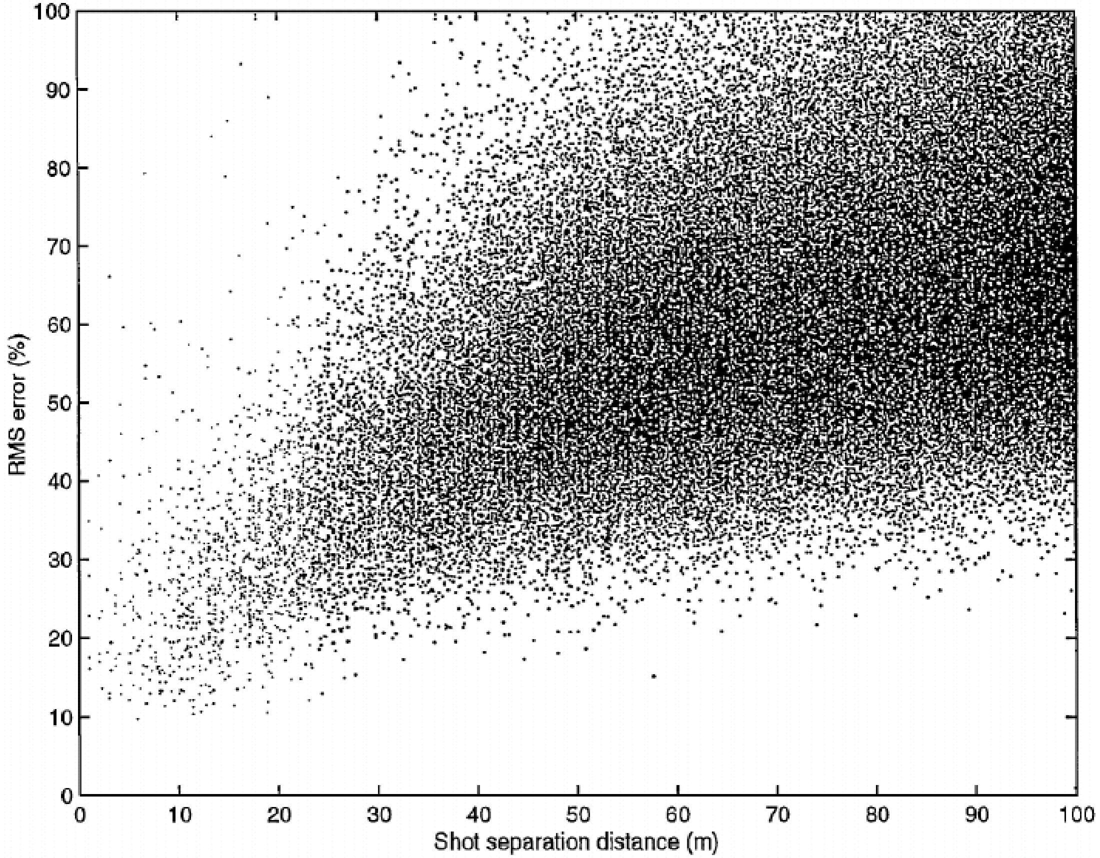
Module 4

Marine 4D acquisition



NTNU
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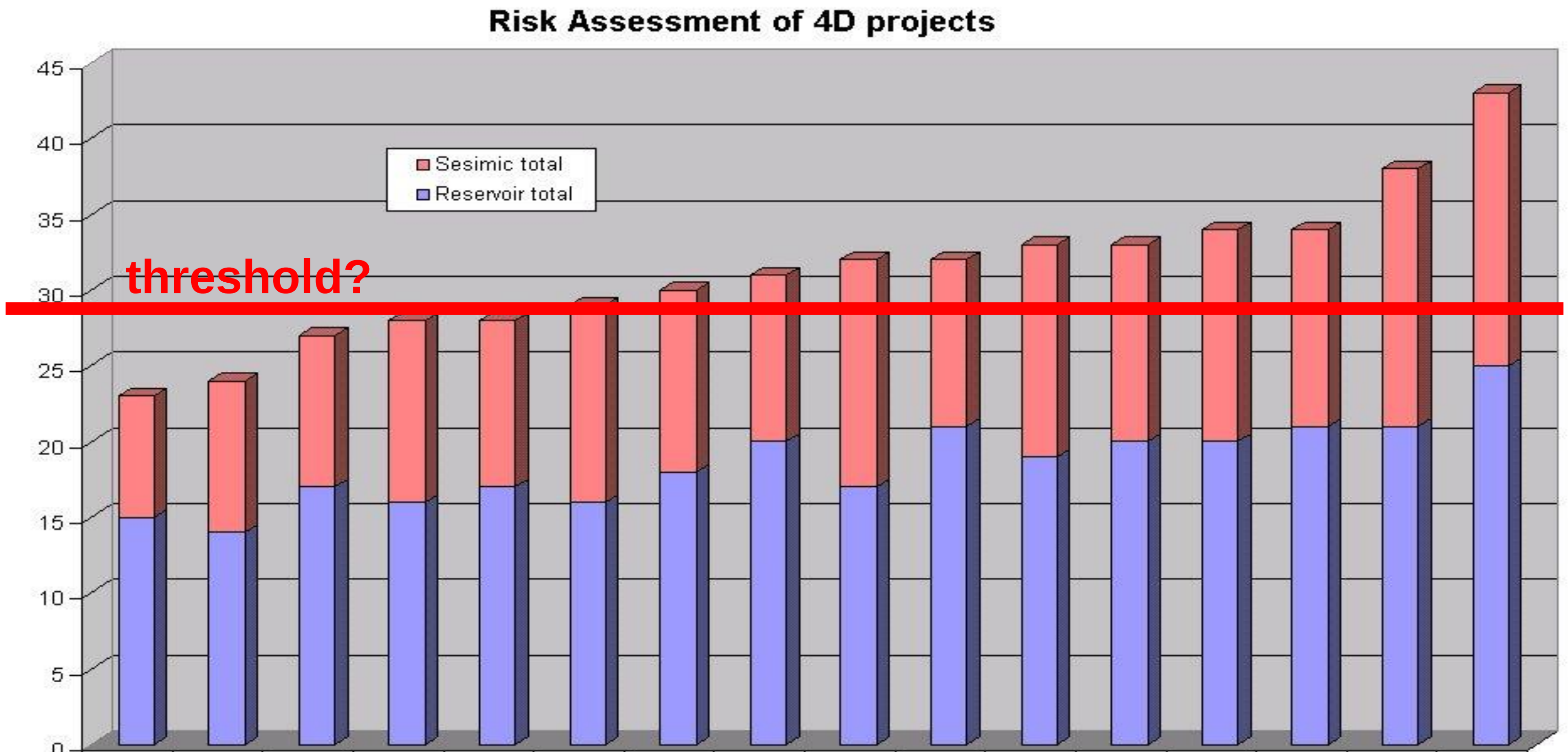
Martin Landrø and Lasse Amundsen

A modern 3D seismic vessel

4D technical risk spreadsheet (after Lumley, 1997, Leading Edge, max 5 points per item)

	Gullfaks	Statfjord	Heidrun	
Bulk modulus	3	3	3	
Fluid compressibility	4	4	4	
Fluid saturation	4	4	4	
Porosity	5	5	5	
Predicted imp. changes	4	4	4	
Sum Reservoir (min 15)	20	20	20	
Image quality	3	4	4	
Resolution	2	3	3	
Fluid contacts	3	3	4	
Repeatability	3	2	3	
Sum Seismic (min 12)	11	12	14	
Sum Total	31	32	34	

Risk analysis of various 4D projects - taken from Ole A. Eikebergs project thesis



	North Sea	Njord	Snorre	Magnus	Draugen	Oseberg	Fulmar	Gullfaks	West Africa	Statfjord	Heidrun	Troll West	Troll East	Alba	Gulf Of Mexico	Indonesia
Sesimic total	8	10	10	12	11	13	12	11	15	11	14	13	14	13	17	18
Reservoir total	15	14	17	16	17	16	18	20	17	21	19	20	20	21	21	25

The role of acquisition and processing is important, but does not contribute more than 20-40% in a risk analysis scheme

Seismic acquisition

- ***3-D marine streamer (hydrophone data, single component)***

- ***Borehole seismic data (multicomponent)***
  - ***check shot used to tie surface seismic to the well (depth conversion)***
  - ***zero offset VSP (Vertical Seismic Profiling)***
  - ***walkaway VSP***
  - ***3D VSP***
  - ***crosswell seismic***

- ***Seabed seismic data***
  - ***Imaging through gas clouds***
  - ***Potential technique for discrimination between sand and shale (lithology)***

Survey planning

- ***Cost sensitive parameters:***
  - ***Number of sources and streamers (cables)***
  - ***Bin line separation distance (distance between each swath)***
  - ***Shape and size of survey***
  - ***Migration aperture***
  - ***Timesharing, weather***
  - ***Cable length***
- ***Less cost sensitive parameters:***
  - ***Source and receiver depths***
  - ***Source strength, width and length***
  - ***Source primary to bubble ratio***
  - ***Shooting direction***

Seismic modelling is an important tool in survey planning

Time-lapse seismic marine acquisition techniques

- ***Towed streamers***

- ***Seafloor receivers***
  - ***cables***
  - ***nodes***
  - ***permanent geophones/hydrophones***

- ***Borehole receivers***
  - ***VSP tools***
  - ***permanent geophones (R&D stage)***
  - ***downhole sources (R&D stage)***

- Most 4D surveys so far have been acquired with towed streamers.

- Acquisition cost has decreased since 3-D was invented.

4D acquisition

- ***Repeatability is important - but one has to be flexible***
  - ***Need repeated 3D data for infill drilling => must expect change in weather conditions => maximum repeatability is limited***

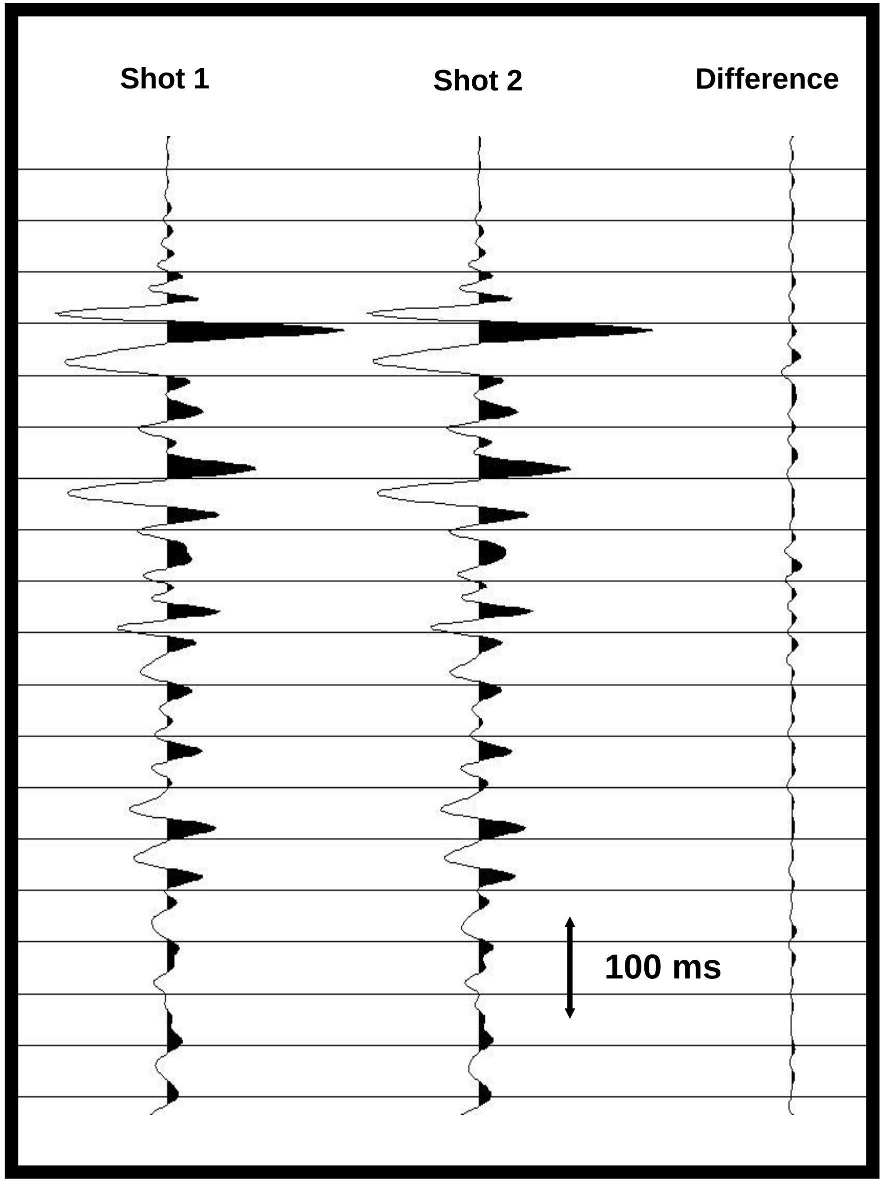
- ***We might see a transition from streamer surveys to seabed seismic surveys - also for 4D studies due to:***
  - ***undershoot problems***
  - ***added value of shearwave data***
  - ***increased repeatability??, especially for permanent seabed sensors***

- ***VSP and crosswell surveys might also become more important in future, but then mainly as a calibration tool towards 3D surface and 3D seabed seismic surveys***

4D acquisition - what kind of data do we need?

- ***Problem dependent:***
  - ***monitoring homogenous fields (Troll and Sleipner) => 2D surface surveys***
  - ***monitoring requiring dense coverage: (Gullfaks,Statfjord,Heidrun..) => 3D surveys***
- ***Chevron choosed to acquire a 3D seabed survey as the second survey at Alba, where a conventional surface survey is the baseline. (Huge Vs contrast)***
- ***The overall goal is often improved reservoir description - might have to sacrifice on repeatability to achieve better mapping of faults***
- ***Intensive well logging at the same time as the seismic acquisition***

NRMS – a way to measure repeatability



$$NRMS = 2\frac{RMS(s_2 - s_1)}{RMS(s_1) + RMS(s_2)}$$

Causes of non-repeatability

- ***Water layer***
- ***Horizontal positions of shots and receivers***
- ***Vertical positions of shots and receivers***
- ***Source and receiver variations***
- ***System variations (recording instruments, processing algorithms)***
- ***Noise (weather, rig noise, other vessels...)***
- ***"geology" changes***

Causes of non-repeatability

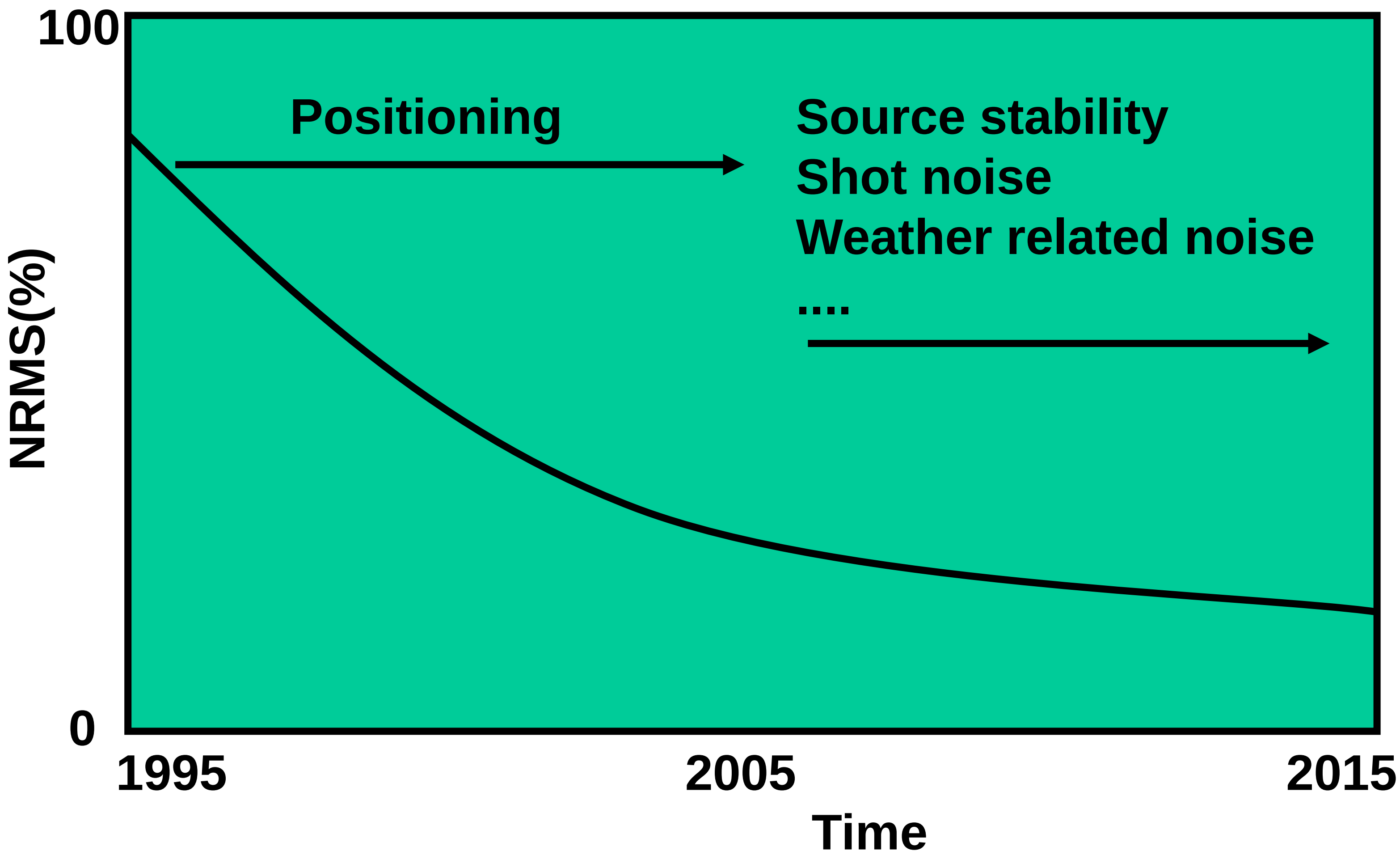
- ***Many non-repeatable factors can be improved***
  - ***positioning***
  - ***tidal effects***
  - ***source and receiver variations***
  - ***system variations***

- ***BUT***
  - ***weather noise is hard to avoid***
  - ***cultural noise***
  - ***perhaps seabed data is less sensitive to weather noise?***

Undershooting

- ***There will always be permanent installations on a producing field - how should such areas be covered by seismic?***
  - ***undershooting using two vessels (poor repeatability)***
  - ***seabed recording***
  - ***no recording (just fill in with old/base line survey data)***
- ***How to handle this problems is essential in the acquisition planning phase of a time lapse survey - some installations are semi-permanent (loading equipment etc)***
- ***Might have to choose between large un-covered areas and different shooting directions between the surveys***

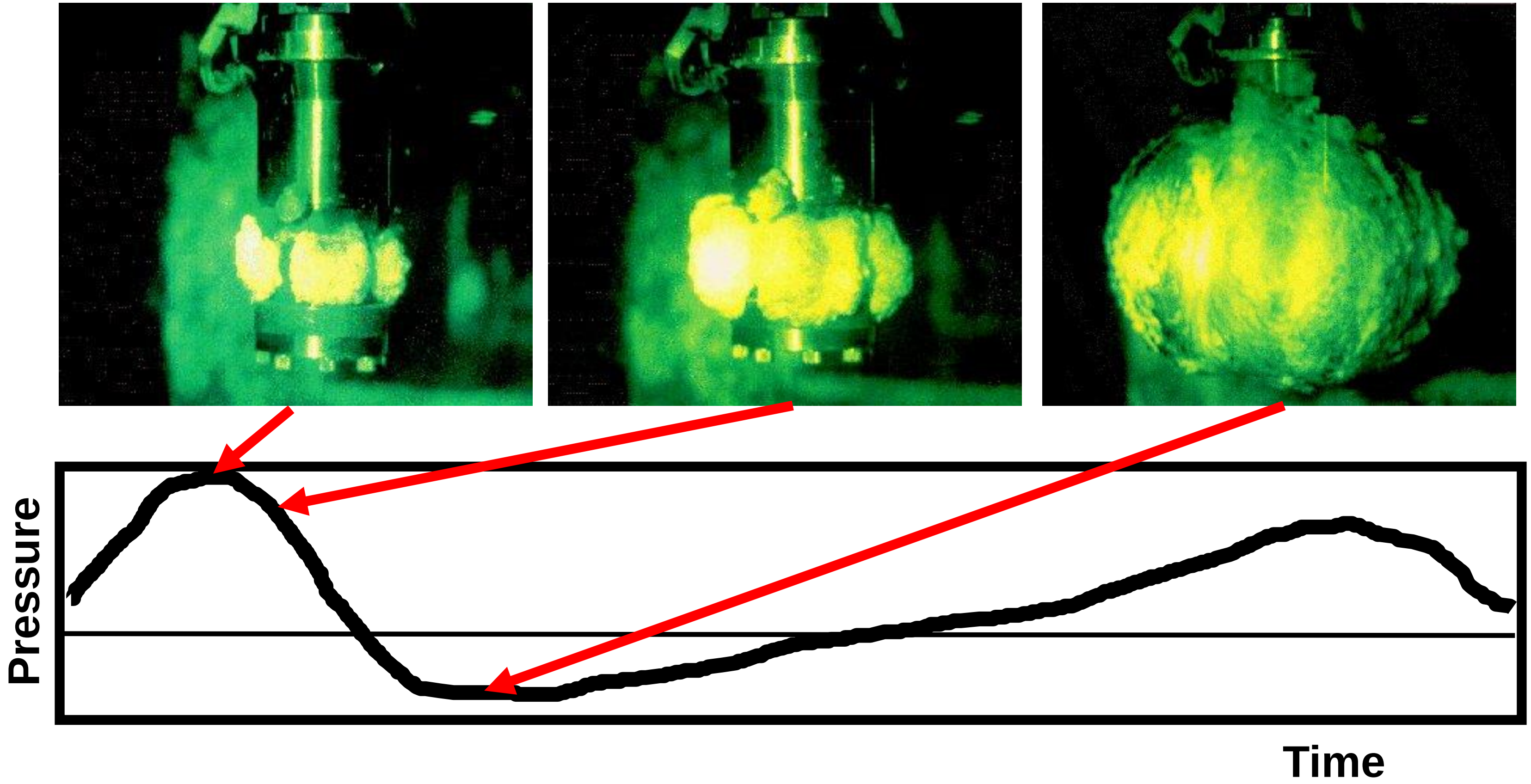
Seismic repeatability



- **Mostly acquisition related improvements**
- **Processing improvements:**
    - **Virtual sources (Bakulin and Calvert, 2004)**
    - **Regularization (interpolation+wavefield reconstruction)**
- **New methods for estimating the 4D signal within the noise**

The seismic signal

Airgun releases high pressure air (140 bar) into the water and a pressure pulse is generated



Highspeed photos of the bubble generated by an airgun

Recorded pressure close to the airgun - notice oscillatory behaviour

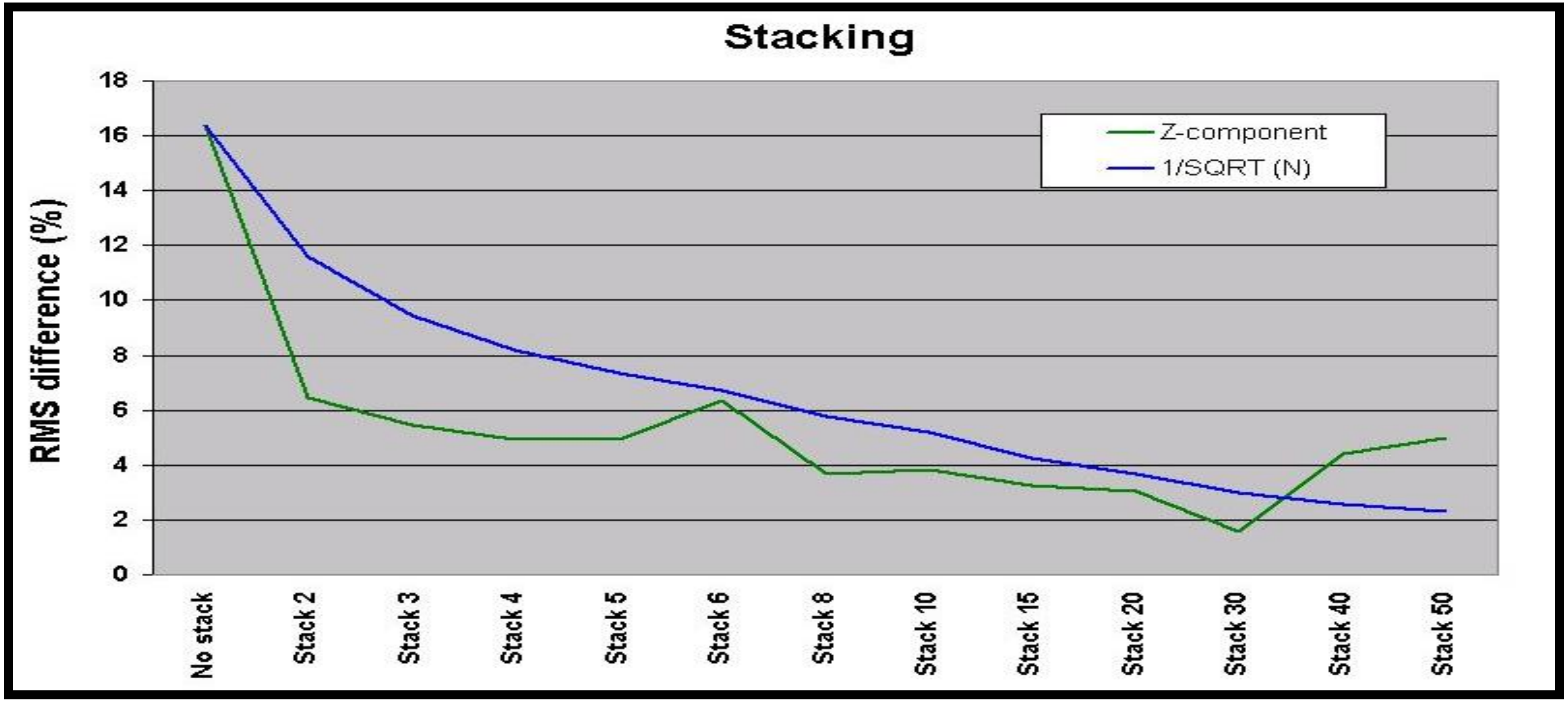
As the pressure inside bubble decreases (due to volumetric increase) the hydrostatic pressure compresses the bubble and a secondary peak (and third…) is observed due to this bubble oscillation (analogy: damped harmonic oscillator)

Causes for changes in source signatures

- ***Gun firing pressure might vary from shot to shot***
- ***Changing weather conditions***
- ***Single guns might drop out***
- ***Water temperature***
- ***Varitations in firing time delays between the guns***
- ***Temperature variations within the gun chamber caused by non-regular shooting (interrupts, weather..)***
- ***Leakage problems (O-rings etc) causes gradual change***

Stacking improves repeatability

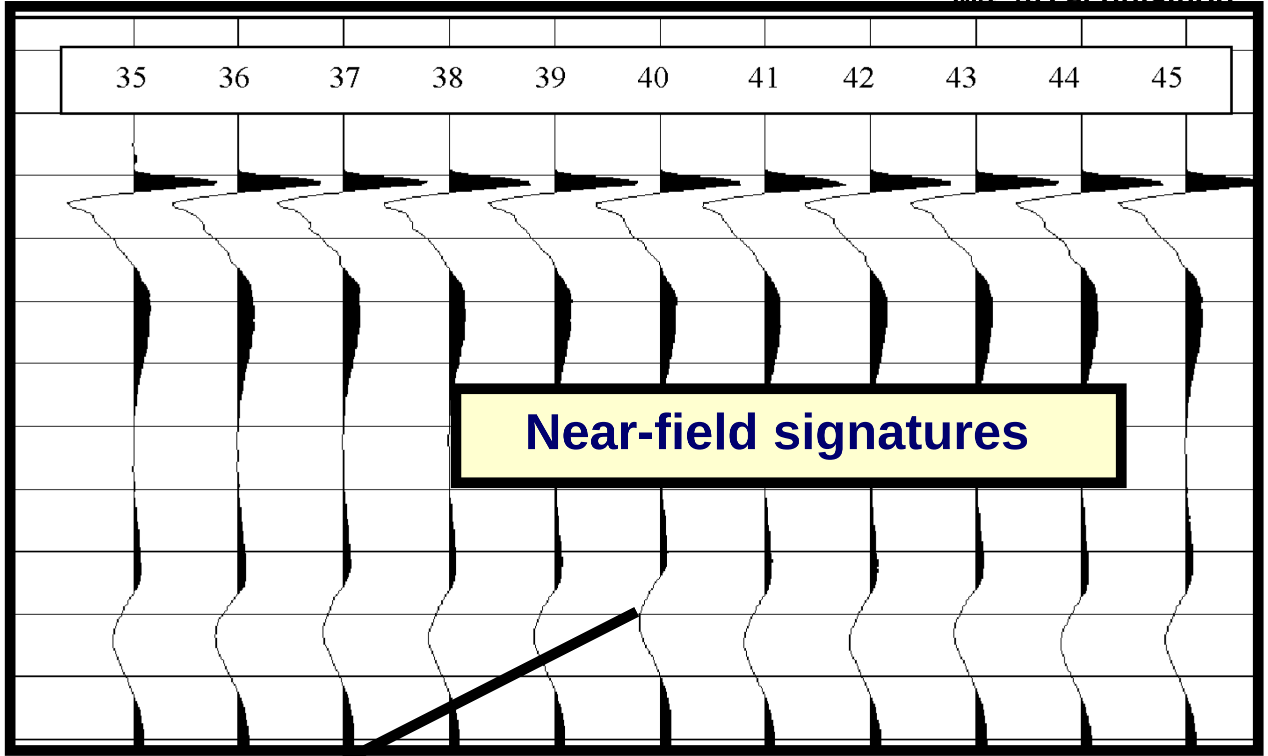
Ref.: Andorsen and Landrø, Journal of Seismic Exploration, 2000



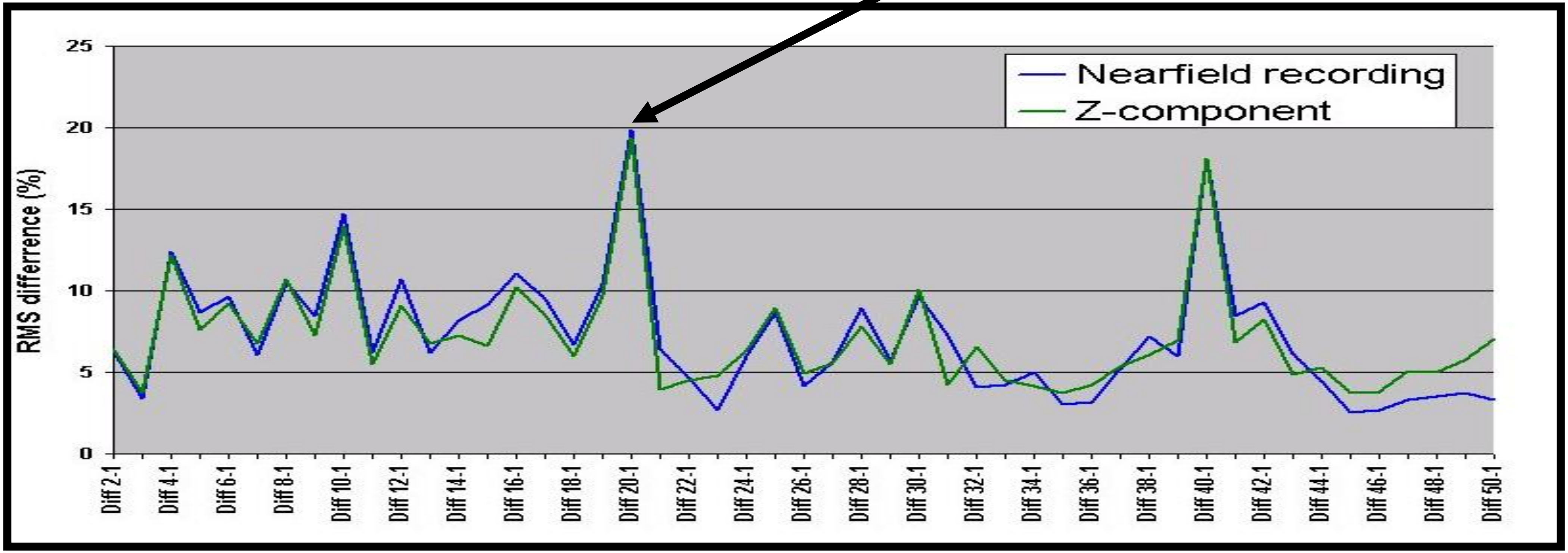
Only source variations in this example - fixed VSP recording and same weather conditions

Notice: Difference increase between fold 30 and 40 - probably due to systematic source variations (bubble period)

Why measure source signatures?



High RMS-errors caused by variation in source bubble time period

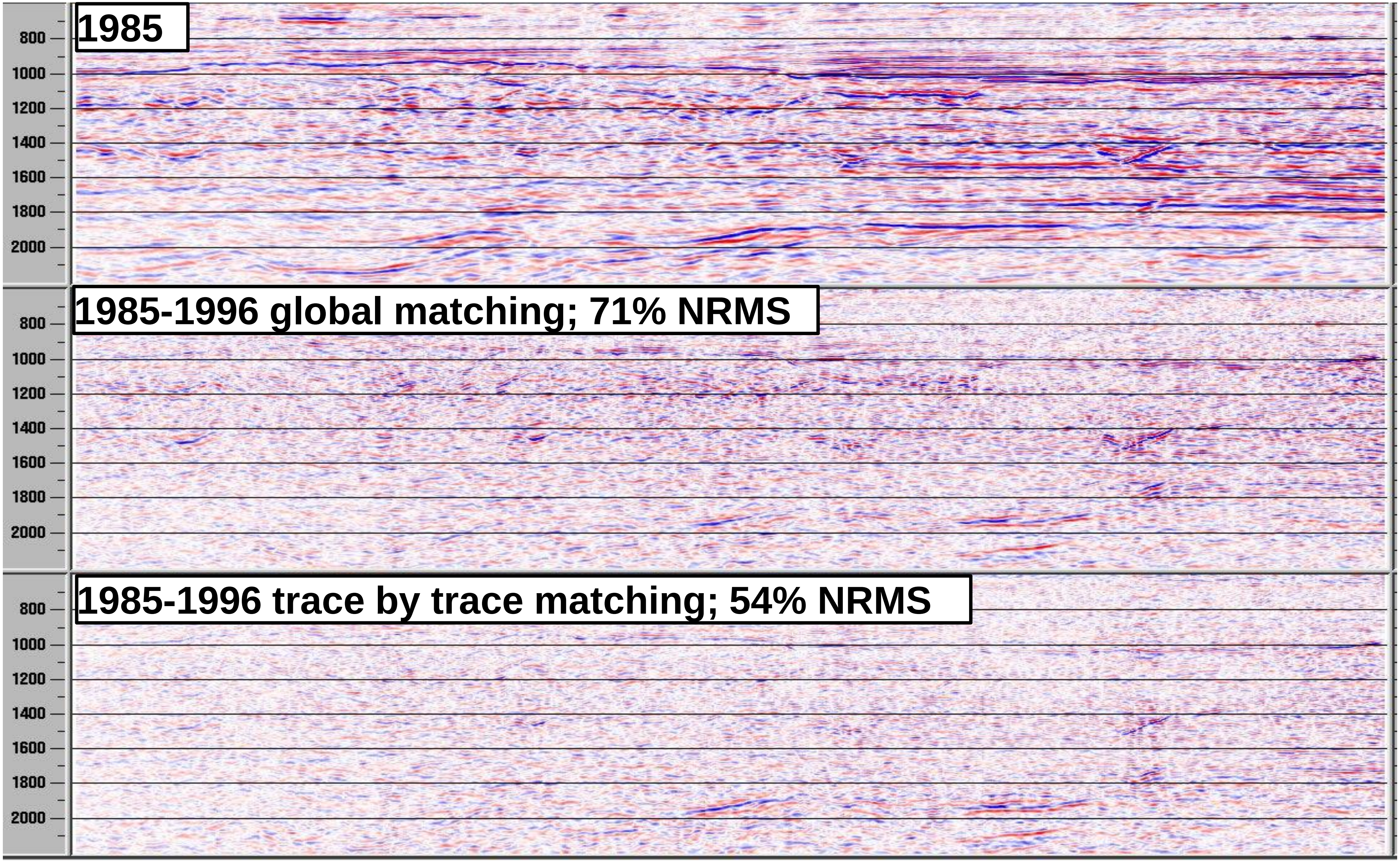


The bubble time period is dependent on firing pressure, gun volume and gun depth (Nooteboom, 1978):

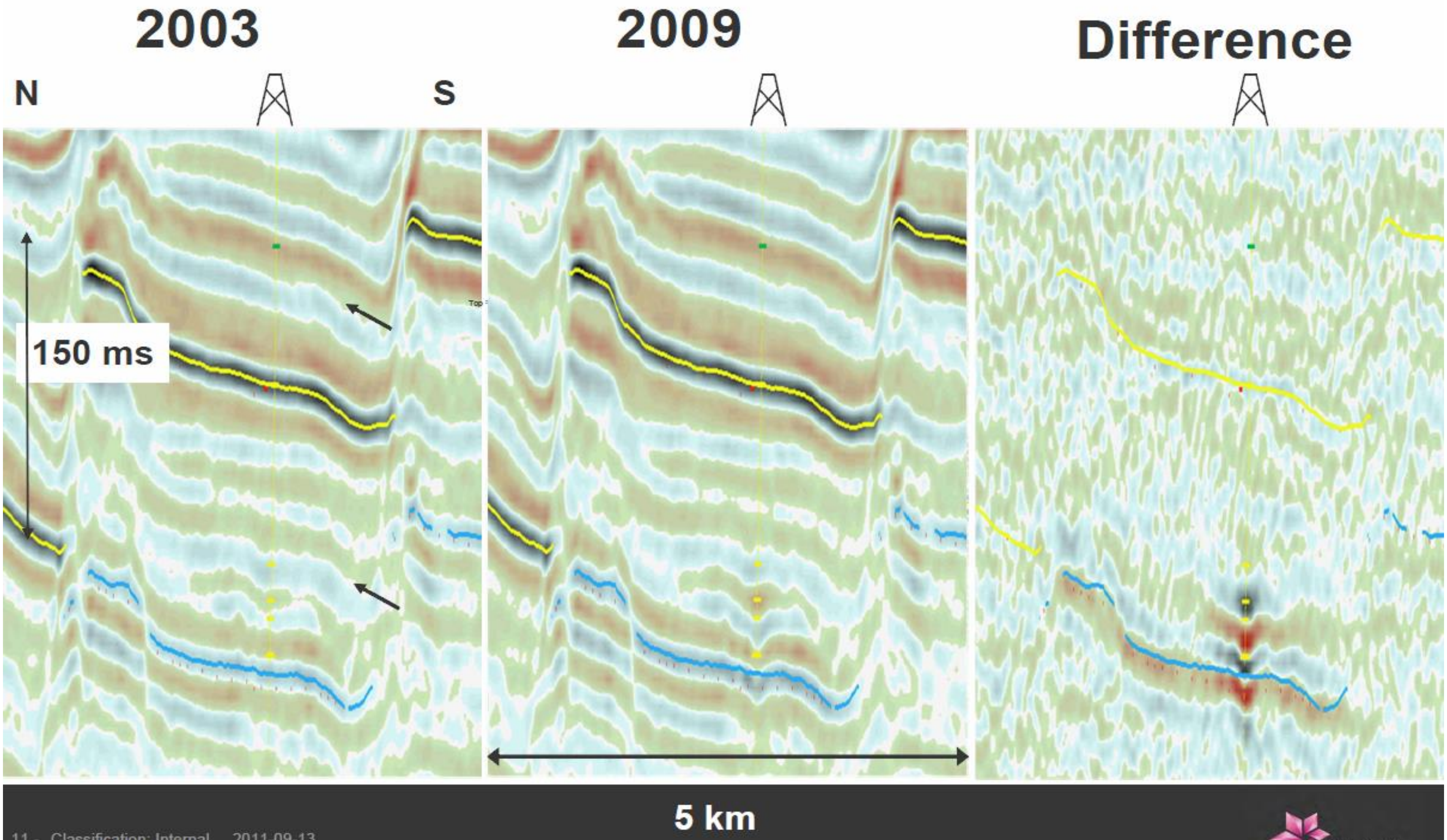
$$T \propto \frac{P^{1/3} V^{1/3}}{P_h^{5/6}}$$

