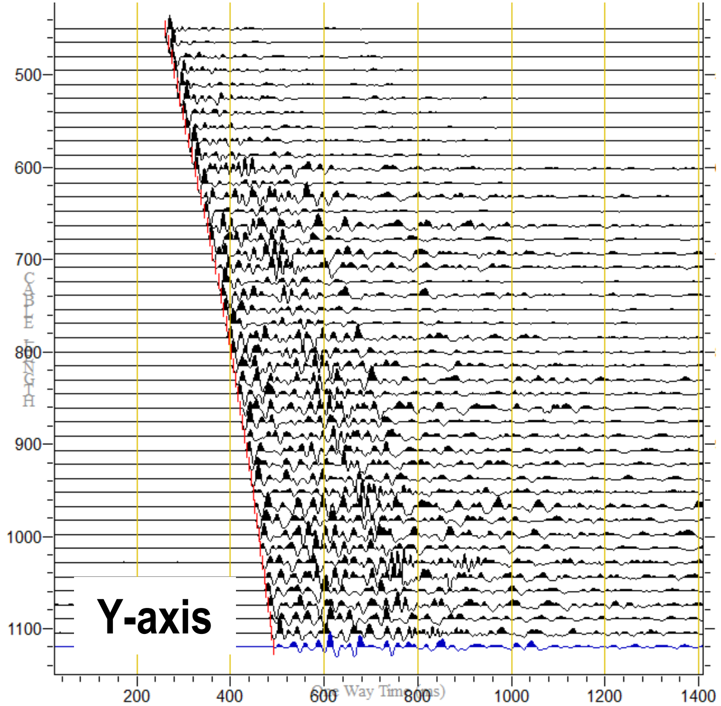
Example-2:



- 3C
- Airguns
- Nearly vertical
- 2, 3, 4 casings

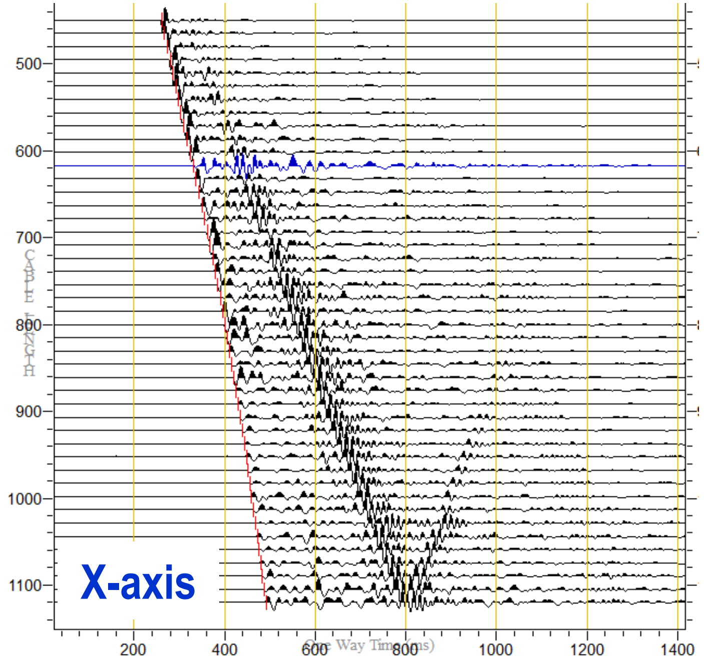






Example-3:

- 4 shuttles (3C)
- Airguns
- Vertical well
- OH and multiple casings



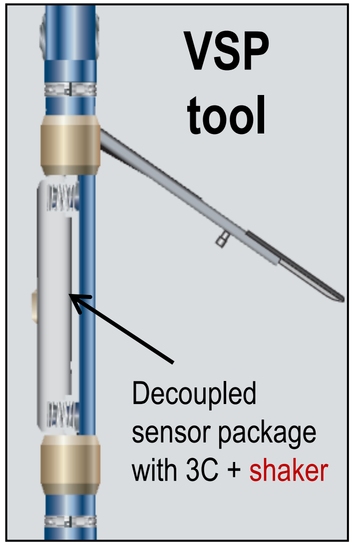
Tube wave noise

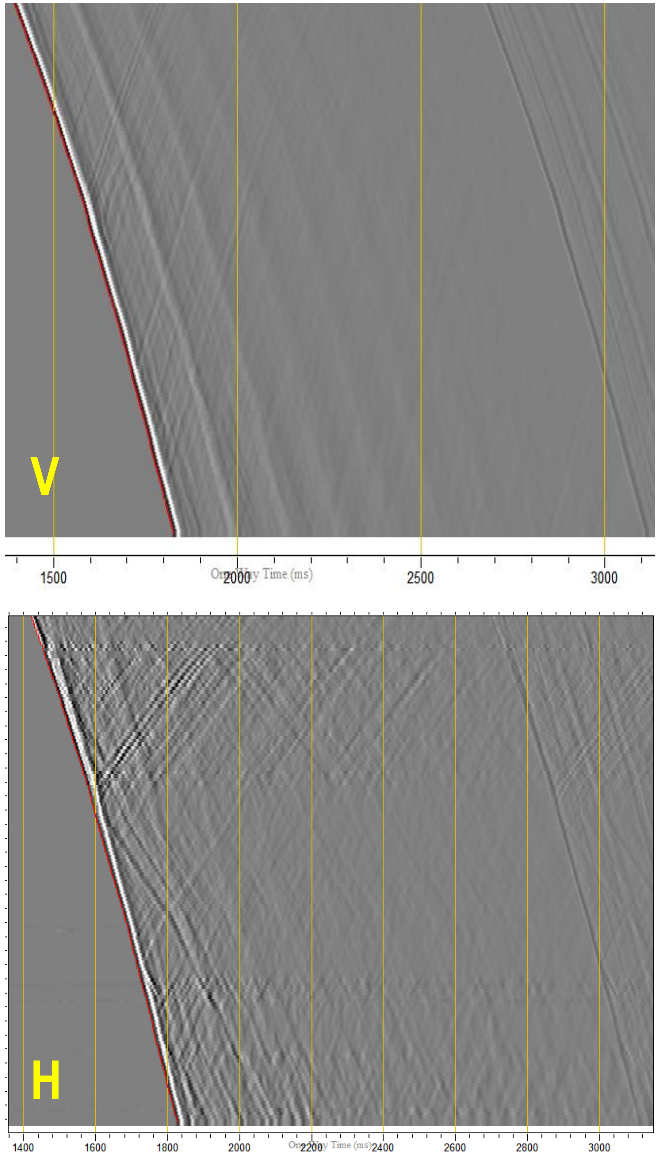
Fundamentals of Borehole Seismic Technology *(Kelsall, Rufino & Guerra, SLB 2022)*

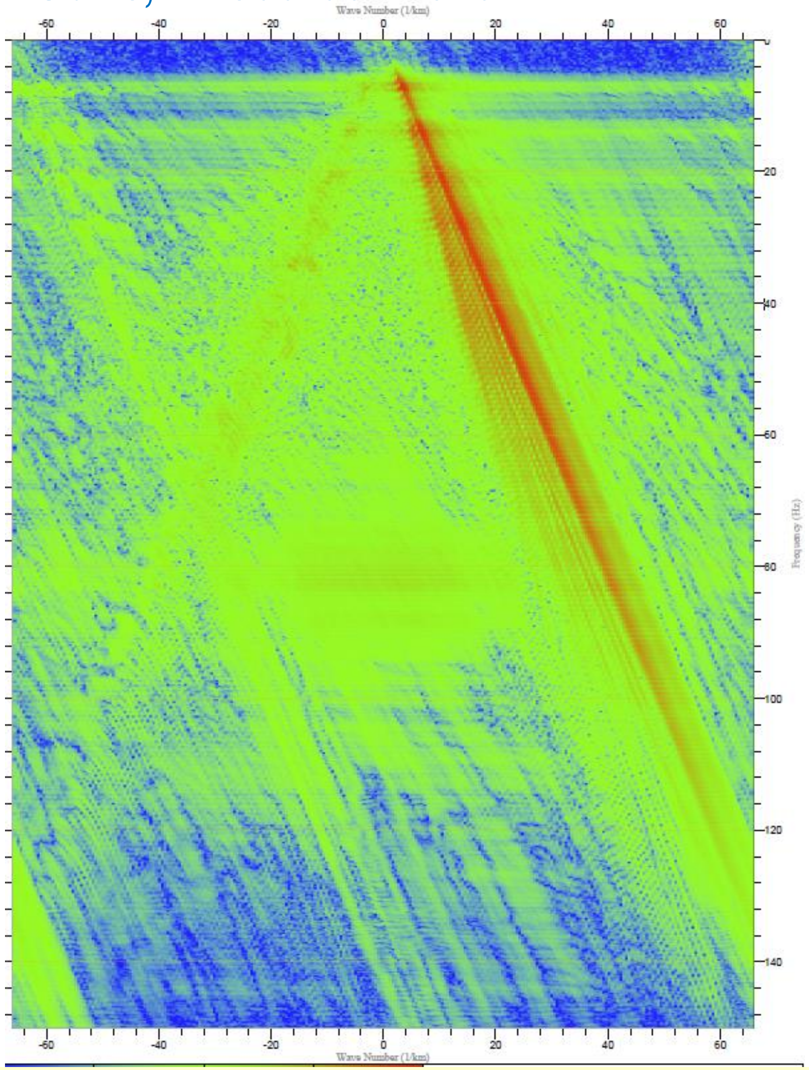
Example of VSP data quality in 3-km deep well

8 shuttles interleaved @7.5 m, Triple G-Guns, In-sea controller

Example-4:



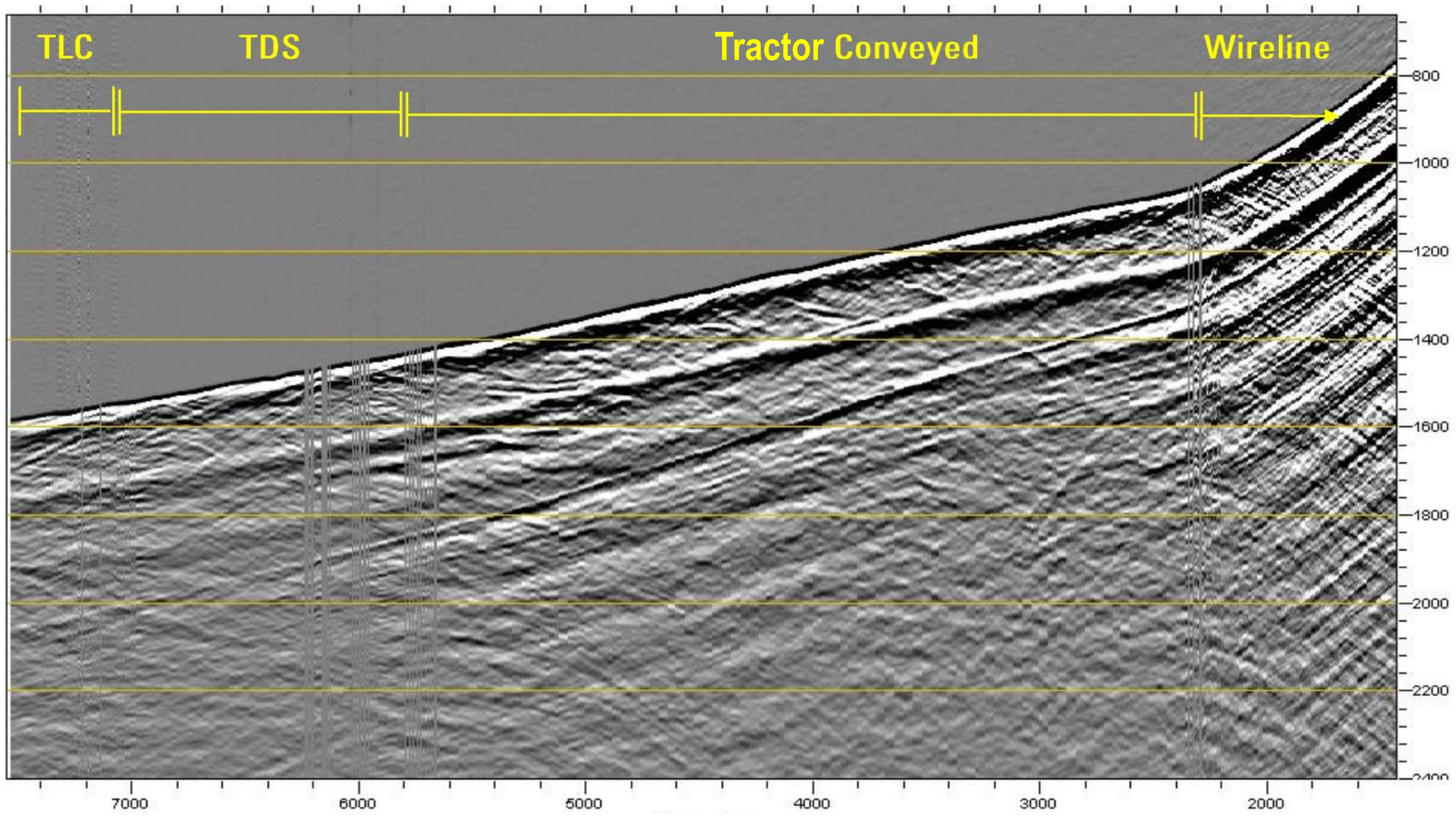




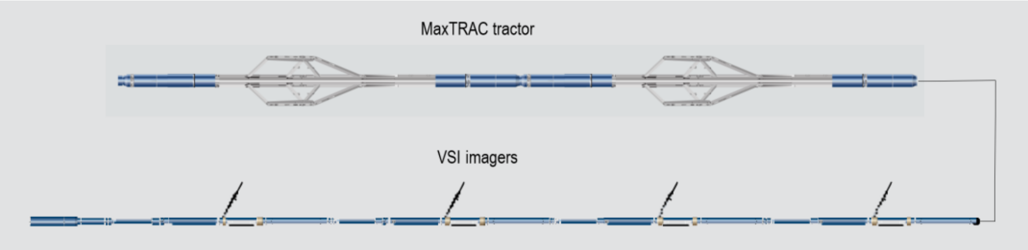
→ **Stronger sources available for deeper targets and/or broadband applications**

Walkabove VSPs: *VSP geophone tool data quality for 4 types of conveyance*

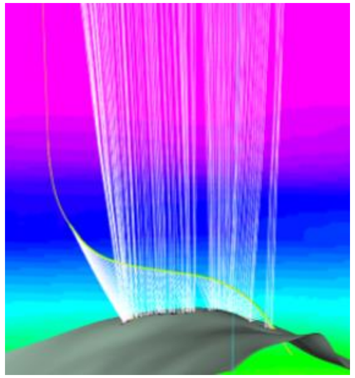
Example-5:



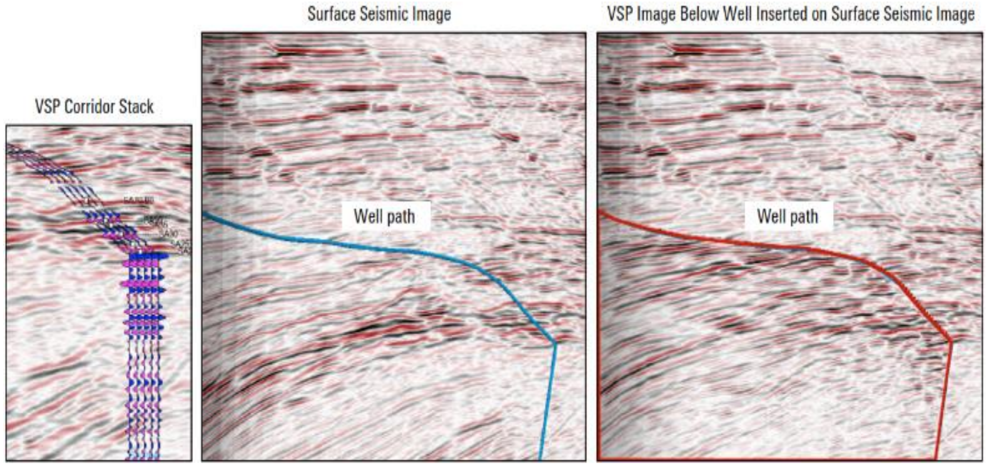
- Well deviation ~ 75°
- TVD > 3 km
- Well step-out = 6 km
- 4-shuttles in all runs except on TLC *(1 tool)*

