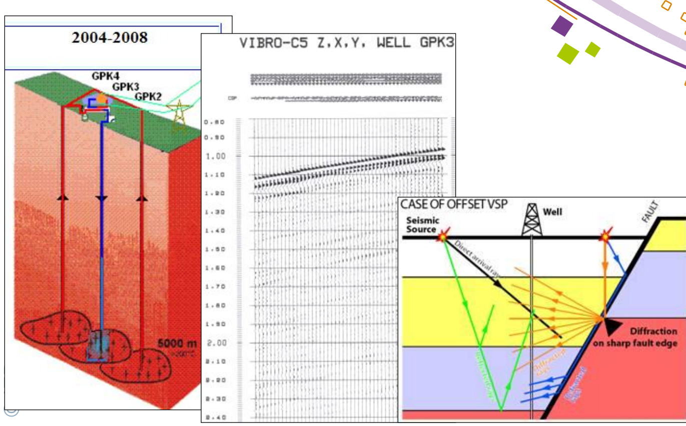
ACQUISITION of MULTI-OFFSET oriented THREE and FOUR component VSP for SEISMIC IMAGING of FAULTS in the deep GEOTHERMAL GRANITE BASEMENT RESERVOIR of SOULTZ, Alsace, France.

Presented in 2007 at SAID, French branch of the SPWLA, special session marking the 80th anniversary of the first logging operation in Pechelbronn, Alsace, France,1927

by: C. Naville, (IFP) ,
A. Gérard, N. Cuenot, J. Place, (EEIG-Soultz),
Maria del Mar MESA SALGADO, (ex IFP, now TOTAL)



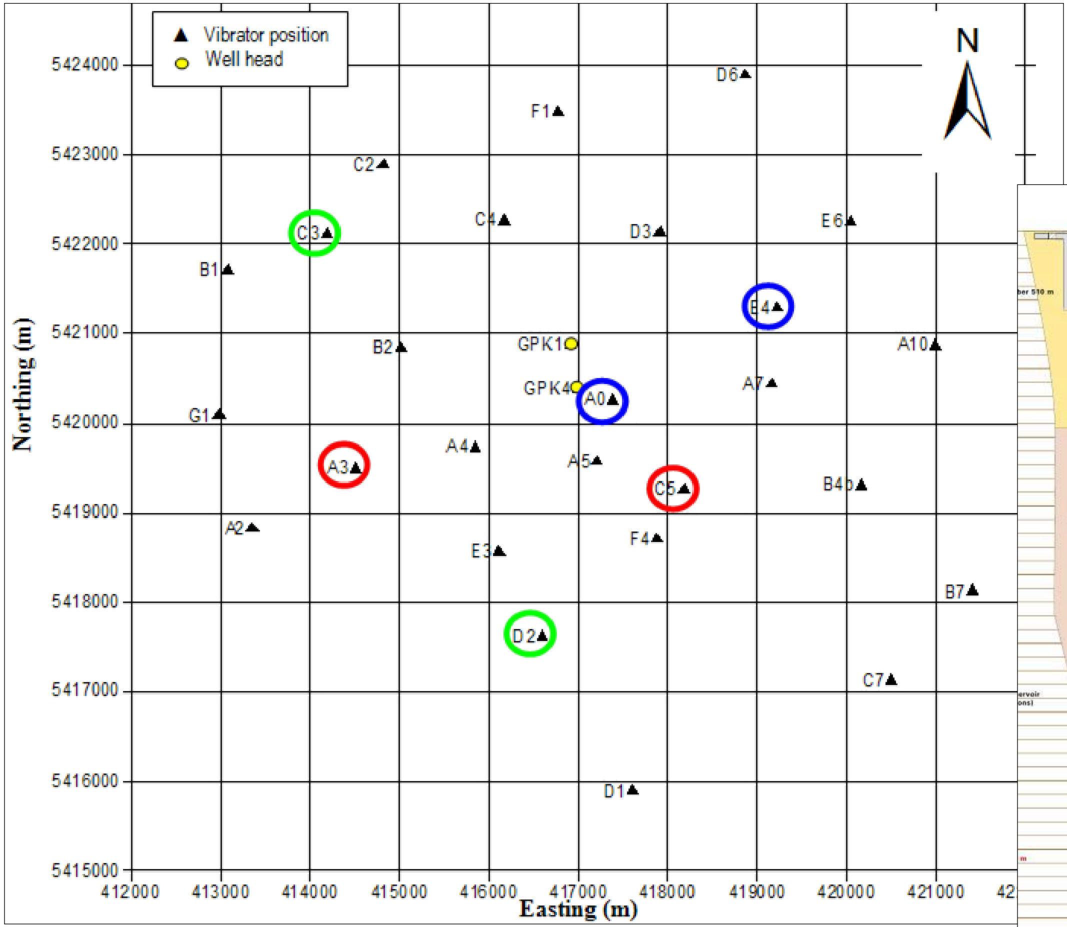
Innovation
Energy
Environment

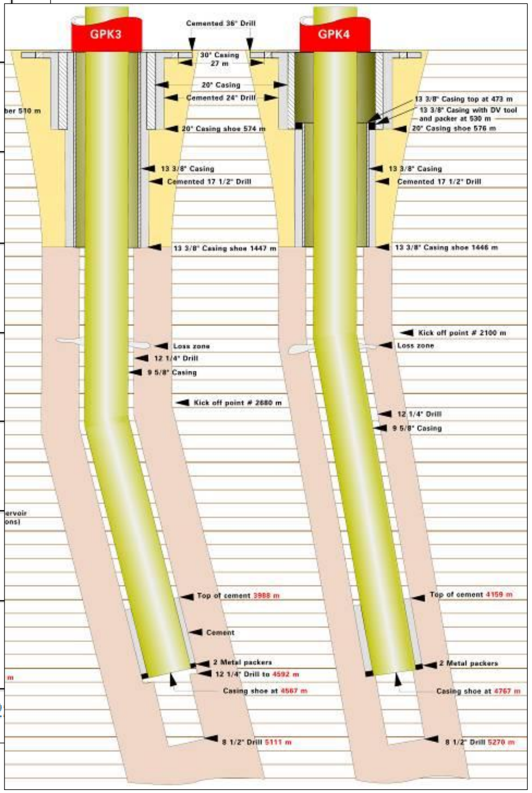
Soultz VSP campaign 2007

- Motivation behind the choice of the VSP method for seismic exploration of the well vicinity up to several hundreds of meter away from the wells.
- Specific VSP acquisition planning, taking in account that no rig was present, the boreholes could be accessible for a one month period, and night work was excluded, within fixed budget limits.
- Acquisition disposal and field operations: double borehole operation, field equipment, including the 200°C temperature rated analog VSP tool equipped with 3 component gimballed geophones and a HT hydrophone, and simultaneous vibroseis recording technique used to maximize production.

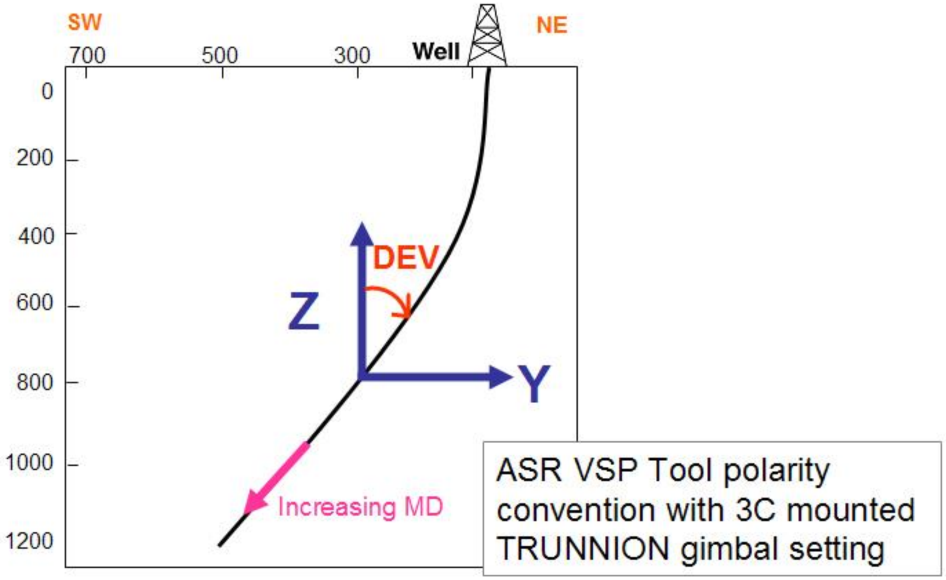
Innovation
Energy
Environment

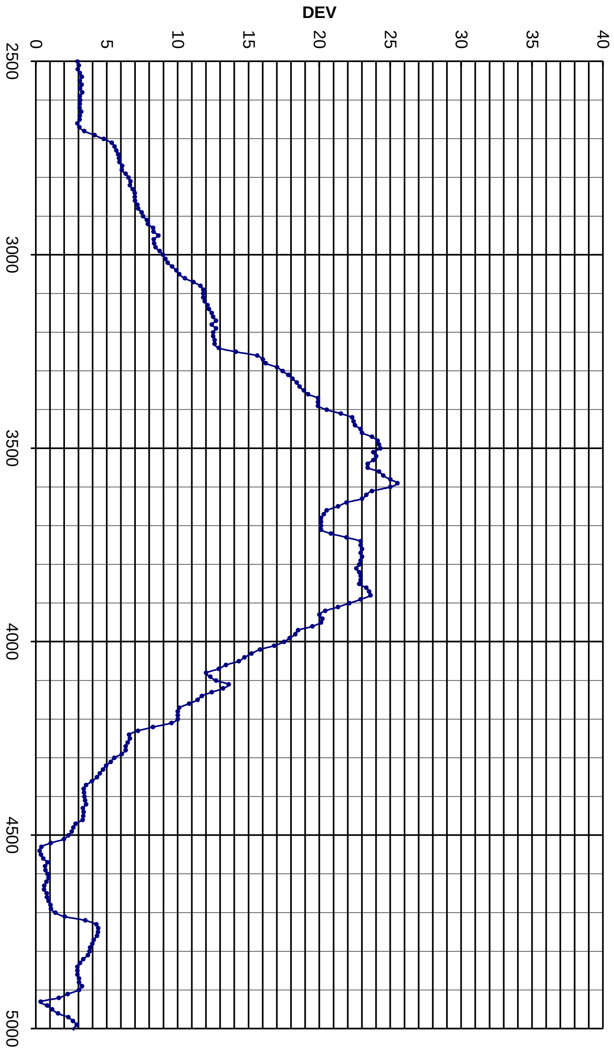
Pre-processing and Orientation of 4 - Component multi-source/multi-offset VSP data from deep wells





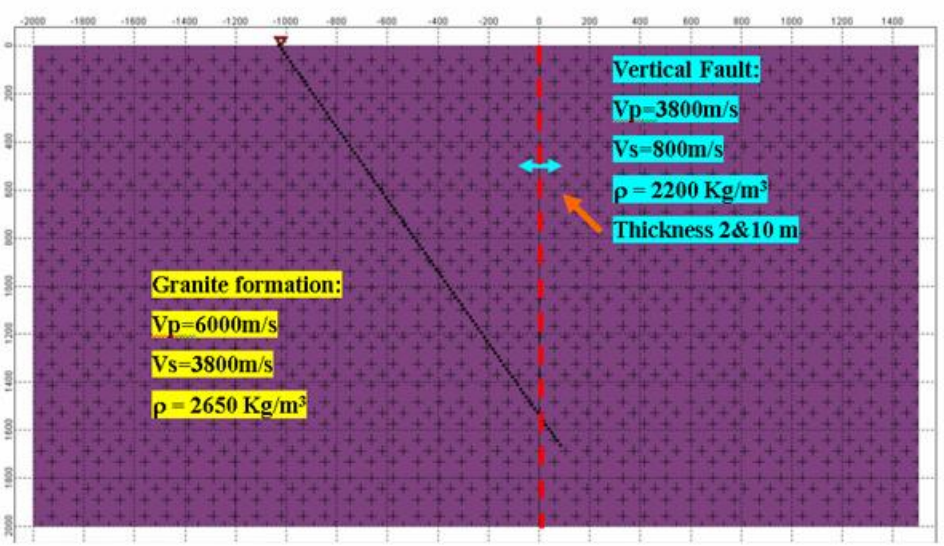
Study on sensitivity of gimballed geophones versus well deviation

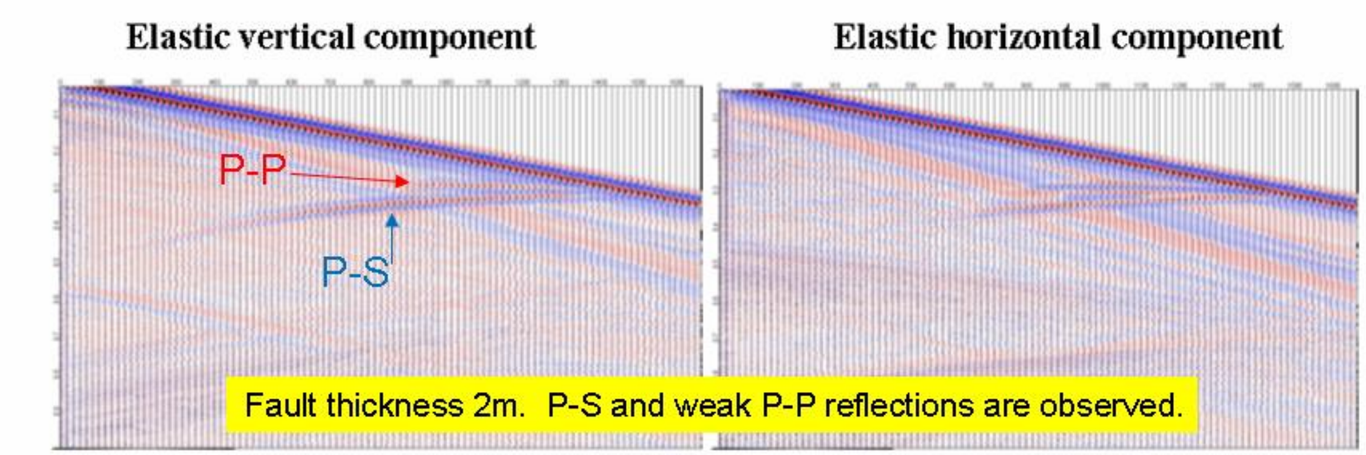




An elastic modeling 2D to tentatively simulate the reflectivity of permeable faults

Results obtained using Tesseral Finite difference Seismic modeling Software





SUMMARY

- **Use of VSP method motivated by: illumination of the well vicinity up to several hundreds of meter away from the wells, demonstrated by 1993 GPK-1 VSP reprocessing, suited to the exploration between wells.**
- **Specific VSP acquisition planning, with removed rig , boreholes accessible for one month period, night work excluded, limited budget.**
- **Specific field equipment and operations: 200°C temperature rated analog VSP probe equipped with 3 component gimballed geophones and a HT hydrophone,**
- **Maximizing field production with VSP tools in TWO boreholes (2 winch units) at same time, and simultaneous vibroseis recording technique.**
- **Pre-processing and preliminary results: observed seismic heterogeneities basement granite raise hope for fault delineation**

ifp Innovation Energy Environment

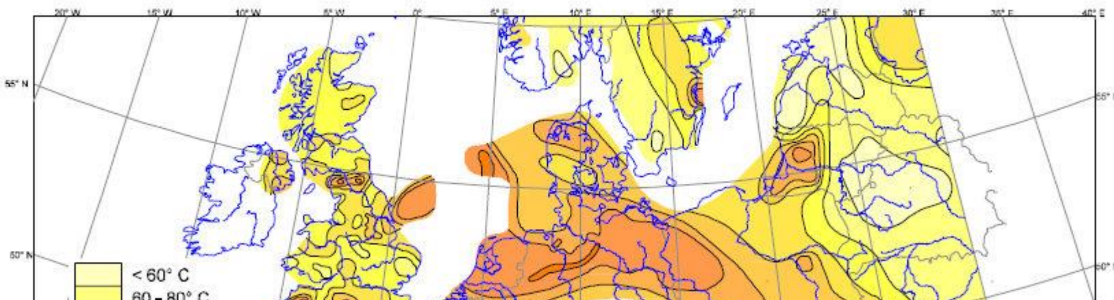
SOULTZ-SOUS-FORÊTS

INTRODUCTION

SOULTZ-SOUS-FORETS

HDR PROJECT SOULTZ

GEO



INTRODUCTION

SOULTZ-SOUS-FORETS

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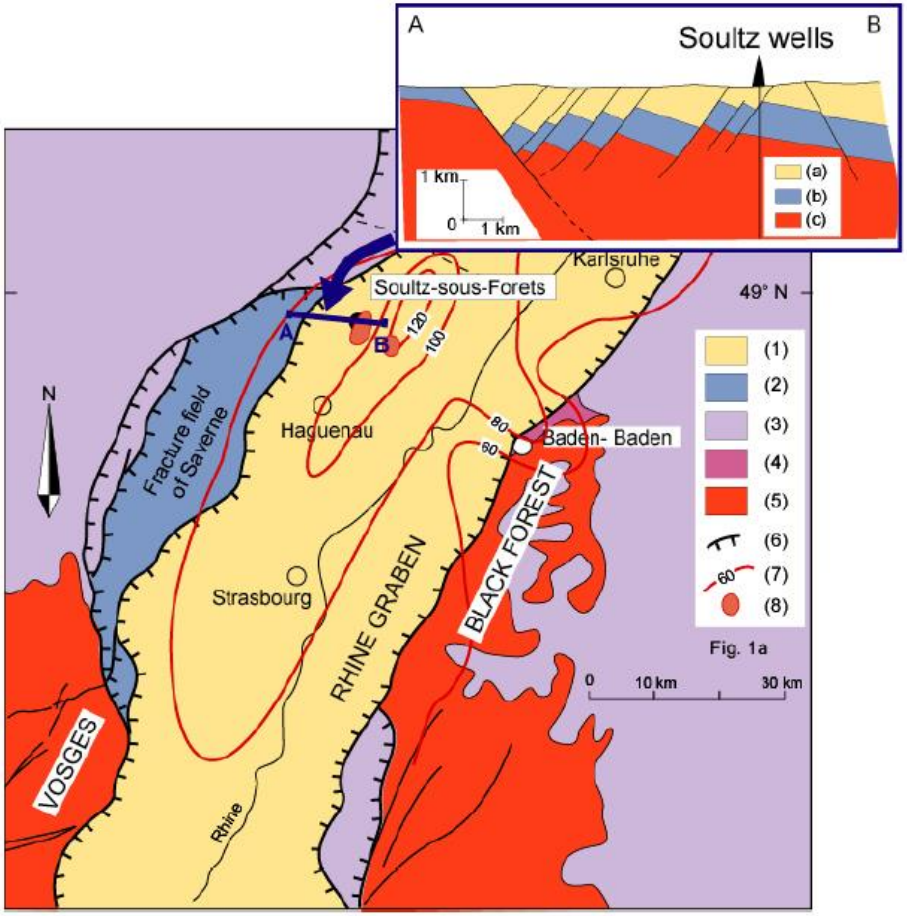
GEOLOGICAL SETTING



Upper Rhine Graben

Hercynian basement

(BESTEC GmbH)

