

HF/HR VSP acquisition, processing, and interpretation in the deviated section of the high-angle geothermal borehole of Grigny GGR5, targeting intra-Dogger thin, porous beds

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Abstract. Defining 5 m thin, or even thinner, porous reservoir beds was the feasibility objective assigned to the High Frequency/High Resolution (HF/HR) look ahead VSP survey to be recorded in the deviated section of a geothermal production well drilled down to the top of the carbonate Dogger aquifer in the Paris basin, around 1500 m in vertical depth, with a landing angle of 65°. The idea was to predict the depth of the first porous bed(s) to be drilled at a high angle, and to determine the minimal DLS (Dog Leg Severity) to be applied by the driller after setting a production casing at the top Dogger level and changing the drilling fluid composition, to avoid directional drilling with sharp angles. A 50–100 m vertical depth range was targeted for the acoustic impedance to be predicted below the top Dogger carbonate aquifer. Besides, a Pilot Hole (PH) was drilled prior to the high-angle leg to assess with full reliability the depth of productive thin beds to be subsequently drilled at a high angle. These actions were undertaken within a global R&D project named “SISMOSUB” aiming reservoir characterization, conducted by the reservoir and drilling engineers of GEOFLUID/GPCIP, in partnership with IFPEN, and partially financed by ADEME (French Agency for Ecological Transition). High Frequency (HF) VSP still represents a frontier seismic domain to investigate, for which technical difficulties are piling up: First, the surface fix source needs to be extremely repeatable and preferably deliver an increased amount of HF energy to compensate somehow for the higher loss of seismic amplitudes with high frequency. Second, the downhole receiver tool or tool string may not present constant vector fidelity of 3 component reception over the whole recording frequency range, mainly in high frequency, due to mechanical coupling characteristics of the VSP tool hardware and the open borehole ruggedness; in cased hole, the mechanical coupling of the VSP tool to the formation is insured by a good cementing quality between casing and borehole wall. Third, the physics of the seismic attenuation is not fully understood and depends on several factors, mainly viscoelasticity and heterogeneity, potentially variable in depth and laterally to the wellbore. Additionally, the geometrical spreading represents the main factor of amplitude decay, independent from frequency, and can be estimated at the processing stage. Surprisingly, the VSP image produced underneath the deviated hole section evidenced a faulted structure. A remarkable abrupt amplitude loss of high frequencies above 120 Hz occurs where the direct P-wave ray crosses one of the confirmed minor faults before reaching Total Depth (TD); secondary downgoing arrivals appear locally in-depth, mainly in the high frequencies, which are not strictly parallel to the first P-wave arrival...

Keywords: VSP, HF VSP, HF/HR VSP, 3C VSP, Look ahead VSP, Oriented 3C VSP, Welltie.

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1 Introduction and motivation for borehole seismic

The target assigned to the present HF VSP was to define reflections from intra-Bathonian porous beds, thinner than 5 m and currently below the surface seismic resolution, but locally reachable using the intermediate “look-ahead” VSP method for predicting reflectors below an intermediate drilled depth: in the present case, the ultimate feasibility objective of the look-ahead VSP survey was to define the depth of the upper porous bed to be drilled at high angle, so that the driller can plan a smooth curved borehole trajectory to reach it. Although very short processing duration was not required in the present case as drilling a deviated Pilot Hole was planned, the drillers wished to obtain from the VSP survey: i) reliable depth prediction information for their initial drilling target, and ii) a fair idea of how fast this information could be established after the end of the VSP survey, in view of similar future situation. A 1D layer earth model from the Ground surface to Dogger reservoir depth with little lateral variations was assumed, in the absence of any other detailed information from surface seismic. Neighboring wells previously drilled in the vicinity of the GGR5 wellhead location showed consistent, near horizontal top Carbonate Dogger depth, but fast lateral intra Dogger facies variations.

A previous geothermal doublet of 65° inclined boreholes was drilled in the Grigny-2 residential area: the first well GGR1 was successfully producing a water flow of 300 m³/h, while it was not possible to inject more than 100 m³/h in the second well GGR2, mainly due to insufficient porous reservoir thickness. The impact points of these two wells at the top Dogger reservoir depth were 1500 m apart in horizontal distance (Fig. 1).

Therefore, a third deviated well GGR3 was drilled into a different azimuth from the Grigny-2 platform and successfully remedied this unfavorable situation. The measured wireline logs GR, Sonic, Density and Neutron porosity (variable area blue fill above 10% porosity) of the three wells are produced on Figure 2, evidencing rapid lateral facies variations in the Dogger carbonate reservoir, south to the new well doublet GGR4-GGR5 to be drilled (Fig. 1).

Then, a borehole survey comprising an HF VSP survey and sparker source tests was envisioned in 2021 as an R&D feasibility project to be partially funded by ADEME. Besides, a pilot Hole (PH) was planned to be drilled and partially cored prior to drilling the high-angle producer Sub-Horizontal (SH) drain, so that the seismic predictions “ahead of the bit” could be verified.

The drilling operator and reservoir engineers wondered how these lateral variations could be detected by P-P seismic reflection, mainly by surface seismic, prior to drilling, which motivated the construction of synthetic seismograms from the recorded sonic and density logs, in different frequency bands, before recording the VSP in GGR5 borehole. The synthetic seismic seismogram results on deviated GGR3 well are displayed on Figure 3: Synthetic seismogram reflection coefficients are computed from sonic log velocity and density logs, transformed in two-way time scale, respectively Vel (m/s) and RHOB (gr/cc)

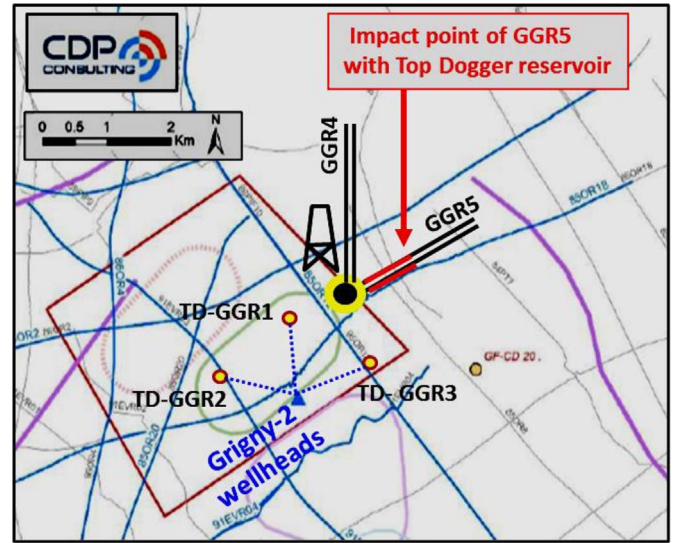


Figure 1. Position plan showing the previous Grigny-2 platform with its three deviated wells GGR1,2,3 and their Total Depth (TD) locations, and the new GGR4-GGR5 drilling rig location. Blue lines are vintage seismic profiles to be reprocessed by CDPconsulting, magenta lines represent interpreted fault tracks at TRIAS level.

tracks 2 and 3 in Figure 3, then filtered at various frequencies to understand the resolution of different seismic methods (center of Fig. 3). Last, filtered reflection coefficients are inverted to acoustic impedance and displayed similarly manner to other log data to make it easier to interpret the results and visually evaluate the resolution, on the right side of Figure 3.

A summary of the seismic resolution analysis conducted by Humphries [6] from existing logs, is produced in Appendix 1, with added suggestions to remedy the sonic log continuity where the borehole diameter and completion change. It can be estimated that the minimal high frequency necessary to discriminate 5 m porous beds from the seismic reservoir signatures of the three wells GGR1, GGR2, and GGR3 (Fig. 3) is about 150 Hz, and 350 Hz to correctly define 3 m thin, porous beds (*i.e.*, $\lambda/4$ resolution thickness).

Past HF VSP surveys in the same Paris basin area in the late 1980s exhibited HF reflection up to 140 Hz at Dogger depth (Naville *et al.* [3], Mougnot et Meunier [4]), which reasonably justified recording an HF VSP survey, while 350 Hz seismic reflection might be obtained using a commercial downhole sparker source and VSP type receiver tools. In contrast, very good HR reflection surface seismic results barely reaching 100 Hz at Dogger depth would allow for an estimated 10 m resolution...

The first part of the present article focuses on VSP acquisition preparation and execution. A couple of High frequency/High Resolution (HF/HR) intermediate VSPs were initially planned to be acquired over the deviated trajectory section of a deviated borehole planned drilled down to the top of the Dogger carbonate geothermal aquifer, 1500 m Total Vertical Depth (TVD) from Ground Level, in the suburban town of Grigny, Southwest of Paris.

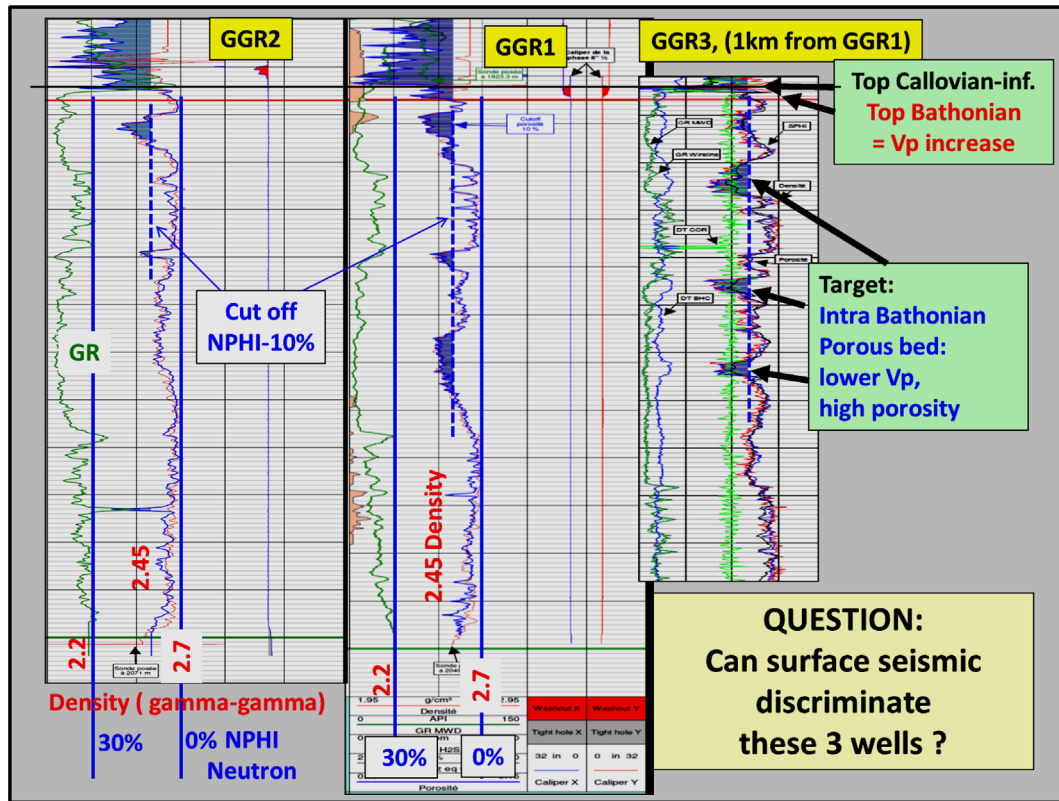


Figure 2. Comparative set of logs in the Dogger carbonate interval for Grigny-2 geothermal well triplet: GR, Density, Sonic BHC (only on GGR3), Neutron porosity NPHI, (track shaded in blue for values over the 10% porosity cutoff).

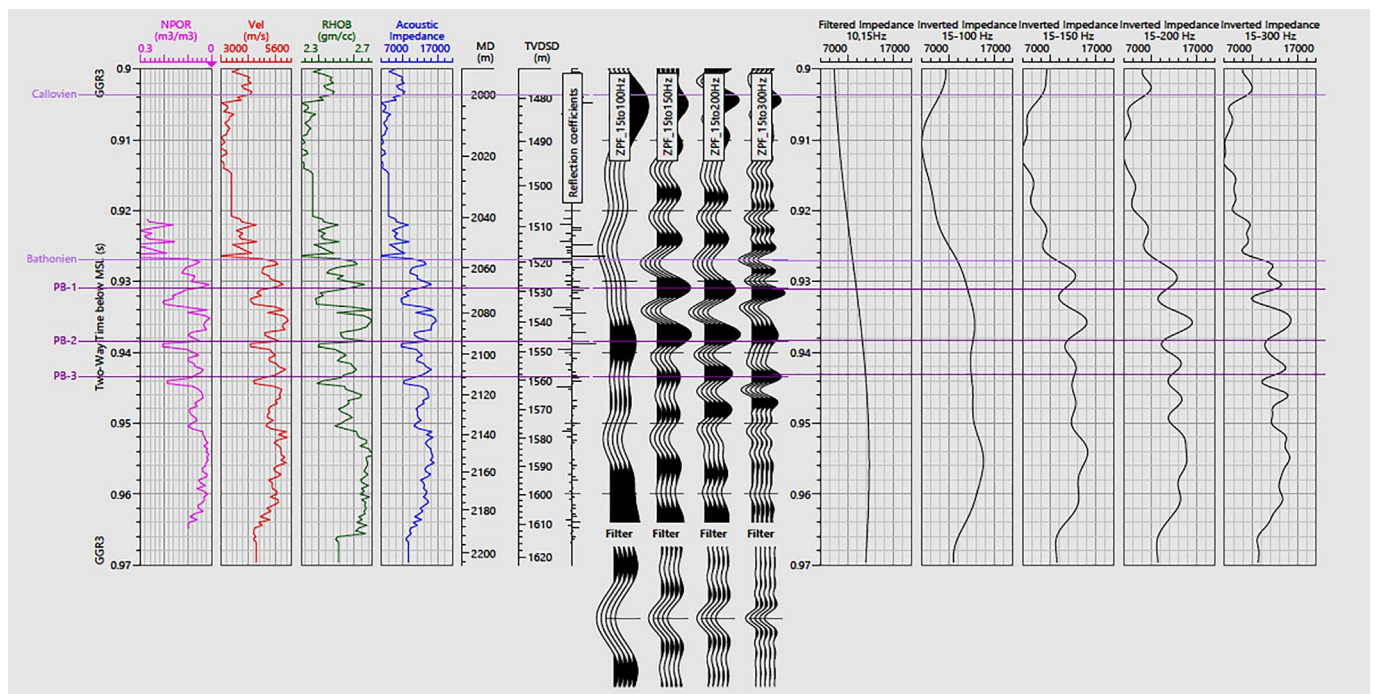


Figure 3. Tracks from left to right of GGR3 well: porosity NPOR, Sonic, Density, Impedance logs, and synthetic seismograms in four increasingly wide frequency ranges, then inverted into impedance to visually appreciate the seismic resolution necessary to visually identify the efficient Porous Beds (PB) encountered by the GGR3 injector borehole. Figure reproduced from Figure 4.3 of Humphries [6].

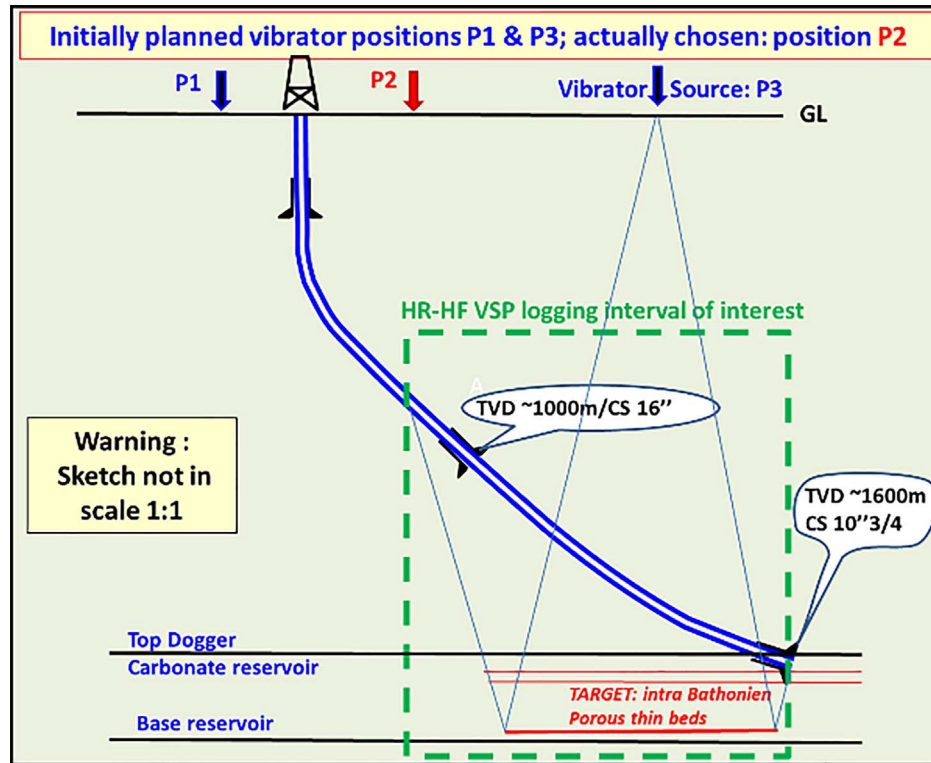


Figure 4. Deviated borehole section planned for a look-ahead purpose VSP survey : vertical plane of deviation. Position P3 was favored but could not be used due to soft, damp ground. Thus, single position **P2** was retained for the vibrator VSP operation.

The second part focuses on the VSP processing route and obtained results, performed in an industrial routine manner, then processing improvements were developed in the third part, to access HF extra seismic imaging information.

The fourth part is devoted to the interpretation and comparison of VSP results with reprocessed surface seismic and synthetic seismograms; the specific HF VSP results of the GGR5 VSP are discussed in comparison with vintage HF VSP results in the same area.