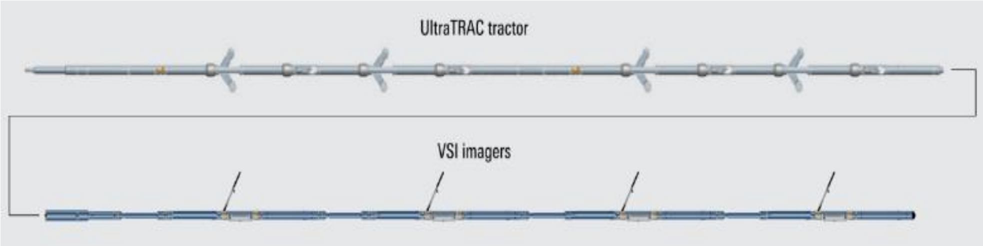


Example-6:



- Well deviation ~ 85°
- TVD > 3 km
- Well step-out = 6 km
- 4 shuttles w/ stiff bridles + Tractor

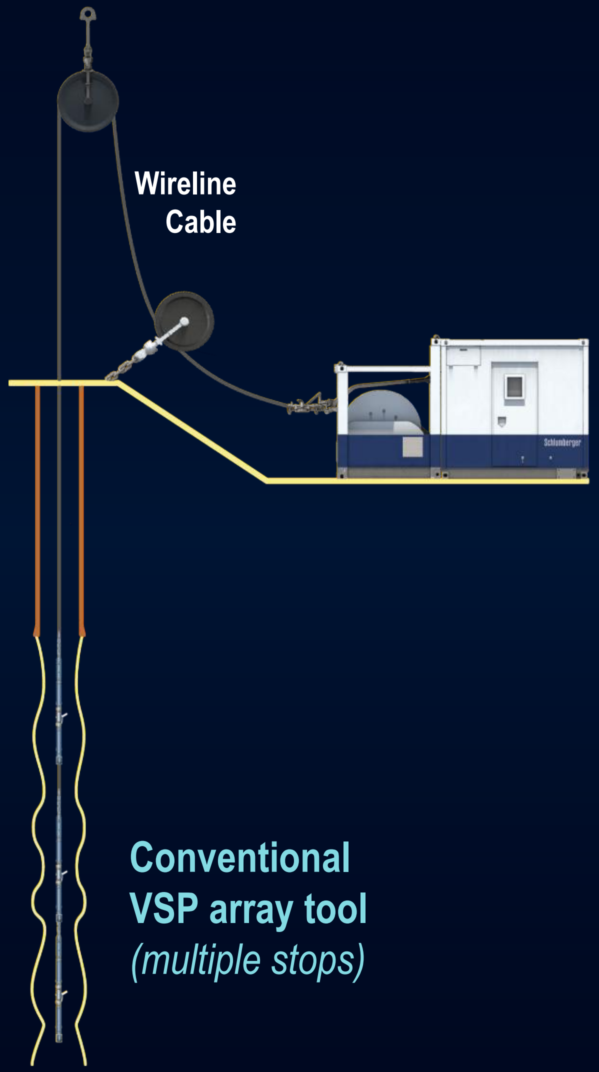


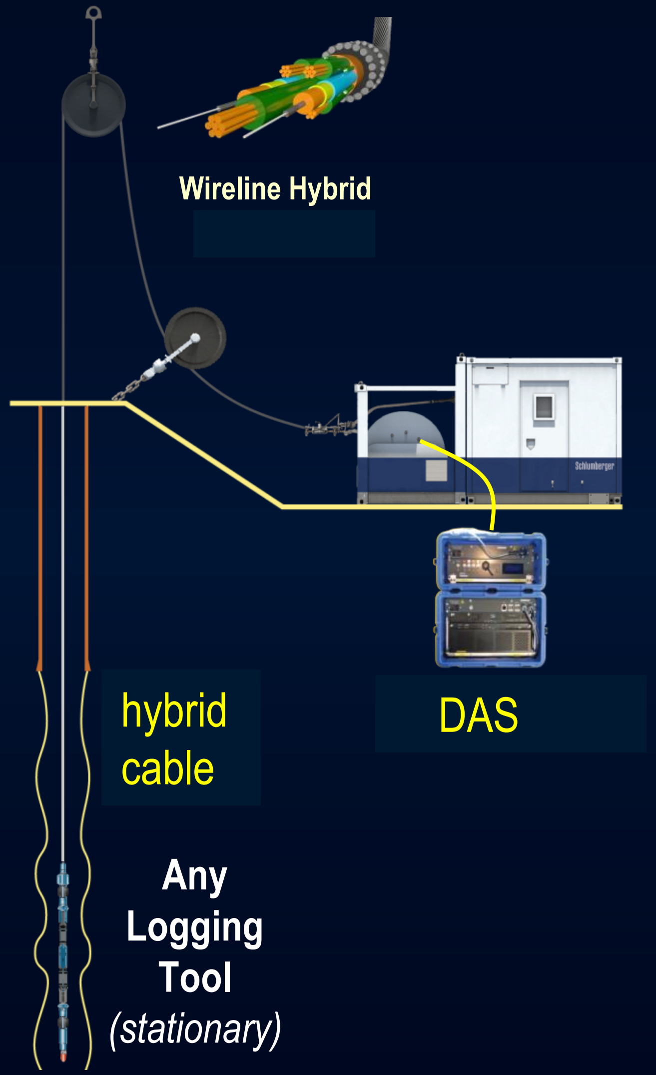


Wireline Well Seismic: *Conventional vs DAS*

Conventional:

- **10 - 20 hours usually, more if TLC**
- Fit-for-purpose VSP tool
- Dedicated logging run

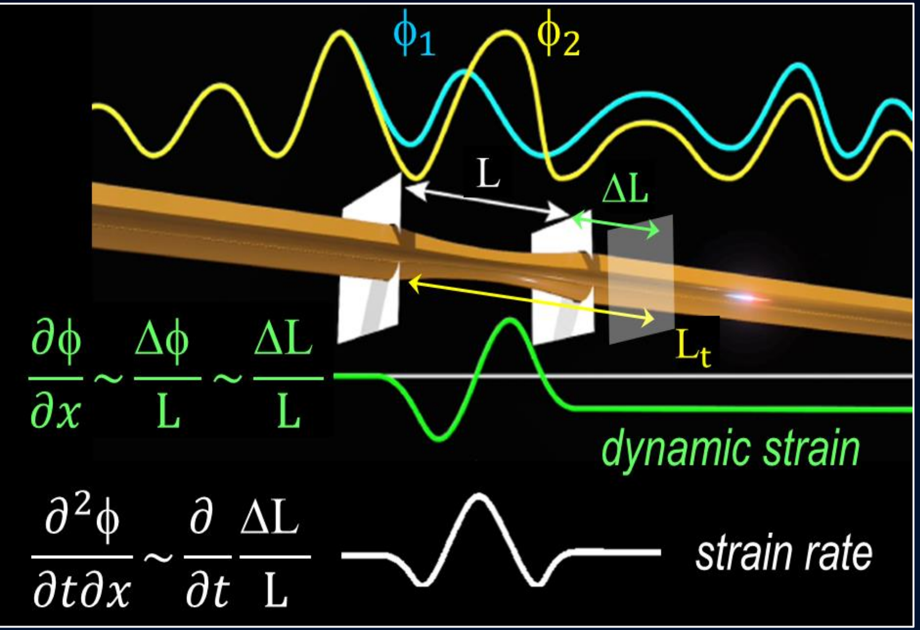


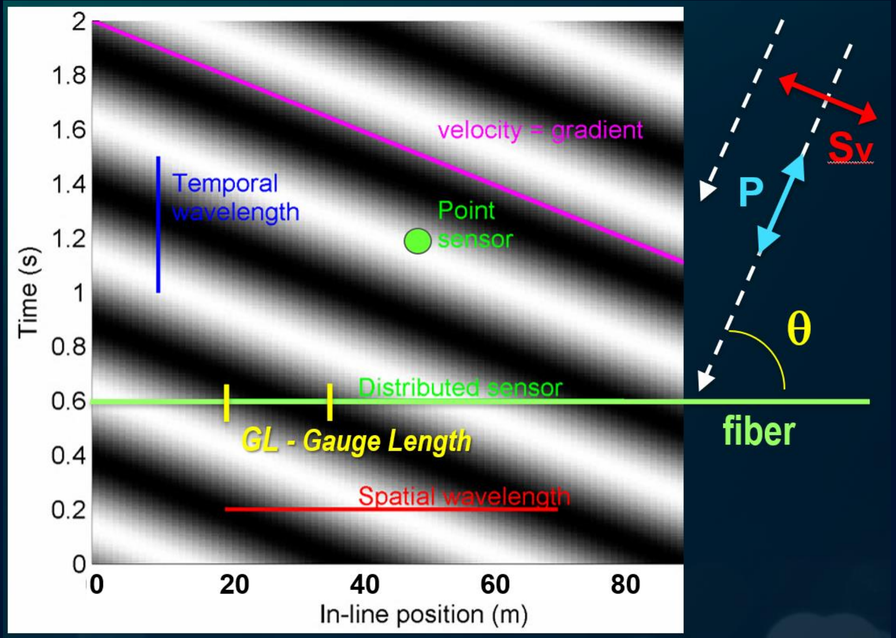


DAS hybrid cable:

- **From 0 to 1 h**
- Logging cable is the DAS receiver
- No additional logging run

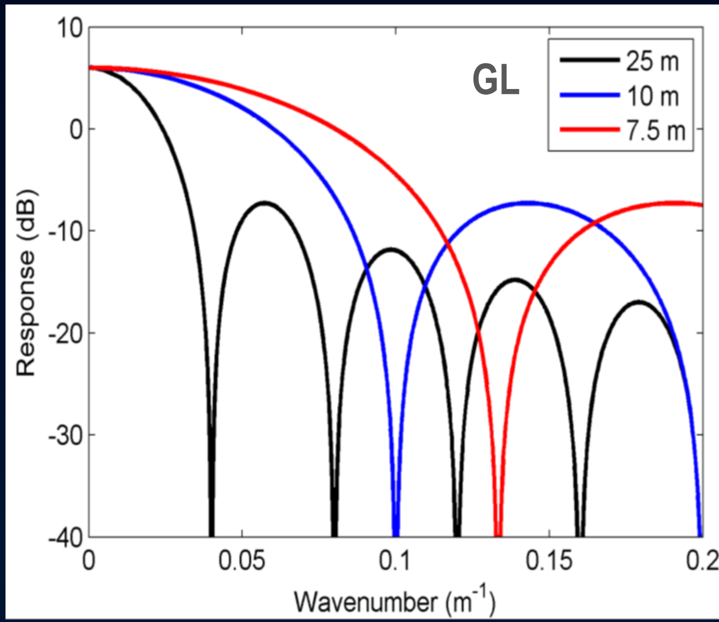
DAS Principles

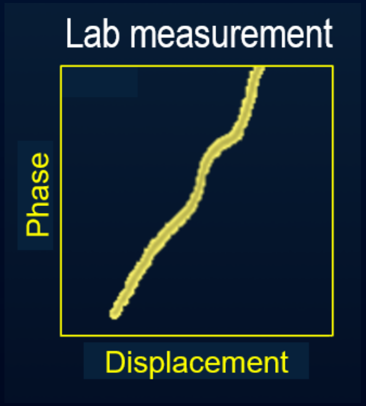




(Adapted from Dean et al., 2015)

Axial response to P-waves vs. GL





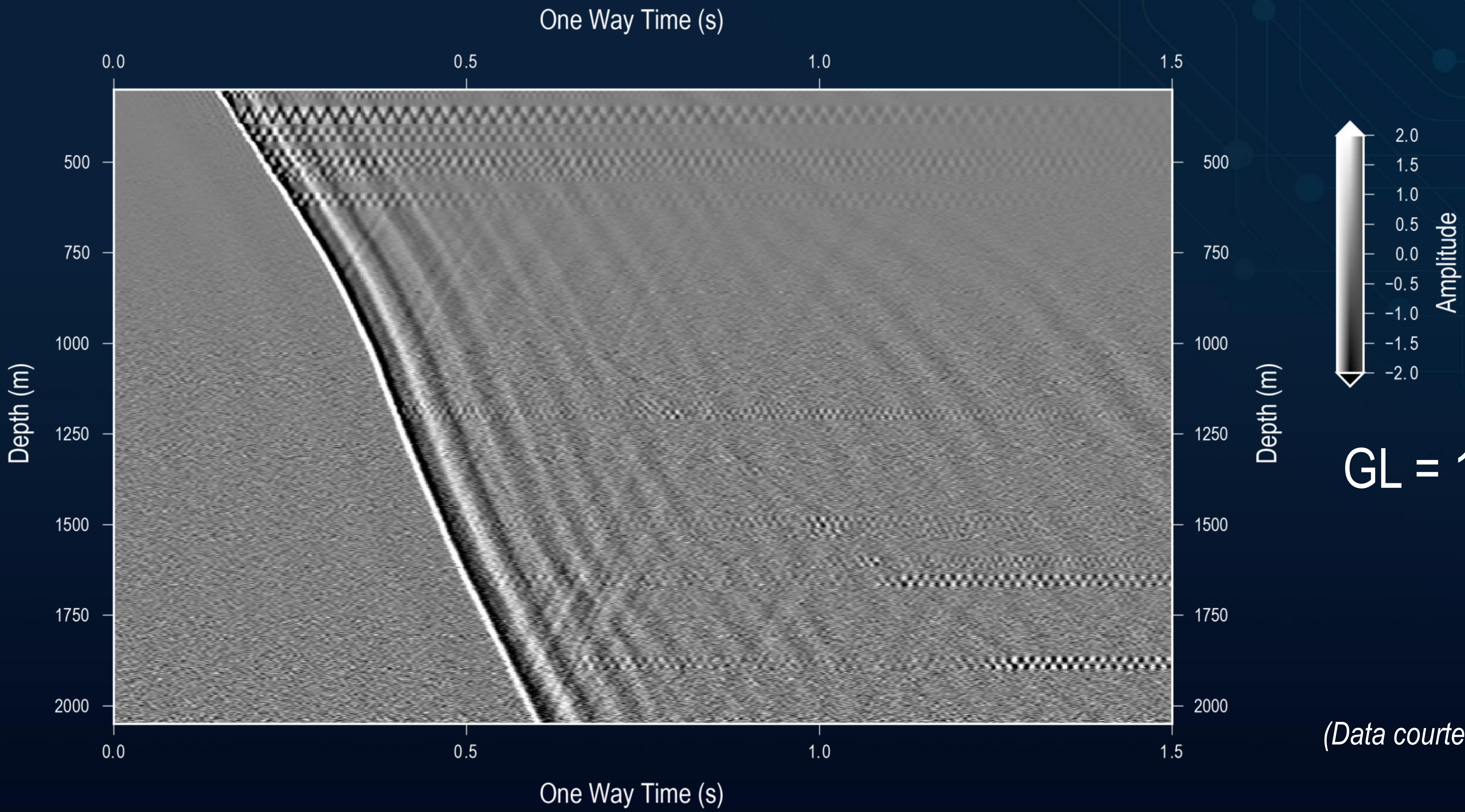
The spatial phase difference over a GL gives the dynamic strain

- The DAS response depends on wave type, wavelength & incidence angle
- For wavelengths λ >> GL:

P-waves: ~ sin(k)/k * cos(θ)^2

Sv-waves: ~ sin(k)/k * sin(θ) cos(θ)

Optimal Gauge Length *(Dean et al., 2016)*: $GL_{optim} \sim 0.6 * \lambda_{dom}$