INTRODUCTION

SOULTZ-SOUS-FORETS

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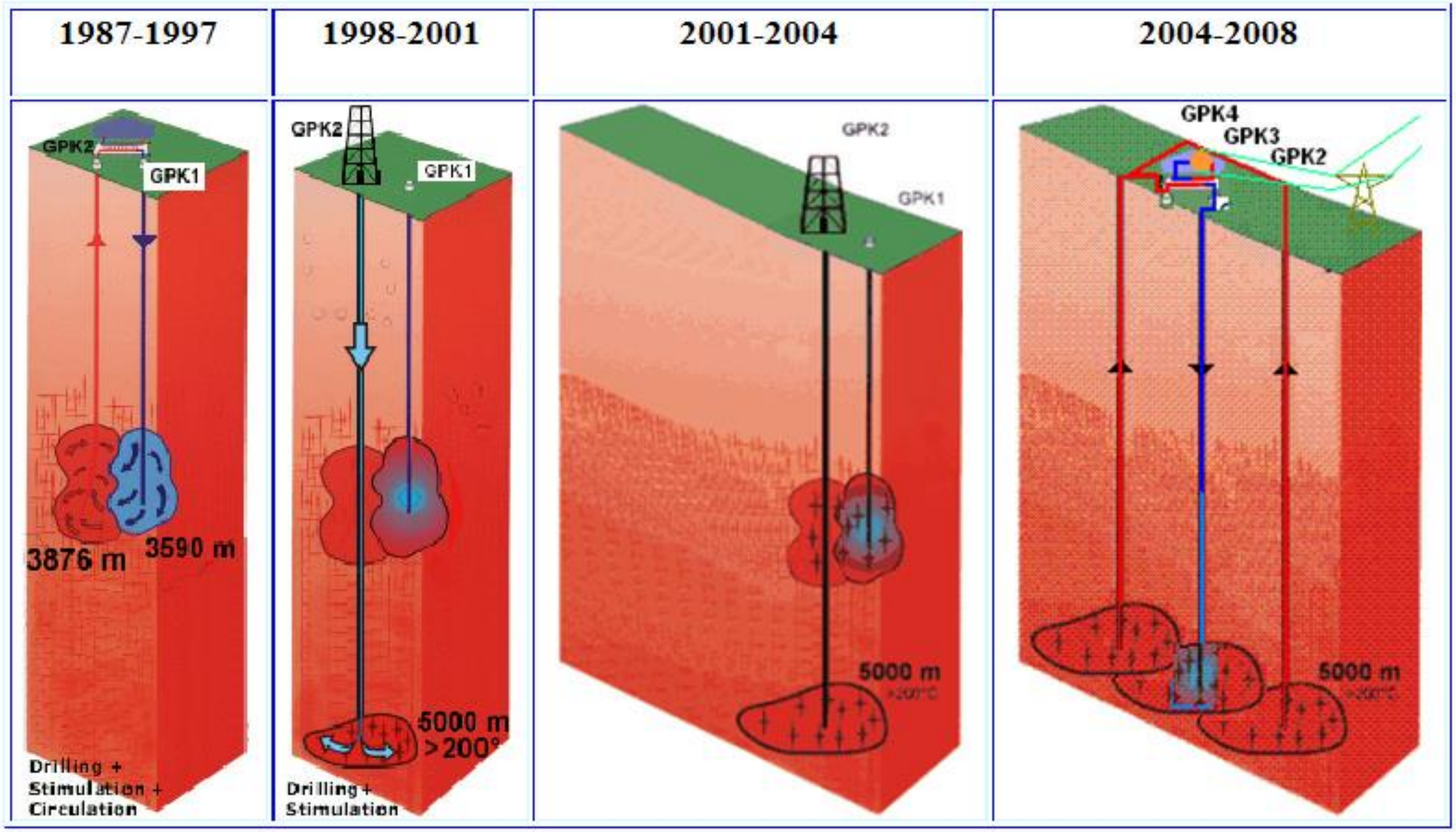
GEOLOGICAL SETTING



HDR PROJECT SOULTZ

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VERTICAL SEISMIC PROFILING METHOD
THE SEISMIC METHOD
MAPPING AND CHARACTERIZATION OF THE SUBSURFACE FRACTURE SYSTEM
THE COORDINATE SYSTEM
VSP SURVEY IN SOULTZ-SOUS-FORÊTS

ACQUISITION AND PRE-PROCESSING
VSP DATA PRE-PROCESSING
SIMULTANEOUS ACQUISITION RESULTS ON GPK-3 / GPK4 VSP SURVEY
SENSITIVITY OF GIMBALLED GEOPHONES

THE FINITE DIFFERENCE NUMERIC SCHEME

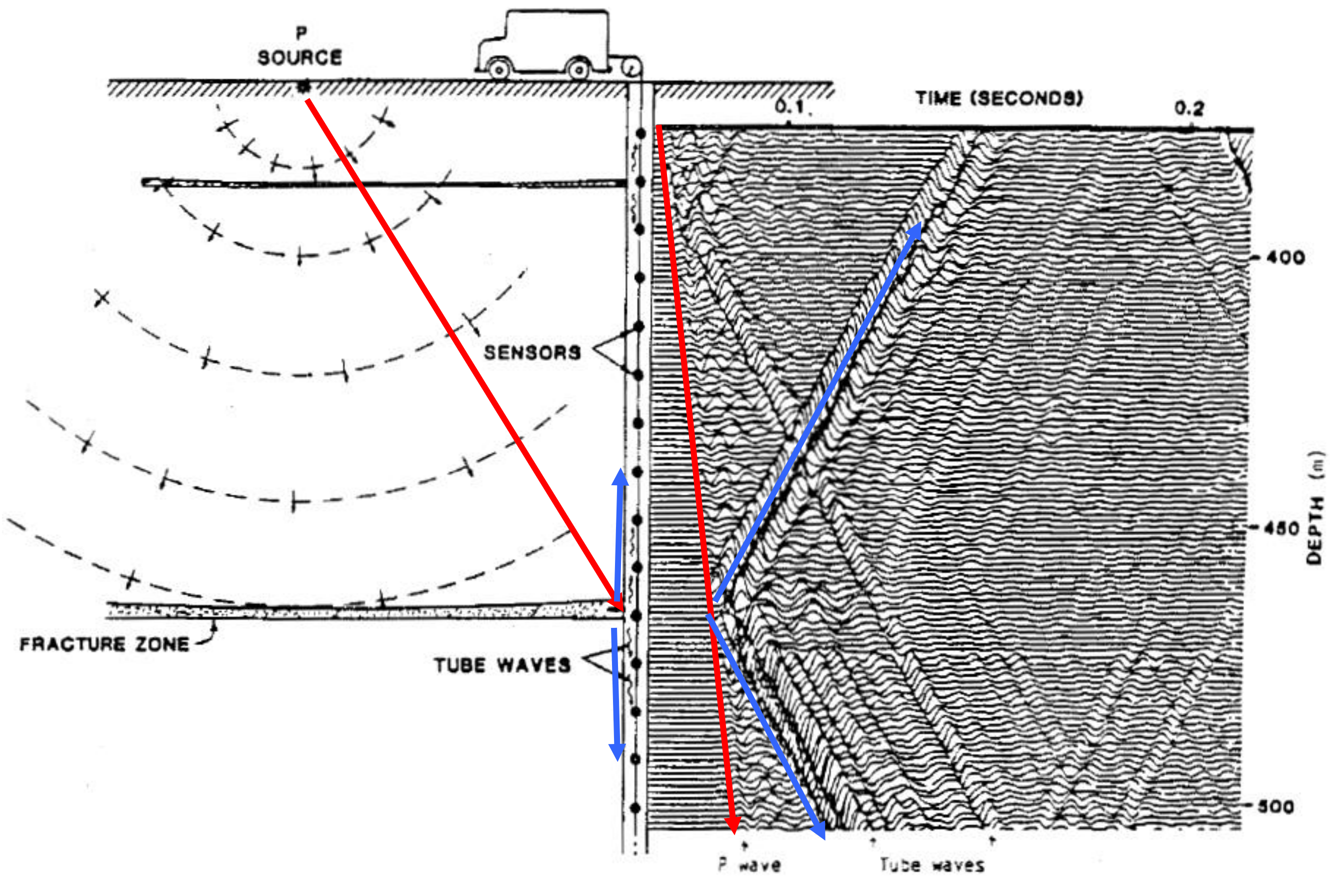
DISCUSSION AND CONCLUSIONS

Why working with 4 Components ?

The correlation of “Tube Wave” Events with Open Fractures in Fluid-Filled Boreholes.

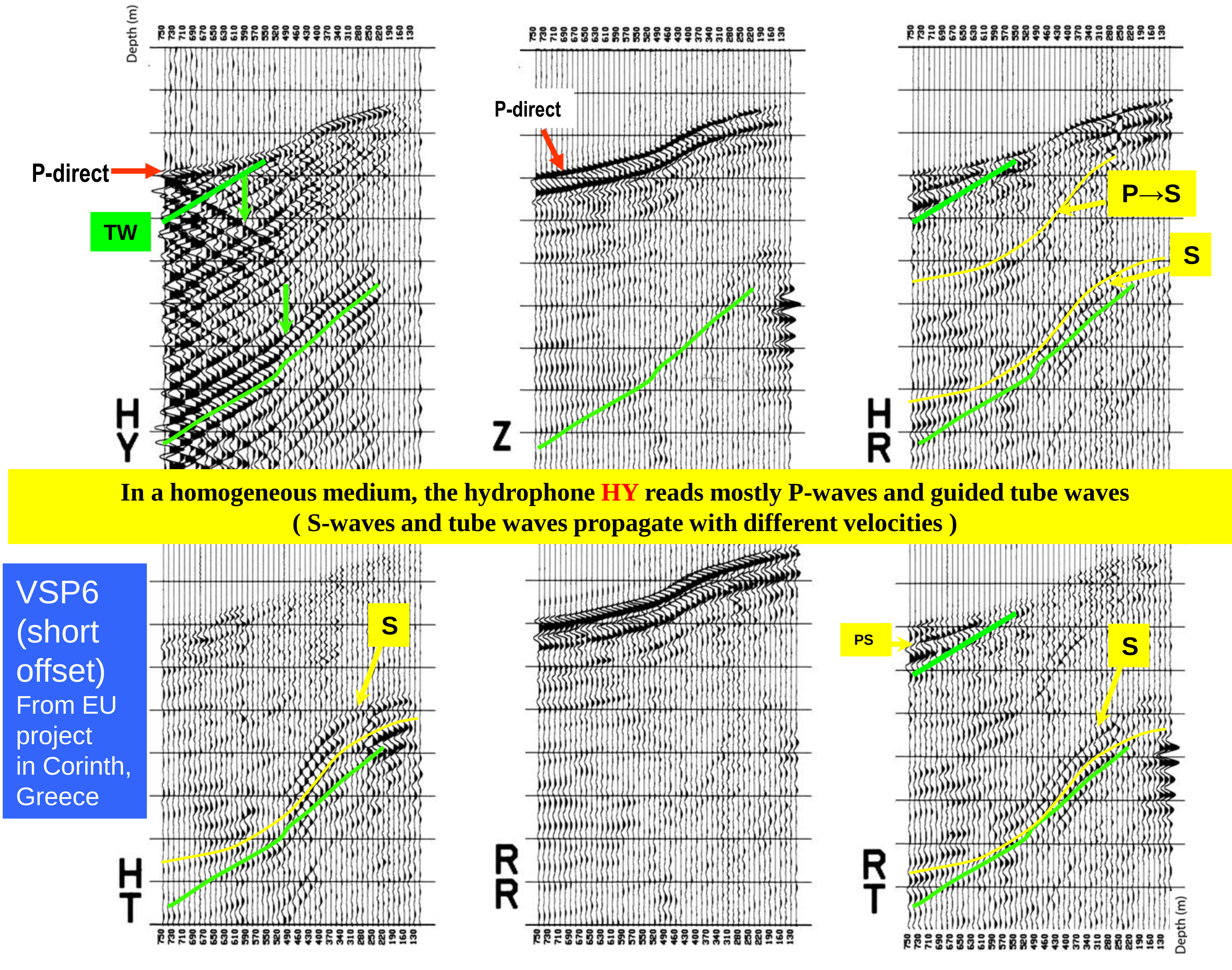
Huang and Hunter

Can. Geol. Surv. Pap., 81-1[a], 361-376. ***1981***



Mechanism of generation of tube waves

Hydrophone VSP section



In a homogeneous medium, the hydrophone HY reads mostly P-waves and guided tube waves
(S-waves and tube waves propagate with different velocities)

ORIENTED 4 COMPONENT VSP FAULTS IN THE DEEP GRANITE BASEMENT AT SOULTZ-SOUS-FORETS

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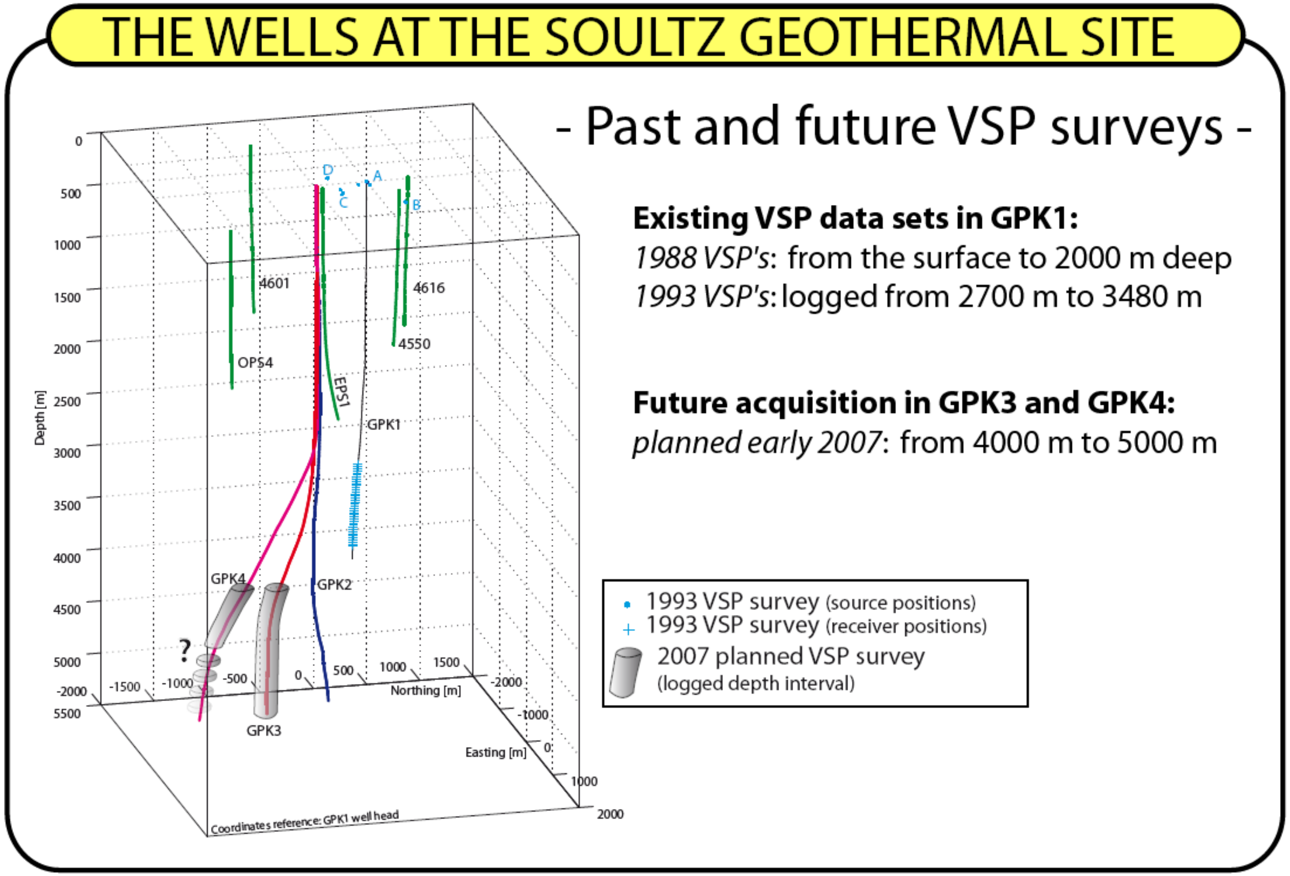
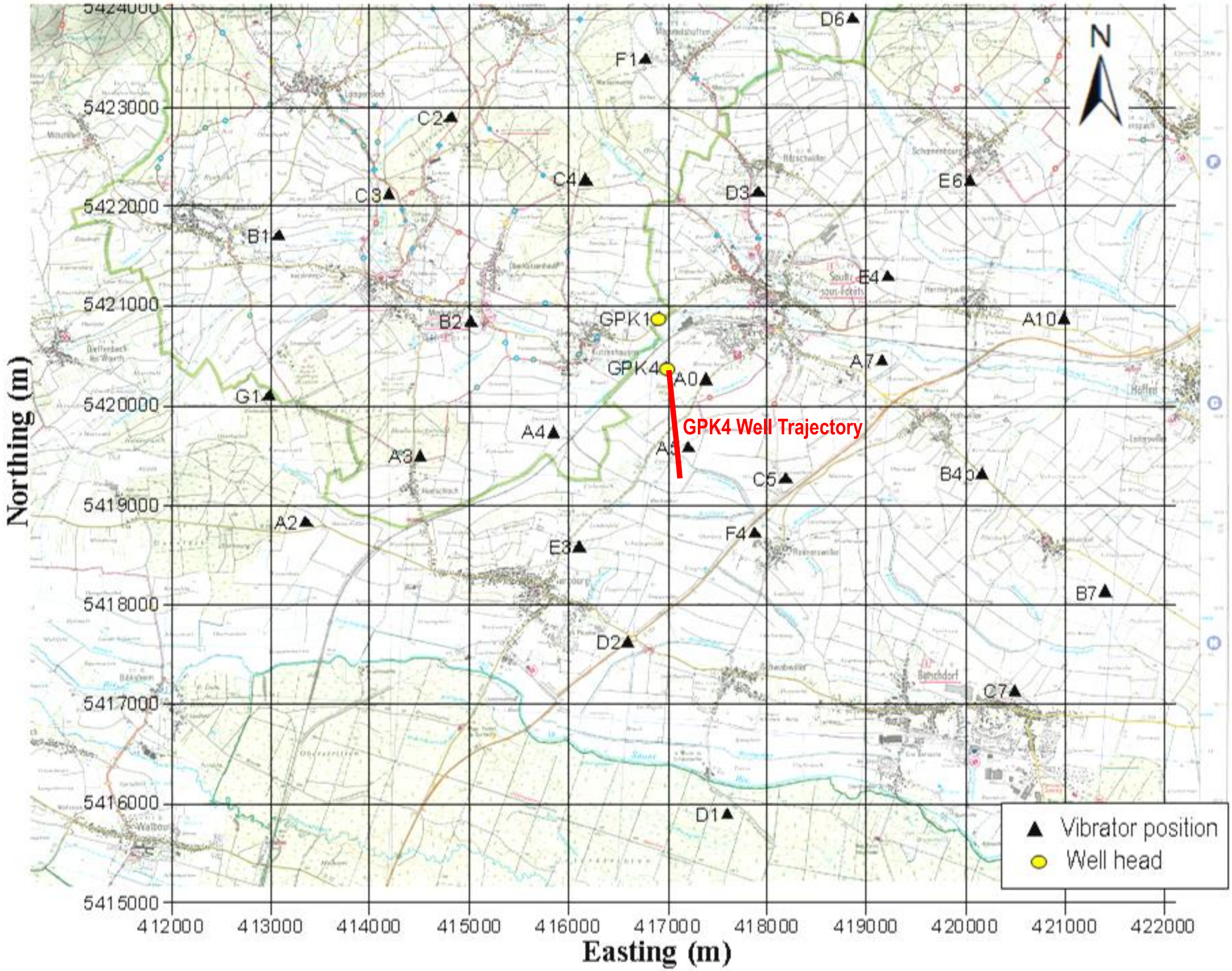
DISCUSSION AND CONCLUSIONS





N
Northing (m)
Easting (m)
5424000
5423000
5422000
5421000
5420000
5419000
5418000
5417000
5416000
5415000
412000
413000
414000
415000
416000
417000
418000
419000
420000
421000
422000
D6
F1
C2
C4
C3
D3
E6
B1
E4
B2
GPK1
A10
A7
GPK4
A0
G1
GPK4 Well Trajectory
A4
A3
A5
C5
B4b
A2
F4
E3
B7
D2
C7
D1
Vibrator position
Well head

Receivers

VSP tool in GPK-3: channels 1-4
VSP tool in GPK-4: channels 5-8
3 surface monitor traces, channels 25, 27, 30,
+ reference sweep channel 31
Interval between VSP station: 20m

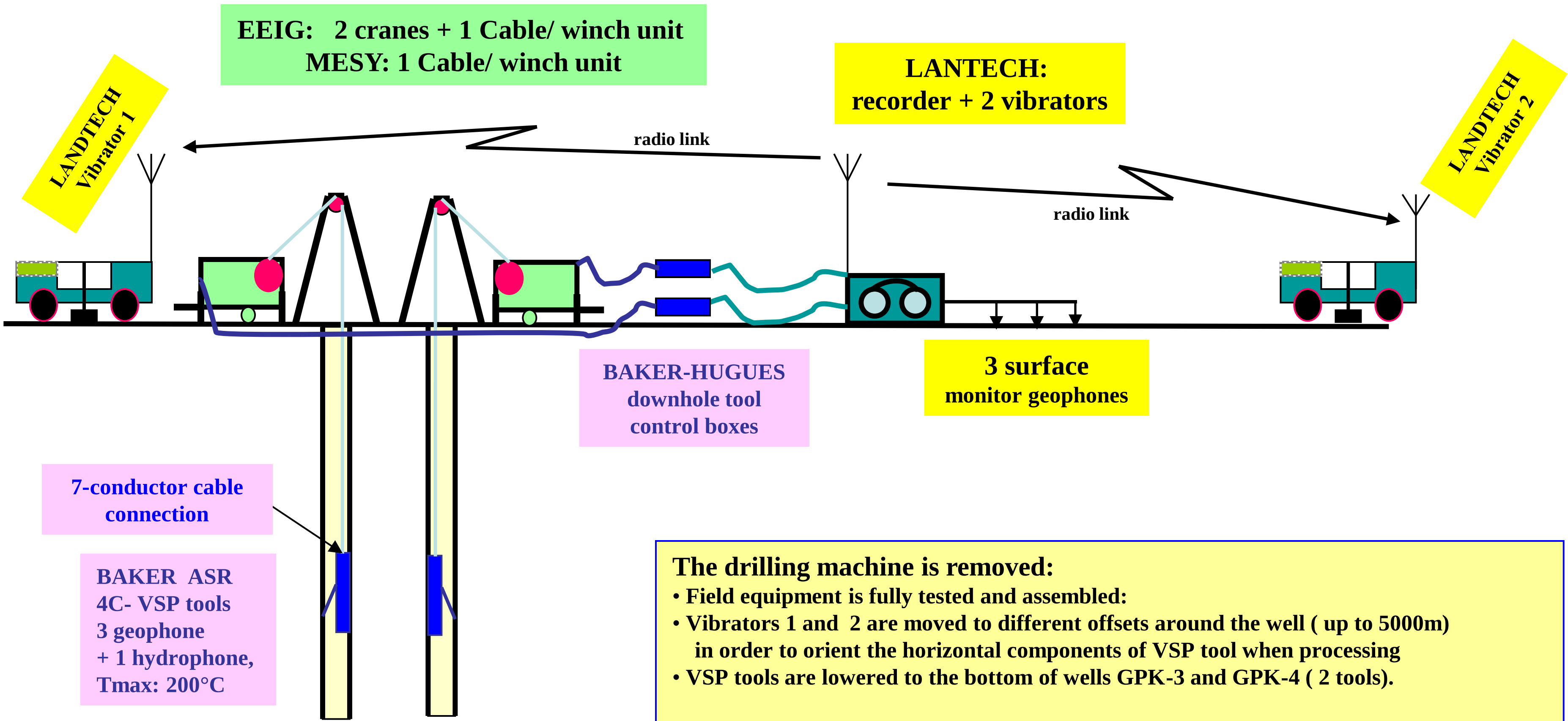
Vibrator Sources

16s sweep, 0,3s tapers + 3s listening, 2ms sample rate
Polarity code for simultaneous acquisition, used on series of 4 sweeps:
upsweep (- - + +) and downsweep (- + - +)

1. Field parameters and operations

DISPOSAL OF FIELD EQUIPMENT

VSP in GPK-3&4 Soultz wells recorded by LANDTECH (2 vibrators + recorder), using MESY and EEIG logging cables and BAKER 4C-VSP downhole tools.