2 VSP survey preparation and field acquisition

2.1 VSP survey overview

Two vibrator sources were initially planned to be located on each side of the Seine River, and activated in a single run, to minimize the rig mobilization time: one vibrator being placed near the vertical projection of the point of impact of the well with the top Dogger reservoir (Position **P3** on Fig. 4), to obtain a near normal incidence inversion of the predicted reflections right below the top Dogger reservoir: this industrial application is commonly known as “look ahead” VSP; the other vibrator being positioned at a short distance from the wellhead (Position **P1** or **P2**) to collect most accurate vertical times and seismic velocities in the vertical hole section above Kick Off point.

Eventually, due to the availability of one vibrator only, and due to the ground softening by heavy spring rains in

the fields around position **P3**, the vibrator was set in an easily accessible industrial site at position **P2** (Figs. 4 and 5), distant from about 350 m from the wellhead, although aside from the vertical plane of borehole deviation. The hard ground single position **P2** would ensure an uninterrupted operation of hundreds of vibrator emissions in a fixed place, with reasonably acceptable incidence of direct and reflection angles at target depth.

Initially, recording with a single wireline seismic tool chain combining a downhole sparker (AST-1/Advanced Sparker Tool) and a multiple receivers VSP toolstring (GEOCHAIN) from Avalon Sciences Ltd (ASL), imperatively operated in the open hole, had been considered in order to tentatively recover intra Dogger reflections of interest up to 350 Hz about, as illustrated on the left side of Figure 3.

Previous tests conducted by ASL in their basement granite open hole test site in 2022 were successful in validating the field operability and the recording technology, however, the amplitude level of Stoneley arrivals was much too high relative to useful seismic body waves, starting with P-wave direct arrivals (not shown). Therefore, an eventual feasibility test would preferably be a crosswell seismic test, with the Sparker source located in an open hole section of one of the geothermal doublet wells, and the VSP receiver toolstring located in the other well, either cased or open hole, as illustrated on the right side of Figure 6. Such seismic geometry sketch would be easily adaptable to the configuration of geothermal doublets in the Paris basin, even if two cable units are needed simultaneously for a Crosswell operation.

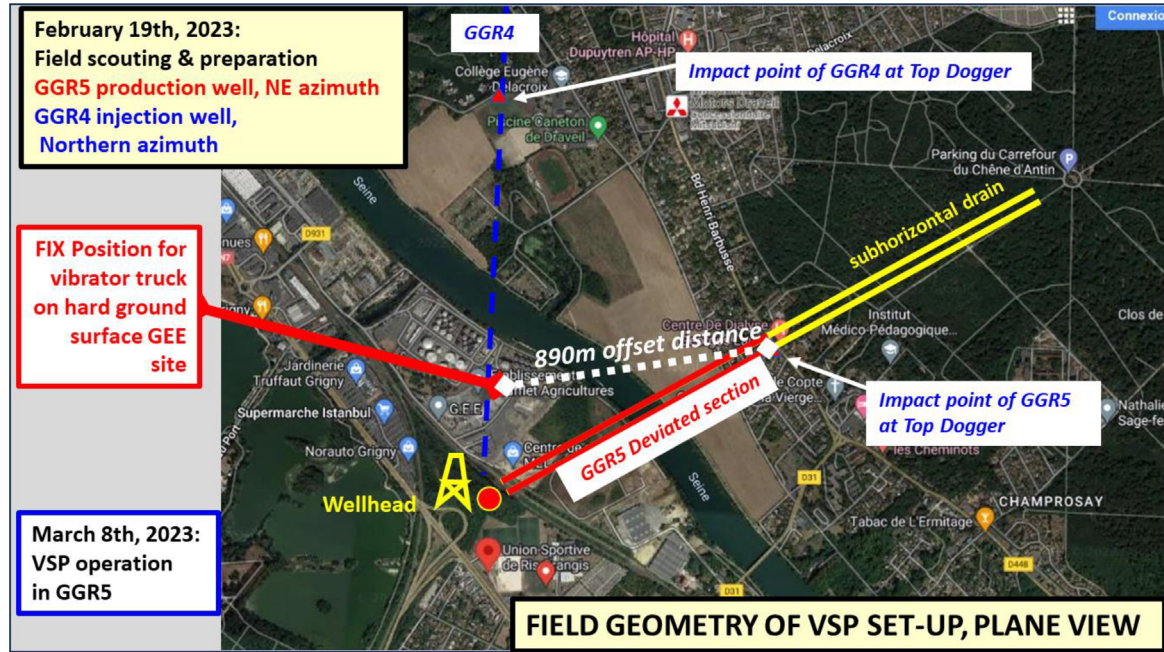


Figure 5. Satellite map and GGR5 hole trajectory with fixed vibrator position 2 retained for VSP (reproduced from page 6 of Naville [1]).

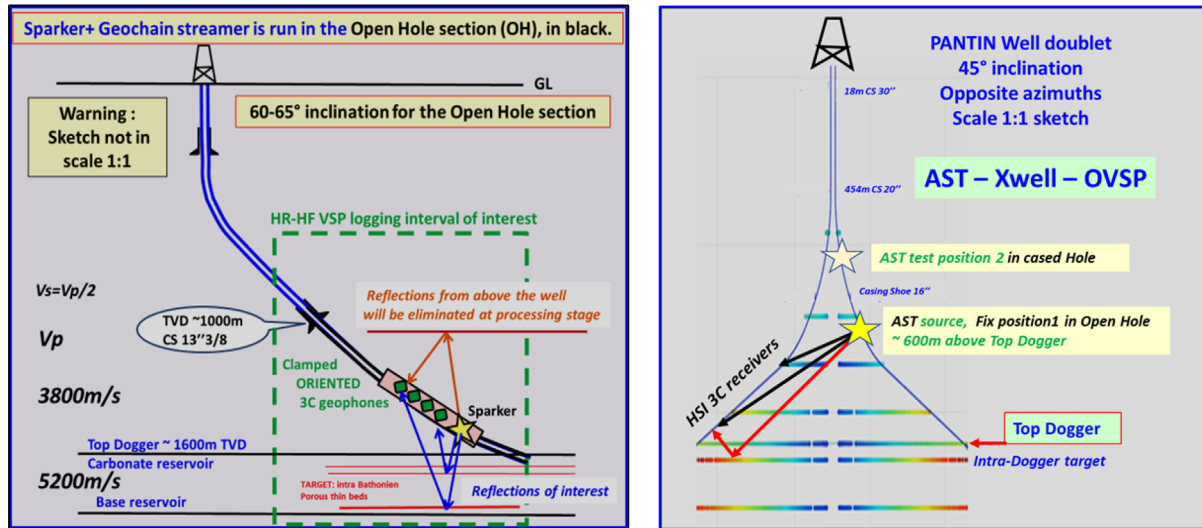


Figure 6. Left: Single well toolstring comprising a downhole sparker source at the lower end of an array of VSP receivers, in the deviated borehole section. Right: Same equipment deployed for a crosswell seismic survey between the two geothermal doublet wells.

2.2 Borehole completion for the VSP operation: open hole or cased hole?

In early 2023, as the drillbit approached the top of Dogger level where the production casing was planned to be set, the question arose of conducting a feasibility test of the combined Sparker downhole source/multiple VSP receiver string, in a sedimentary formation hole, in the low deviated part (*i.e.* $<40^\circ$ inclination, right below Kick off depth),

while pondering the risks of getting stuck with this long, souple wireline seismic string in the 60° deviated lower section of a production geothermal well.

Due to safety reasons, the project partners decided to postpone the (sparker + VSP receiver) feasibility test onto a future geothermal well with a lower inclination and canceled such test in the present Grigny GGR4/GGR5 well doublet: consequently, the field VSP survey would occur after setting the production casing over the whole borehole

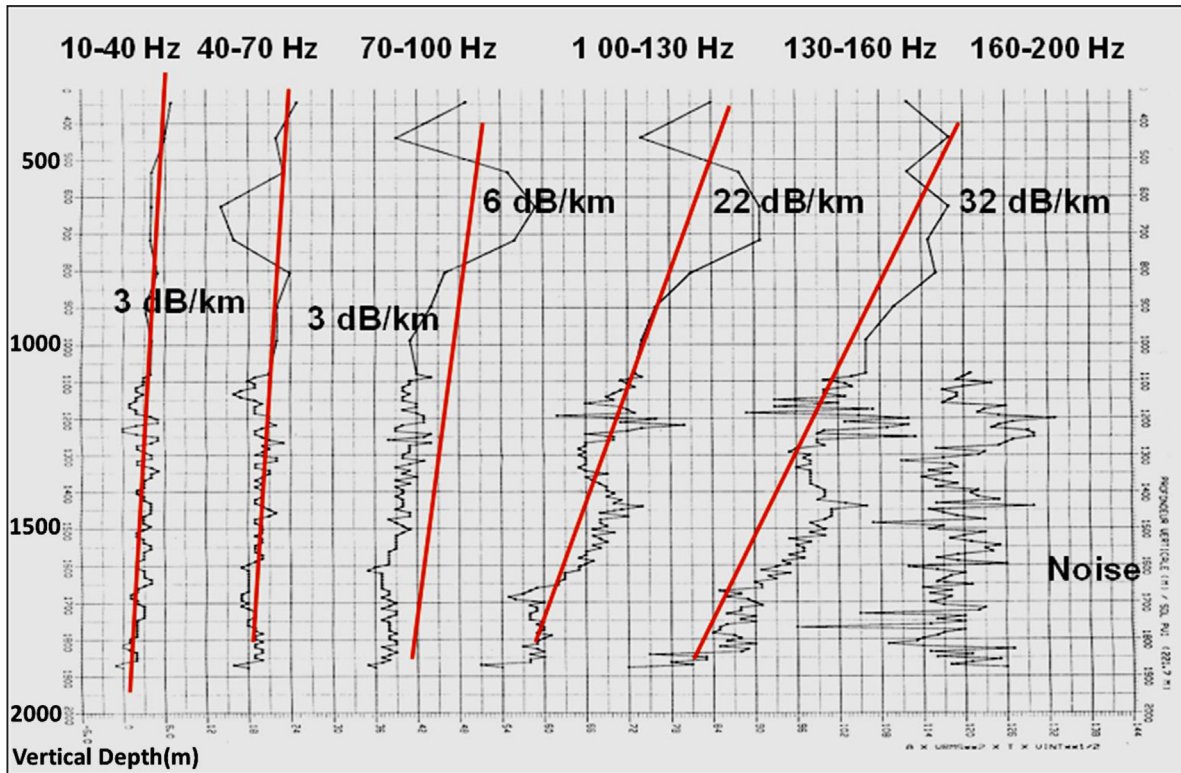


Figure 7. Attenuation curves computed as compensated plane wave amplitude at normal incidence $[A \cdot V^2_{rms} \cdot T \cdot (v-int)^{0.5}]$ from measured direct arrival VSP amplitude A and vertical time T versus vertical depth and versus frequency, in near 1D stratified medium. Figure modified from Naville *et al.* [3].

length, which provided extra time to address permitting issues about positioning the vibrator truck above the deviated borehole trajectory.

Unless in last resort, positioning a powerful vibrator truck on the crowded drilling area was not desirable for many reasons: buried network(s) underneath the platform, undesired tube wave generation from close source proximity to wellhead, etc. . .

2.3 VSP upper frequency emitted

The GGR5 VSP experiment was inspired by the HF VSP recorded in the eastern Paris basin oil field in 1991, with a similar top Dogger target vertical depth, as described in legends of Figures 7 and 8 of Mougenot and Layotte [2].

The quasi-null, amplitudes observed on the random waveform direct P-wave arrival above 160 Hz and above the 1850 m top Dogger depth, as summarized in Figure 7 reproduced from Naville *et al.* [3], led us to reduce the upper frequency of the vibrator sweep to 175 Hz.

2.4 Surface vibrator sweep parameters

Taking into account the very slow VSP acquisition rate when using a single-level VSP tool, and a long logarithmic upsweep with a Log30 parameter in the 1991 VSP experiment (Mougenot and Layotte [2]), a conservative Log parameter of 7–15 was anticipated for the Grigny-GGR5

VSP acquisition, as segmented sweeps are not a built-in programmable option. One can observe that a Paris basin VSP recorded with a linear sweep would easily result in a VSP corridor stack up to 100 Hz dominant frequency, as shown by Figure 8, left track, equating to a quarter wavelength ($\lambda/4$) resolution of 5 m.

Therefore, increasing the vertical stacking order was deemed to reach a good Signal Noise Ratio (SNR) at frequencies higher than 100 Hz, as the downhole dynamic range of the downhole GEOCHAIN digitizer is superior to the surface digitizing characteristics of the surface recorder used in a distant past for recording the 1991 eastern Paris basin VSP.

Once the upper sweep frequency is chosen, a few ground positions are tested on the field to maximize the usable drive level (displacement amplitude of the vibrator baseplate) over the whole sweep duration, within acceptable distortion limits: in the present case, the drive level was set to 70% by the vibrator field operator, resulting in the following parameters: Sweep Log 7, Length 25 s, Taper 500–500, Frequency 5–175 Hz, Drive level 70%.

2.5 Downhole receiver toolstring

In order to speed up VSP field operations, a 7-level downhole 3-C geophone string was deployed by wireline in the 65° deviated 10 3/4" cased hole. The high deviation angle justified lowering this 108 m long VSP toolstring after

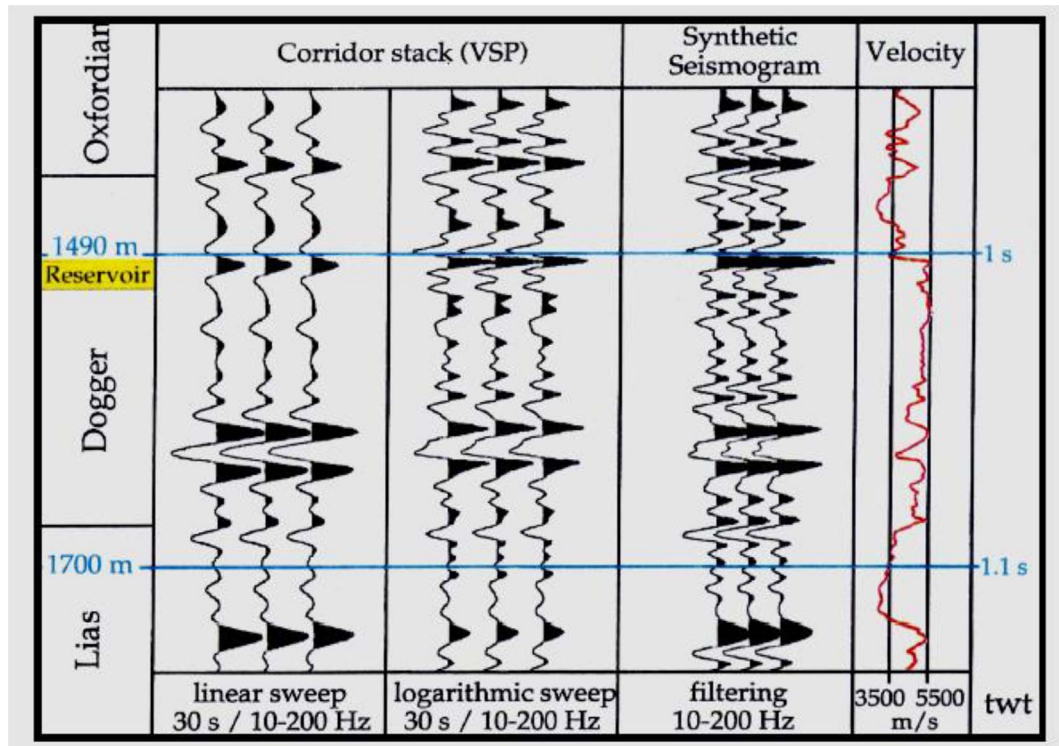


Figure 8. Comparison of VSPs from different sweeps with a synthetic seismogram, modified from Figure 2 of Mougenot et Meunier [2]: the zero offset VSP was recorded in a cased vertical test well located about 5 km to the south of Grigny.

casing and cementation of the deviated hole section, rather than into the open hole, to secure the toolstring descent. Since the length of interconnection cables was 15 m, a 7.5 m depth increment was defined in order to produce high-resolution imaging results, for both P-P and P-S wave-mode reflections. Since no major 3-component (3C) orientation difficulty was expected in the fairly 1D Paris basin propagation medium, a 7-level receiver toolstring of fix 3C geophones was preferred to a 5-level VSP toolstring equipped with HSI (High Side Indicator) inclinometers.

2.6 Recording procedure

An active railway line was running between the VSP vibroseis source position and the wellhead position, therefore no wireline connection could be established between the vibrator and the VSP recording unit located inside the logging truck (Fig. 9).

Since no encoder vibrator electronic unit radio linked to the vibrator truck was available to accommodate the VSP field observer, microsecond GPS-referenced start times were recorded separately by the vibrator electronic recorder and by the Downhole VSP tool recorder: the synchronization of emitted sweep signals and uncorrelated received signals was performed from recorded GPS start times prior to correlation. Time stamping the sweep signals within the seismic receiver records was achieved in a timely manner at the pre-processing stage using the VSPROWESS seismic processing software.

The field Quality Control (QC) was thus performed by the observer in real-time from uncorrelated data. Field correlations were done at the beginning and sporadically during the VSP run. Since the maximal recording length of the Geochain VSP receiver array was 2 min, two records of 2 min were performed at every VSP array tool station, each including a salvo of four 25 s sweeps recorded back-to-back, resulting in 8 emitted sweeps per receiver toolstring position.

As the GGR5 wellhead is located inside a fork of suburban train lines (Fig. 5), significant traffic noise on the downhole geophones generated was expected to occur about every 15 min. Fortunately for the field observer, a train strike in the Paris area allowed a smooth, uninterrupted VSP acquisition run.