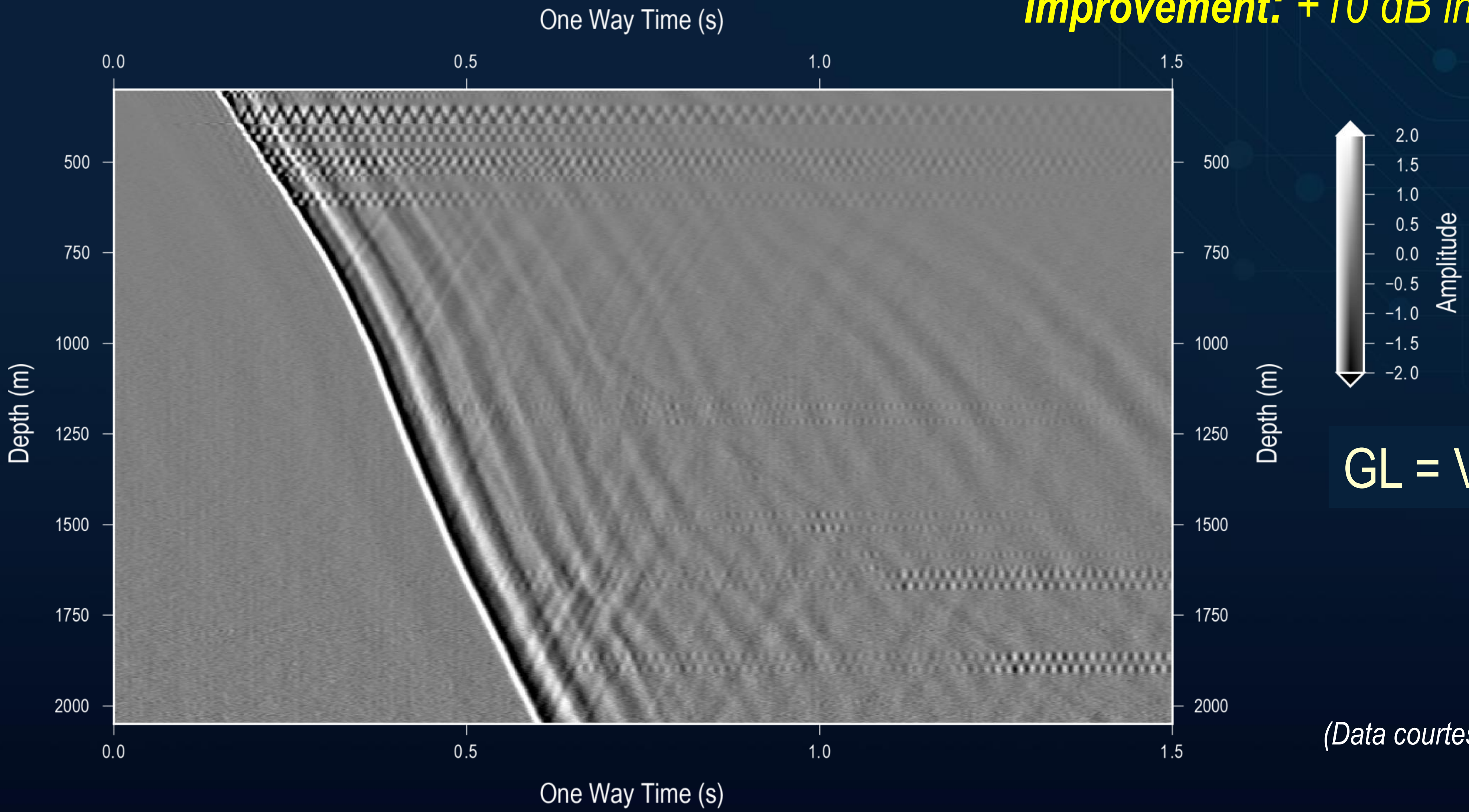


GL = 10m *(fixed)*

(Data courtesy of Velvet)

Optimal Gauge Length *(Dean et al., 2016)*: *$GL_{optim} \sim 0.6 * \lambda_{dom}$*

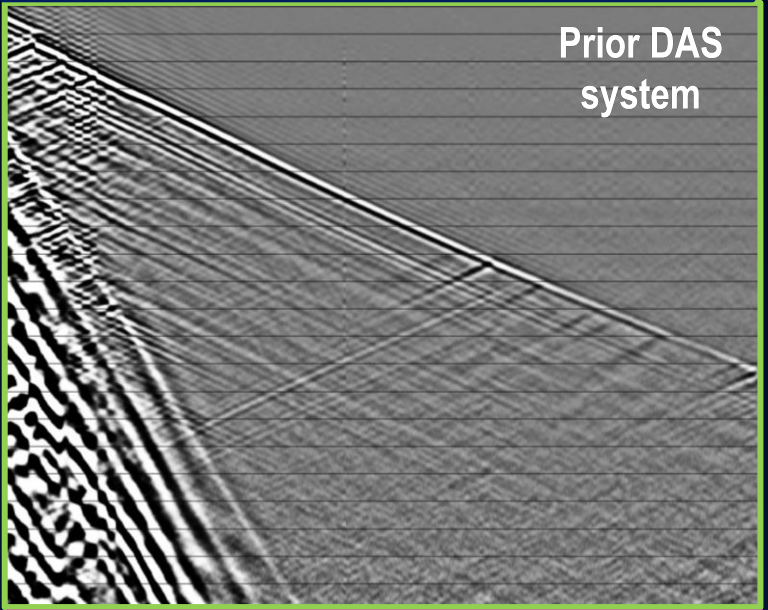
***Improvement:** +10 dB in SNR*

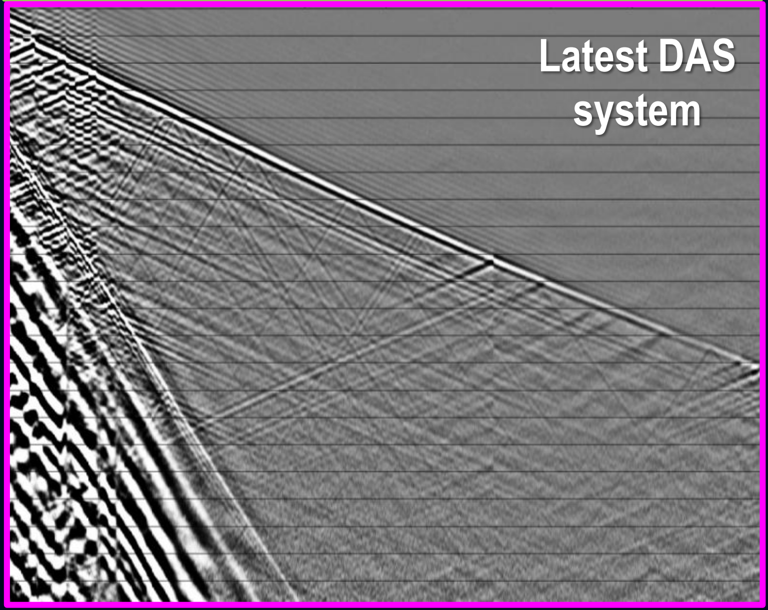


GL = Variable

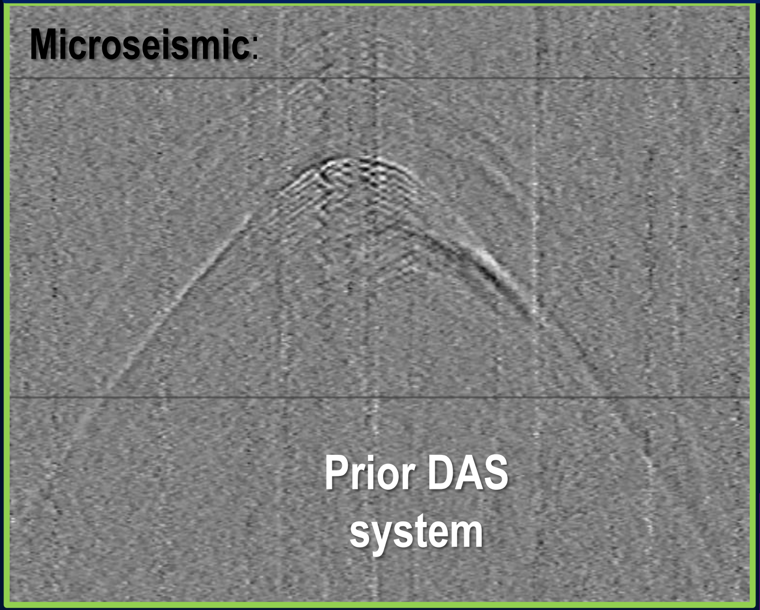
(Data courtesy of Velvet)

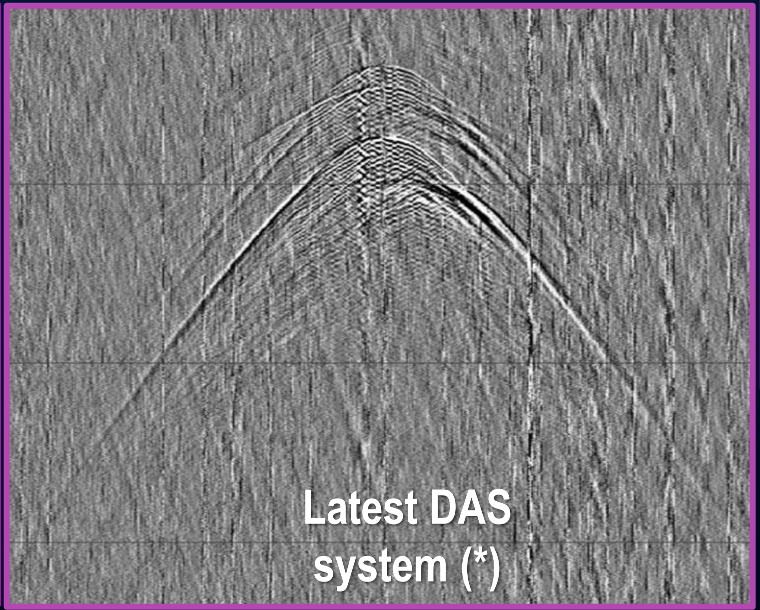
DAS + Sonic vertical well *(60 ft slack)*
Vibro ZVSP, hybrid cable *(USA, 2022)*





DAS microseismic during hydraulic fracking, hybrid coax cable *(USA, 2021)*





DAS: *some key specs*

- Pulse Frequency Rate (PFR)
- Gauge Length (GL)
- Dynamic range
- Sensing range
- Max. optical budget loss
- Max. number of fibers

Number of fibers		Up to Two	
Sensing range @ 6.4m gauge length		Up to 65 km per fiber	
Minimum gauge length		1.2 m	
Maximum number of channels		25,000 per fiber (1.6 m channel pitch)	
Standard operating wavelength		1550.12 nm [193,400 GHz] [CH34]	
Measurement type		Quantitative	
Minimum detectable signal (Noise Floor [NF])	5 km	-80 dB Rad.Hz-½ [Equivalent to an axial strain of 1.5 pε.Hz-½]	
	50 km	-60 dB Rad.Hz-½ [Equivalent to an axial strain of 15 pε.Hz-½]	
Linearity		Harmonic distortion typ. < -40 dB	
Crosstalk isolation		> 80 dB	
Acoustic Frequency Range	Min	< 1 mHz [Arbitrarily selectable]	
	Max	Nyquist -> 10 kHz @ 5 km	
Dynamic range (front of 5 km fiber) = largest linear signal / noise floor		155 dB @ 1 Hz	135 dB @ 10 Hz

(*) Sensitive to low frequency tube waves ~5 kft/s and to high frequency microseismic

Example-7:

Fiber Optics Cable Deployment

Cemented
behind casing

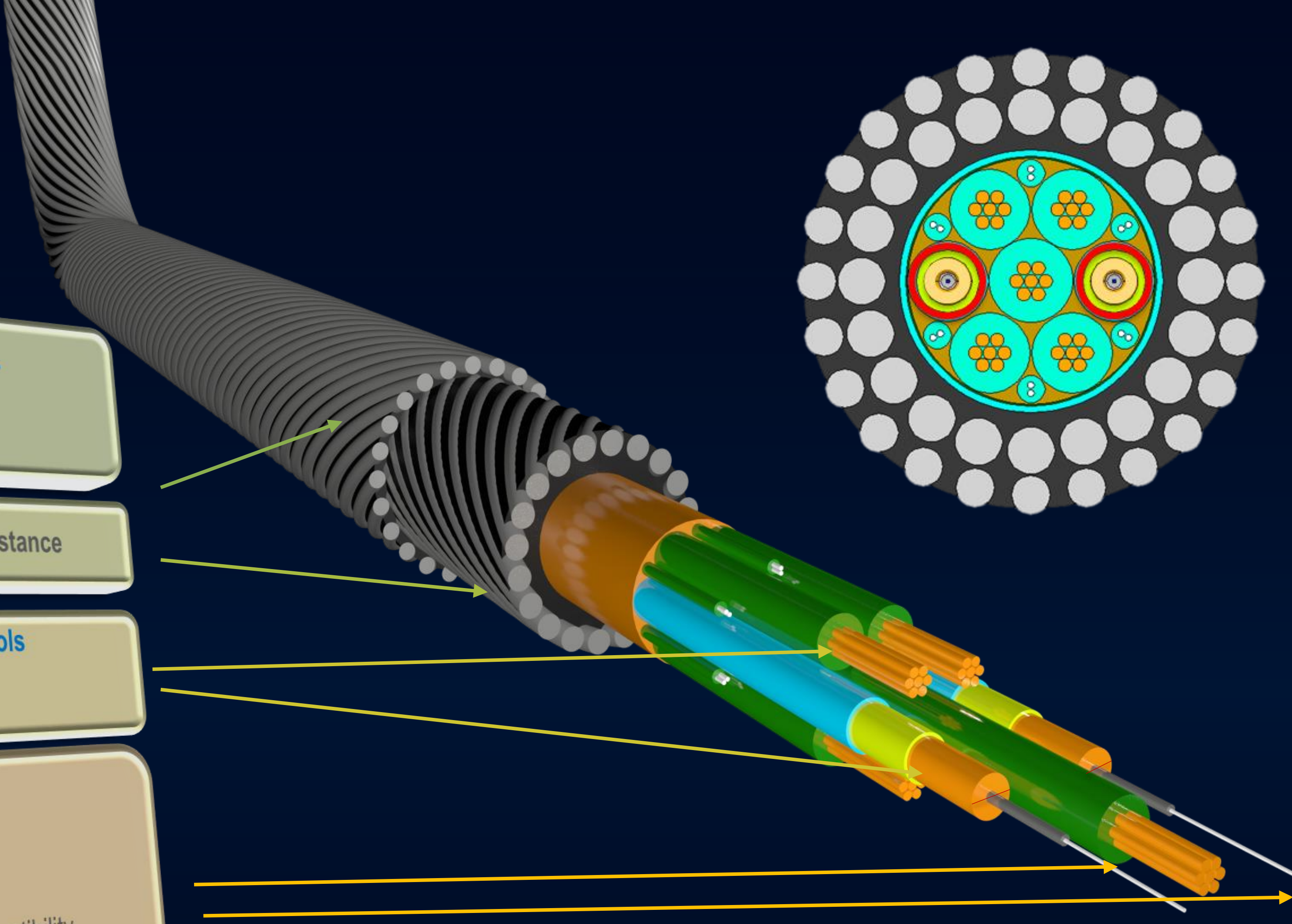
Strapped to
tubing

Coiled Tubing carrying
optical fibers

Hybrid Wireline Logging cables

Coaxial and heptacables

Hybrid FO Logging Cable:



Armor Matrix with Intermediate Jacket

- Normal Strength: 10-13k lbf SWL
- Extra Strength: 18k lbf SWL
- Torque Balanced

Core Jacket

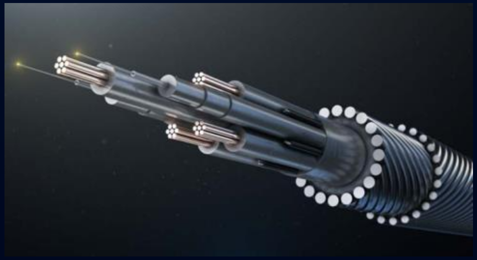
- Double layers – Compression Resistance

Electrical Conductors

- Compatible to ALL existing WL tools
- #16AWG with 2.6 A
- Center 1600 Vdc, Helical 1100 Vdc