IPP : Technical coordination
EEIG: global organisation

The drilling machine is removed:

- Field equipment is fully tested and assembled:
- Vibrators 1 and 2 are moved to different offsets around the well (up to 5000m) in order to orient the horizontal components of VSP tool when processing
- VSP tools are lowered to the bottom of wells GPK-3 and GPK-4 (2 tools).

Recording cycle:

- VSP tools are clamped in both wells GPK3 & GPK4
- Vibrator 1 and Vibrator 2 are activated simultaneously with orthogonal sweep codes,
- VSP tools are unlocked and moved up simultaneously in both wells GPK3 & GPK4

•One run per day during daytime, including the VSP tool maintenance and vibrator moves

Table 1. Logged interval in GPK3-GPK4.

Date	Run	dataset	Source Position Number	Vibrator Positions	logged interval (m)		GPK3 length	GPK4 length	Cumulated length	GPK3	GPK4	Observation
					GPK3	GPK4				ASR VSP Tool number		
30/03/2007	**0**	**0**		A0-A10*	3200-4500	3200-4500	1300	1300	5200	3192		Test run; move A10 to E4
02/04/2007	**1**			A0-E4*		1500-3200		1700	3400	3190, Hydro 3	3191, Hydro 2	
03/04/2007	**2**	**1**		A0-E4*		800-1500		700	700	3190, Hydro 3	3192, Hydro 2	Water inside tool 3191
04/04/2007	**3**	**1**		A0-E4*	3080-3200		120		240		3192, Hydro 2	Failure tool 3190 + hydro 3
05/04/2007	**4**	**1**	**1-2**	A0-E4*	4500-4800		300		600	3192, Hydro 2		GPK4 cable maintenance
10/04/2007	**5**	**2**	**3-4**	A3-C5*	3800-4800	3800-4800	1000	1000	4000	3192	3447	
11-12/04/2007	**6+7**	**3**	**5-6**	A2-A7*	3900-4800	3980-4800	900	820	3440	3192	3447, Hydro 3	
13/04/2007	**8**	**4**	**7-8**	C3-D2*	3540-4800	3540-4800	1260	1260	5040	3192	3446	
16/04/2007	**9**	**5**	**9-10**	B4b-C7*	3900-4900	3900-4900	1000	1000	4000	3192	3446	
17/04/2007	**10**			A5-B7*	4000-4980	4000-4980	980	980	3920	3192	3446, Hydro 2	
18/04/2007	**11**	**6**	**11-12**	A5-B7*	3000-3980	3000-3980	980	980	3920			
19/04/2007				A4-A10*			0	0	0	3446, Hydro 2	3192	Water inside ASR 3446
19/04/2007	**12**	**7**	**13-14**	A4-A10*	3680-4920	3620-4290	1240	1300	5080	3447	3192	
20/04/2007	**13**	**8**	**15-16**	B2-E6*	3800-4900	3800-4900	1100	1100	4400	3192	3447	
23/04/2007	**14**	**9**	**17-18**	D3-D6*	3500-4900	3500-4900	1400	1400	5600	3447	3192	
24/04/2007	**15**	**10**	**19-20**	F1-C4*	3260-4900	3260-4900	1640	1640	6560	3447	3192	
25/04/2007	**16**	**11**	**21-22**	E3-C2*	3500-4900	3500-4900	1400	1400	5600	3447	3192	
26/04/2007	**17**	**12**	**23-24**	B1-D1*	3800-4900	3800-4900	1100	1100	4400	3447	3192	
27/04/2007	**18**	**13**	**25-26**	G1-F4*	3800-4900	3800-4900	1100	1100	4400	3447	3192	
								TOTAL LOGGED LENGTH (m)	70500			

18 days

Vib I sweep: 88 - 8 Hz {- + - +} - **Vib II*** sweep: 8 - 88 Hz {- - + +}

Observation: because of the downhole tool failures, several run/days were necessary to complete some dataset recordings; the field glitches complicates the subsequent preprocessing operations.

A total of 5 VSP Tools have been used to complete the survey

Géothermie Soultz

Acknowledgments

EEIG and the authors thanks all the people who contributed to the success of the VSP operation!

EEIG:
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- Gérard Krall
- Pascal Elter

MeSy:
- Gerd Klee
- Florian Seebald
- Ulrich Weber

Landtech:
- Andreas Sotiriou
- Christos Skarpelos

Baker-Hugues:
- Juriaan Claudius

VSP DATA PRE-PROCESSING

The data are pre-processed, in order to provide sorted and documented seismic traces represented in time-depth displays.

The main pre-processing operations include:

- **Data transfer from SEG-2 Field format**
- **Edition, Label, Vertical stack, correlation**
- **Orientation into geographic coordinates**
- **Output SEG-Y format**

The Geocluster software of CGG is used in order to carry out the basic Pre-Processing of **4C-VSP** of multiples runs:
52 VSP Datasets with set of 4 Component sensor, recorded in **2 wells** simultaneously and with **2 sources** in surface.

VSP DATA PRE-PROCESSING

LANDTECH SA
WELL SEISMICS

FIELD REPORT

Client:	**EEIG Soultz**
Project:	**Soultz VSP**

Location : SOULTZ	Instrument: Bison Jupiter	Correlation : Yes
Line : VSP07_A0_E4	Number of channels: **31**	Number of auxilliary : 1 (ch 31)
Date : 03/04/2007	Sampling Rate: **2 msec**	Tapers : 0,3 sec
Survey Type : VSP	Record length: **3 sec**	Sweep Length : 16 sec
Receiver interval : 20 m	Offset Vib I : A0	Vib I sweep : 88 - 8 Hz {- + - +}
Hydrophone : Yes	Offset Vib II: E4	Vib II sweep : 8 - 88 Hz {- - + +}
Geophones : Yes (Ch25,27&30)	GPK3 Channels: 2 =X, 3 =Y, 1 =Z, 4 =Hydrophone	
Downhole Sensor : ASR	GPK4 Channels: 6 =X, 7 =Y, 5 =Z, 8 =Hydrophone	

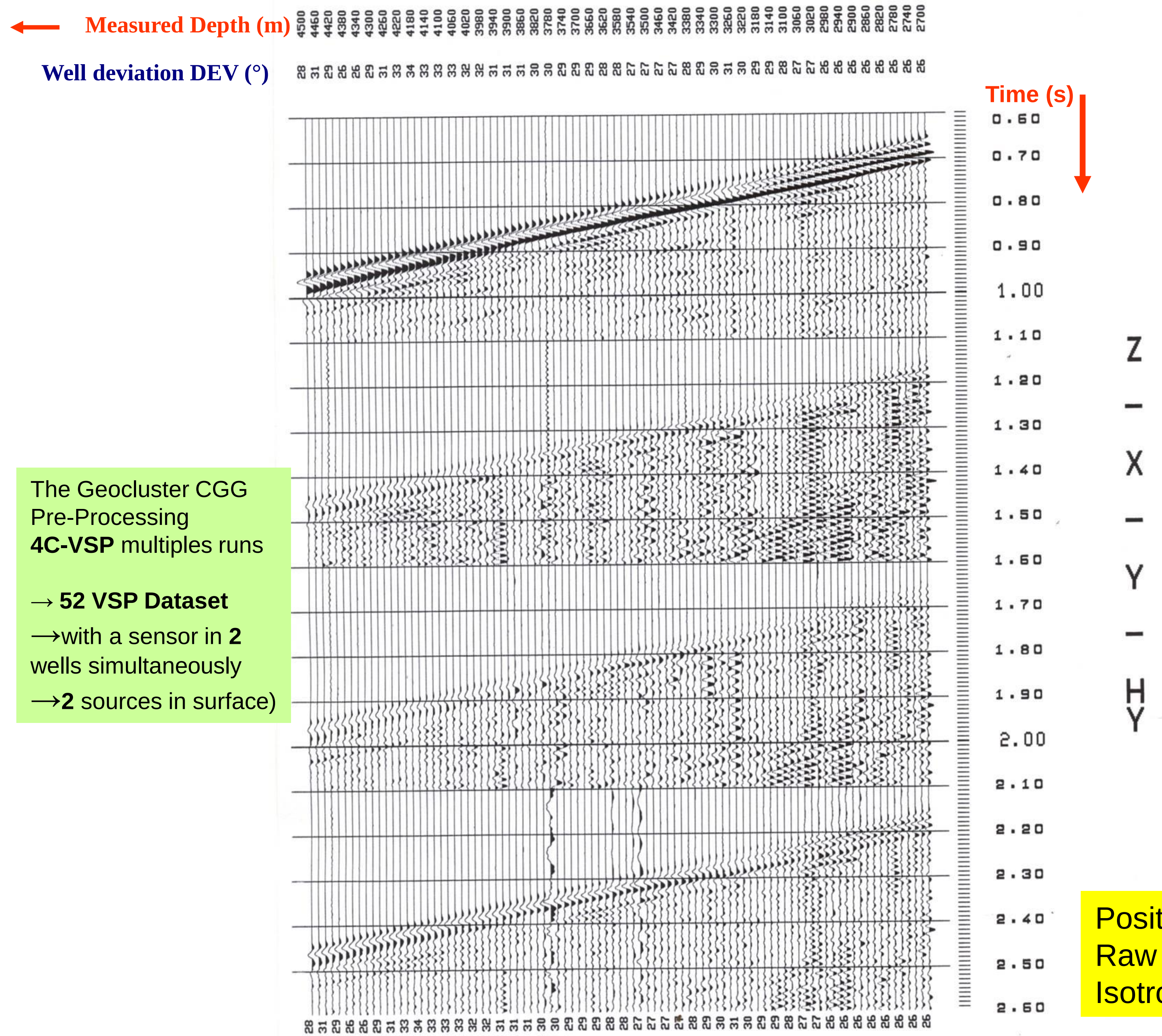
Record Number	Seq. #	GPK3 depth (m)	GPK4 depth (m)	Vertical Stacking	Remarks
1	0	2500	2500	1	VibII
2	0	2500	2500	1	Vib II
3	1	2500	2500	1	Vib I
4	1	4500	4500	1	Start acquisition at 12;45
5	2	4500	4500	1	
6	3	4500	4500	1	
7	0	4500	4500	1	
8	1	4500	4500	1	
9	2	4500	4500	1	
10	3	4500	4500	1	
11	0	4500	4500	1	
12	1	4500	4500	1	
13	2	4500	4500	1	
14	3	4500	4500	1	
15	0	4480	4480	1	
16	1	4480	4480	1	
17	2	4480	4480	1	
18	3	4480	4480	1	
19	0	4480	4480	1	

SEQUENCE # 0			
	ESG	*Vib I*	*Vib II*
Sweep	8-88 Hz /0^0	88-8 Hz /180^0	8-88 Hz /180^0
SEQUENCE #1			
	ESG	*Vib I*	*Vib II*
Sweep	88-8 Hz /0^0	88-8 Hz /0^0	8-88 Hz /180^0
SEQUENCE # 2			
	ESG	*Vib I*	*Vib II*
Sweep	8-88 Hz /0^0	88-8 Hz /180^0	8-88 Hz /0^0
SEQUENCE # 3			
	ESG	*Vib I*	*Vib II*
Sweep	88-8 Hz /0^0	88-8 Hz /0^0	8-88 Hz /0^0

Input field data:
One file per uncorrelated record, 19 sec length, 2ms sample rate, format SEG-2, headers labeled with channel number only.

The output **3C/4C-VSP** data: Correlated and oriented in geographical coordinates, SEG-Y standard format with all relevant information in trace headers:
Measured Depth (MD), **True Vertical Depth, Source Position Code**, **channel-component number**.

GPK4



The Geocluster CGG Pre-Processing **4C-VSP** multiples runs

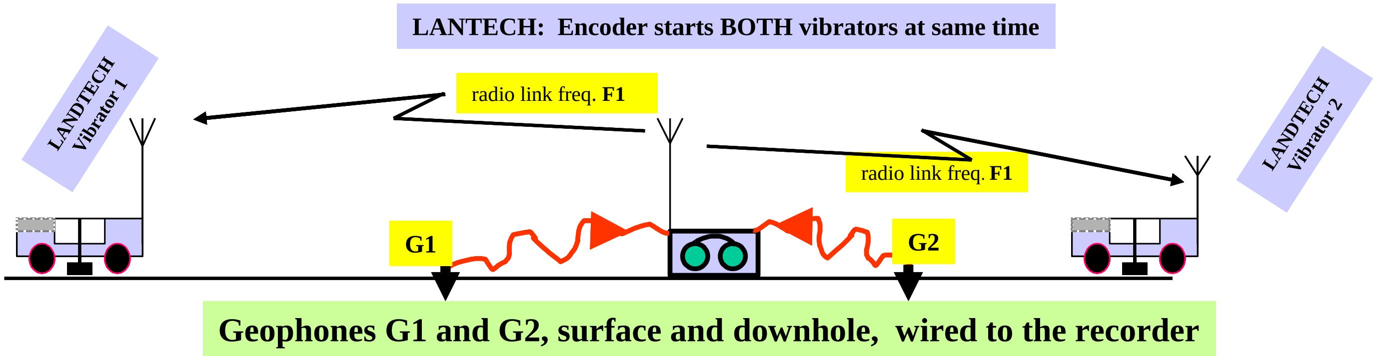
→ **52 VSP Dataset**

⟶with a sensor in **2** wells simultaneously

⟶**2** sources in surface)

Position Vibro A0
Raw 4 Component
Isotropic Display

SIMULTANEOUS VIBROSEIS ACQUISITION PRINCIPLE



Vib I is programmed with following series of 2 upsweeps (8-88 Hz, 16 sec + 2 sec listening), without modifying the polarity, the polarity code is: (+ for 0°, - for 180° phase). Sweep 1 (0°), sweep 2 (0°) the polarity code is **(+, +)**

Vib II is programmed with following series of 2 downsweeps (88 – 8 Hz, 16 sec + 2 sec listening), with polarity change, the polarity code is: (+ for 0°, - for 180° phase): sweep 1 (0°), sweep 2 (180°) the polarity code is **(+ , -)**

Signal A is recorded from Vib I, signal B from Vib II.

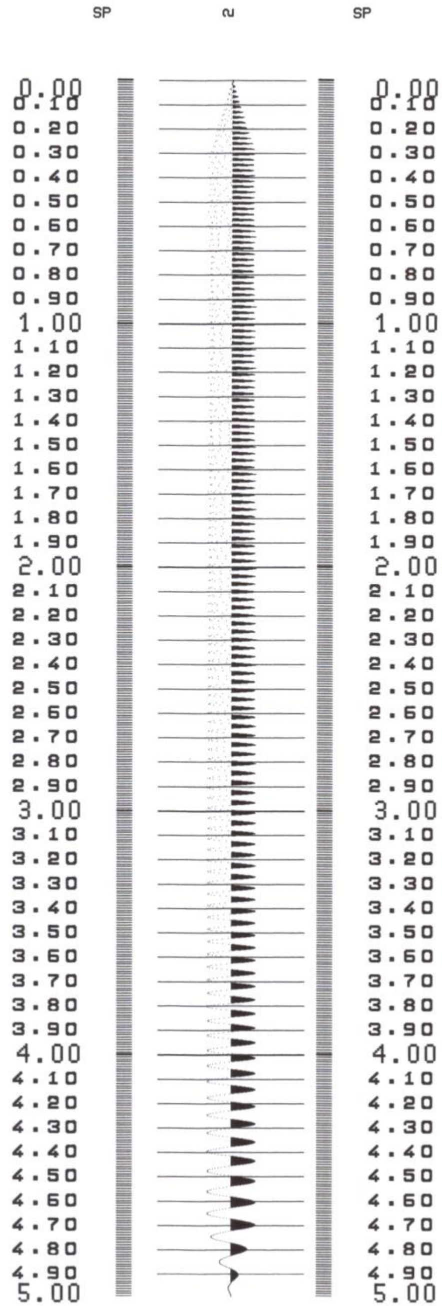
Record R1 = A + B
Record R2 = A - B

Signals from the two vibrators are separated at pre-processing stage, by computing:

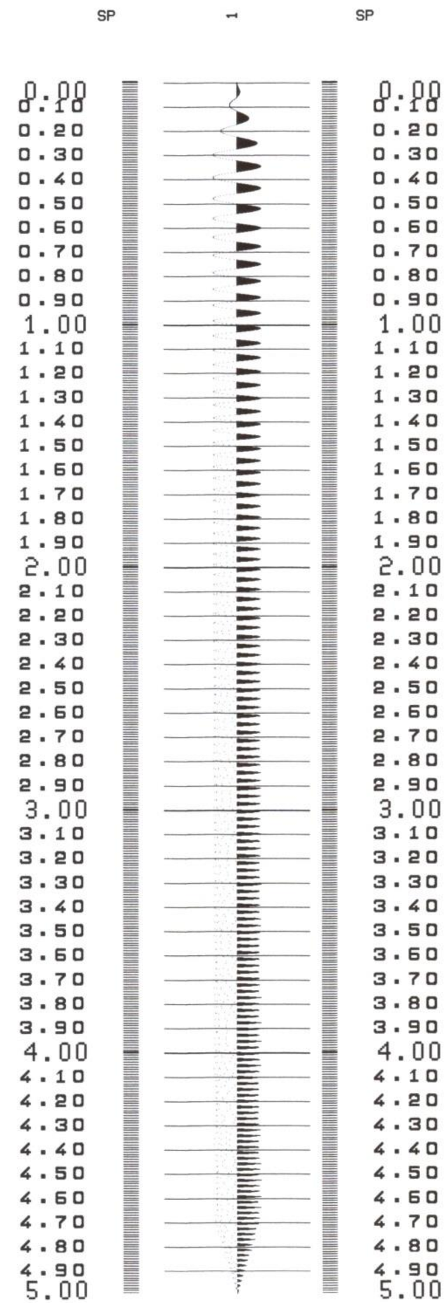
(R1 + R2) = 2A, to be correlated by upsweep 1
(R1 - R2) = 2B, to be correlated by downsweep 2

Thanks to the high repeatability of the vibrator sources, the signal separation can reach 55db
In practice, signals differing by an amplitude factor of 10 (20db) to 100 (40db) can be nicely separated.

