Estimating S-wave velocities and changes from tube waves

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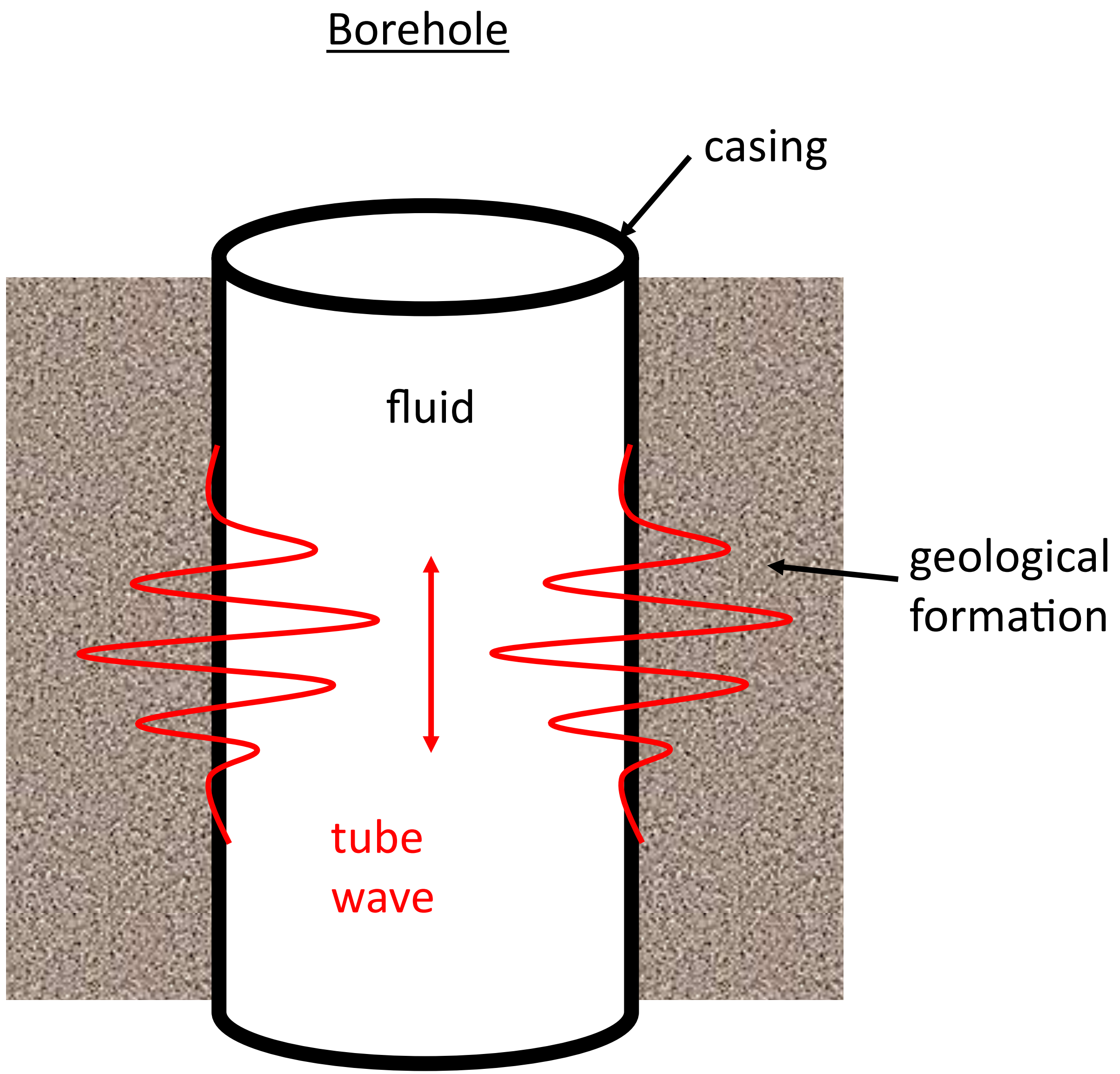
Tube Wave

- Tube wave history
  - Lamb (1898), Biot (1952), Somers (1953), …
- Generated at interfaces striking the borehole
  (Hardage, 1981)
- Usage:
  - identification of fractures
    (Hornby et al. 1989; Li et al., 1994)
  - permeability of formation when coupled to borehole fluid
    (White, 1965; Chang et al., 1988; Winkler et al. 1989)
  - estimate S-wave of formation from acoustic logging
    (Stevens and Day, 1986)
  - often considered as noise in VSP



Motivation

Is it possible to estimate the Shear Modulus and S-Wave velocity changes in the geological formation by measuring Tube waves?

Advantages

- Fixed source position
  - position and firing time is not required
- Only hydrophones are required
  - free from mechanical noise (Peng, 1996)
  - low-cost
- Permanently installed system
- Might use passive seismic recordings

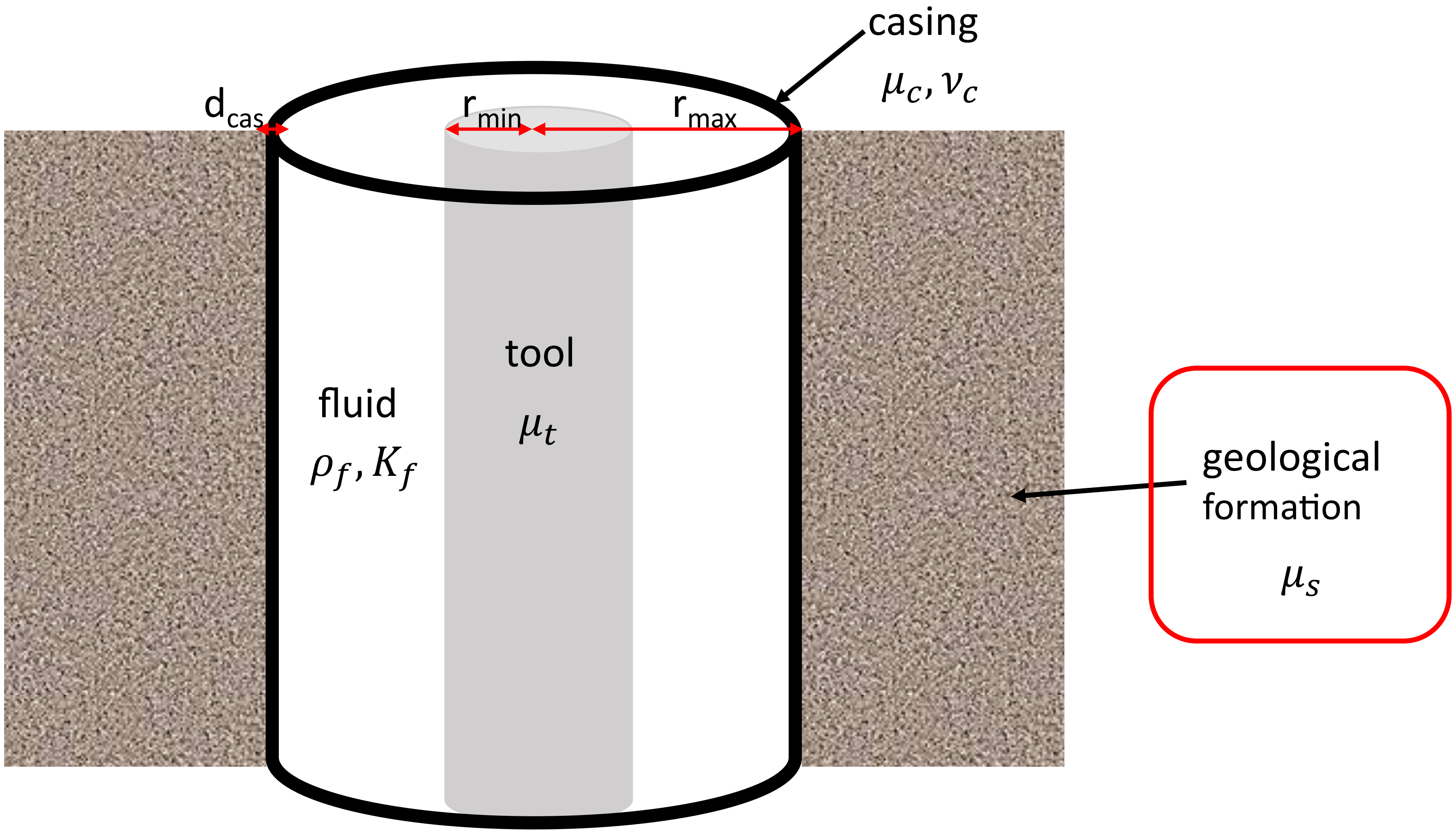
Problems

- Precise estimation of tube wave velocity
- Tube wave depends on several borehole parameter (casing, logging tool, borehole fluid)

Theory

Theory

Important parameter for Tube wave vs. Shear Modulus of formation

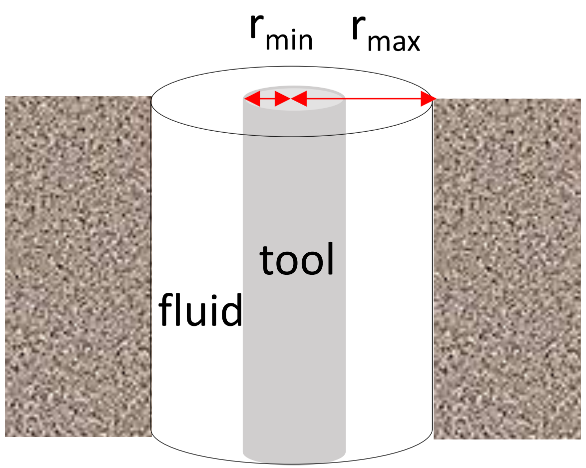


Theory

(1) Only logging tool:

(Marzetta and Schoenberg, 1985)

$$v_{t1} = \left\{ \rho_f \left[\frac{1}{K_f} + \frac{1}{1-\eta} \left(\frac{1}{\mu_s} + \frac{\eta}{\mu_t} \right) \right] \right\}^{-\frac{1}{2}}$$

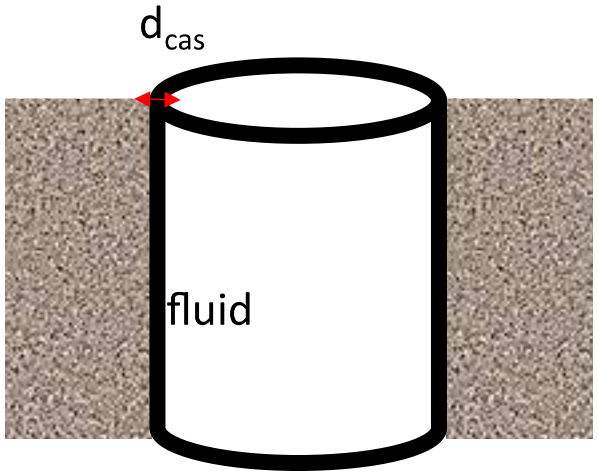


(2) Only casing:

(Marzetta and Schoenberg, 1985, Norris 1990)

$$v_{t2} = \left\{ \rho_f \left[\frac{1}{K_f} + \frac{1}{N} \right] \right\}^{-\frac{1}{2}}$$

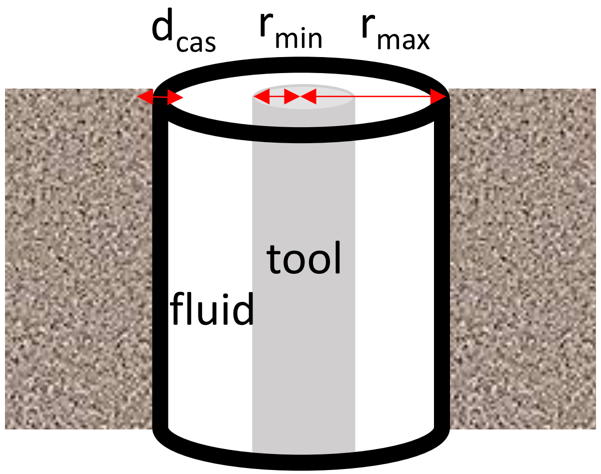
$$N = \frac{2(1-\nu_c)\mu_s + (\mu_c - \mu_s)(1-a^2)(1-\beta\nu_c^2)}{2(1-\nu_c) - \left(1 - \frac{\mu_s}{\mu_c}\right)(1 - 2\nu_c + \beta\nu_c^2)(1-a^2)}$$



(3) Logging tool and casing:

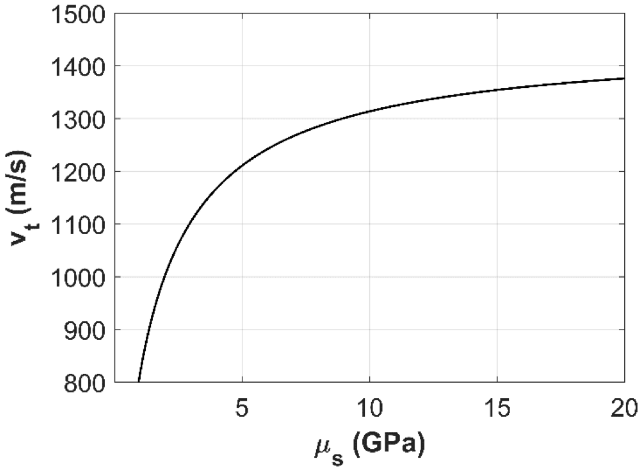
(Norris, 1990)

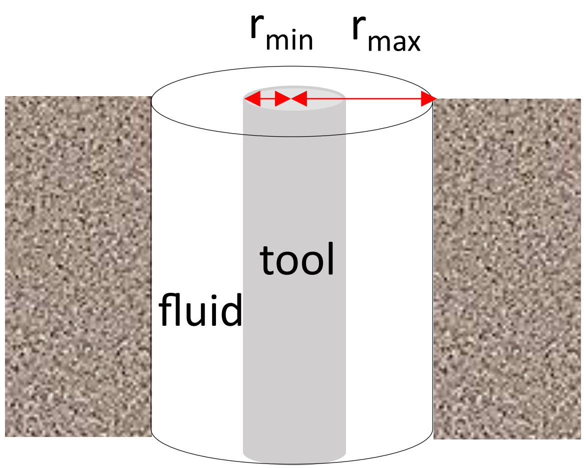
$$v_{t3} = \left\{ \rho_f \left[\frac{1}{K_f} + \frac{\eta}{(1-\eta)\mu_t} + \frac{1}{(1-\eta)N} \right] \right\}^{-\frac{1}{2}}$$



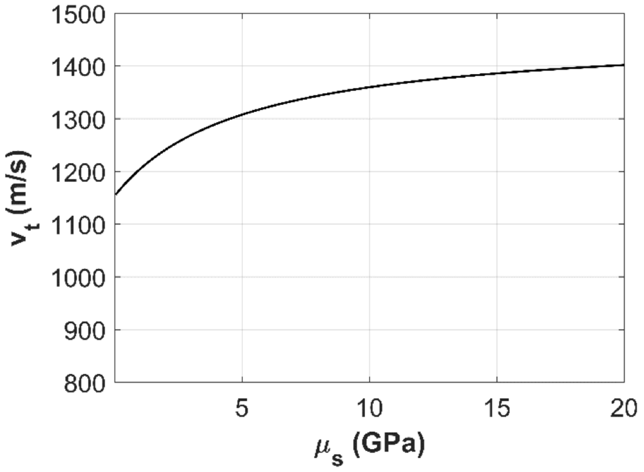
Theory

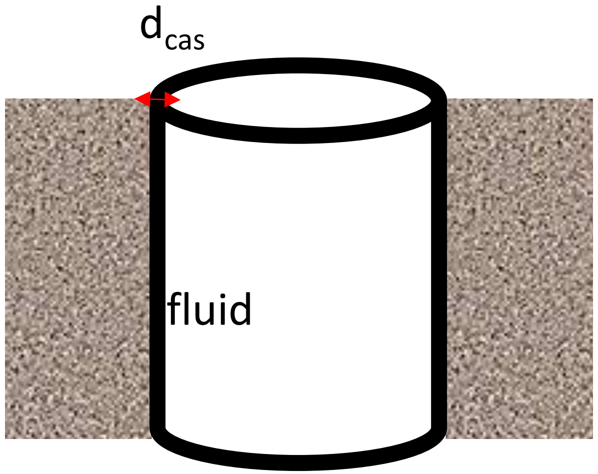
(1) Only logging tool:



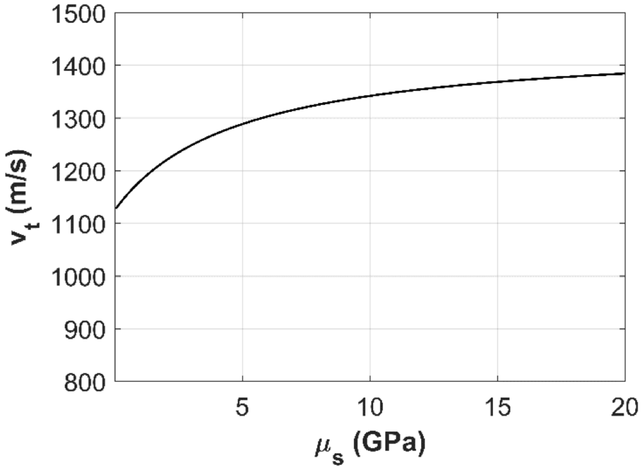


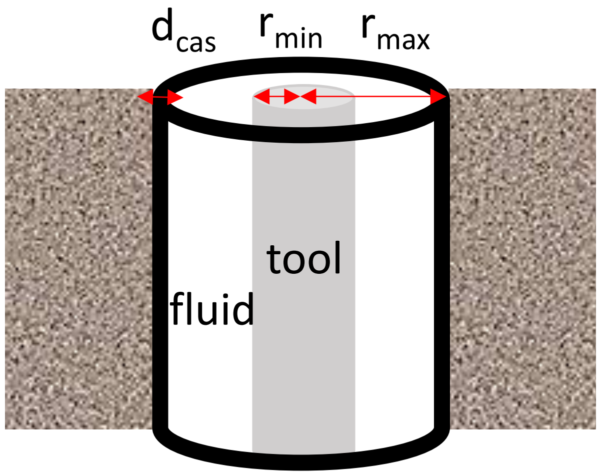
(2) Only casing:





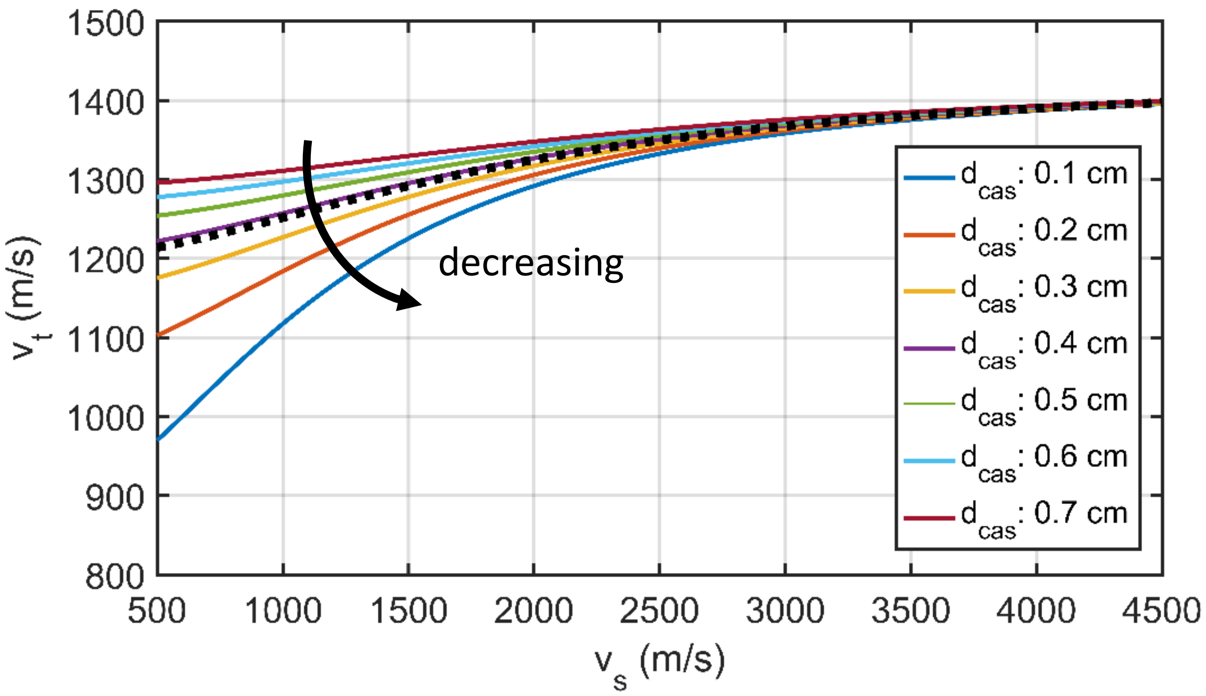
(3) Logging tool and casing:



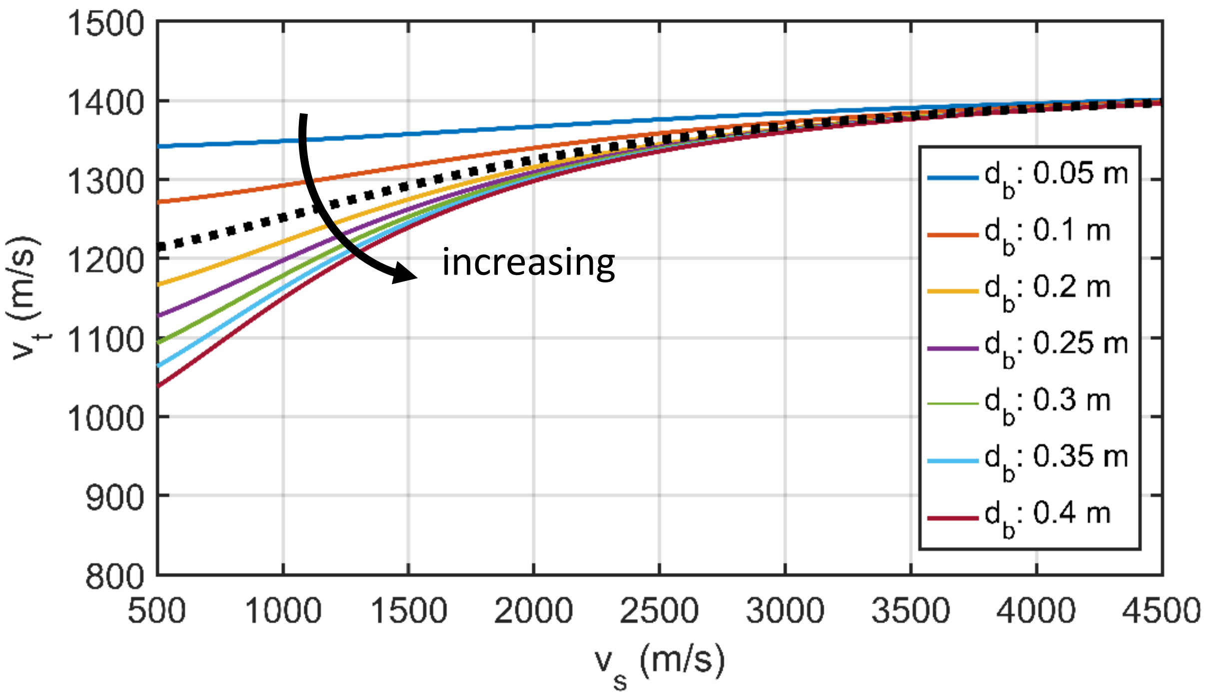


Sensitivity to different parameter

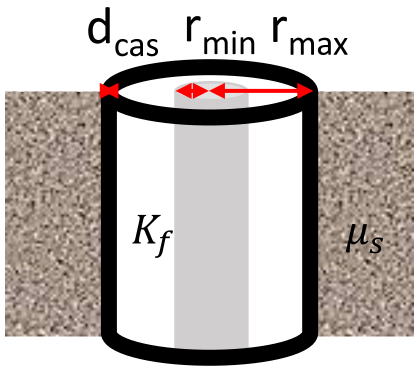
Casing thickness



Borehole diameter



...... reference



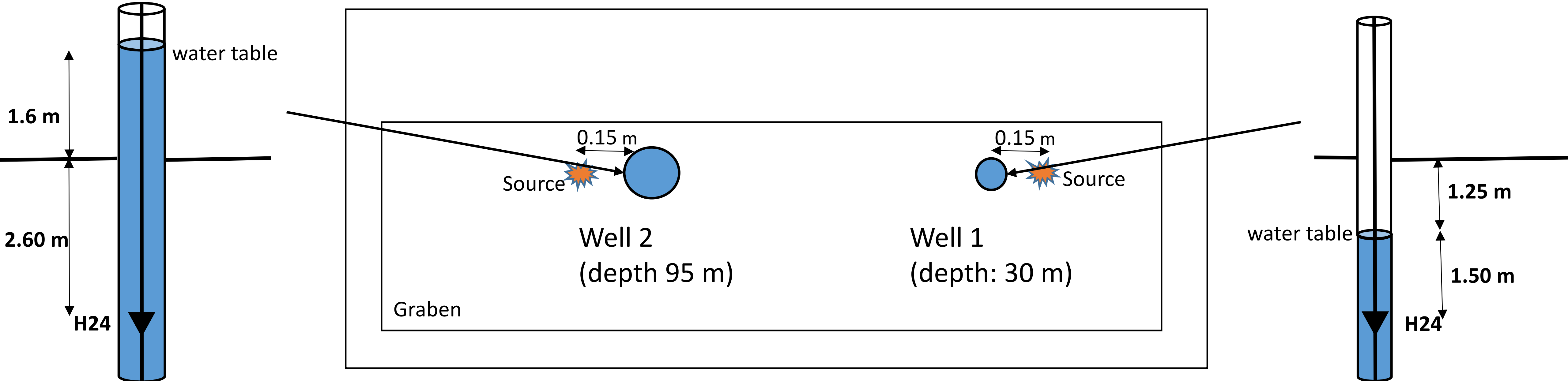
Experiments

Experiments

Workhall

Wells

Source



Experiments

Receiver: 24 channel hydrophone array

- spacing: 1 m
- frequency range1 Hz – 10000 Hz

Tests:

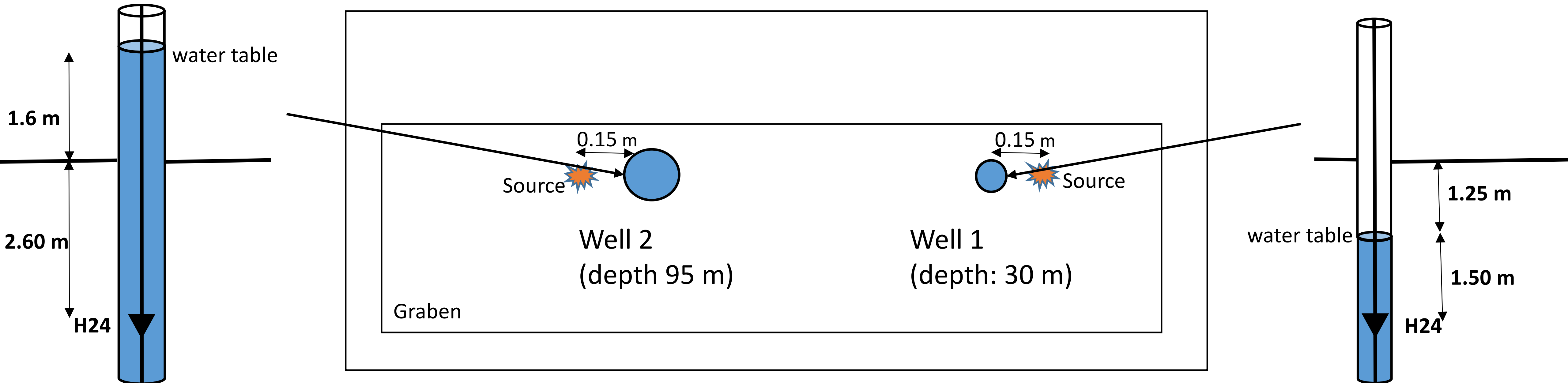
- Well 1: September 17, October 17 and March 18
- Well 2: October 17

Well 1:

- diameter: 15 cm
- casing thickness: 4 mm

Well 2:

- diameter: 30 cm
- casing thickness: 5 mm



Results

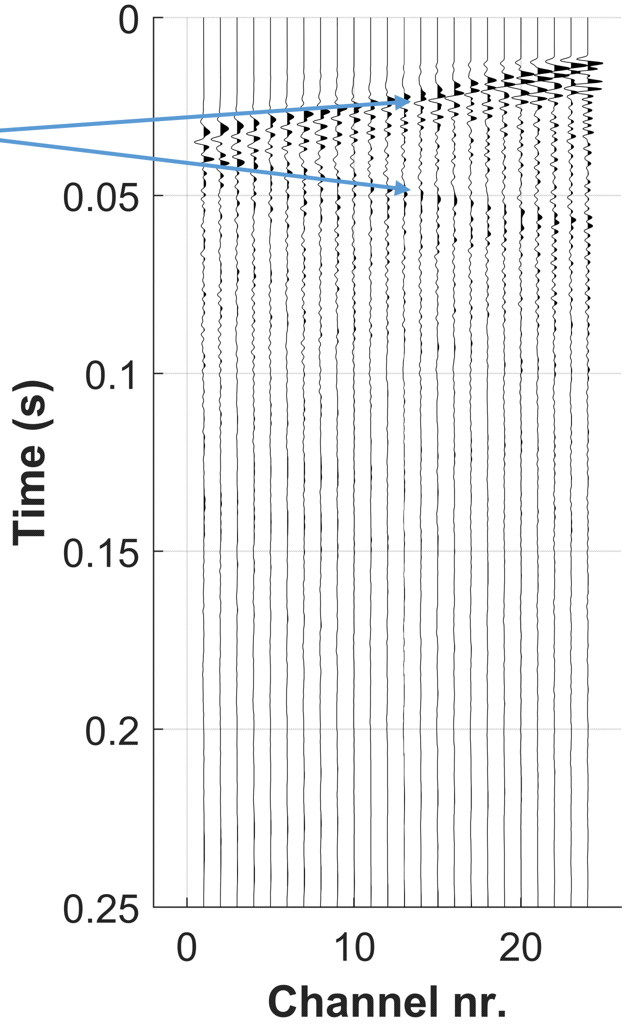
Recordings

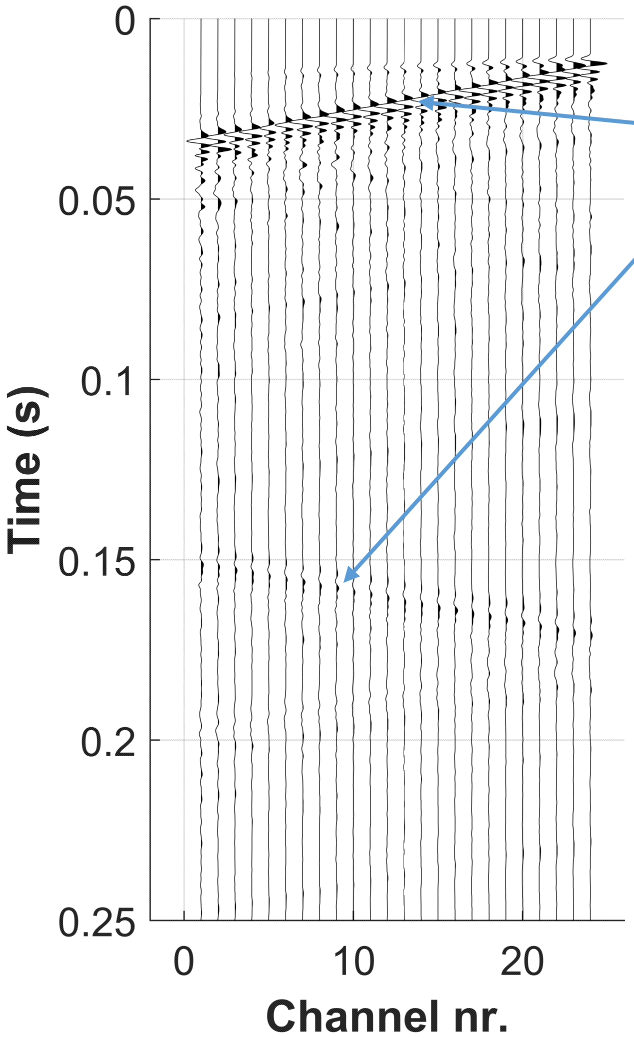
Well 1 (30 m)

Well 2 (95 m)