The vibrator was operated in slip-sweep/simple repetition sweep mode (ex: Rozemond [7]), for a series of 4 consecutive sweeps in a 2-min continuous record manually triggered by cell phone communication between the wireline unit and vibrator operator (Fig. 9).

A surface monitor phone was recorded to check the source repeatability.

An additional favor was asked of the drilling team prior to the VSP acquisition, consisting in refraining from filling up the borehole with drilling fluid after Pulling the drill-string Out Of the Hole (POOH), which was gracefully granted by the GEOFLUID drillers. Such action results in minimizing the amplitude of undesirable guided tube waves (Stoneley waves) generated in the near-surface when

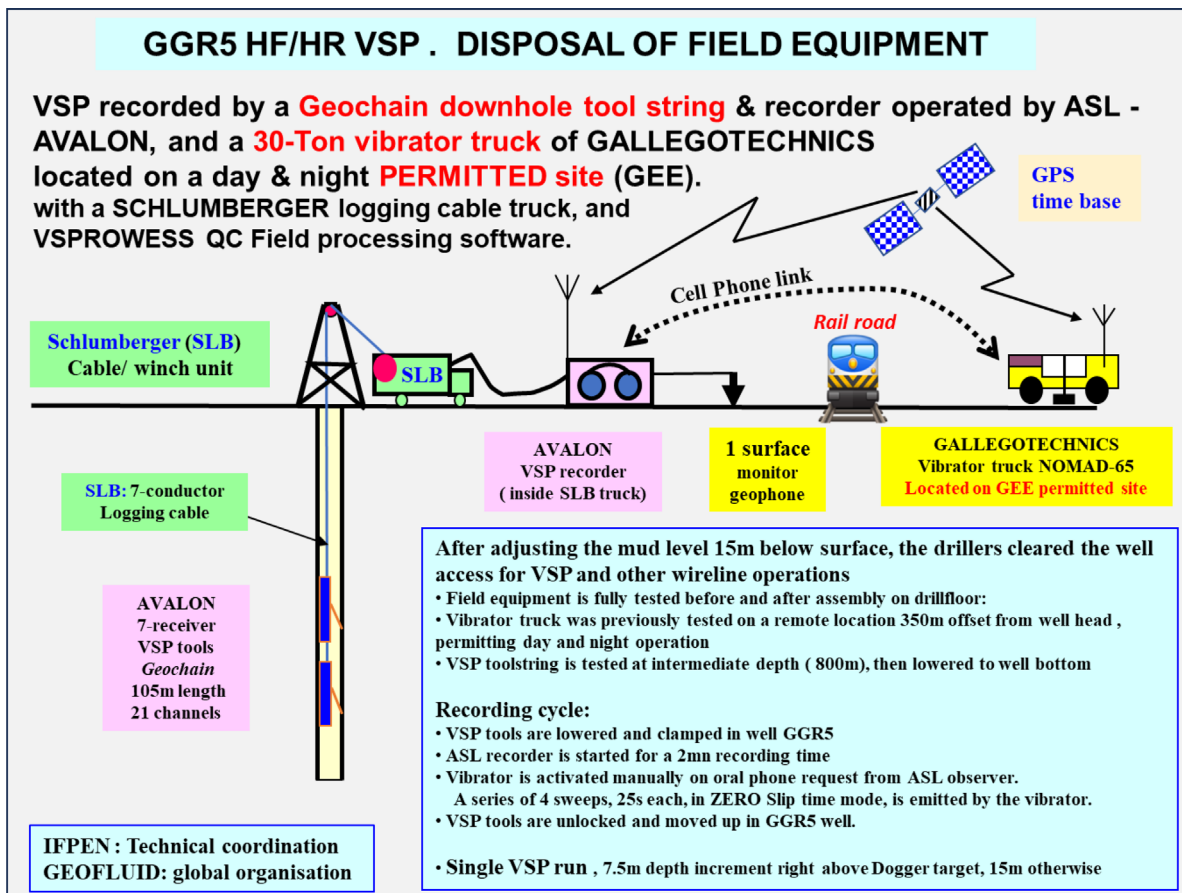


Figure 9. VSP field recording chain, using GPS time synchronization. Figure reproduced from page 7 of Naville [1].

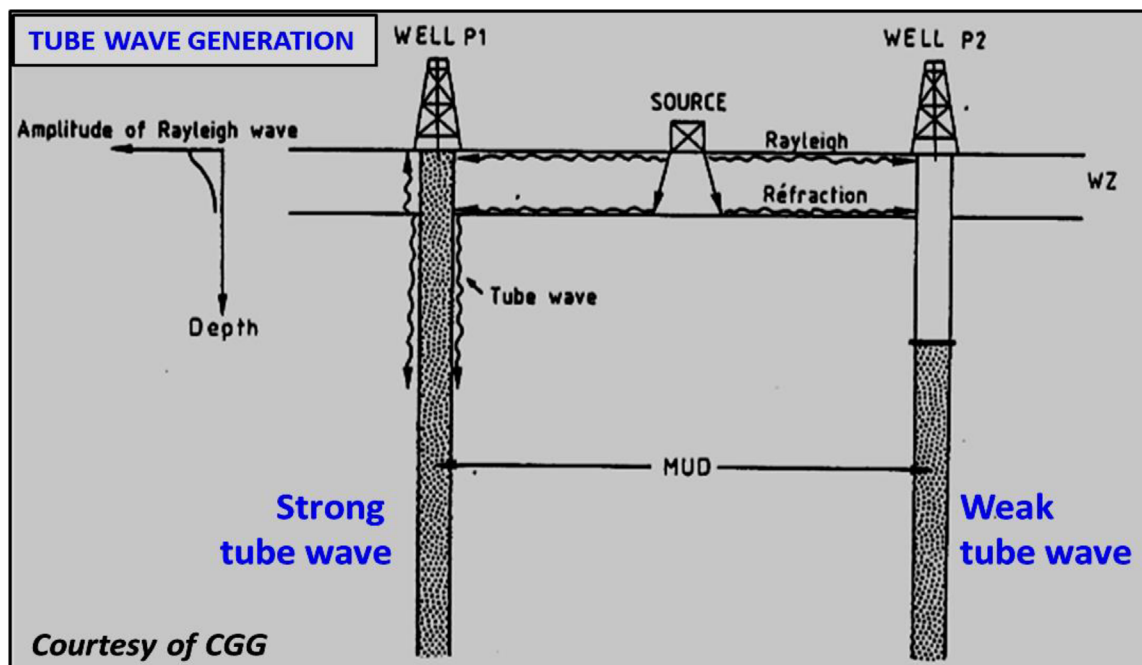


Figure 10. Tube waves observed on VSPs are excited in the upper part of the mud column (left): they can be attenuated by lowering the top of mud column into the borehole.

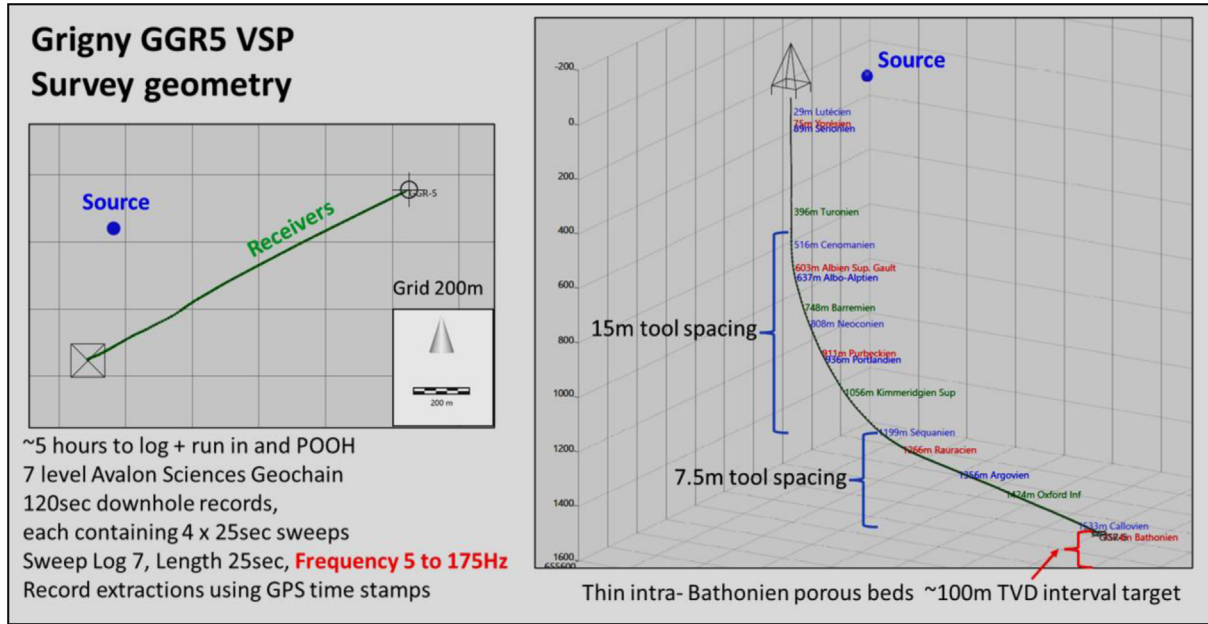


Figure 11. GGR5-VSP, survey geometry, and summary of field parameters: plan view (left), 3D view (right). Figure modified from Figure 1.2 of Bailey [8].

the Vibrator source is located close to the wellhead, and propagating to the well bottom, as illustrated by the sketch Figure 10.

Illustrations of the VSP field operation, VSP geometry, pre-survey ray tracing, and used equipment are online in Naville *et al.* [1]. The field parameters were adjusted following the feedback from the 10–200 Hz VSP recorded by an Oil and Gas company consortium in the eastern Paris basin in 1991, summarized in Mougenot et Layotte [5].

A summary of the VSP geometry and field parameters is produced in Figure 11.

3 VSP 3C processing, using an industrial processing route

3.1 Stacked 3C data

Poor traces/records were omitted prior to commonly measured depth (MD) trimmed mean stacking. The stacked data were then correlated using the pilot sweep, after checking the high quality of emitted vibrator signal repeatability of force control emitted signals over the whole 5–175 Hz sweep range. Trim stacking applied at each VSP toolstring position is intended to eliminate any spurious noise over the whole length of the uncorrelated raw data, as the vibrator source delivers a highly repeatable signal, which has been verified at the preprocessing stage, with a time dispersion inferior to 1 ms (*i.e.* less than 1/10 period of the upper sweep frequency) between unit correlated records at each toolstring position.

Figure 12 right side shows the stacked 3-component (3C) VSP data in tool component collections VZ, HX, HY. Overall, the data is of good quality. The horizontal component data for tool 3 in particular shows some poorer

coupling which occurred during the course of VSP acquisition. No tube wave arrival is apparent in the dominant frequency bandwidth of 5–100 Hz.

The surface geophone located near the well head, at about 400 m from the vibrator source, showed a stable low-frequency first arrival time (5–100 Hz), but slightly delayed secondary arrival after a heavy rain shower, which does not affect underground seismic propagation (Fig. 13). This display stresses the importance of finding a ground area hard enough to set the vibrator source for recording a land VSP, to secure the phase and amplitude repeatability requested of the emitted signal.

3.2 Three-component orientation, frequency content, amplitude compensation

The data were geographically orientated using conventional first arrival maximization procedures and measured borehole trajectory angles. It was assumed that the propagation medium was nearly 1D (*i.e.*: horizontal layering), enabling a nearly 2D seismic propagation close to the vertical plane of borehole deviation in the deep section of the GGR5 well. Figure 12-left side shows the orientated data: Vertical, East, and North components, top to bottom.

Since the layering is near horizontal, the following processing operations have been performed in the vertical-radial plane containing the source and current receiver, whose azimuthal orientation is slowly rotating with the receiver depth: such processing is usually named “2.5D”. Besides, Figure 11-right shows that this vertical-radial processing plane is nearly stable in the E-NE azimuthal direction for the deep receiver interval.

Figure 14 shows the three components after orientation, named: “P-down maximized” and “P-down-minimized”, in the vertical-radial processing plane, and “X-line horizontal”,

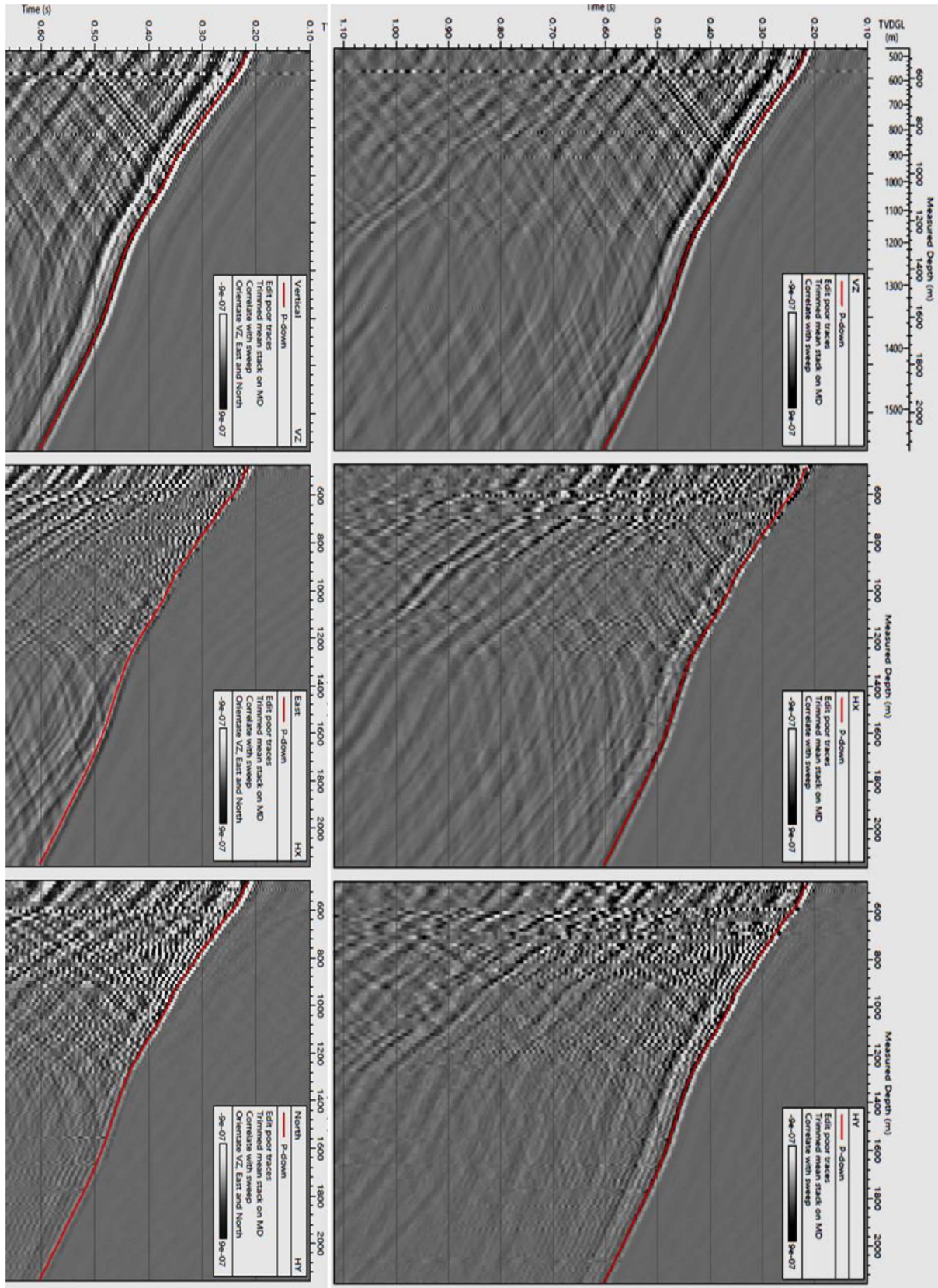


Figure 12. *Right:* Raw correlated 3C stack, VZ/HX/HY downhole toolstring components. *Left:* Geographically orientated 3C VSP data: Vertical, East, North components. No apparent tube wave arrival, deep P-P reflections appear mainly on the HX component (middle) before orientation, then on Vertical after orientation (top left). Figure reproduced from Figures 2.5.2 and 3.1.1 of Bailey [8].