It is also dependent on water temperature and the temperature inside the firing chamber

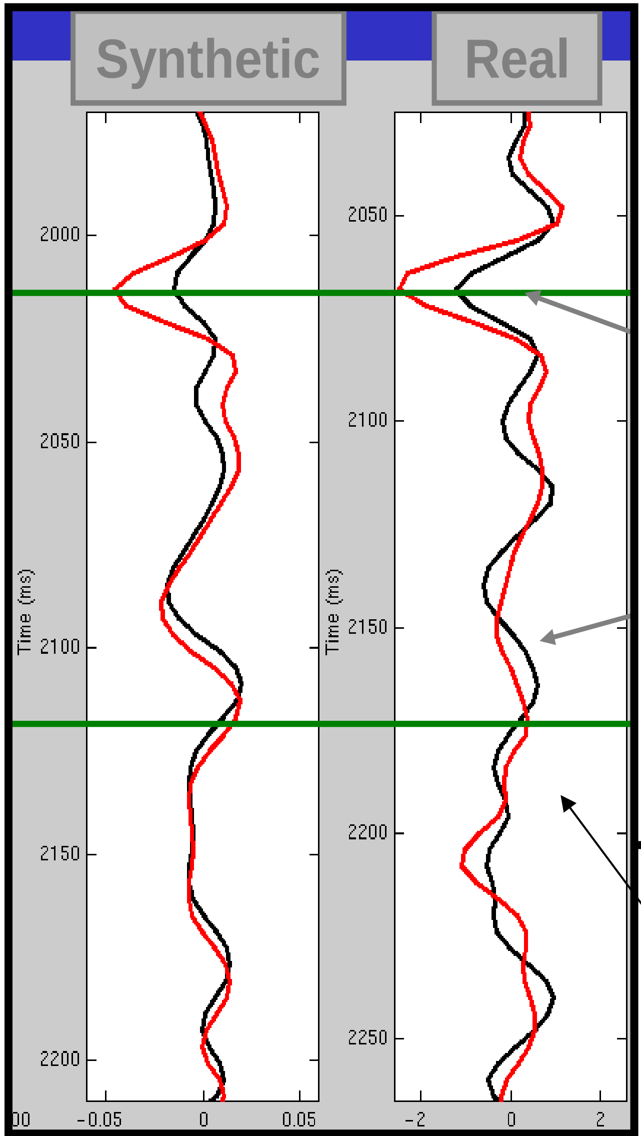
15 years ago: 50-90% NRMS - GULLFAKS

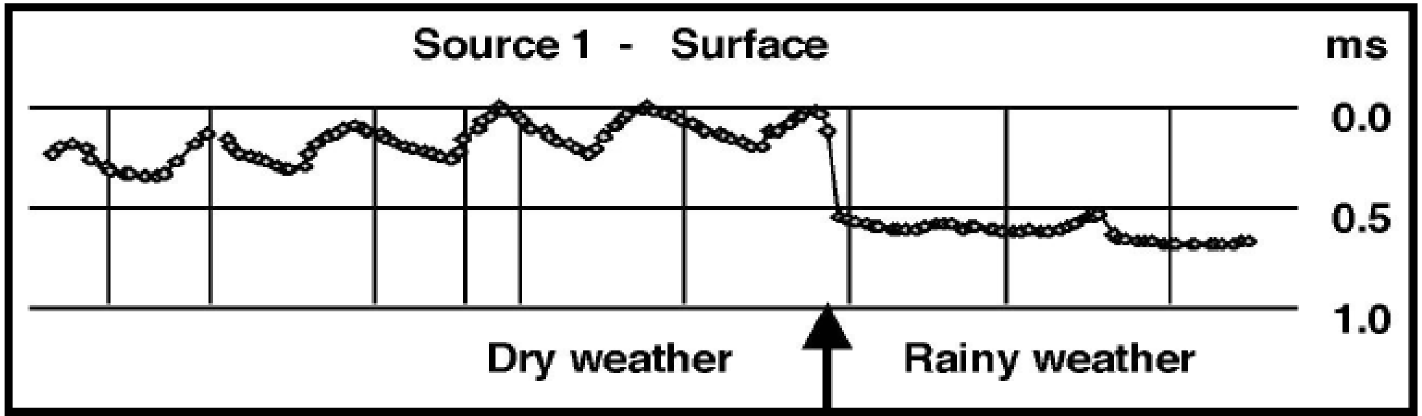


14 years later: Snøhvit, 15 % NRMS



Time shift picking is often noisy – challenge for future!





From Meunier et al, 2001, TLE: "Reservoir monitoring using permanent sources and vertical receiver antennae – The Cere-la-Ronde case study".

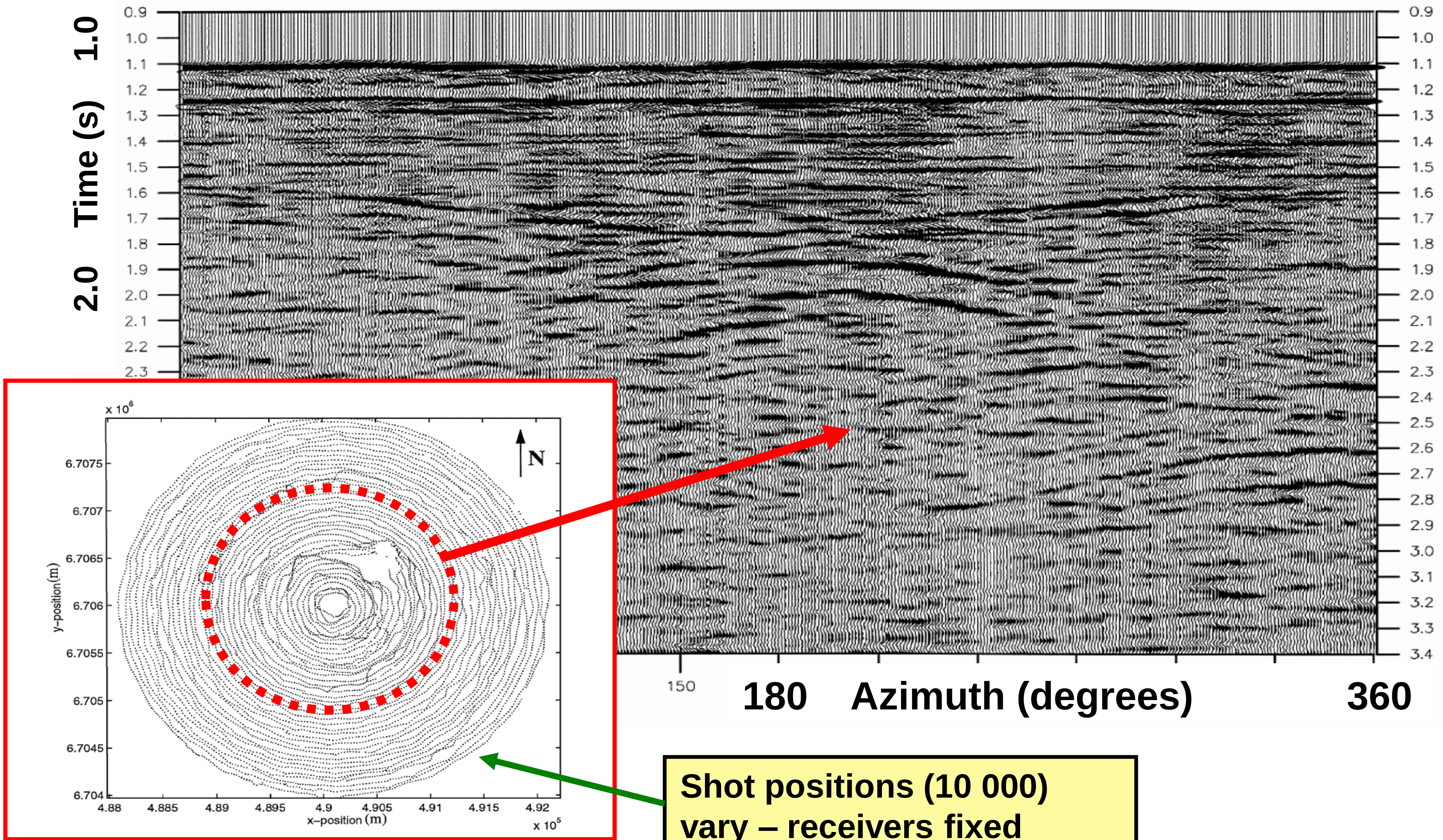
Resolution in timeshifts is of the order of 20-50 microseconds!

Resolution in timeshifts is of the order of 0.5-2 milliseconds! (both for cross-correlation and picking)

From Landro et al, 2001, First Break: "Mapping reservoir pressure and saturation changes using seismic methods – possibilities and limitations".

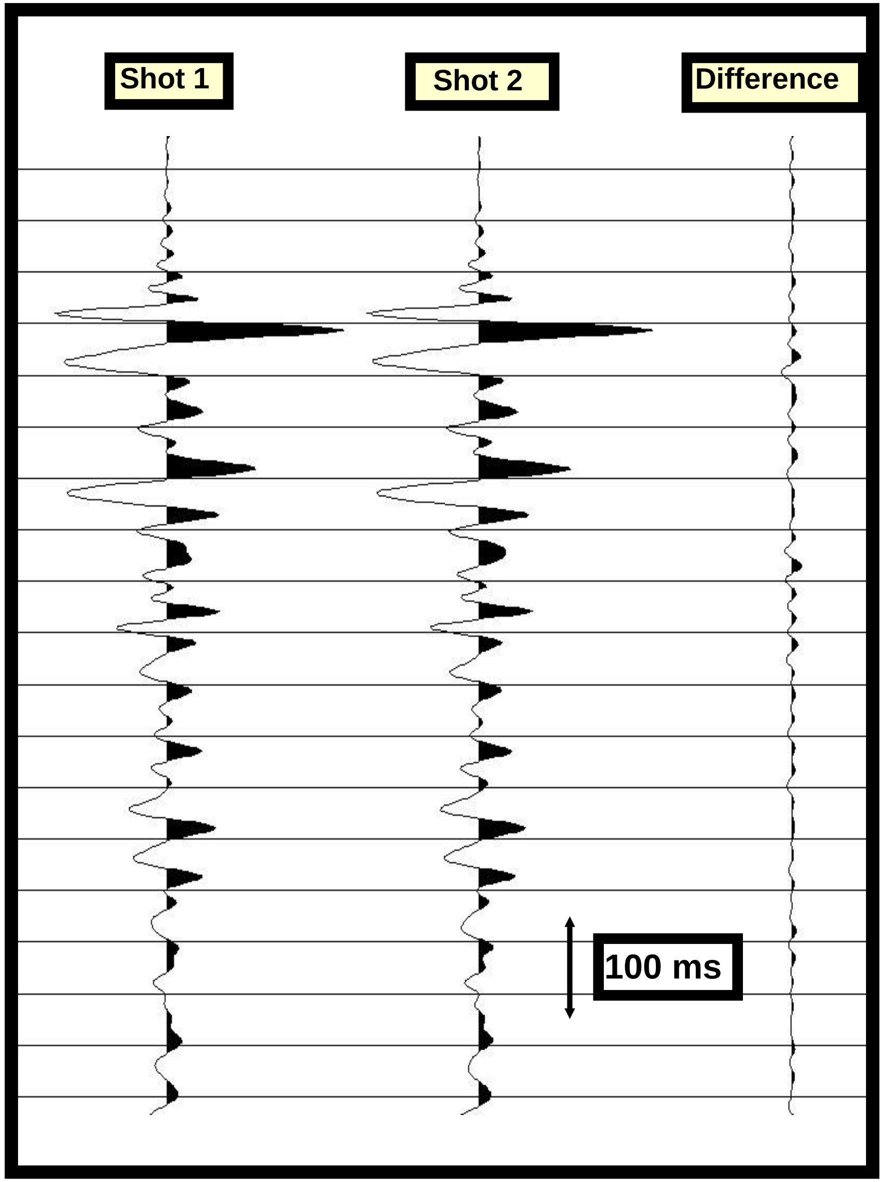
3D VSP experiment (Oseberg Field) shows significant seismic amplitude variations with azimuth

Ref.: Landrø, Repeatability issues of 3D VSP data, Geophsyics 64, 1999

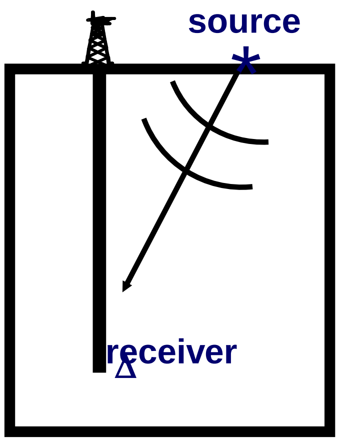


Shot positions (10 000) vary – receivers fixed

Repeatability of VSP data

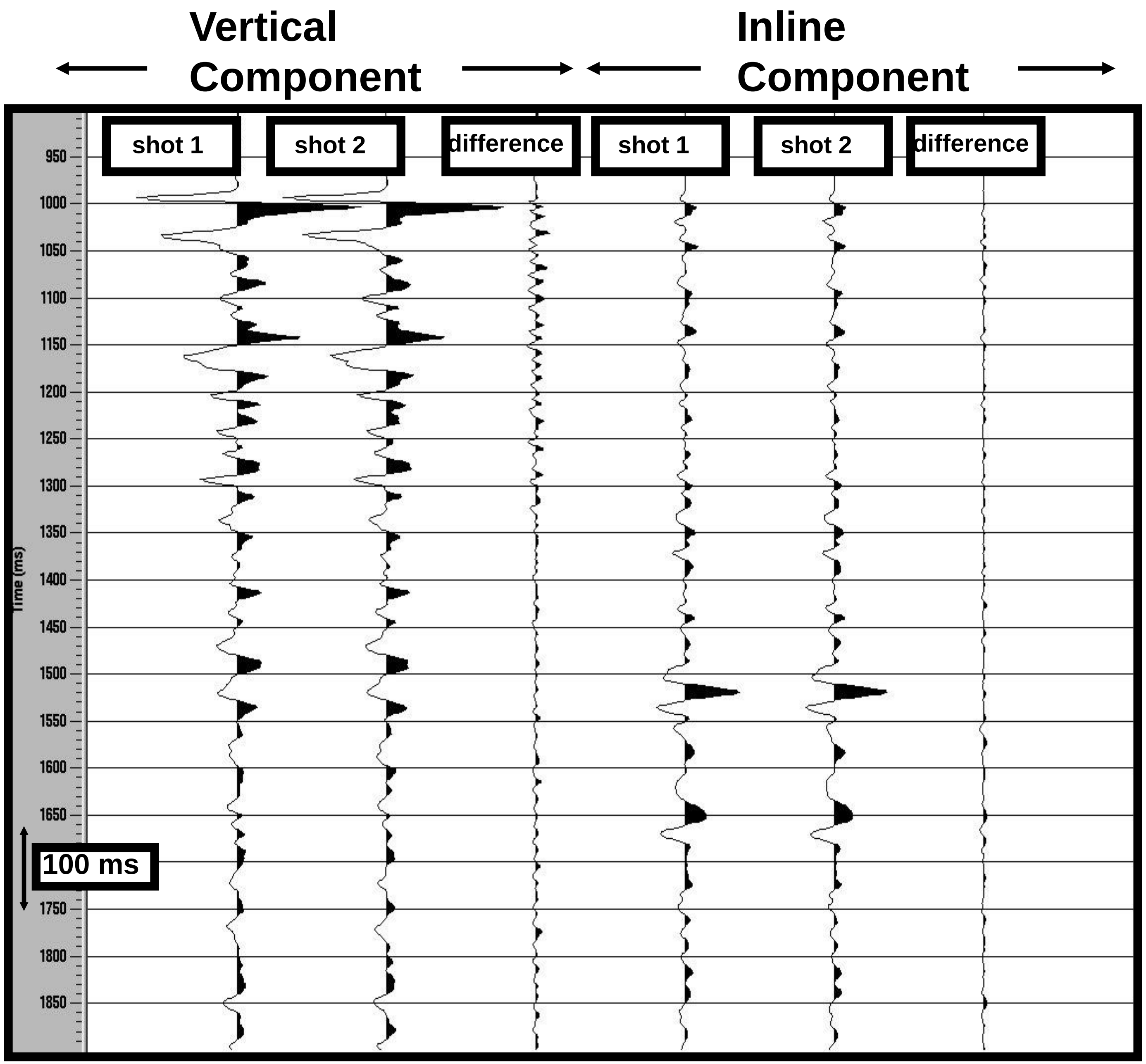


Repeatability of VSP data (Vertical Component) -
two shots with position discrepancy less than 5 meters.
Less than 2 days between shots

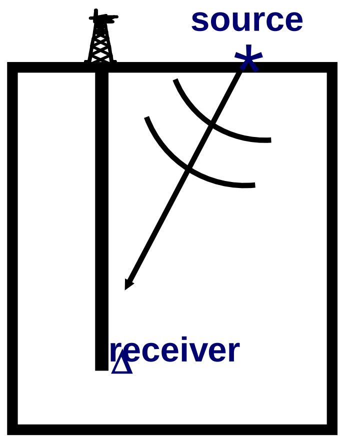


RMS value of difference trace is 8% of original trace - VSP tool was kept fixed in well

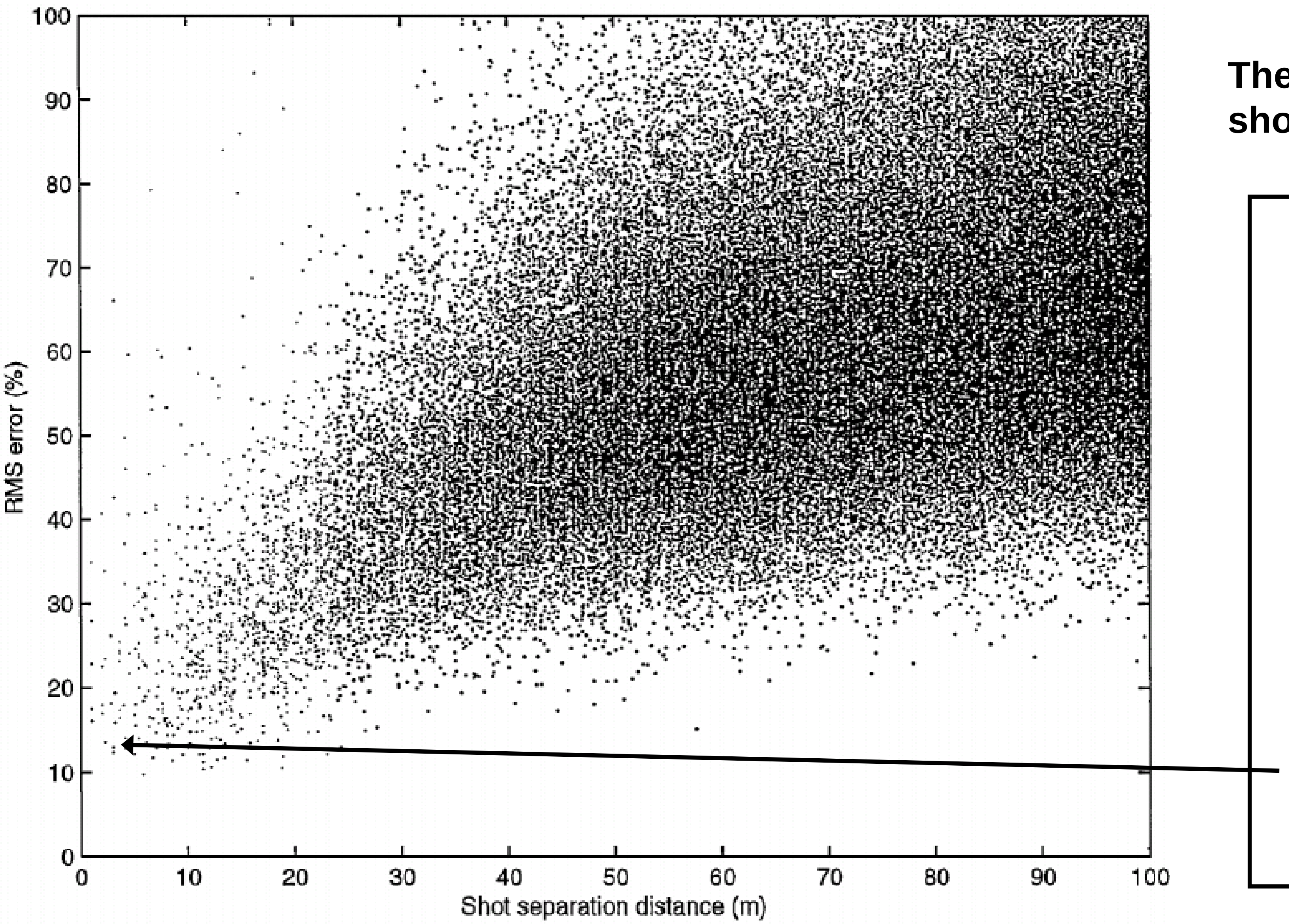
Comparison of repeatability of x and z component VSP data



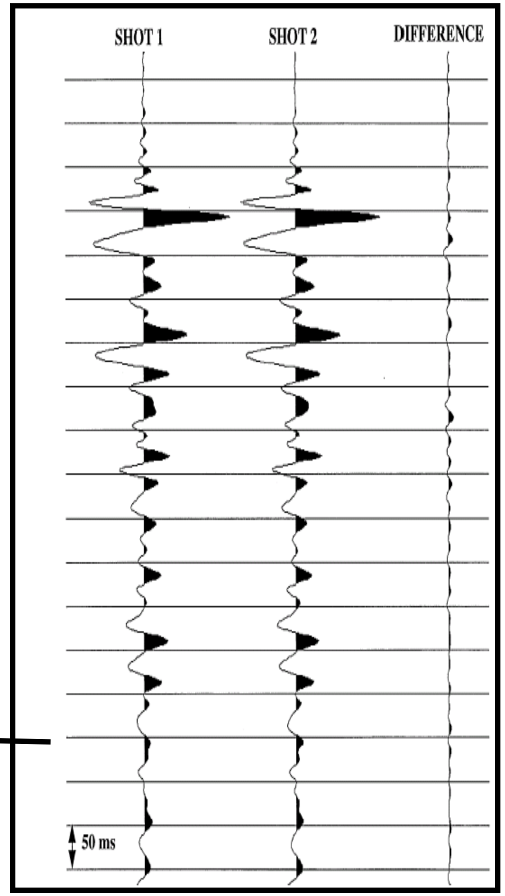
The Inline component data are as repeatable as Vertical component VSP data - given that positioning is accurate within 5 meters



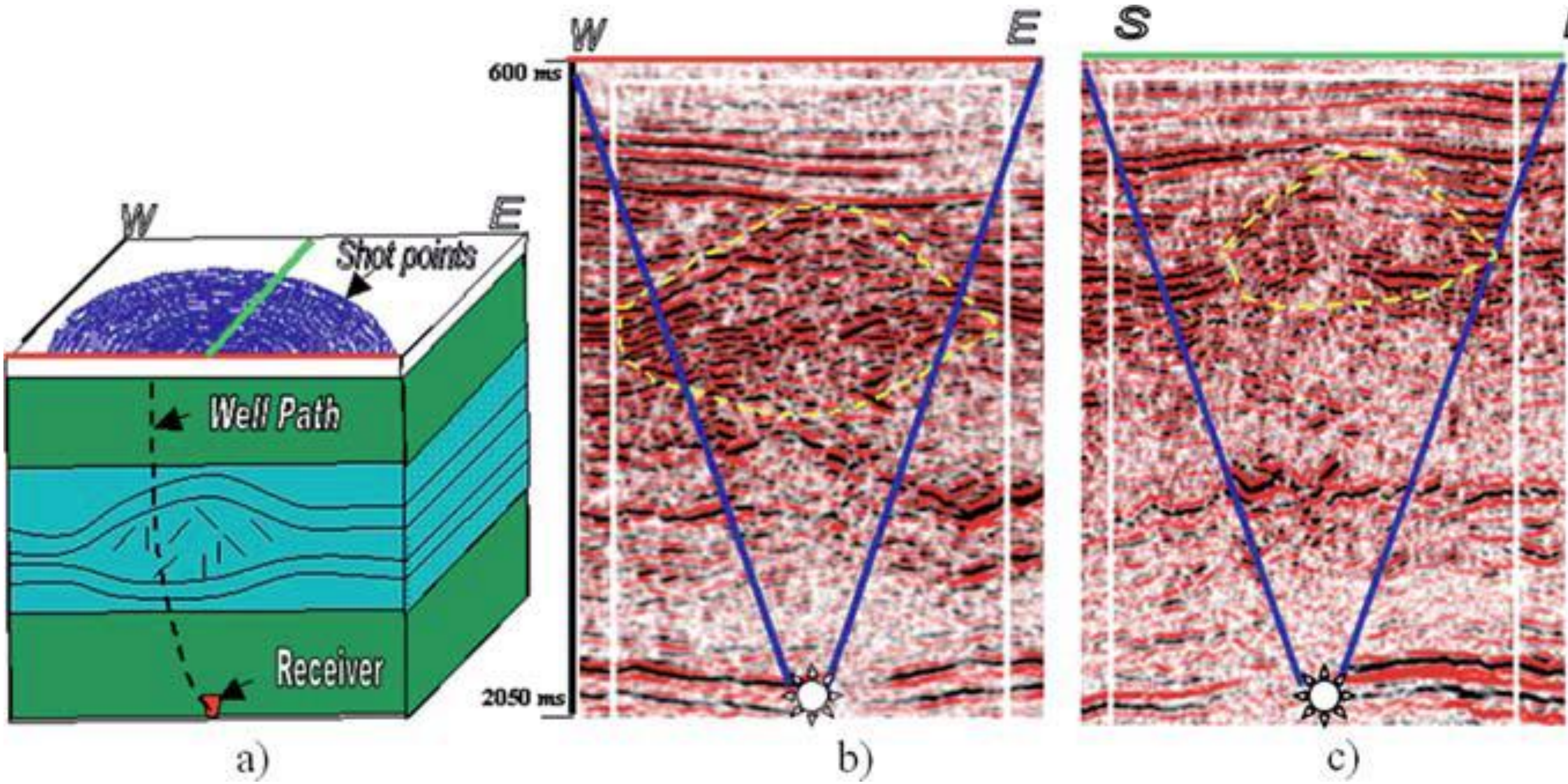
RMS error between pairs of shot records as function of shot separation distance – NO measurements lower than 10% => Positioning does not solve all repeatability problems..



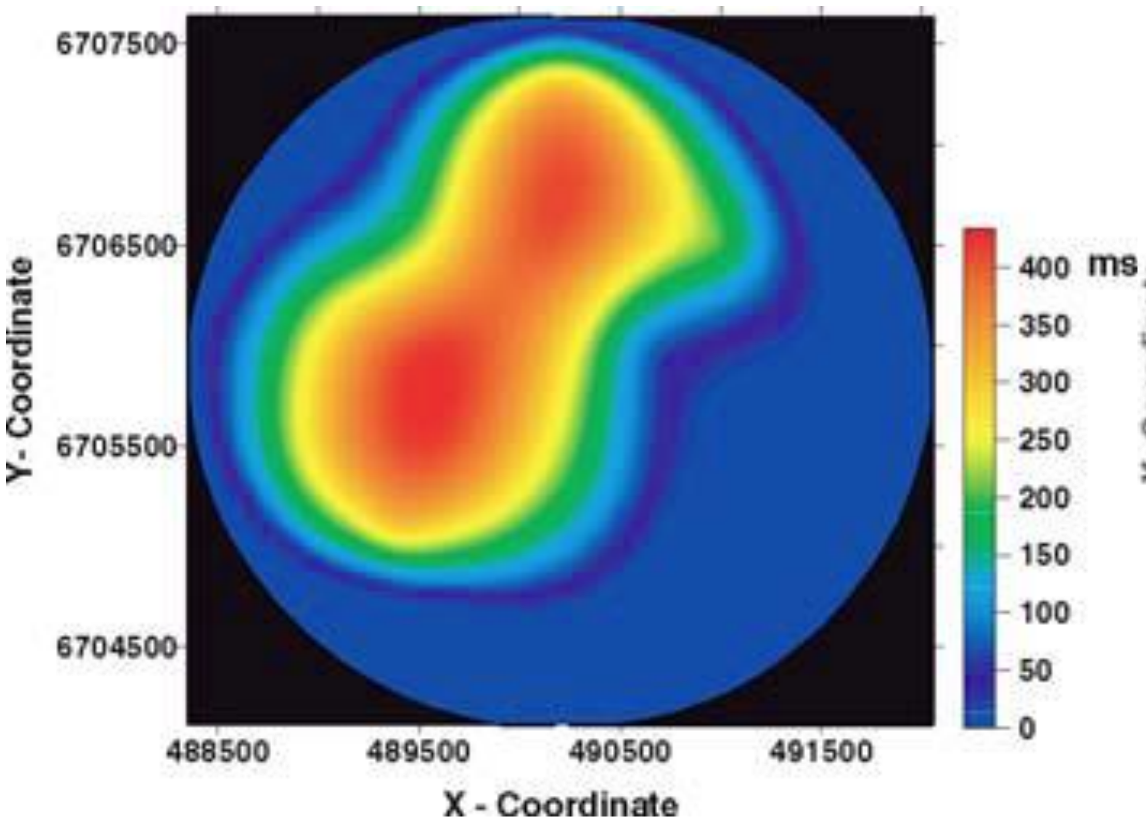
These two traces have shot separation of 5 m



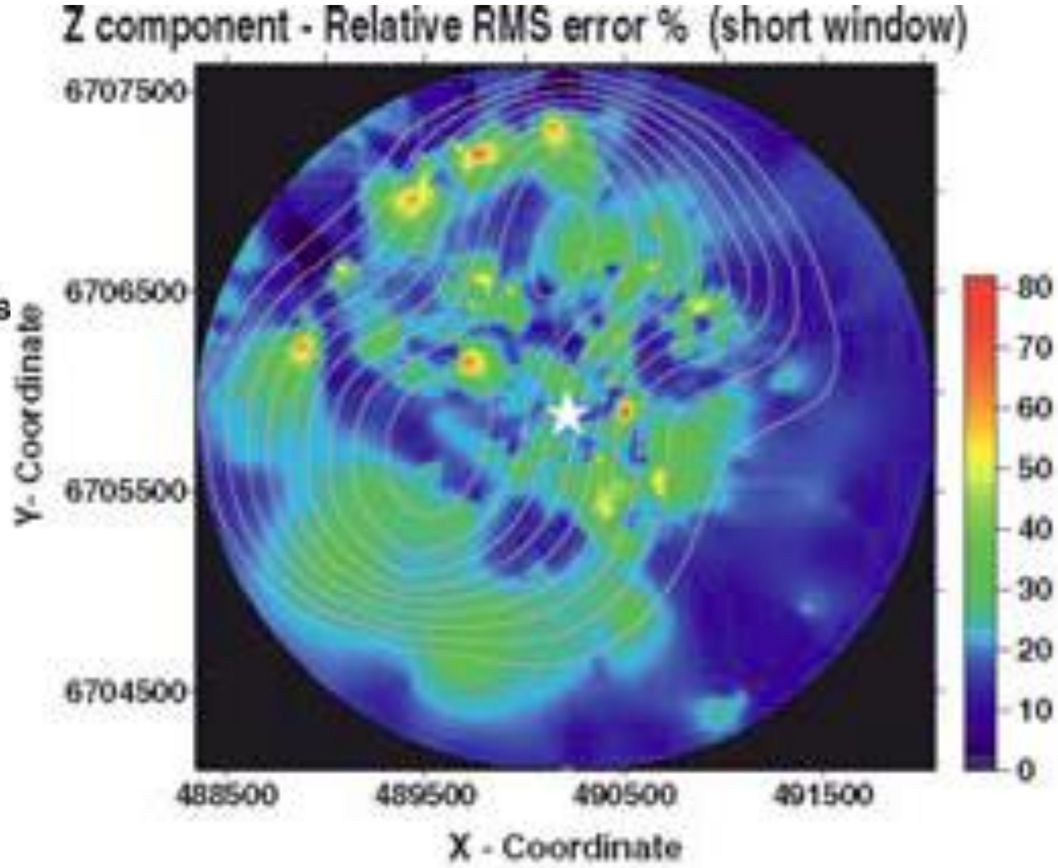
Why this huge spread in the variogram?



Correlation between NRMS and overburden lens?