bandpass filter: 50 Hz – 450 Hz

Down- and upgoing
Tube Wave

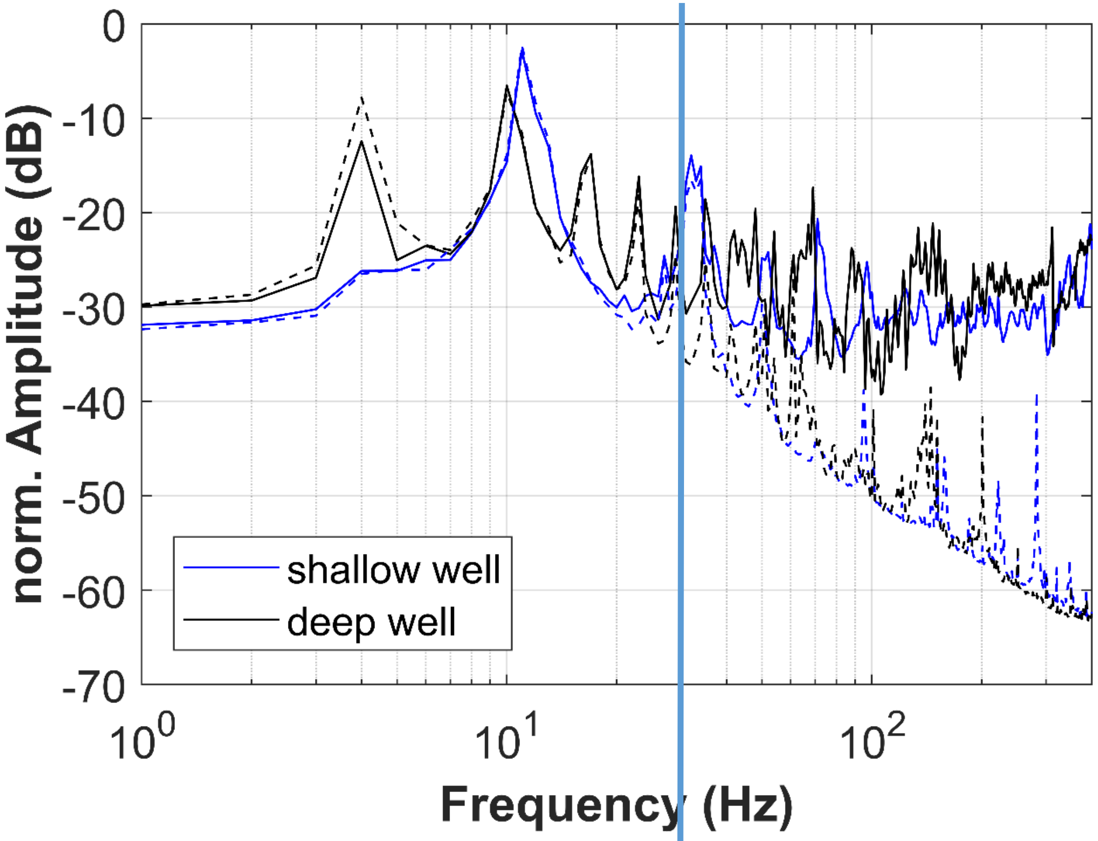




Down- and upgoing
Tube Wave

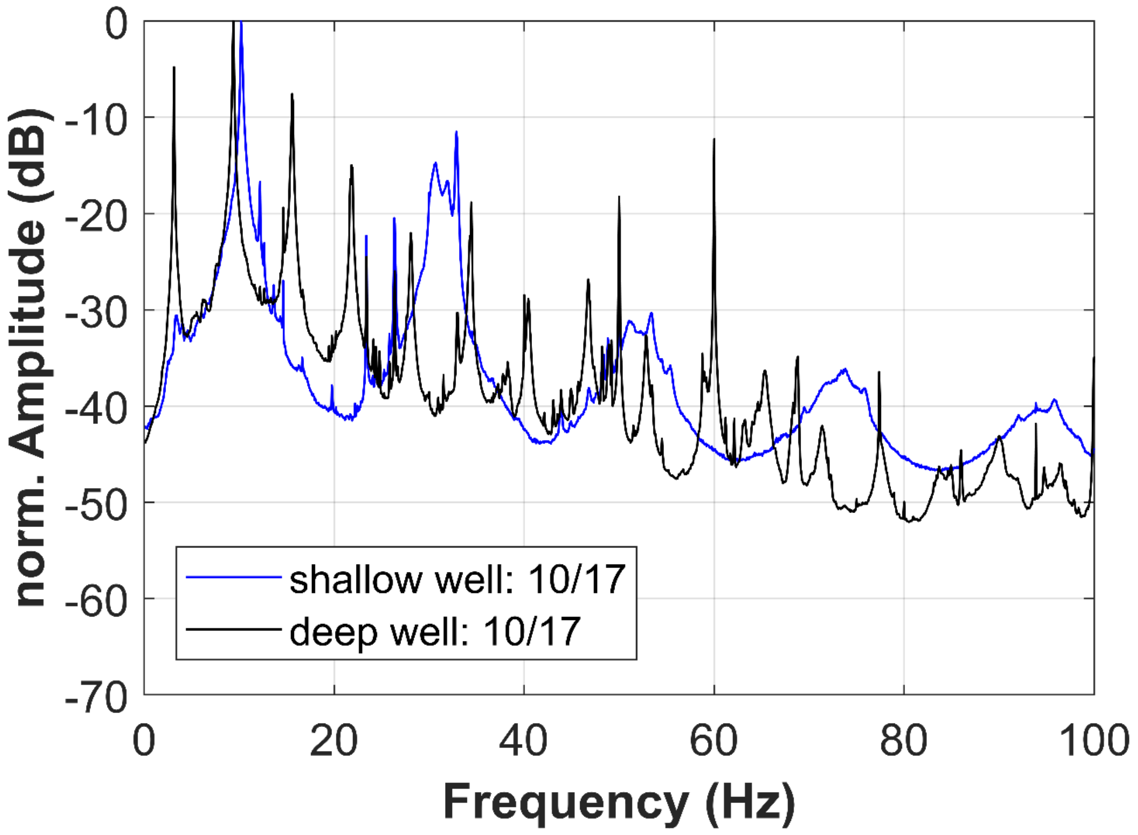
Recordings

Active recordings and noise



> 30 Hz: signal above noise level

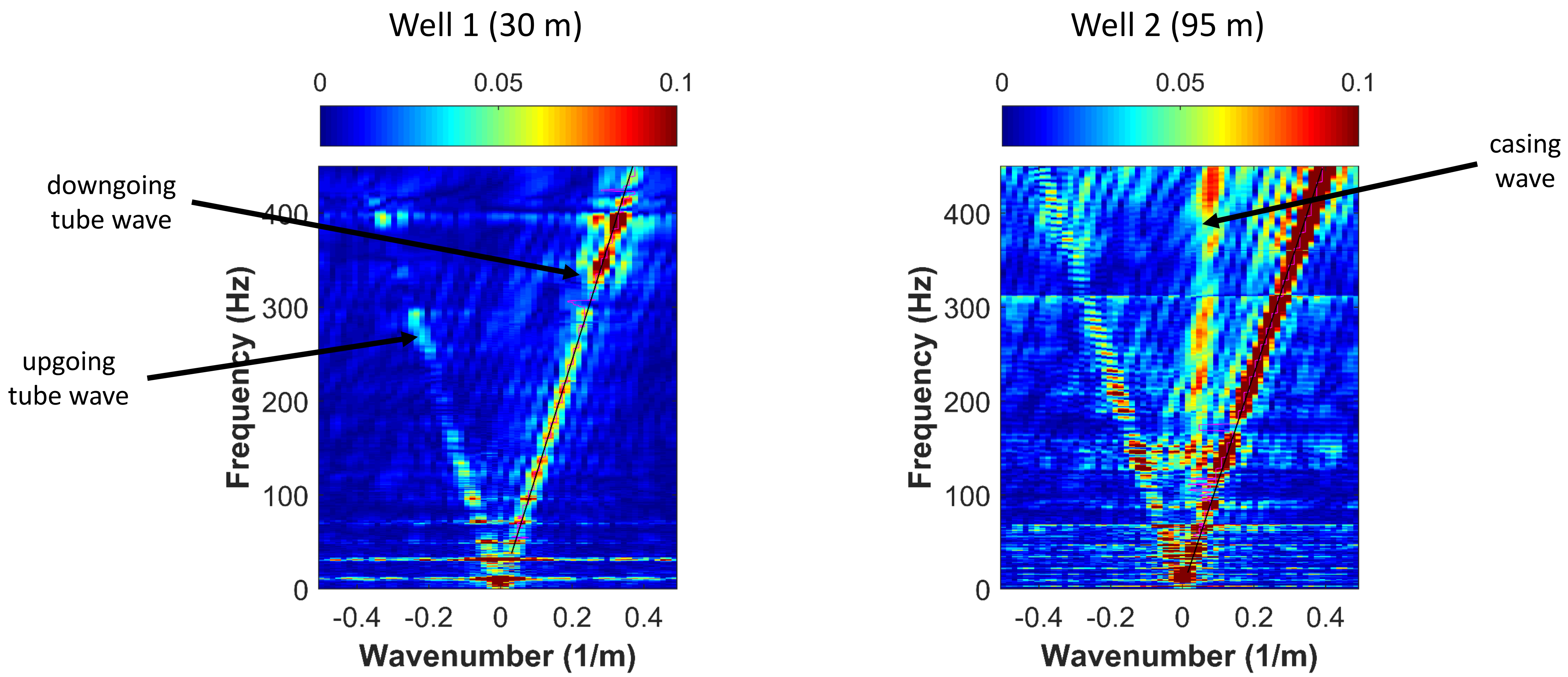
Passive recordings



Peaks at $f = \frac{1200\frac{m}{s}}{4*z_w}(2m-1), \quad m = 1,2,3,\ldots$

- Shallow well Δf = 20 Hz
- Deep well Δf = 6 Hz

Tube Wave Velocity



Least-squares line fit to estimate velocity

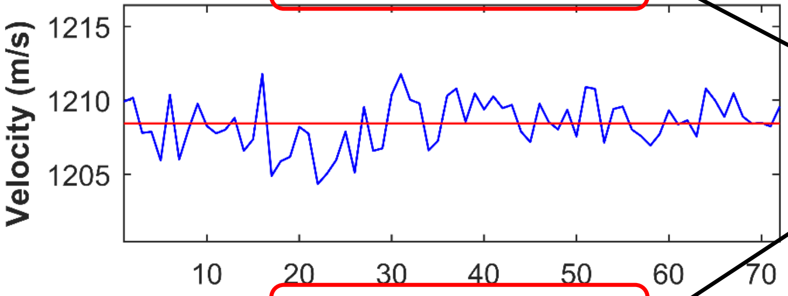
- between 50-450 Hz
- dispersion effect: velocity decrease < 0.02 % between 0-1000 Hz

Tube Wave Velocity

Well 1 (30 m)	Well 2 (95 m)

September 17

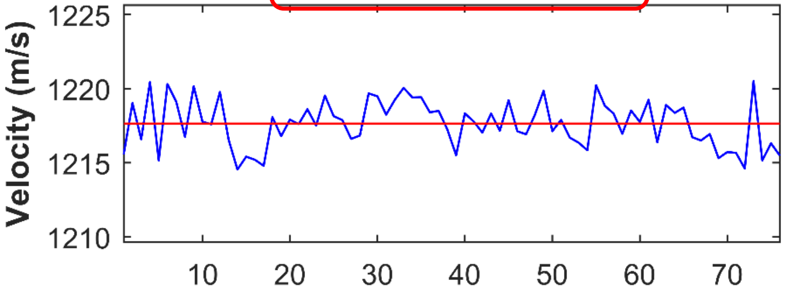
$v_t = 1208.4 \pm 1.7$ m/s



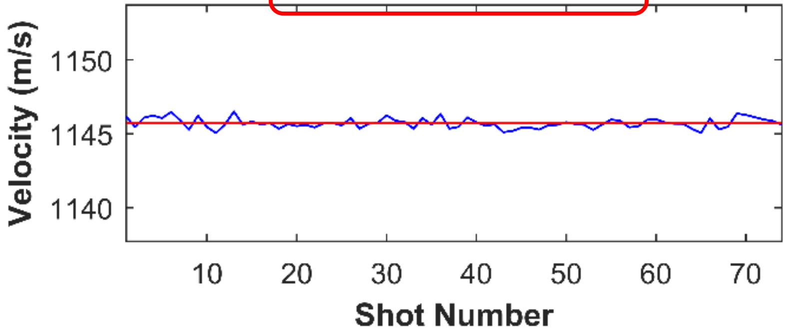
could be caused by temperature difference in borehole fluid
(1°C → 2 m/s)

October 17

$v_t = 1217.6 \pm 1.6$ m/s



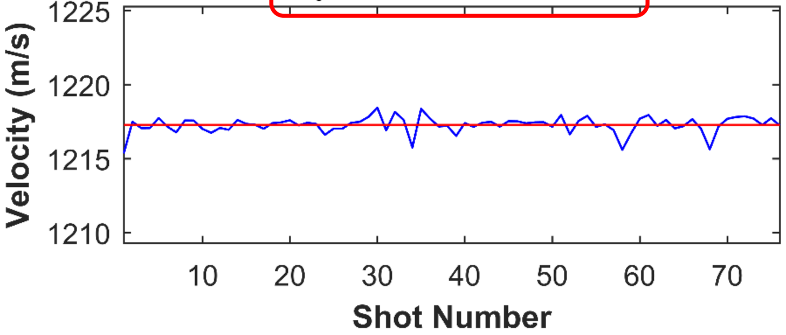
$v_t = 1145.7 \pm 0.3$ m/s



October 17

March 18

$v_t = 1217.3 \pm 0.6$ m/s

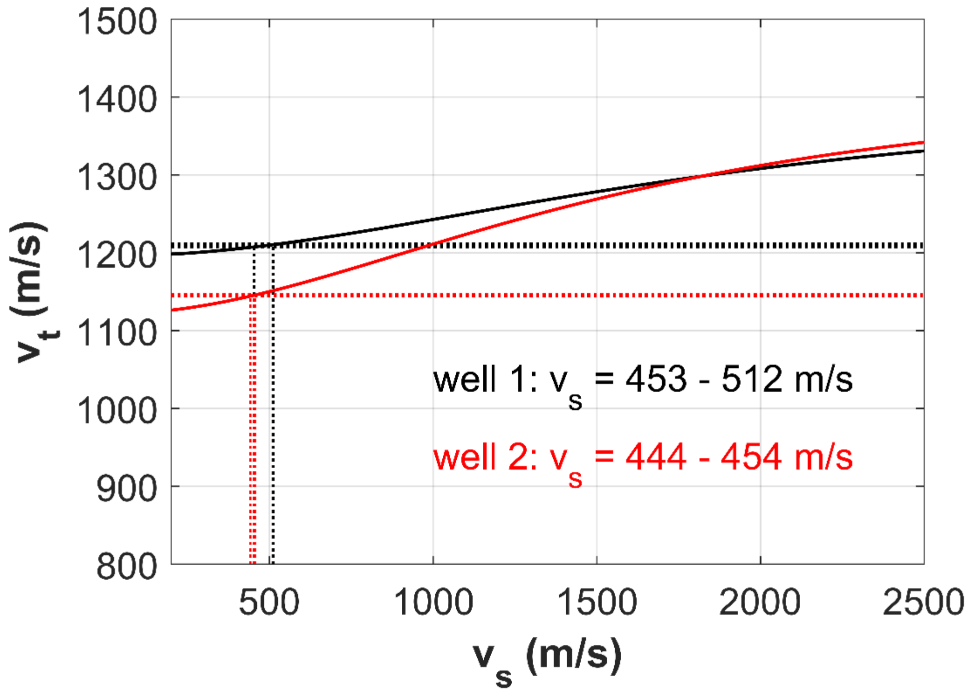


→ High accuracy in results

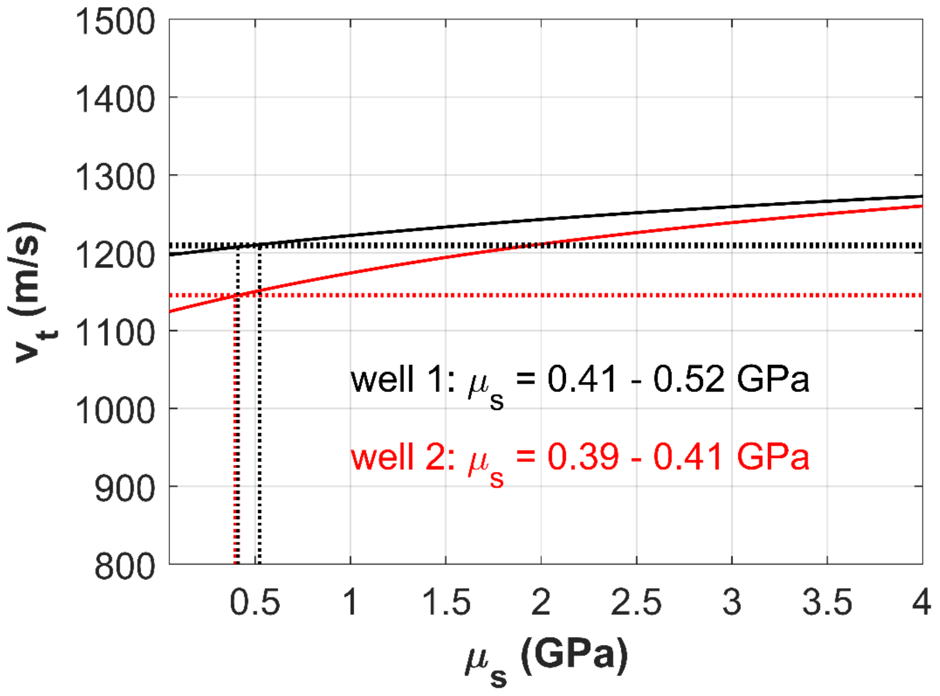
Estimated Formation Properties

S-wave velocity

(ρ = 2000 kg/m^3)



Shear modulus



Smaller estimated range in well 2

- higher accuracy of tube wave velocity
- different borehole geometry

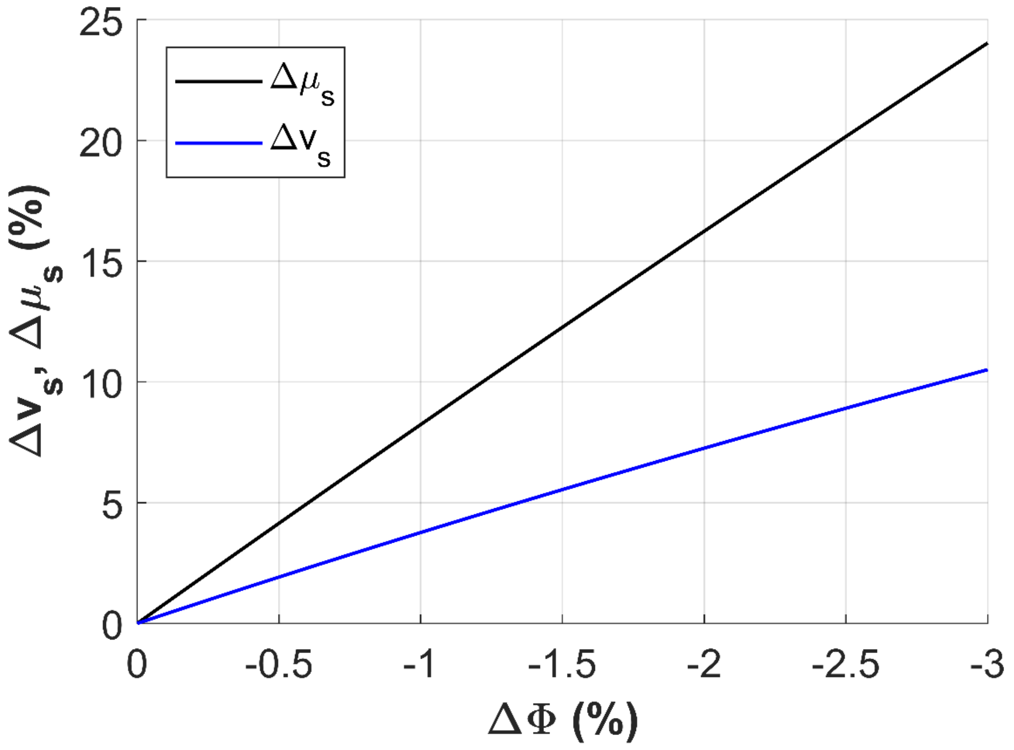
Field example

Field example: CO_2 injection

Changes due to CO_2 injection

Precipitation of salt

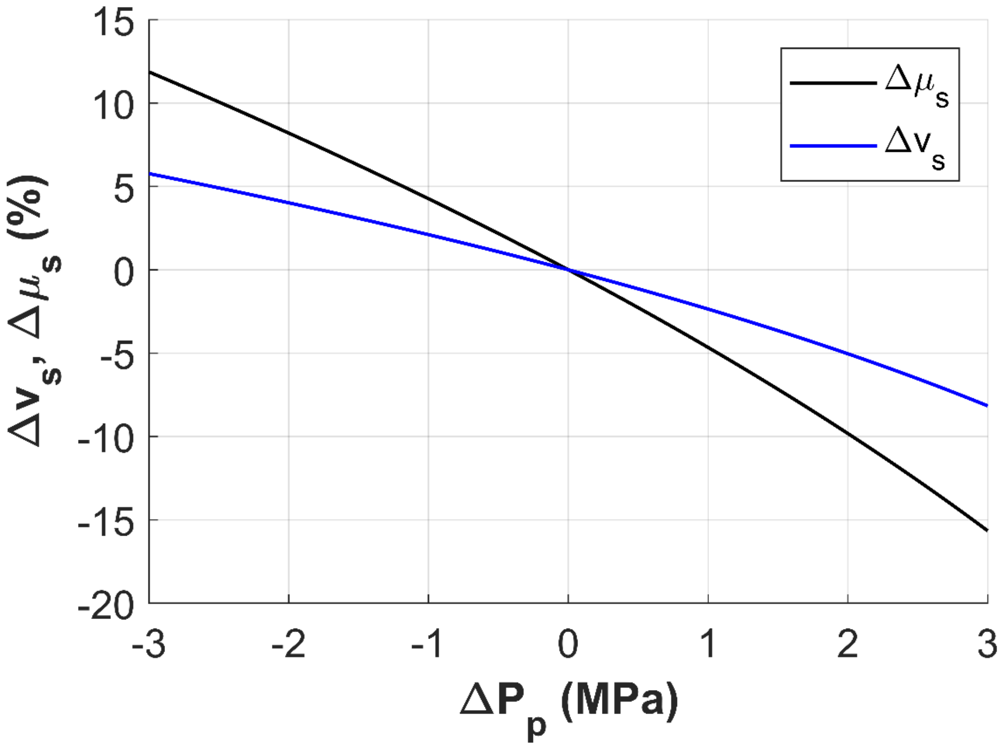
(Lab examples: Vanorio et al., 2011; Grude et al. 2014)