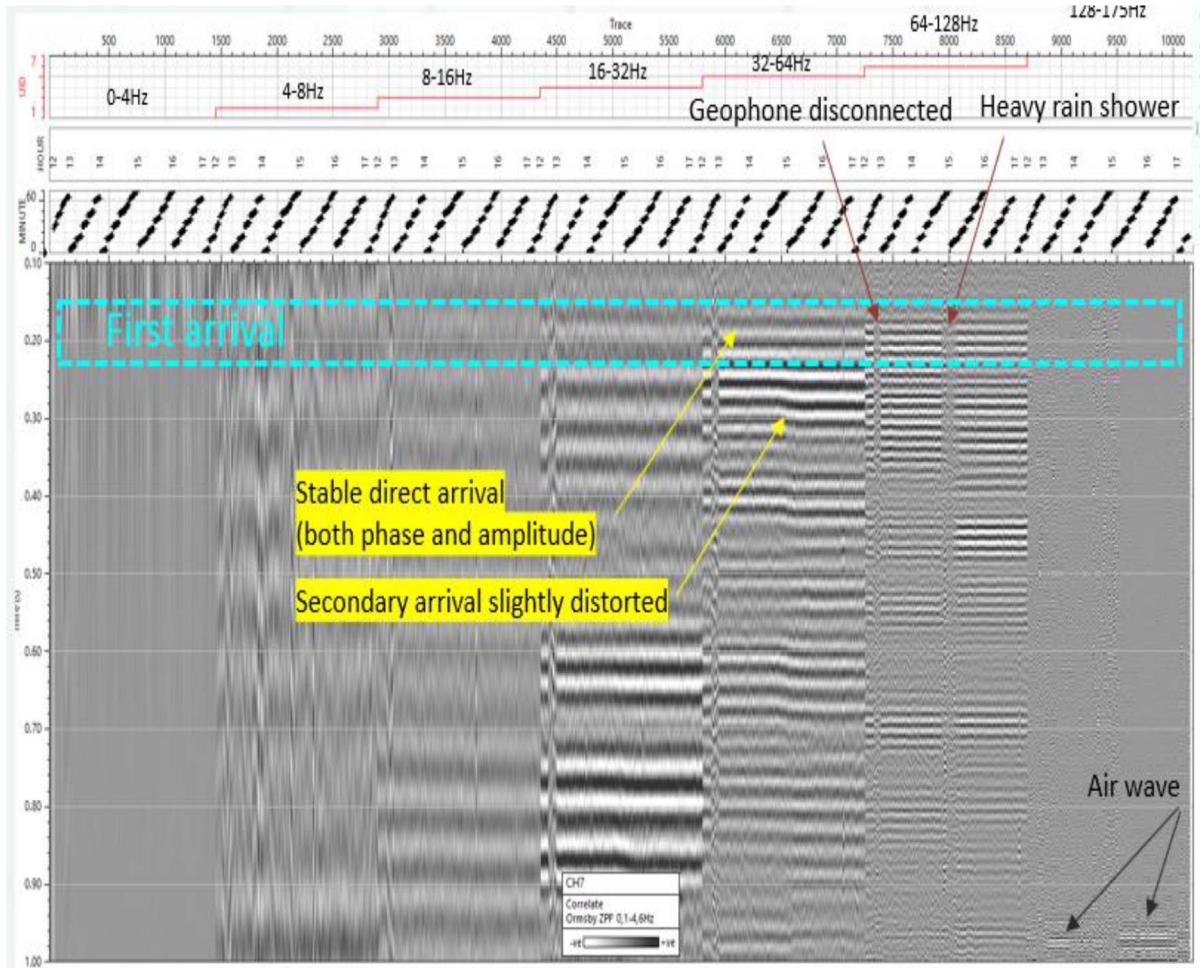


Figure 13. Surface geophone after correlation and Octave analysis up to 175 Hz. First arrival waveform coherency is shown, as well as surface condition changes due to heavy rain. Air wave appears as the dominant seismic event in the 128–175 Hz frequency band, as expected in surface seismic.

orthogonally: one can verify that the “P-down maximized” component holds most of the direct arrival low-frequency energy, attesting its near linear polarization, and that the orthogonal “X-line horizontal” component holds negligible reflected seismic energy, thus has been discarded in further processing.

Additionally, the orientated 3C VSP dataset of Figure 14 is displayed after amplitude compensation for geometric spreading, called divergence, determined as an exponential ramp function $T^{1.1}$ of VSP vertical time T , followed by a Cross-normalization of the 3C on the P-down first peak amplitude of maximized P-down component.

Appendix 2 explains how to estimate the spherical divergence amplitude loss from a nearly zero offset VSP recorded in a low deviated borehole (1D approximation). The VSP-derived value of the divergence amplitude loss is in excellent agreement with the spherical divergence used in surface seismic in the Paris basin sedimentary interval.

Aside from spherical divergence loss, identical for all frequencies, considerable transmission loss is visually apparent below the Kimmeridgien, 1100 m MD, above 90 Hz, as shown by the bandwidth filter tests performed on the

P-down component oriented along the maximal polarization amplitude (Fig. 15): the green marks on the two HF leftmost columns indicate unusual amplitude losses versus depth.

Figure 15 attests that the incident P-down signal remains coherent up to 175 Hz, although with amplitude fluctuations above 120 Hz pertaining to possible structural heterogeneities of the propagation medium.

Since the main target of the VSP lies within 100 ms after the first arrival to define intra-Dogger stratigraphic information, it was deemed that signature deconvolution with the P-downgoing incident wavetrain would compensate for the frequency-dependent transmission loss for all VSP bandwidth, as long as the incident P-wavetrain remains coherent with depth.

FK spectra of the deep VSP raw data selected below 1700 m MD for the most relevant geographical two components Vertical and Horizontal-East are shown in Figure 16.

The incident P-down signal is reasonably strong up to 150 Hz, but the desired reflected signal mainly apparent on the H-East component (P-up) looks very attenuated above 120 Hz.

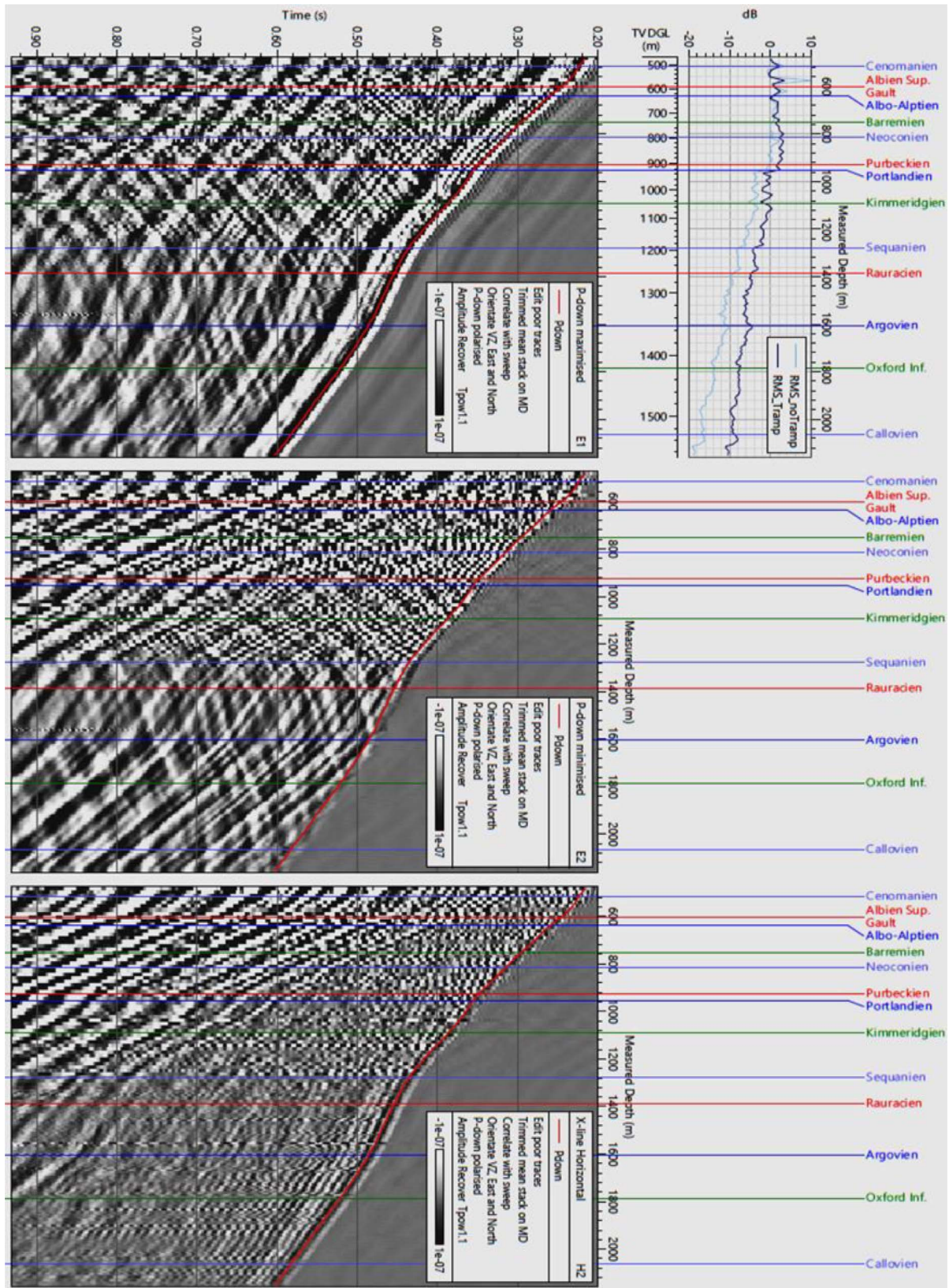


Figure 14. 3C VSP data orientated in the vertical-radial processing plane, top to bottom: "P-down maximized", "P-down-minimized", and orthogonal "X-line horizontal", compensated for spherical divergence, cross normalized to direct P-down peak amplitude. Figure reproduced from Figure 3-2.1 of Bailey [8].

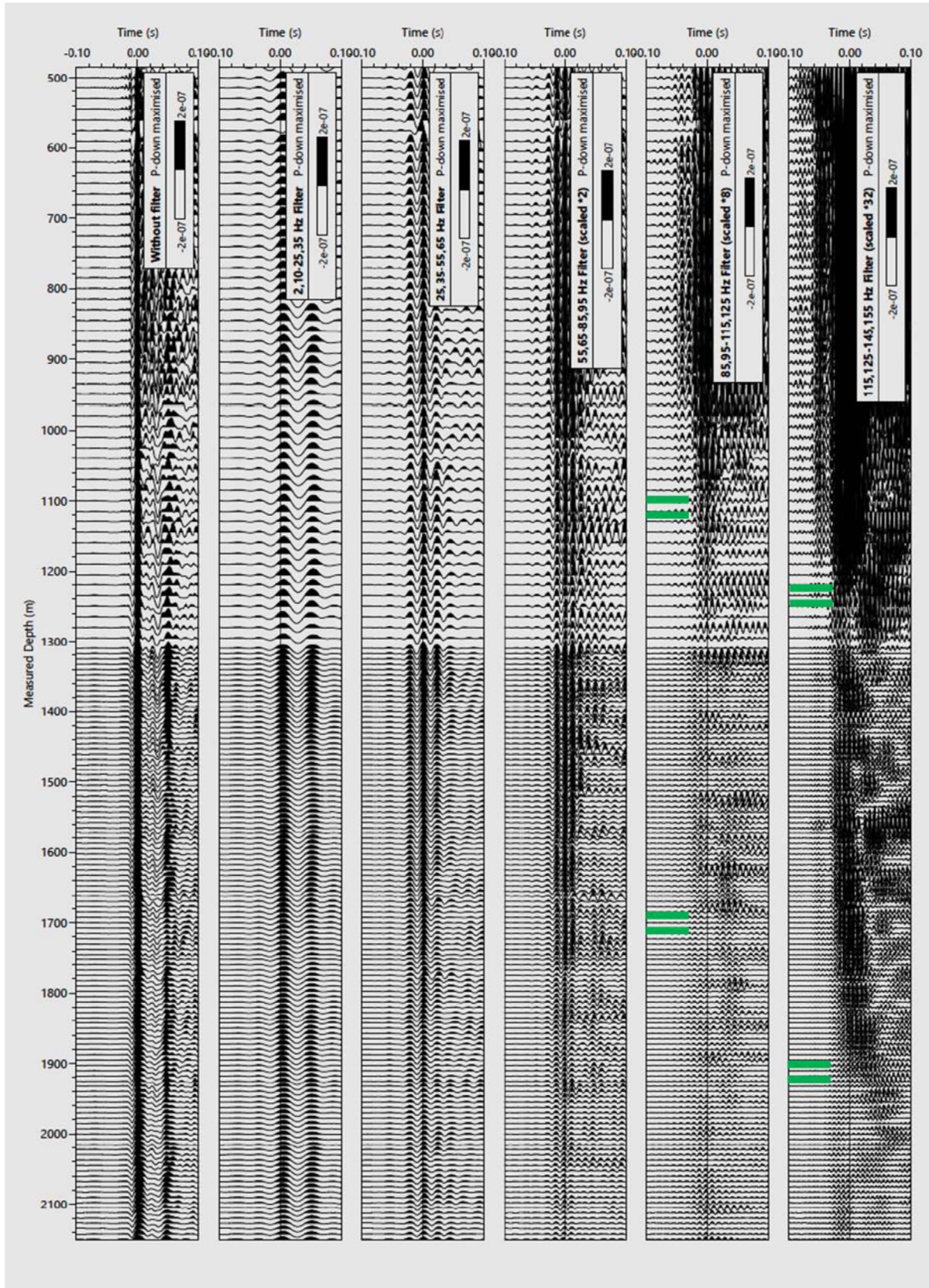


Figure 15. VSP first arrival displayed in consecutive 30 Hz frequency bands, all cross normalized on raw unfiltered first arrival peak (left column), exhibiting abrupt amplitude losses (green marks) and coherency of downgoing signal. Figure *modified* from Figure 3.3.3 of Bailey [8].

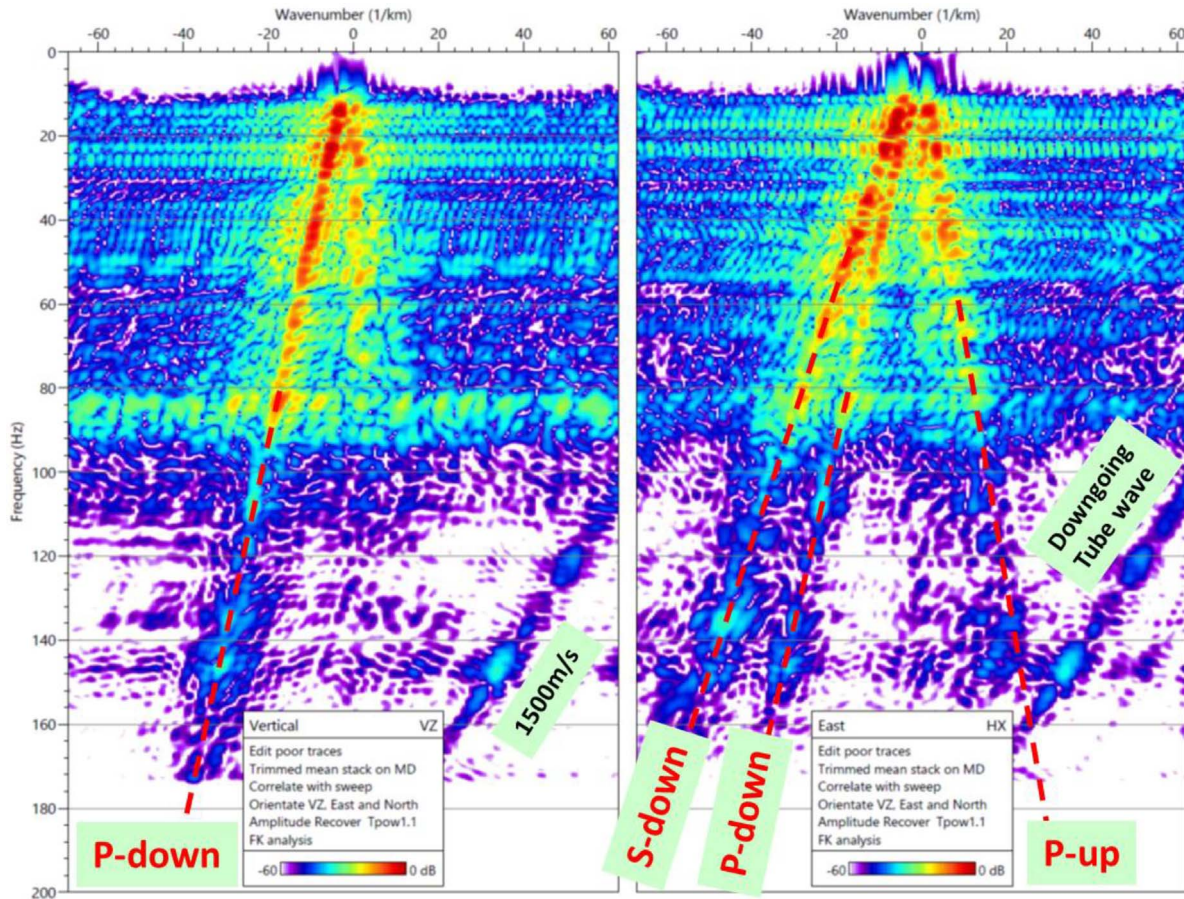


Figure 16. FK analysis of two components raw data (Vertical and H-East) in deep interval 1390 m TVD (mid-Argovien) to Total Depth 1560 m (near top Dogger): Direct P-down and PS-down are clearly present up to 170 Hz, reflected P-up arrivals are present mostly on the East component, with weak amplitude above 100 Hz. Residual aliased tube waves still appear above 100 Hz, close to sound velocity in water (1500 m/s), in spite of all efforts accomplished on the field to reduce their energy. Figure *modified from Figure 3.3.2 of Bailey [8]*.

The highly repeatable vibrator source signal emitted on stable ground with a modern vibrator electronic unit, combined with the wide dynamic range of the modern downhole electronics used for recording the GGR5 VSP cannot account for the observed amplitude losses and the possible time arrival dispersion between low and high frequencies of the first arrival peak.

3.3 Vertical times, interval velocity, deconvolution, model calibration

P-down time picks were corrected to the vertical assuming straight-line travel path. Figure 17 shows the resulting graph of the P-wave velocity profile versus vertical depth TVDGL, labeled with the main geological formation tops indicated by the drill site geologist.

Considering the strong amplitude loss on high frequencies of first VSP arrival near the top Dogger, a conservative short signature, about 200 ms (180 ms from first peak time), was defined for the signature wavelet for deterministic deconvolution, with a 2% noise stabilization, to provide

the best chances to recover HF intra-Dogger targeted reflections within 100 ms after the VSP direct arrival (Fig. 18), at least up to 120 Hz in a first approach.

A layered velocity model was built to fit the recorded VSP data by means of ray tracing. Some slightly dipping structures are indicated from the VSP imaging so that a smooth flat layer model was deemed appropriate. The dipping structure within the VSP is preserved. An average velocity of 4885 m/s below the top Bathonien was derived from the neighboring GGR3 borehole sonic log used in Appendix 1.