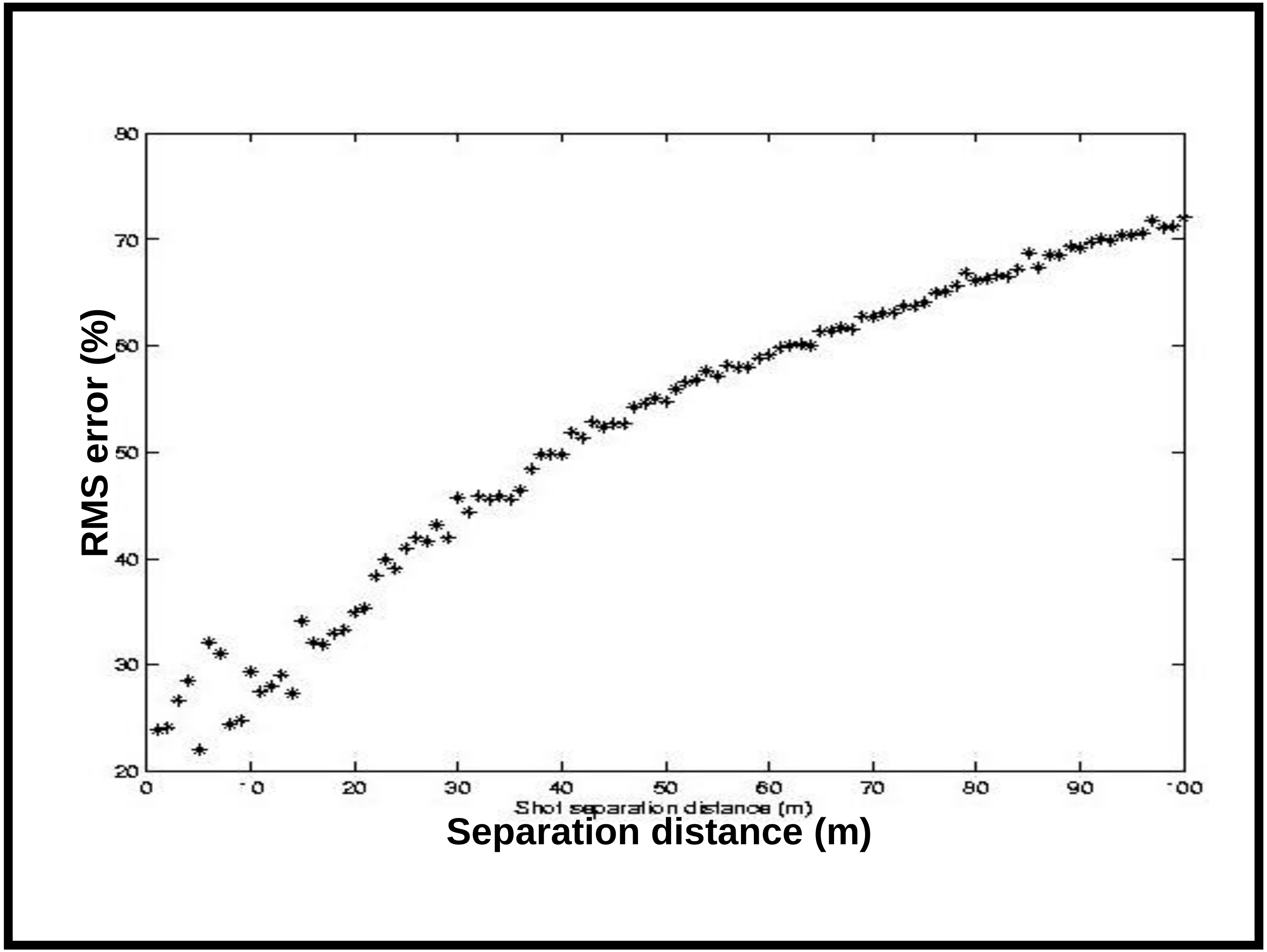
Interpreted overburden lens



NRMS for 3D VSP data

Ref: Misaghi and Landrø, Gephysical Prospecting, 2007

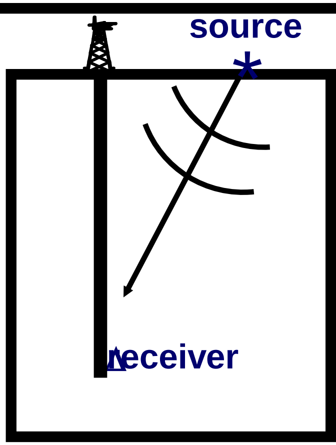
Variation in NRMS with shot separation distance for 3-D VSP data



RMS error computed from unfiltered VSP data

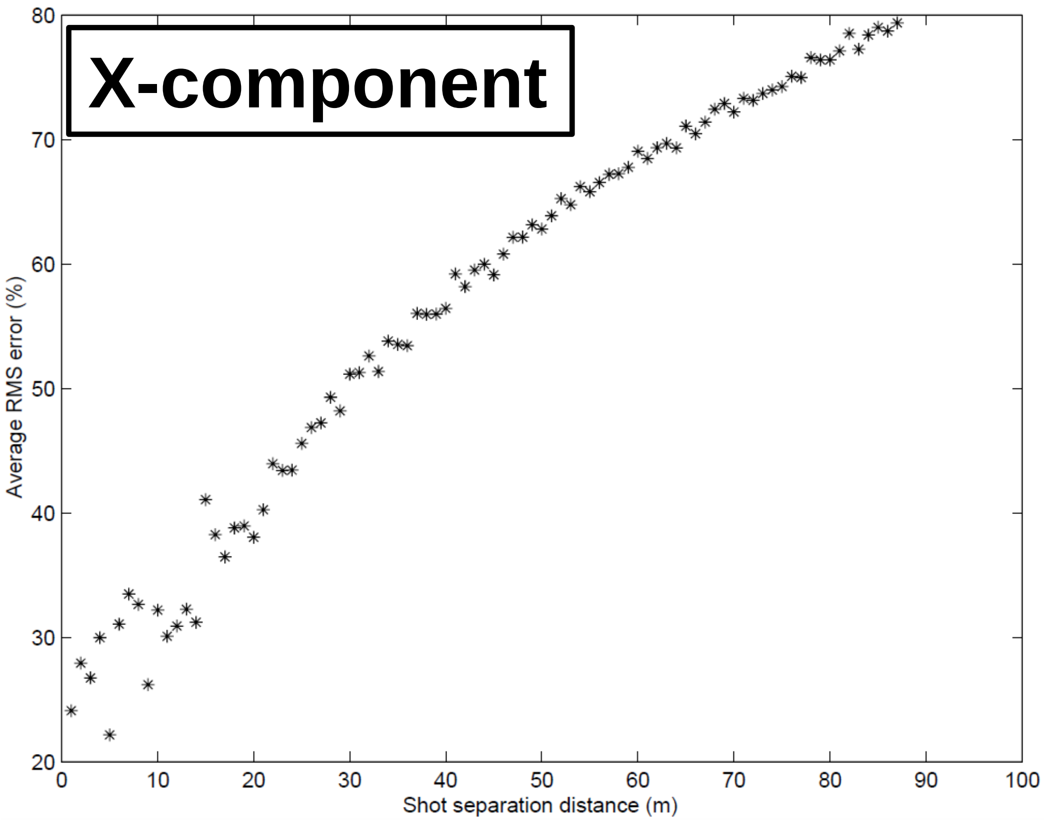
Average of several shot pairs for each separation distance

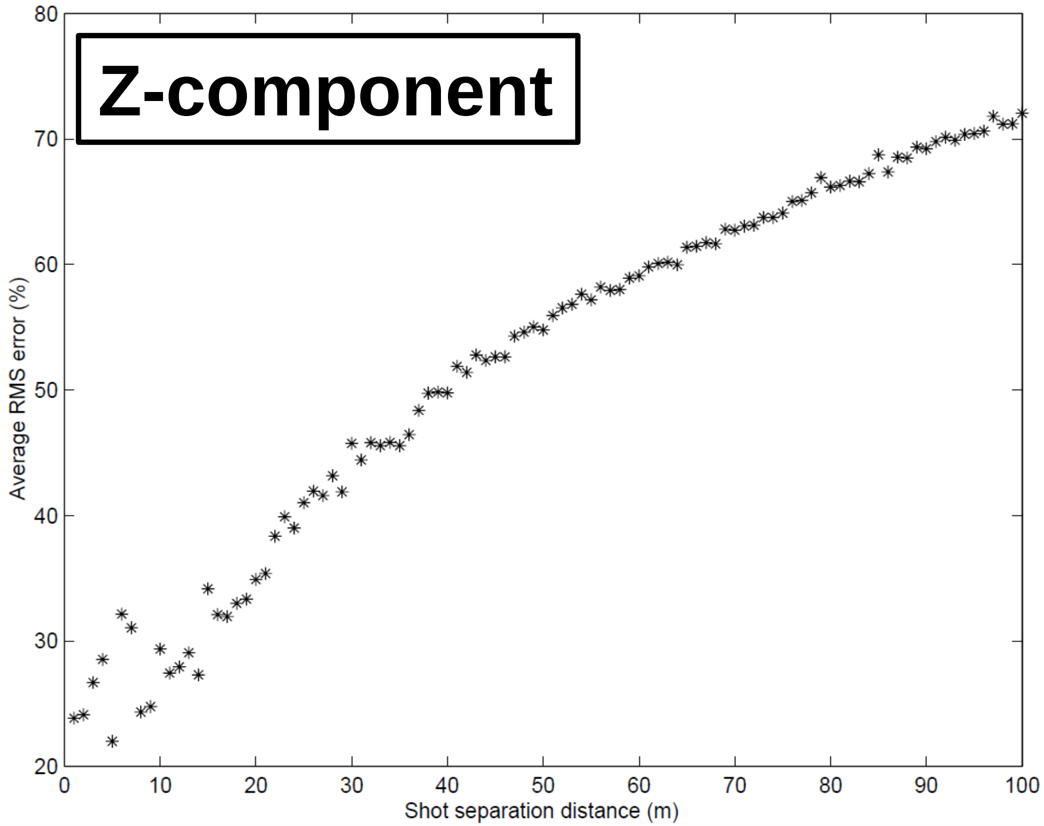
z-component (x-component is slightly less repeatable versus separation distance)



Notice that even for a transmission experiment repeatability is very sensitive to changes in source positions

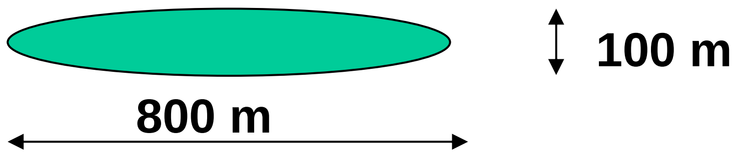
Comparing average NRMS – X and Z

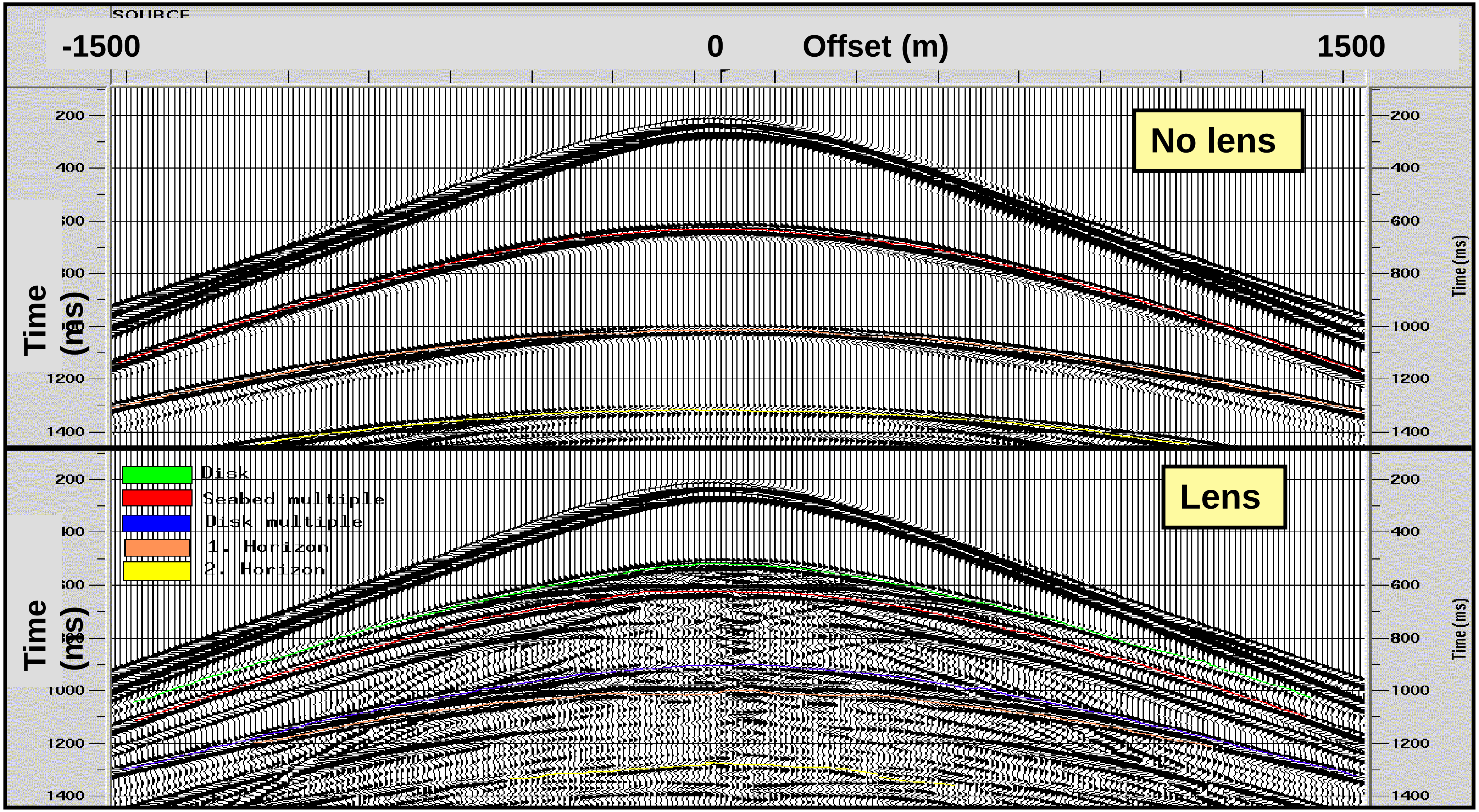




X-component NRMS increases more rapid with shot separation – similar for position errors less than 10 m

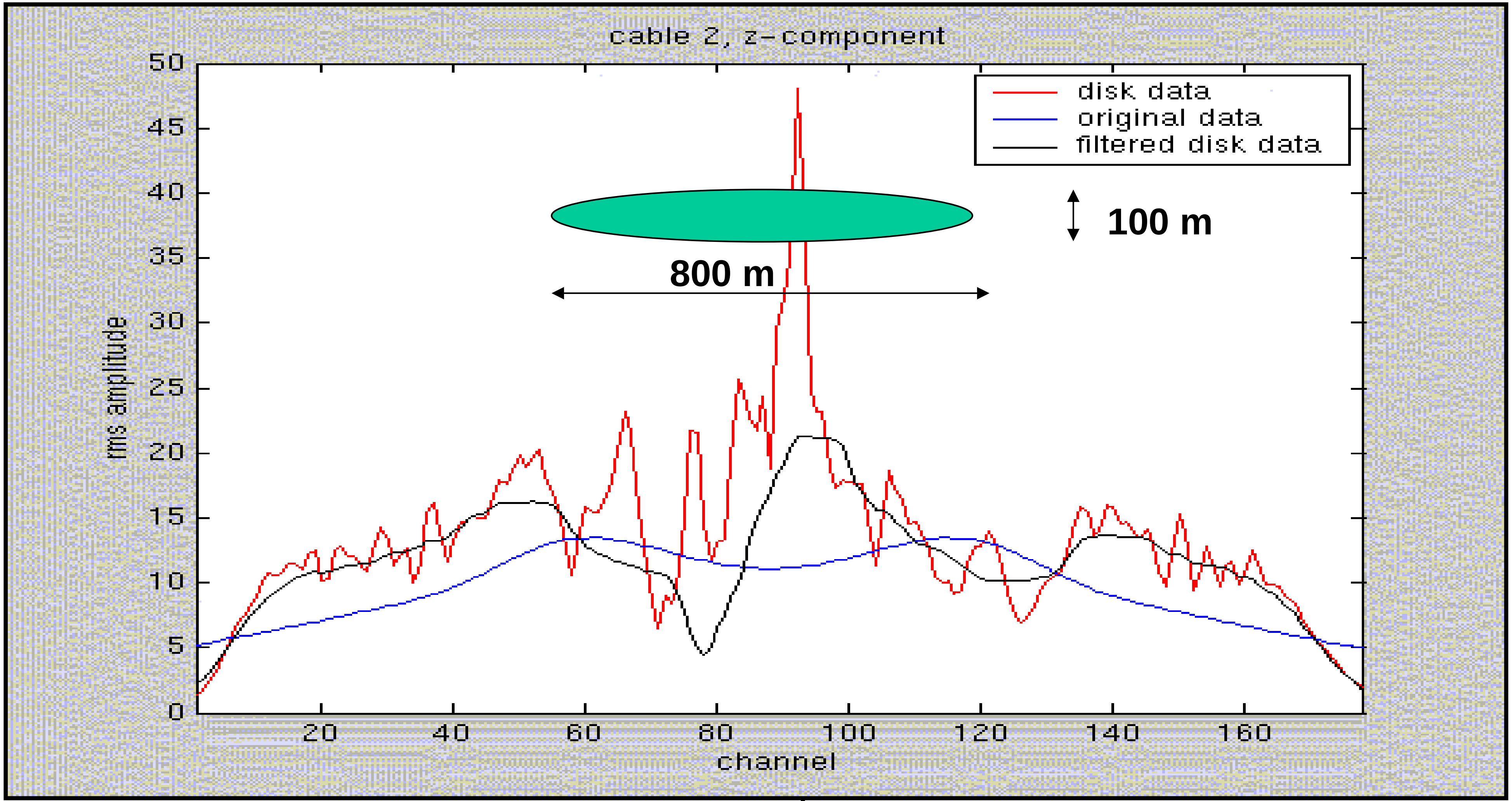
Effect of an overburden lense @ 600 m





Note: Shot postion not straight above lens centre

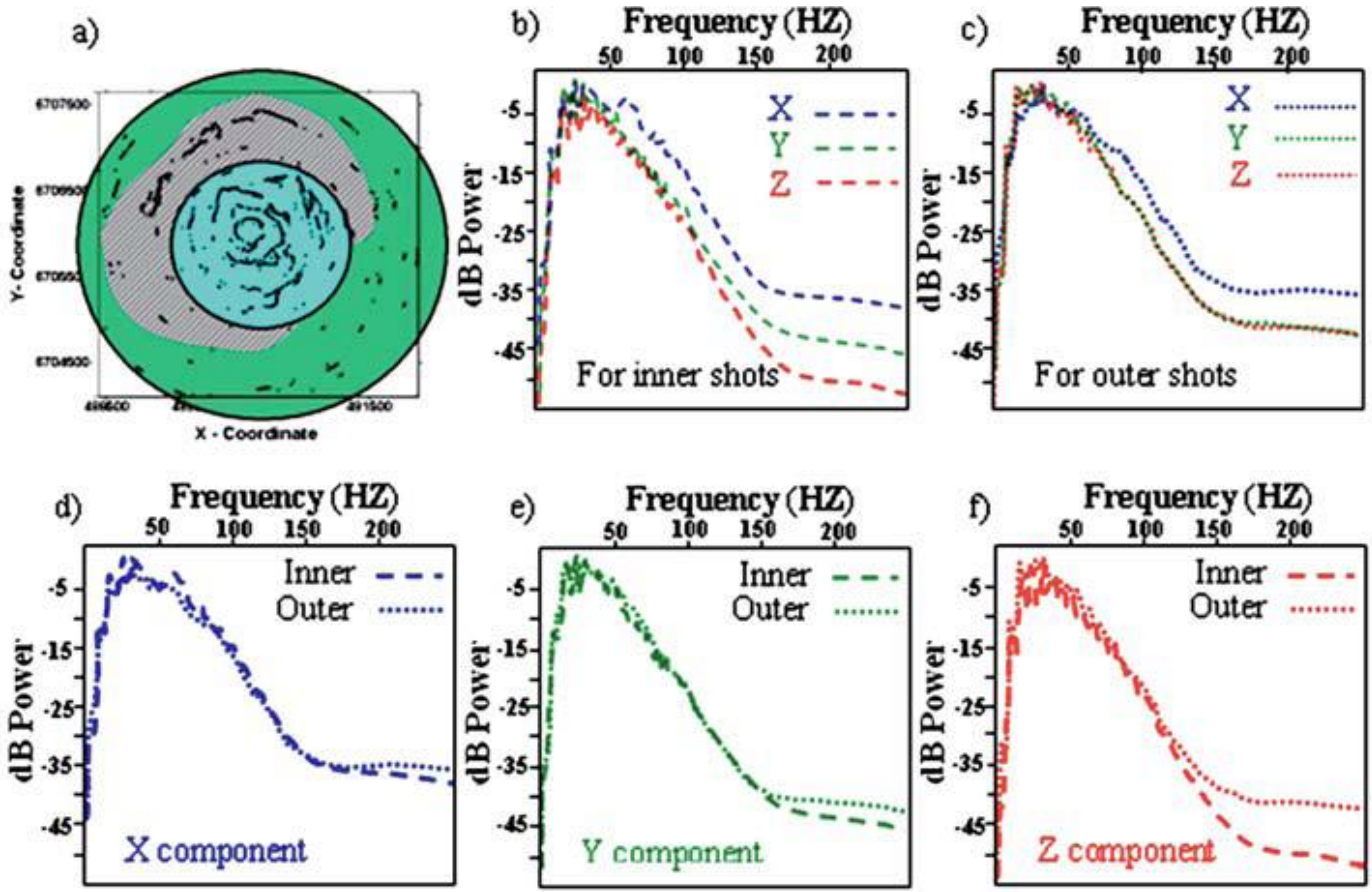
Comparison of RMS-level – reflector 1



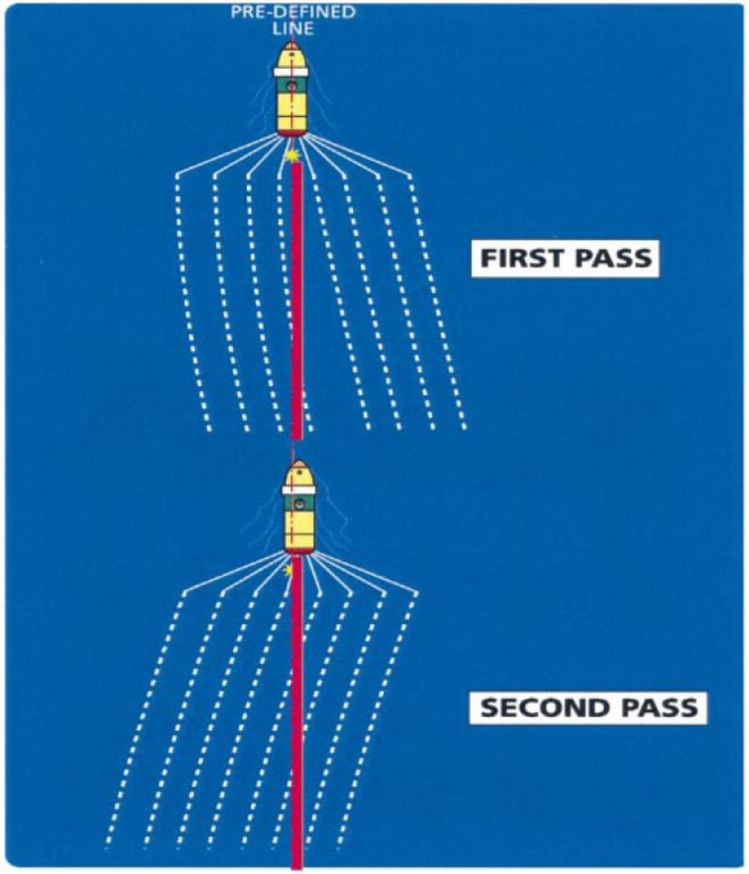
Rapid amplitude variations => poor repeatability caused by mispositioning

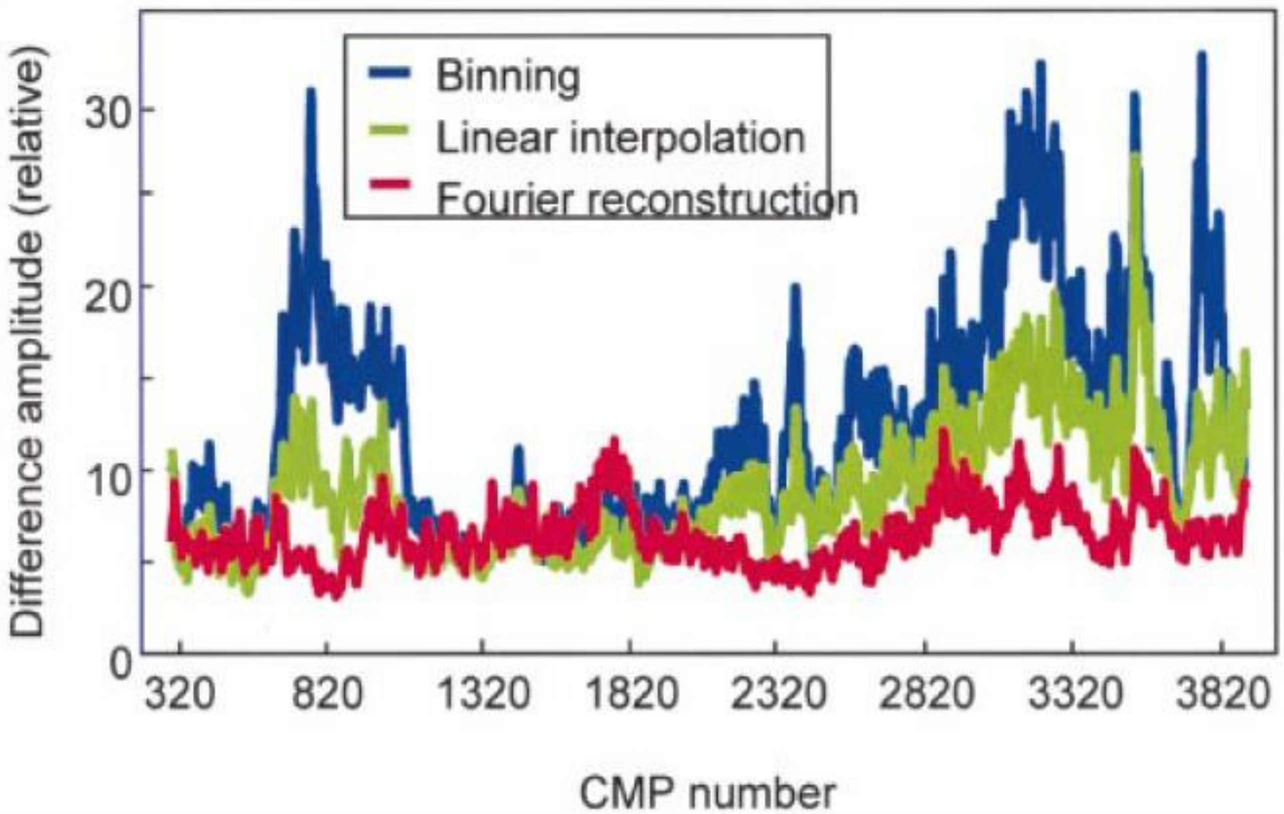
Could this be a frequency effect?

Since repeatability is increasing with less high frequencies, we compared the frequency content for inner and outer traces:



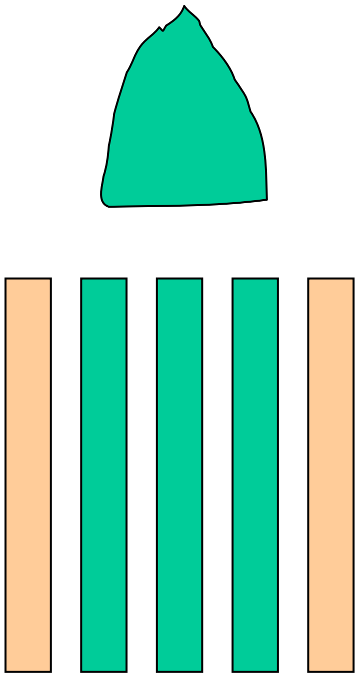
Using the multistreamer concept for improved 4D repeatability

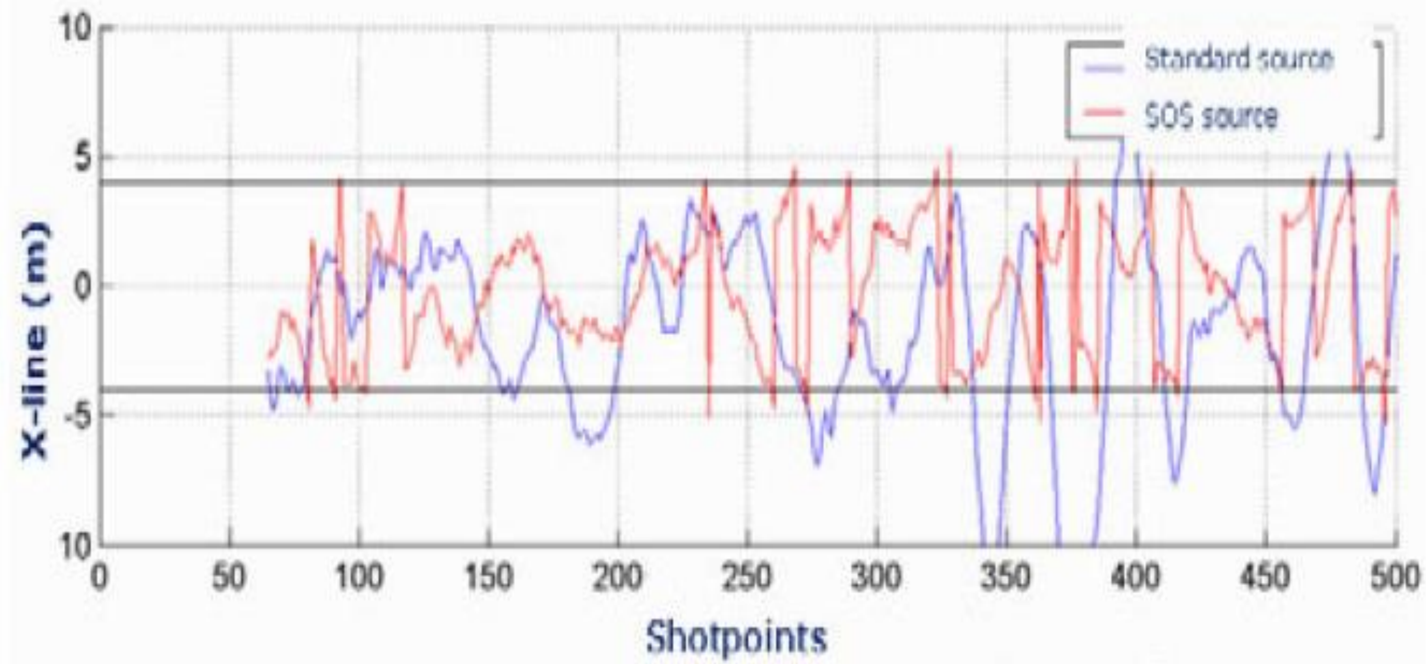




*Ref.: Eiken et al., Geophysics, **68**, 2003*

Using multiple sources for improved repeatability





Idea: Activate the 3 subarrays that are closest to desired shot position

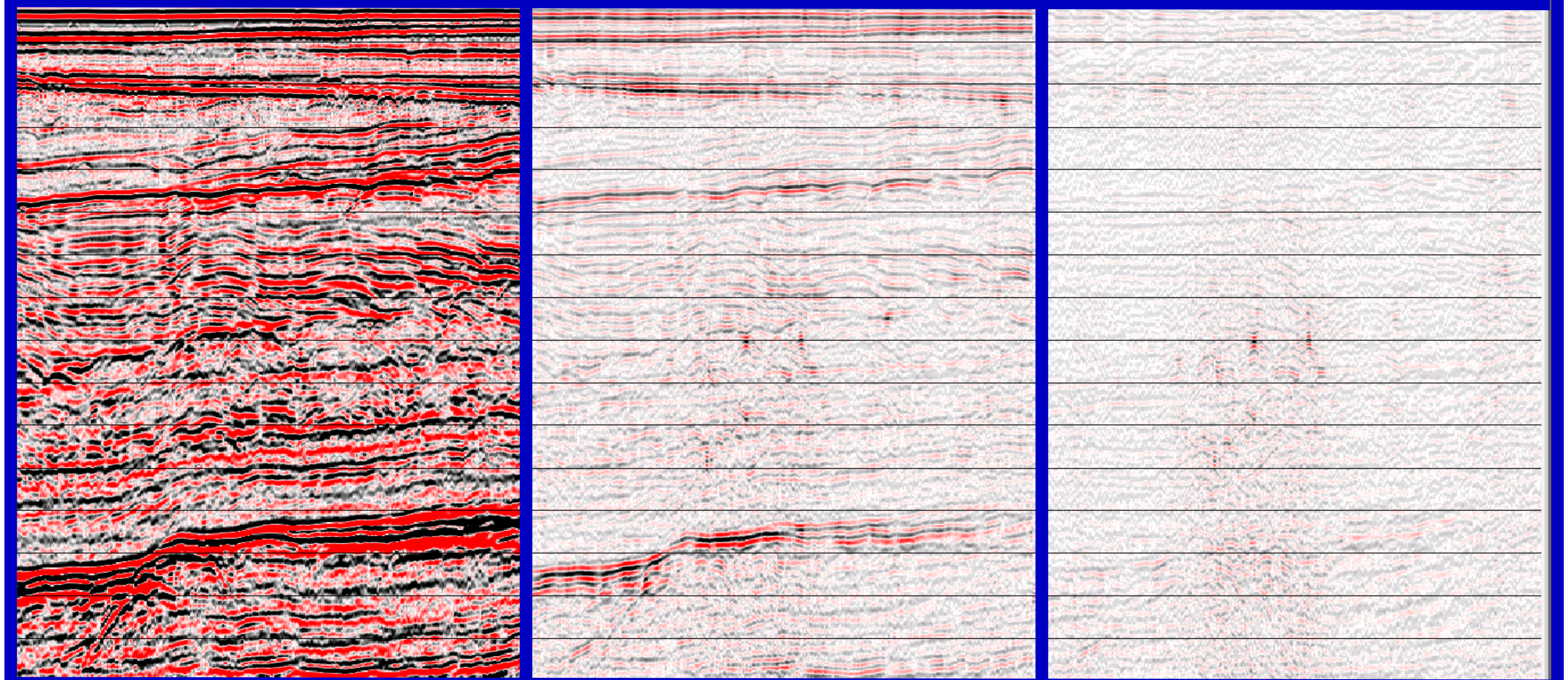
Ref.: O. Næss, SEG 2005

Changing sealevel (tides) influences repeatability - 2D dense streamer acquisition

Ref.: Eiken, O., Waldemar, P., Schonewille, M., Haugen, G. U. and Duijndam, A., 1999, A proven concept for acquiring highly repeatable towed streamer seismic data, 61st EAGE Meeting.

STATOIL

stack	difference stack	difference stack after 40-60 cm tidal correction

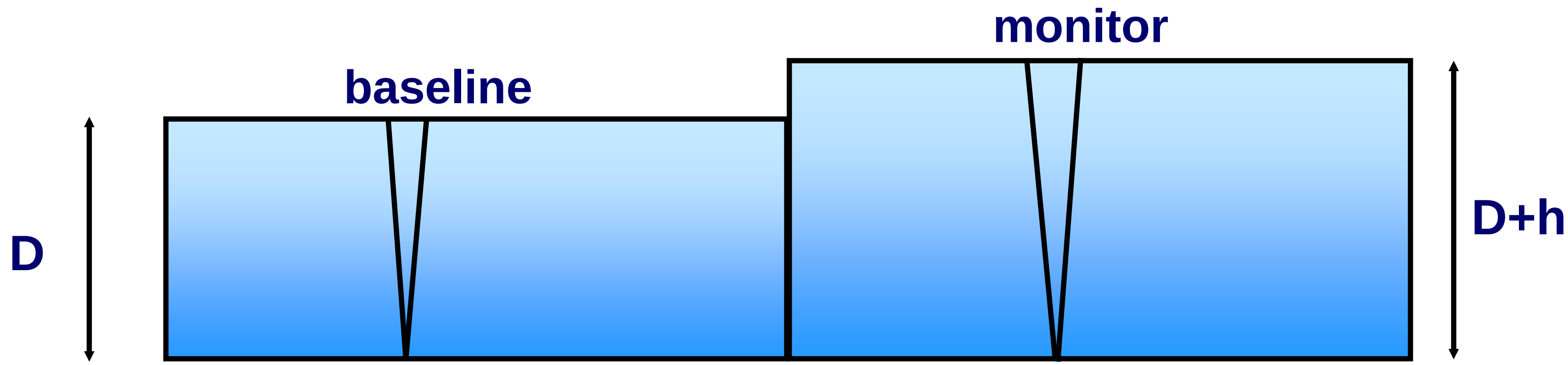


	RMS difference ~ 15 %	RMS difference ~ 6 %

Tidal effects

- considering reflection from sea bottom only

Assume a tidal shift h between baseline and monitor survey



$$\Delta t = \frac{4Dh}{c4\sqrt{D^2 + x^2}}$$

Tidal correction is depth and offset dependent

Relative error due to time shift: $\frac{\Delta S}{S} = 4\pi f \frac{h}{c}$

Example: h=0.5m and f= 50 Hz => rel.err. ~ 21%

Relative error due to change in raypath: $\frac{\Delta S}{S} = \frac{h}{D}$

Example: h=0.5m and D=100m => rel.err. ~ 0.5%

Statics caused by tides

Exact:

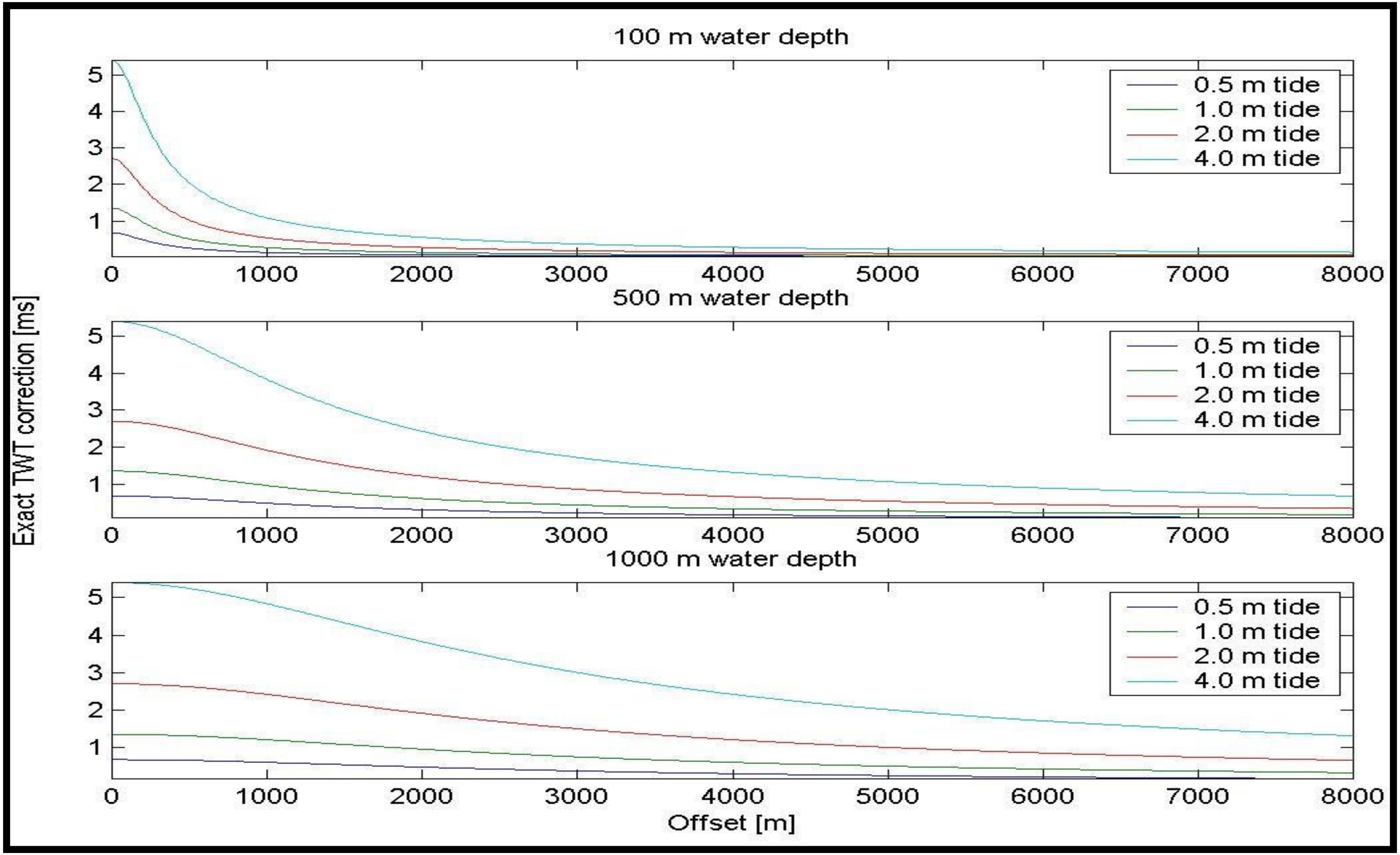
$$\Delta t = \frac{2}{c}\sqrt{h^2 + \frac{x^2}{4}}\left[\sqrt{1 + \frac{2h\Delta h + (\Delta h)^2}{h^2 + \frac{x^2}{4}}} - 1\right]$$

Approximation, as function of incidence angle (in water layer) (η):