- sandstone, initial porosity Φ = 0.3
- salinity: 50000 ppm

Pore pressure P_p increase

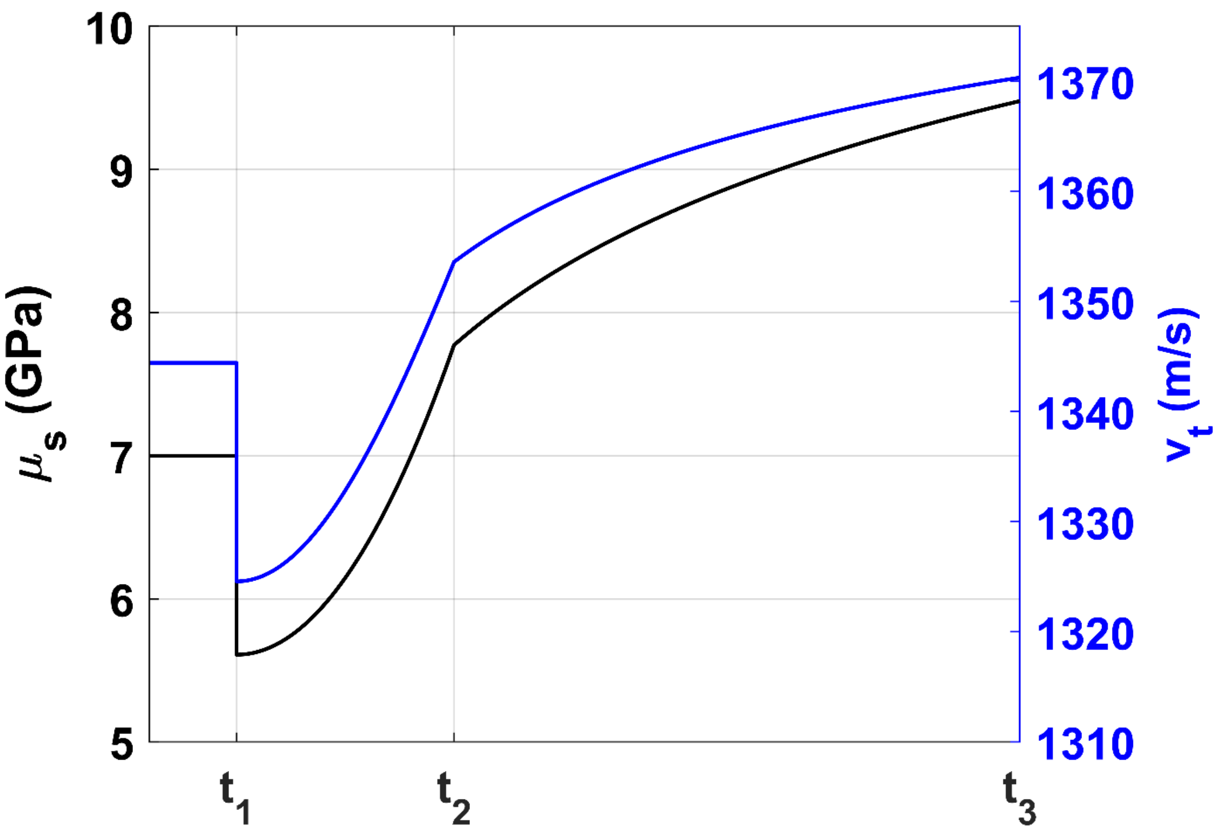
(Field examples: Duffaut and Landrø, 2007; Grude et al. 2014)



- inital P_p = 7.5 MPa (ca. 750 m depth)
- Hertz-Mindlin model

Field example: CO_2 injection

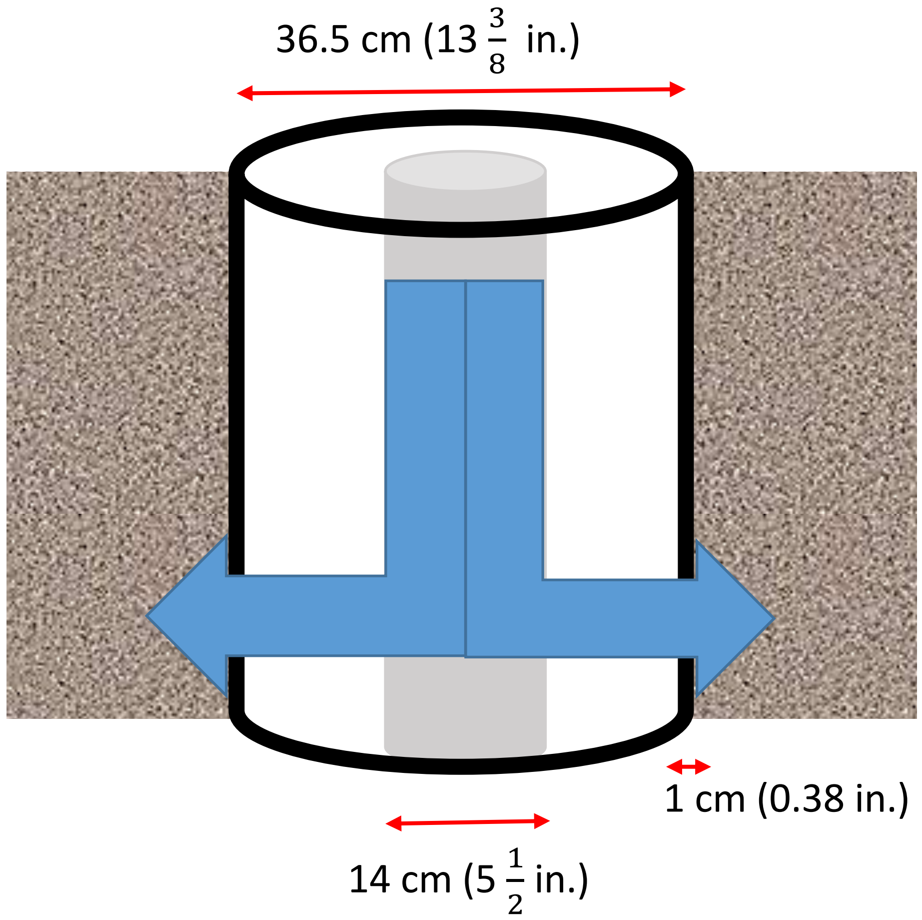
Time steps during CO_2 injection



t_1: injection starts

t_2: injection stops

t_3: initial pore pressure is reached



- inital P_p = 7.5 MPa (ca. 750 m depth)
- decrease of 2.5 MPa due to injection

Conclusion/Discussion

- Absolute estimation of shear modulus/S-wave is diffucult
  - additional measurements required
- Monitoring could be feasible
  - temperature in borefluid should be measured
  - high accuracy of measured tube wave velocity required
- Feasiblity depends on geological setting and borehole set-up
  - borehole should have: thin casing, large diameter, small casing shear modulus
  - geological formation with low initial shear modulus
- Advantages
  - no firing time and source location required (Passive Seismics?)
  - hydrophones: cheap, permanent monitoring system (Fibre Optics?)
- Disadvantages
  - tube wave depends on several parameter

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Norwegian University of Science and Technology Trondheim

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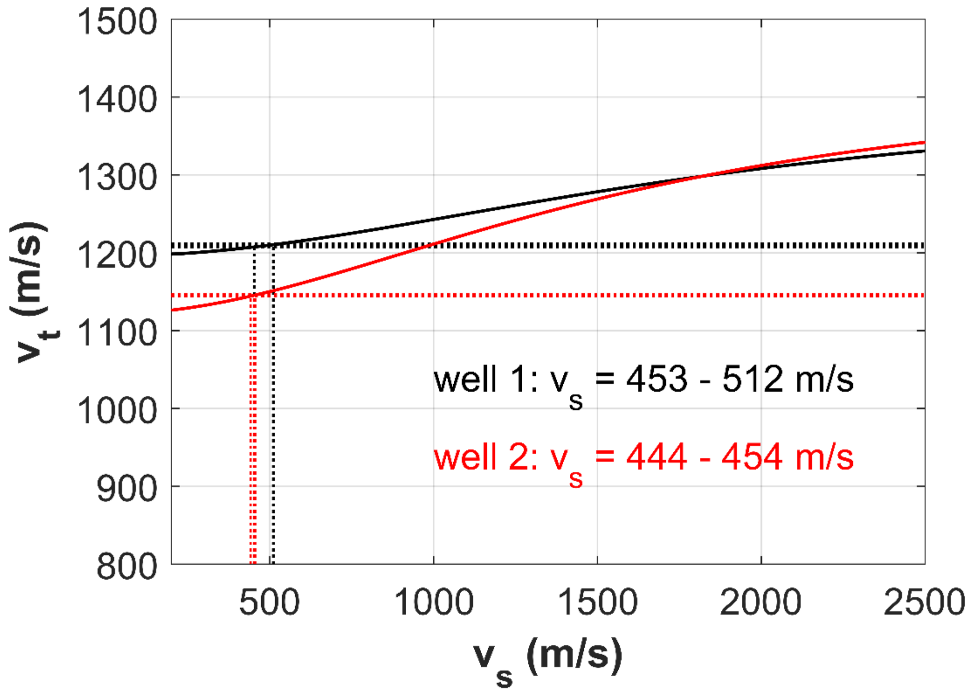
Appendix

Estimated Formation Properties

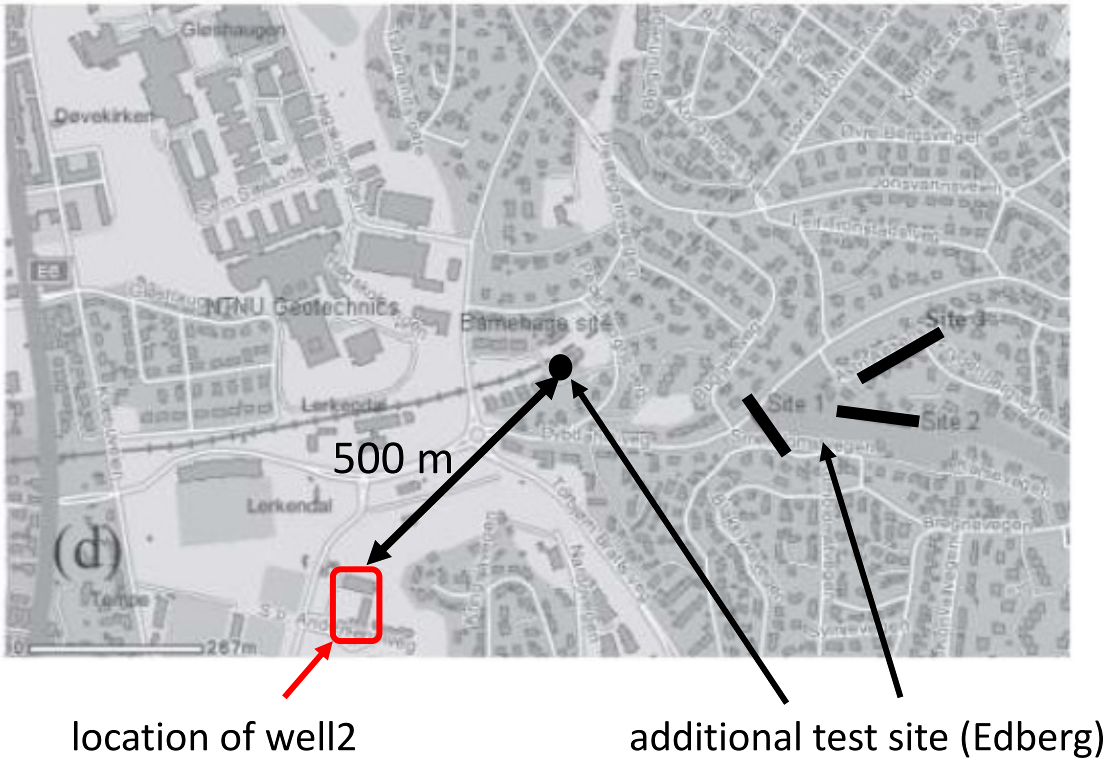
S-wave velocity

(ρ = 2000 kg/m^3)



''Reference'' test site Edberg

Long and Donohue, 2007



v_s at wells ca. 450 m/s
(down to 26 m depth)

v_s at Edberg site ca. 300 m/s
(down to 10 m depth)

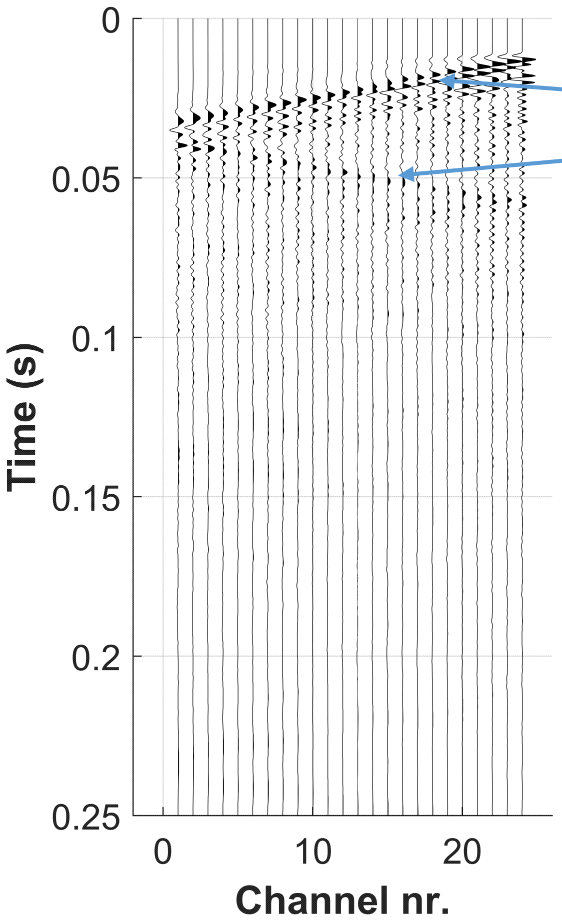
Outline

- Theory
  - Relation between Tube wave and S-wave in the surrounding formation
- Experiments
  - Set up and parameter
- Results
  - Measured Tube wave
  - Estimation of S-wave in the surrounding formation
- Discussion
  - Sensitivity analysis
  - Theoretical field example
- Conclusion

Recordings

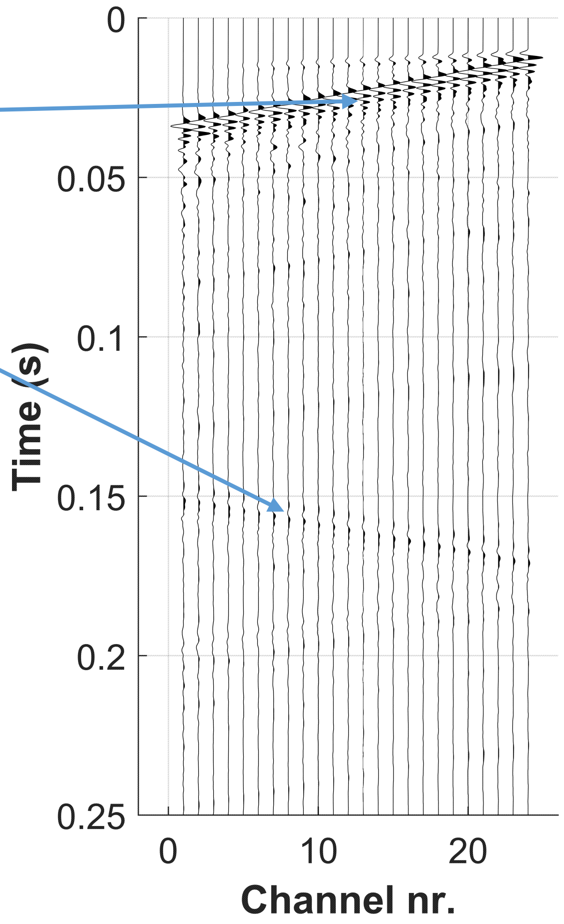
bandpass filter: 50 Hz – 450 Hz

Well 1 (30 m)