Fiber Optic Conductors

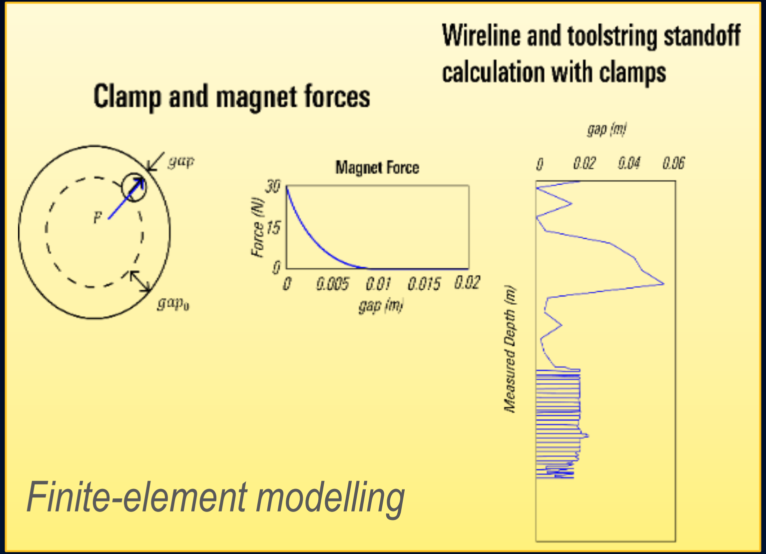
- 2 x SM (< 190-200ºC)
- 20,000 psi
- Optical Fibers in Copper Shell
- Position 1 and 4 for Reverse Compatibility



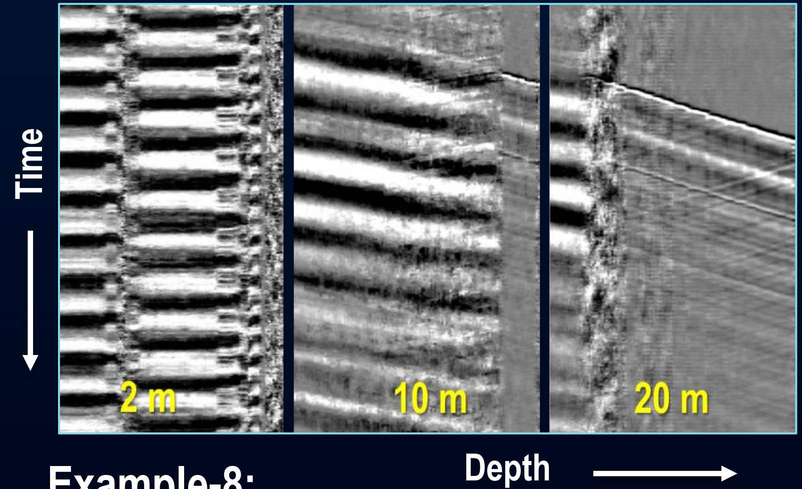
www.slb.com/Optiq

Cable coupling modelling: *magnets and/or cable slacking*

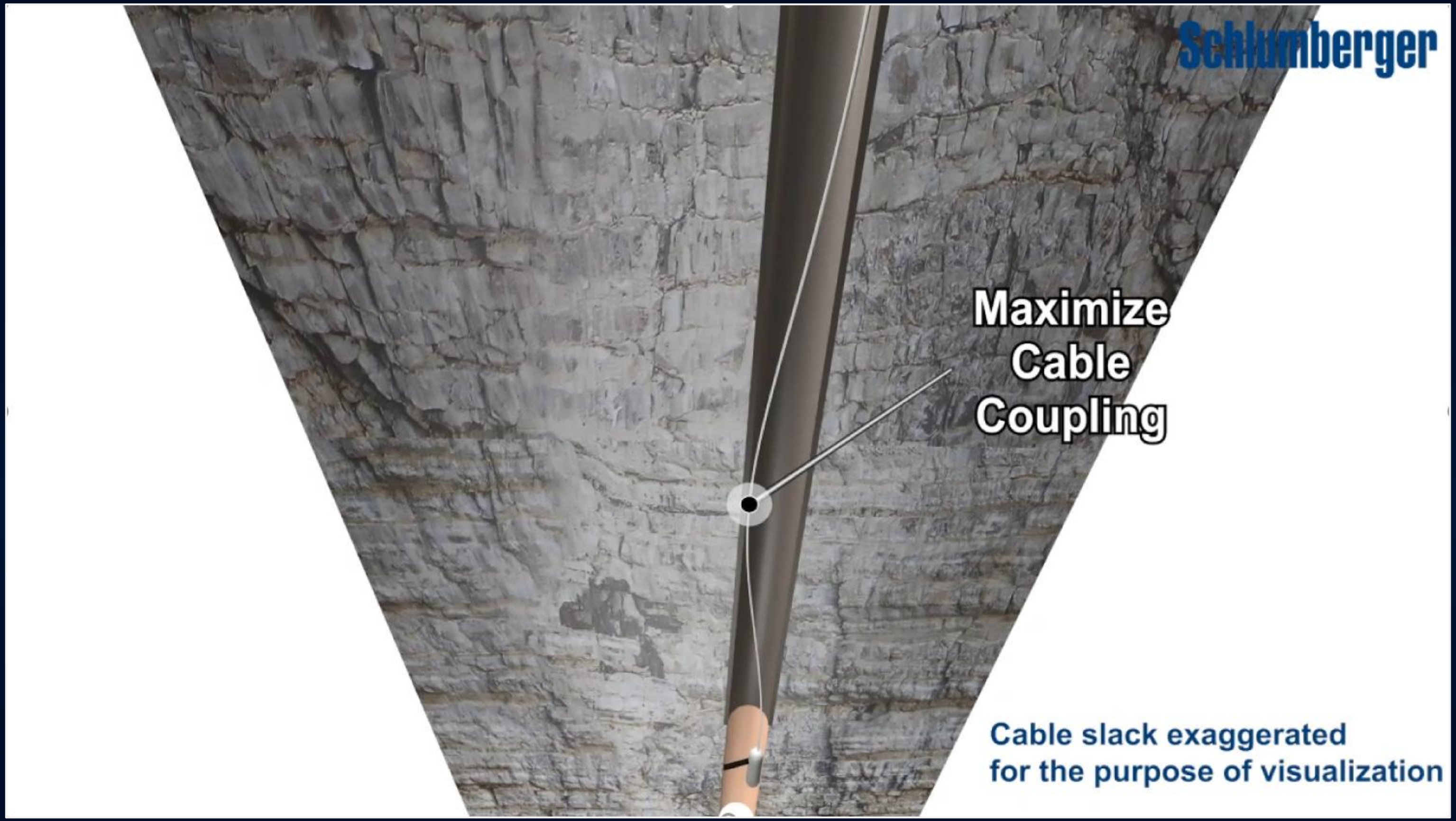
Tension release *(slack)* & magnetic clamps



Amount of cable slack



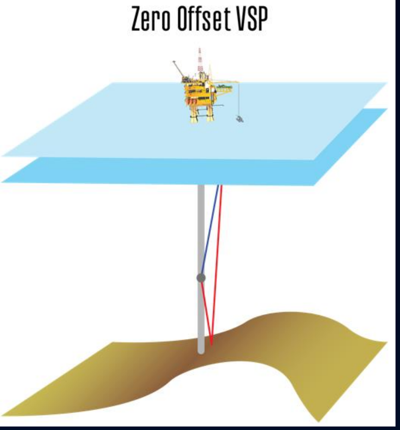
Example-8:



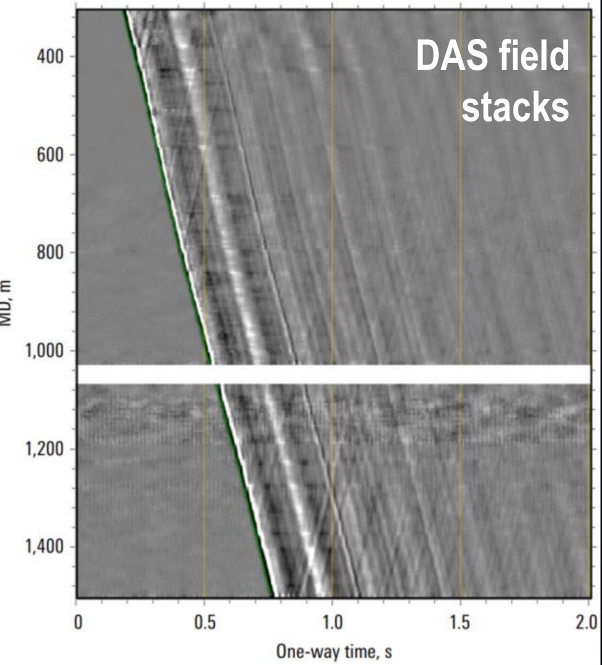
Early prototype of small magnetic cable clamps

→ *Currently cable slacking is preferred*

DAS-MDT: *ZVSP Norway (2019)*

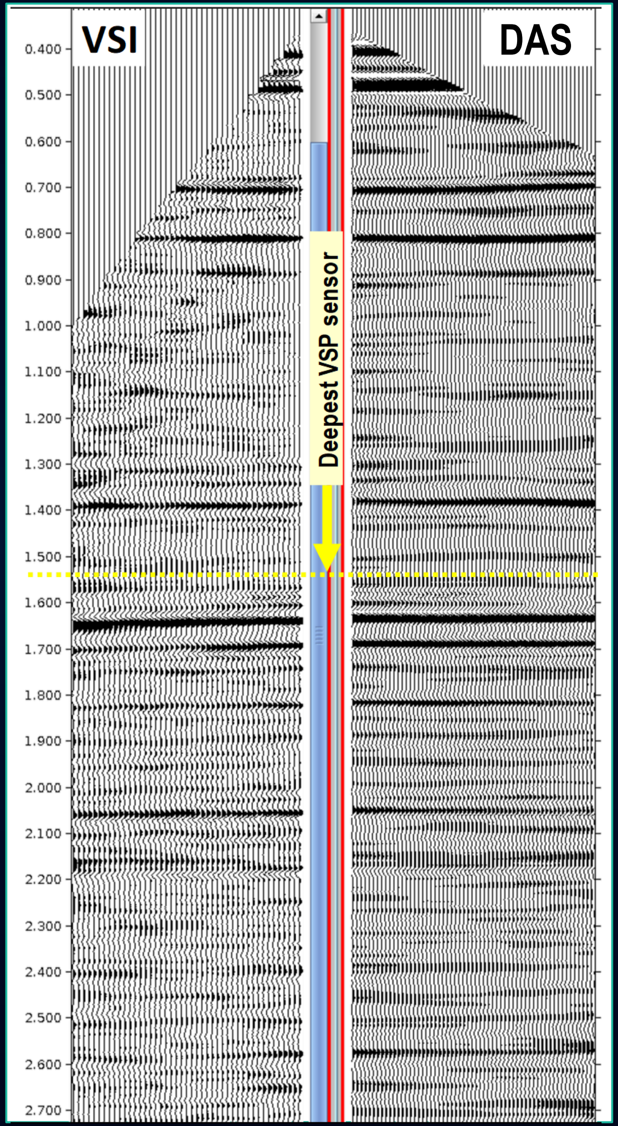


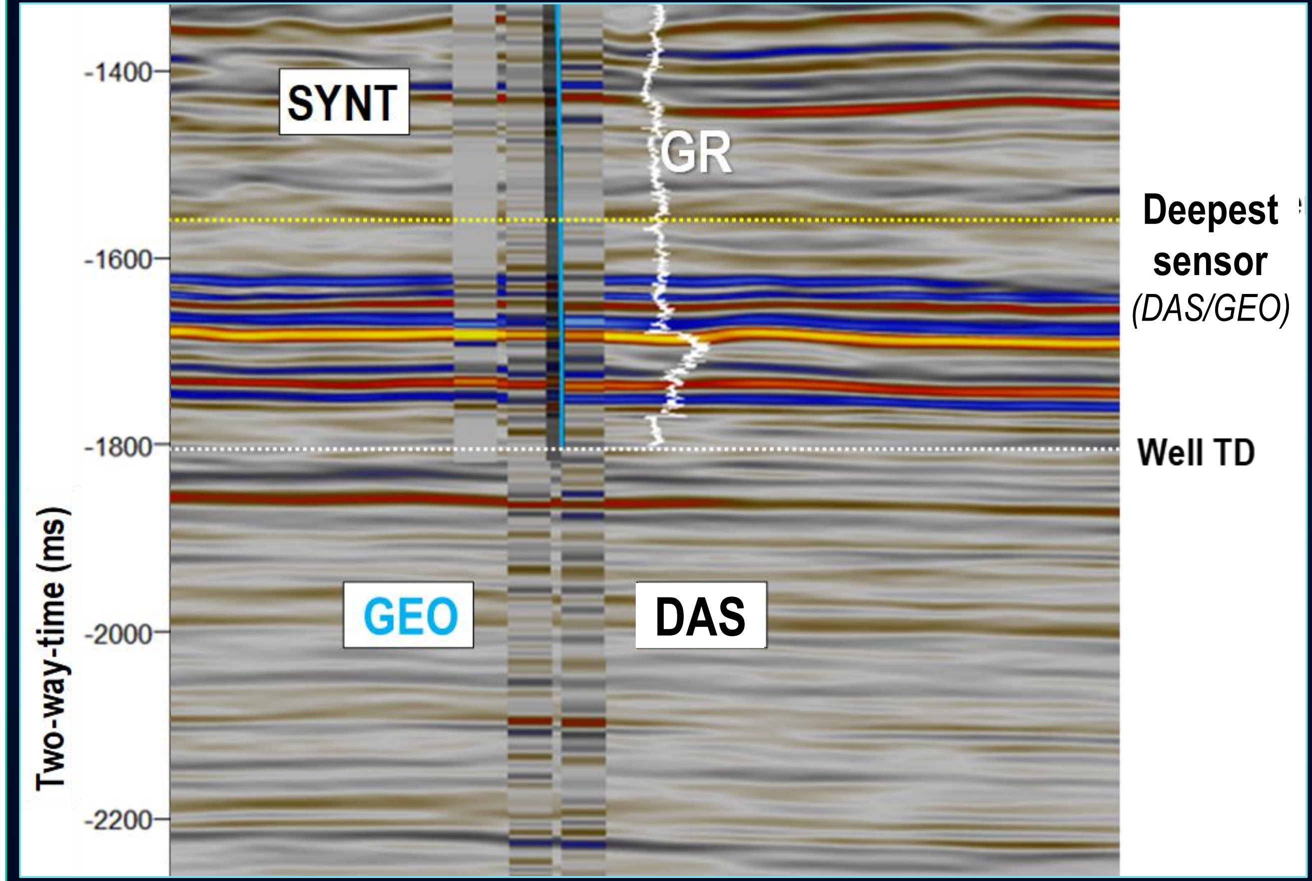
Example-9:



(Guerra et al., 2020)