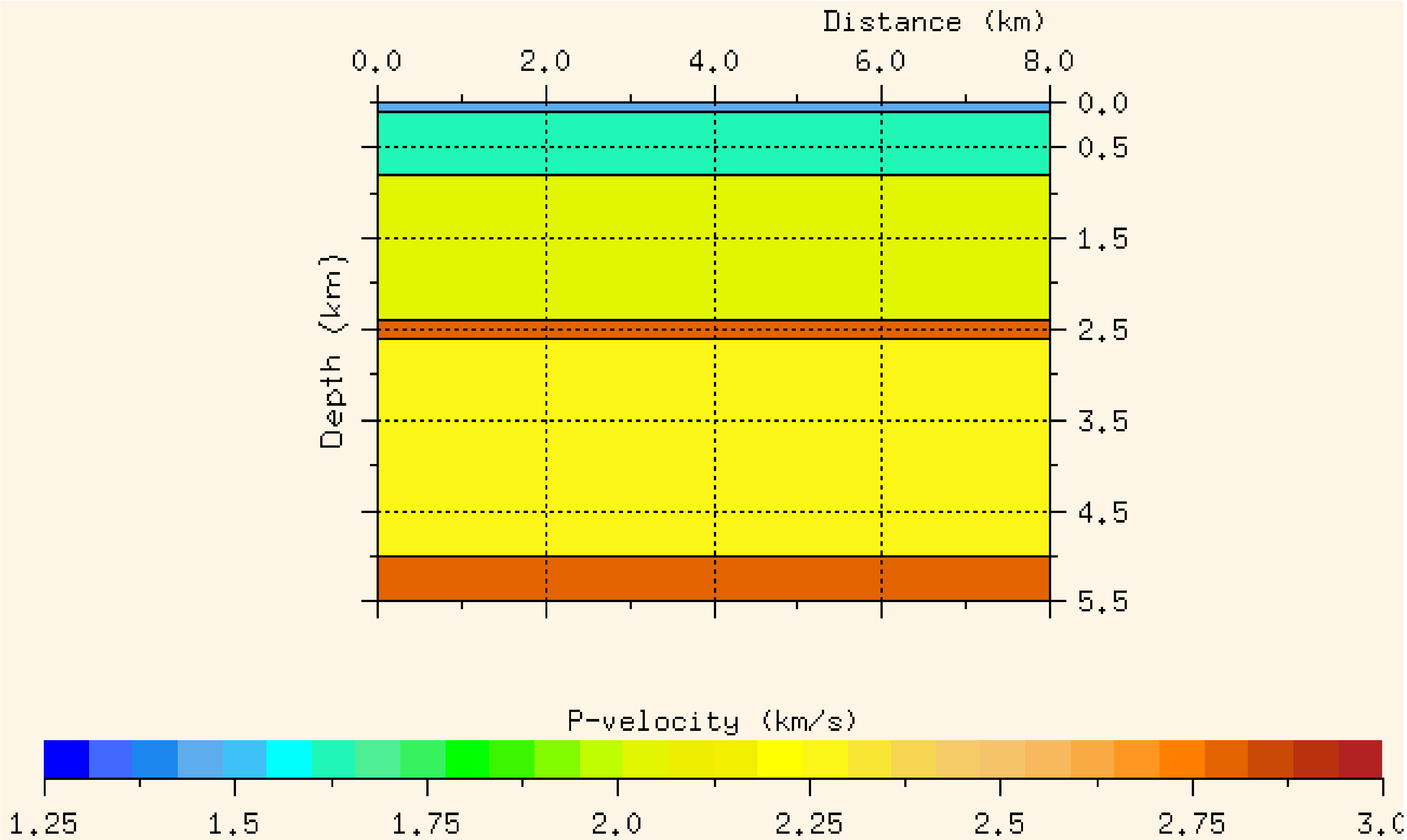
$$\Delta t = \frac{2\Delta h \cos\theta}{c}$$

Offset dependent tidal timeshifts

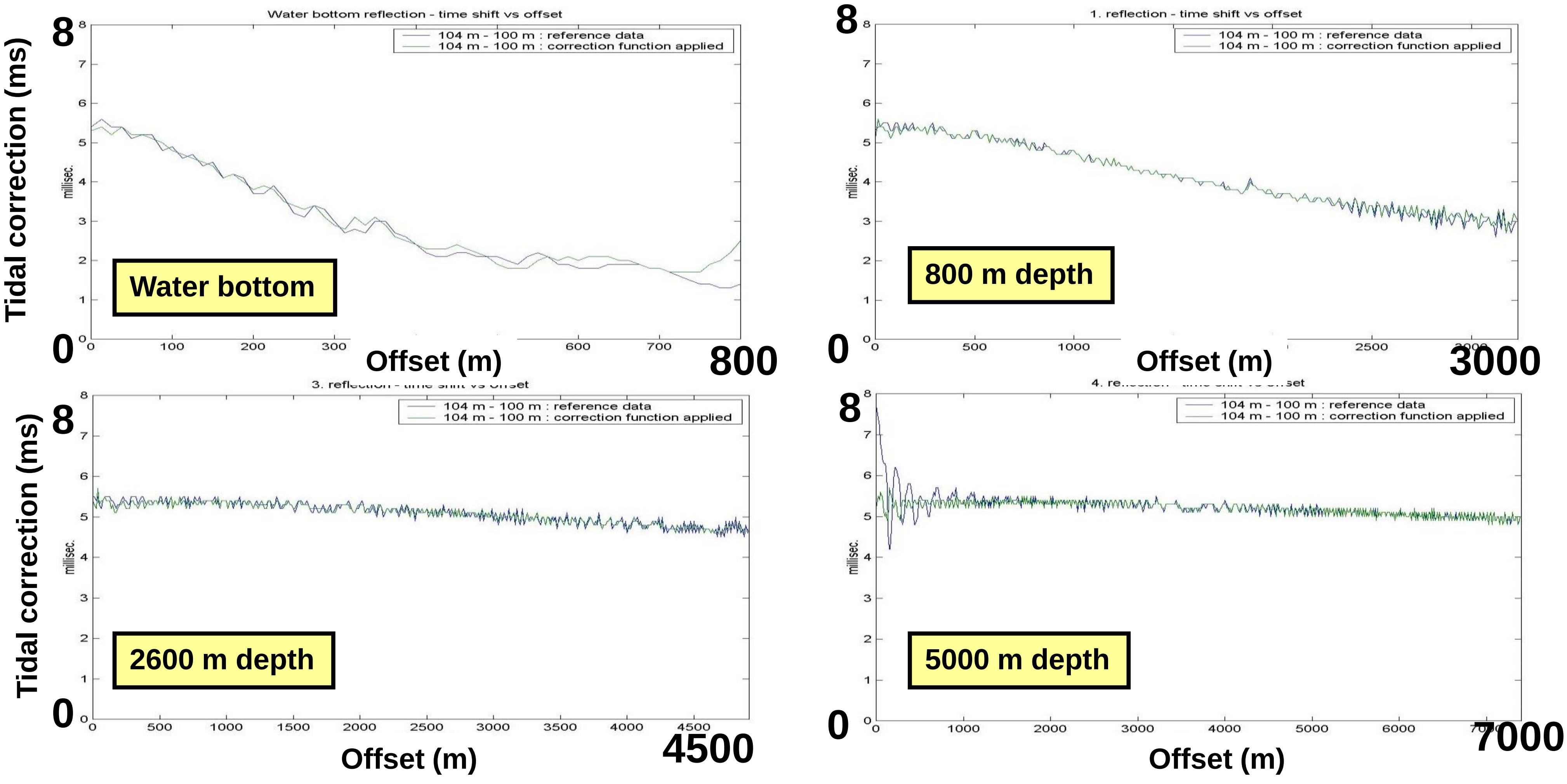
Project thesis of Håvard Åsli, 2001



Two models with water depths of 100 m and 104 m

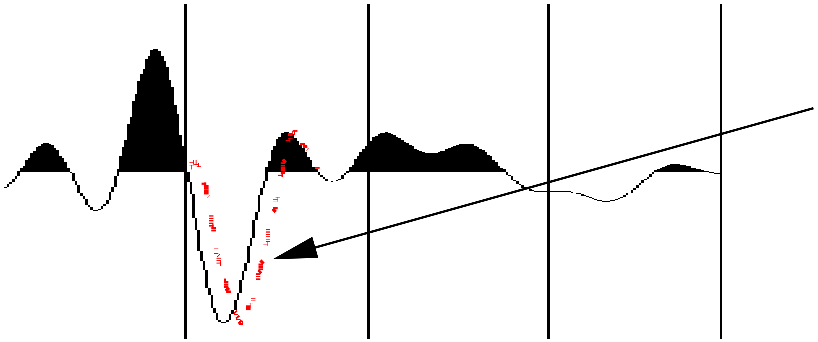


Comparison between approximate offset dependent tidal correction and exact, modeled tide for reflectors 1,2,4 and 5 – notice that offset dependency decrases with target depth



Sea roughness and non-repeatability

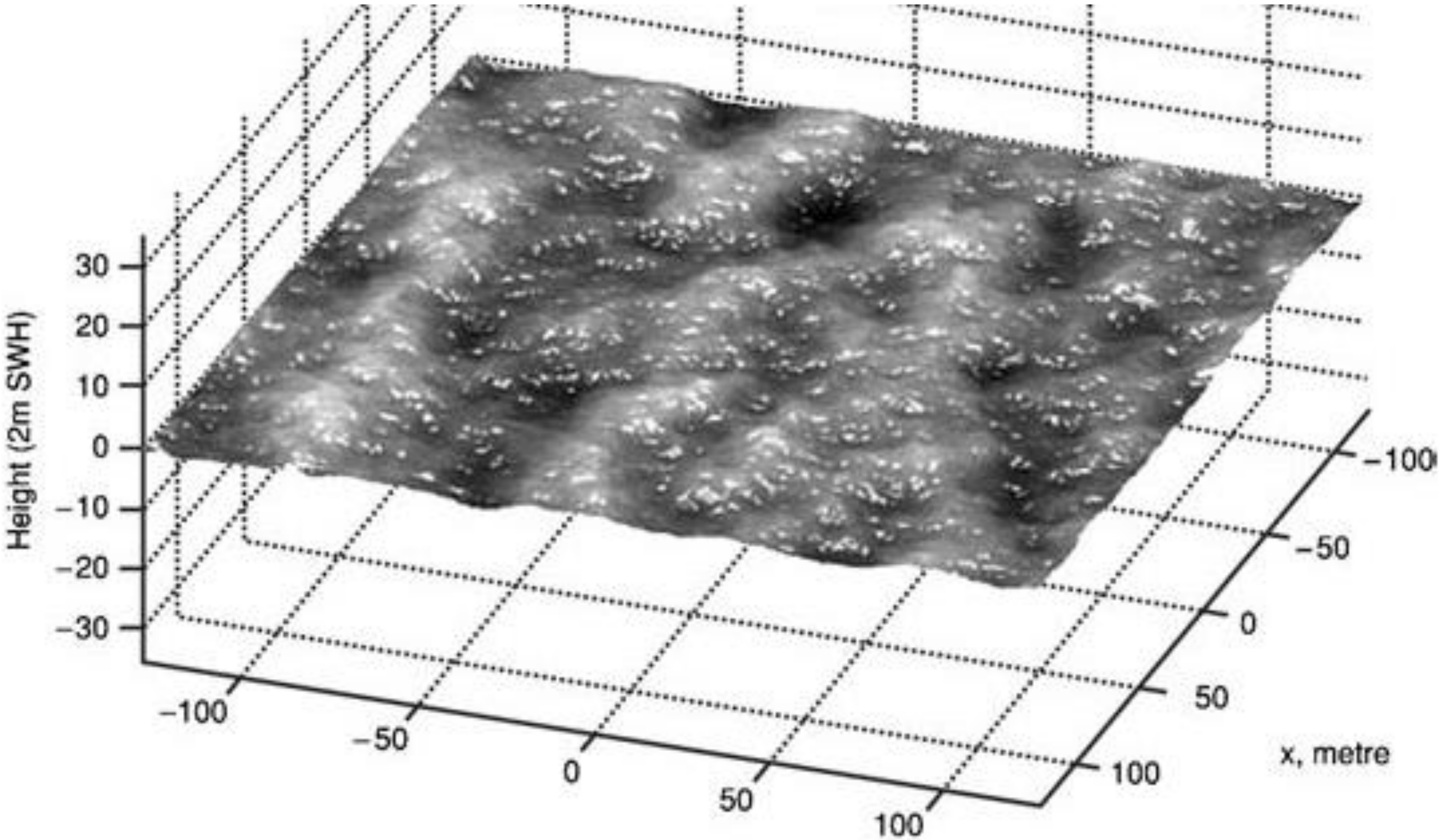
- Robert Laws and Ed Kragh, 62nd EAGE meeting Glasgow, 2000

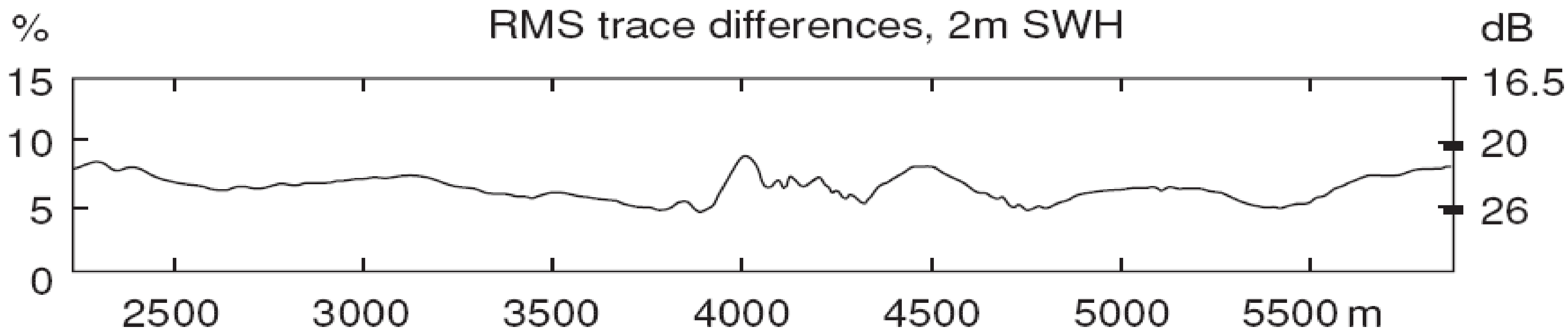


Changes in the sea ghost reflection response

A synthetic study showed 5-10% RMS differences due to rough seas - fold=48 and 2 m dominant wave height

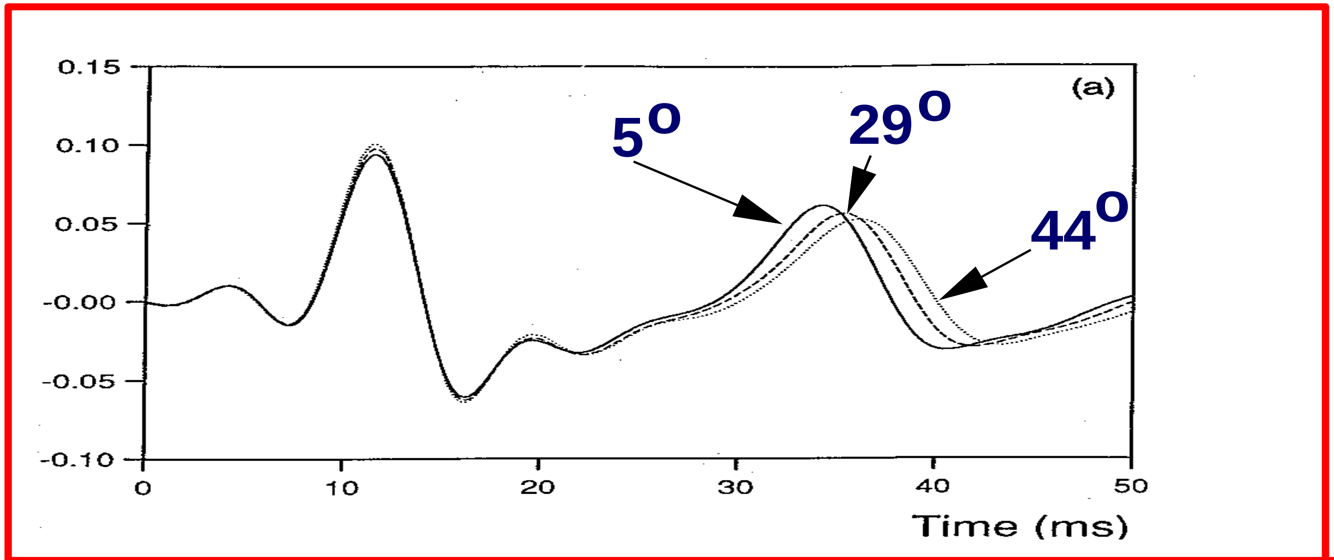
Simultating the effect of sea surface roughness on 4D



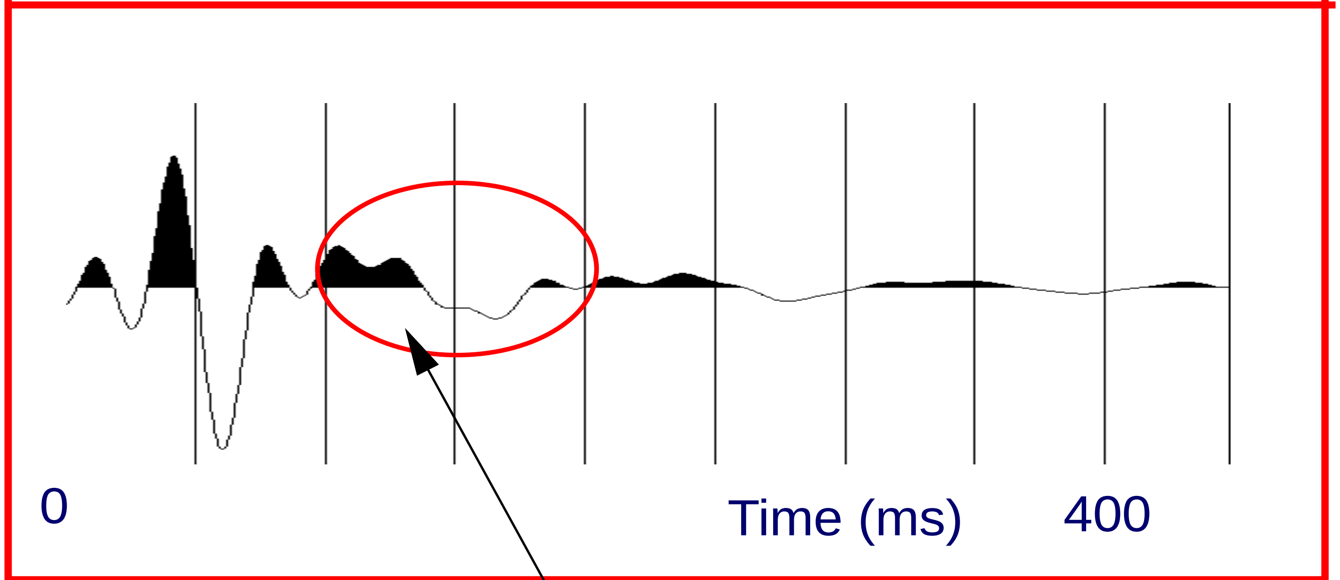


Laws and Kragh, 2000

Changes in air gun source signature due to water temperature changes



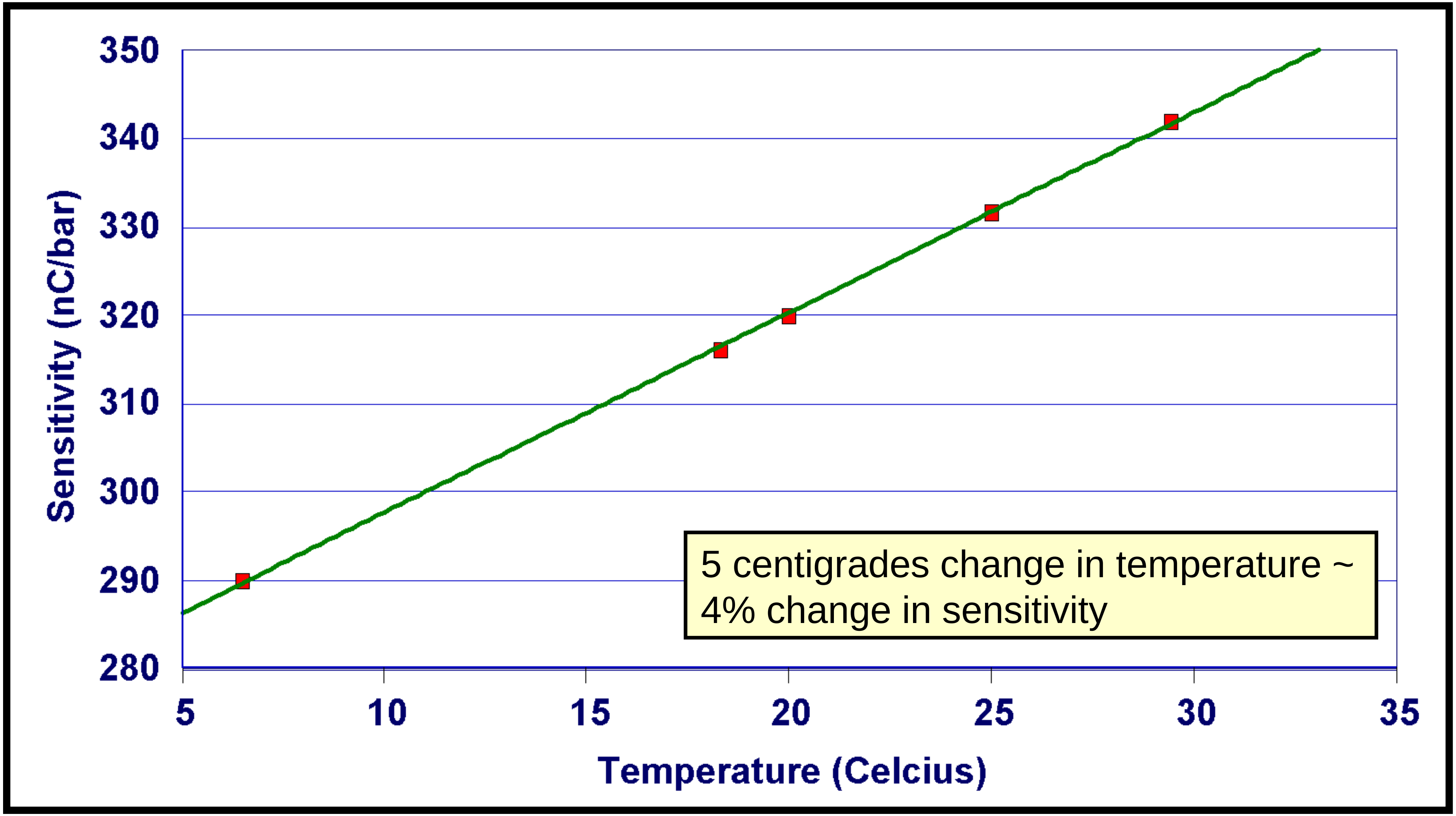
1.6 cubic inch airgun fired in a water tank

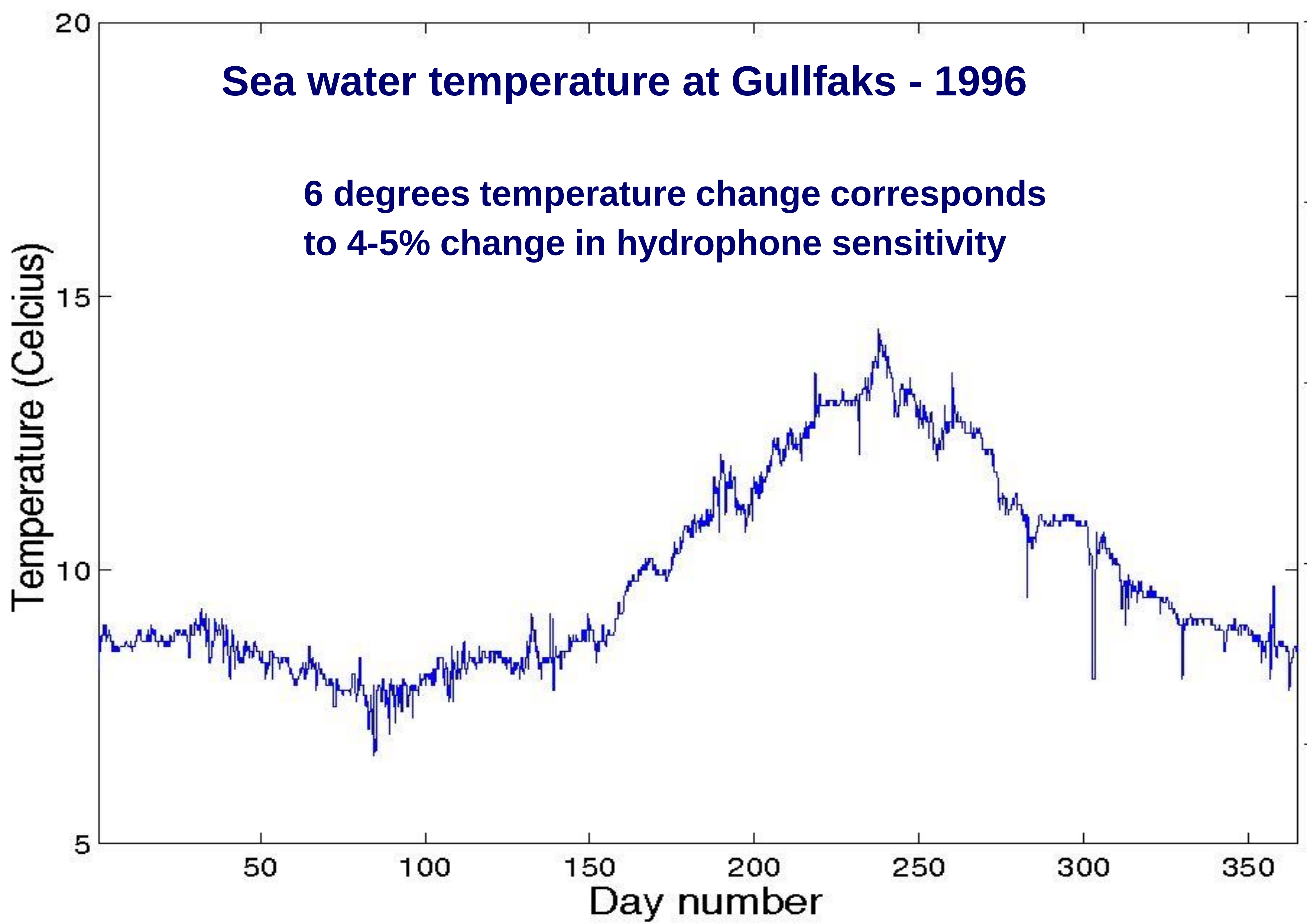


Conventional airgun array - typical primary to bubble ratio (40Hz) is 4.5

Expect changes in this part due to temperature changes; 10 degrees change gives a time shift of approximately 1.3 ms

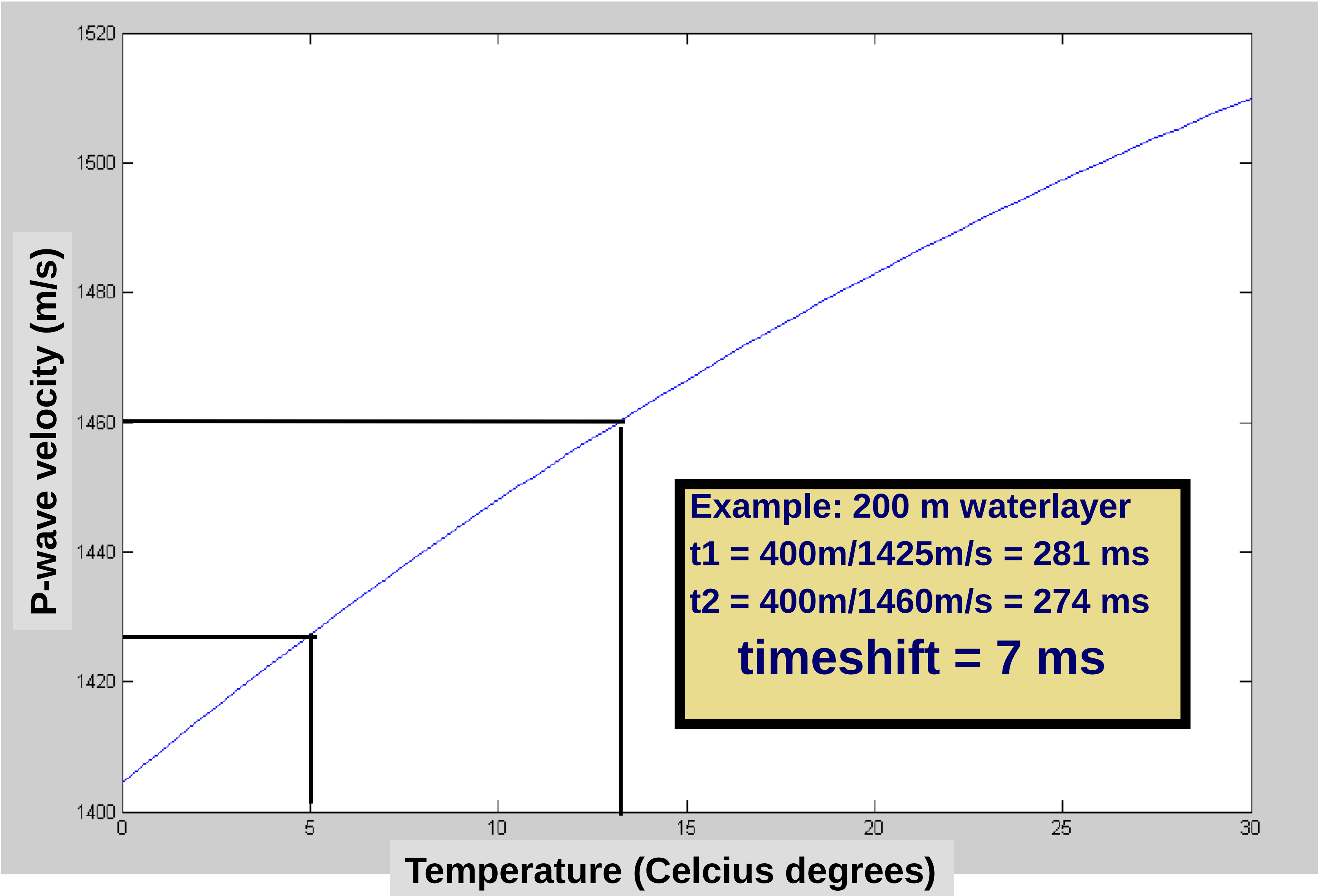
Hydrophone sensitivity varies with water temperature





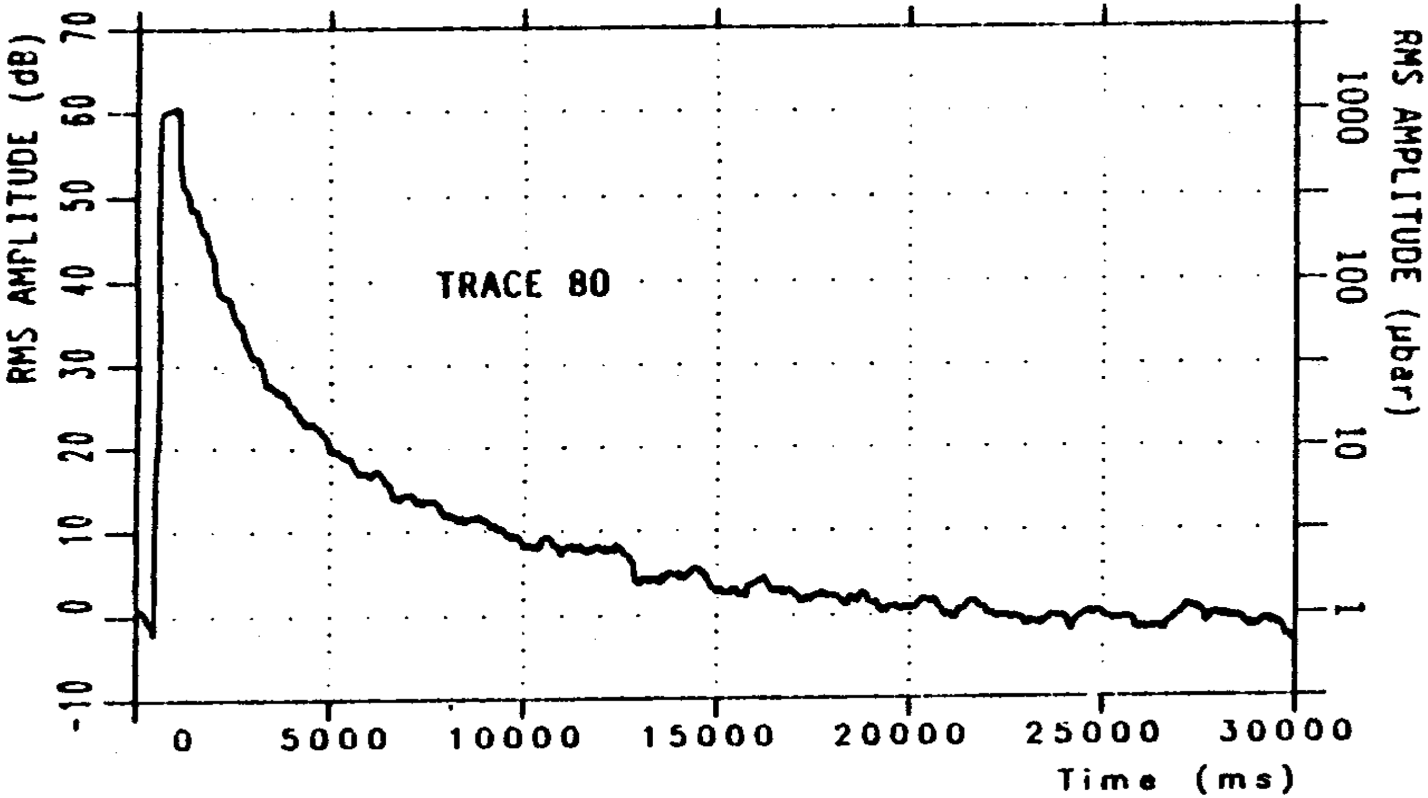
Sea water temperature at Gullfaks - 1996
6 degrees temperature change corresponds
to 4-5% change in hydrophone sensitivity
Temperature (Celcius)
20
15
10
5
50
100
150
200
250
300
350
Day number

P-wave velocity in water versus temperature



8 degrees increase => Delta-VP=30 m/s

Shot generated noise:
Need to increase shot interval for increased repeatability?