Figure 19 shows the model fit with the VSP down-going arrivals. The ray-trace model of P-down arrival time and polarisation vector is deemed a good fit for the data. The vector fidelity for tool 3 in particular may be adversely affected by the poor tool locking, as previously mentioned. A V_p/V_s ratio of 2 is used throughout the model which generates a model P-S down that closely fits the shear moveout in the leftmost track data (green arrival curve).

From the maximized P-down component, the P-down wavefield was enhanced using a 7-trace median filter.

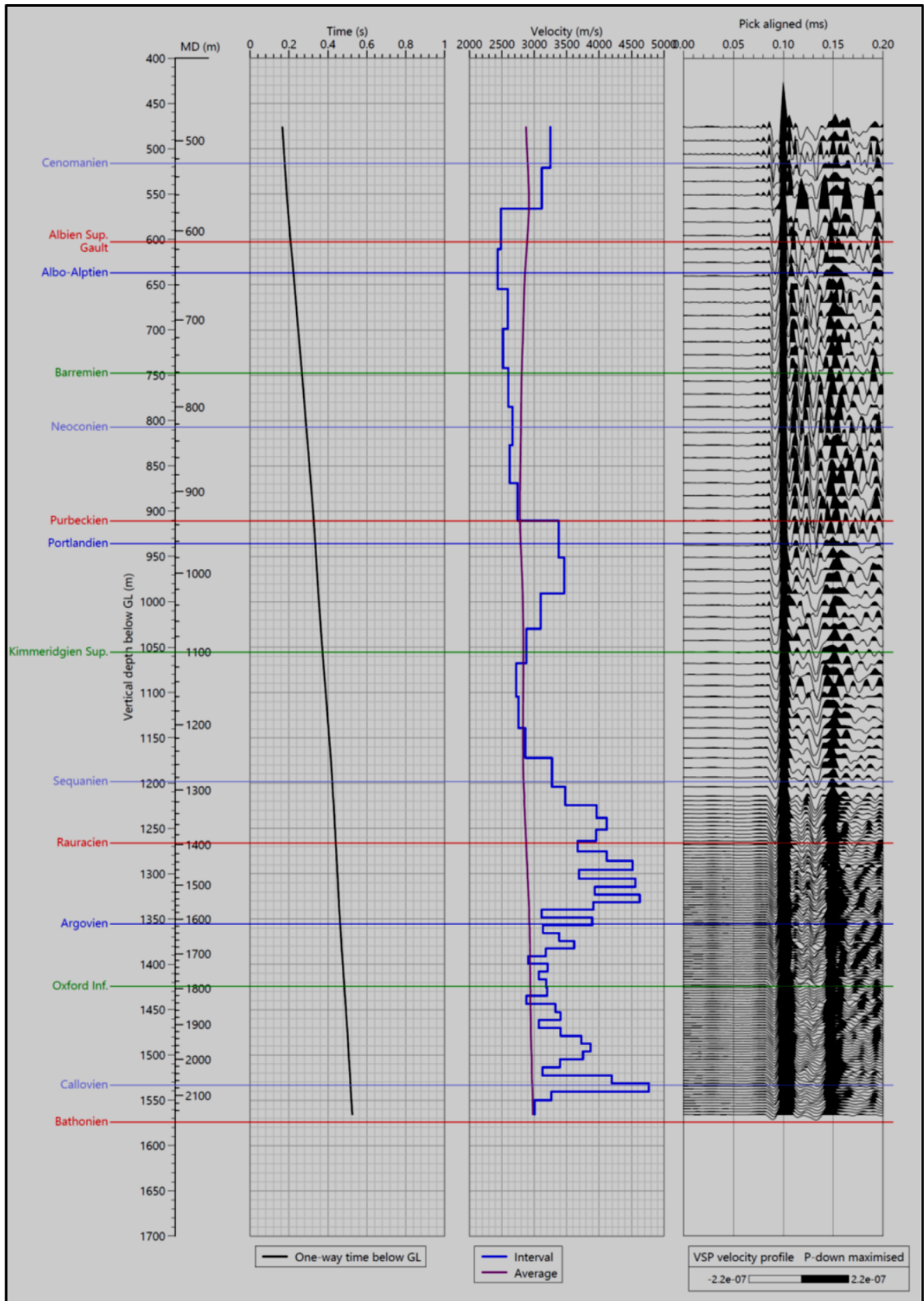


Figure 17. VSP velocity profile versus TVD-GL/True Vertical Depth. Figure reproduced from Figure 3.4.1 of Bailey [8].

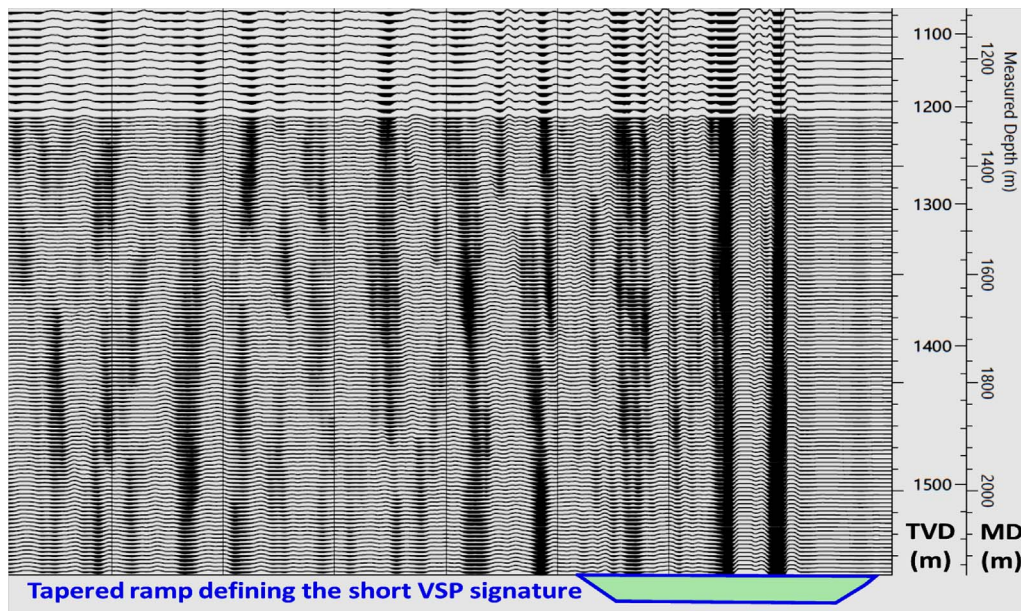


Figure 18. P-down wavetrain separated, after divergence amplitude compensation estimated from VSP. Note the remaining interferences within the signature time window below 1200 m TVD. Hopefully, the relative stability of the first arrival waveshape below 1450 m TVD, would help preserve the targeted intra Dogger reflections within 100 ms two way time after direct arrival, or about 200 m depth prediction below the borehole. Figure *modified from Figure 3.6.1 of Bailey [8]*.

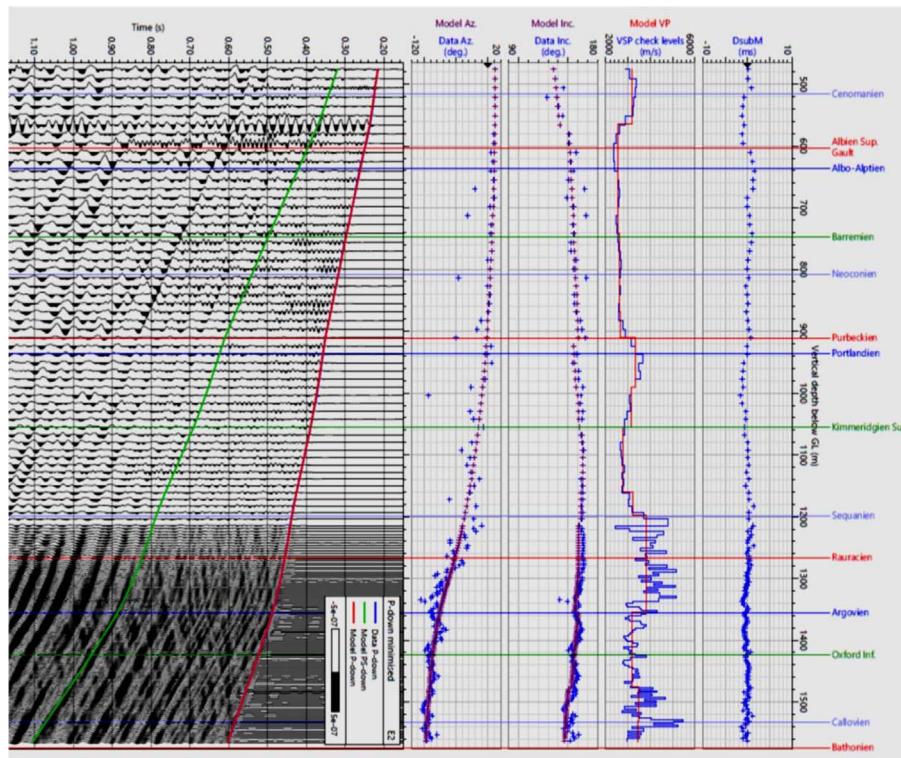


Figure 19. Right to left: the first track DsubM is the difference in ms between the picked data P-wave arrival and the ray-trace modeled arrival; the drift is within ± 1 ms. The 2nd track shows the layered velocity profile Vp in red and VSP interval velocity in blue. The 3rd track shows the model P-down inclination angle in purple, and data measured inclination in blue. The 4th track shows the model P-down azimuth angle in purple, and data measured azimuth in blue. The trace data on the leftmost track is the minimized P-down component which holds the majority of the P-S down signal. Figure *reproduced from Figure 3.5.3 of Bailey [8]*.

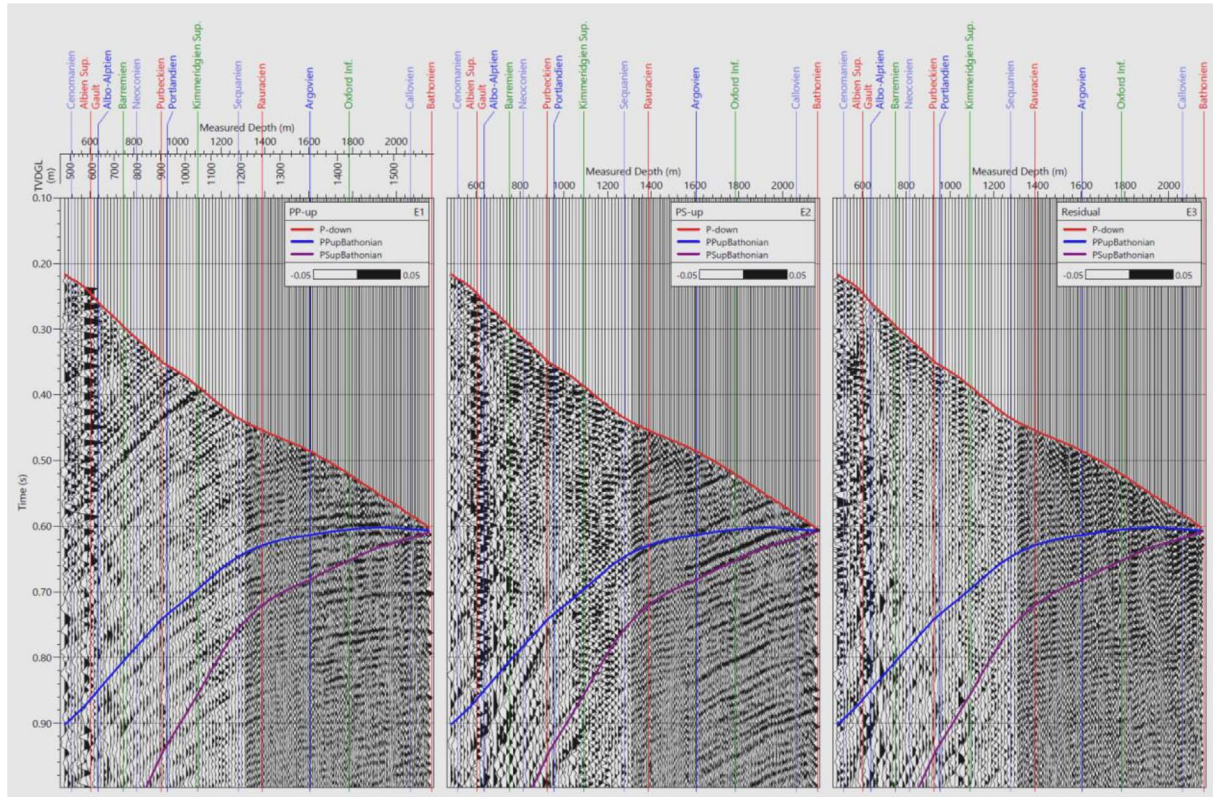


Figure 20. True amplitude display of the deconvolved three components after model-based separation of the upgoing wavefield, left to right: P-P reflections, P-S reflection, residuals on horizontal orthogonal component. Amplitude variations versus receiver depth and versus reflection two-way time below deviated hole are respected and meaningful. Figure reproduced from Figure 4.1.1 of Bailey [8].

A 21-trace median was used to enhance the P-down wavefield used as a signature for the deterministic deconvolution (Fig. 18). Using the model PS-down moveout, the S-down arrivals were also enhanced with a 7-median filter and subtracted.

The deterministic deconvolution was then applied to the 3 components of the upgoing wavefield, with the signature defined in Figure 18 and with a 2% noise stabilization.

Since most of the upgoing reflected energy lies on Vertical and H-East components underneath the deep deviated hole section, a zoomed version of these two deconvolved components in the deviated hole section is displayed on the top half of Figure 21, to enable a closer examination of the deep target section. The 3C processing procedure is qualified as “isotropic” when the same linear operations are applied identically on the three components so that polarisation if reflected arrivals can be read and used at a later time.

A model-based time variant polarisation was applied to further refine the separation of P and S upgoing wavefields, with output result in Figure 20. Modelled PP-up and PS-up reflected arrivals from the top Bathonien carbonate aquifer are shown to fit the moveout in the field data, respectively along the blue and red curves. The residual amplitude level on the rightmost horizontal component is quite weak, attesting that the wave modes are well separated by the

polarisation process over a large Bathonien interval targeted.

A zoomed version of the separated PP-up and PS-up components is displayed on the bottom half of Figure 21, illustrating the efficiency of the wave separation when compared with the upgoing wavefield Vertical & East components displayed on the top half of Figure 21: for instance the slanted event around 1800 m MD/0.62 s time on the vertical projection of the intra Bathonien PP-up wavefield (top left) clearly corresponds to a PS reflection residual which disappeared on the fully separated PP-up wavefield (bottom left).

3.4 VSP corridor stack

PP-up and PS-up VSP corridor stacks were generated from the 9-trace median filtered enhanced pre-migrate data obtained after the application of Normal Move-Out (NMO) correction derived from the ray-trace model. The NMO correction operation replaces the VSP reflections at the right depth and/or at the right vertical two-way time, to facilitate matching the VSP results with surface seismic image and with a synthetic seismogram built from sonic and density logs, for the seismic interpreters and geologists.

A corridor close to the first arrival was selected and the first five corridor traces on the transposed PP-up wavefield

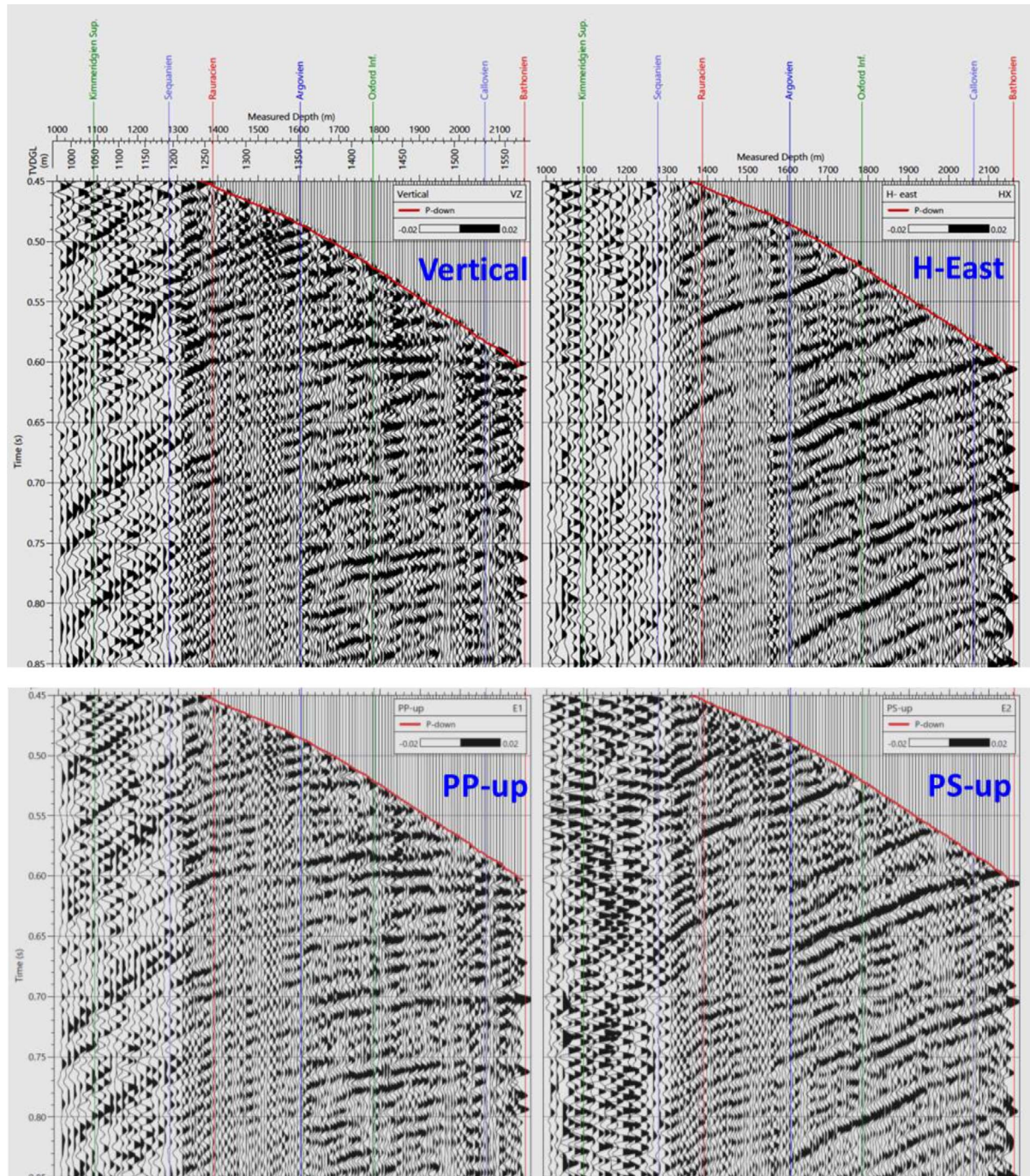


Figure 21. Top: isotropic deconvolved upgoing wavefield on components vertical (left), and Horizontal-East (right). Bottom: model-based separated deconvolved upgoing wavefields P-P (left), P-S (right). Figure assembled from Figures 3.6.4 and 4.1.2 of Bailey [8].