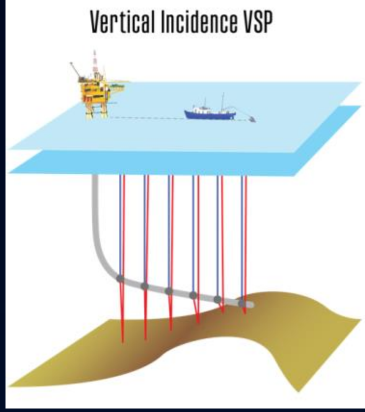
Transposed VSP displays





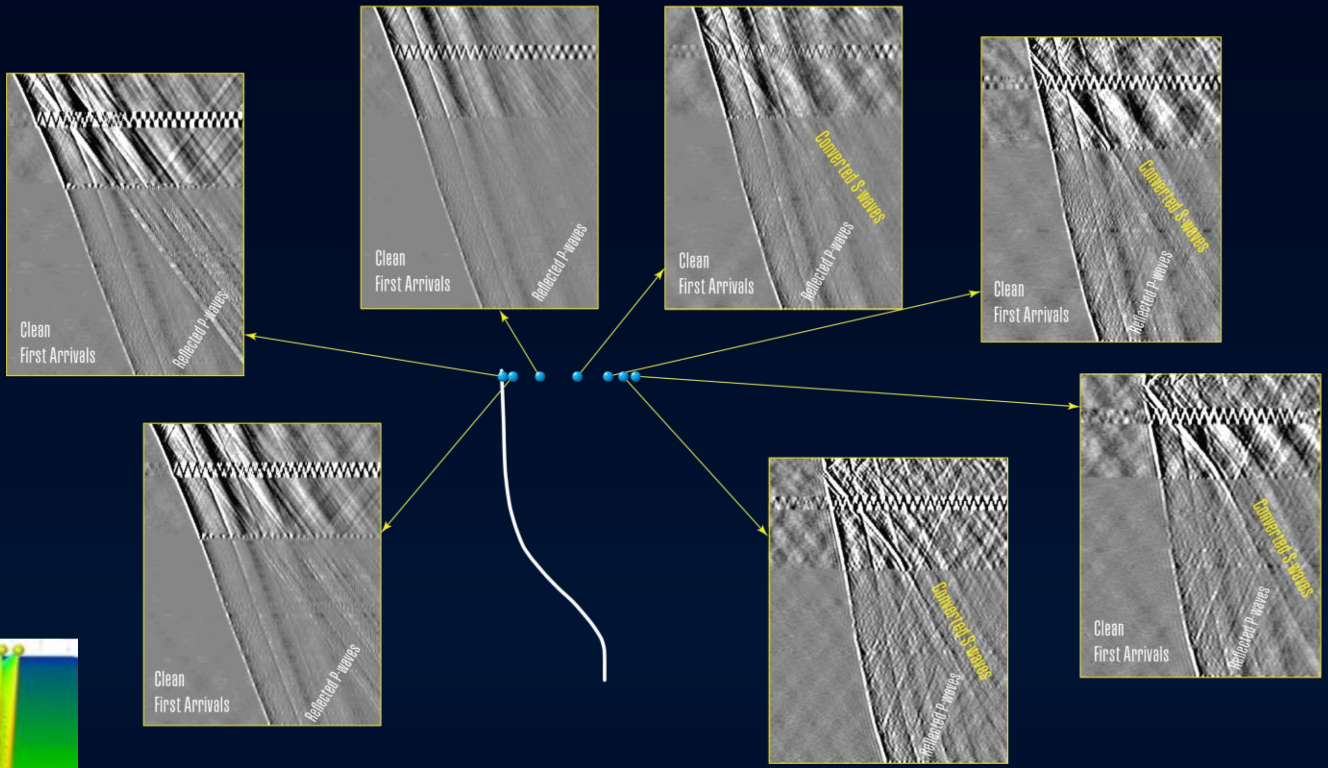
- DAS hybrid cable; Cable slacks of 20 - 30 m used
- **Four-way well ties over 5-80 Hz, > 1 km lookahead**

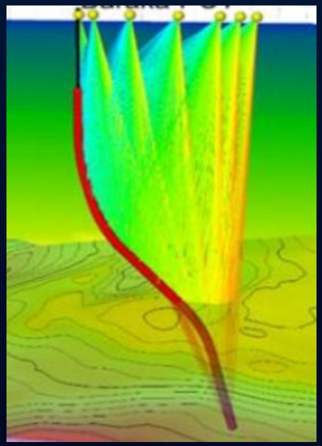
DAS during CBL logging: *Vertical Incidence VSP examples (2021)*



Example-10:

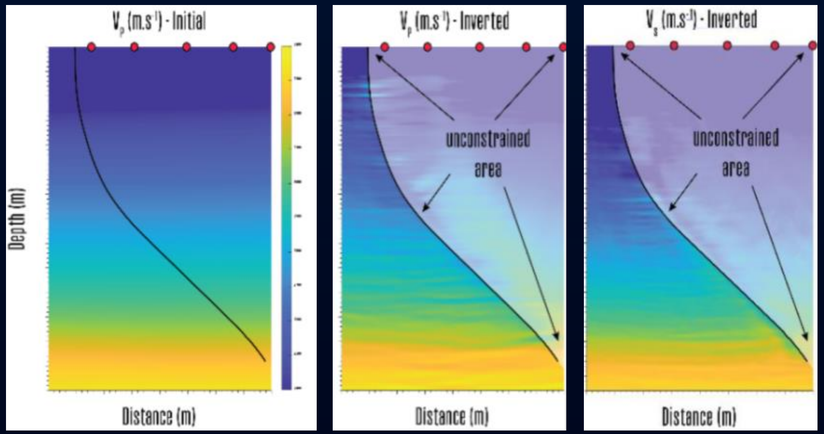
raw stacks



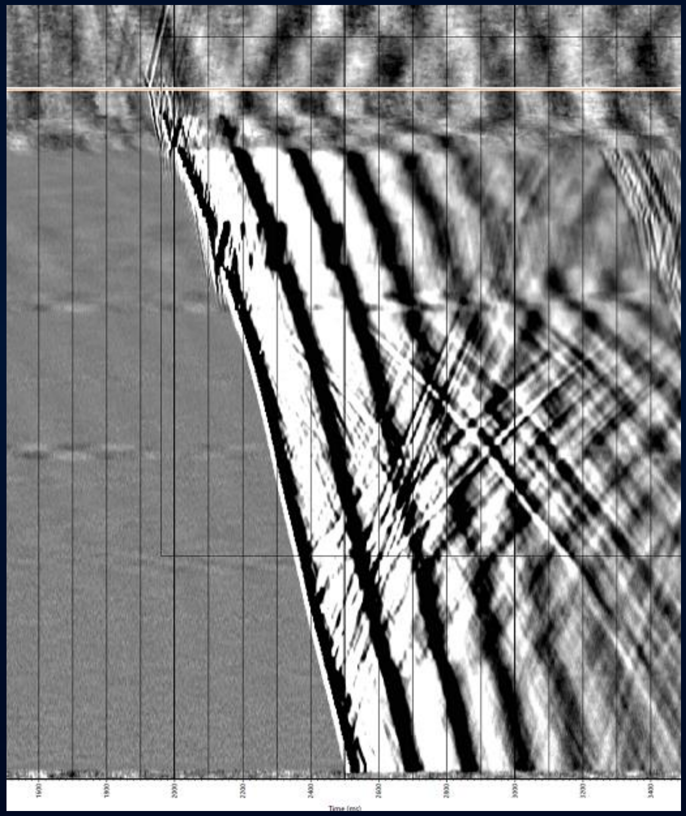


(Bettinelli et al., 2021)

eFWI results:



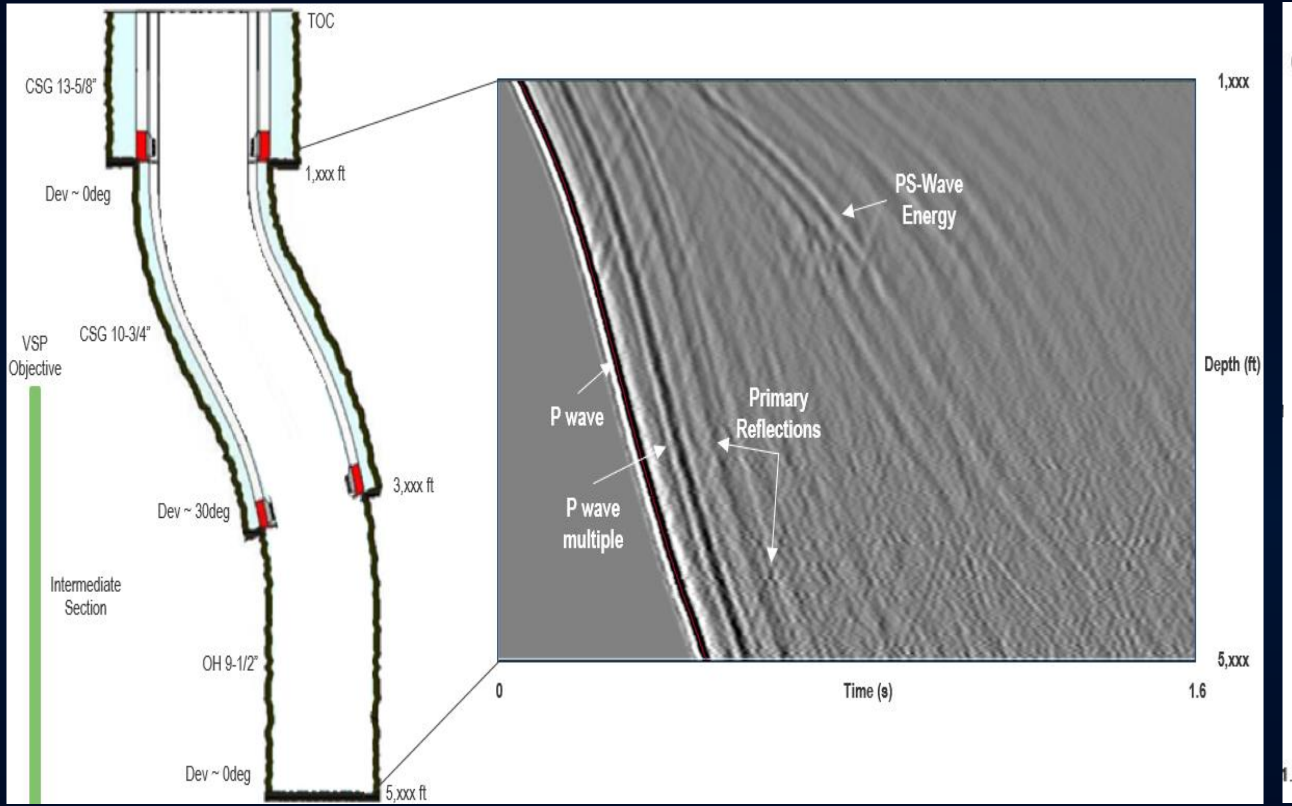
Example-11:

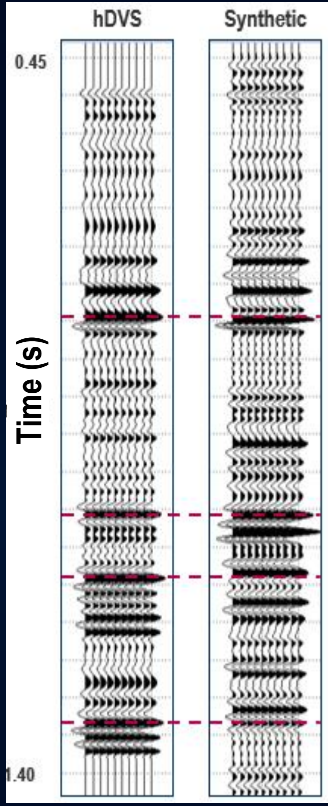


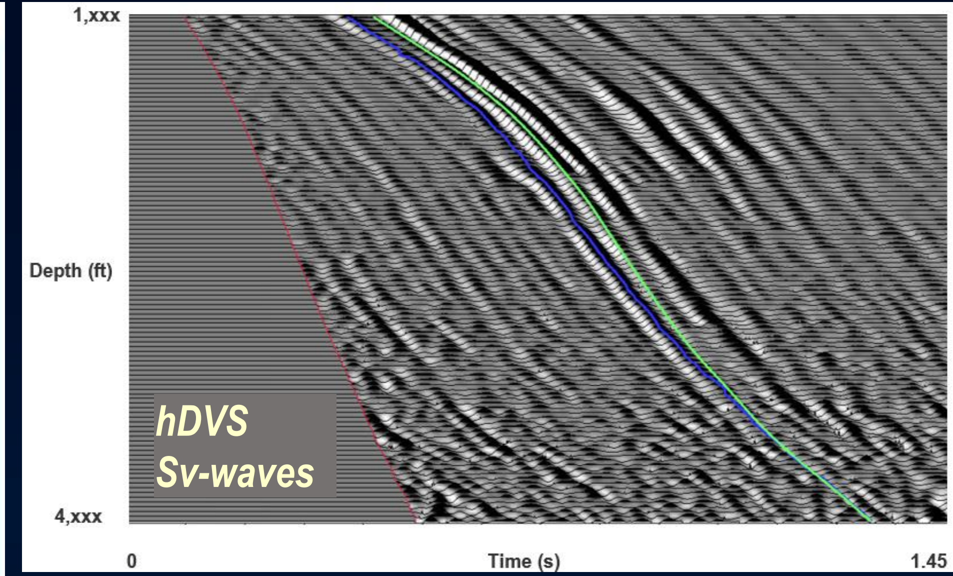
DAS during Sonic+Images: *raw stacks*

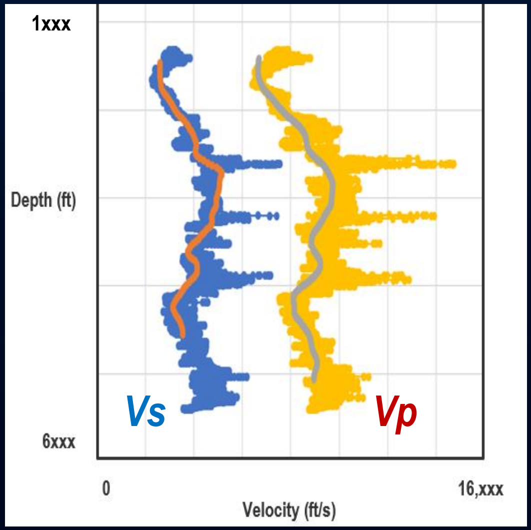
Hybrid cable: *DAS-Sonic VSP, Colombia (2019)*

Example-12:









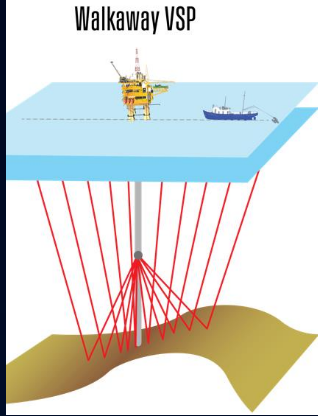
(Martinez et al., 2020)

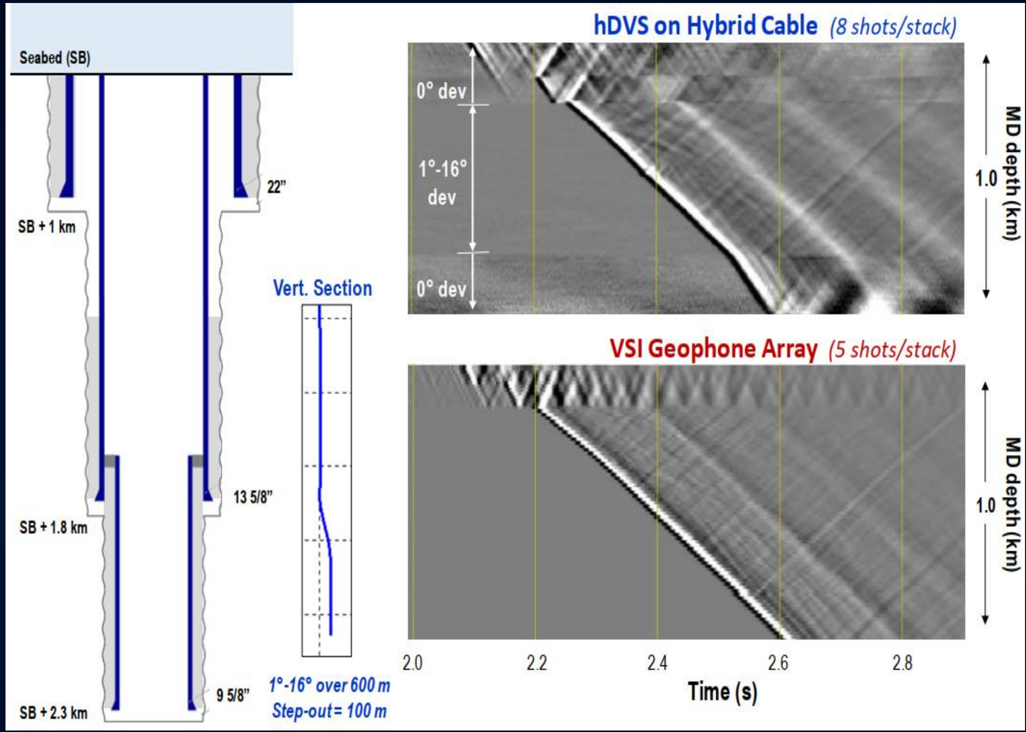
- Objective record Checkshot in S-shape well
- DAS data recorded during Sonic-Images run