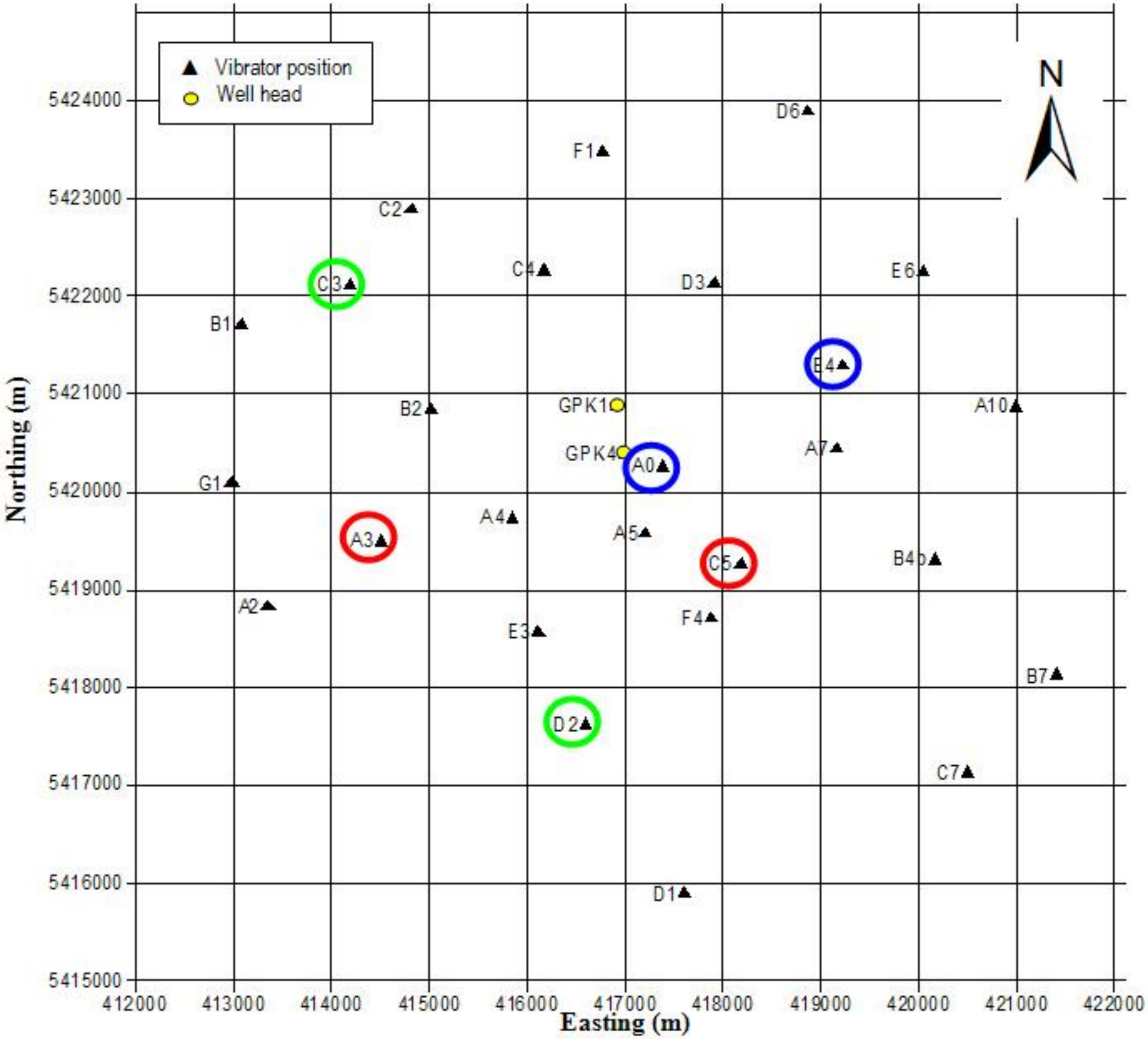
DOWN SWEEP 48-8



UP SWEEP 8-48

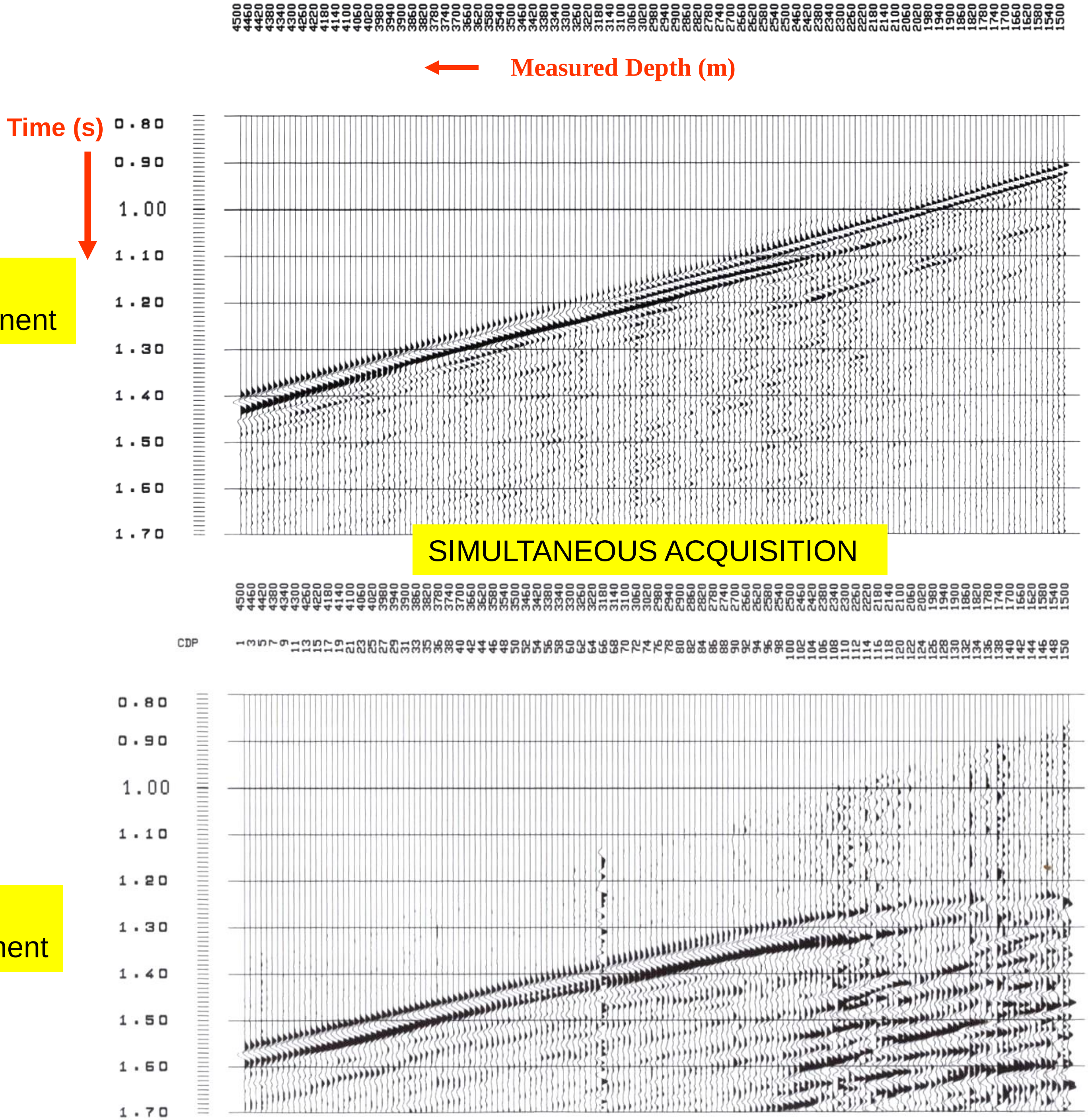


Simultaneous Vibroseis acquisition principle



GPK4

Vibro A0
Z Component



SIMULTANEOUS ACQUISITION

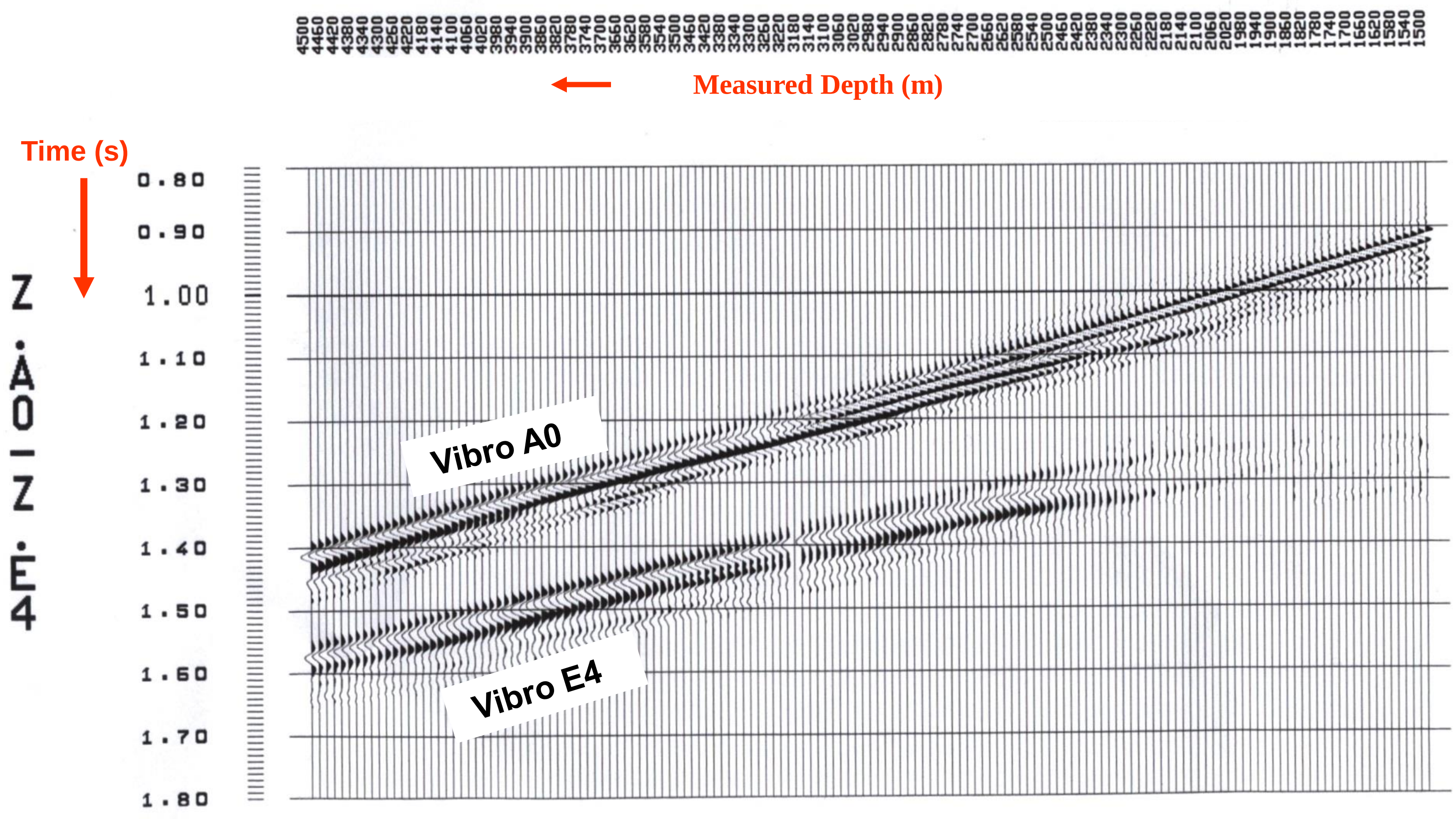
Normalized amplitude

Vibro E4
Z Component

Illustration of Signal Separation

Direct arrivals from the simultaneously activated vibrators

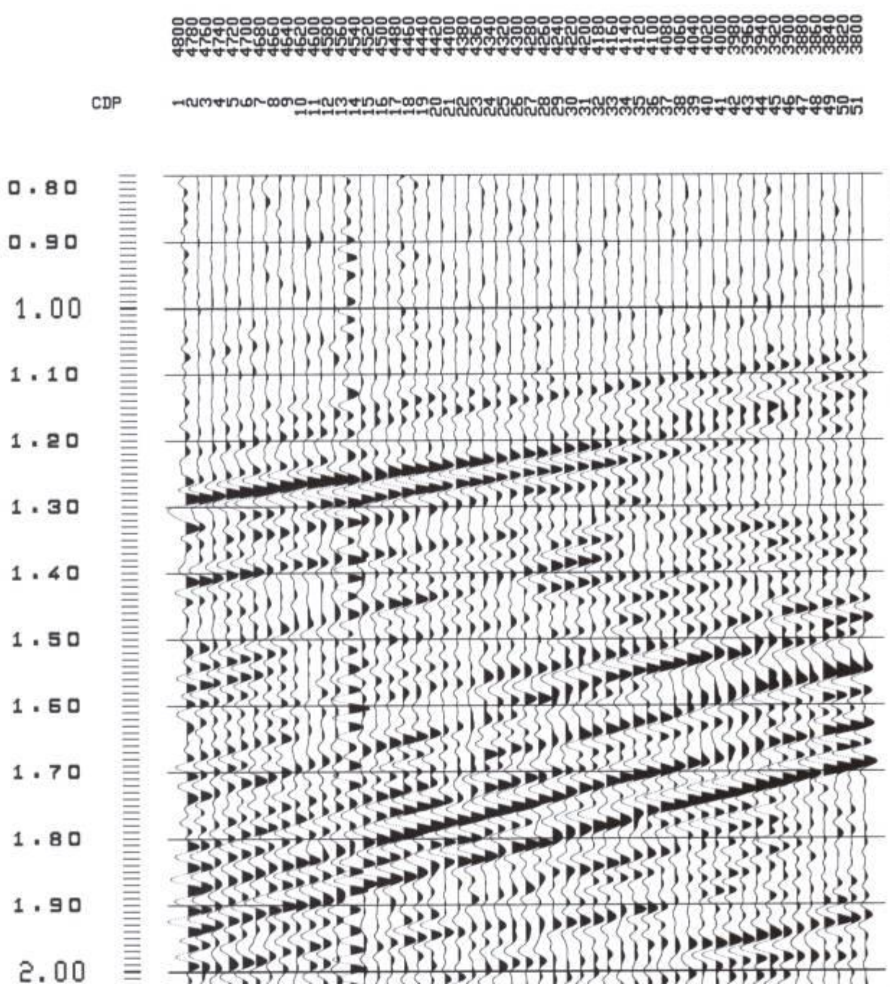
Superimposed at same time scale; Vertical Component