(Fig. 22 – center display) were stacked to produce the VSP corridor stack (Fig. 22 – right display). The VSP corridor stack was initially produced in in-depth scale, with the look-ahead velocity model using the 4885 m/s velocity below the top Bathonien.

As reprocessed surface seismic time sections were produced in TWT time only, the VSP corridor stack was converted to TWT using the same velocity model.

3.5 VSP imaging, structural observations, inversion, and look-below prediction

Figure 23 shows a plan view of the VSP PP-up reflection points assuming a flat layer model. The reflection points are color-coded with the reflection incidence angles, which are of a mid-angle range. The selected 2D image projection, for both PP-up and PS-up images, is indicated by the red

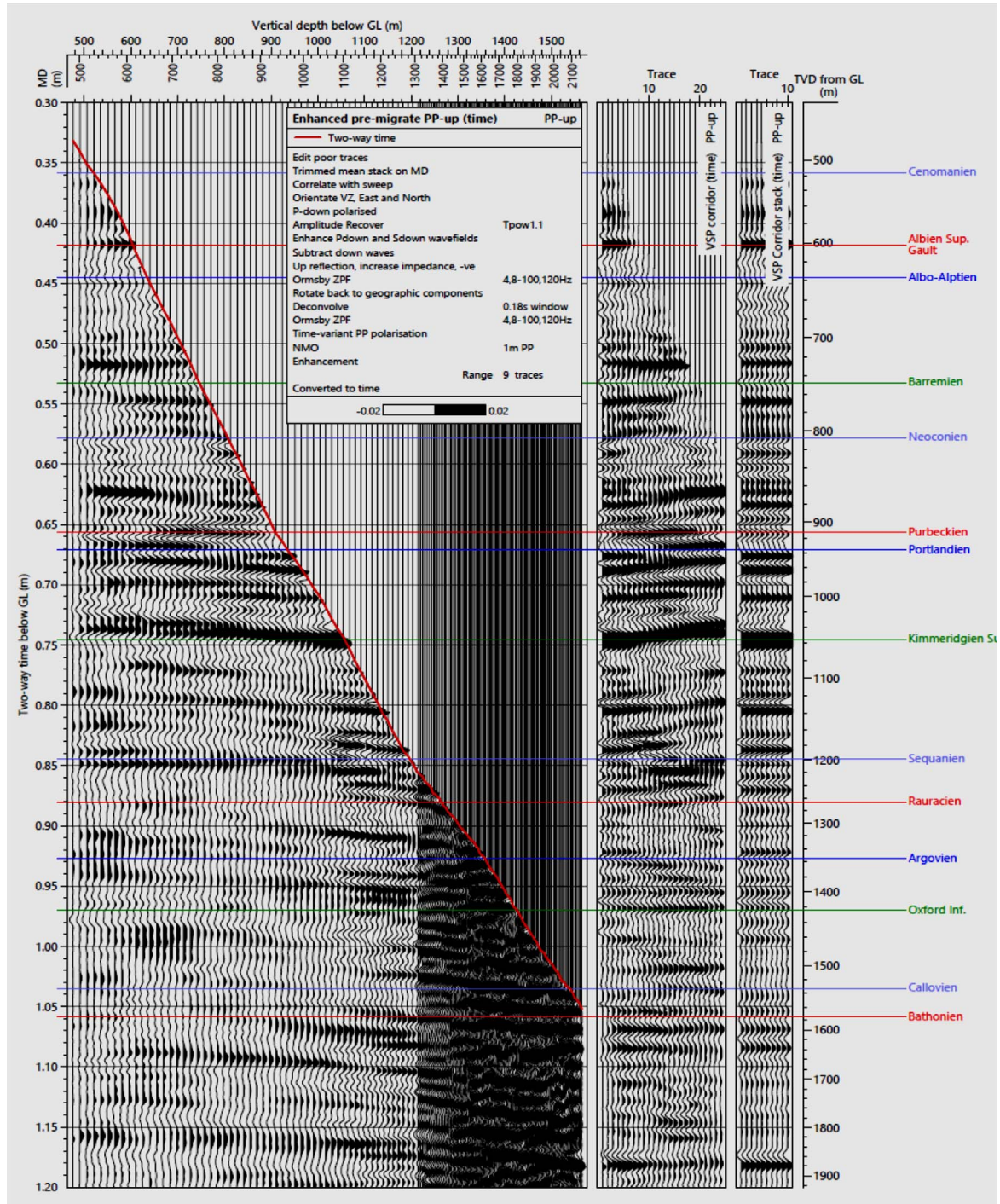


Figure 22. VSP PP-up corridor stack in Two Way Time (TWT), reproduced from Figure 4.2.1 of Bailey [8].

dot line which closely fits the well path for the top Bathonien reflectors, in the deep part of the deviated well section. The image projection is focused on coverage close to the well path and through the target reflections, mainly from the deep borehole section where the receiver MD depth increment is 7.5 m, appropriately chosen to avoid aliasing the PS reflection events. The coverage to the shallower

receivers is more out of the vertical plane of well deviation and will be muted from the final VSP image.

The enhanced NMO corrected and pre-migrated data was used for the imaging. A depth CDP (Common Depth Point) mapping 2D image was constructed into a 10 m bin sampled at 1 m in depth, for both PP-up and PS-up reflections. A surgical mute has been applied to omit

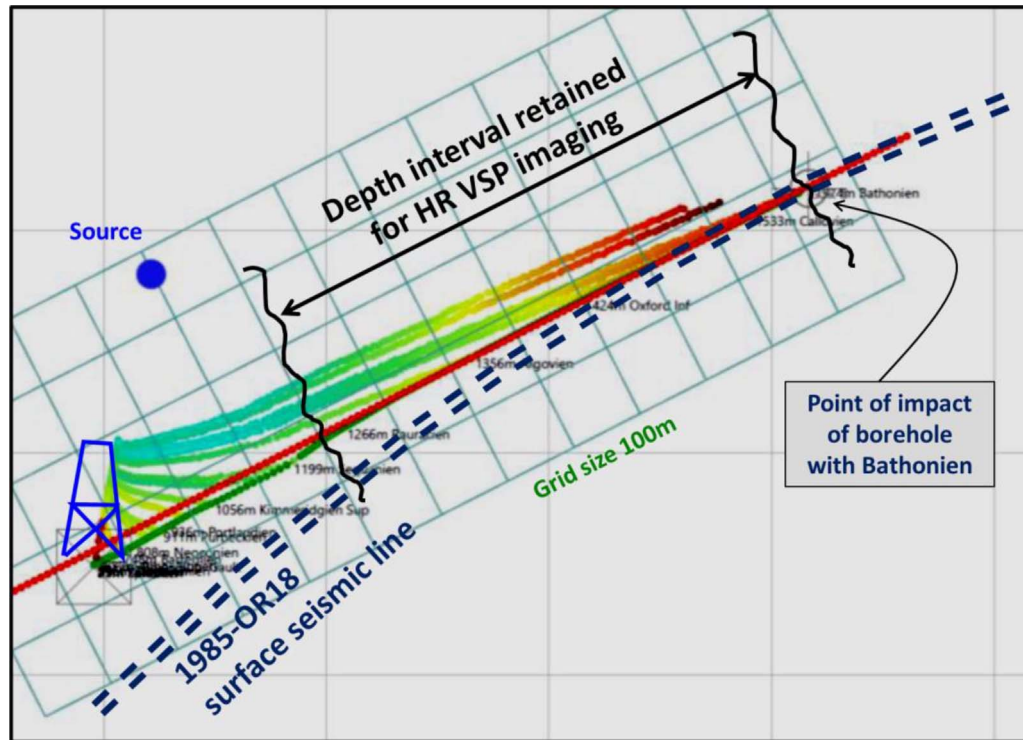


Figure 23. VSP PP-up reflection points (blue source, green receivers, image line red points close to well path, and dash line track of surface seismic line 85OR18. The incidence angle for the intra-Bathonien reflections extends from 15° (light green), 23° (yellow), up to 37° (dark red) near the NE point of impact. Figure modified from Figures 4.3.1 and 7.3.1 of Bailey [8].

out-of-plane reflections to shallow receivers. The reflections to shallow receivers are used in the VSP corridor stack for a shallow well-tie response.

The depth PP-up and PS-up images have been converted to twt time in Figure 24, using the VSP-derived vertical stretch and squeeze function, to facilitate surface seismic calibration.

The model look-ahead velocity V_p 4885 m/s was used for the PP-up imaging (V_s 2442.5 m/s), as this was deemed the best match with nearby GGR3 well data. Depth predictions for events beneath the well can be picked directly from depth scale VSP images.

Main faults F1 & F2 are drawn on the bottom half of Figure 24, underlining lateral interruptions of reflectors. Many additional small faults are present on both PP and PS images. Fault F1 is marked by reflector interruptions as well as fast lateral reflector interferences, indicating that the fault strike is far from orthogonal to the source-receiver azimuth, while fault F2 is marked by a clear interruption of many reflectors, with quite no PS reflected energy in the southwestern compartment below Oxfordien horizon. Argovien, Oxfordien, and Callovien reflectors show a clear step fault pattern for F2, lowering the NE compartment. Some small local dips are visible in the image. The area dips are not deemed large enough to warrant being included in the model. The Callovien and top Bathonien reflectors indicate a definite small down-dip toward the Northeast, enhanced by several minor step faults. Considering the source position, out of the well deviation vertical plane (Fig. 23), the

interpreter must keep in mind that the 3D spatial positions of PP and PS reflection are slightly different on the images projected on the vertical plane of well deviation (Fig. 23). In particular, the Callovien-Bathonien reflectors show different continuities in PP and PS modes. Note that the PS-up CDP image on the right side of Figure 24 is presented in P-wave two-way times and exhibits a vertical resolution nearly twice as high as the PP-up image.

Remark: The 10³/₄ production casing got unexpectedly stuck at depth 1924 m and 1918 m MD (*i.e.* 1.00 s twt) during descent, possibly in a borehole washout interval related to the presence of nearby faults weakening the borehole wall stability...

To assist in a depth prediction of potential low velocity/high porosity target beds beneath the well an inversion of the VSP PP-up image to acoustic impedance was performed. The inversion performed assumes a normal incidence reflection response, which is not the case for the present GGR5 VSP survey. The absolute values of the inverted response could be altered as the reflector amplitude generally varies with the incidence angle.

Trace inversion of the time PP-up image into velocity and acoustic impedance was performed by combining the high-frequency VSP trace and a low-frequency velocity profile taken from the VSP calibrated model extended below the top Bathonien by the average value of sonic log velocity in the GGR3 nearby well. Figure 25 shows a display of the VSP PP-up inverted image converted back to vertical depth from Ground Level (TVD-GL) for direct reading.

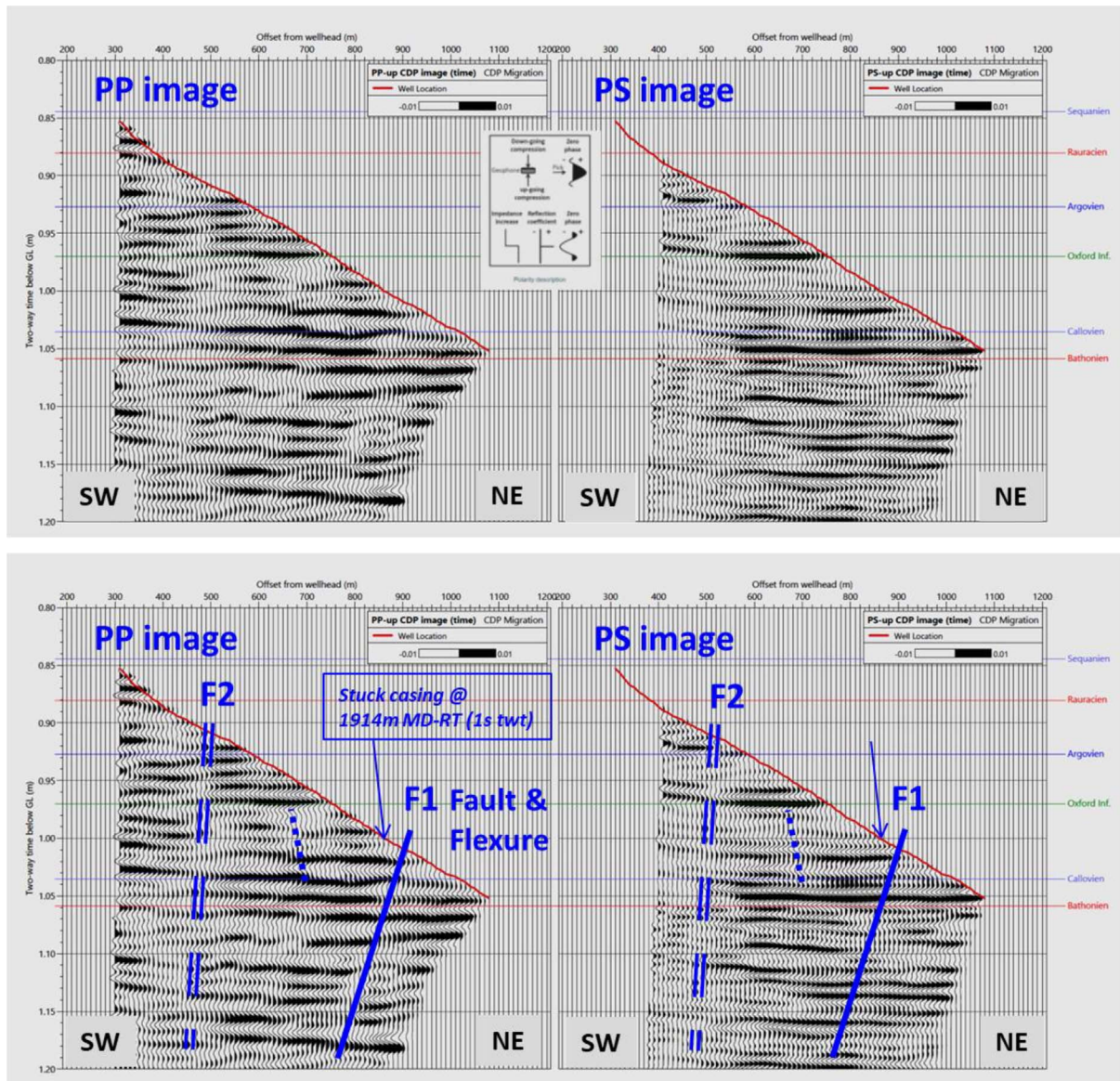


Figure 24. PP-up and PS-up reflection images converted to time (tw). Main apparent faults are underlined on the bottom display, on BOTH images. The reflectors surrounding the top Bathonian are slightly dipping to NE, and affected by several step faults, attenuated by lateral enhancement and migration. On the right side, the PS image converted to P-wave twt scale is restituted with higher definition due to the shorter shear wavelength. Figure modified from Figure 4.3.3 of Bailey [8].

The pilot hole encountered a depth interval of lower relative sonic velocity and density at 1600–1612 m, which was revealed productive; the deviated pilot hole is located about 100 m to the north-eastern border of the VSP image at this depth.

3.6 Intermediate VSP result summary

The SISMOSUB project was hoped to showcase a good example of a seismic application for geothermal prospects, by introducing the VSP techniques to tentatively help the drilling process, to finely calibrate surface seismic images, and to explore the high frequency seismic domain.

The results of the GGR-5 VSP were performed with the above in mind. The VSP processing was performed in a staged and timely manner. If required (and contracted) **fast turnaround** (<24 h) can easily be achieved for this type of project.

Good quality 3C geophone data was efficiently acquired from a single source location. The available location was not considered ideal, especially for look-ahead objectives, but still delivered good reliable results.