→ Job took < 1 h,   → 5 m slack

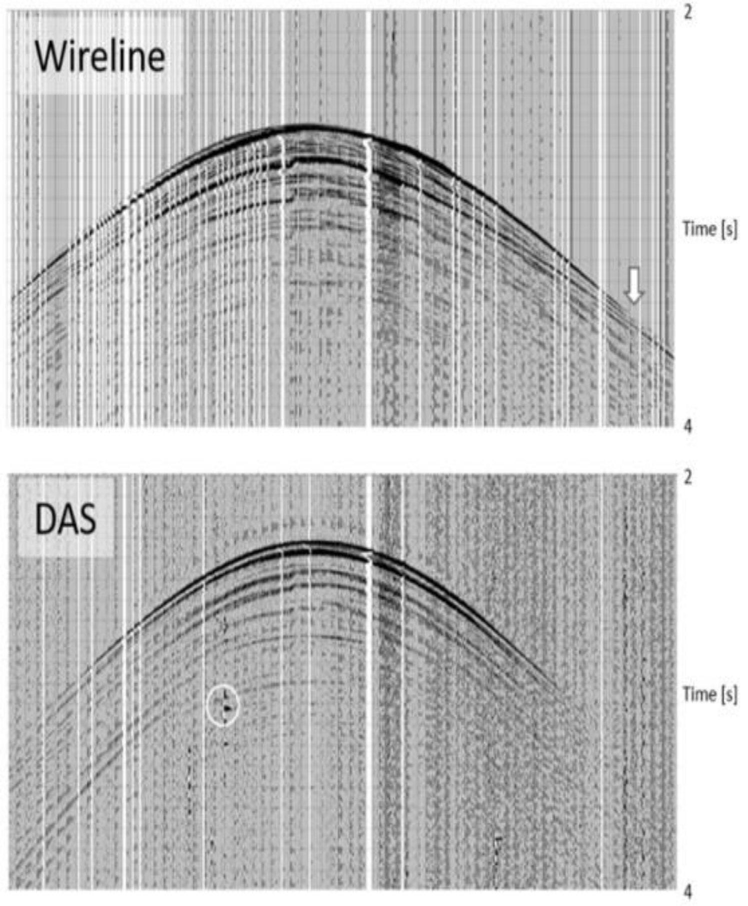
DAS + Geophones Walkaway

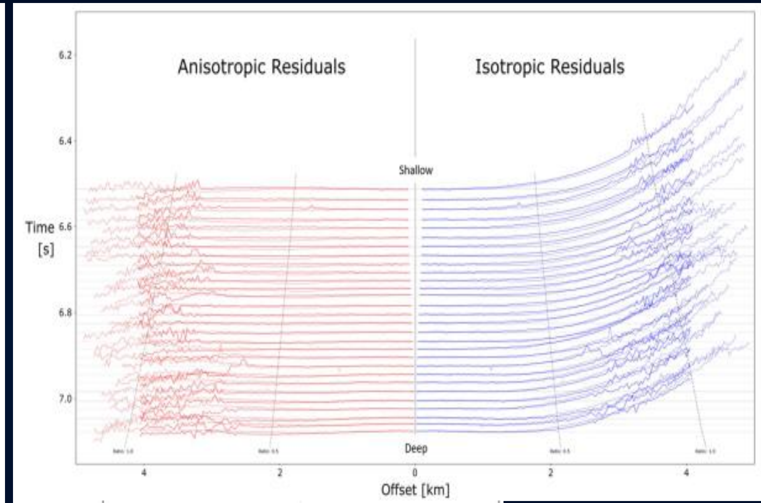
Deepwater West Africa (2019)

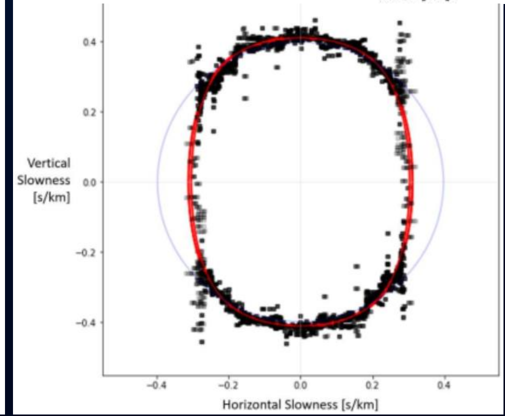




Example-13:







- → **Anisotropy calibration**
- → **No rig time**
- → **1.5 m slack** *(could not apply larger slack)*
- → **Good data for deviation > 1º**

Thomsen

ε = +0.35

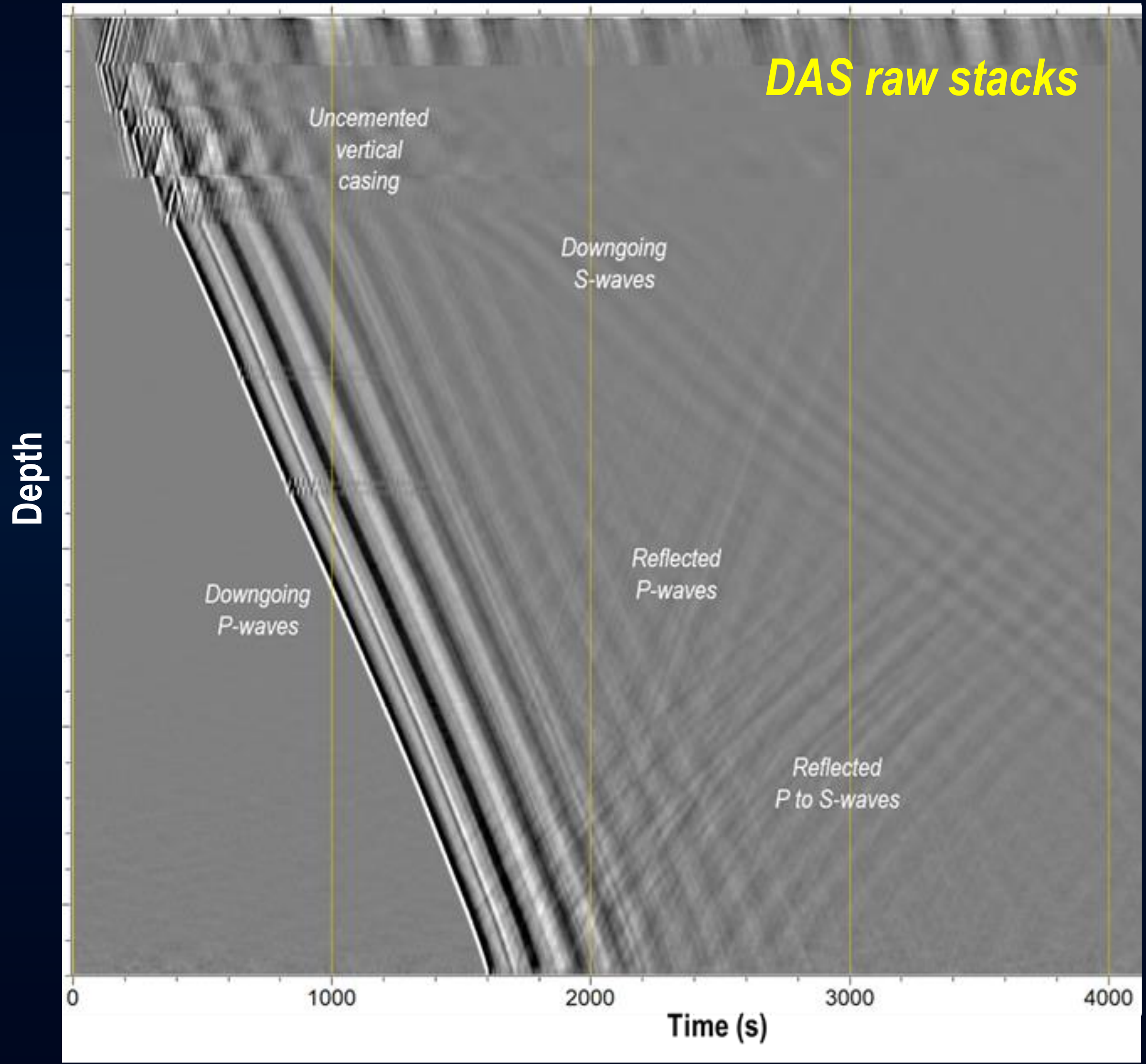
δ = -0.05

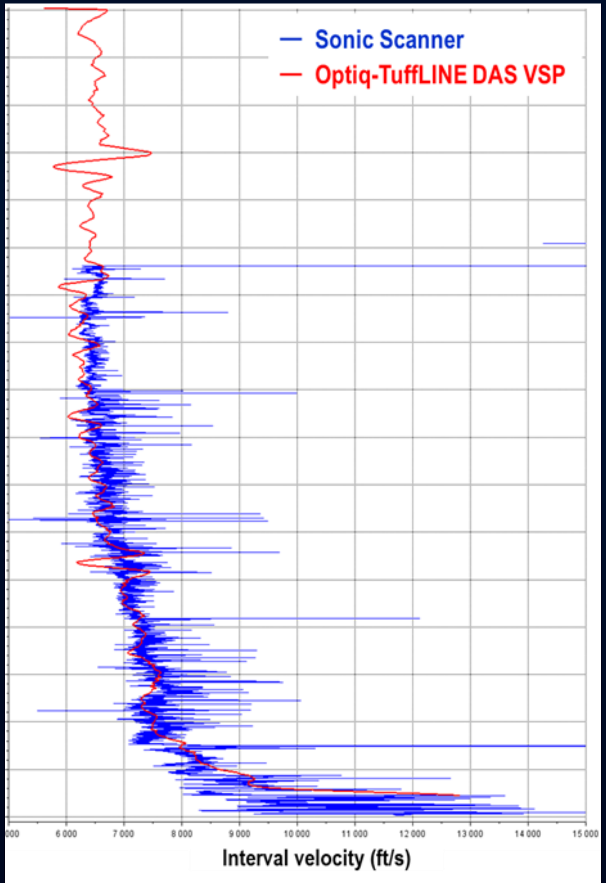
(Horne et al, 2020)

Latest DAS hybrid cable run with XPT-MSIP

DVSP, UK (Q4 2021)

Example-17:



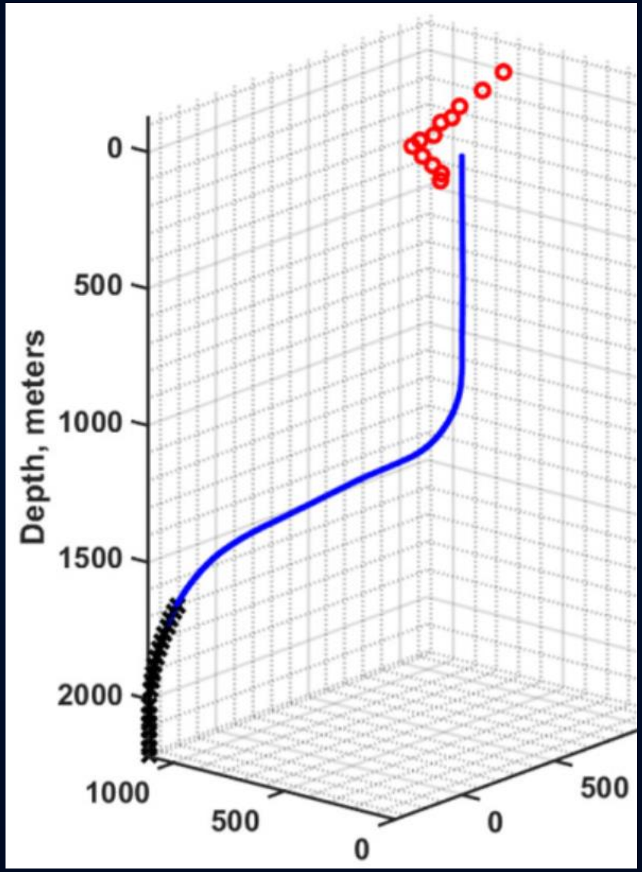


- TVD ~ 10,000 ft
- Deviated well → **5 ft slack**
- 3x 250 in^3 airguns
- 30 shots → **10 min**
- **VSI run cancelled**

- DAS hybrid cable pulled up to 18 klbs alright in another exploration well *(2022)*

Reservoir properties via Full Waveform Inversion *(FWI): uses full VSP waveforms*

Example-14:



Podgornova et al. (2020)

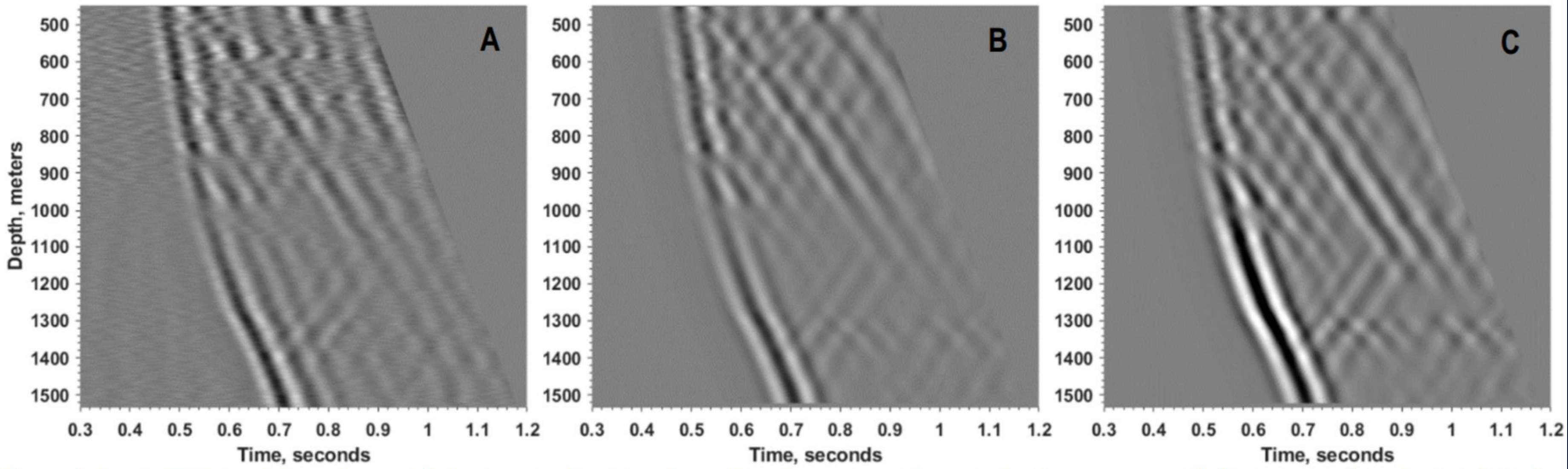
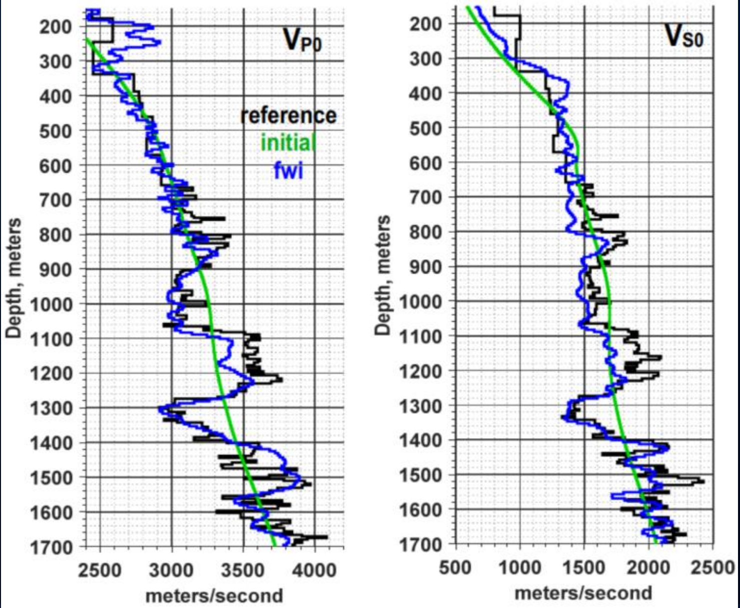


Figure 2. Real DAS data filtered up to 30 Hz for shot 9 with 880 m offset from the well head (A). Reconstructed DAS by FWI (B). Modeled DAS for FWI final model and source wavelet without the azimuthal term in equation 7 (C).