Ref: Marine Seismic Noise: Seres Report T.29.02/89 by Landrø, Haugen, Sødal, Nielsen and Vaage

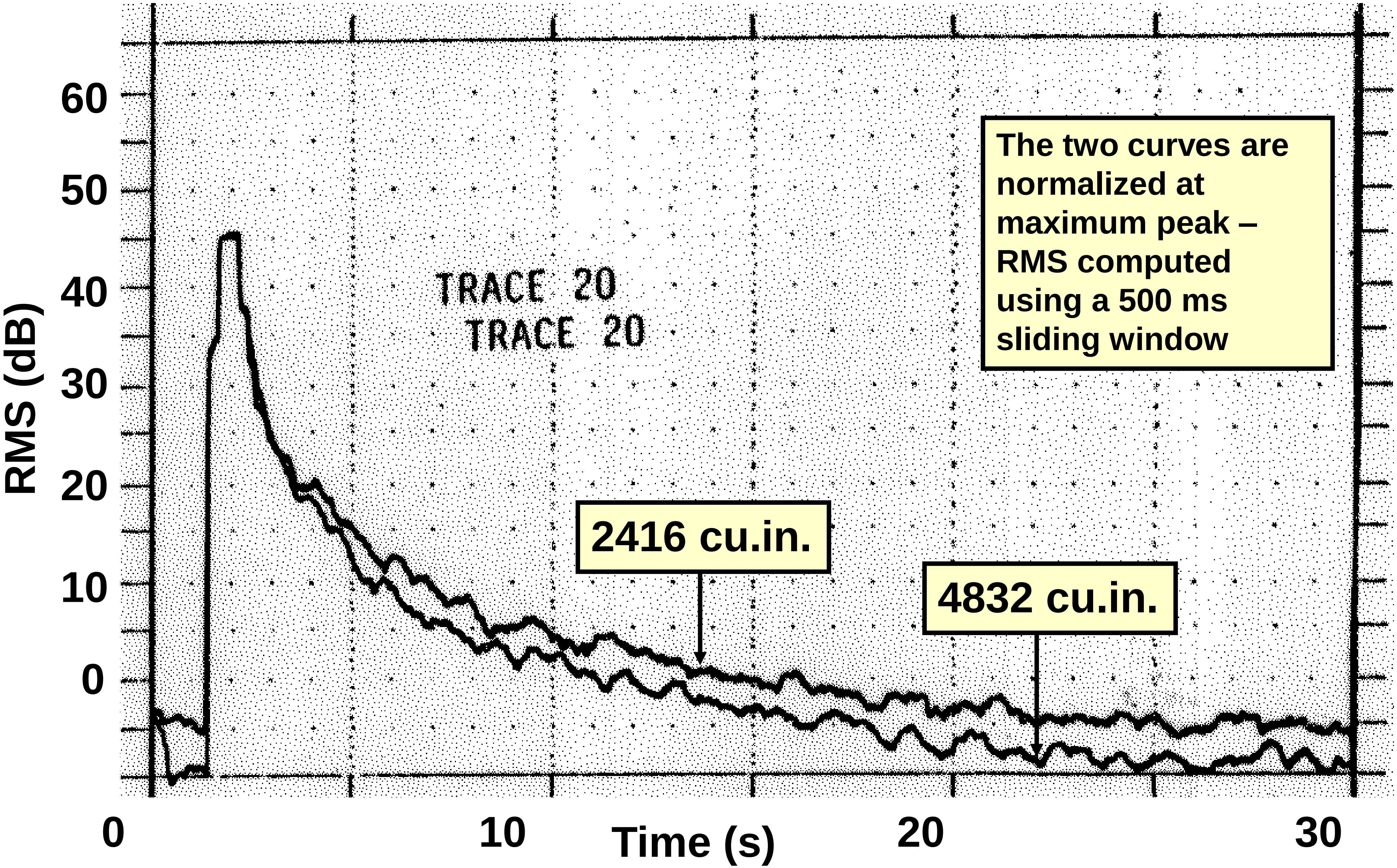
Example:

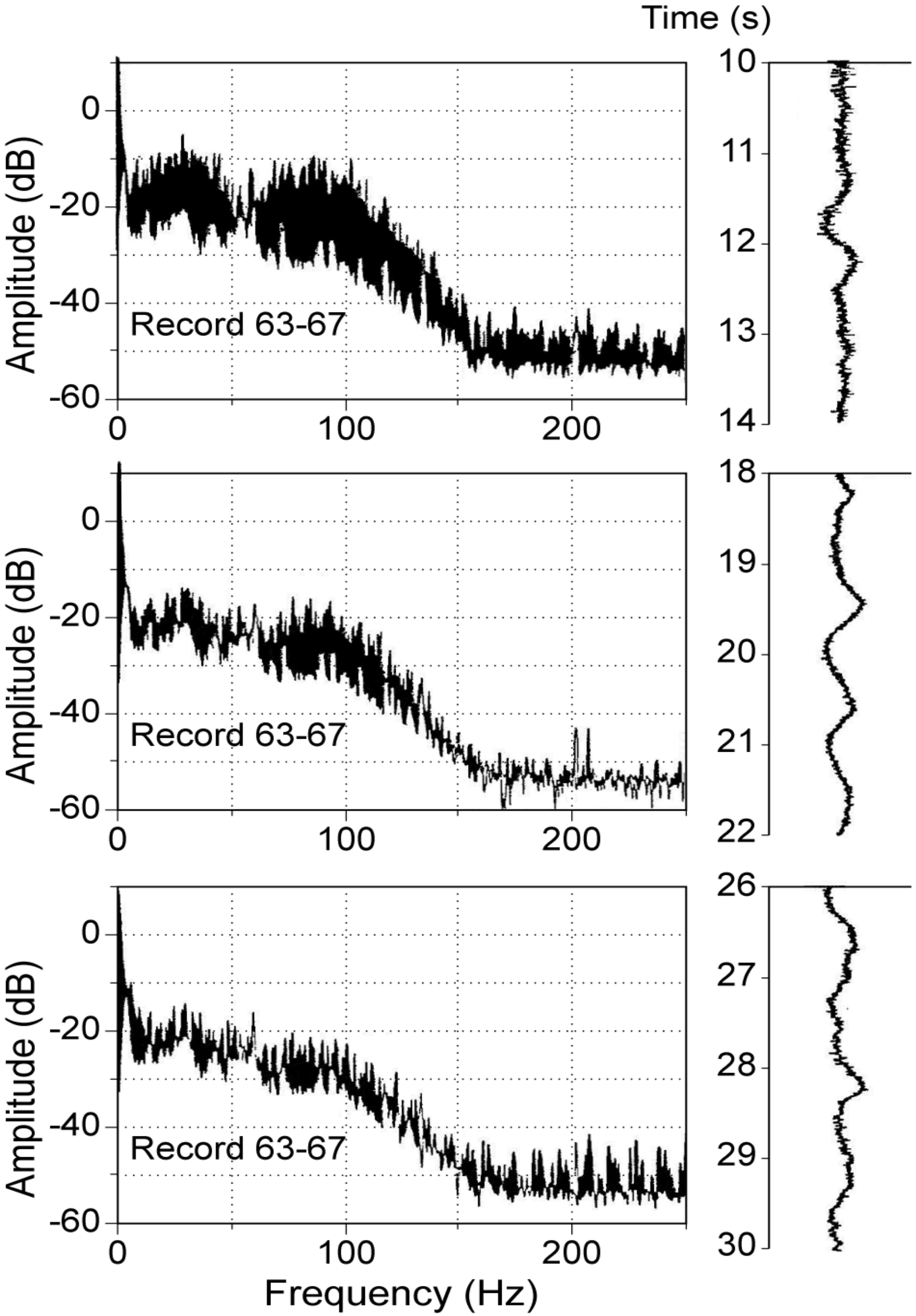
Reflection coefficient = 0.01; 3000 m depth; attenuation loss of 0.1 and a source strength of 60 bar-m =>

Signal = 0.01*60/(6000*10) = 10 microbar

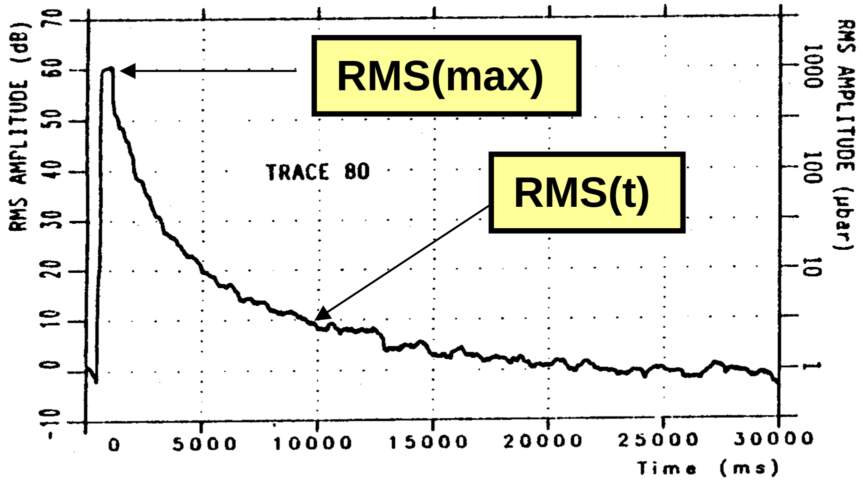
If reflection change is only one tenth of this we need 1 microbar resolution…

Doubling the source volume means different amplitude decay





Comparing shot generated noise from the previous shot with ambient noise



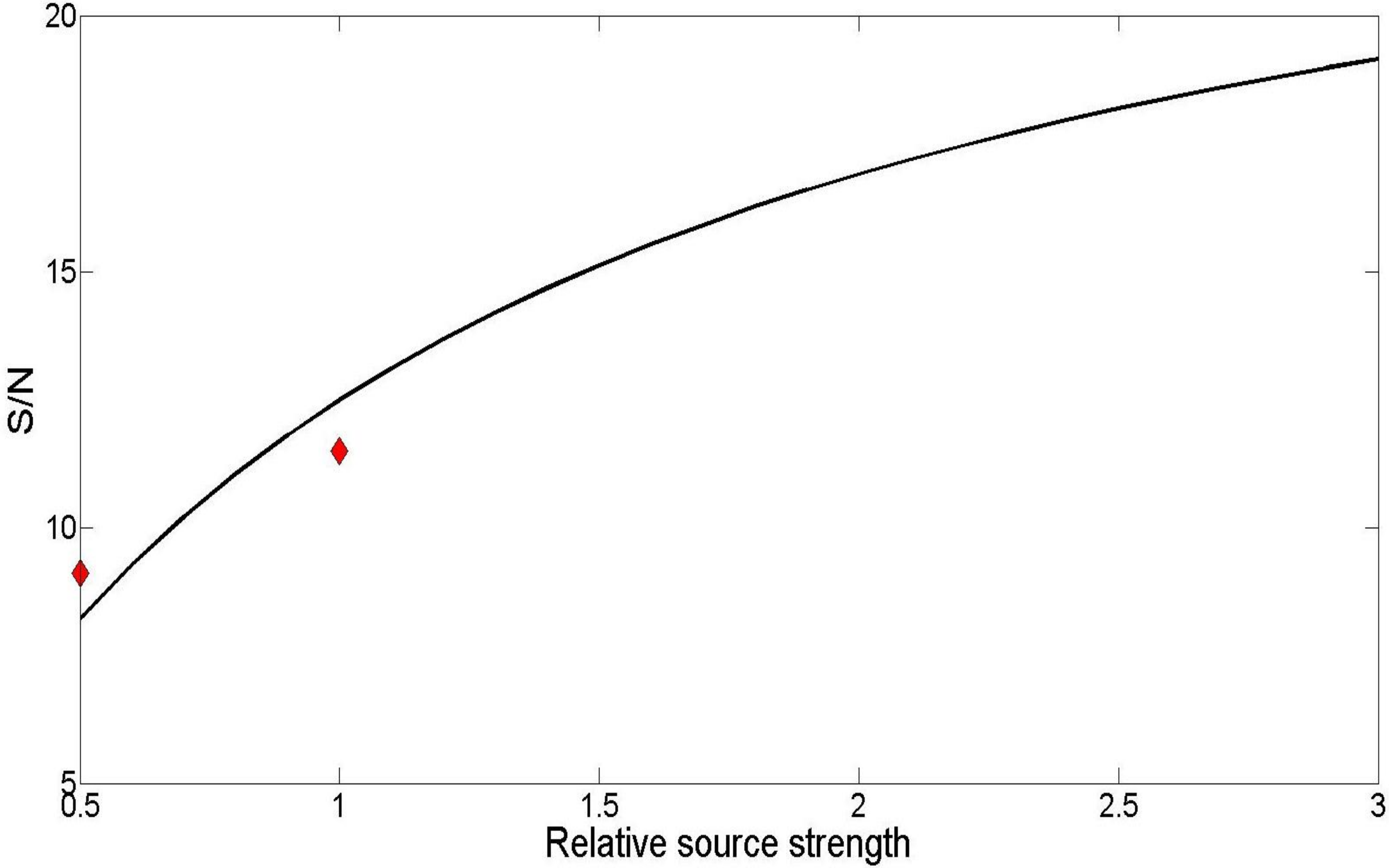
Define the RMS(max)/RMS(t) level as a measure of ”signal to noise ratio”

RMS(max)/RMS(t)	2416 cu in	4832 cu in
10 s	112	126
20 s	253	314
30 s	400	445

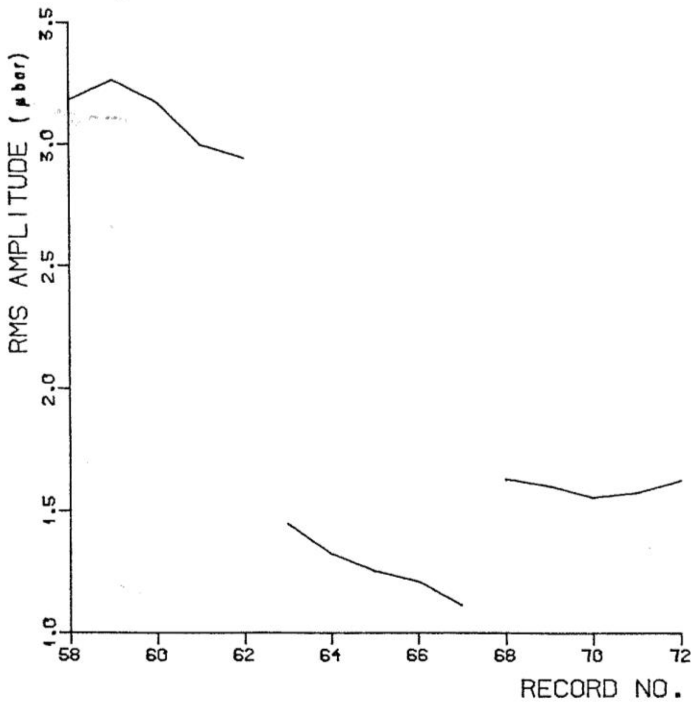
Indicate that the influence of shot generated noise is slightly less (10%) for a big gun array compared to a small one

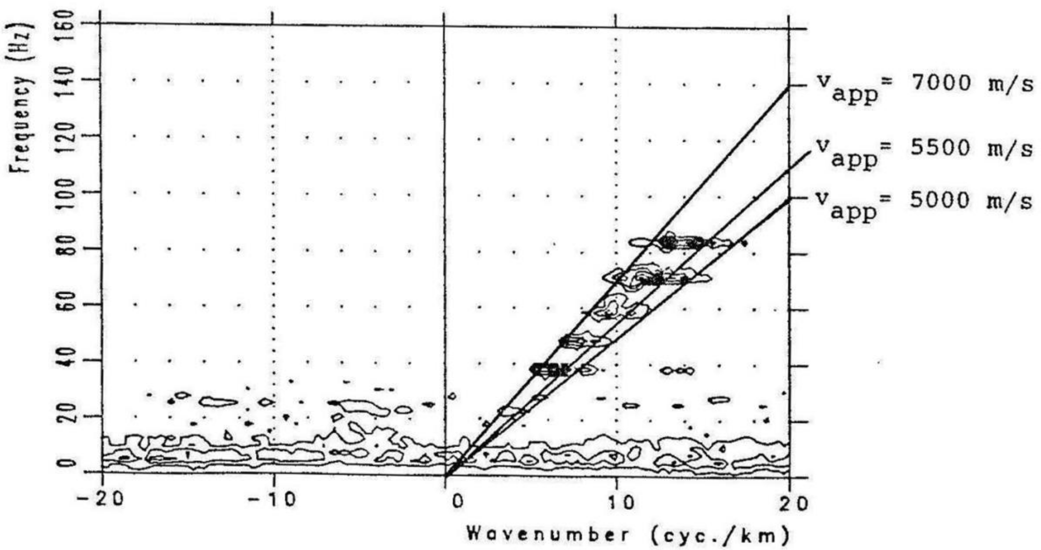
S/N versus source strength

Note: N=Noise from previous shot



Semi-continuous monitoring of background noise



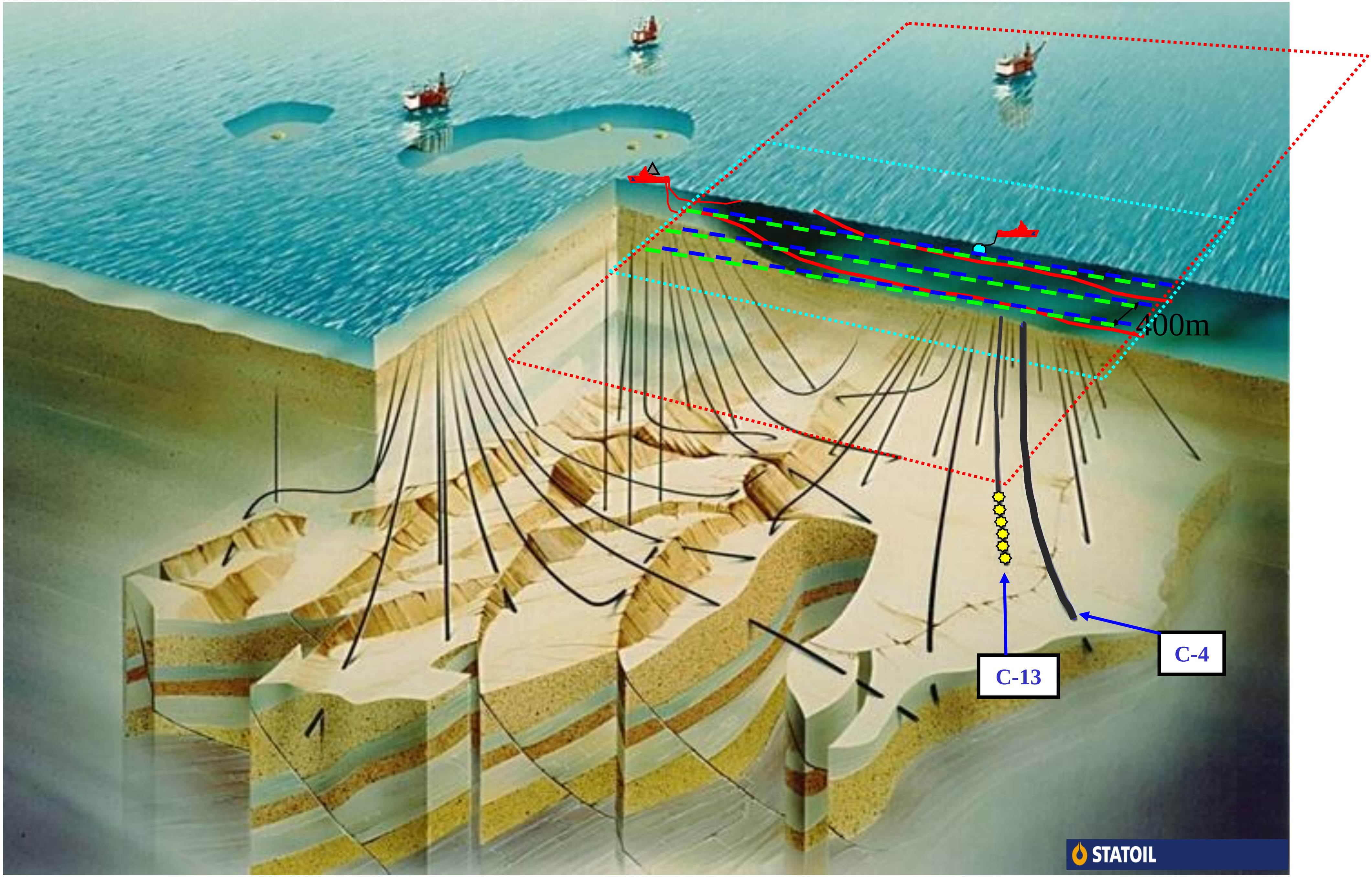


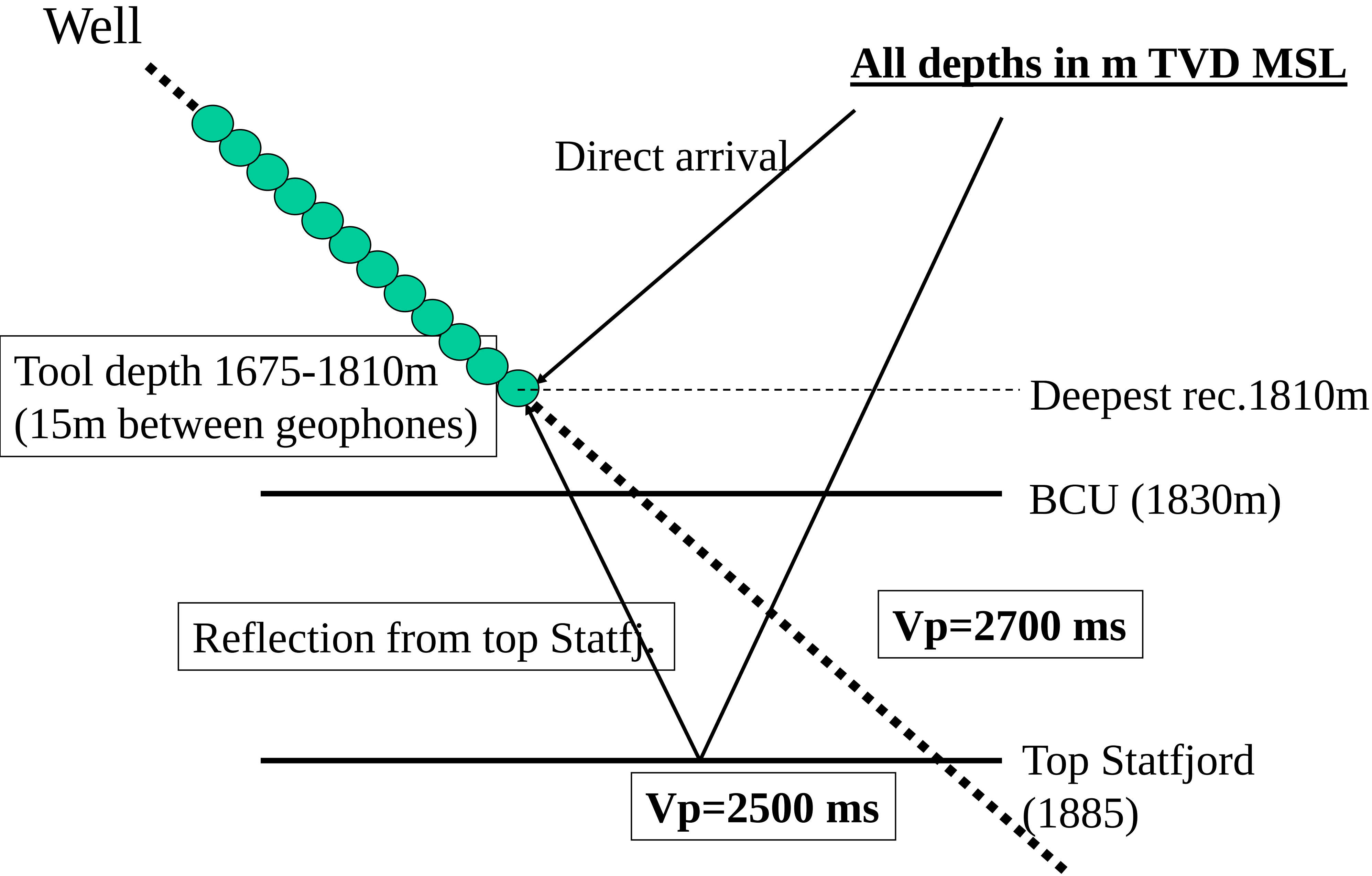
Significant variation in ambient noise levels are observed for the shot records shown to the left.

Fk-analysis shows that the high noise level (3 microbar) is caused by distant ship traffic

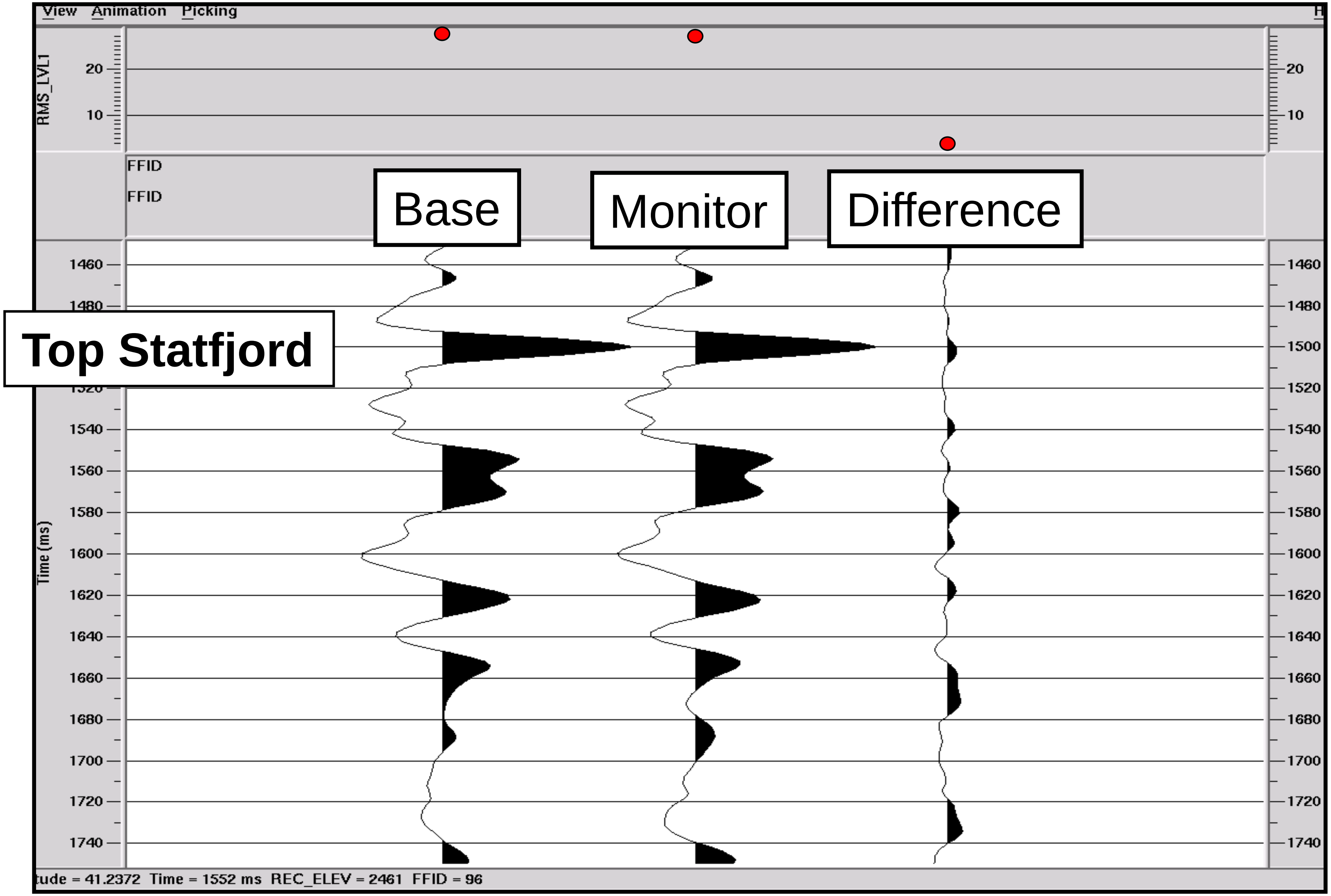
Continuous monitoring of background noise might therefore be useful as additional, diagnostic information. For permanent arrays, it is possible to record ambient noise records inbetween regular shooting.

OBC / VSP Acquisition




Well
All depths in m TVD MSL
Direct arrival
Tool depth 1675-1810m
(15m between geophones)
Deepest rec.1810m
BCU (1830m)
Reflection from top Statfj.
Vp=2700 ms
Top Statfjord
(1885)
Vp=2500 ms

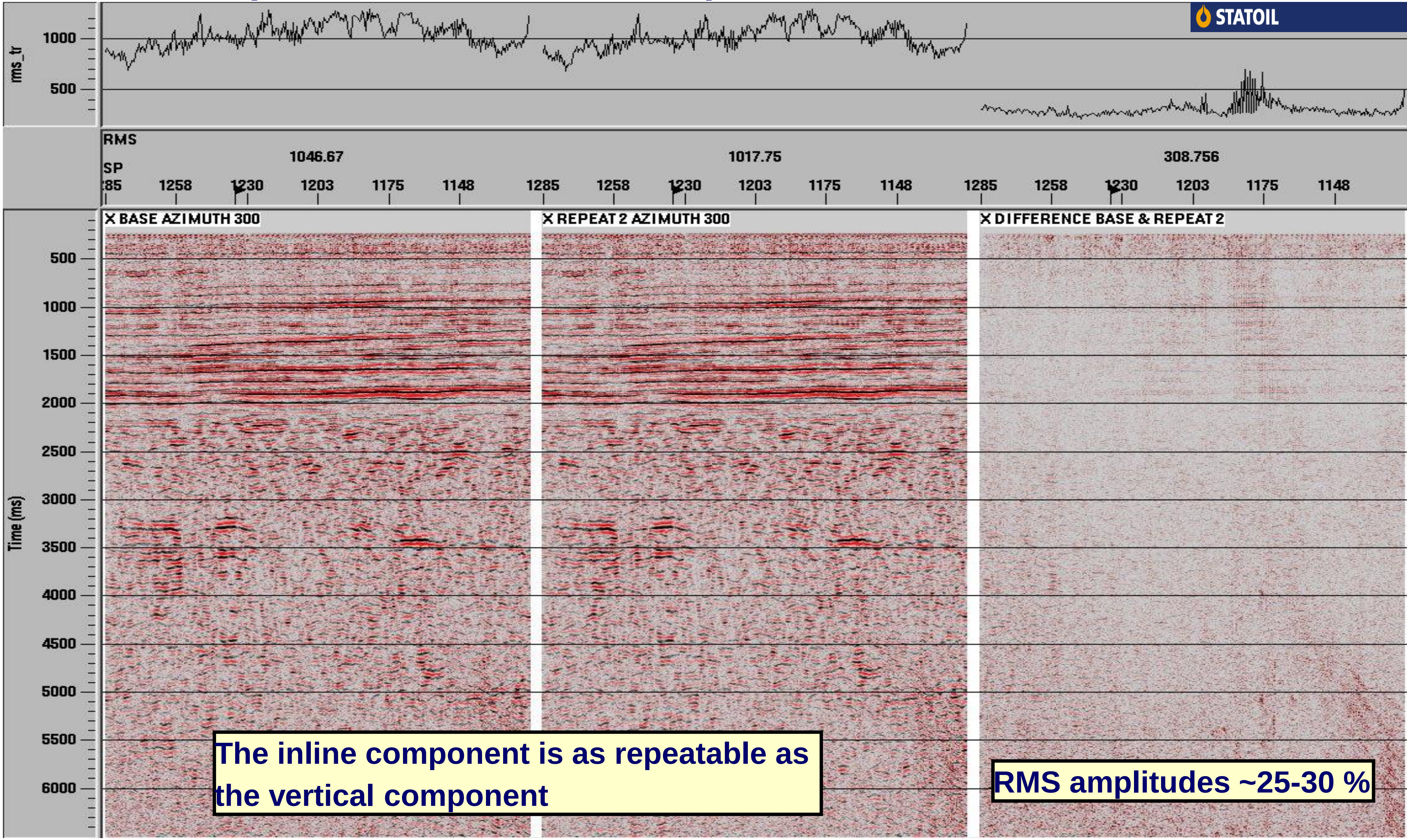
Superstack (FFID 71 – 96): 14% rms error, 5% amplitude decrease at top Statfjord



Permanent systems

- Several field examples: Valhall and Ekofisk fields in Norway
  - Trenched seafloor cables, surveys every 6 month
  - High repeatability, monitor surveys cheaper, but upfront costs are high
- Statoil will install permanent systems at Snorre and Grane fields in 2013
- Petrobras: Jubarte field
- Easy to combine with passive seismic
- Semi-permanent systems (OBN or OBC) is an alternative (leave equipment for weeks or months)
- Fiberoptic receiver cables at Ekofisk, electrical systems at Valhall, Snorre and Grane

Repeatability of seafloor cables
Inline Component stacks, Base, repeat and difference



The inline component is as repeatable as the vertical component

RMS amplitudes ~25-30 %

LOFS: Valhall permanent installation

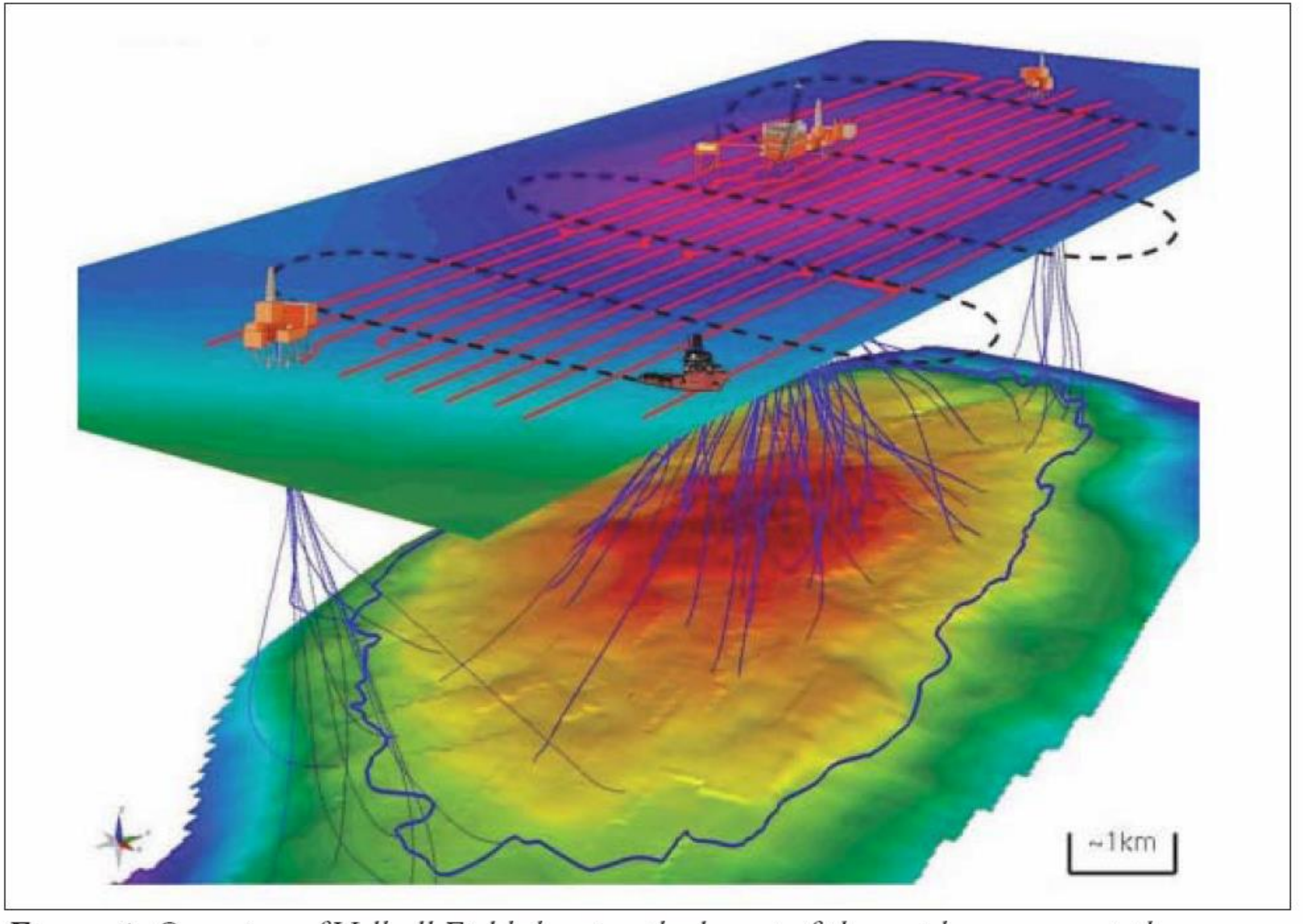
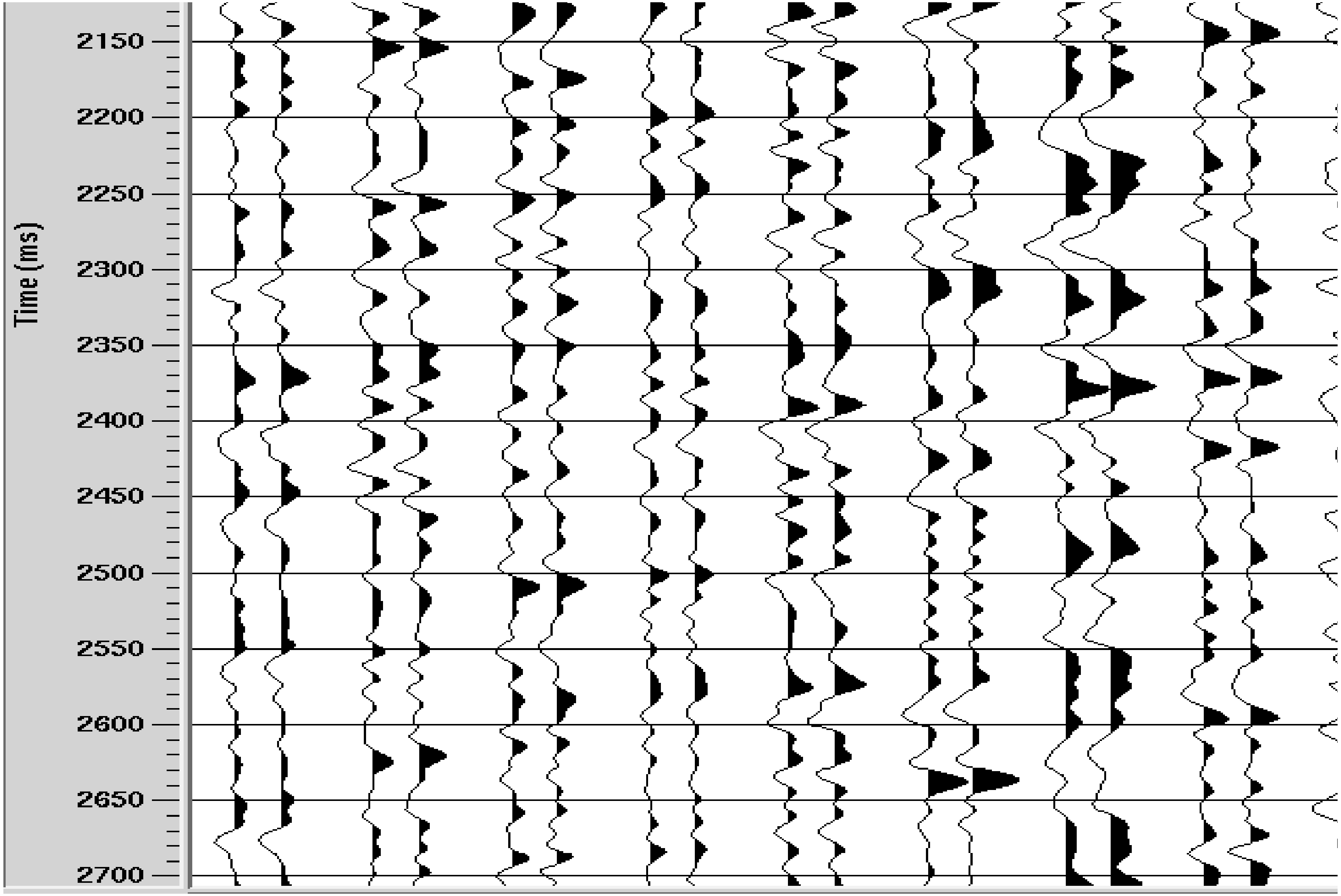


***Figure 1.** Overview of Valhall Field showing the layout of the geophone array at the sea floor (red lines), the top of the reservoir, the outline of the field (dark blue line), and the wells (thin blue lines).*

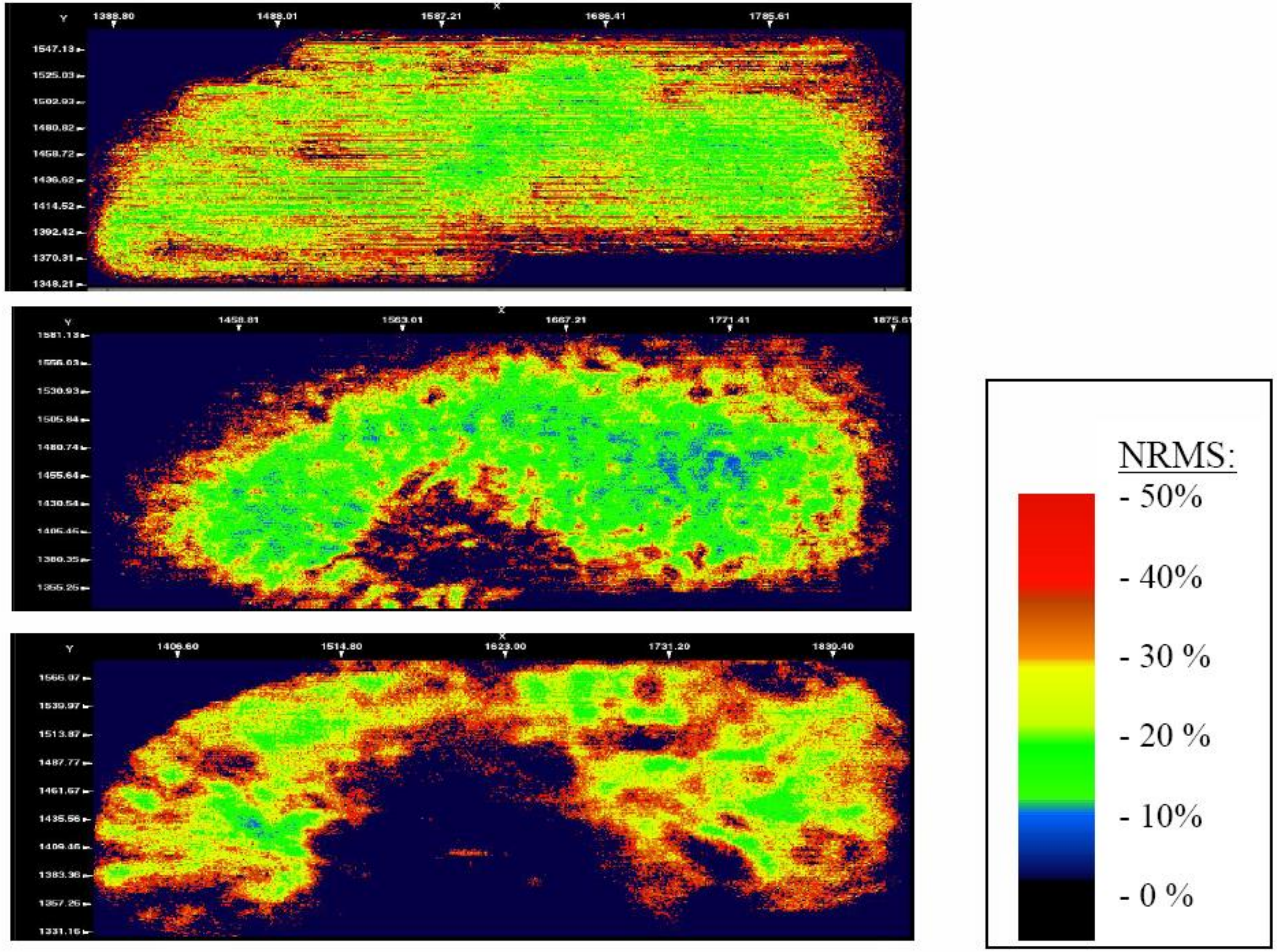
Gestel et al., TLE 2008

Repeat seismic channel pairs



Barkved et al., 2004

Valhall LOFS-data, NRMS-levels for 3 horizons (700, 1500 and 2500 ms)