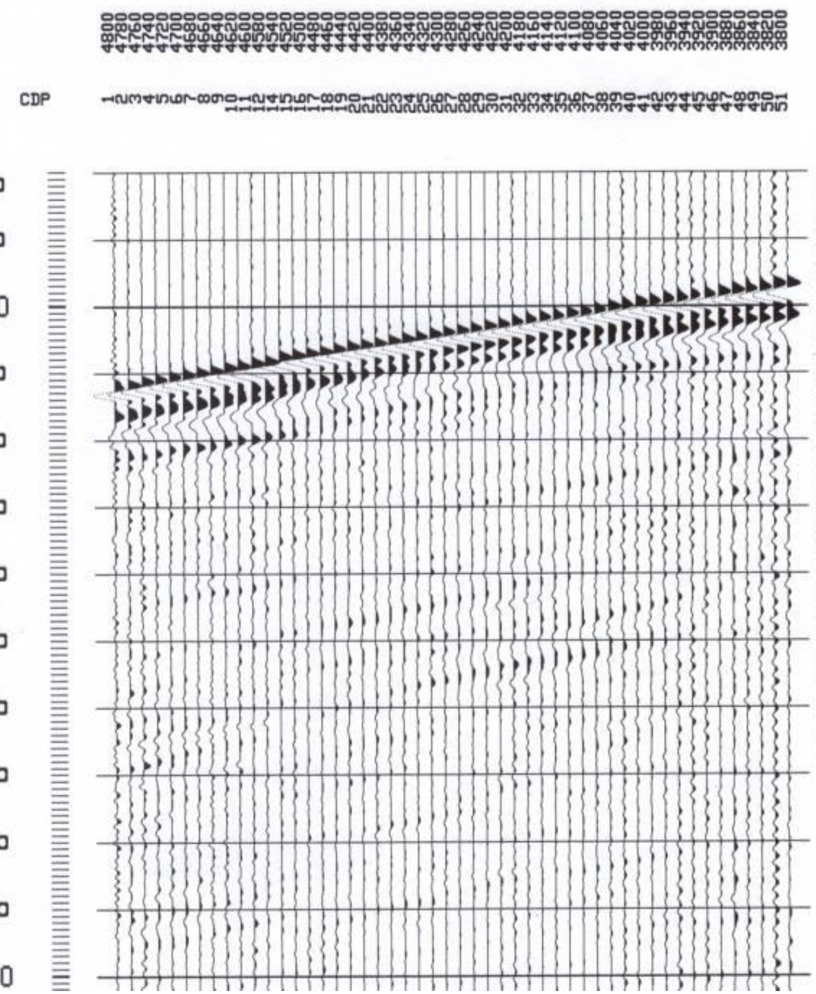
True amplitude

GPK3

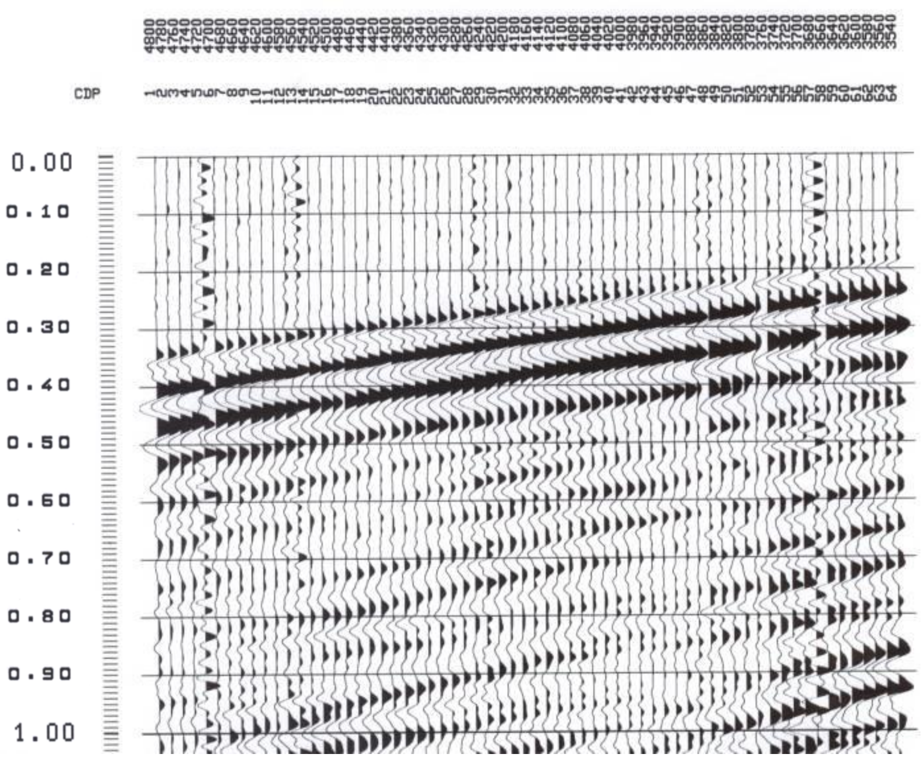
VIBRO-A3 HC45HZ GPK3



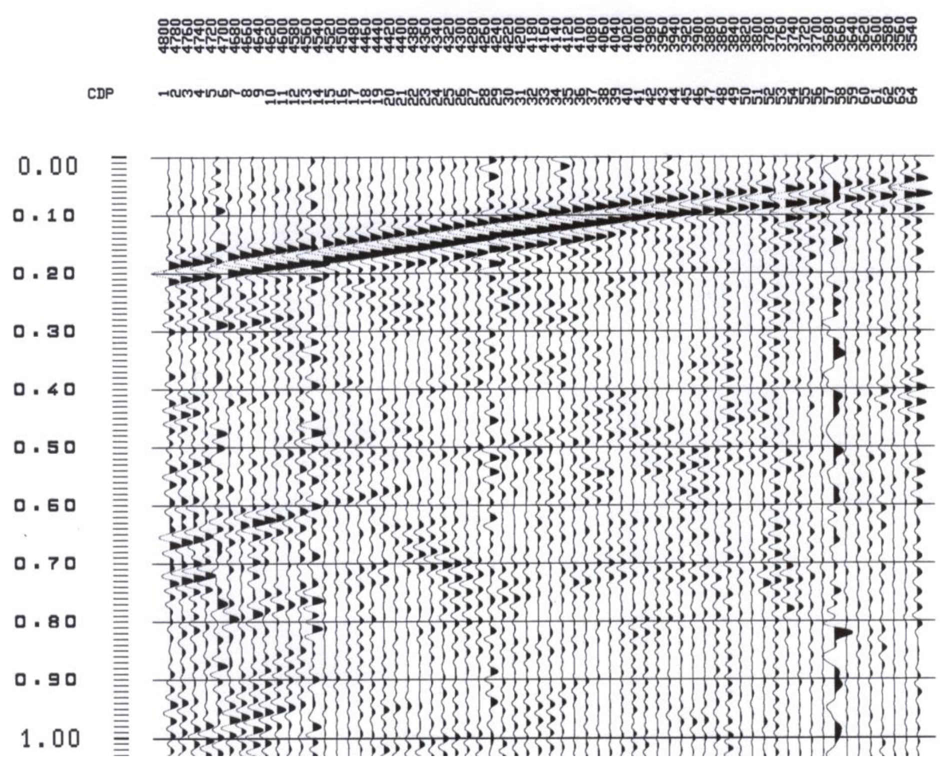
VIBRO-C5 Z,X,Y, WELL GPK3



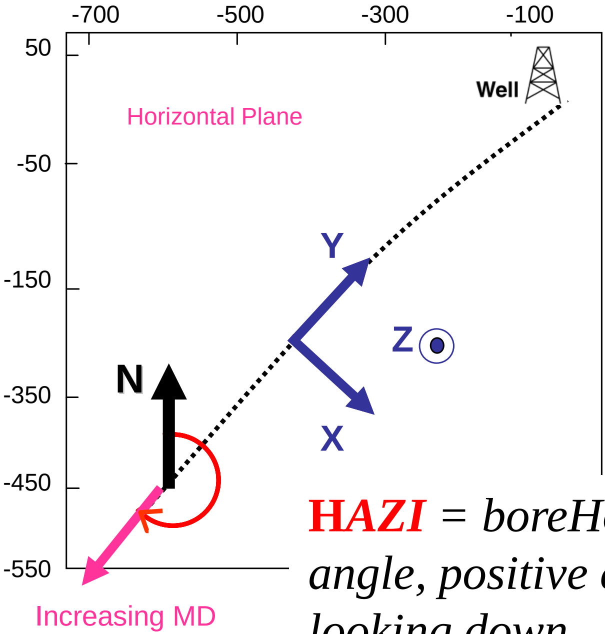
VIBRO-C3 Z,X,Y,HY WELL GPK3



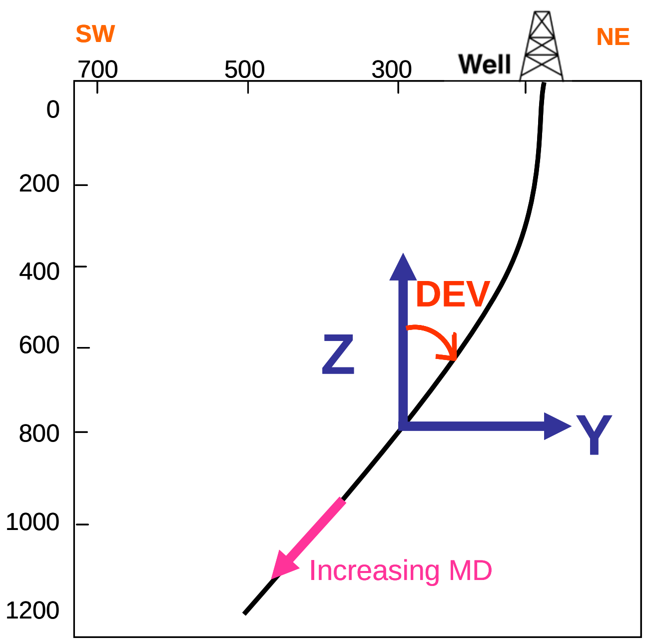
VIBRO-D2 Z,X,Y,HY WELL GPK3



VSP tool used for acquisition

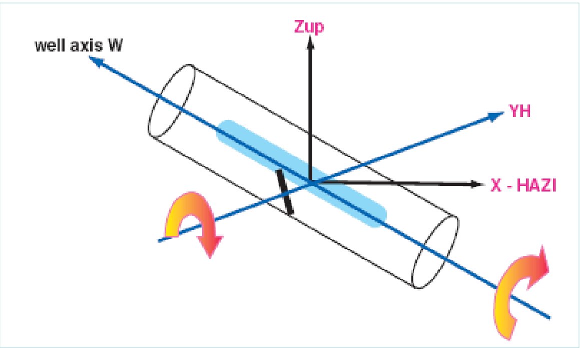


HAZI = *boreHole AZImuth angle, positive clockwise, looking down*



DEV = *Vertical deviation angle*

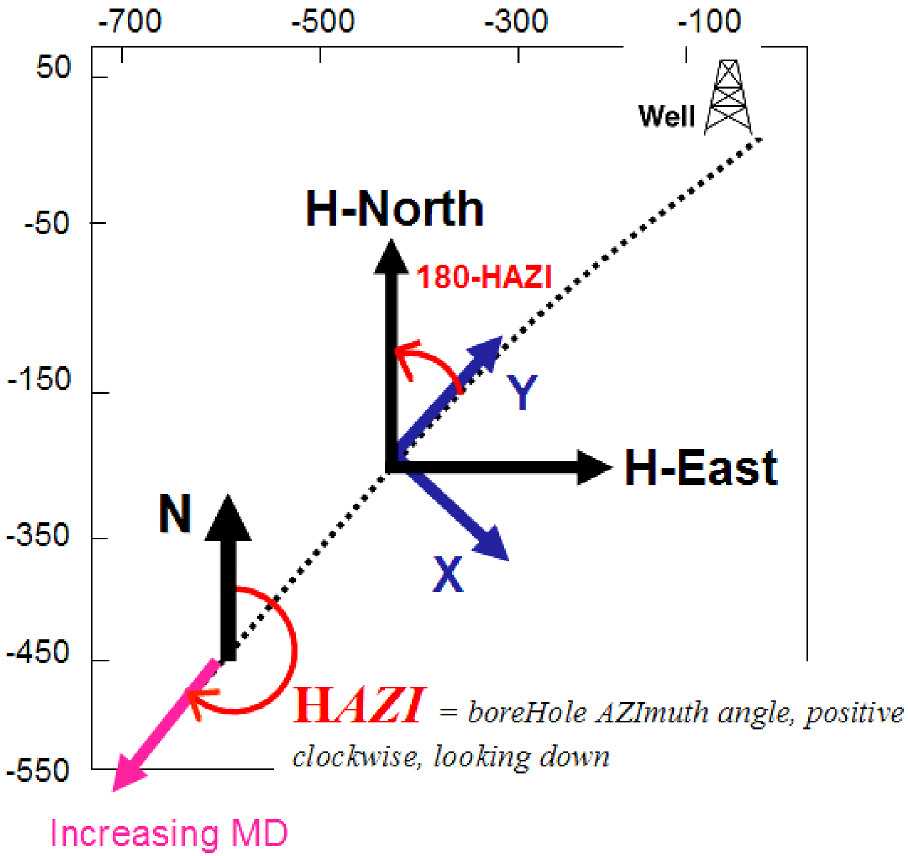
ASR VSP Tool polarity convention with 3C mounted TRUNNION gimbal setting

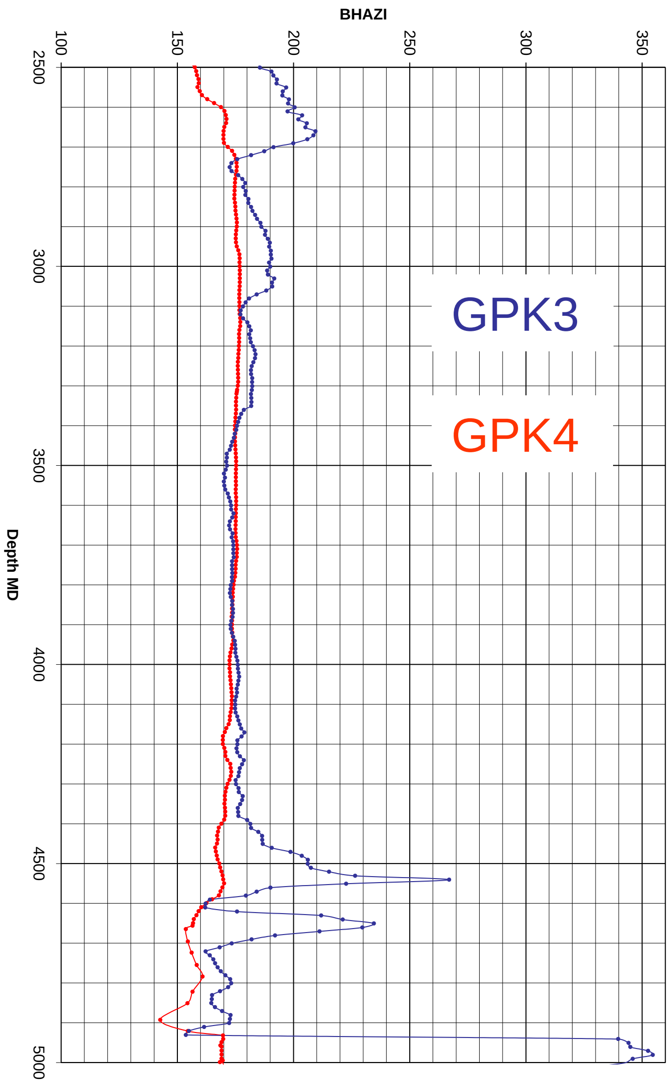


One gimbal is free to rotate around the VSP tool axis (W), the other gimbal is free to rotate around the horizontal axis (YH) orthogonal to the well deviation vertical plane. X-HAZI is oriented toward Hole AZimuth direction (360°).

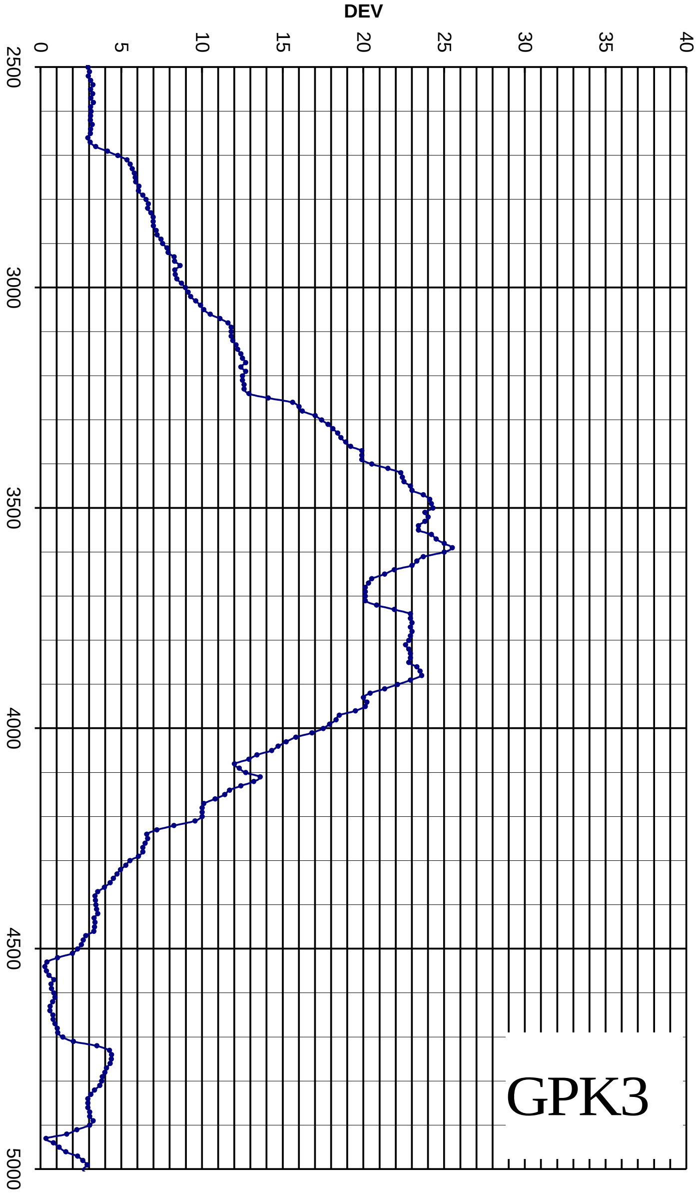
Display of oriented 3 components

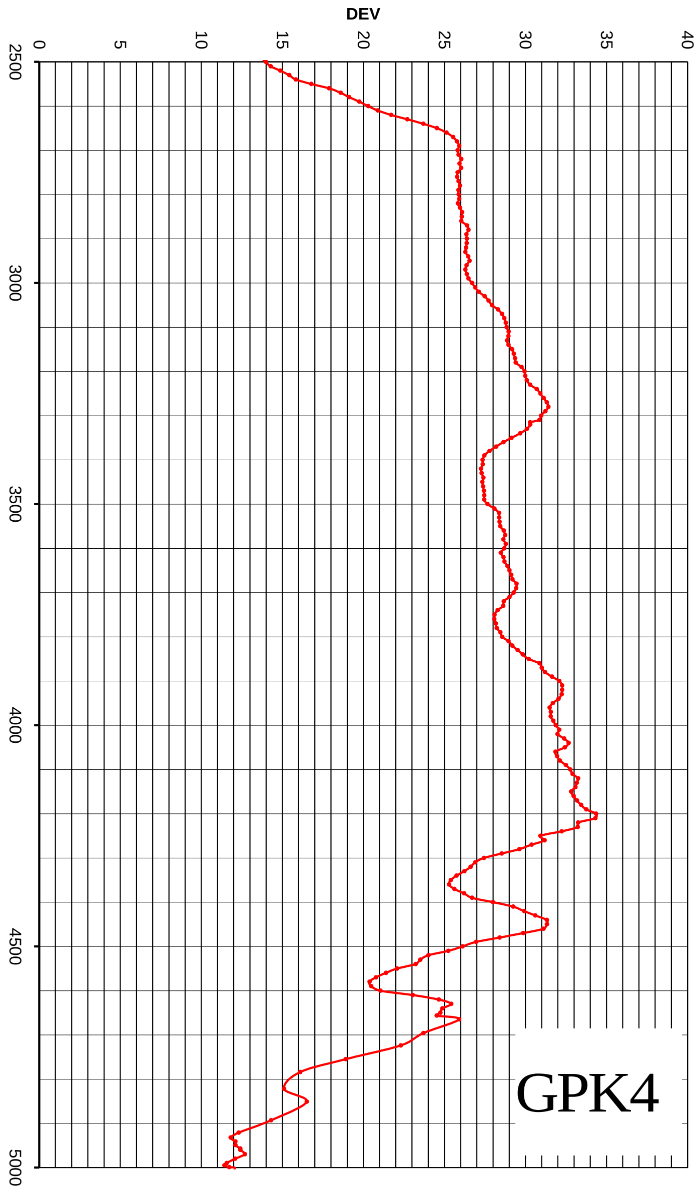
After rotation of horizontal components Y and X by an angle of 180°- HAZI, (HAZI = BoreHole AZImuth)





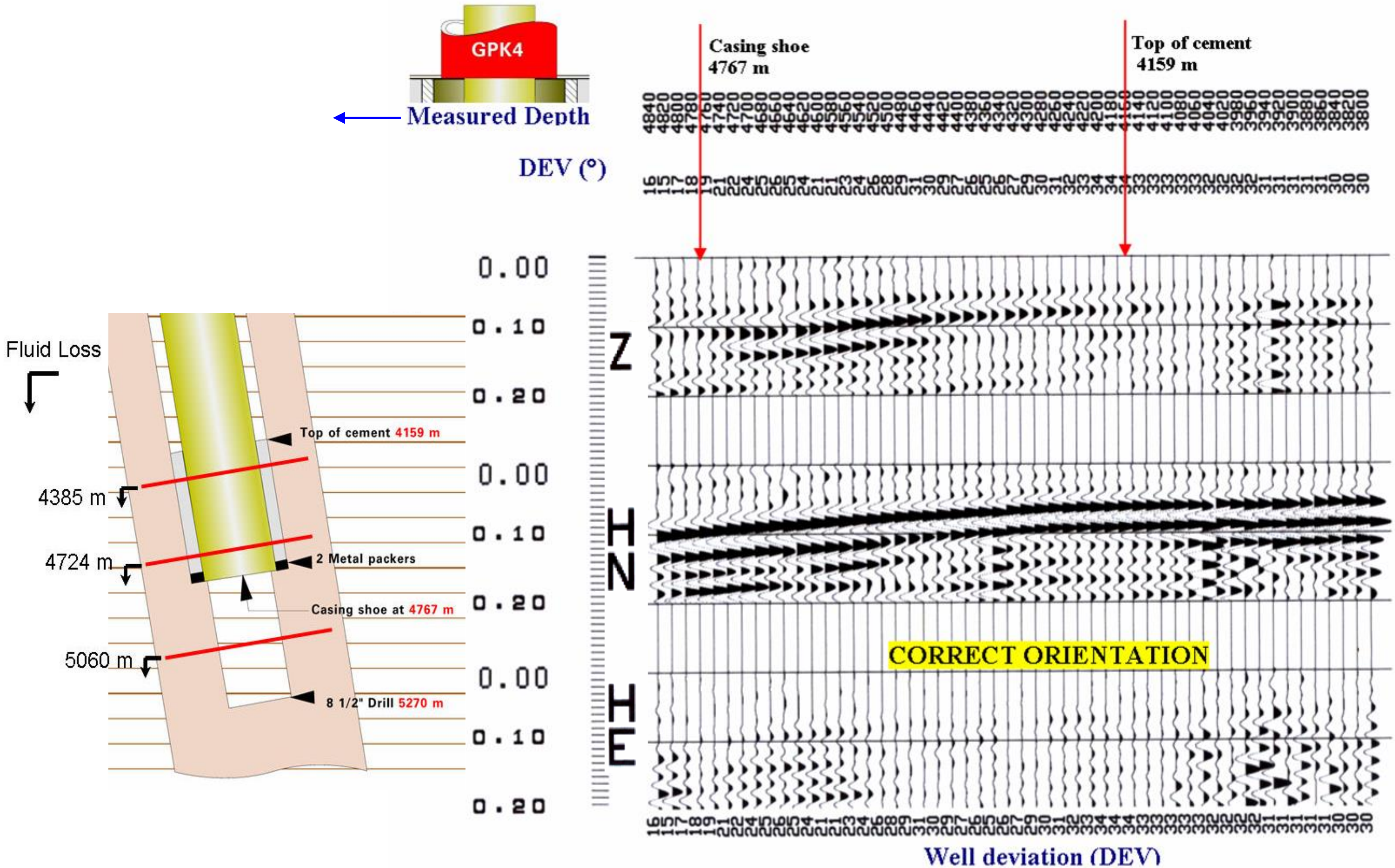
Vertical Deviation (°) in GPK3 and GPK4 (2500-5000 m).