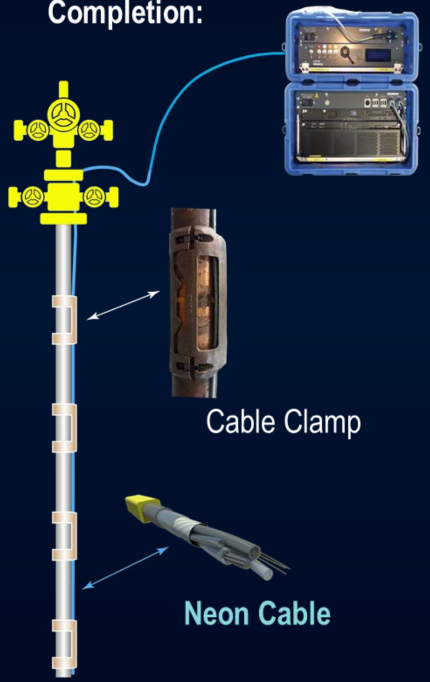
- 2D FWI algorithm inverts for 2D property model and includes 3D well deviation effects
- The algorithm handles mild property variations in the horizontal direction
- In this example the MOVSP survey had narrow aperture and TI-anisotropy could not be resolved

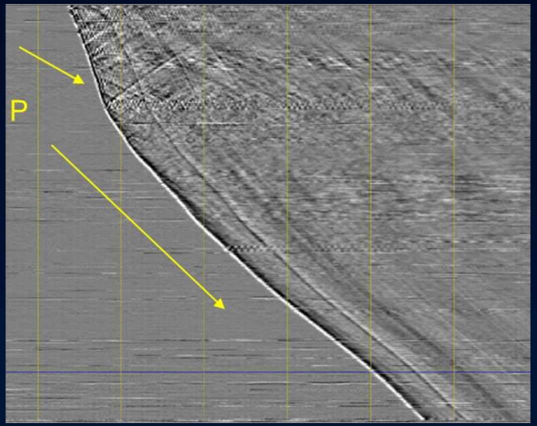
Permanent fibers DAS monitoring

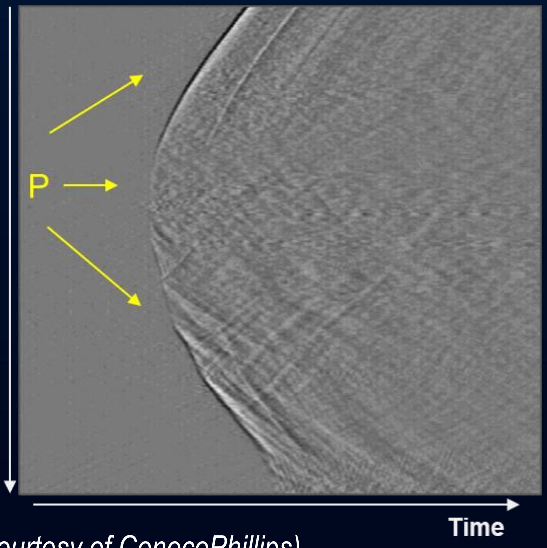
Importance of flow noise attenuation

Example-15:

Ekofisk DAS VSP test, Norway (2013)





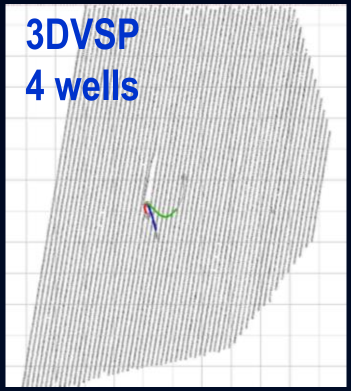


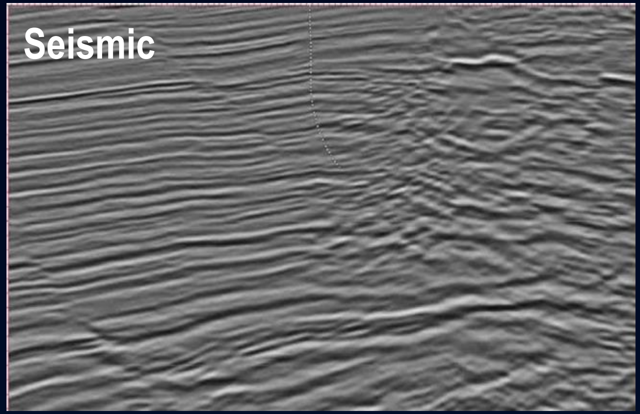
(data courtesy of ConocoPhillips)

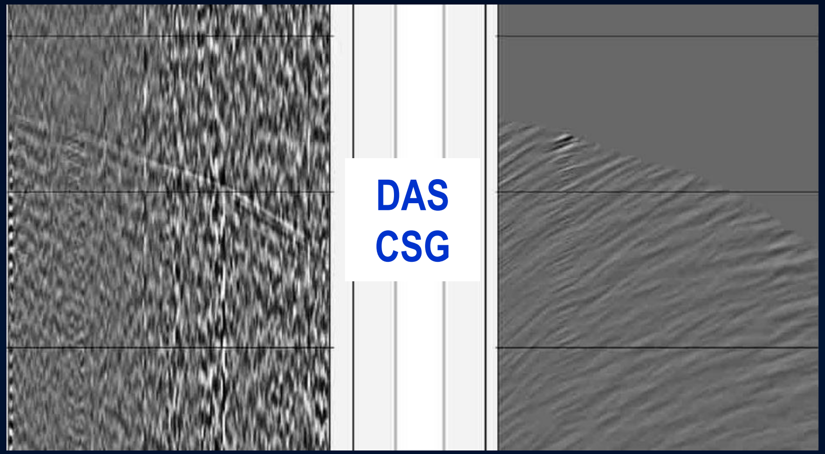
Example-16:

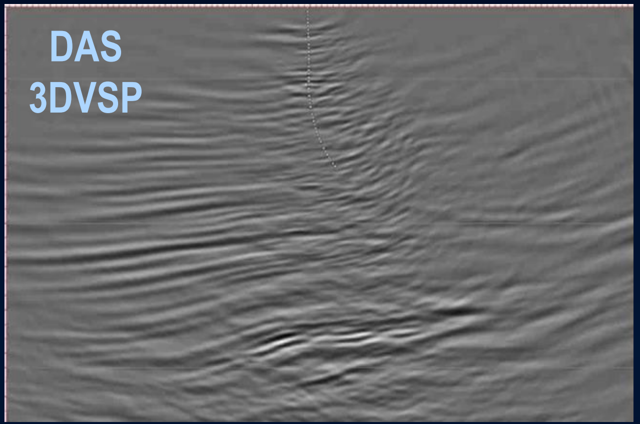
Producing wells
DAS 3DVSP (2020)

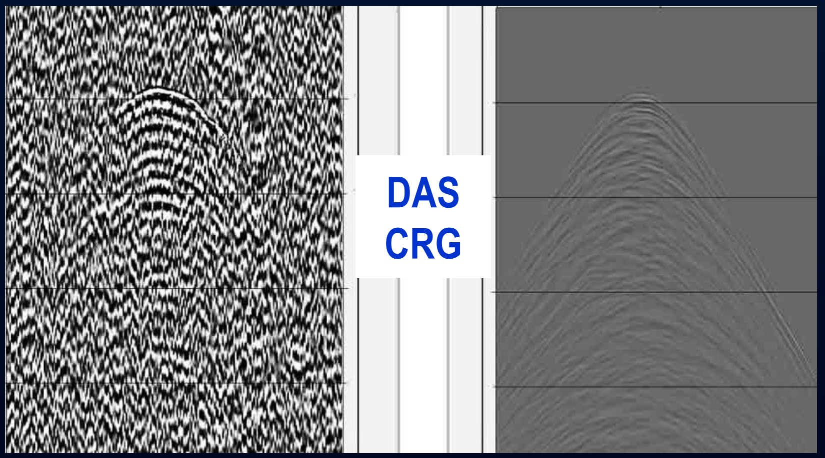
- Velocity model calibration
- Higher-res imaging
- Time-lapse seismic

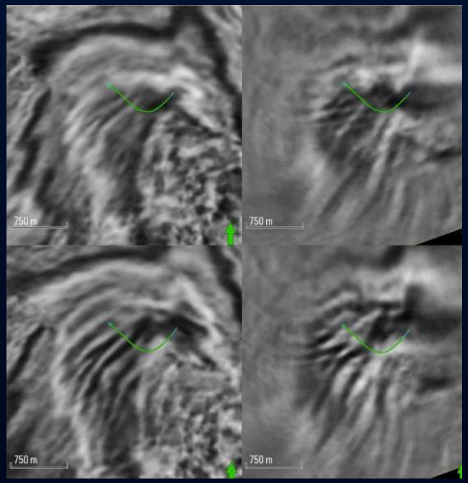












DAS 3DVSP *(right depth slices)*

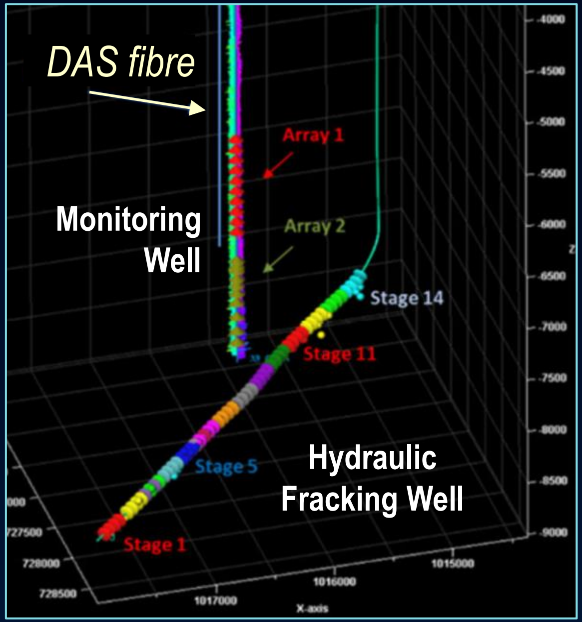
Ali et al. (2021)

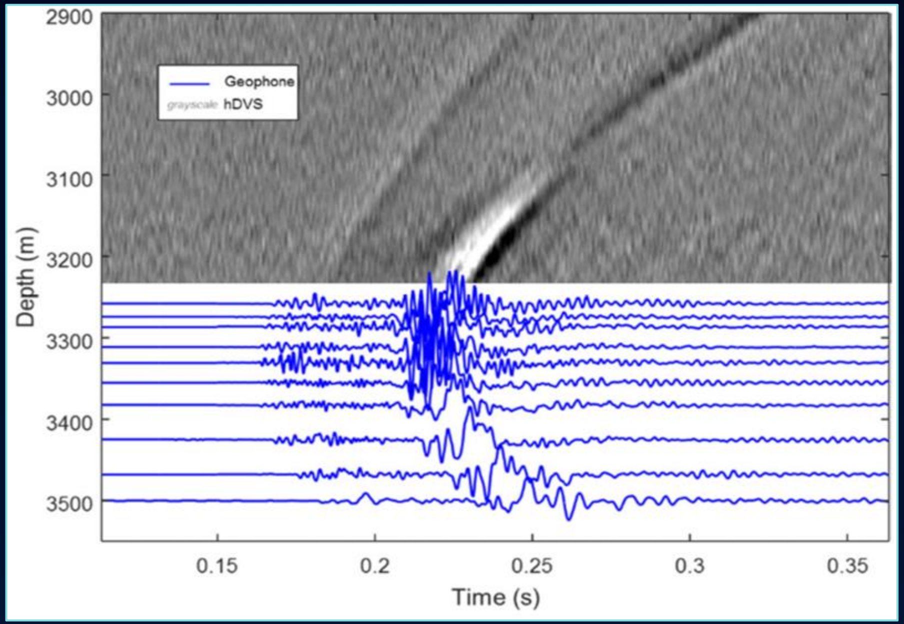
Fibers cemented behind casing: *DAS microseismic, USA (2015)*

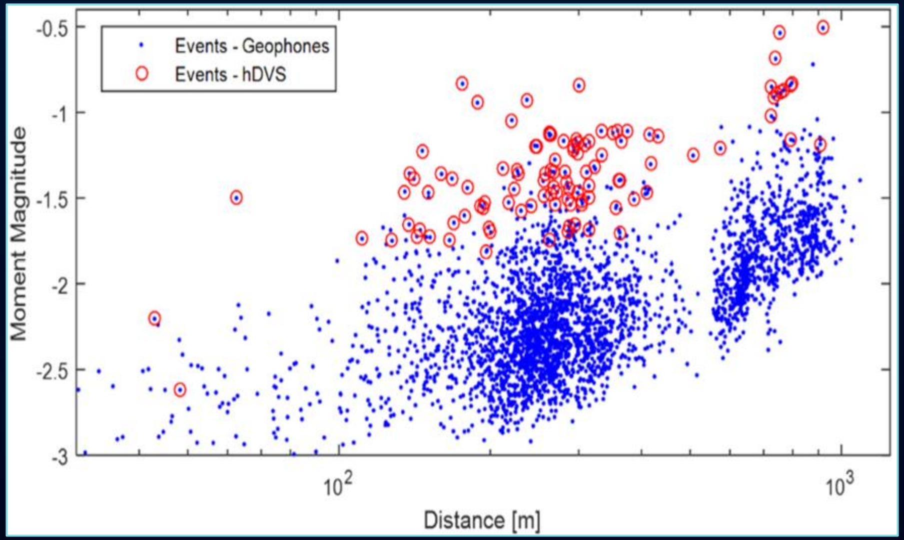
Example-18:

Cemented fibers

DAS laser interrogator





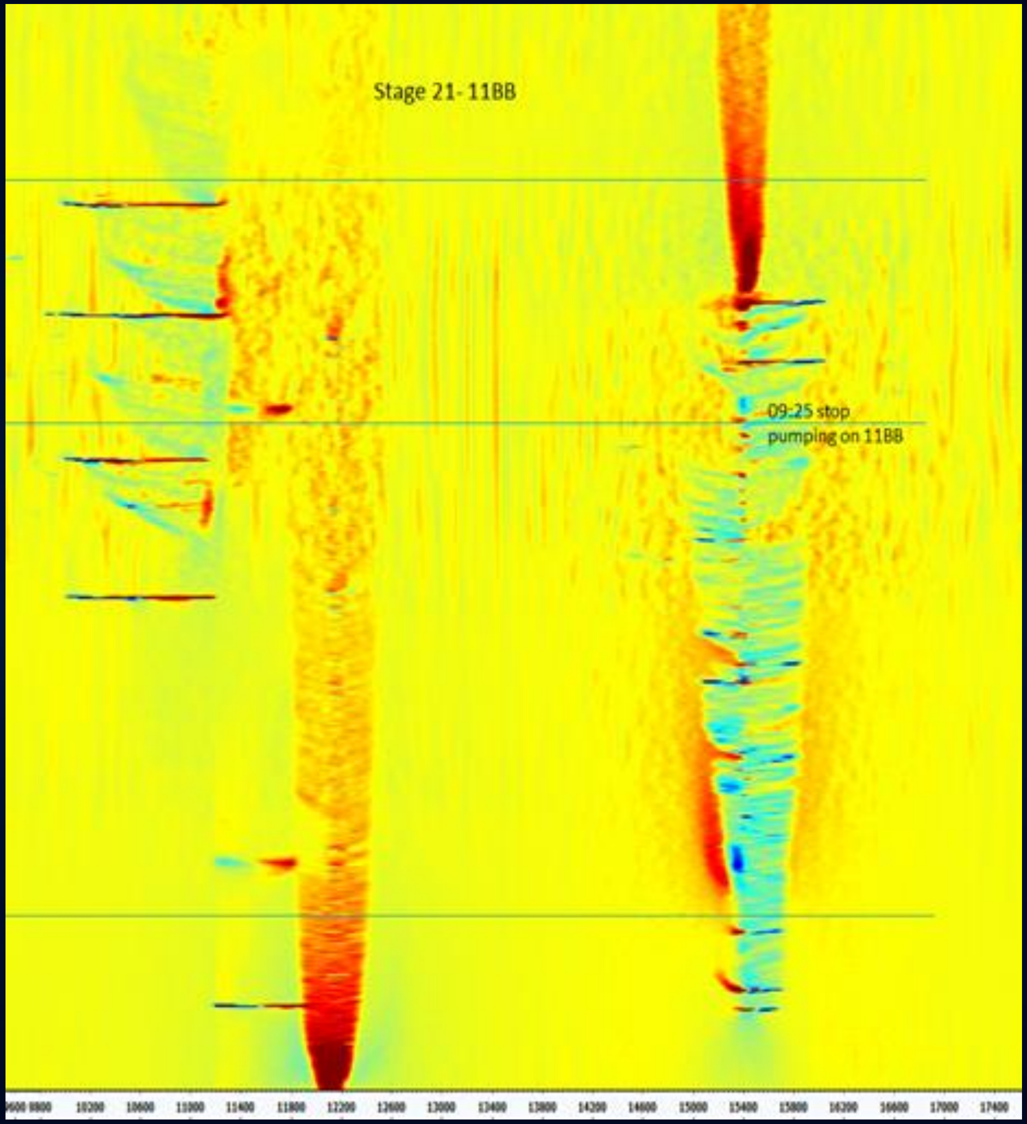


(Molteni et al., 2016)