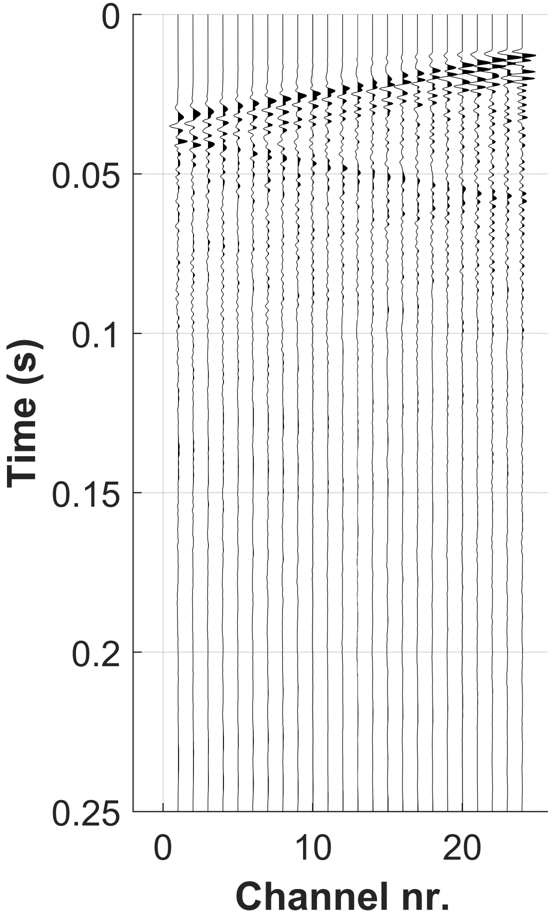
Down- and upgoing
Tube Wave

Well 2 (95 m)

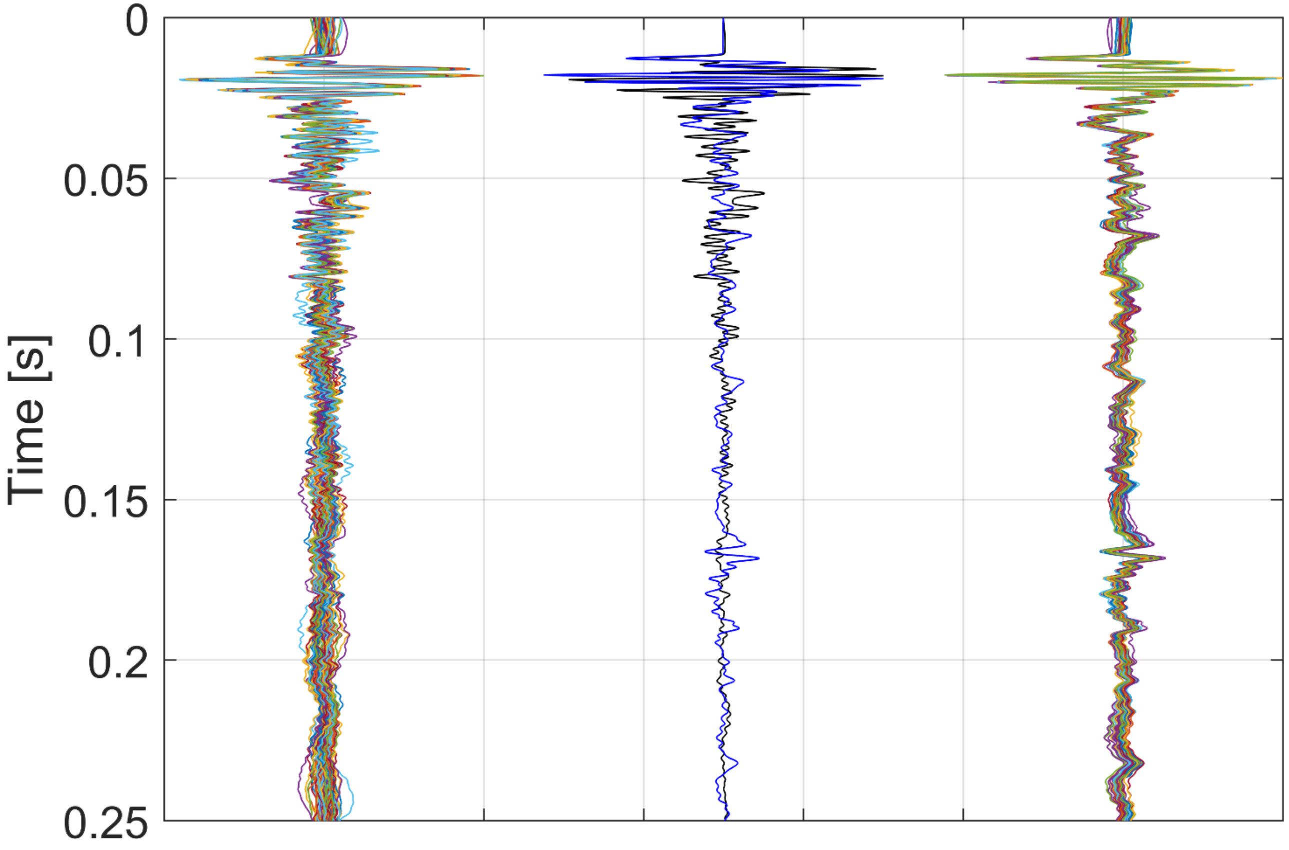


Recordings

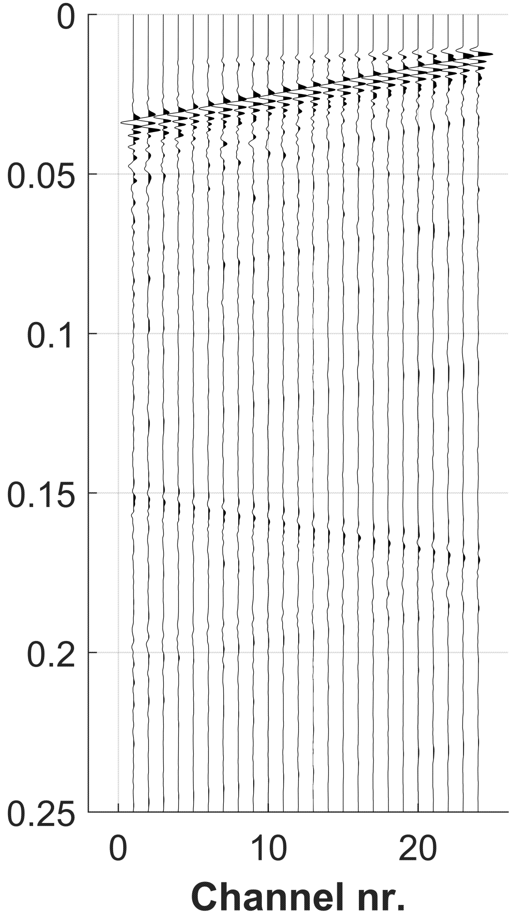
Well 1 (30 m)



Single receiver (Nr.: 20)



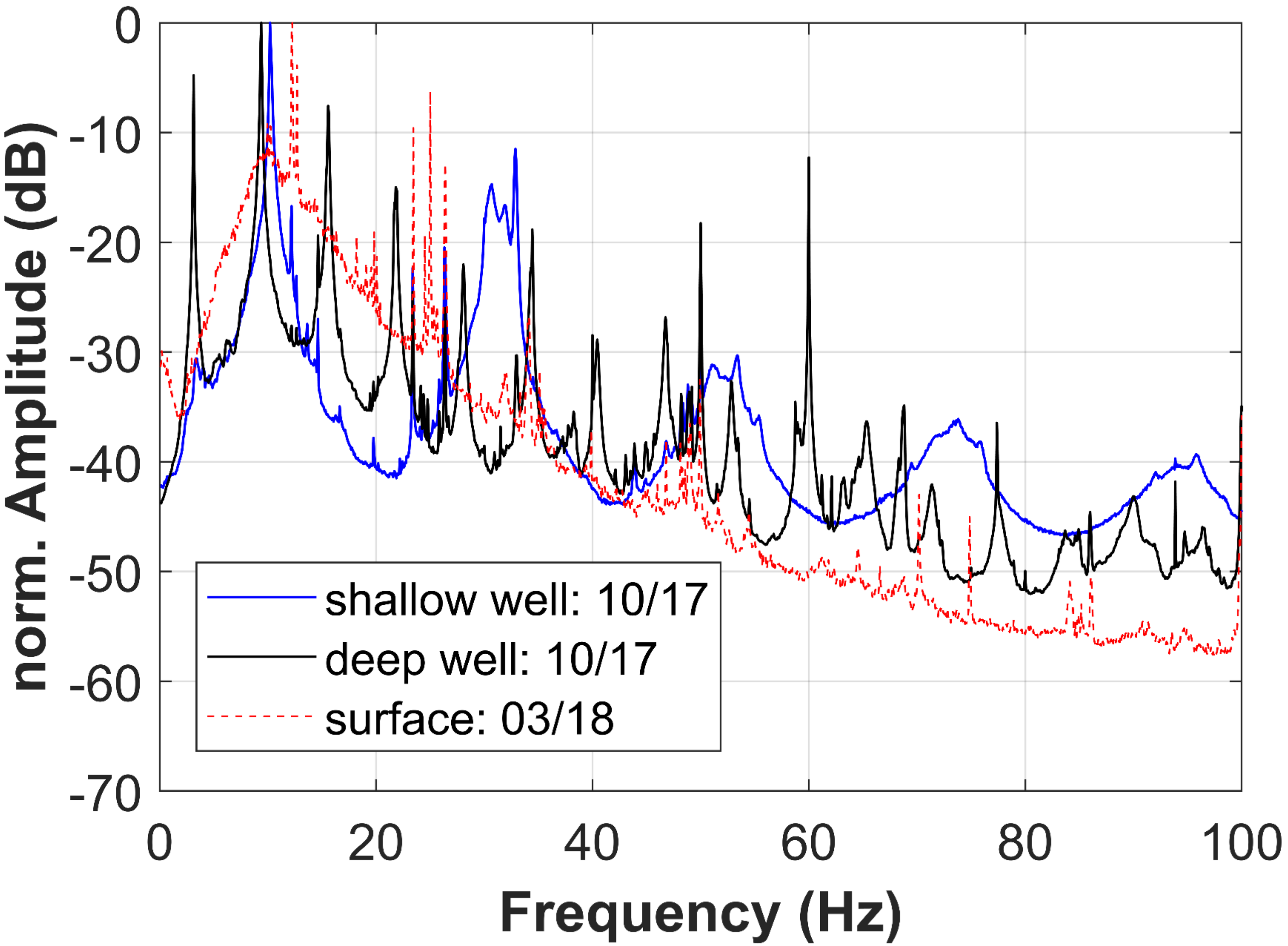
Well 2 (95 m)



- repeatability of 80 hammer shots
- longer repeatable signal in deep well

Recordings

Passive recordings

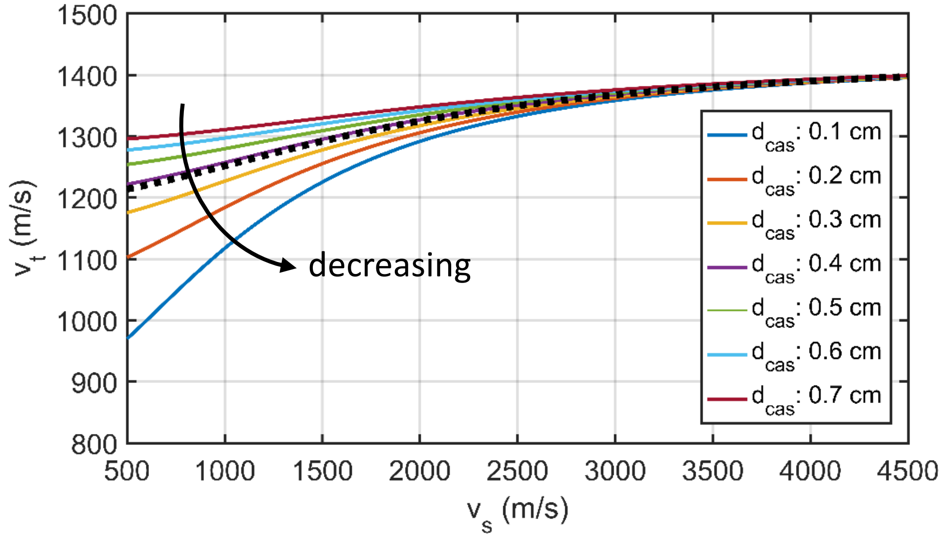


Peaks at $f = \frac{1200\frac{m}{s}}{4*30\ m}(2m-1), \quad m = 1,2,3,\ldots$

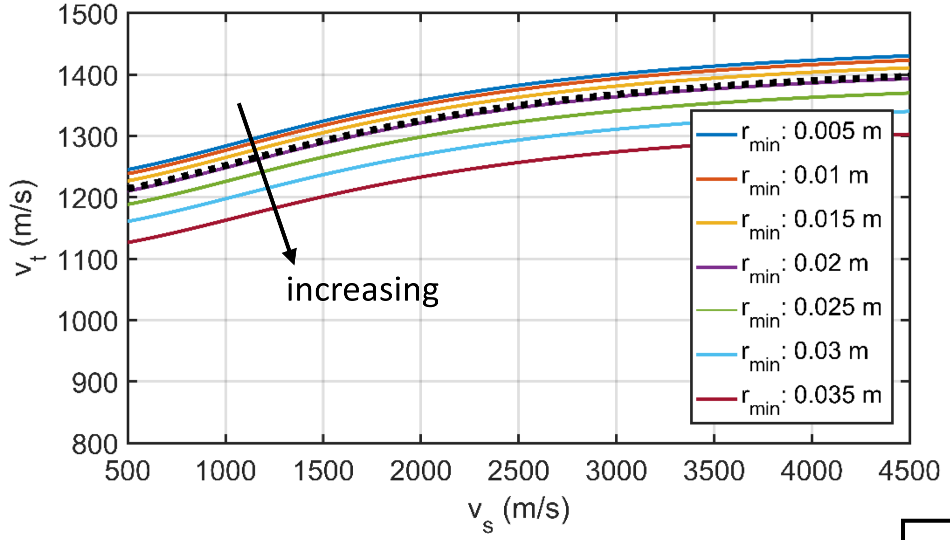
- Shallow well Δf = 20 Hz
- Deep well Δf = 6 Hz