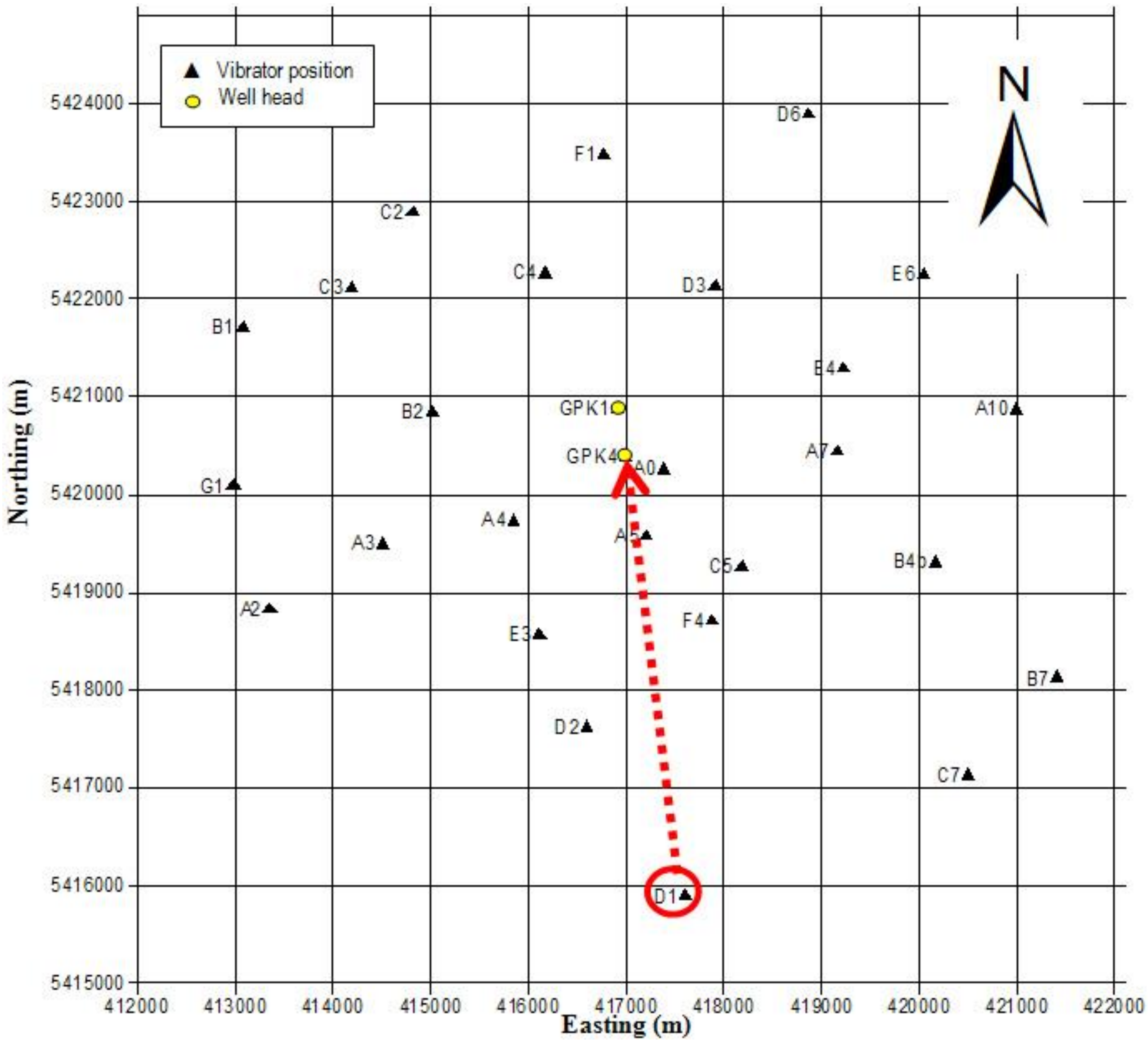


Display of oriented 3 components

After rotation of horizontal components Y and X by an angle of 180°- HAZI, (HAZI = BoreHole AZImuth)



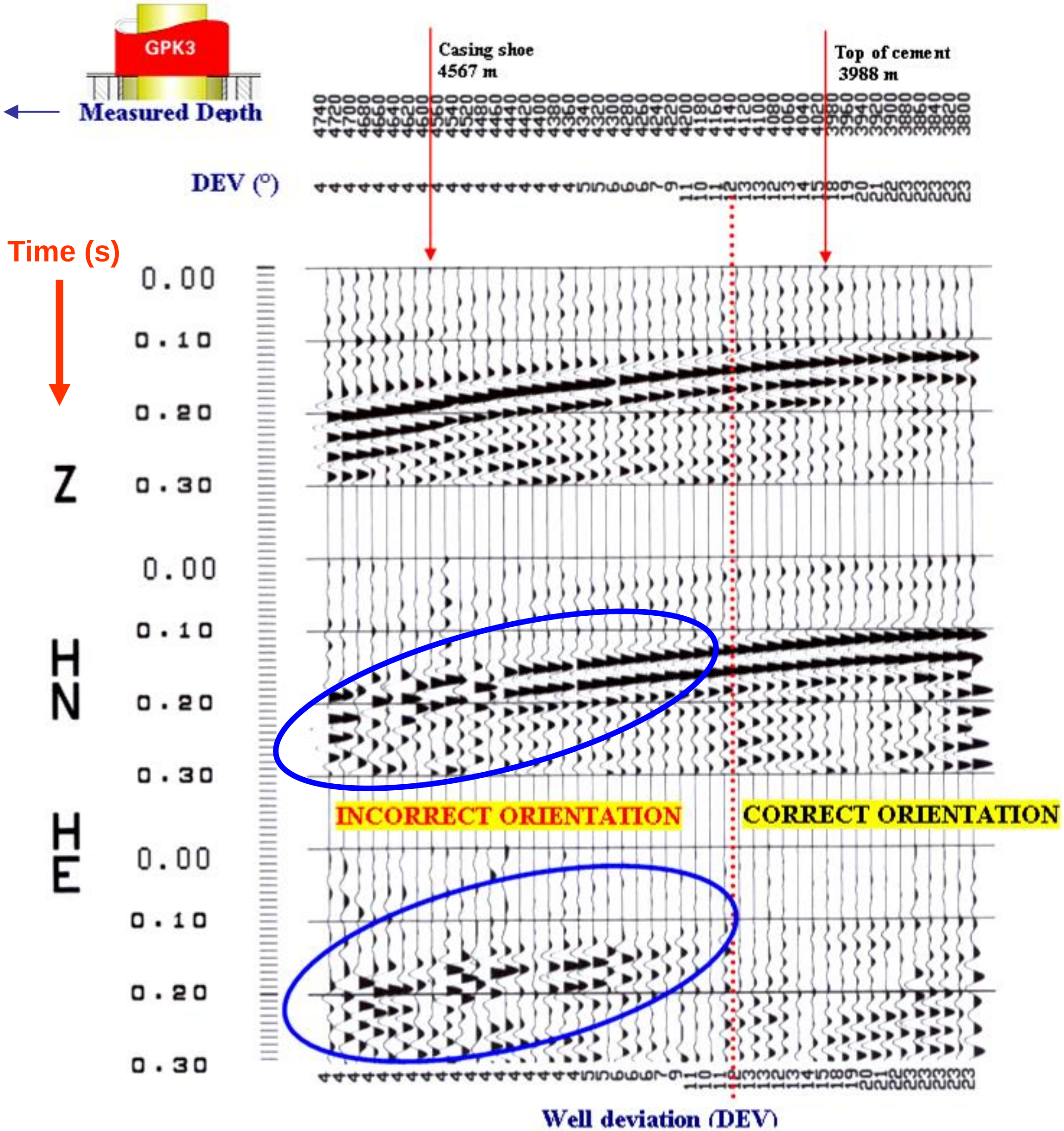
3C VSP data are correctly oriented where the well DEViation angle DEV is sufficiently large (here **DEV >16** degrees).



One can observe that the direct P-wave
is mostly polarized linearly in the North-South vertical plane.

Display of oriented 3 components

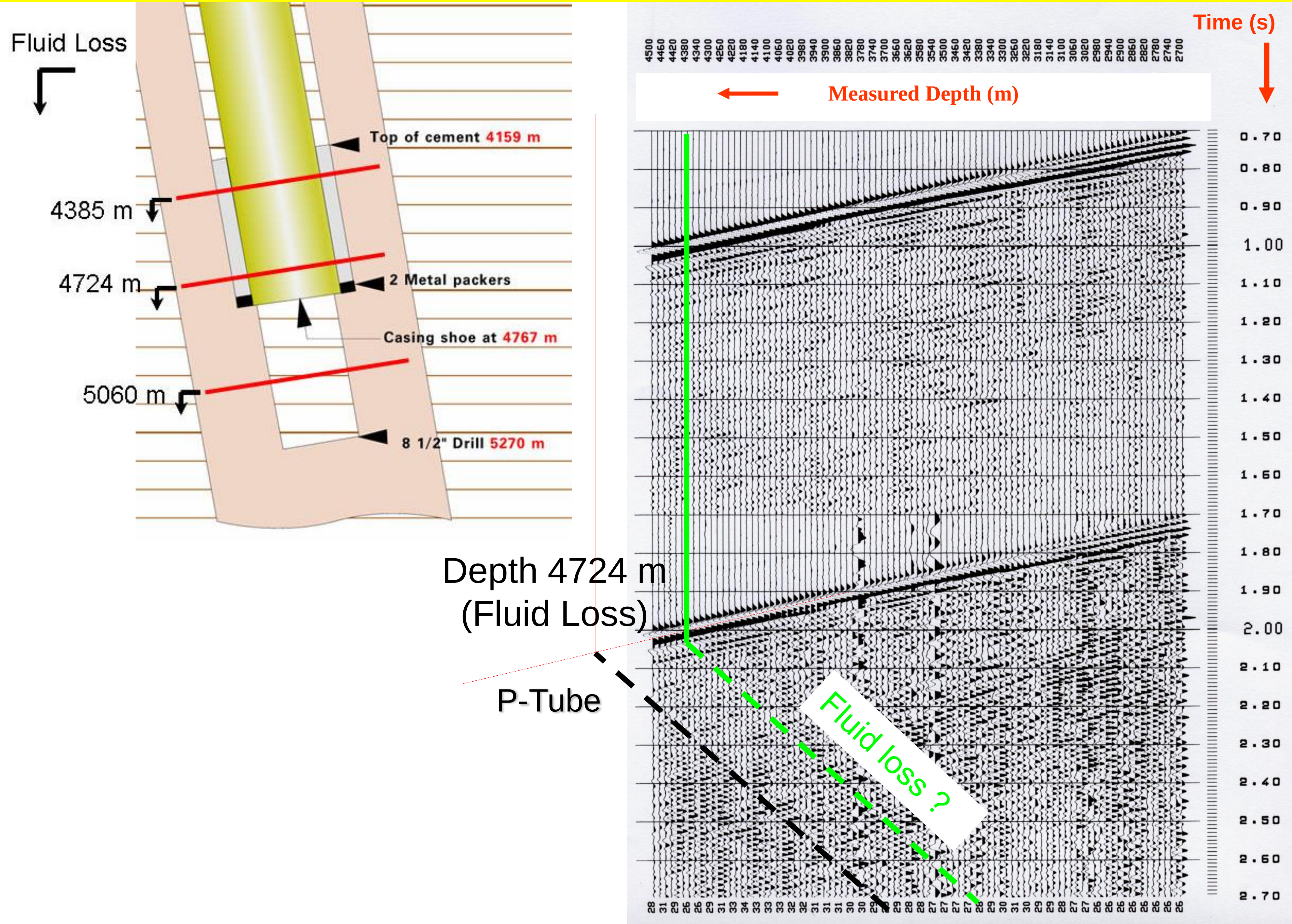
After rotation of horizontal components Y and X by an angle of 180°- HAZI, (HAZI = BoreHole AZImuth)



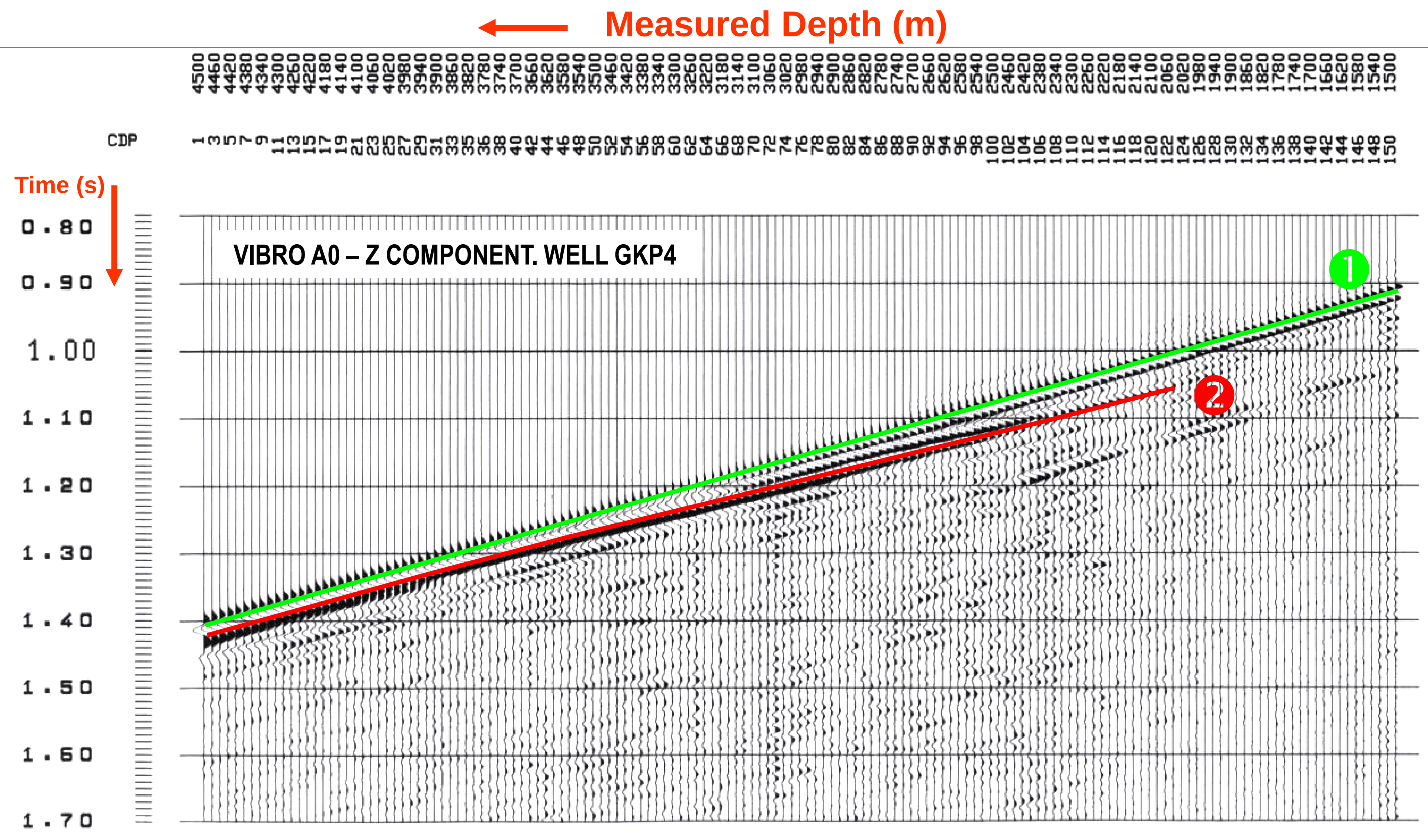
High amplitude residuals on HE component means that the gimbals did not rotate for lower values of well deviation **DEV <12°.**

FIRST GEOPHYSICAL OBSERVATIONS

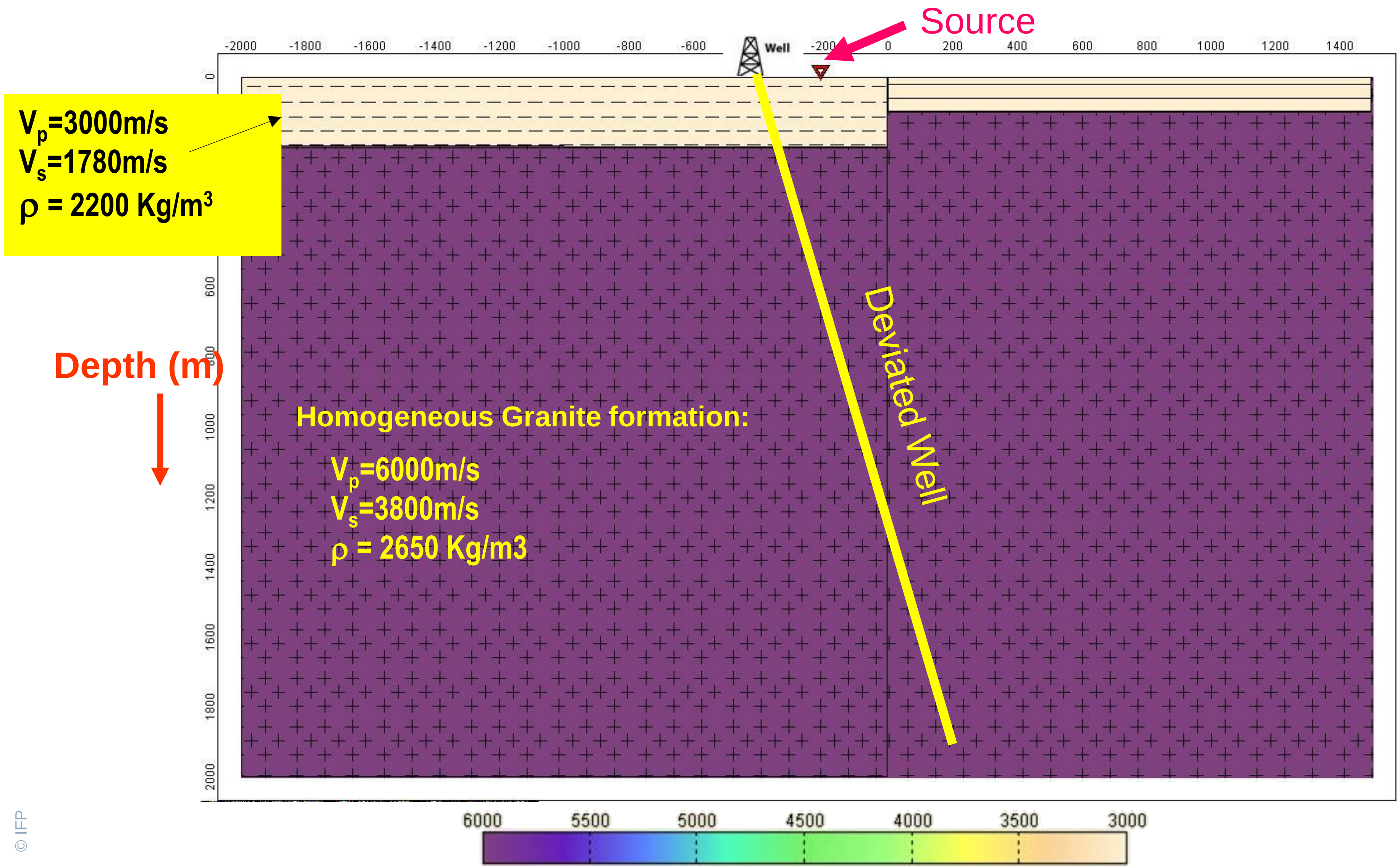
P-Tube converted arrivals



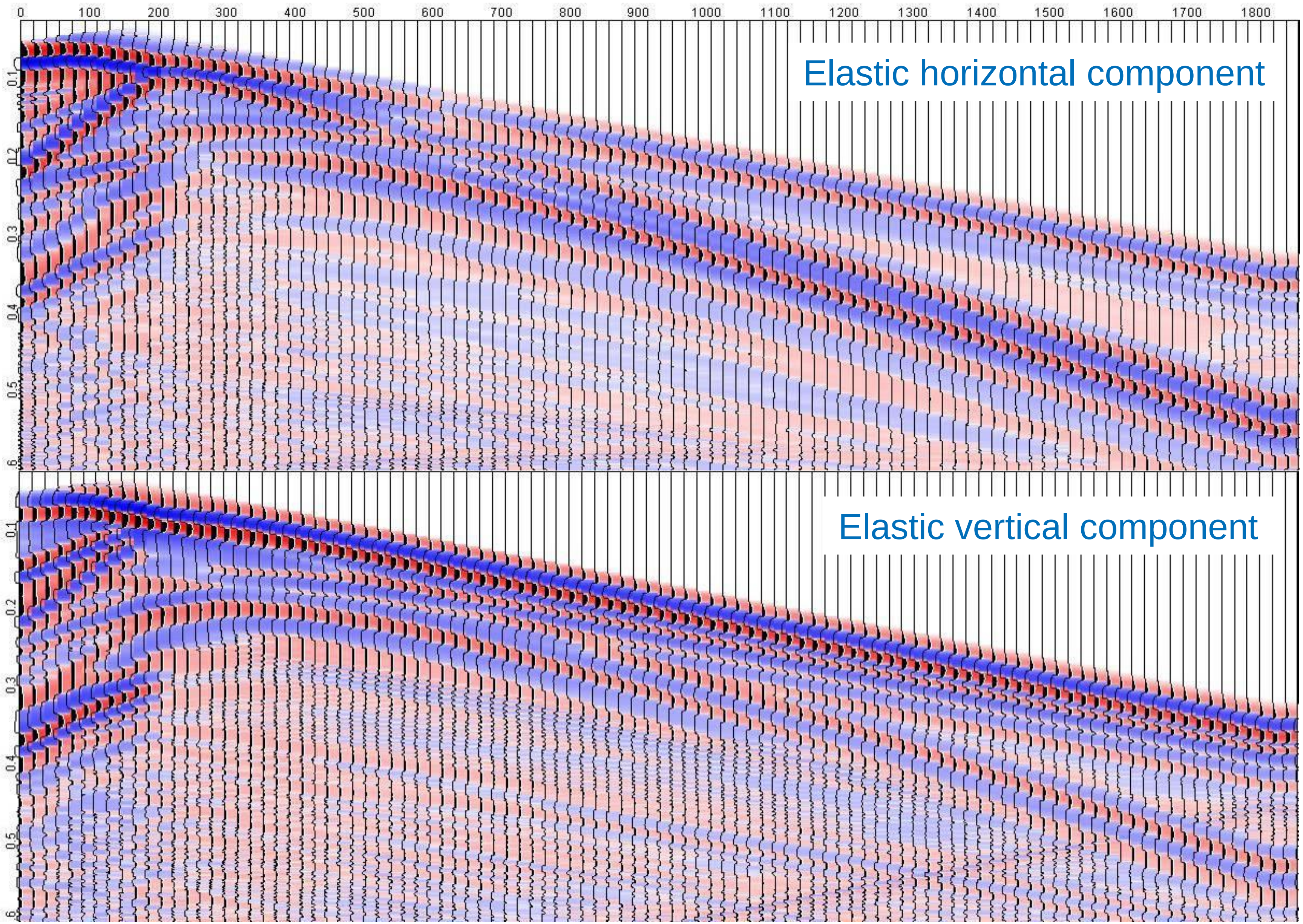
Double arrival typical of refraction arrivals **along a major fault**, or simply occurring from an additional seismic path generated by the presence of a step-like structure at the top of the crystalline basement.