Kommedal et al., EAGE 2005

Comparing 3 difference sections from Valhall

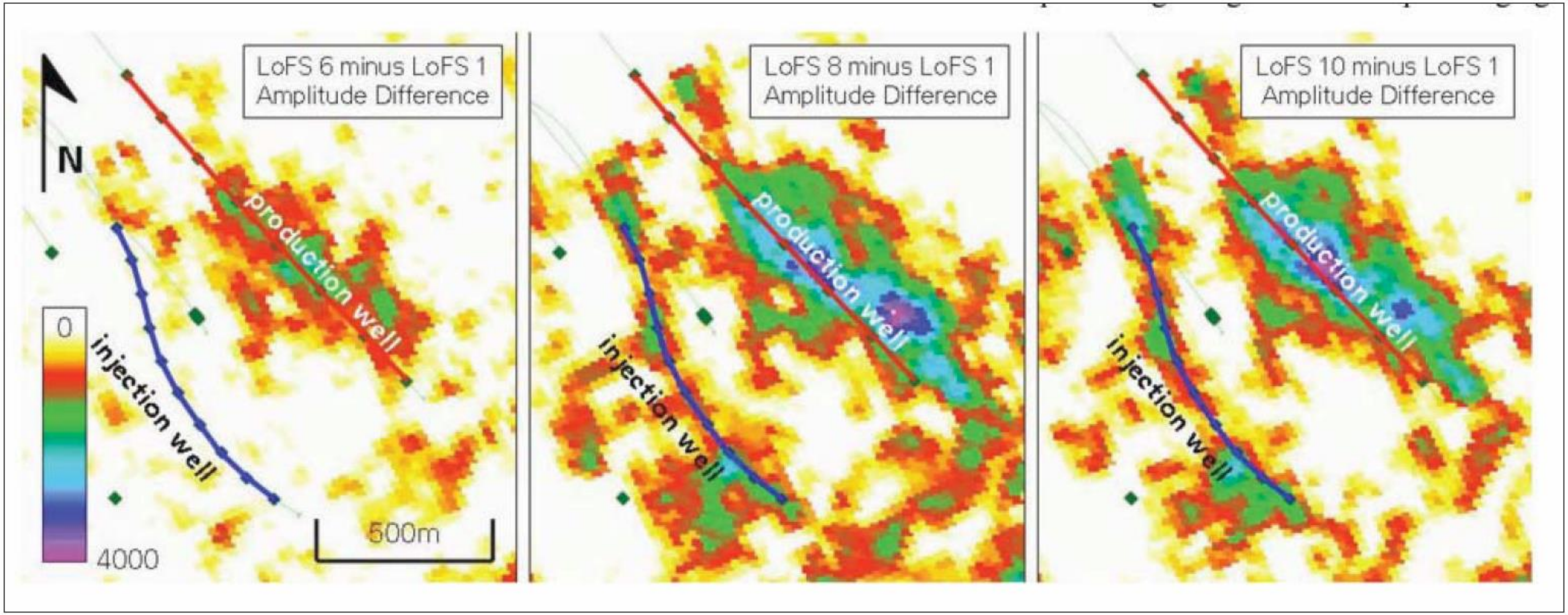


Figure 7. *The acoustic impedance difference responses (thickness of amplitudes) for LoFS surveys 6, 8, and 10, all related back to LoFS survey 1. This shows the response of the water injector (in blue) and the nearby producer (in red). LoFS 6 was the last survey before injection started so no response is observed around the injection well.*

Gestel et al., TLE 2008

The importance of 4D multiple correction

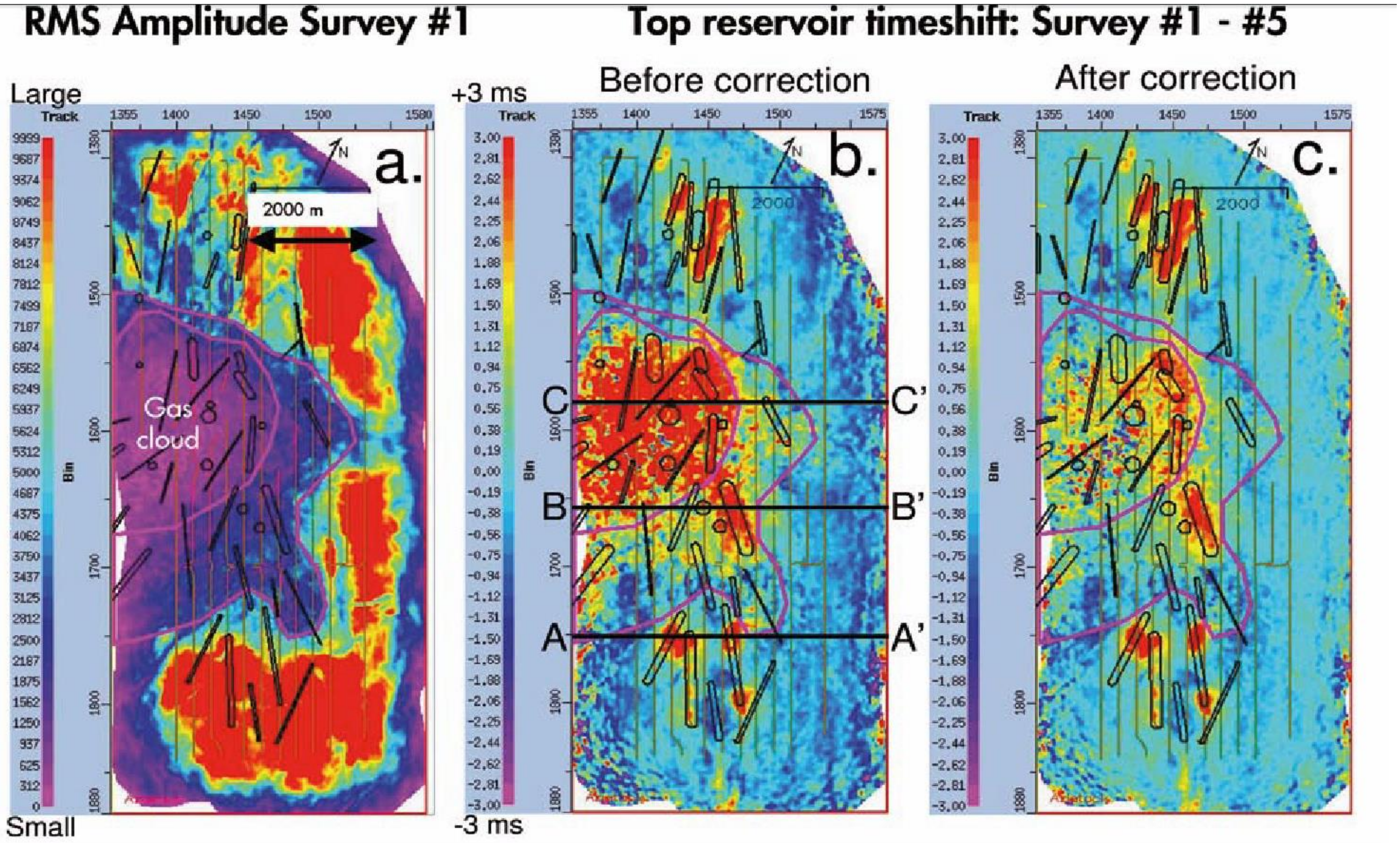
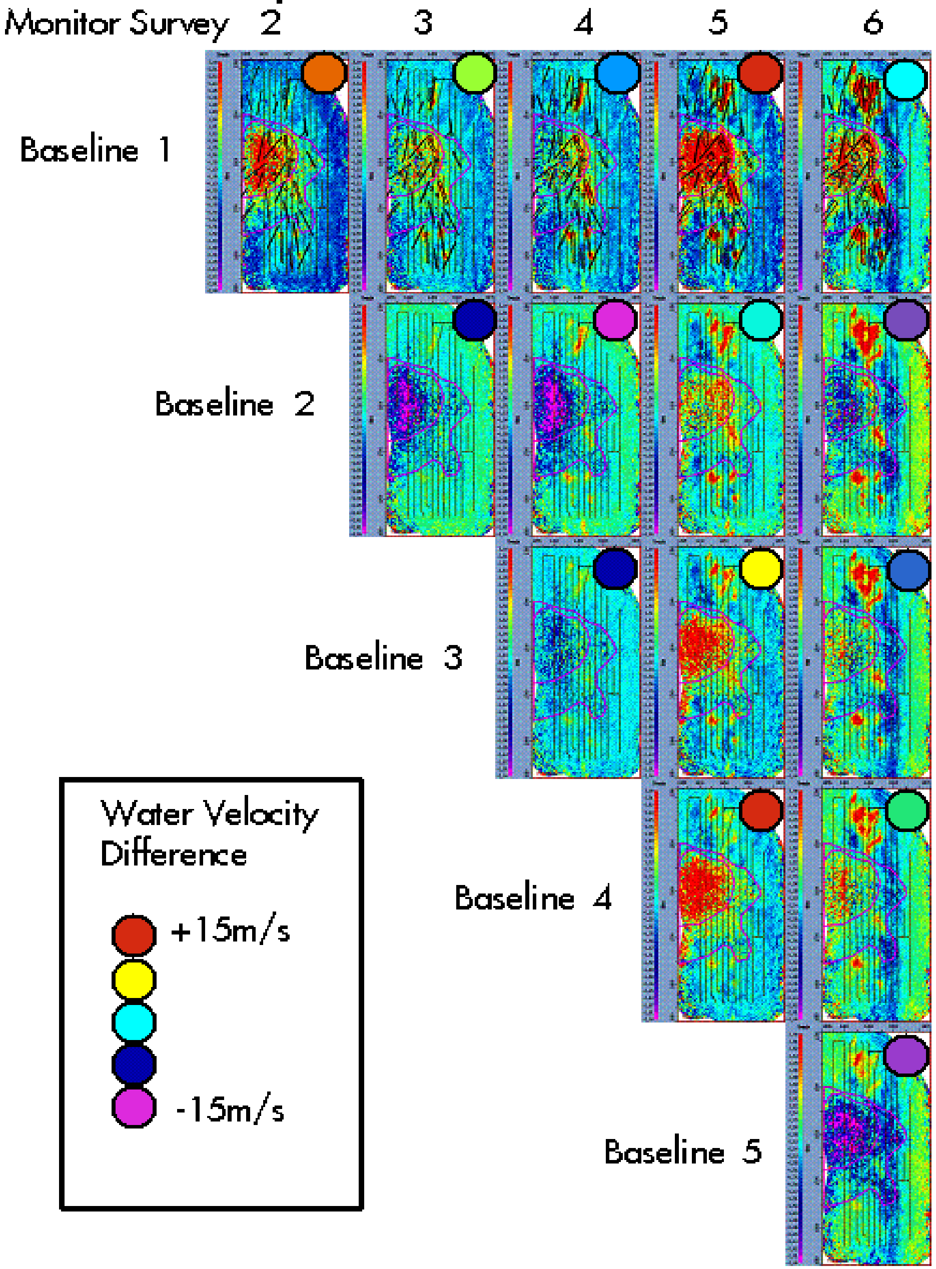


Figure 4 RMS energy from survey #1 measured at top reservoir event (a). Top reservoir time-lapse time-shifts between survey #1 and #5 before (b) and after (c) correcting for multiples. Purple polygons indicate outlines of the outer and inner gas clouds. Black Polygons in (b) and (c) indicate amount of oil production between the time of survey #1 and #5 and are drawn around the producing well perforations.

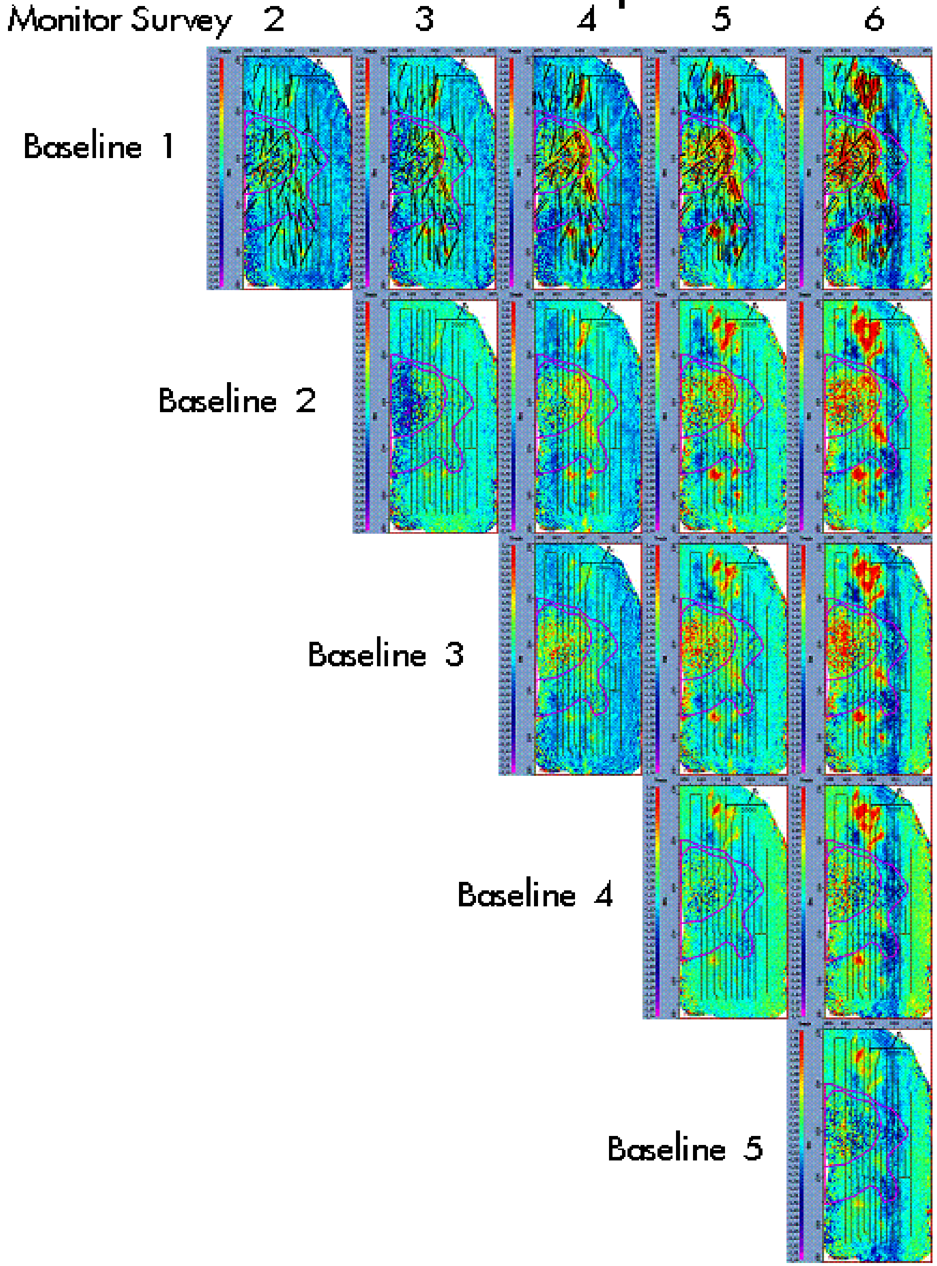
Hatchell, Wills, Didraga First Brea

Impact of water velocities/multiples

Top reservoir timeshifts

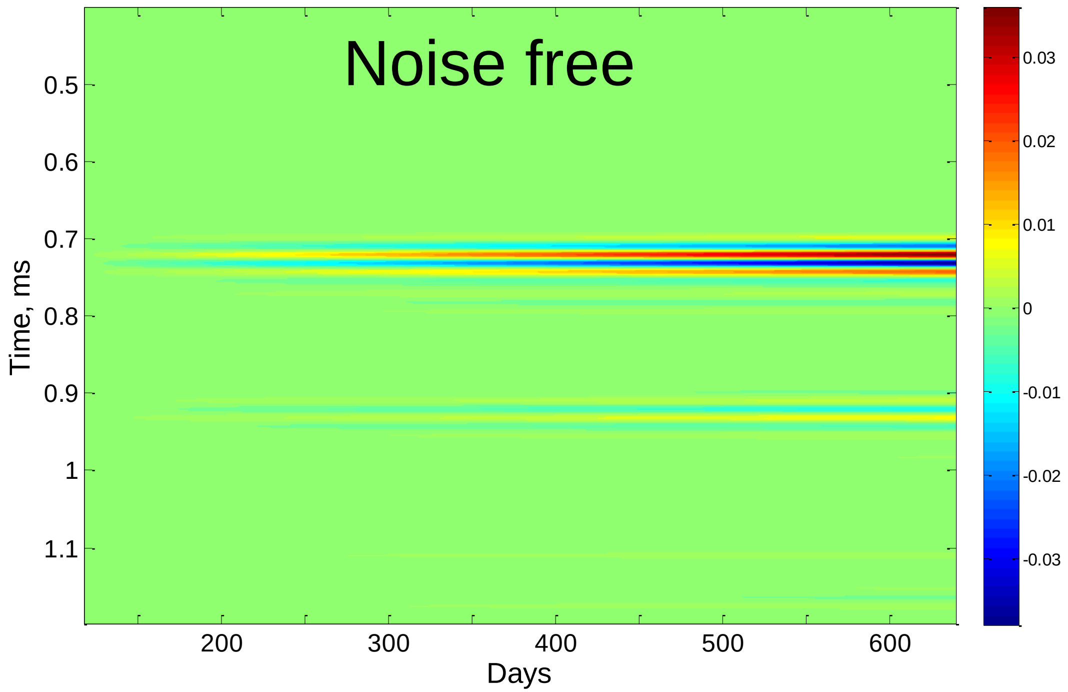


After data adaptive removal



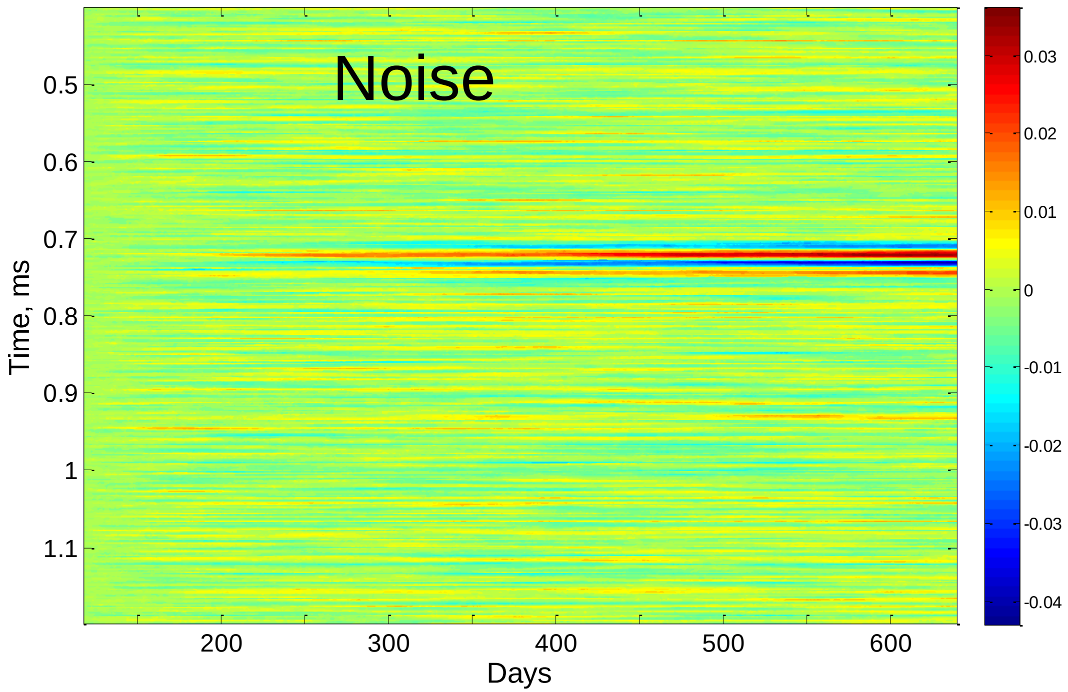
Hatchell, Wills, Didraga First Brea

Other possibilities using permanent arrays:



-Passive seismic monitoring

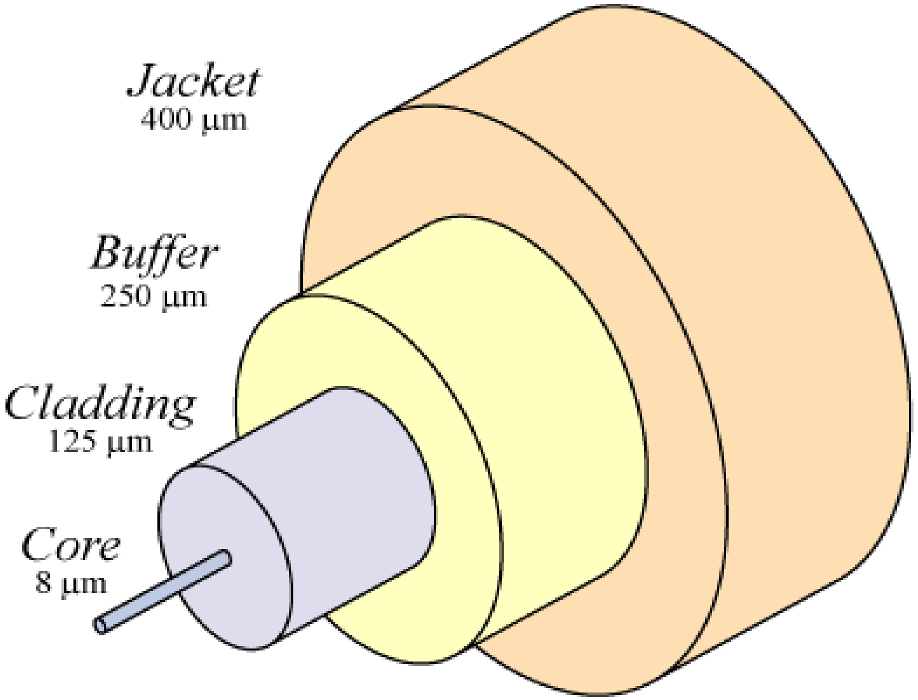
-Ultrafrequent stacking over selected well locations (spot-monitorig)

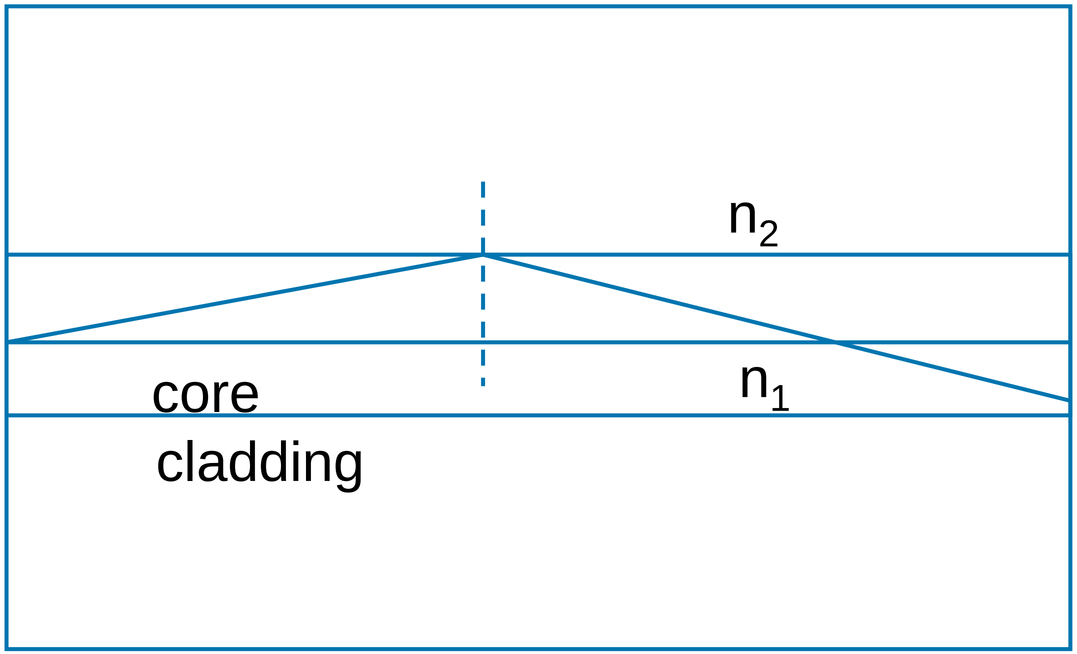


Assuming one trace acquired per day – capturing cumulative production

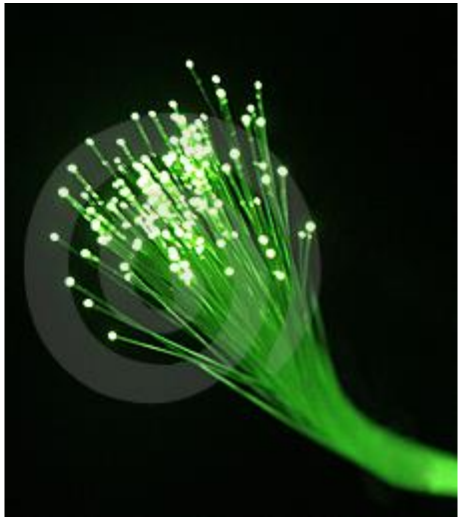
Measuring seismic with light: The fibre optic method

Transmitting light in a fibre:

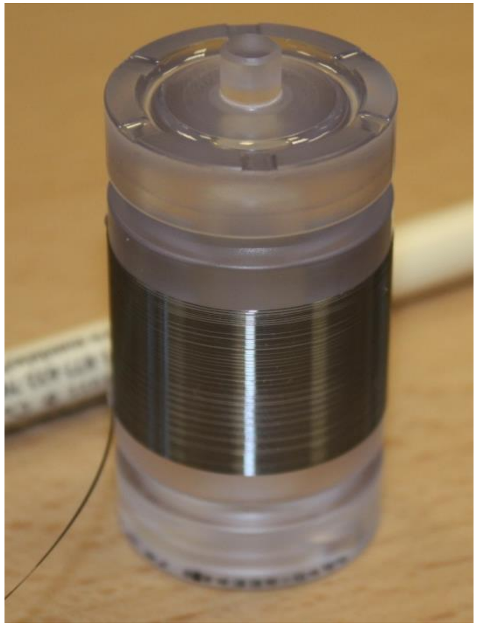




Fiber optic sensors (Optoplan)



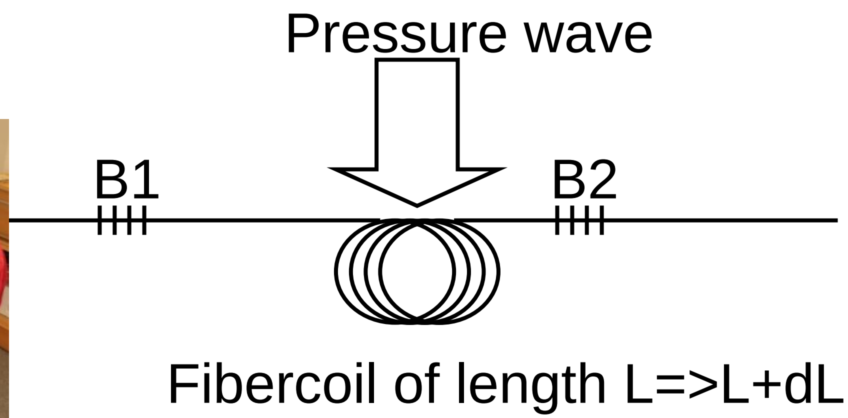
Hydrophone:



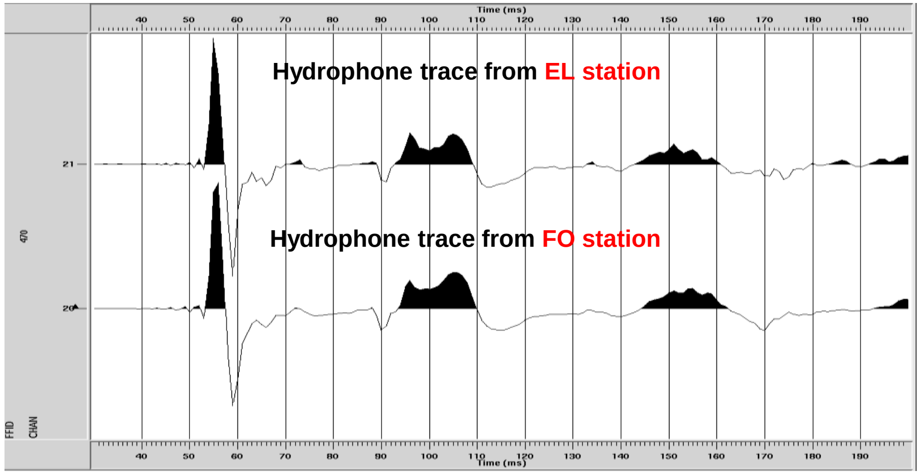
1 x

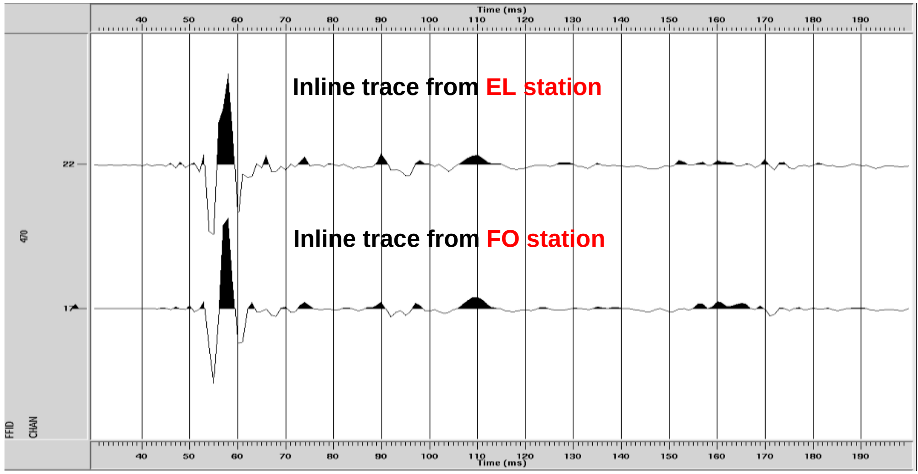
Accelerometer:

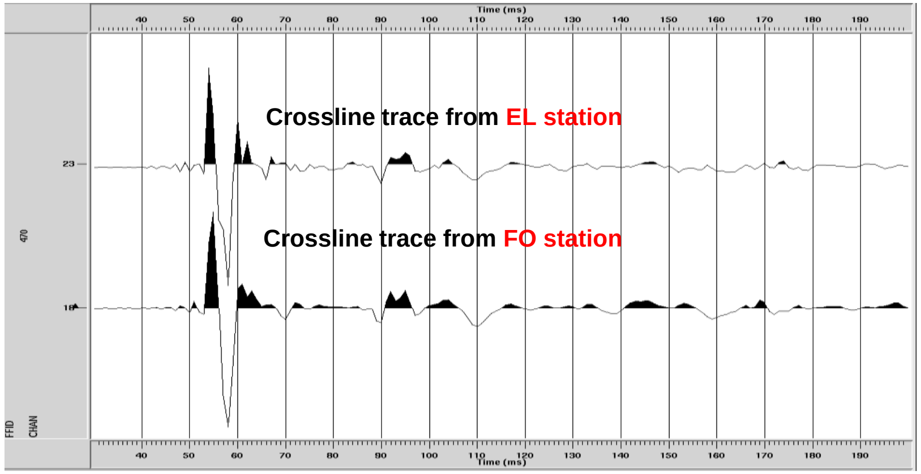
3 x

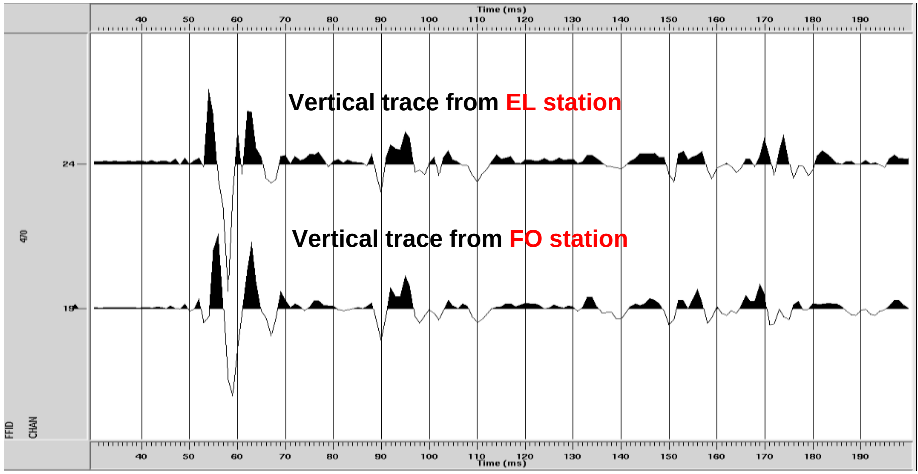


Trondheim Harbour Test - Comparison with MEMS



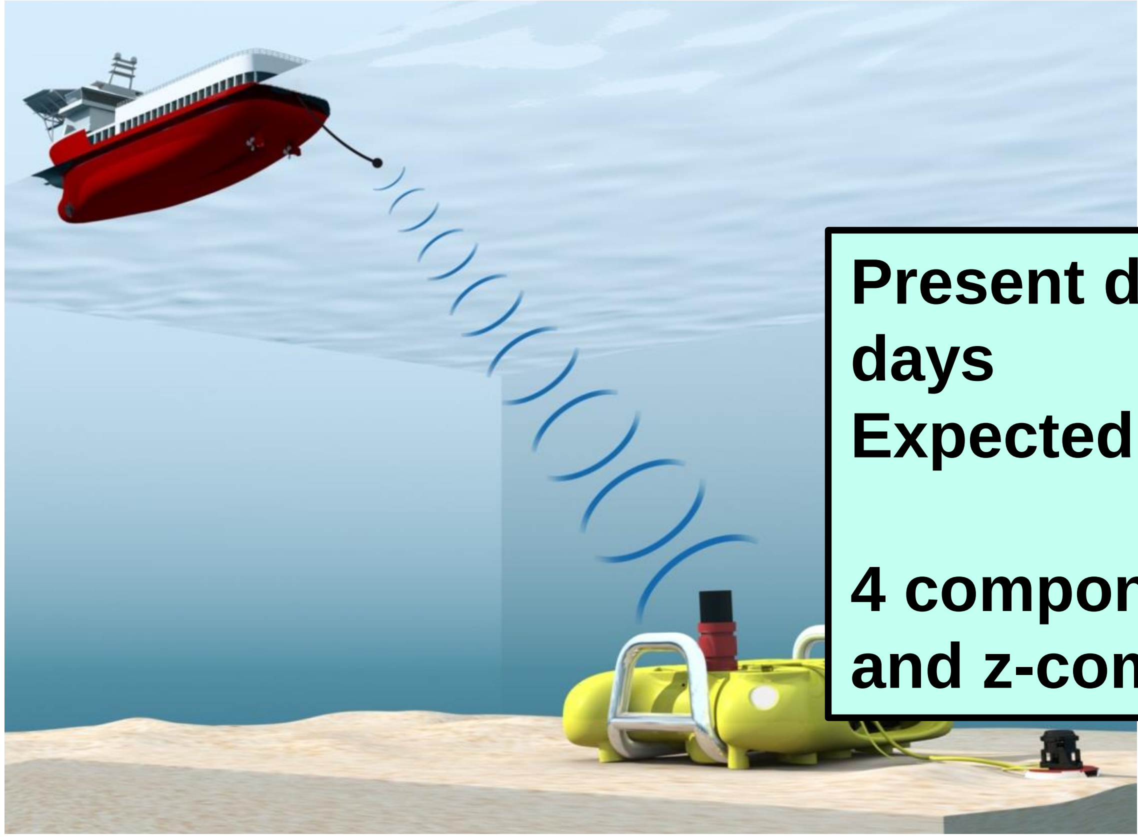






OptoPlan

Nodes and 4D



Present day battery capacity: 60-80 days
Expected future: ~200 days

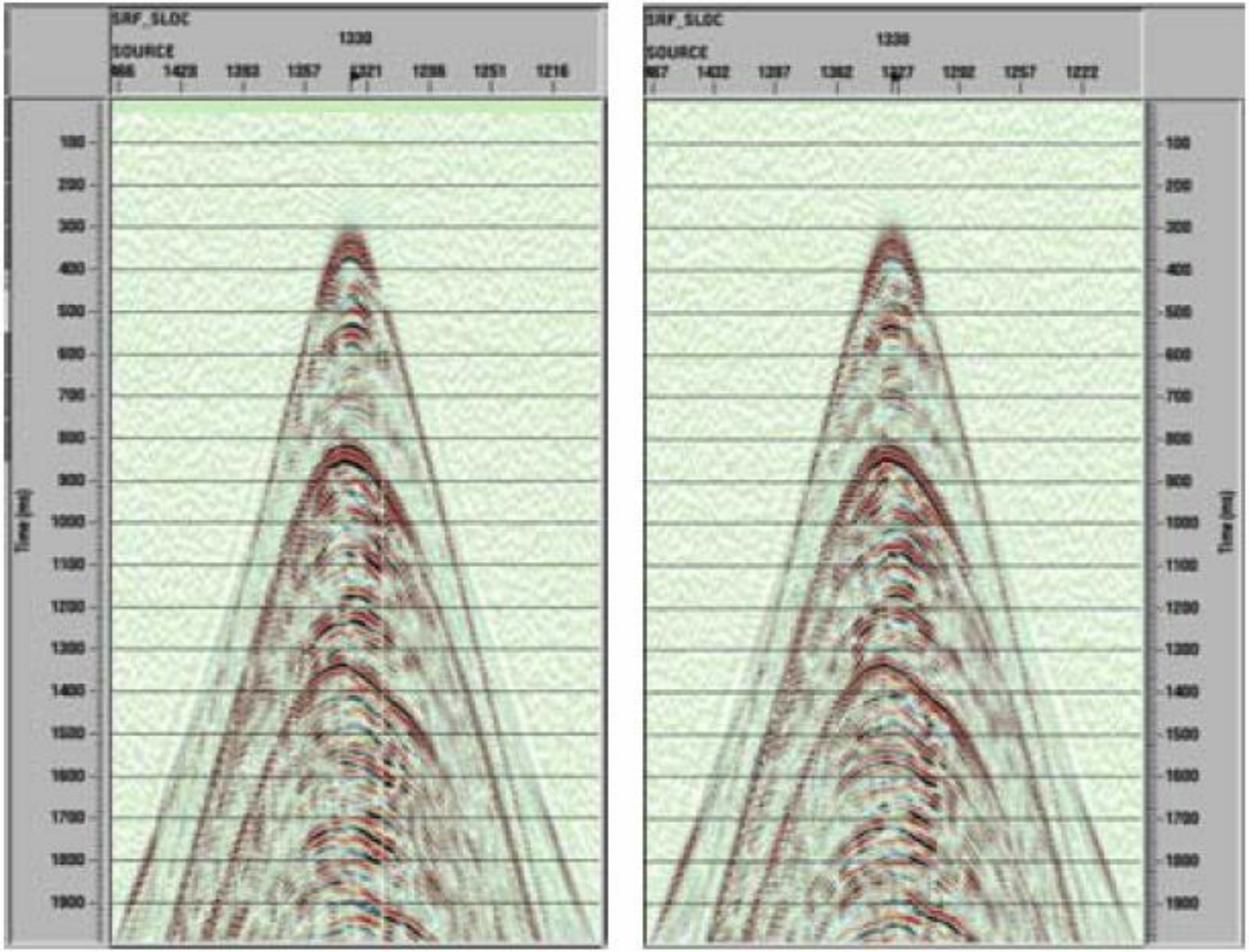
4 component recordings – true x, y and z-components

Applications:
- Deep water
- 4D at fields heavy equipped with seabed installations
- Semi-permanent (3-6 months) 4D
- Monitoring of subsurface leakage

Permanent systems?