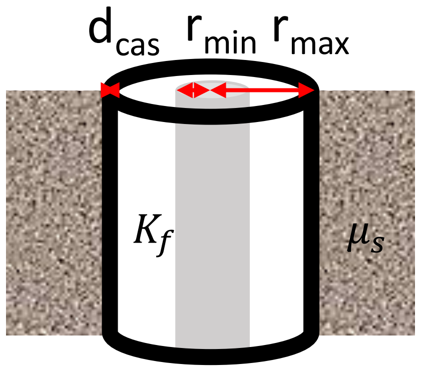
Sensitivity to different parameter

Casing thickness



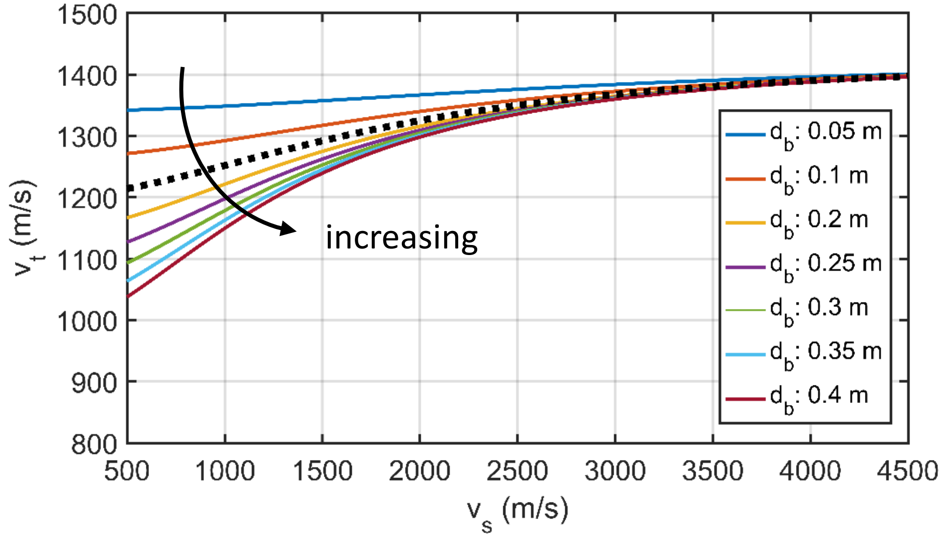
Tool thickness



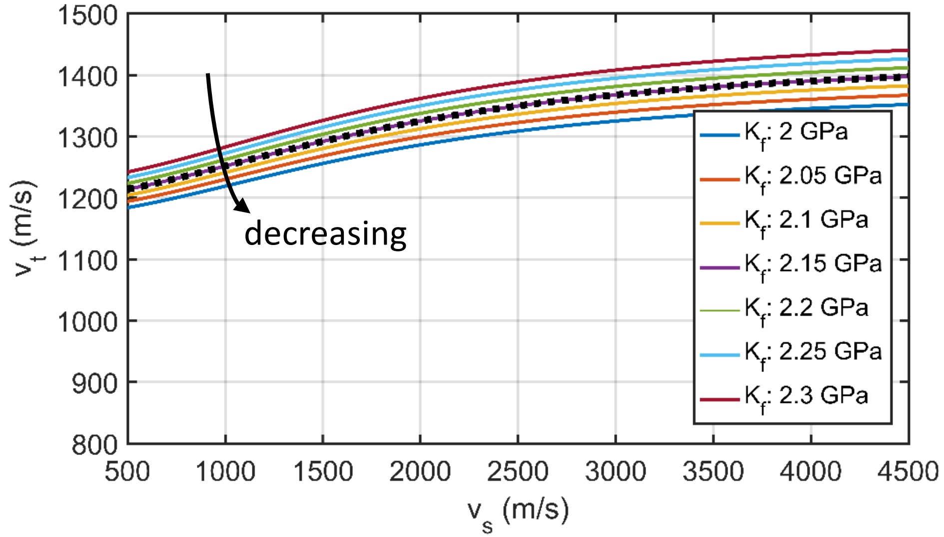


⋯⋯ experimental result

Borehole thickness



Bulk Modulus: borehole fluid

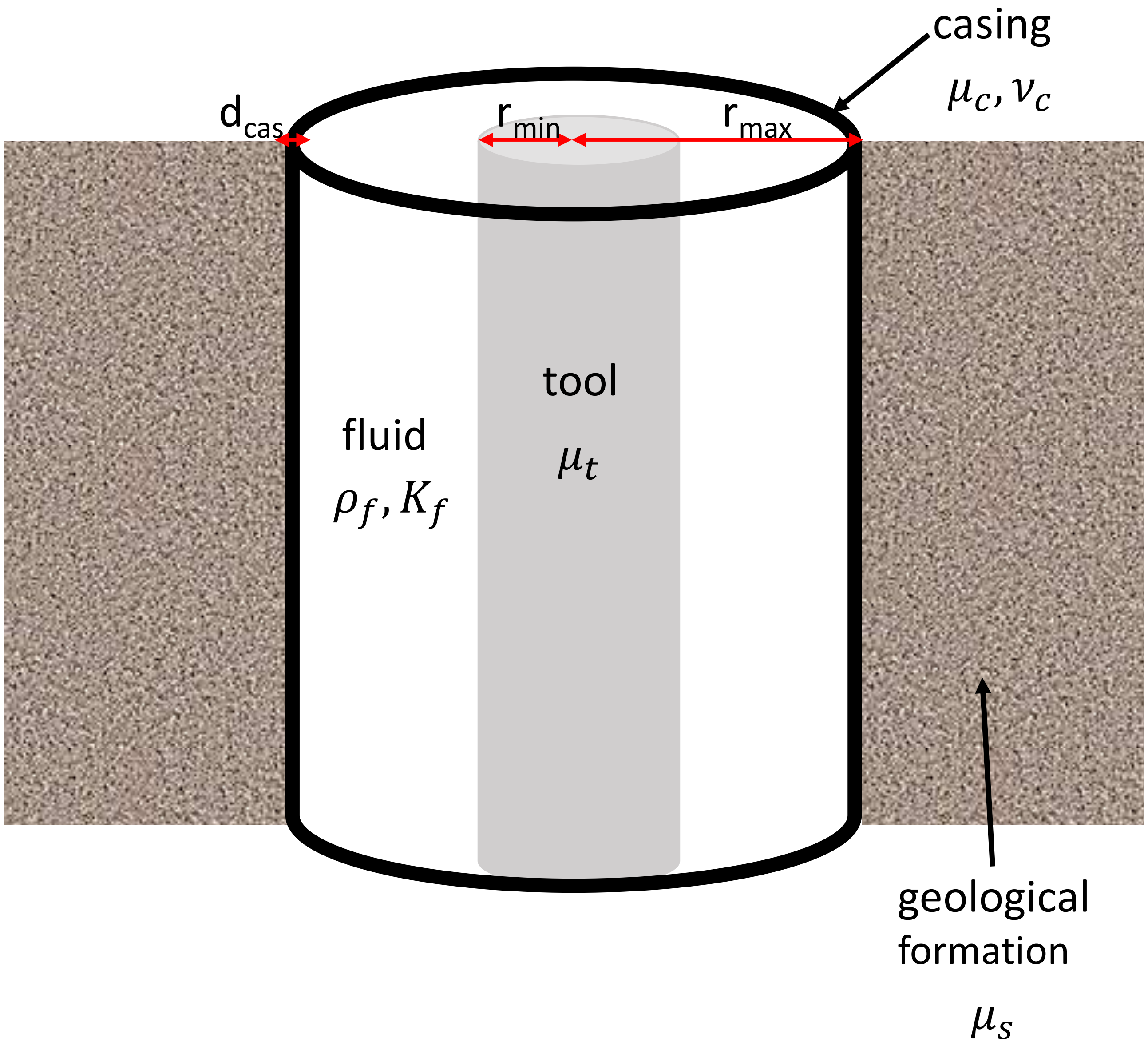


Paramter

- Geometry
  - $r_{\min} = 0.035\ m$
  - $r_{max} = 0.07\ m$
  - $d_{cas} = 0.0038\ m$

  ➡ $\eta = r_{min}^2 / r_{max}^2$

  ➡ $a = (r_{max} - d_{cas}) / r_{max}$
- Fluid → Water
  - $\rho_f = 1000 \frac{kg}{m^3}$
  - $K_f = 2.15 * 10^9\ Pa$
- Casing → Steel
  - $\mu_c = 77 * 10^9 Pa$
  - $\nu_c = 0.3$
- Logging tool → Keflar
  - $\mu_t = 2.9 * 10^9 Pa$



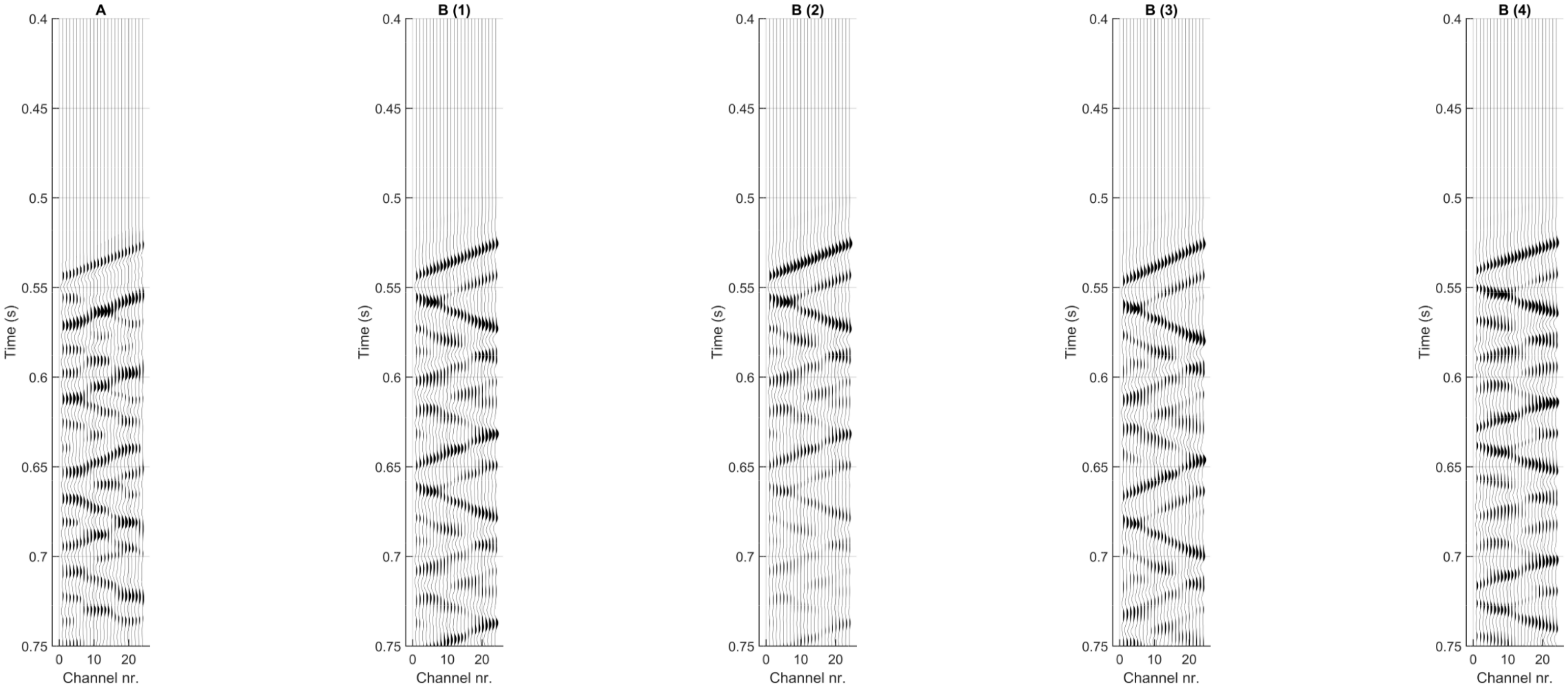
Measured and Modelled Data

Recorded data:

- stacked
- f-k filtered

Model:

- tube wave starts at borehole head
- different velocities, reflection coefficients at bottom, no attenuation



$v_t = 1250 \frac{m}{s}, R_b = 0.9$ $v_t = 1250 \frac{m}{s}, R_b = 0.7$ $v_t = 1100 \frac{m}{s}, R_b = 0.9$ $v_t = 1500 \frac{m}{s}, R_b = 0.9$

Tube Wave dependency

- Velocity of the tube wave is influenced by (Galperin, 1985)
  - **the borehole casing**
  - **elastic constants of surrounding formation**
  - elastic constants of drilling fluid
  - the logging tool

- Intensity of the tube wave is influenced by (Galperin, 1985)
  - contact between casing and formation, e.g. cementation - better coupling → higher intensity
  - density of the fluid - lower density → lower intensity
  - depth below water level - increasing depth → lower intensity
  - for Geophones: applied force for clamping the tool - higher force → lower intensity

Vs change due to loading

In soil

- Boussinesq's formula

$$\sigma_z = \frac{Q}{z^2} I_B$$

Boussinesq stress coefficient: $I_B = \frac{3}{2\pi} \frac{1}{\left(1+\left(\frac{r}{z}\right)^2\right)^{\frac{5}{2}}}$

r = offset

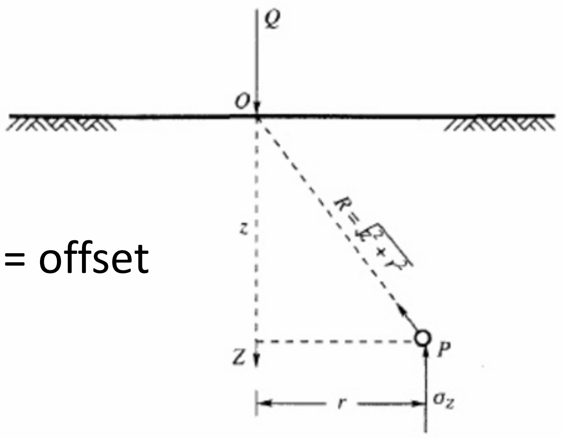
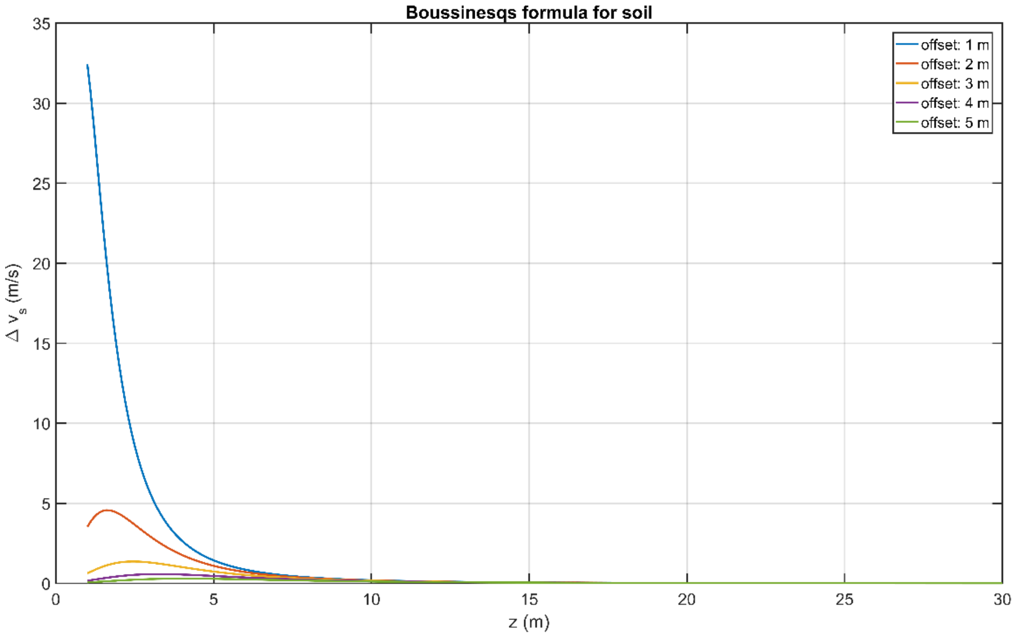


Figure 6.1 Vertical pressure within an earth mass



Force at surface:

- $m = 200000\ kg$
- $A = 100\ m^2$
- $g = 10\ m/s^2$

Vs change due to loading

In rocks

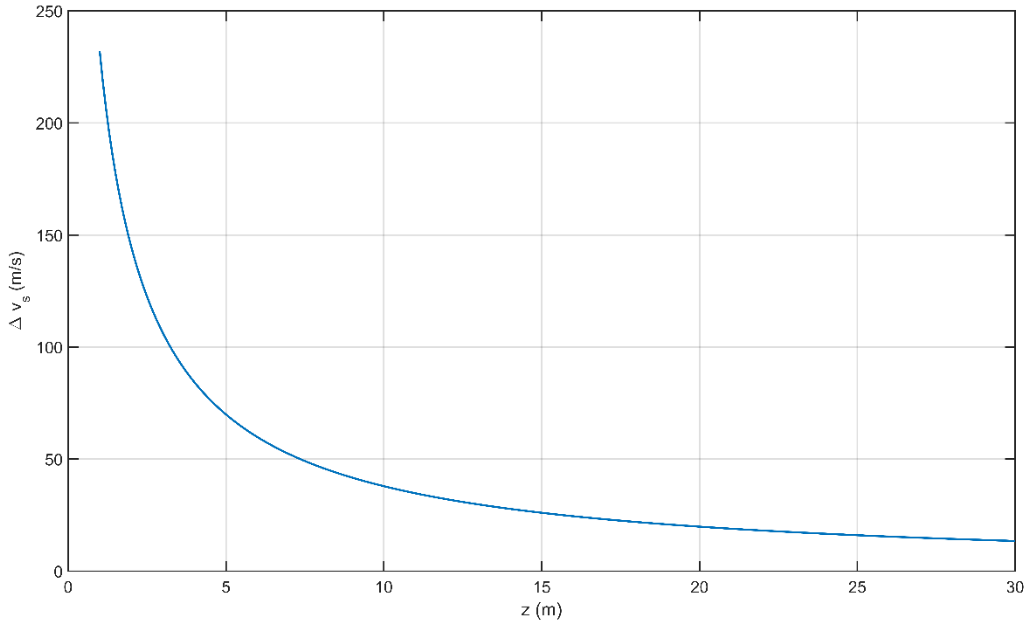
assuming $v_s = v_{s0} * \left(\frac{P}{P_0}\right)^{\frac{1}{6}}$

$$P_0 = P_{lit} - P_{pore}$$

$$P = P_{lit} + P_{load} - P_{pore}$$

$$P_{lit} = \rho_r g z, \quad P_{pore} = \rho_f g z,$$

$$P_{load} = \frac{mg}{A}$$



Force at surface:

- $m = 200000\ kg$
- $A = 100\ m^2$
- $g = 10\ m/s^2$

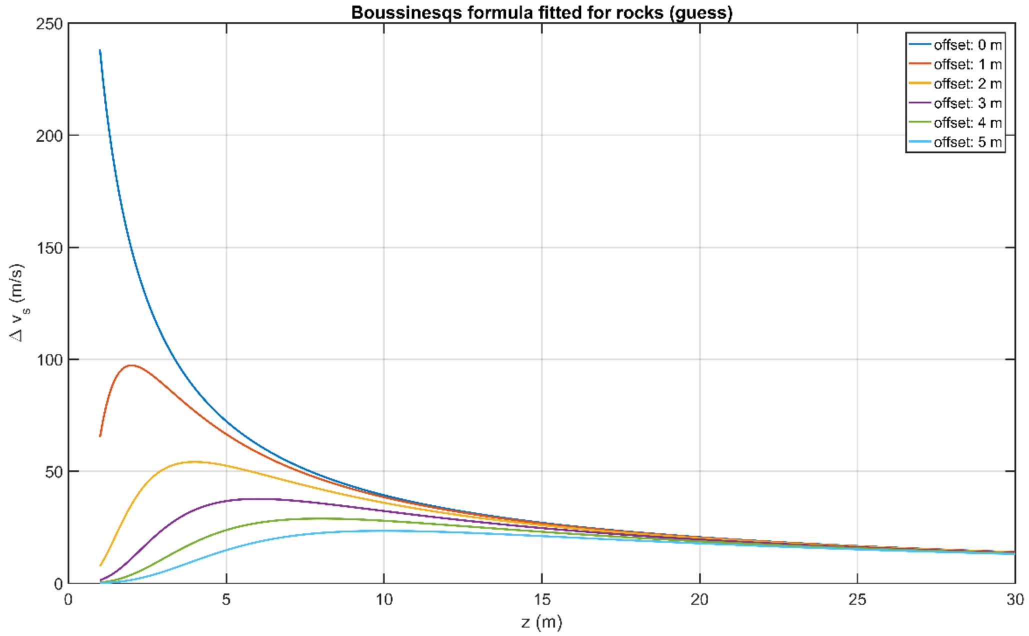
Vs change due to loading

In rocks

- Modified guess of Boussinesq's formula

$$P_{load} = P_{surface} \, I_2$$

$$I_2 = \frac{1}{\left(1+\left(\frac{r}{z}\right)^2\right)^{\frac{5}{2}}}$$



Force at surface:

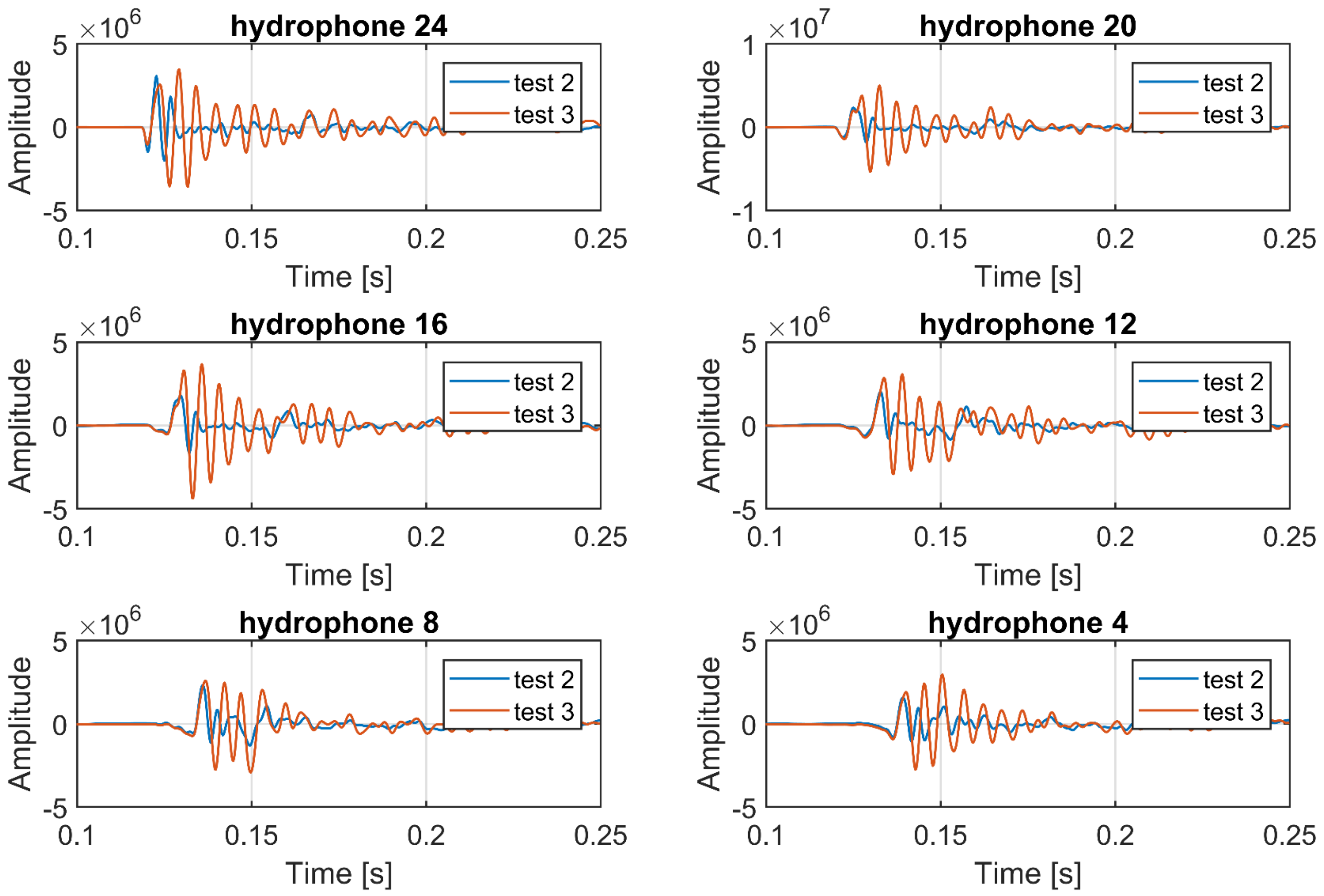
- $m = 200000 \; kg$
- $A = 100 \; m^2$
- $g = 10 \; m/s^2$

$$\Delta v_s = \pm 20 - 30 \, \frac{m}{s}$$

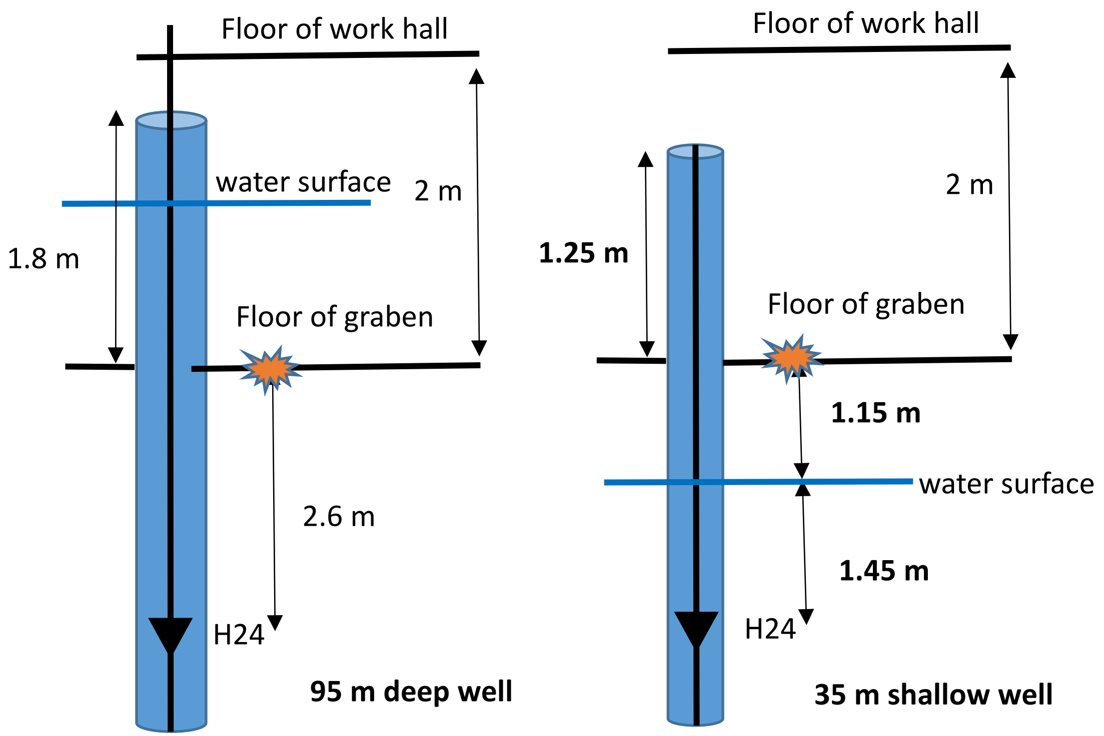
1. Holding construction of hydrophone array

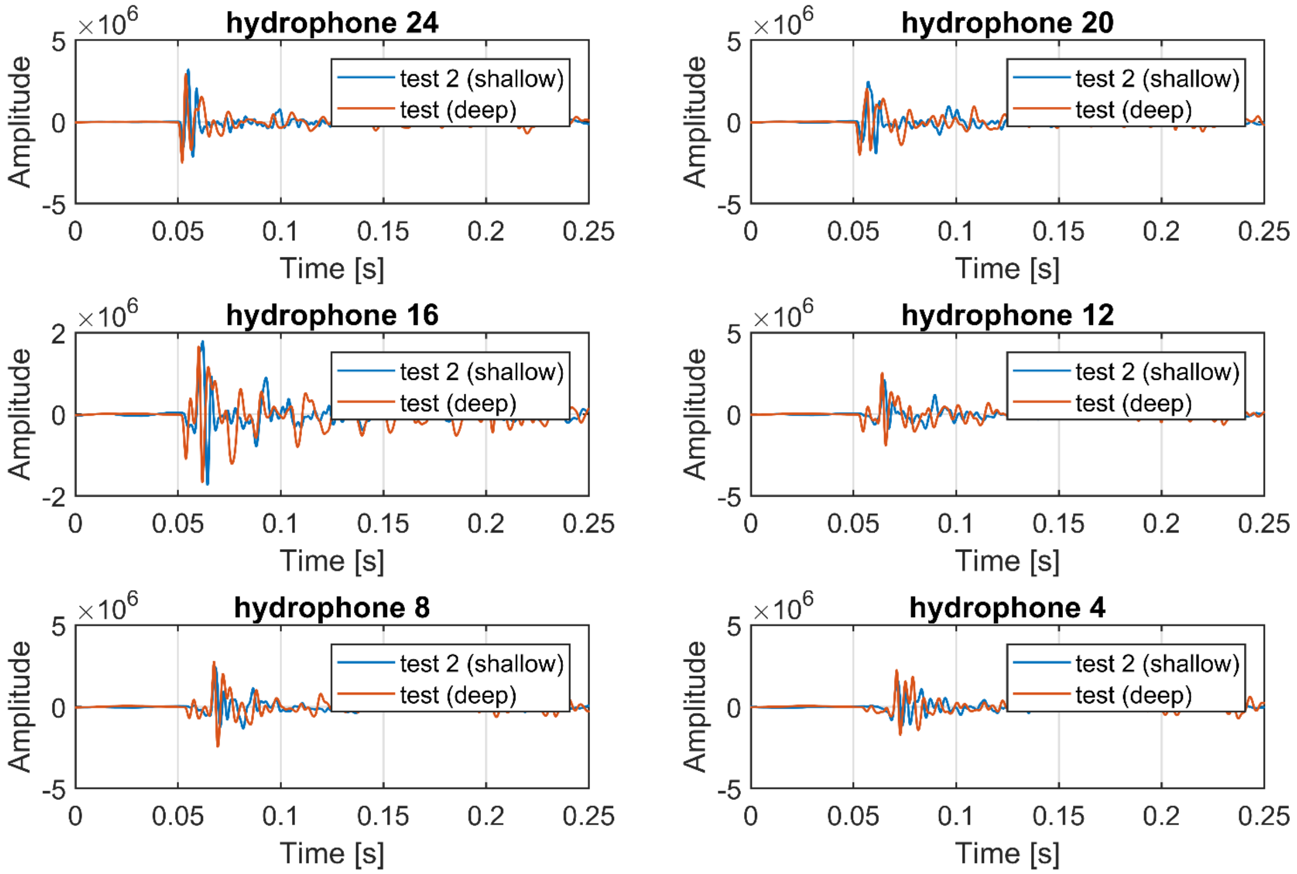
- holding board: ''seals'' the well and more energy is kept inside the borehole (test 3)

- holding metal frame: nearly open to the top of the borehole (test 2)



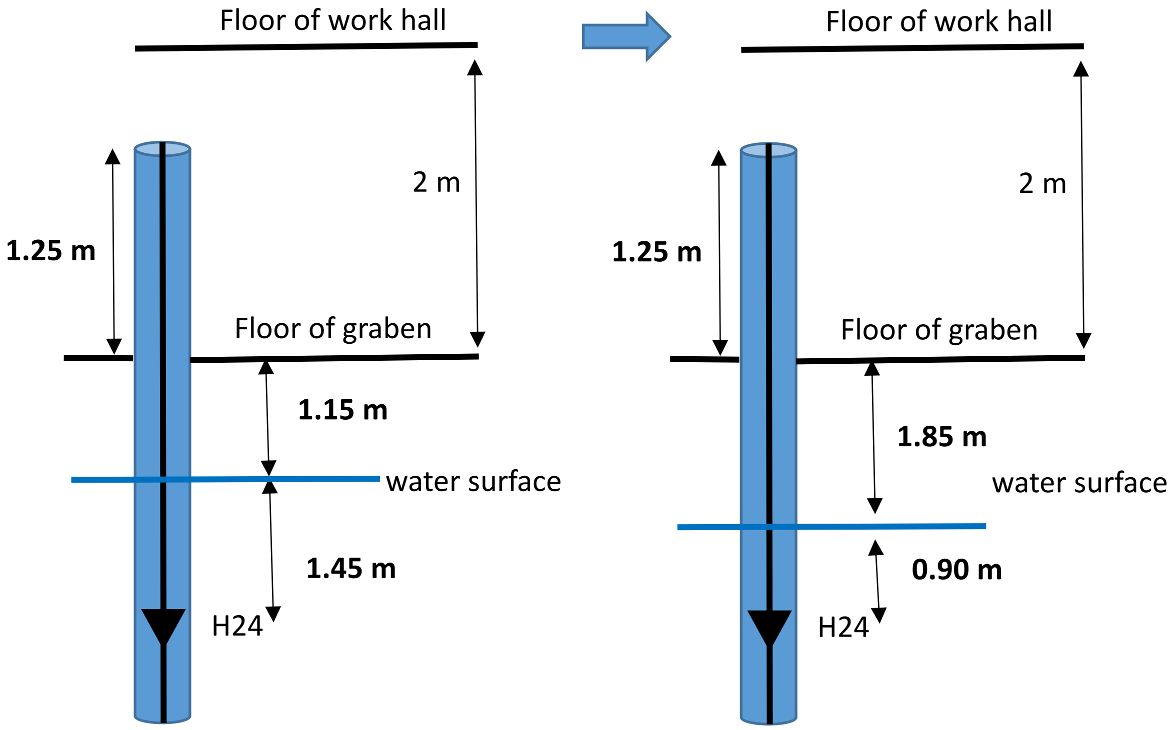
2. Position of water table in well





- different interaction of first downgoing tube wave and ghost reflection in shallow and deep well

3. Variation of water table position



Effective pressure change of 0.01 Mpa

$$\Delta \mathrm{p_e} = (\rho_r - \rho_f) * \mathrm{g} * \Delta z$$

Δz = difference in water table

→ max. 0.1 % velocity change (1.2 m/s in v_S)
(Hertz-Mindlin)

Effective pressure change of 0.01 Mpa

$$\Delta \mathrm{p_e} = (\rho_r - \rho_f) * \mathrm{g} * \Delta z$$

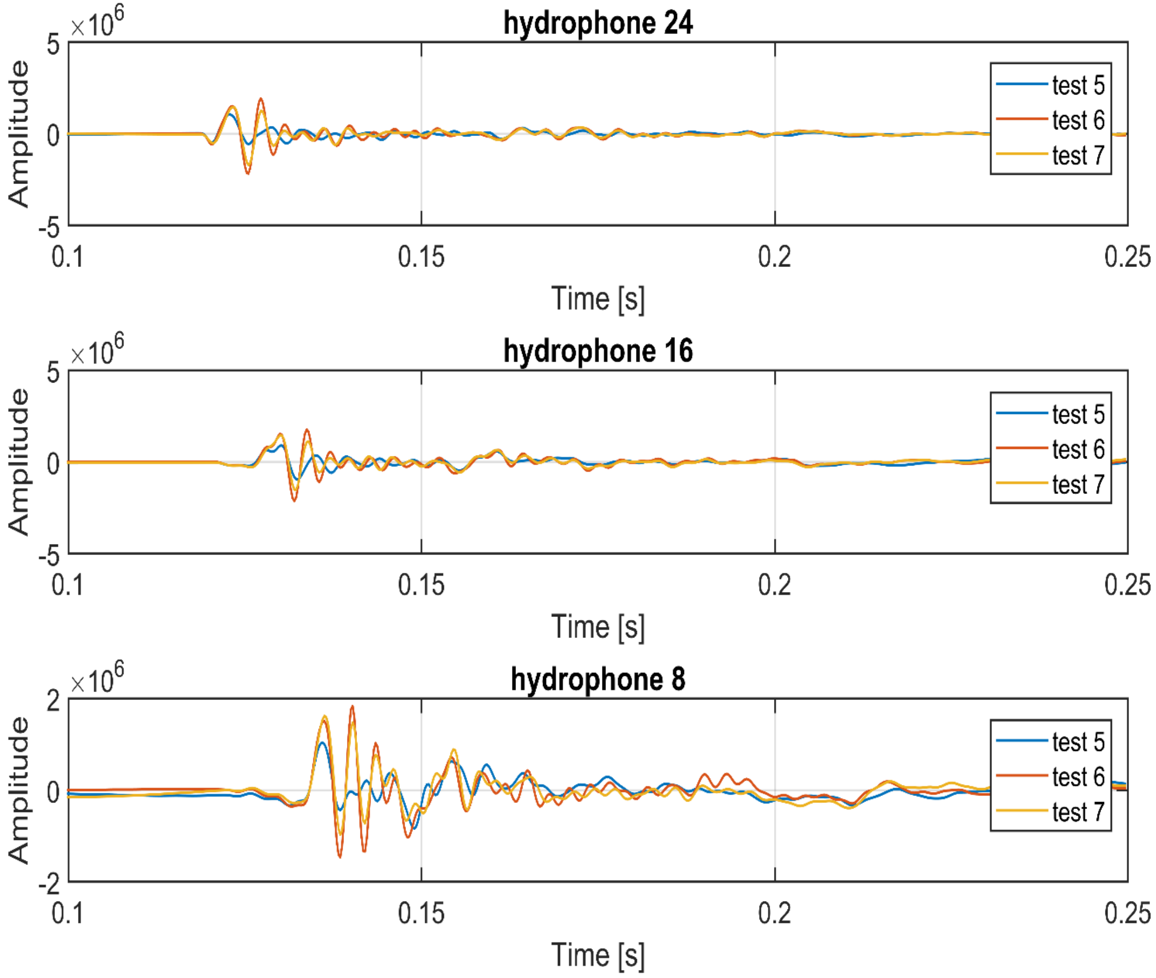
Δz = difference in water table

different for near surface soils/unconsolidated rocks???