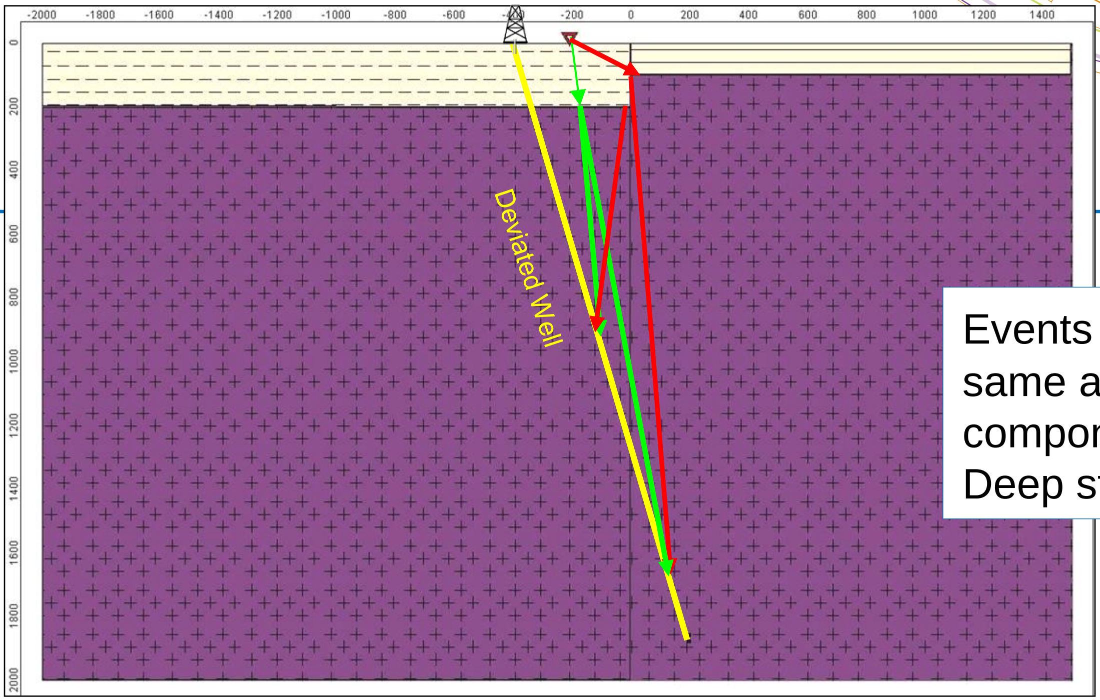


Model 1. Fault Model Without Velocity Contrast

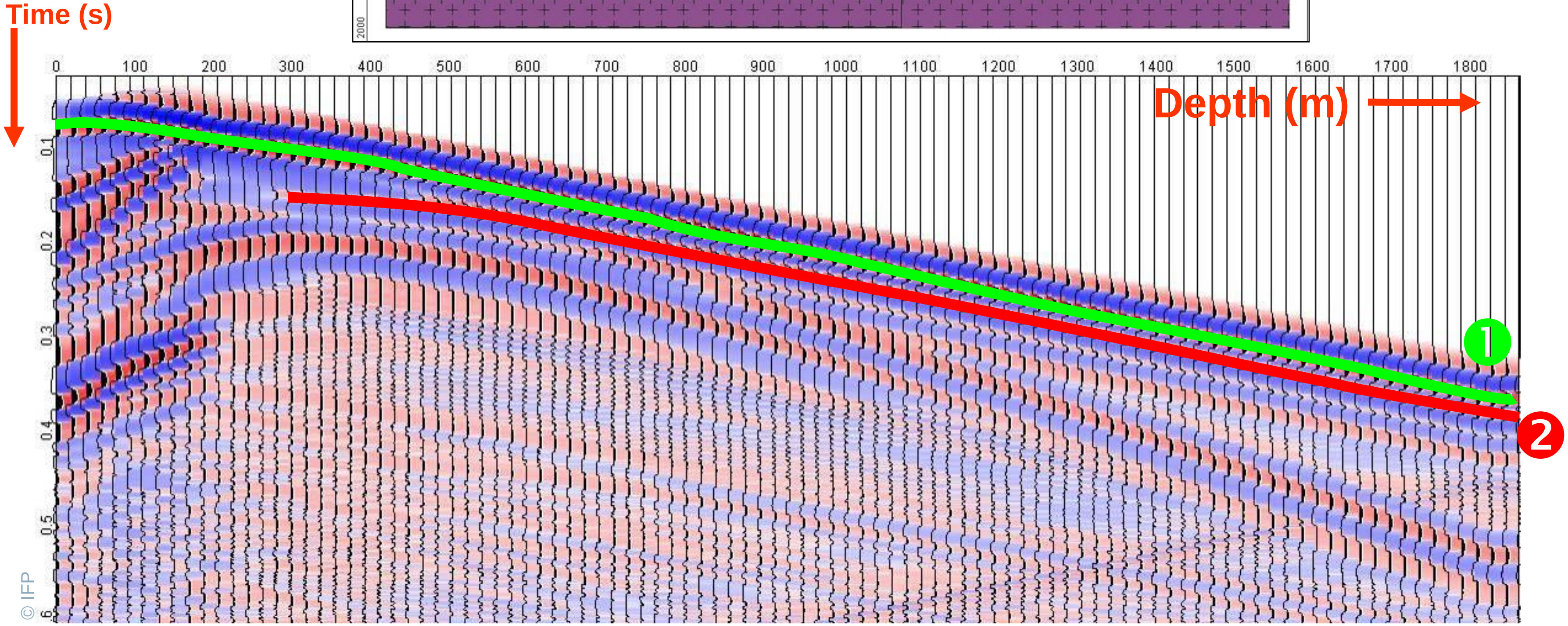


Model 1. Fault Model Without Velocity Contrast



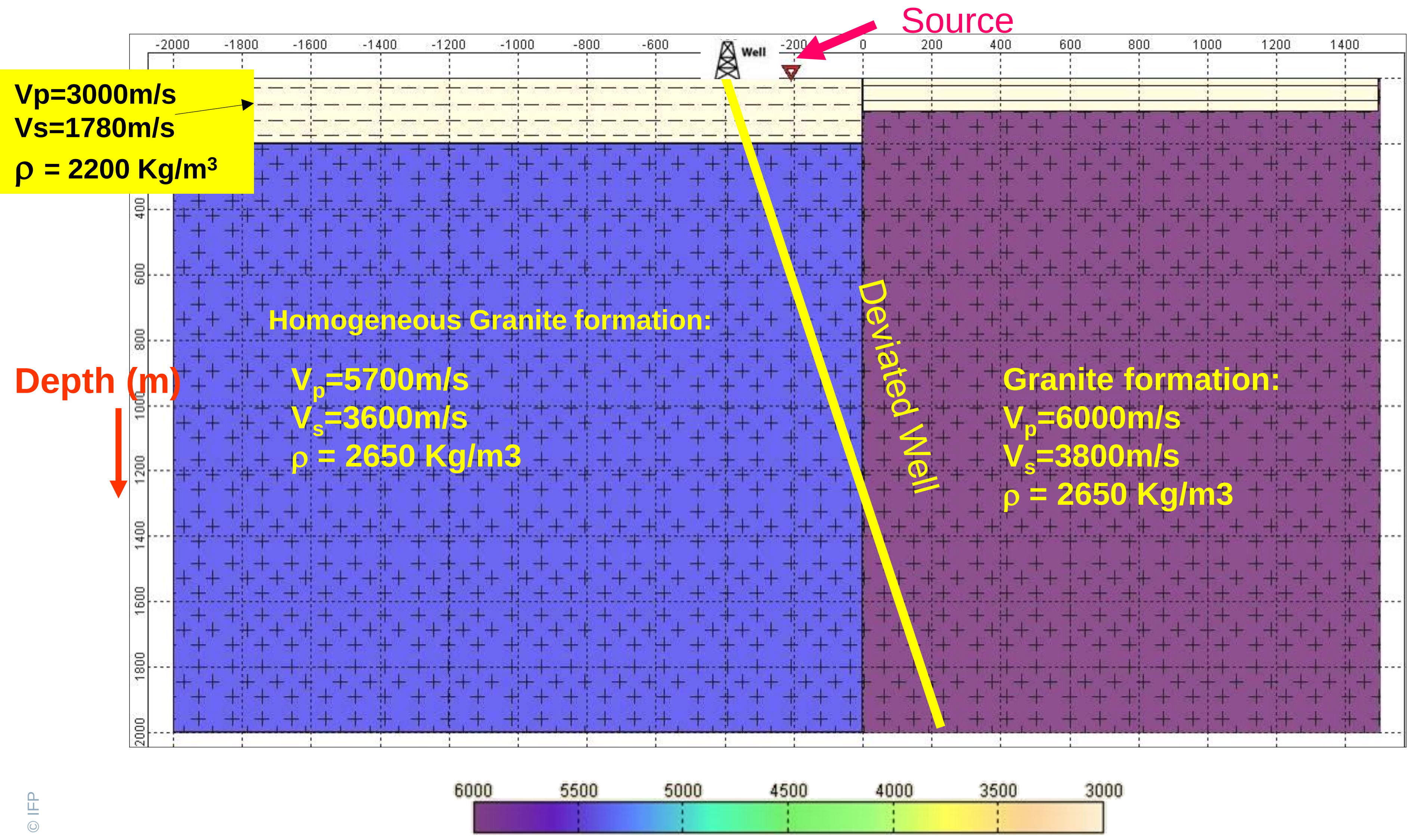


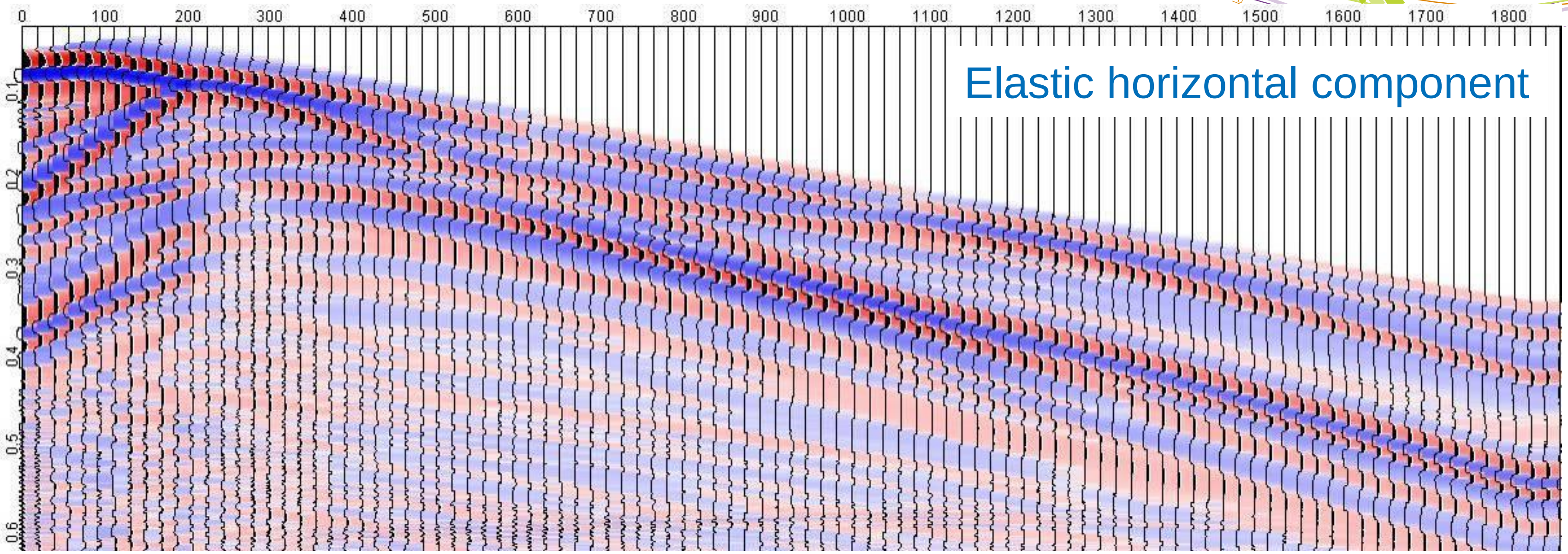
Events ❶ and ❷ with same apparent velocity component.
Deep station >1000 m