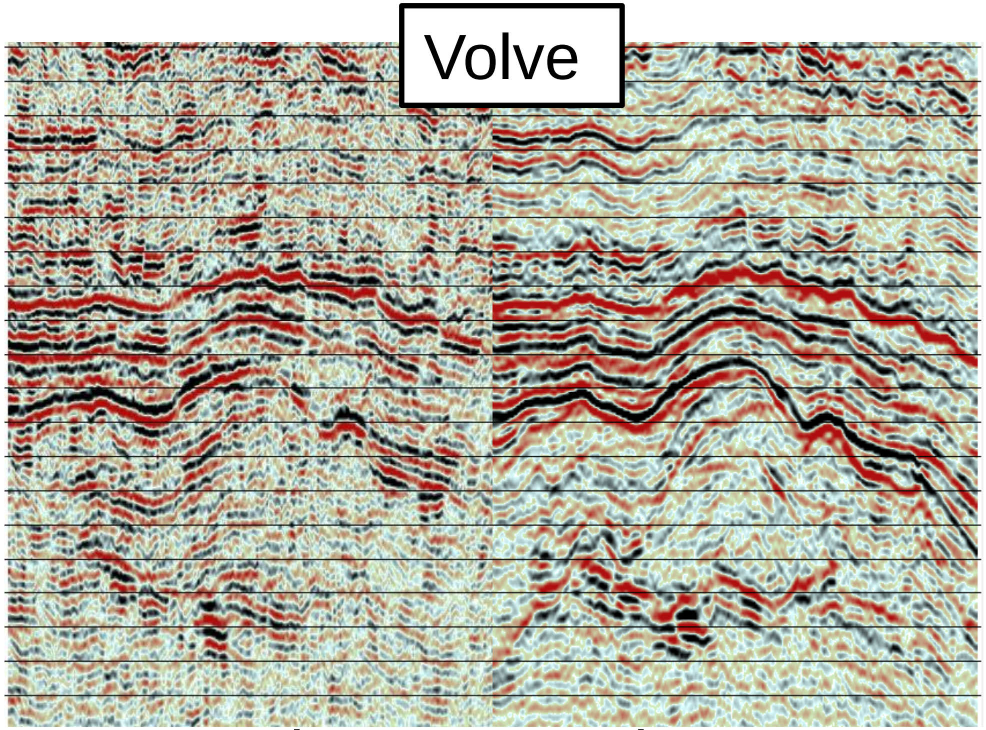
- Two field examples: Valhall and Ekofisk
- High repeatability, monitor surveys cheaper, but upfront costs are high
- Easy to combine with passive seismic
- Semi-permanent systems might be an alternative: leave OBC or nodes for months..

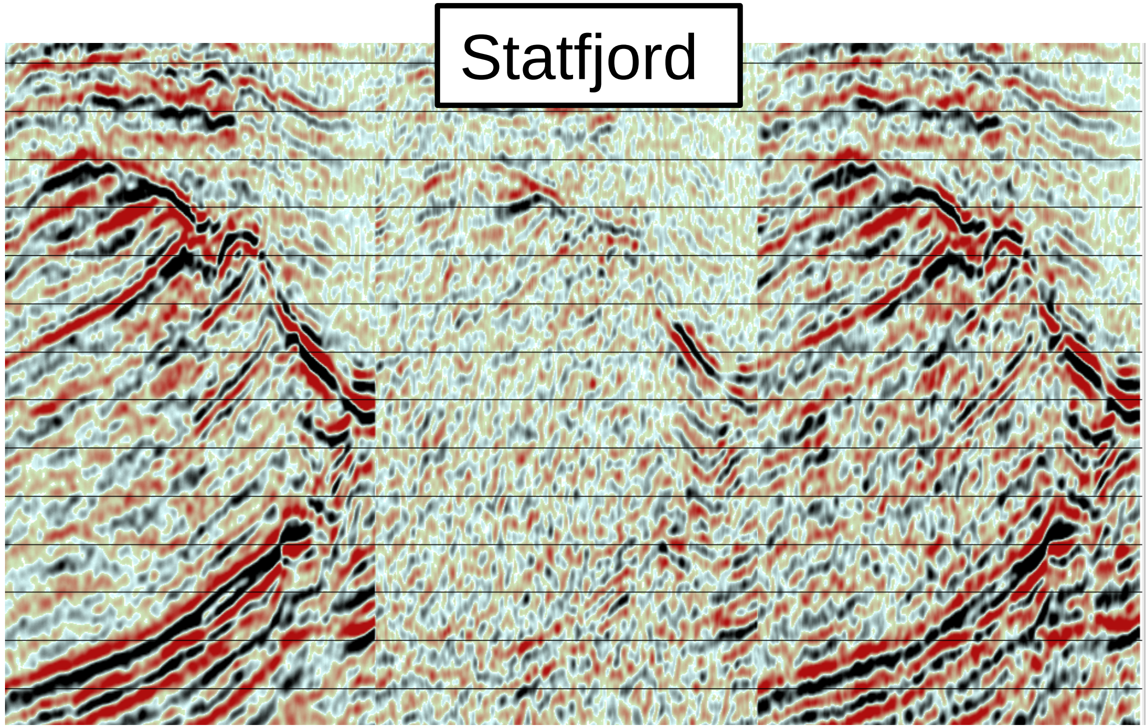
Comparison of node z-component (left) and OBC z-component (right), Heidrun



Thompson et al, SEG, 2010

Comparing images: Node versus cable





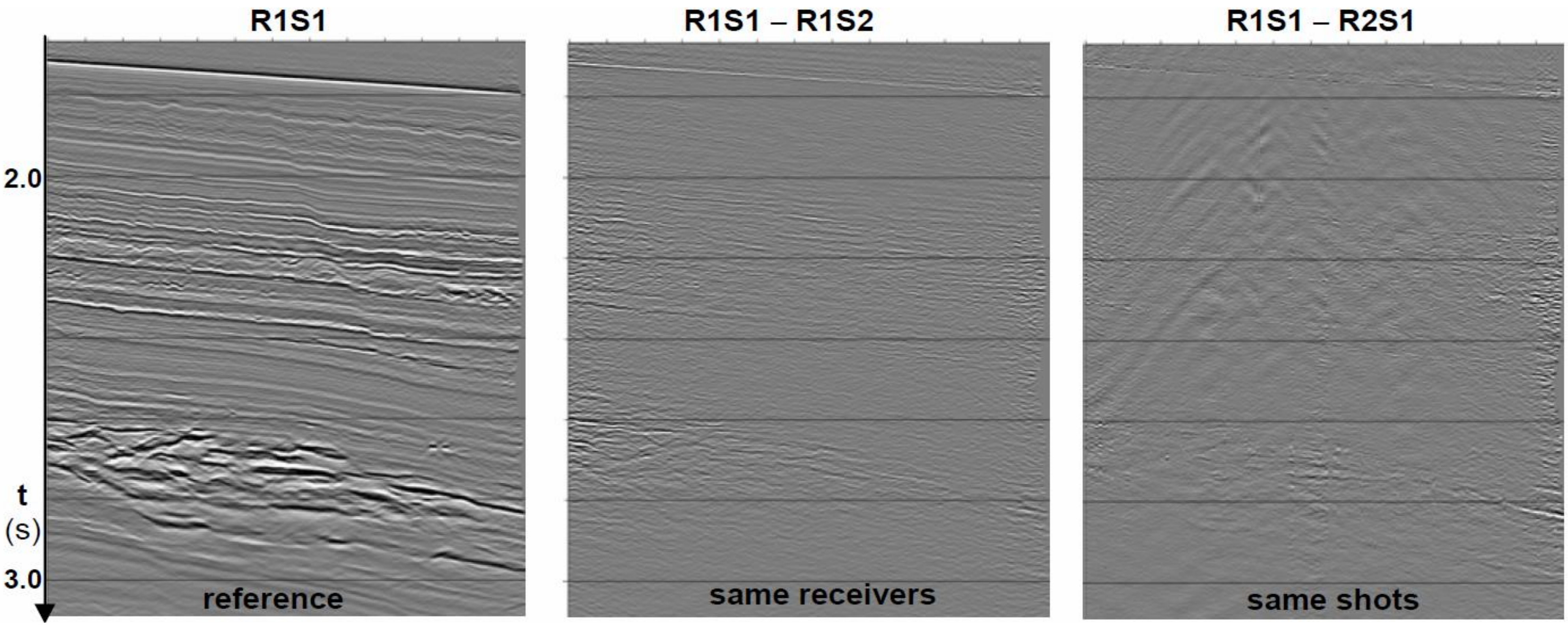
Ref.: Thompson et al., SEG, 2010

Reservoir depths: 2500-3000 m

Thompson et al., 2010: **Weaker image from node data is mainly attributed to sparser receiver sampling**

This effect DECREASES with target depth: Deeper targets can tolerate larger distance between nodes

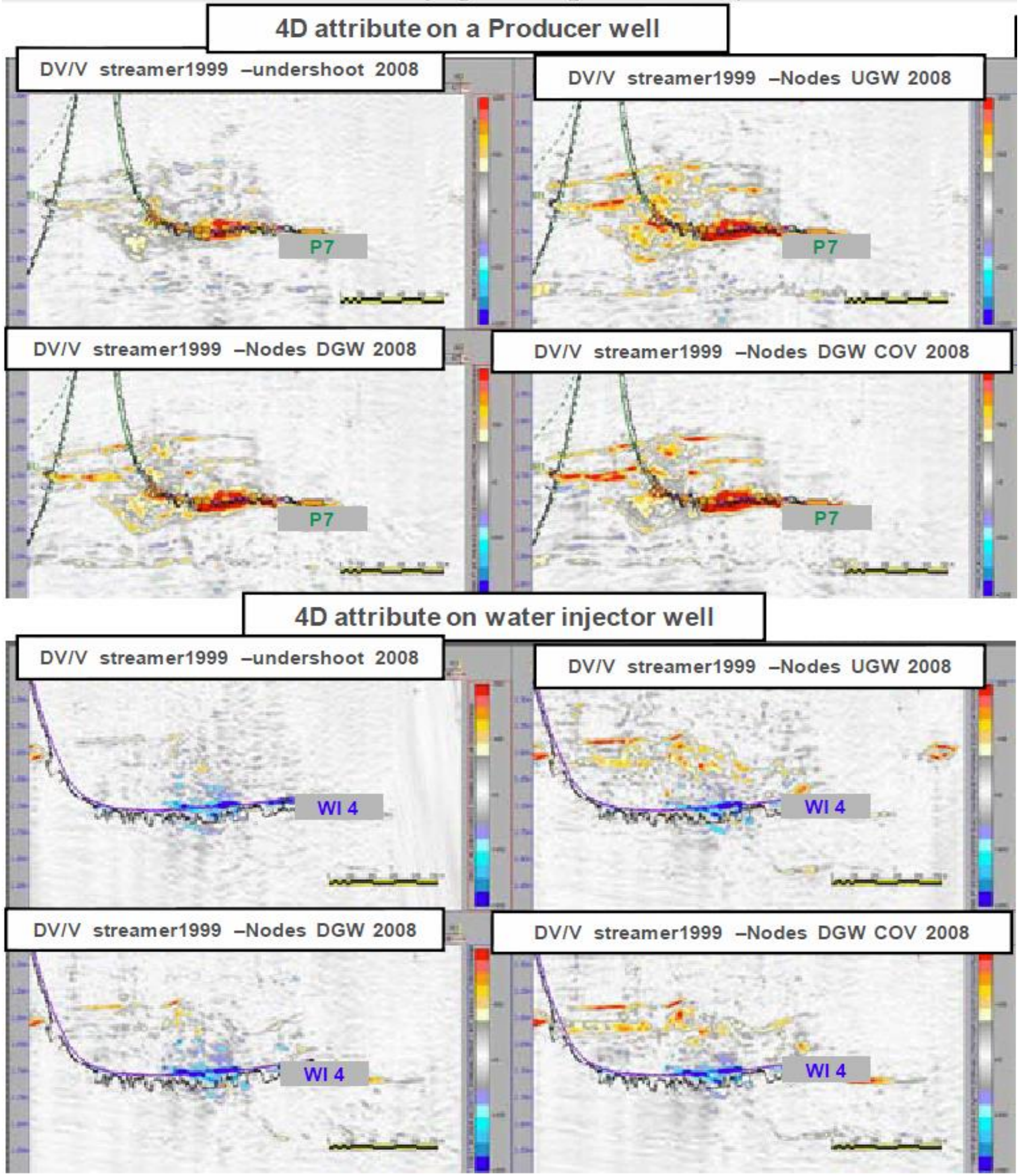
Node repeatability – deepwater (1300 m) Angola



A short testline was used: 29 receiver pair nodes ~ 5 m apart

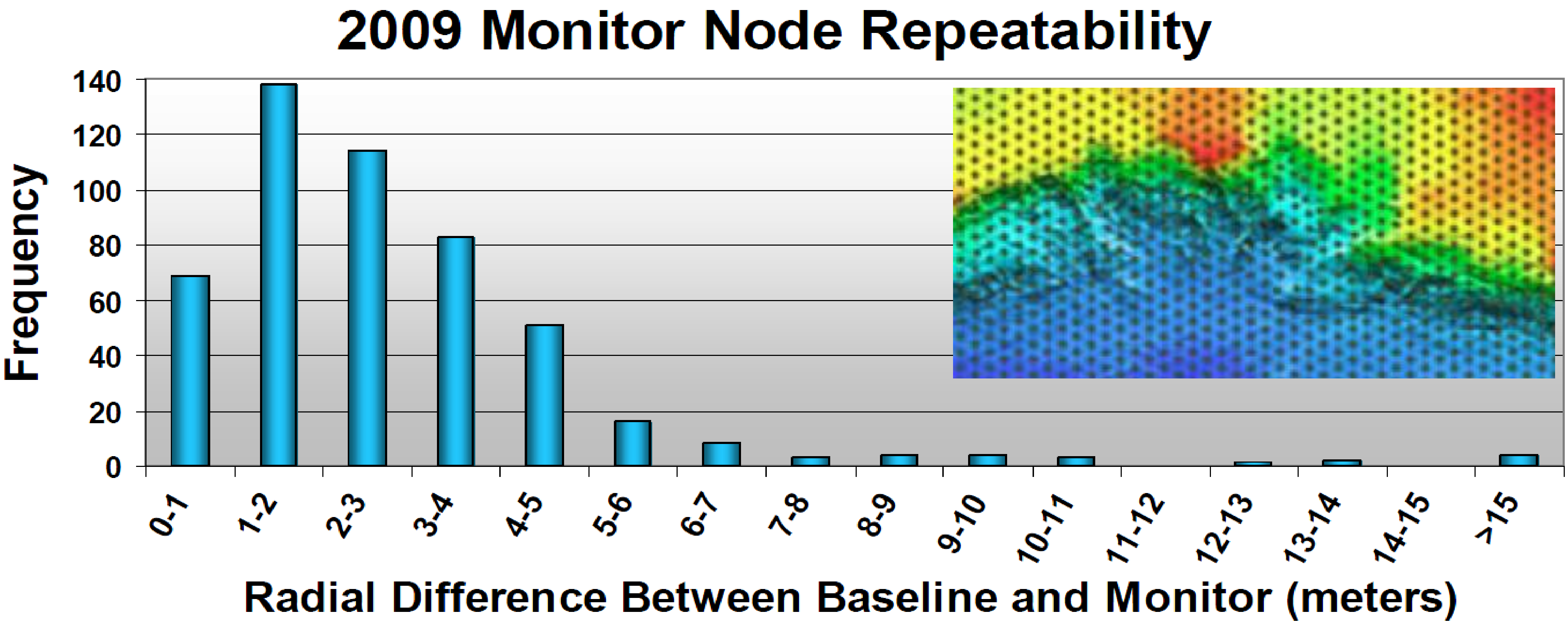
Boelle et al., 2010, SEG-abstract: Apart from the low frequency noise, the node repeatability is better than the source repeatability

Nodes and streamer data - Dalia field



Brechet et al., EAGE 2011

Antlantis 4D: First repeated node project

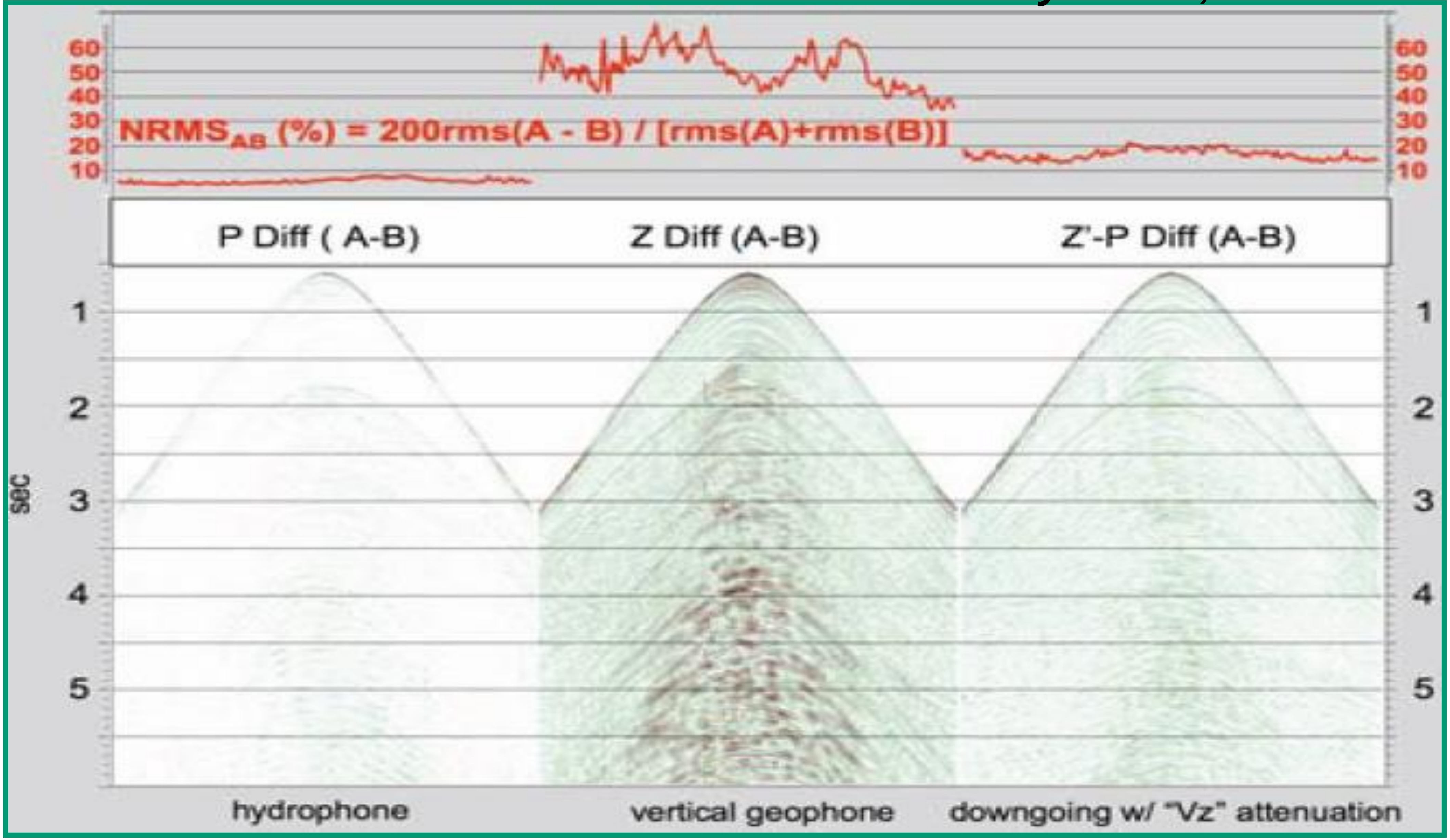


Ref.: G. Beaudoin, SEG 2010.

- 91 % of nodes were delivered to within 5 meters of the 2006 baseline survey
- waterdepths between 1300-2200 m

Node repeatability – Deimos field

Hays et al., SEG 2008

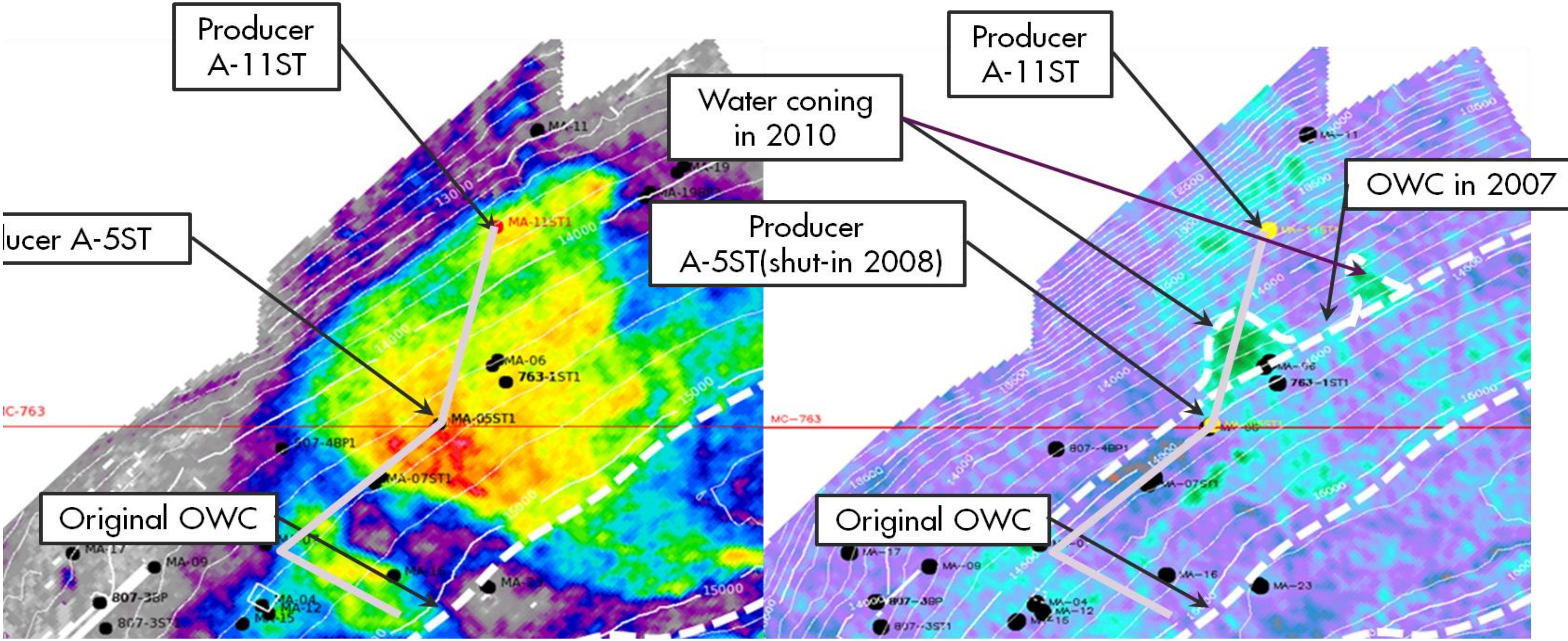


2 m between node A and B. relative high NRMS on geohone attributed to Scholte wave

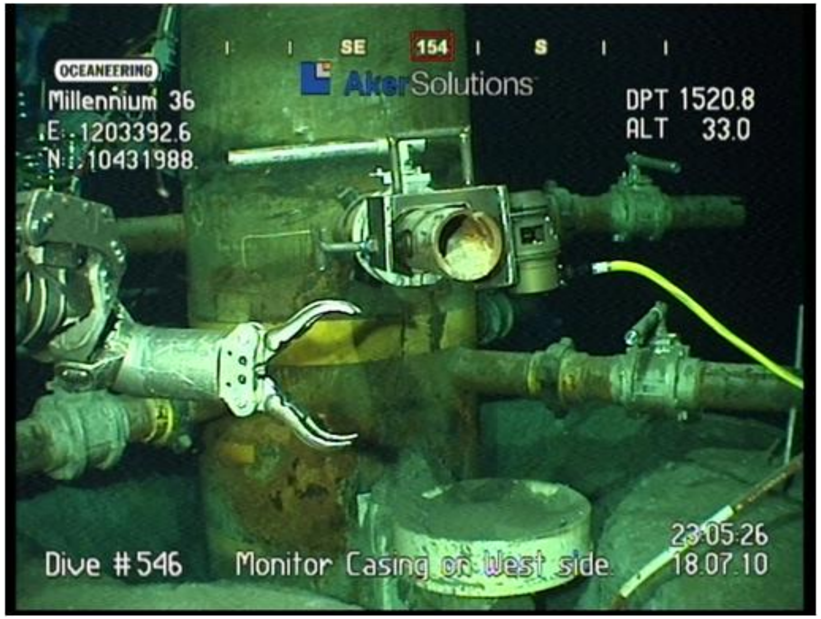
First node 4D: Mars field (2007-2010)

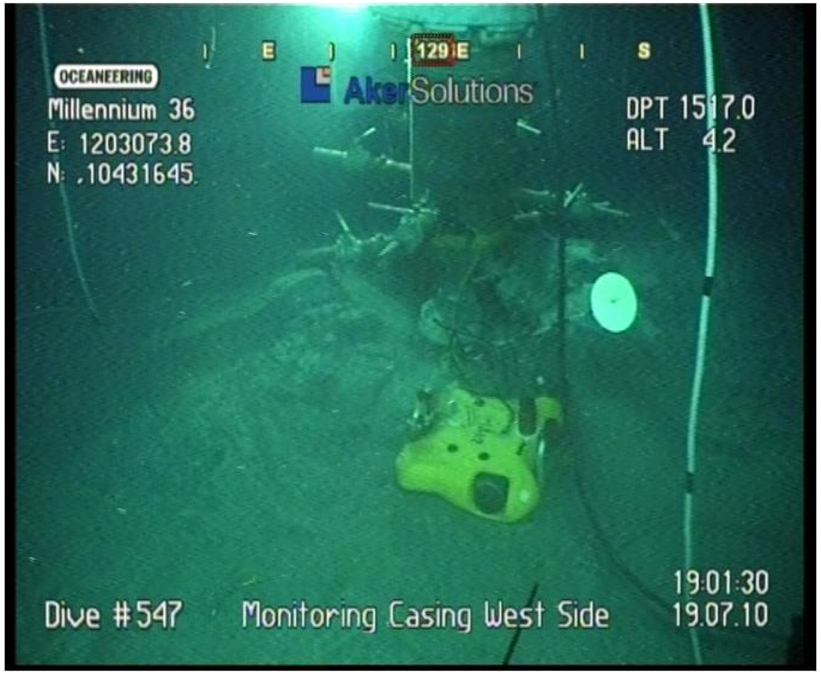
Ref.: Stopin et al., SEG 2011

NRMS = 6 %, hexagonal 400 m grid

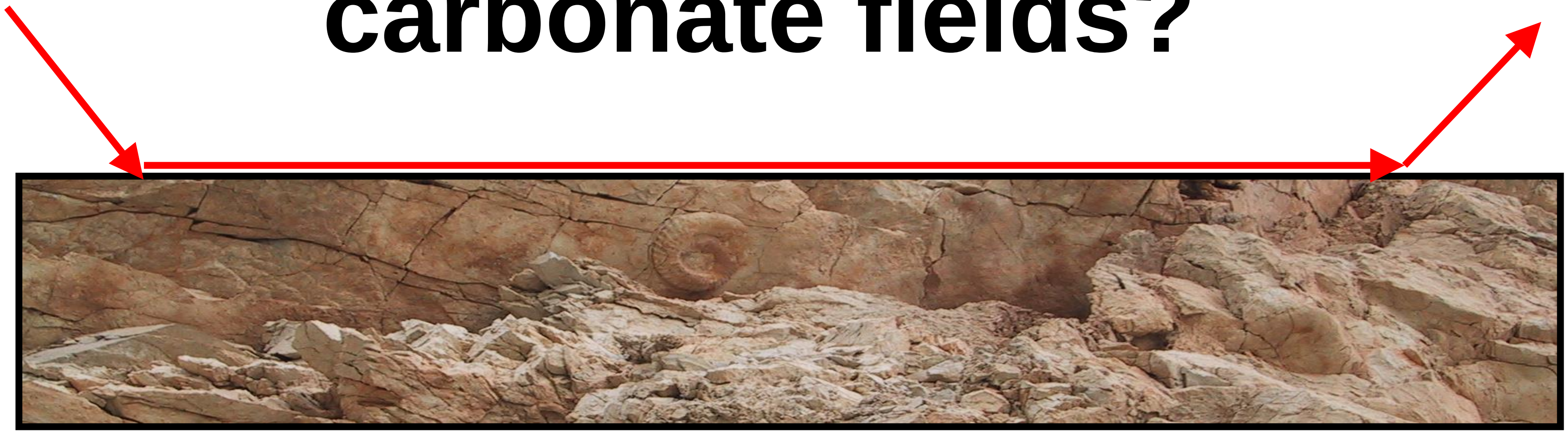


Macondo Field Oil Spill, Gulf of Mexico





Time lapse refraction seismic
–
a tool for monitoring carbonate fields?



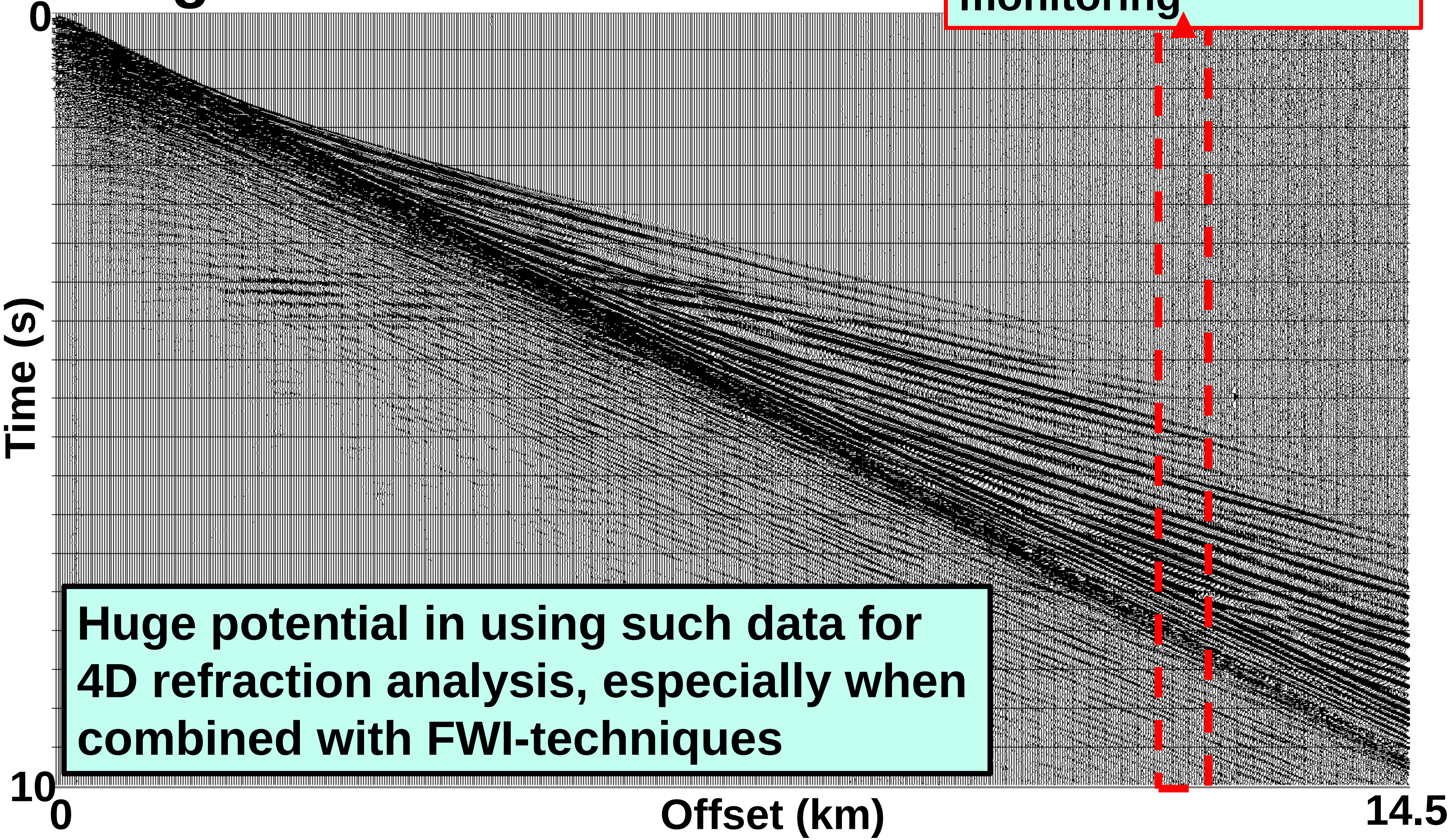
by

M. Landrø (NTNU) , A. K. Nguyen, (SINTEF) and H. Mehdizadeh, (NTNU)

SEG 2004

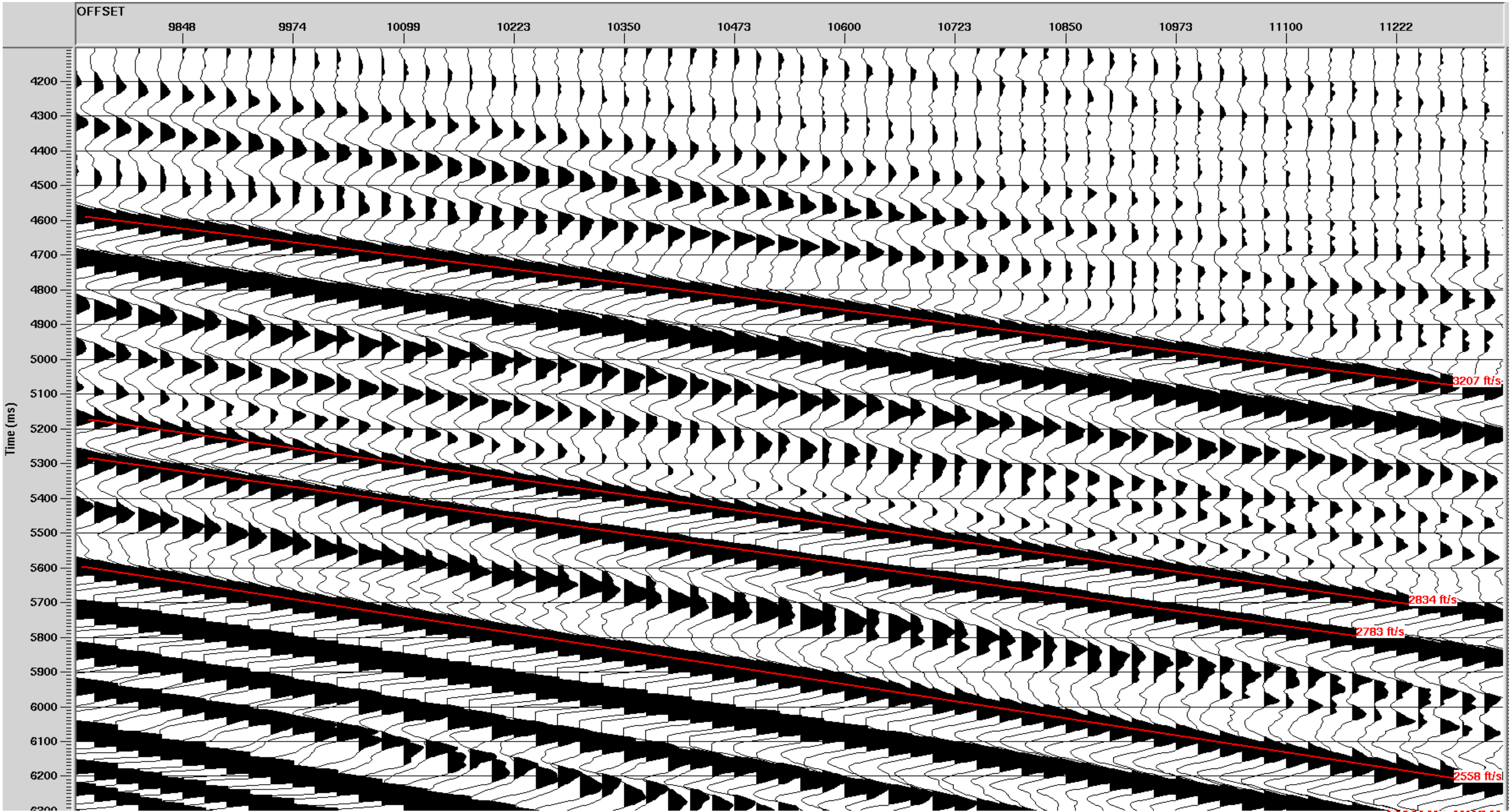
Long offset node data - single receiver

Use a few nodes for shallow 4D monitoring



Huge potential in using such data for 4D refraction analysis, especially when combined with FWI-techniques