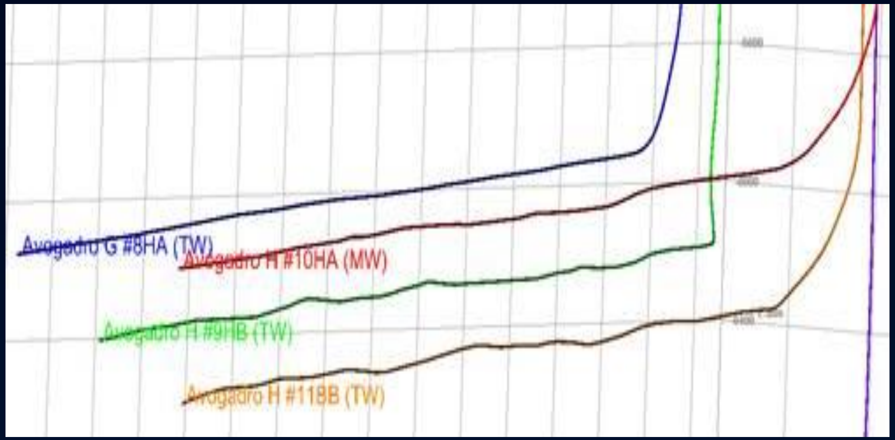
- Best SNR possible for DAS data
- No azimuth information except if monitoring from multiple wells
- *Location accuracy can be improved by combining DAS + geophones*

Microseismicity & low-frequency strain due to fluid injection

Example-19:

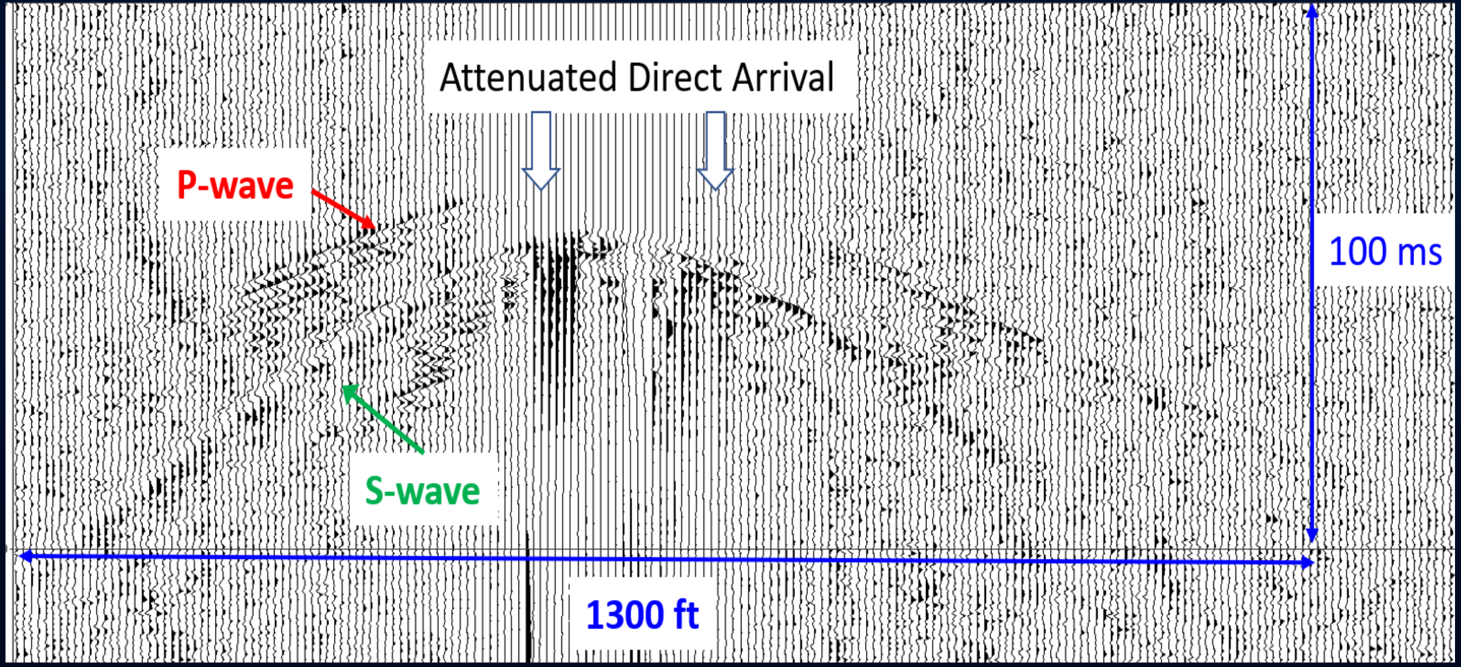


DAS Low-Freq strain-rate map *(1 mHz – 2 Hz)*



SM Fiber on coaxial cable, not cemented.

Previous generation laser interrogator data shown

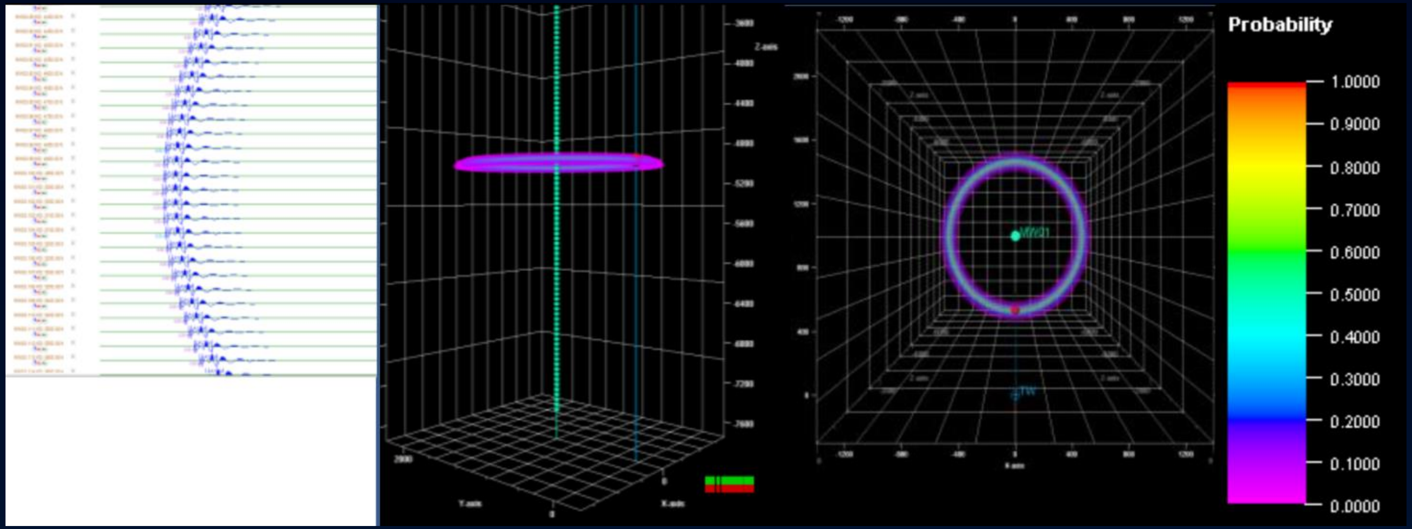


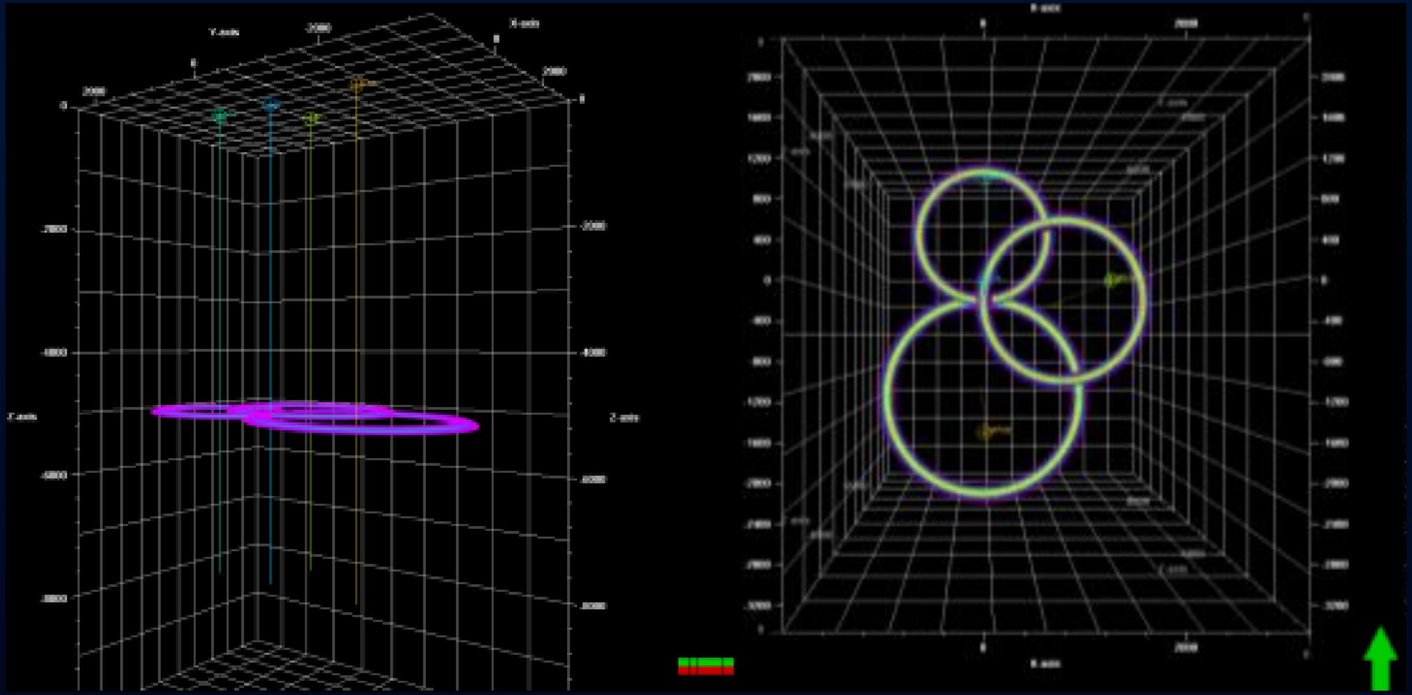
DAS microseismic events *(10 Hz – 1000 Hz)*

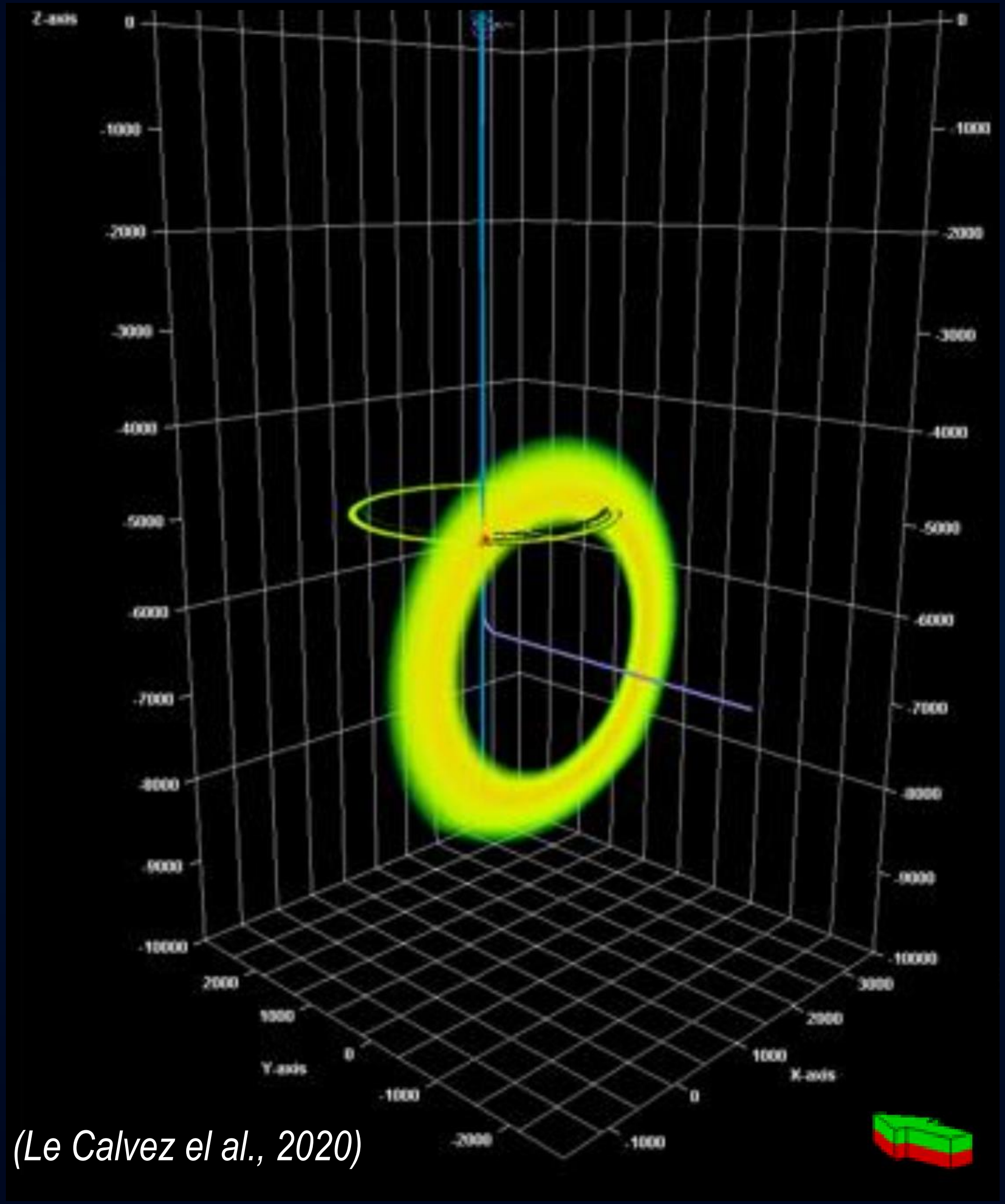
(Wilson , 2021)

Example-20:

Microseismic event location uncertainty with DAS







(Le Calvez el al., 2020)

Value to Customers

QHSE

- Elimination of a logging run
- No downhole equipment
- Elimination of NPT
- Reduced environmental footprint

More Data

- Effortless high-density velocity curve
- Data along the entire wellbore
- All wells

Cost

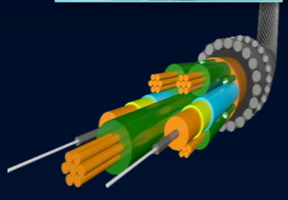
- Basic Seismic 12-24hrs to minutes
- Reduced logistics
- Long-term seismic improvement for the field

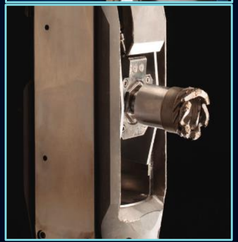
More…

✓Leak Detection
✓Completions Diagnostics
✓4D Seismic
✓Surface-Downhole Seismic
✓Microseismic
✓…

Lower operational risk → **Right evaluation of complex formations** → **Reduce overall total cost of ownership**

NOTE: *VSP 3-C data has advantages in uncemented intervals and in advanced applications but needs a dedicated run. GEO + DAS are interesting in Walkaway & 3DVSP*





Q & A