Depth VSP processing has been performed for the VSP corridor stack. 2D VSP images along the well path were produced in both PP-up and PS-up wave modes, with higher resolution in PS-converted mode, yielding similar structural features, thereby assessing the reliability of

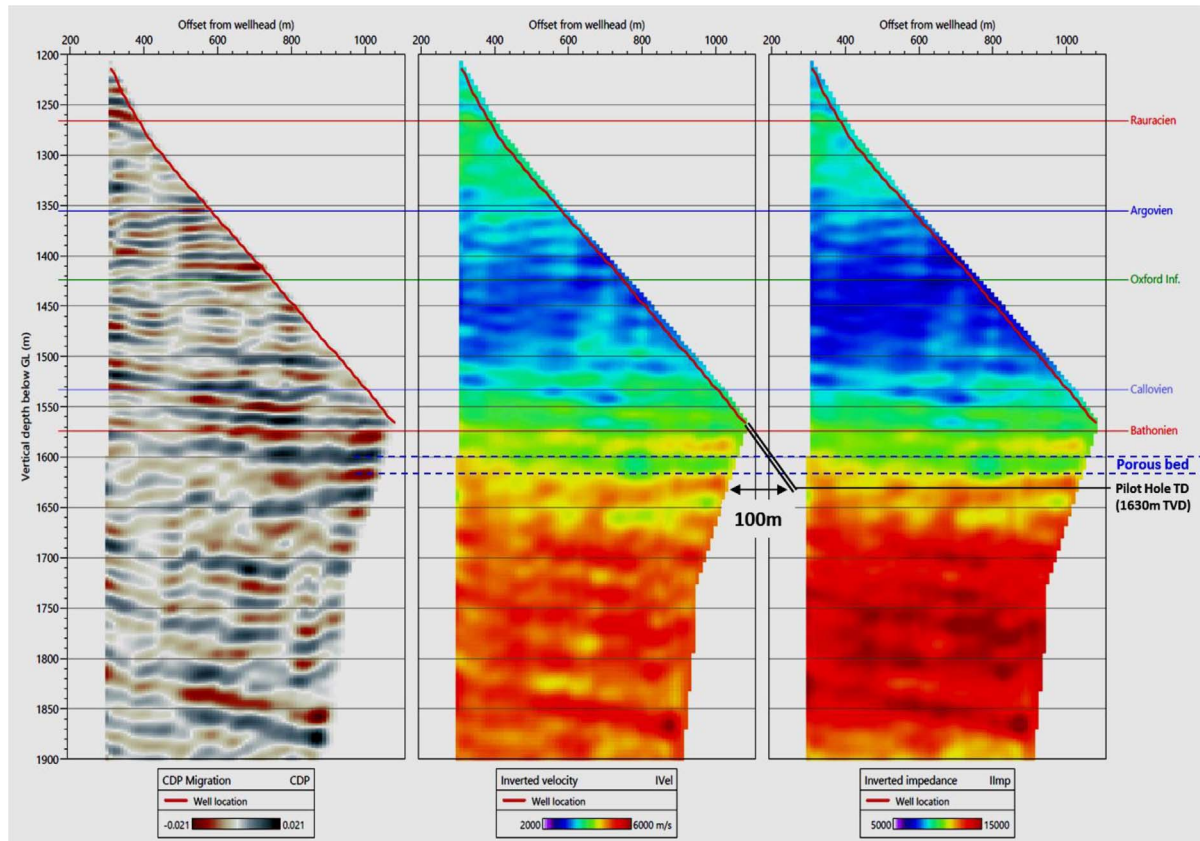


Figure 25. PP-up image inverted, displayed in-depth scale. The VSP inversion predicted a porous zone below/ahead, which was confirmed by the pilot hole drilled after the VSP operation. Figure modified from Figure 5.1.1 of Bailey [8].

VSP imaging techniques. A VSP velocity model with horizontal layering was calibrated for both P-wave and S-wave velocities. Results for both P-wave and S-wave were also converted to time using the P-wave TWT model profile.

The interpretation and prediction of the target porous structure beneath the VSP Total Depth (TD) was an important objective for this VSP, and the lookahead section had been confirmed by the pilot hole drilled in this instance, meaning that no fault step was present in the 100 m interval between the VSP image and the pilot hole.

To assist in the prediction below, the VSP depth image was inverted to acoustic impedance. The low-frequency velocity model ahead was qualified by the nearly well GGR-3 sonic log. From the inverted VSP data, the project VSP interpreter picked a porous reservoir interval starting from about 1600 m TVDGL.

Initial logged results from the pilot hole show a true porous zone from about 1598 m to 1610 m. A more detailed evaluation of the VSP accuracy and benefits for fine structural geology will follow.

Considerable efforts and attention were devoted to VSP acquisition and VSP processing imaging of the whole domain underneath the borehole deviated section, in both PP and PS reflection modes, revealing unknown geological structures, namely many sub-seismic faults marked by either interfered step faults patterns or brutal lateral interruption of reflectors. The reliability of the processing

software and the extensive experience of the processing operators yield credibility to the complex structure observed underneath borehole deviation. Fruitful exchanges between VSP processing operators took place to optimize the VSP acquisition and processing parameters on mutual technical agreement.

Reaching a VSP prediction of 100 ms TWT or 200 m depth below the borehole trajectory up to 100 Hz seems to be a feasible challenge in the Paris basin for any further VSP survey using a single-position vibrator source.

4 Extra VSP processing of HF frequencies

VSP data frequencies higher than 90 Hz suffer from severe attenuation, despite the field efforts to generate HF signal (the Log7 sweep reaches 100 Hz at 10 s, 175 Hz at 25 s). The dynamic range of the GGR-5 correlated stacked VSP dataset seems sufficient even if a higher Log sweep value was recommended at the acquisition stage to improve the S/N ratio above 100 Hz, as suggested by vintage R&D VSP surveys (Mougenot et Meunier [4]).

Extra processing actions were carried out to recover VSP reflections above 100 Hz, and to identify plausible HF seismic propagation physical difficulties.

First, the direct arrival signal remains coherent versus depth down to total depth, despite the abrupt amplitude

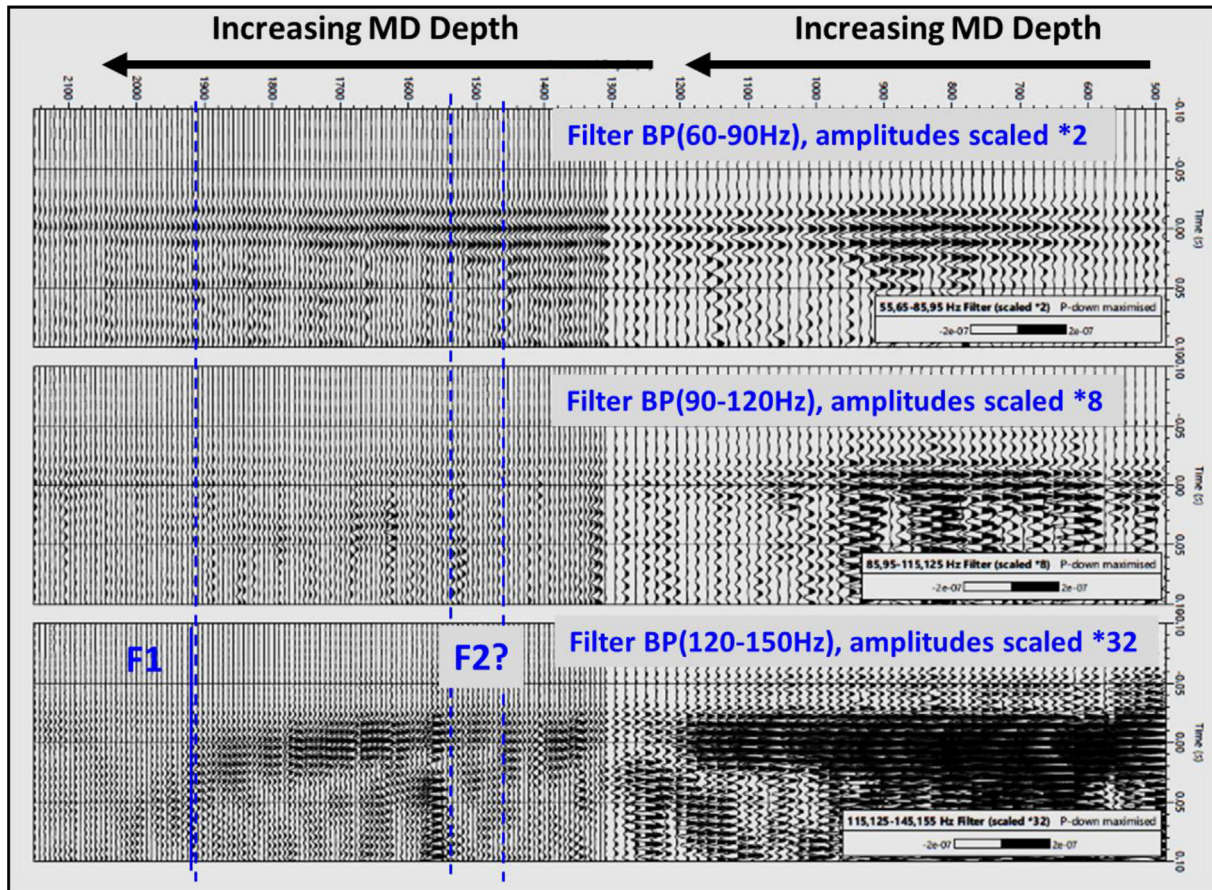


Figure 26. VSP first arrival filtered in the high-frequency bands, after cross normalization on full bandwidth raw first arrival peak. The direct arrival signal remains coherent versus depth down to the deepest VSP level, in spite of the abrupt amplitude losses observed at certain depths. Figure modified from Figure 3.3.3 of Bailey [8].

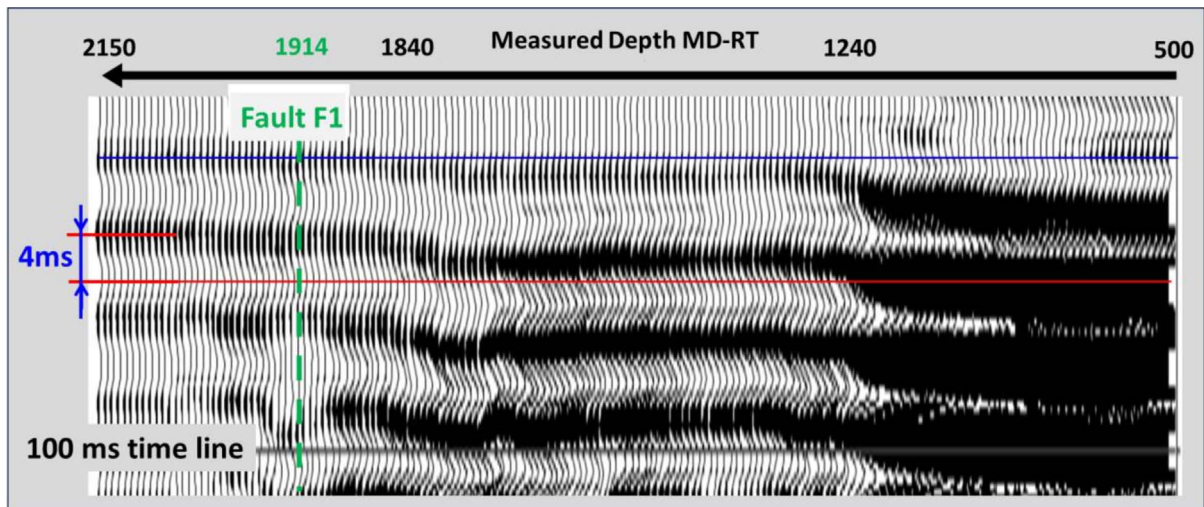


Figure 27. Downgoing raw P wavetrain flattened at 100 ms, full bandwidth amplitude peak normalized, then Low Cut filtered LC 120 Hz. Constant gain display. The dominant frequency corresponds to 150 Hz (7 ms period) on this display. The observed amplitude losses are relative to the amplitude of the first peak signal below 60 Hz.

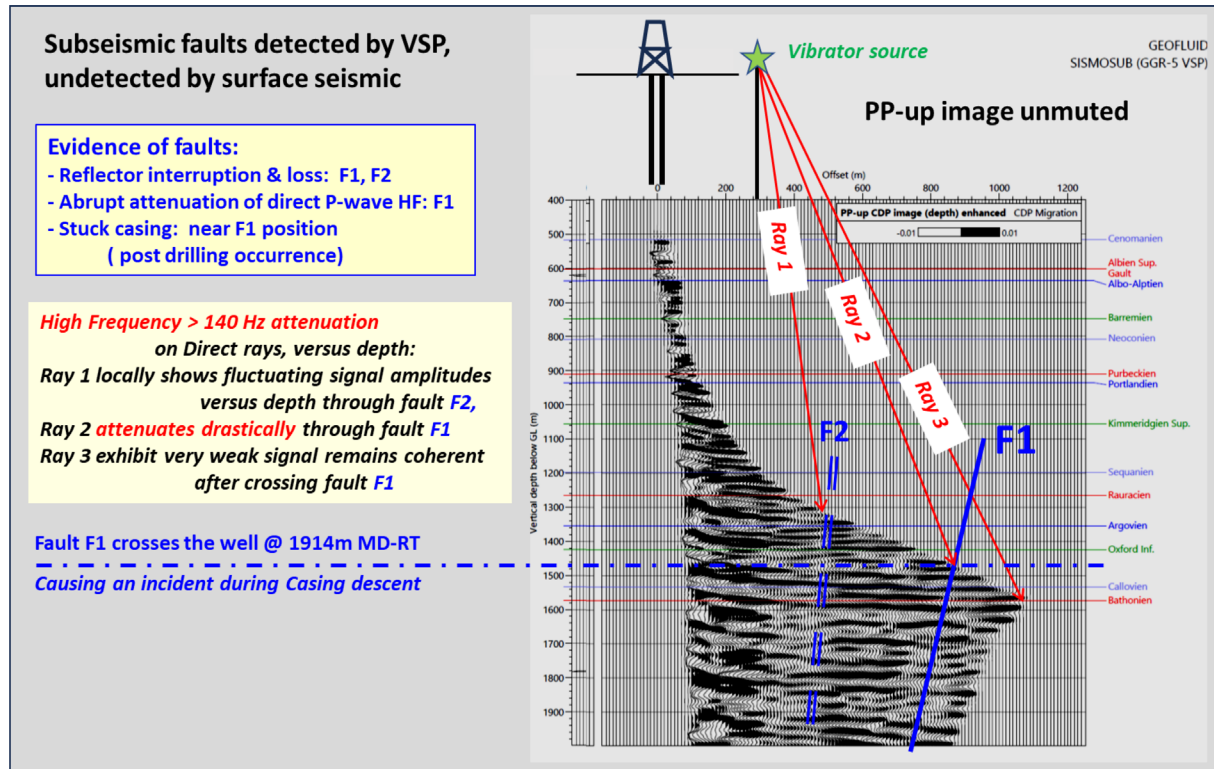


Figure 28. Geometry of seismic propagation through the faults F1 and F2 evidenced by the reflection PP-up VSP image underneath the borehole trajectory. Presentation figure *modified from Bailey [8]*.

losses observed at certain depths (Fig. 26, enlarged from Fig. 15). This coherency constitutes the main feature enabling the processing operations of wave separation and deconvolution.

Second, even if the LC-filtered first arrival exhibits definite signs of P-wave velocity dispersion (*i.e.* the high-frequencies of the seismic signal travel faster than the low frequencies), the abrupt time delays observed at 1240 m and 1840 m MD are locally accompanied by abrupt amplitude losses (Fig. 27). Again, the depth coherency of the HF content of the seismic signal and the small propagation time difference between observed between LF and HF do not impair using velocity filters for wave separation processing routines.

Third, the overview of the VSP geometry (Fig. 28) and structural VSP imaging features indicate that the step Faults F1 and F2 clearly identified on the PP-up reflection image are crossed by the well at depth locations where large amplitude losses are observed on the HF content of the direct ray arrivals. Therefore, the observed faults F1, and F2 can be likely attributed to boundaries between rock compartments of hectometric size, although the VSP cannot assess that these faults extend vertically above the borehole trajectory much higher than the Rauracien horizon.

Therefore, due to the large amplitude contrast between LF and HF contents in the P-down incident's first arrival, the signature deconvolution parameters have been questioned. This deconvolution is performed in the Fourier domain by dividing the amplitude spectrum of the received

reflection signal by the amplitude spectrum of the signature wavelet signal.

At the deterministic deconvolution stage, we consider what bandwidth to include and what level of stabilization noise is appropriate. Using 0% stabilization gives a balanced spectrum on the result of the P-down wavelet auto-deconvolution, limited to the high cut filter applied on the deconvolved result, if lower than the upper sweep frequency. Very low values of the signature signal spectrum should not be null to avoid zero "division by zero" fatal errors in the computer, thus a small stabilizing factor is commonly added (also called "prewhitening").

It must be noted that the deconvolved seismic reflections may NOT show a balanced frequency spectrum for the final reflection spectrum, as the series of reflecting coefficients in the subsurface may depart from having a white spectrum (a default hypothesis made by Kunetz [14] in 1961).

Encouraging effects on widening the deconvolved PP-up reflection results have been obtained by decreasing the stabilization factor, as shown in Figure 29:

On the top half of Figure 29, within the same frequency bandwidth **LC 120 Hz**, decreasing the pre-whitening from **2% to 0.5%** marginally improves the resolution and the separation between fault compartments.

The bottom half of Figure 29 shows improvements in the resolution using **0.5%**, and **0%** stabilization factors with a wider bandwidth (**LC 140 Hz**), all other parameters being identical.