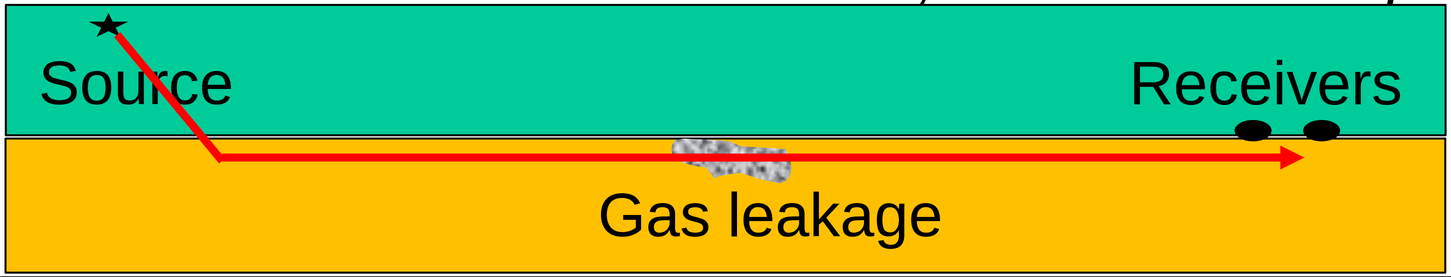
Strong headwaves at 10 km offset – velocities from 2500-3200 m/s; excellent for 4D

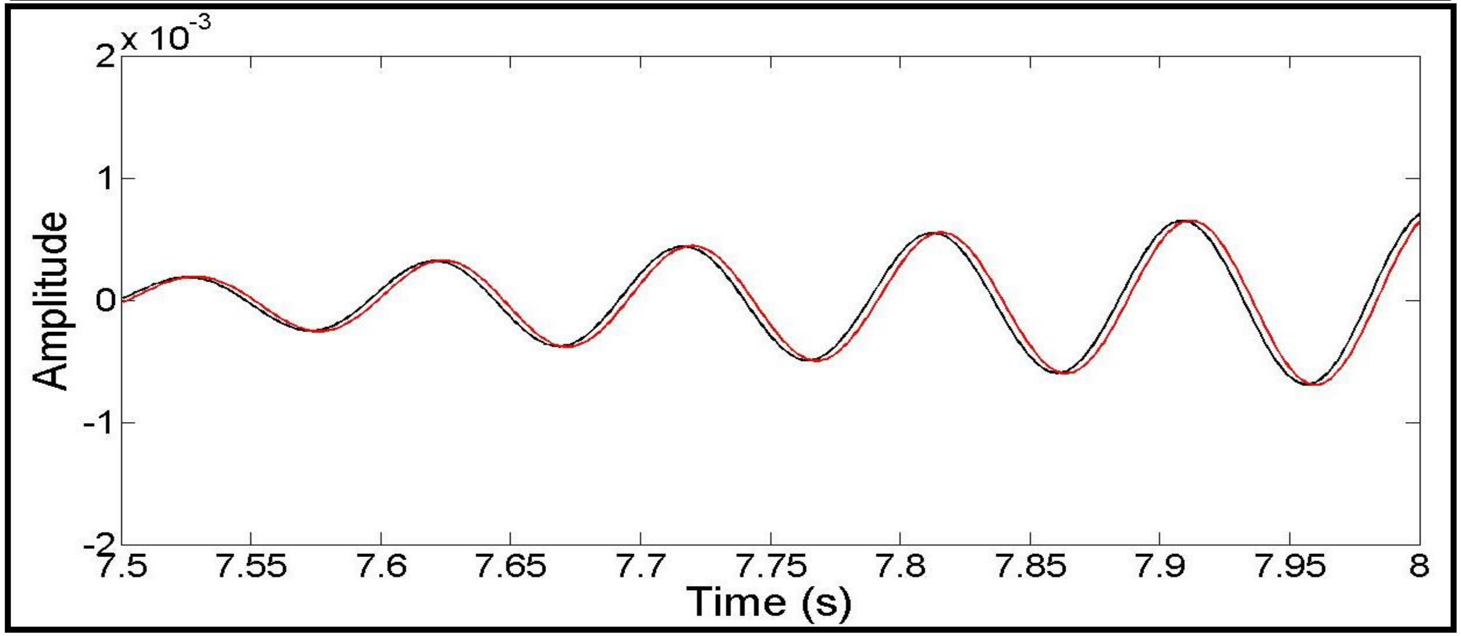


ROSE 2013

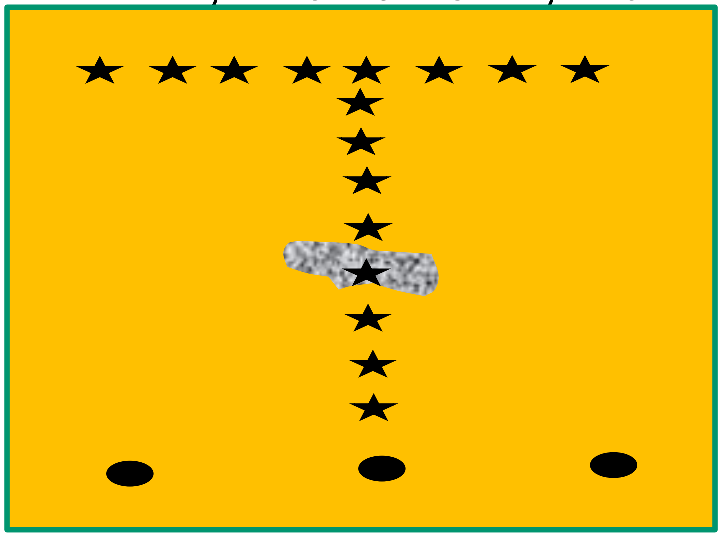
Using Water Layer Normal Modes to Detect Shallow Gas and CO2 Leakage

Landrø and Amundsen, EAGE workshop on PRM, Trondheim, 2011



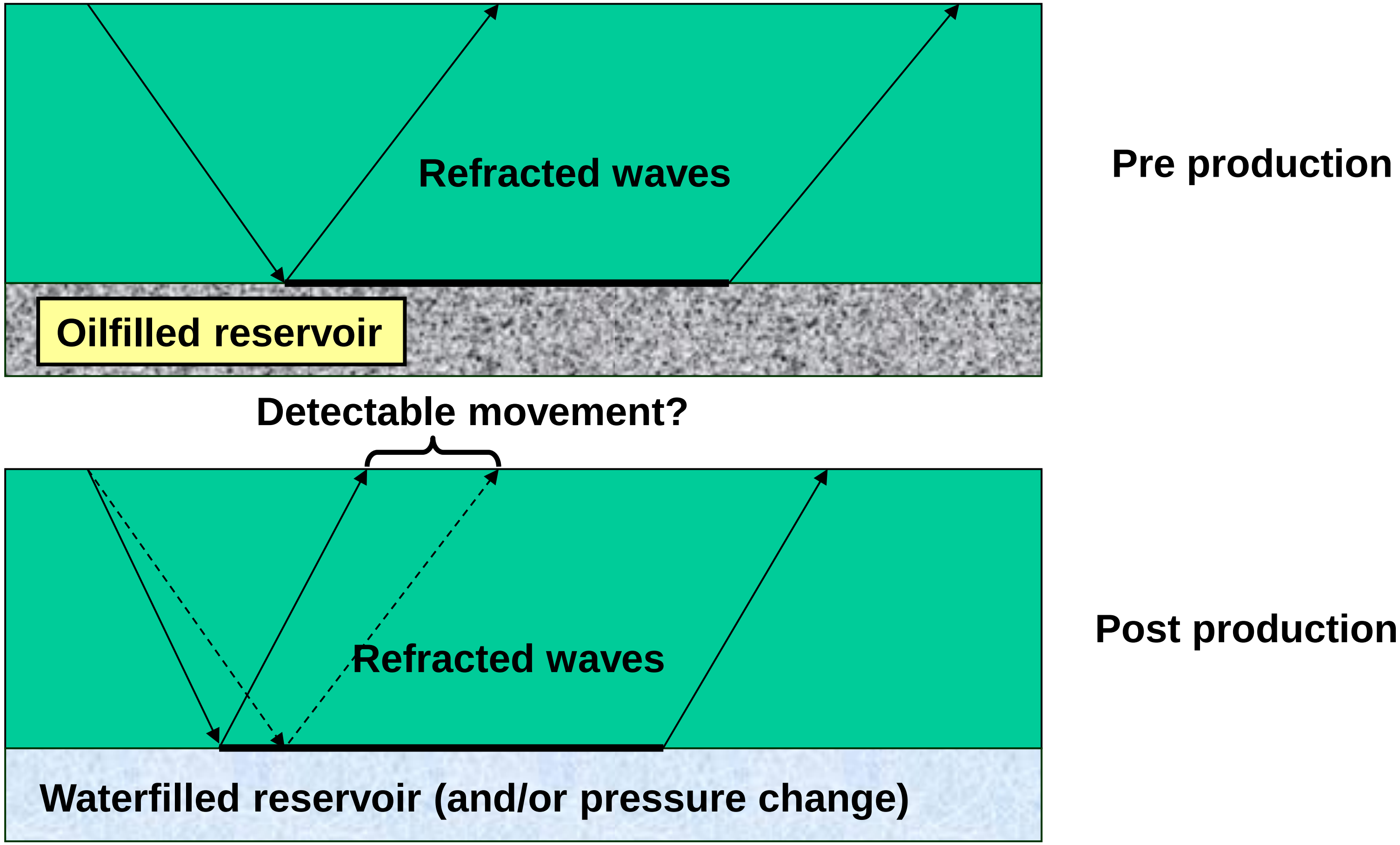


Modeled refracted wave for a two-layer model: black line: base line; red line: reduction of 50 m/s in layer two for an area of 200 m midway between source and receiver



Example: 3 nodes and some hundred shots covering the area where leakage might be expected

Time-lapse refraction seismic

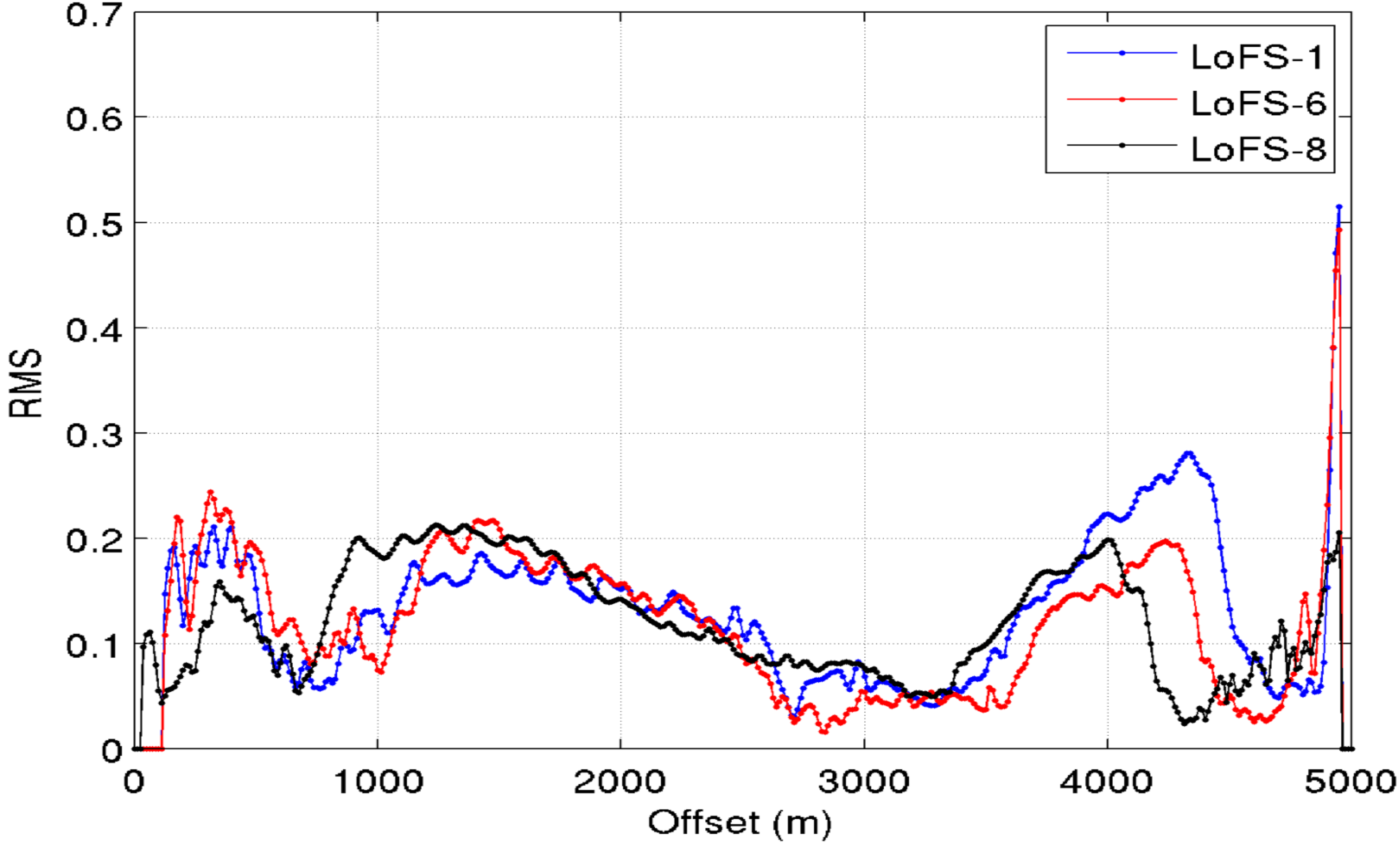


Water replacing water => increased velocity => decreased critical angle

Pore pressure decrease => increased velocity => decreased critical angle

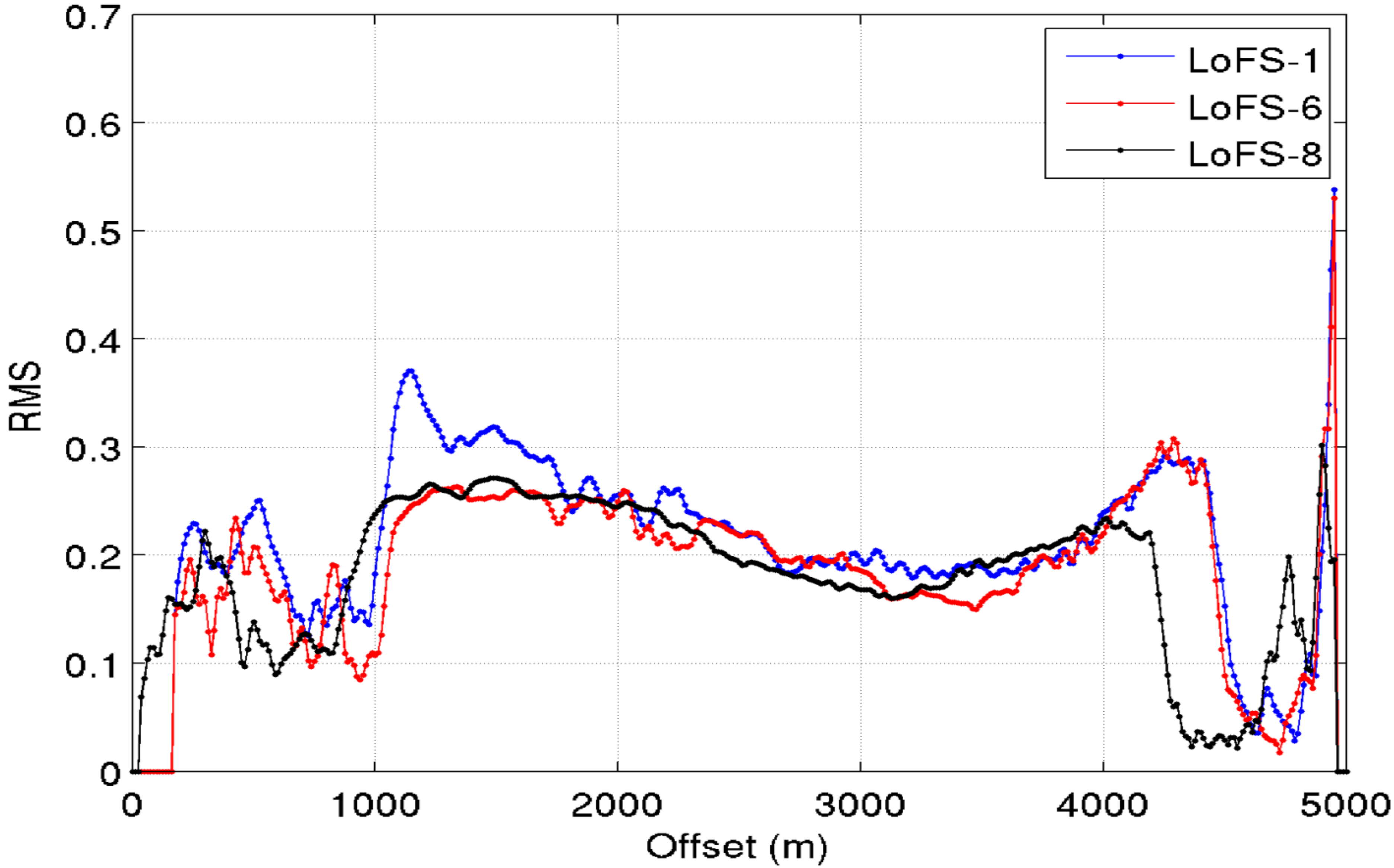
In addition to amplitude changes, there will also be associated tim

Example of RMS amplitude analysis



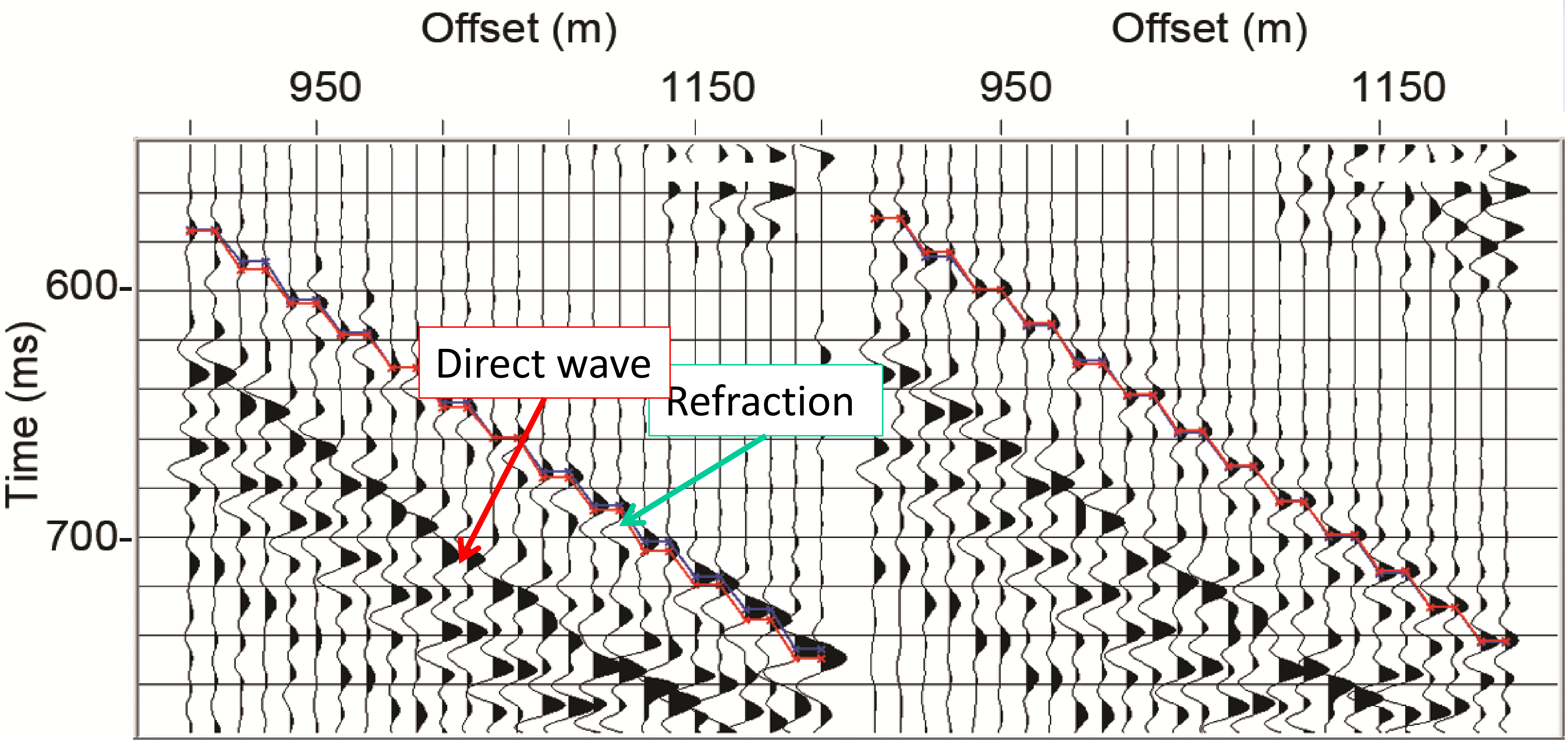
Systematic decrease in XM from LOFS-1 to LOFS-8

Example 2 of RMS amplitude analysis



No change from LOFS-1 to LOFS-6, followed by a significant change

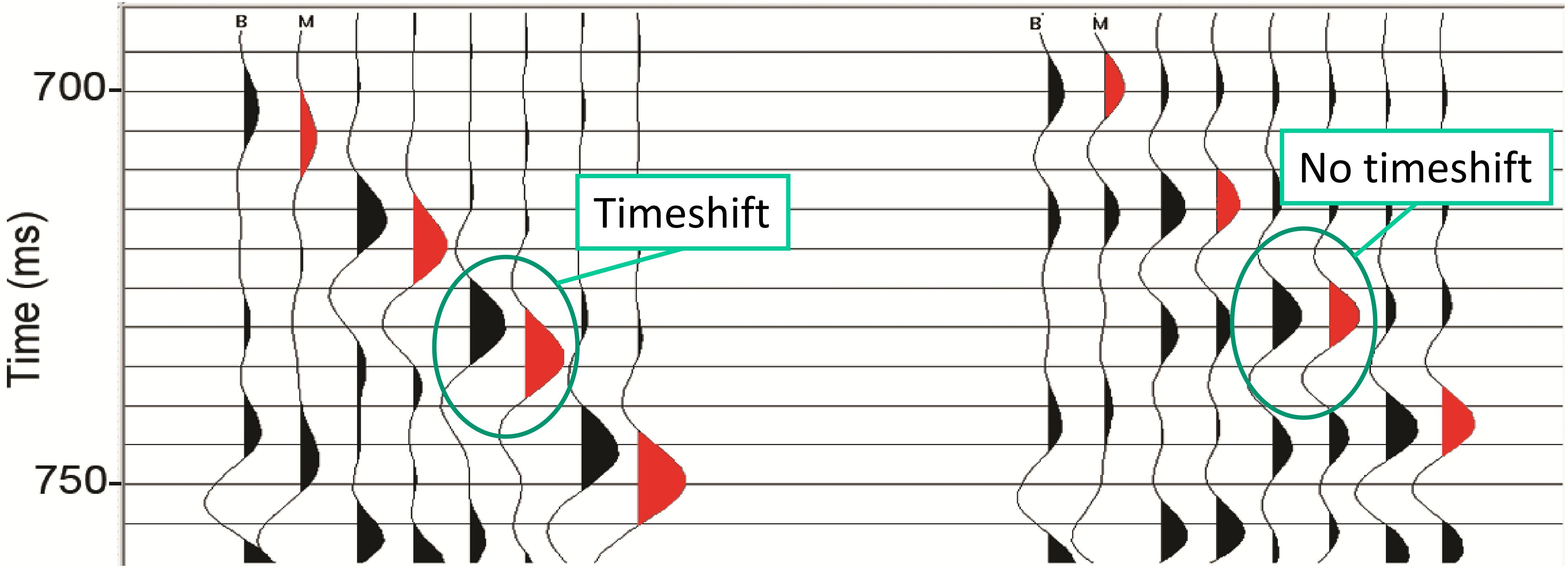
2/4-14 subsurface gas leakage example, merged base and monitor



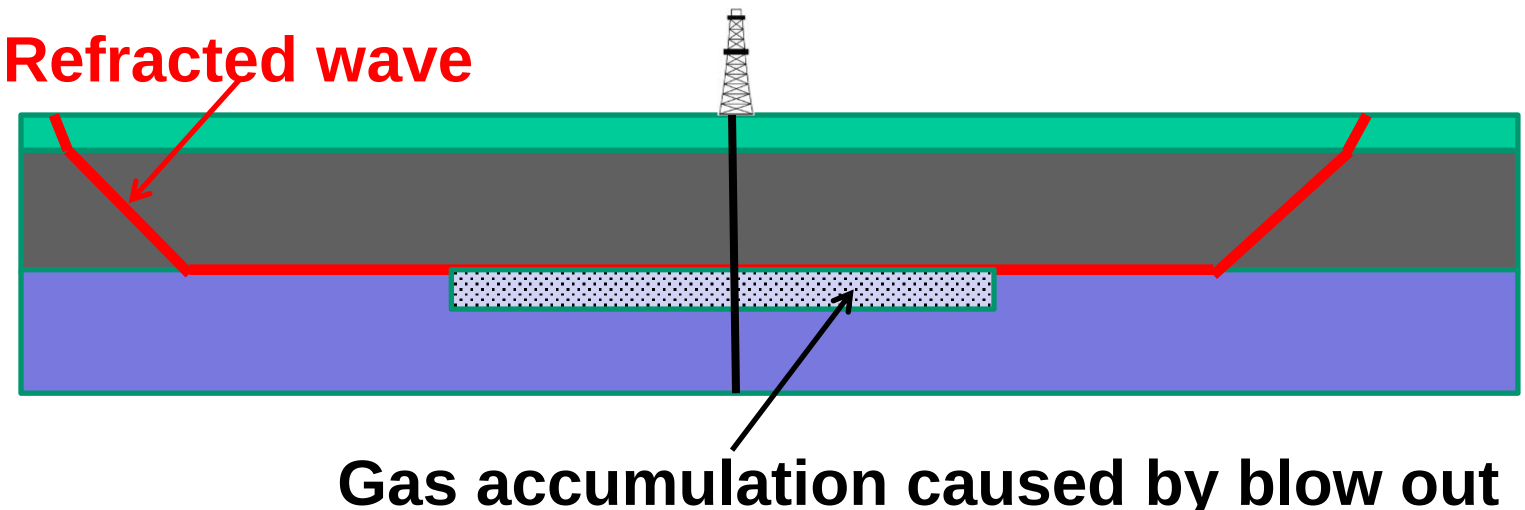
Close to well-14

Far from well

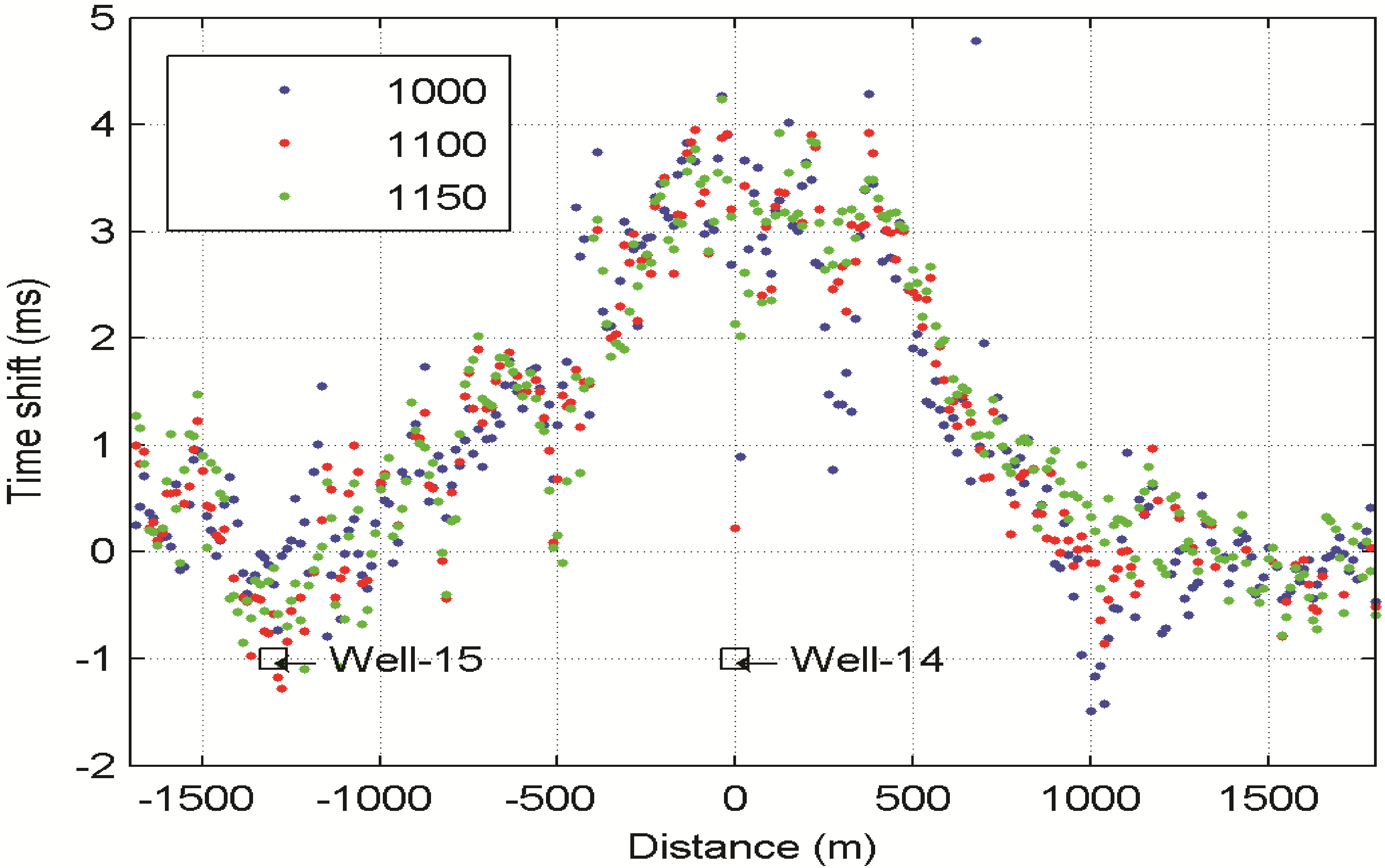
Merged base and monitor, zoomed



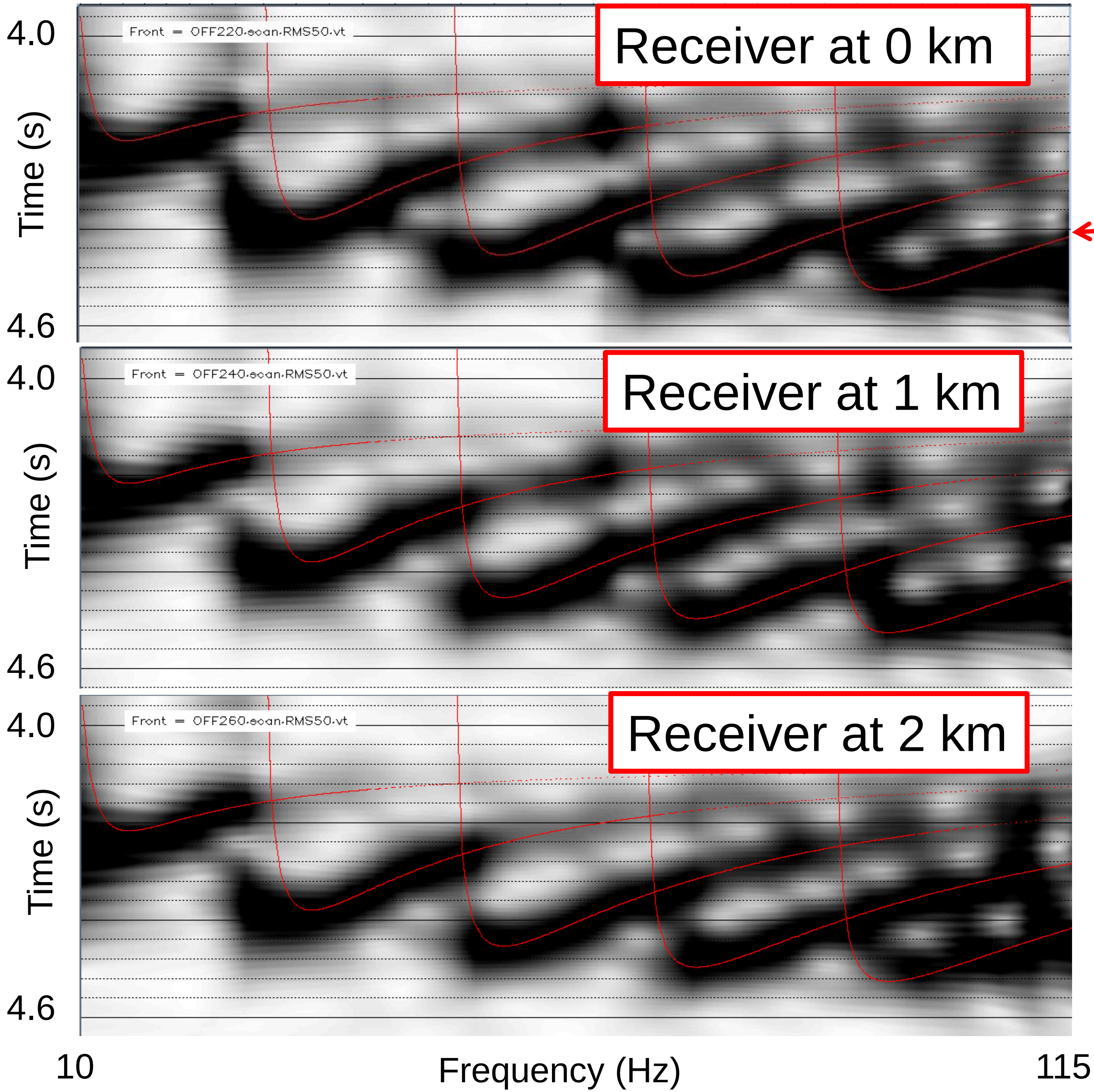
Close to well-14 **Far from well**



4 D refraction timeshift analysis



Normal modes – Valhall – 6 km offset



Red lines: Modeling results using V1= 1470 m/s,
V2= 1700 m/s and density ratio of 1.6

Minor shifts are observed => lateral variations in seabed velocities

Ref.: Landrø and Hatchell, Geophysics 2012

Nodes and 4D refraction analysis

- **4D refraction analysis can be used for relatively sparse receiver locations**

- **The emerging technology on Full Waveform Inversion opens new possibilities**

- **Near surface monitoring: Normal modes**

Converted wave and 4D

- Very few published examples
- Potential is definitely there
- Time will show…

Gravity and CSEM

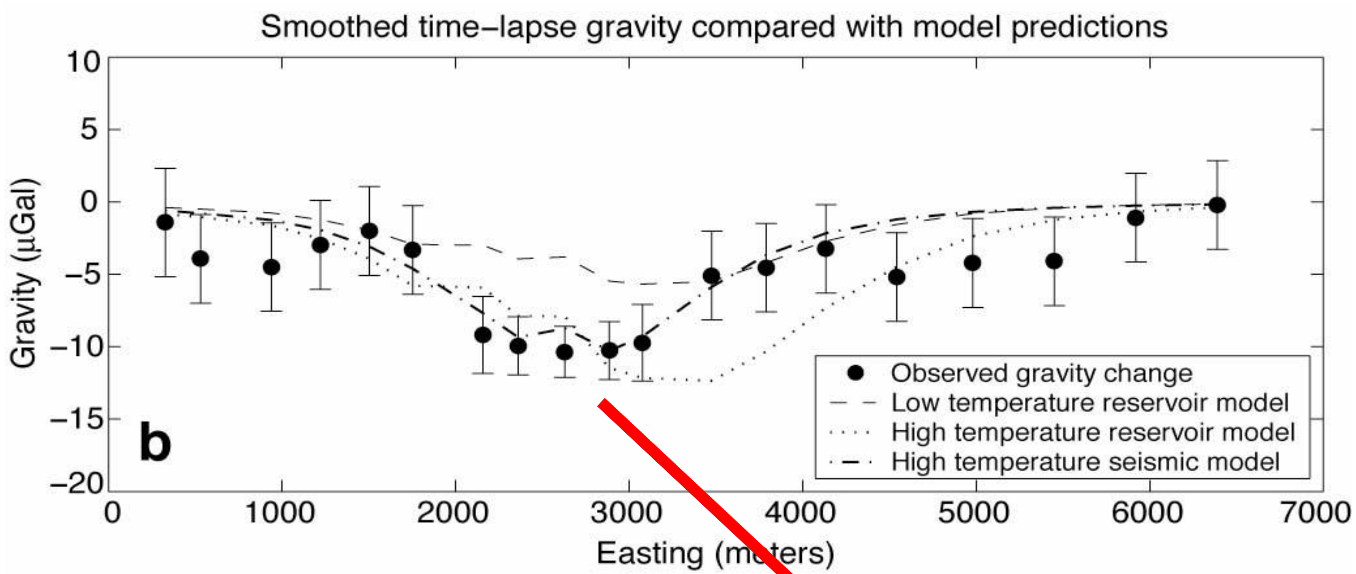
- **Best for shallow targets (CO_2- storage and leakage)**
- **Low spatial resolution**
- **Complementary information (density and resistivity)**

Shear waves and 4D

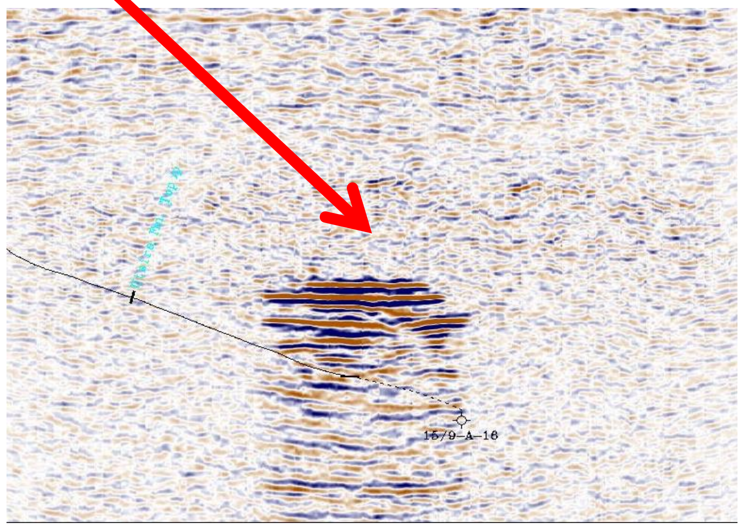
- Very few published examples
- Potential is definitely there
- Need for research and ideas
- Need for improved processing
- Potential: Pressure-saturation, fracture detection caused by production, …

Combine 4D gravity and 4D node?

Operational similarities and complementary 4D information



Courtesy: Statoi



Summary

- **Nodal 4D most probably used for deep water and fields with severe seabed obstacles**

- **Interesting option for semi-permanent monitoring**

- **Nodes can be used for 4D refraction methods**

- **Monitoring of underground leakage and CO_2**