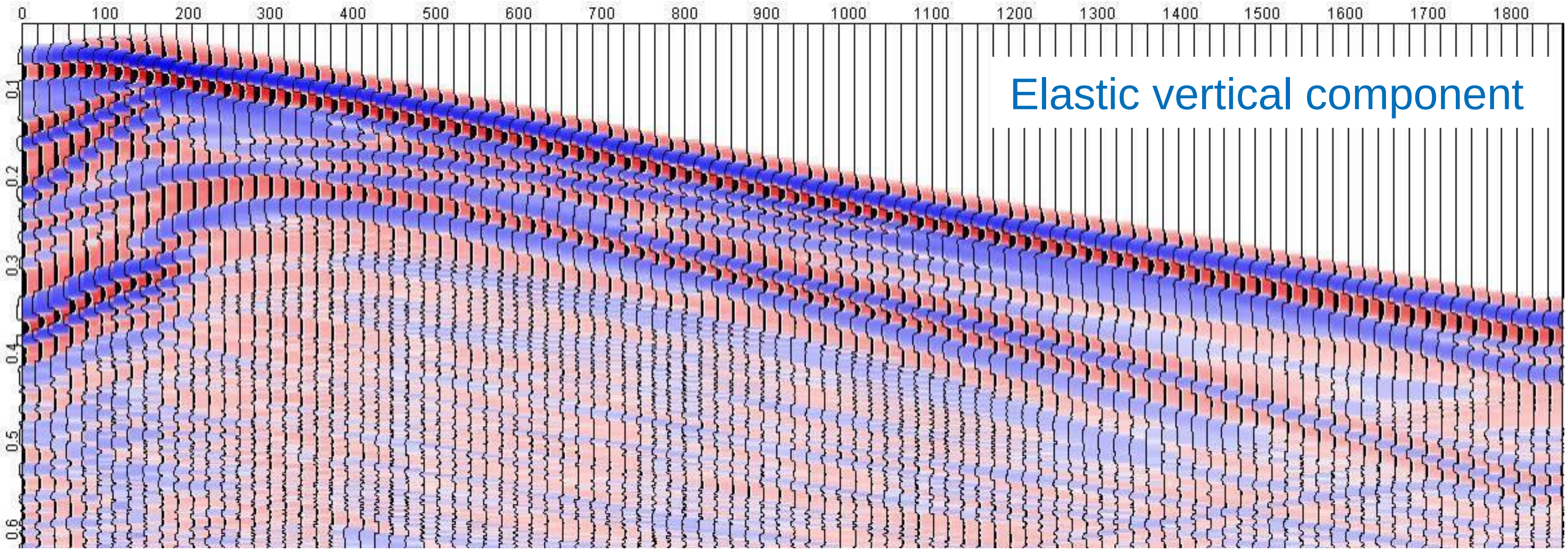
Elastic vertical component

Model 2. Fault Model With Velocity Contrast

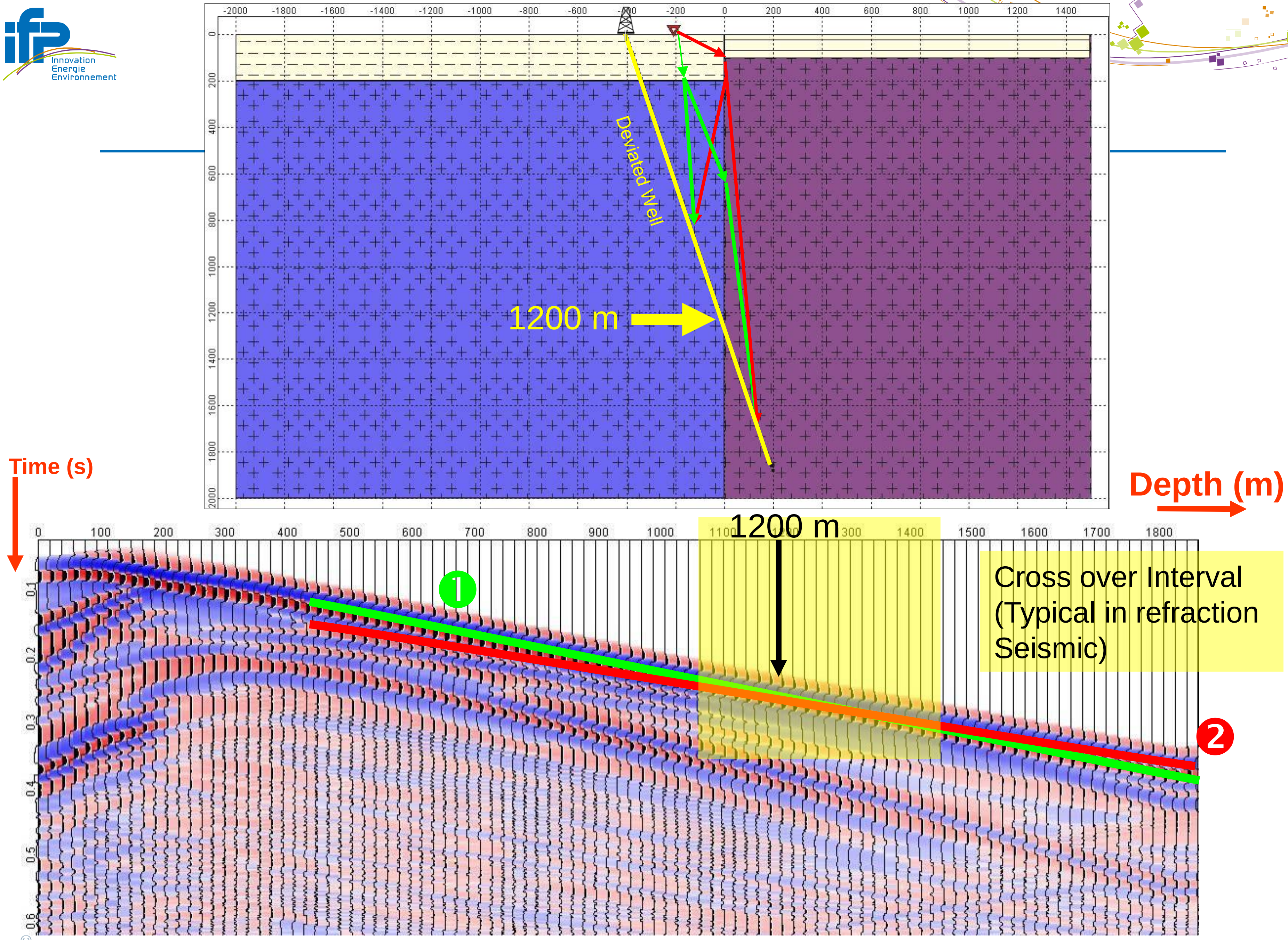




Elastic horizontal component

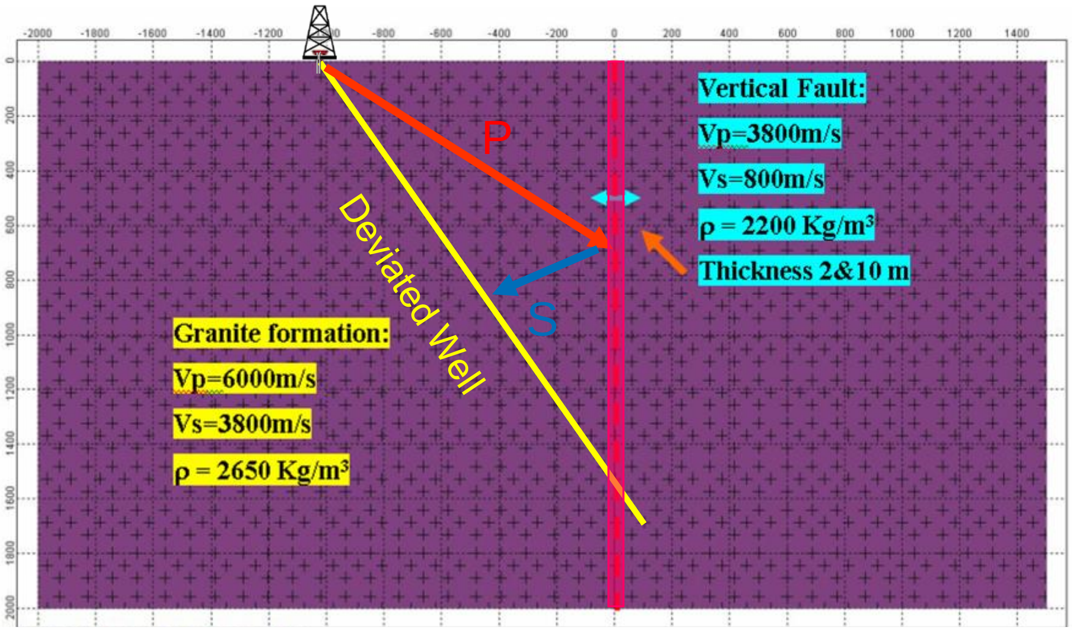


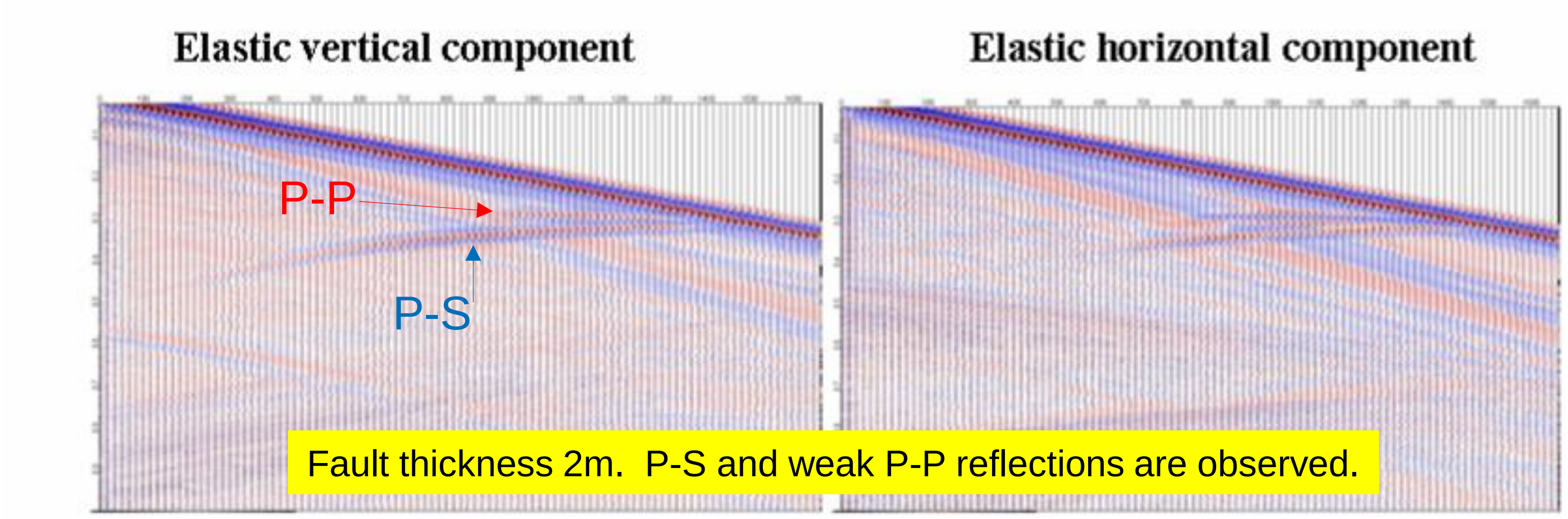
Elastic vertical component



Elastic vertical component

Model 3. Vertical Fractured Corridor in homogeneous granite





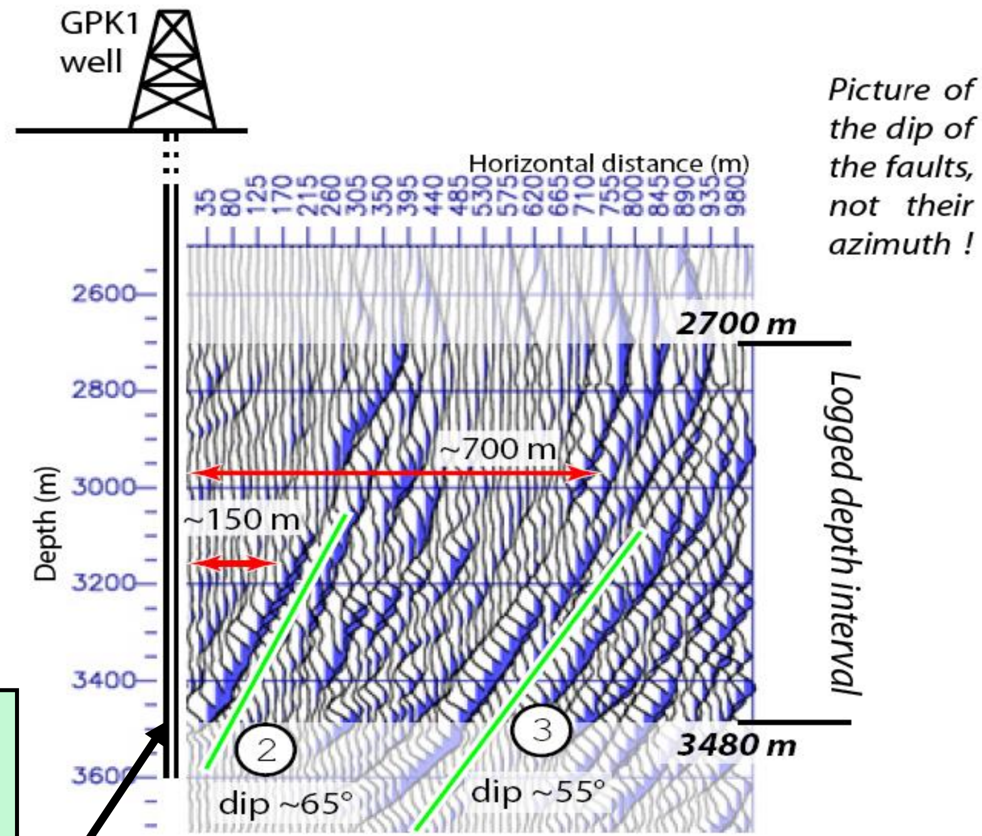
Fault thickness 2m. P-S and weak P-P reflections are observed.

SOULTZ DEEP GRANITE BASEMENT GEOTHERMAL SITE

SELECTIVE reflection imaging of highly dipping permeable fault **in CONVERTED P-S MODE ONLY,** using **oriented three component** Vertical seismic Profiling (**VSP**).

Result from well GPK-1(ref; Poster presented in *Workshop ENGINE, Potsdam* (PLACE J. *et al.* *November 2006*).

2D depth migration of converted P-S reflections on vertical component
(azimuth of image undetermined)C



The dip of the structures can be read directly on the depth migrated seimic image at a scale 1:1.

Fault intersecting the well at depth 3490m,
Permeability is confirmed by Flow logs,
65°DIPvalue is confirmed by the UBI log

CONCLUSIONS

Innovation Energie Environnement

Conclusion

- A correct orientation of the 3C with gimballed geophone/trunnion setting seems to be obtained with well DEViation DEV angle value larger than 12°

- Double arrival typical of refraction arrivals along a major fault, or an additional seismic path generated by the presence of a step-like structure at the top of the crystalline basement.

- Unexpectedly, very few P-tube converted events are observed in the open hole section, in relation with known permeable fracture/faults intersecting the well.

Conclusion

- The 2D finite element seismic modelling of a thin permeable fault :
  - P-P and P-S reflection at high incidence angle
  - Necessary to have a velocity contrast across a highly dipping fault in order to generate a secondary refracted arrival and a crossover between the arrivals propagated in both fault compartments

Conclusion

- The pre-processing of the VSP data acquired with simultaneous acquisition technique with several vibrators (2 wells + 2 vibrators sources here) can be achieved in a quick and timely manner.

- Modern vibrator encoder/decoder electronic boxes enable reliable orthogonal encoding of several vibrators activated simultaneously

Thank you for your attention

Innovation
Energy
Environment

Appendix-1: P-Tube conversion events

Observation and proposal by C. Naville, 2007

HYDROPHONE VSP OBSERVATIONS

P-Tube conversion signal on a downhole hydrophone sensor in a borehole

ASSUMPTION: A permeable fracture geometry is assimilated to a plane within a radius around the well, how the fracture dip could be determined using a multi-azimuth/multi-offset VSP technique.

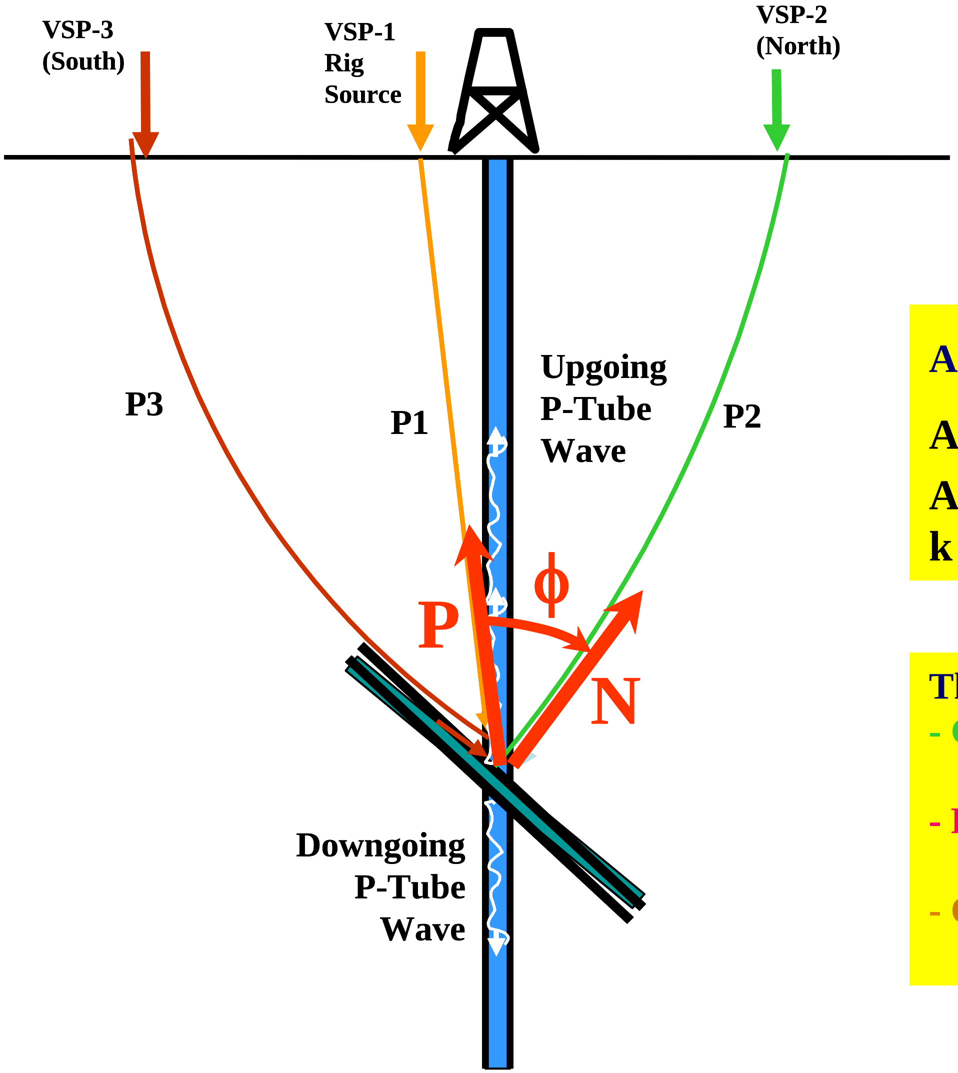
The tube wave pressure***,*** measured by a downhole hydrophone, and generated from a permeable fracture pressured by an incident P-wave with displacement velocity vector ***Up*** , measured by oriented 3C geophones, and propagating along a direction P making an angle θ with the vector normal to the plane fracture N, is proportional to the product : ***Up cos***θ : (<u>sketch on next slide</u>).

We start from the expression of the fracture displacement at the intersection depth of the hole by the fracture : $\zeta 0 = Up \cos\theta$

WARNING: Above mathematical expressions NEED to be fully revised.

Sketch of principle

Possible determination of the Dip of permeable fractures from from P-Tube converted waves from multi-offset 4C-VSP in open hole



Angle $\phi_i = (N, P_i)$

Amplitude of P-Tube wave:

$A(Tube_i) = k. A(P_i) \cos(\phi_i)$

k = cste depending on permeability

Thus, on arrival to the 4C-VSP tool in the well

- Green ray at normal incidence:

maximal amplitude of the ratio A(Tube)/A(P)

- Red ray in the fracture plane

generates NO tube wave: A(Tube)/A(P) = 0

- Orange ray at intermediate incidence

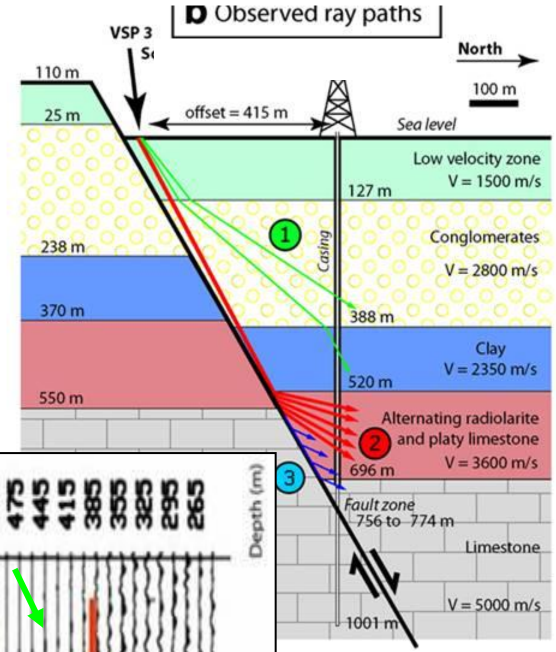
yields an intermediate value of A(Tube)/A(P)

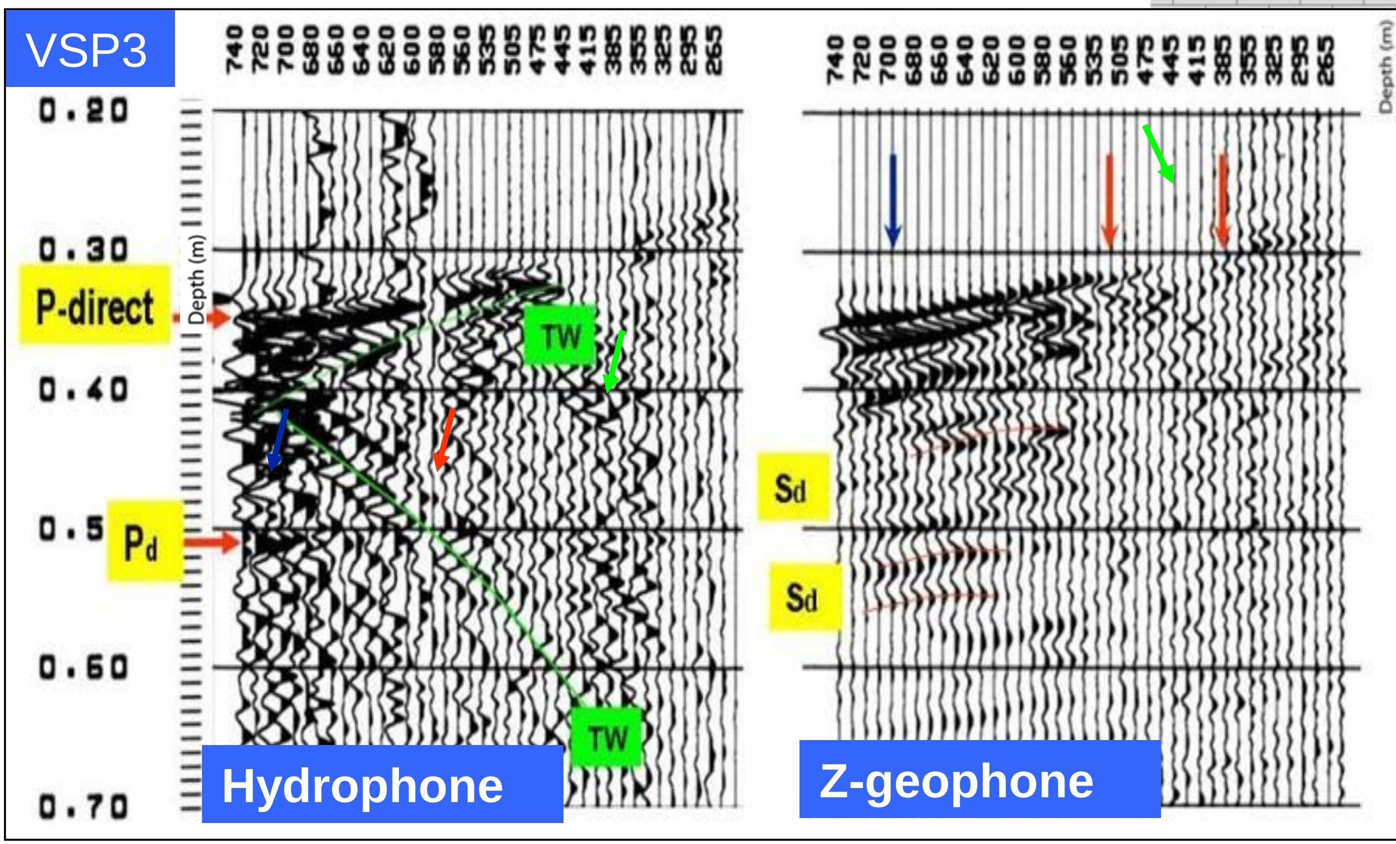
EU Scientific Drilling in Corinth, Greece:

VSP3, recorded with a 4C downhole tool, shows:

- On Z component, a very weak direct P wave arrival (1, green), + P - diffractions (2-red + 3-blue)

- On Hydrophone, P-Tube conversions (TW) are generated by permeable faults crossed by the well





Detection of Subsurface Fractures and Permeable Zones by Analysis of Tube Waves S23.5

W. B Beydoun, C. H Cheng and M. N Toksöz, M I T.

$$\frac{P^t}{P^\alpha} = C(L_0)\frac{w\beta^2\cos(\phi)[1-(c\cos(\vartheta)/\alpha)^2]I_0(nR)}{\cos(\vartheta)c^2\alpha[1-2(\beta\cos(\vartheta)/\alpha)^2]}$$

Where,

$\frac{P^t}{P^\alpha}$: tube wave to P-wave amplitude ratio

ϕ : angle between incident P-wave and borehole axis

Generated tube wave pressure amplitude in borehole fluid in the vicinity of the fracture

$\zeta_0 = u_p \cos\theta$

du_p/dt, or A(P), is the P wave arrival velocity obtained from oriented 3C geophone. $dup/dt = - i\omega u_p$, thus:

$p^T \sim i\omega$ OP. C(K) dup/dt $\cos\theta$

OP is the geophone to hydrophone transfer OPerator

Then, after deconvolution:

$p^T/A(P) \sim \omega$ C(K) $\cos\theta$

WARNING:

- ***Mathematical expressions of above MIT paper NEED to be re-formulated for a 3D situation.***
- ***Expressions in the green box on the right are a CONJECTURE.***

Appendix-2: recovering alternate polarity random glitches of a vibrator electronic unit on successive sweeps

Comment by C. Naville, 2007 : Simultaneous vibro acquisition requests the most reliable vibrator encoders

Example of same Z component after correlation of orthogonal signals and application of the corrective alternate polarity code.

Left: INCORRECT signal recovery   Right: CORRECT signal recovery