4. Radial position of hydrophone array

not centered

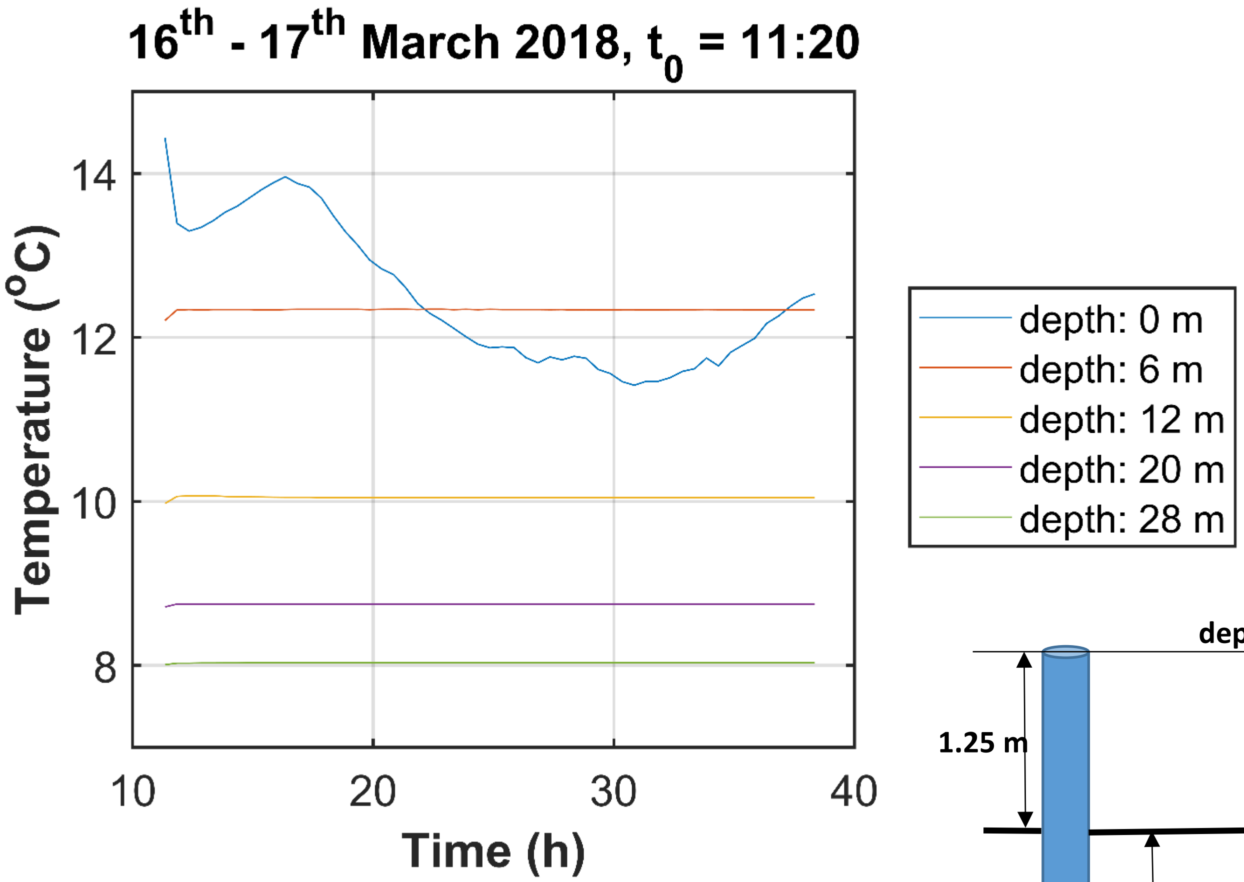
centered

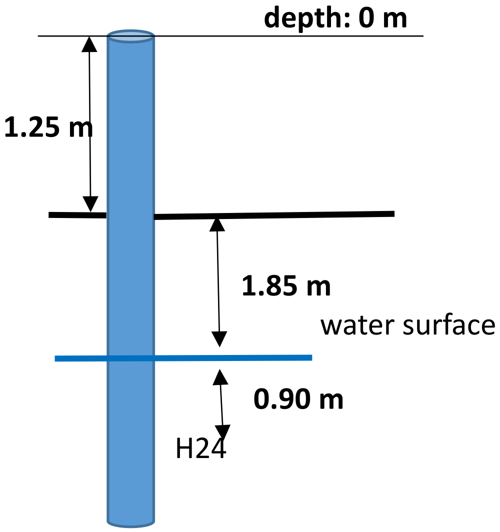


- change of wave form, interference with other waves for different hydrophone positions → impact on velocity estimation in fk-domain
- should not cause a change of the tube wave velocity (Norris, 1990)

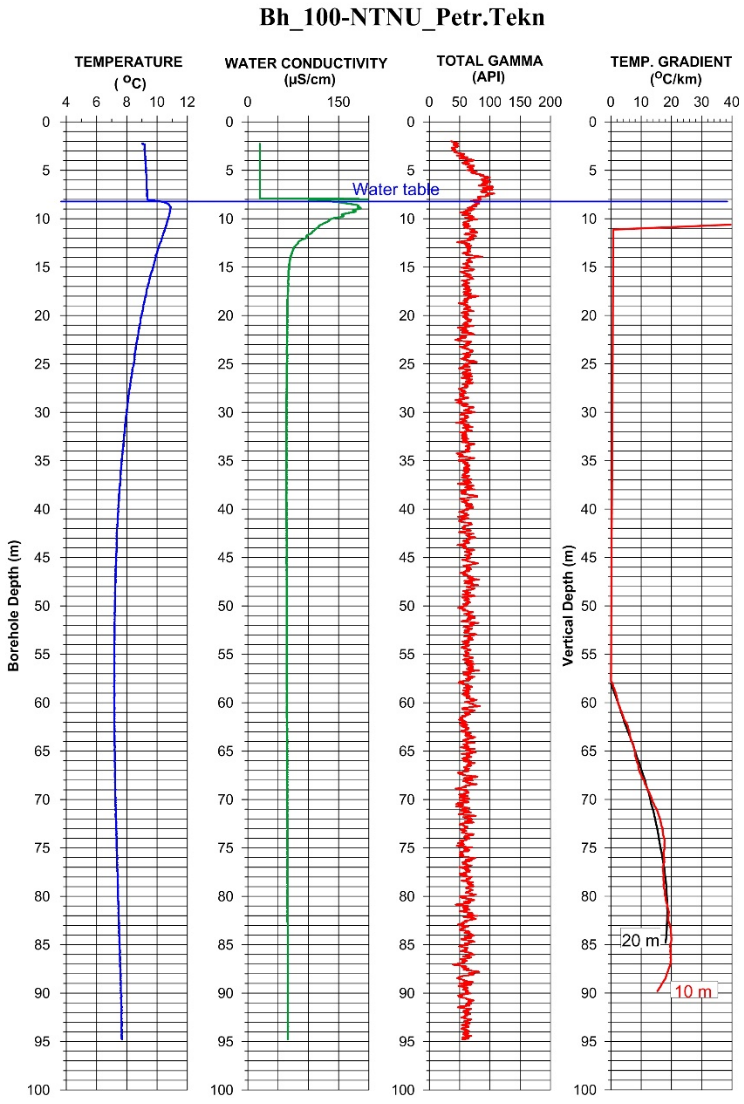
- Test 5: not centered
- Test 6,7 : centered

5. Temperature effect





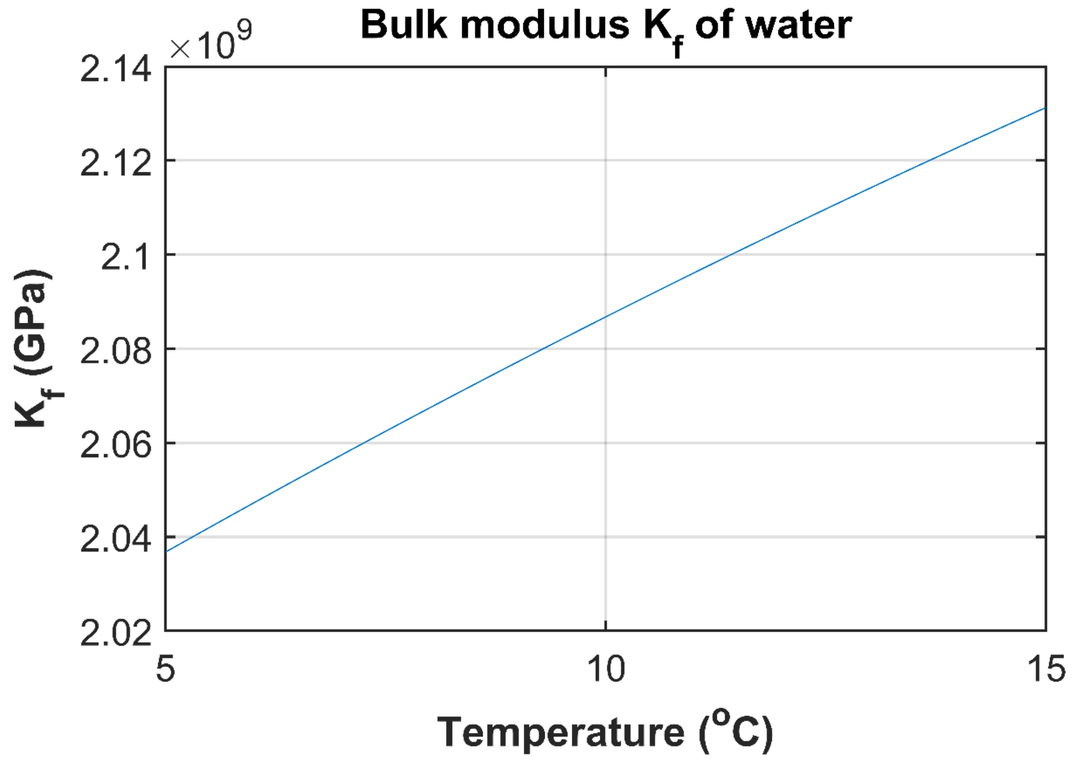
Deep well: 22.11.2016

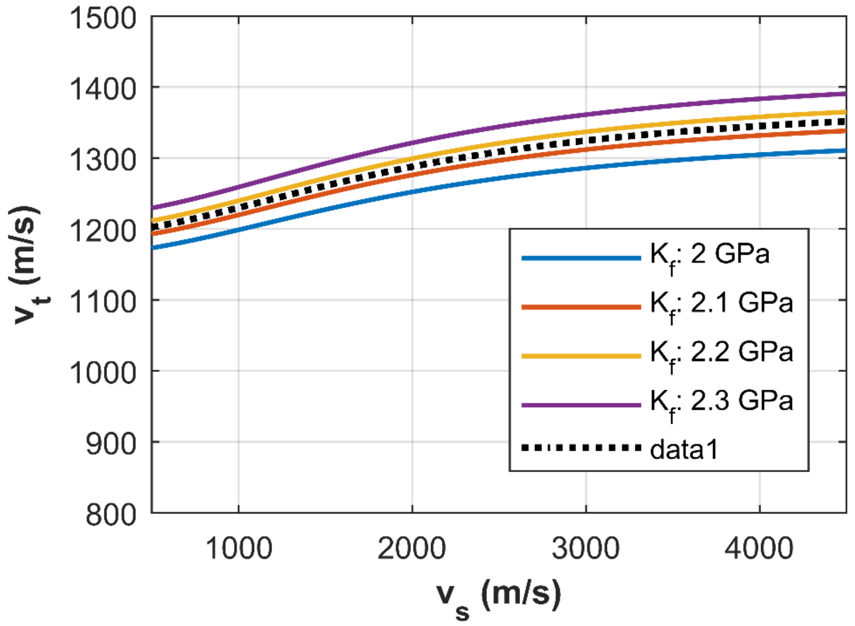


5. Temperature effect

Dixon, 2007:

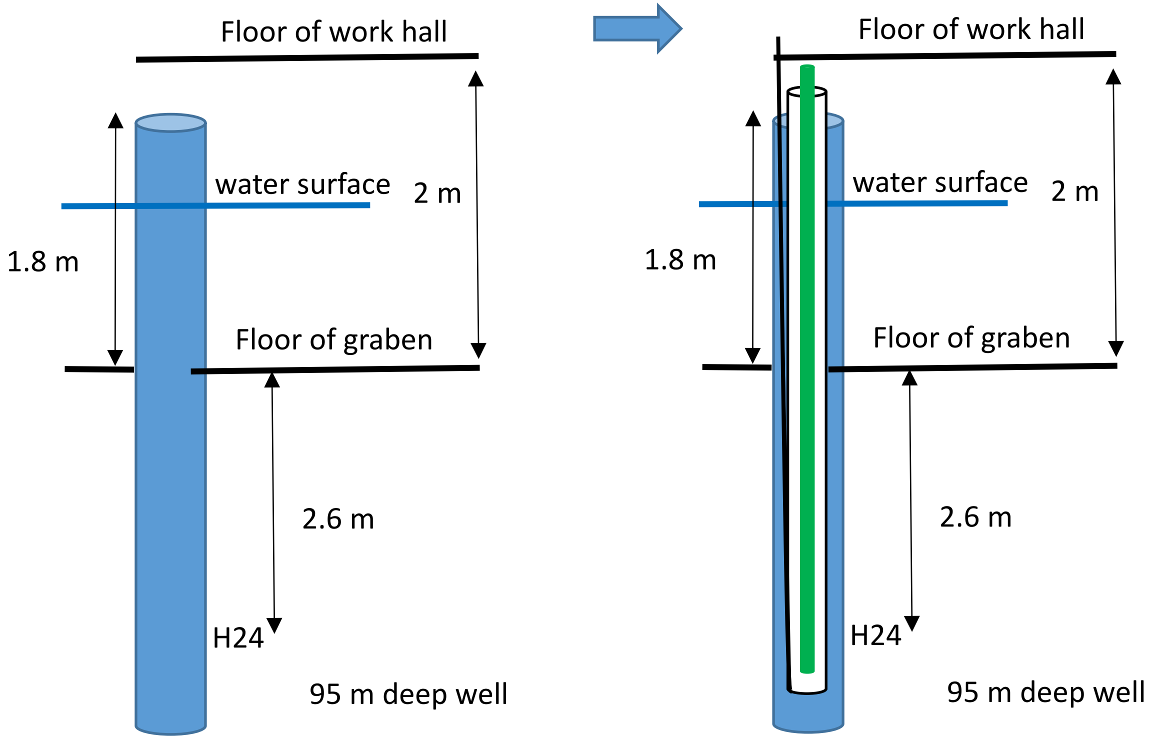
$$K_f = 2.29 * 10^9(1 - 48 * 10^{-6}(T - 53)^2)$$

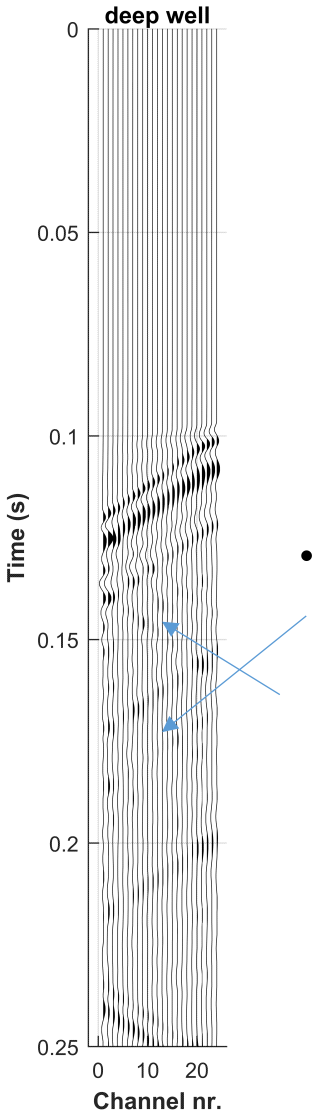




6. Interaction with second well/near field effect

Tool installed in deep well



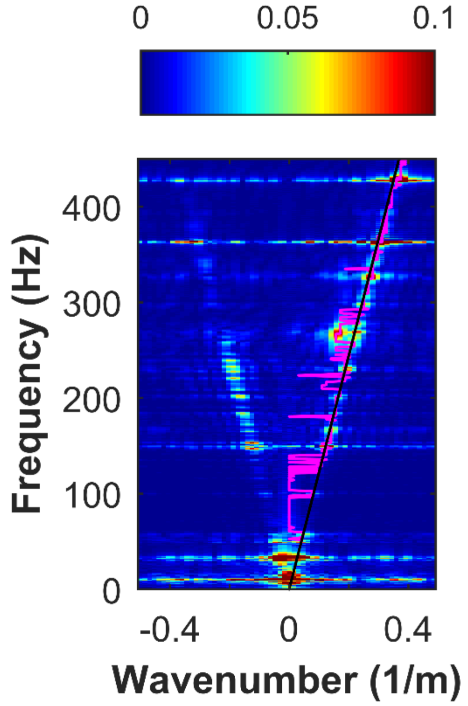


- hydrophones in deep well also show upgoing waves earlier than first bottom reflection
    - is recoridng in deep well inpmacted by shallow well and vice versa?

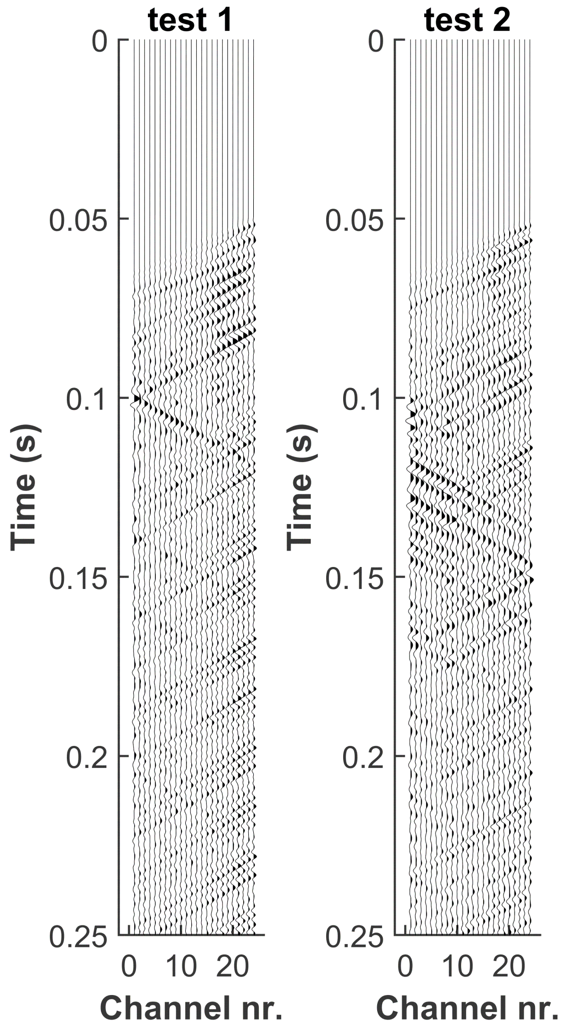
6. Interaction with second well

Frequencies between 50 – 450 Hz are used

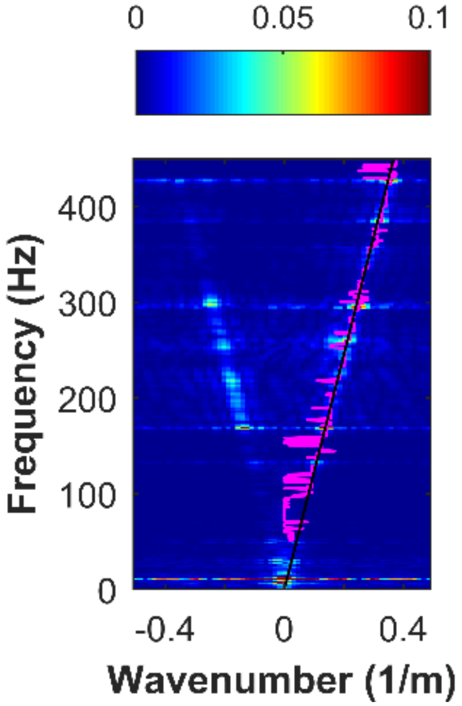
test 1



1224.5 ± 3.3 m/s



test 2



1225.7 ± 4.2 m/s

7. Background noise (surface waves)