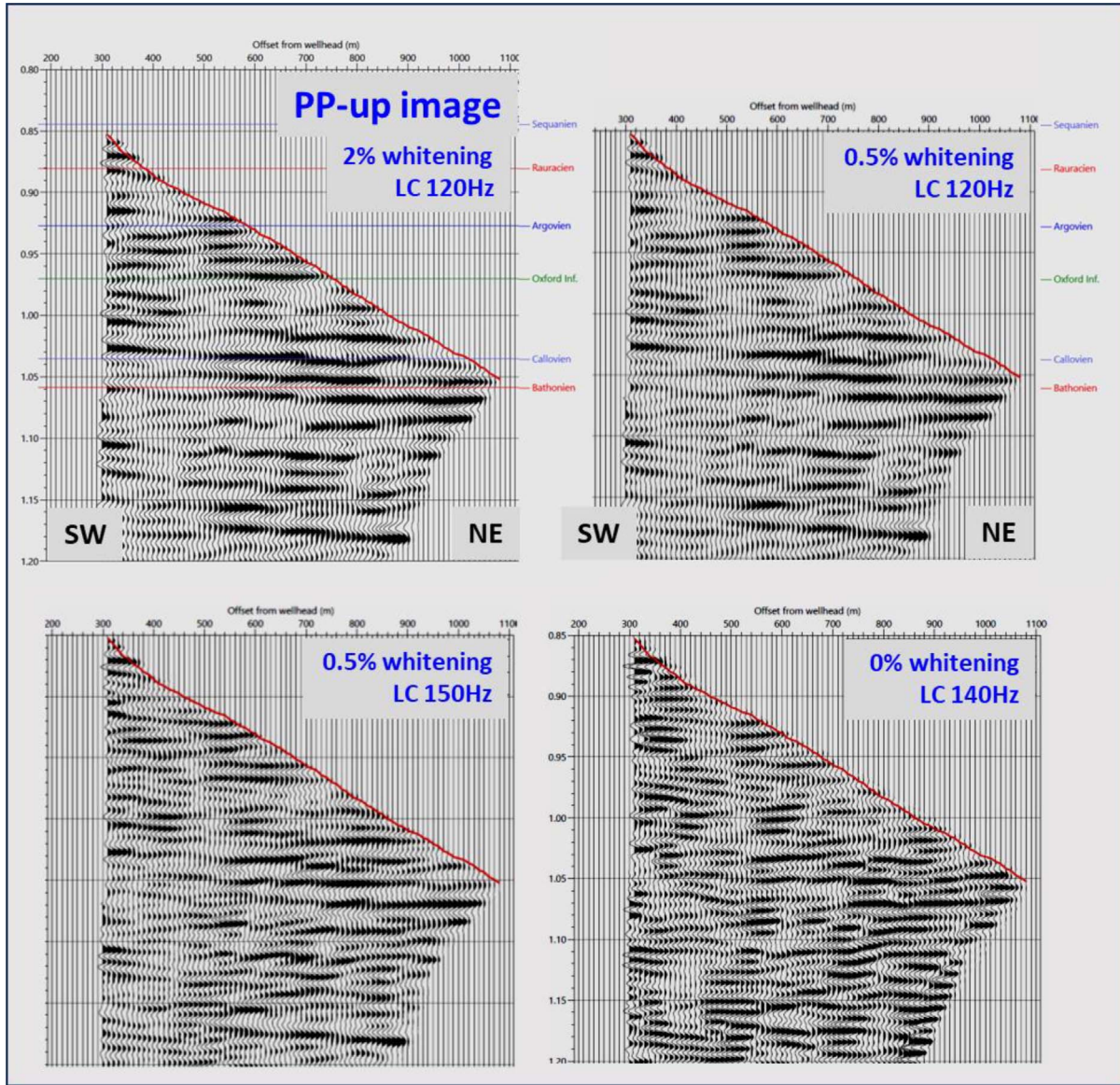


Figure 29. Tests of deterministic shaping deconvolution parameters using the SAME signature, but different stabilization factors and LC filters. Figure assembled from Figures 4.3.3, 7.1.4, 7.1.5 and presentation of Bailey [8].

The images produced with 0.5% and 0% pre-whitening (Fig. 29 Bottom) show the same main reflecting compartments as the top images; the same 9 trace median filter enhancement was applied to all datasets prior to migration. Reducing the number of traces of the enhancement filter would reduce the smeared aspect of the final VSP images.

Short signature length and severe/very small stabilization factors are justified in the present prediction VSP study as the high frequencies have quite low amplitudes (30 to 36 Amp. Db less than 120 Hz relative to frequencies lower than 60 Hz) and the prediction depth below the well is within 100 ms or 100 m in depth.

In short, the coherency of the incident P-down wavelet with depth, the high dynamic range of the VSP signal and the high precision of modern processing computers enable

obtaining high resolution in borehole imaging, within reasonable SNR limits.

5 VSP results and surface seismic

A set of surface seismic lines surrounding the Grigny wells GGR1,2,3,4,5 was reprocessed by CDPconsulting (position plan on Fig. 1). In particular, line 85OR18 is positioned very closely to the high angle well GRR5, in the same azimuth (Fig. 23), which gives an excellent opportunity to compare the VSP and surface seismic image, with the same SEG polarity convention on both images: an increase of impedance being represented by a negative, white trough.

The VSP images have been overlayed on the seismic line by projecting to the closest matching location trace.

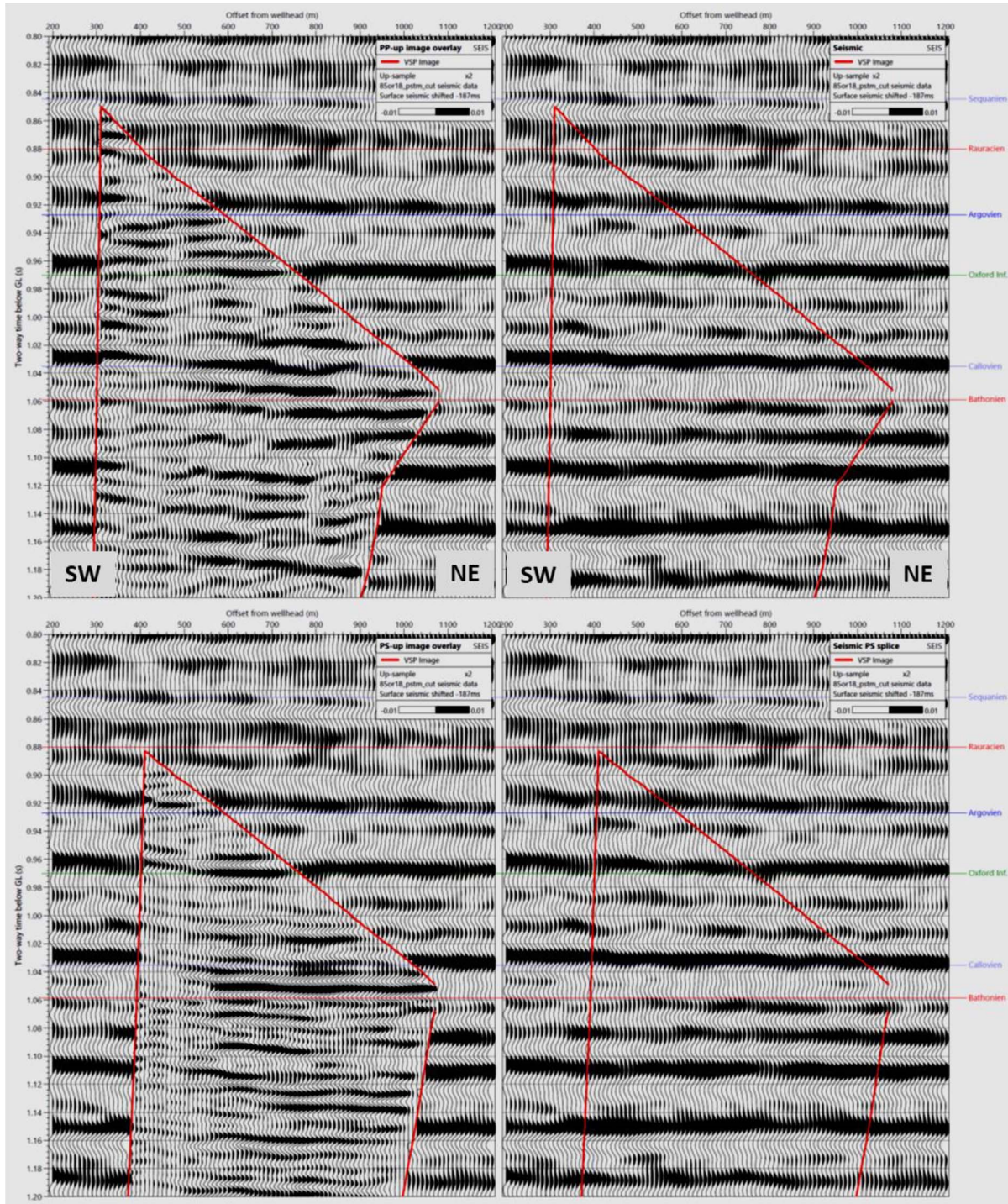


Figure 30. Top: Overlay of PP-up VSP image 120 Hz on PSTM surface section. Bottom: Overlay of PS-up VSP image 120 Hz on PSTM surface section. Figure reproduced from Figure 7.3.2 of Bailey [8].

The surface seismic data has been time shifted by -187 ms, corresponding to Floating Datum Plane (FDP) time determined from the surface seismic statics, to fit with the Ground Level (GL) time origin of the VSP images and P-wave VSP corridor stack. The PP-up and PS-up VSP images at 120 Hz, deconvolved with 2% whitening are overlaid on the 850R18 PSTM migrated section on Figure 30.

To say the least, the mismatch between the VSP image and the low-frequency surface seismic section looks flagrant in Figure 30, except for the gentle downdip towards NE. The faults and reflector interruptions observed on the VSP image barely yield any hint of the surface seismic image. Figure 31 shows the surface seismic section split apart at the well location (the well is projected onto

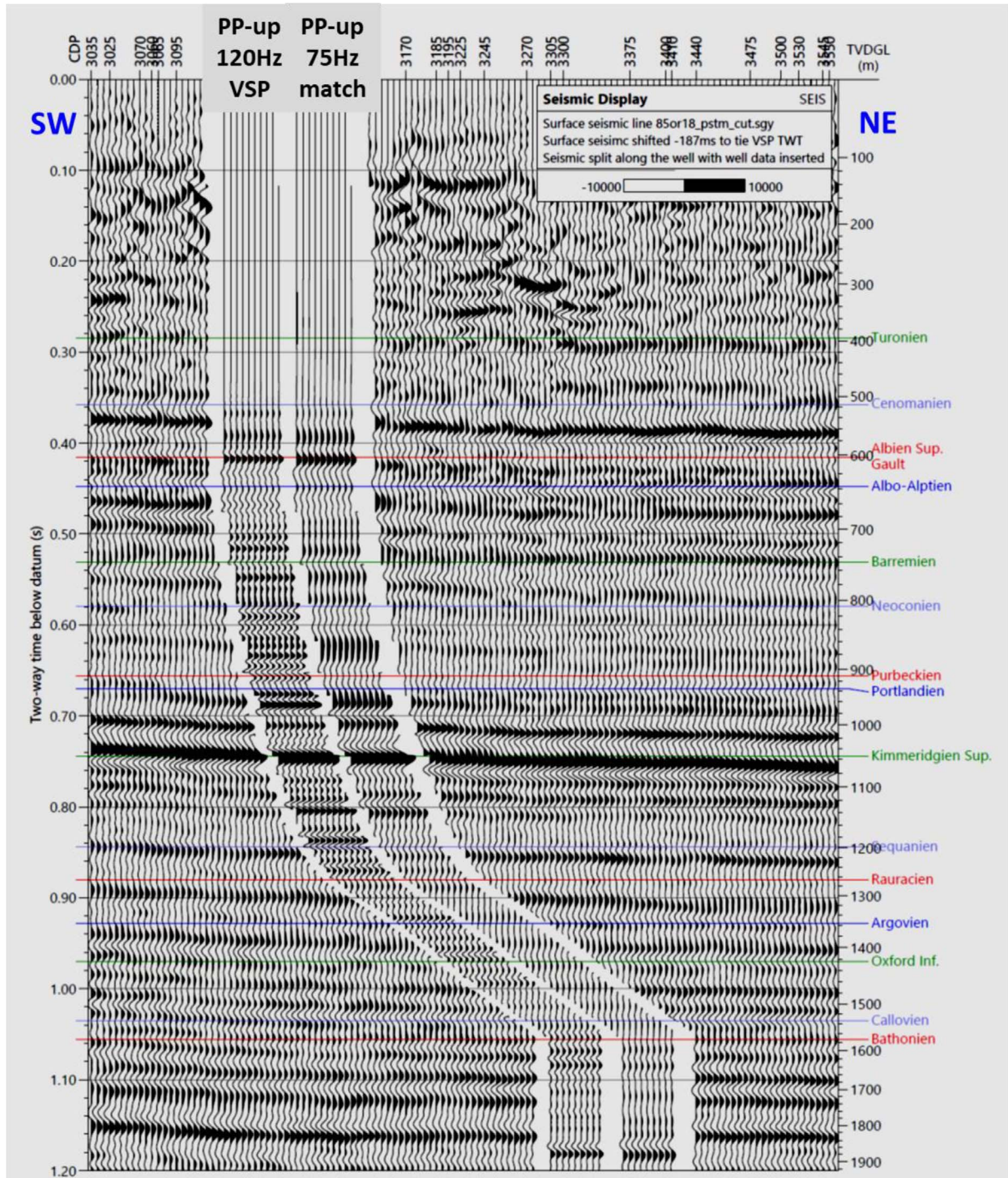


Figure 31. Time well tie with surface seismic (times from Ground level fitting with Floating Datum Plane- FDP of surface seismic). Figure reproduced from Figure 7.4.1 of Bailey [8].

the surface seismic line) and with the P-wave VSP corridor stack inset at 120 Hz and 75 Hz (seismic match) responses.

The discrepancies between the VSP corridor stack and the surface seismic image below the Kimmeridgien horizon including Dogger reflections on Figure 31 can be explained by the numerous geological faults evidenced on the VSP

images below the deviated borehole trajectory; these small throw step-faults are considered “sub-seismic” on the surface seismic images. By construction, the Fresnel zone of the reflections seen by the VSP is reduced relatively to the surface seismic one, especially where the reflector-source distance is much smaller than the surface source to receiver distance (ref: Hardage [14]), thus small throw faults are

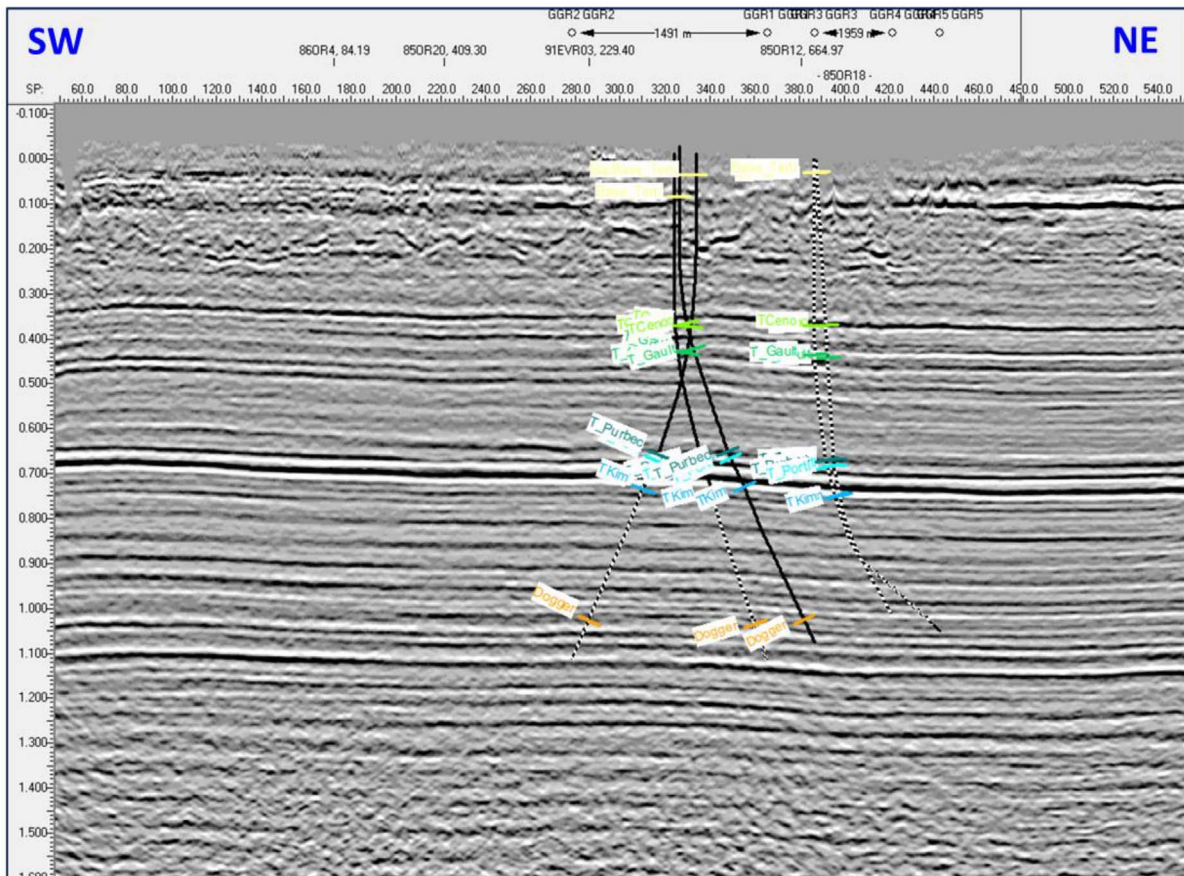


Figure 32. PSTM migrated surface seismic time section 85OR18, with projected trajectory of boreholes GGR1, GGR2, GGR3, GGR4, and GGR5. Vintage line reprocessed by CDPconsulting. Figure reproduced from Figure 23 of Vicelli *et al.* [16].

easily detected, in particular in a wide corridor stack domain.

Considering the faulted pattern evidenced by the GGR5-VSP at Dogger level, it was legitimate to examine closely the seismic surface 2D image of profile 85OR18 (final migrated image Fig. 32, plan view on Fig. 1) in the vicinity of GGR-5 well to tentatively pinpoint any clue of the faulting seen by the VSP.

The map of the top carbonate Dogger, produced in time (twf) on Figure 33-top, shows a gentle platform aspect with weak knolls and troughs of large diameters, without any noticeable fault. The depth converted map of the top Dogger horizon, on Figure 33-bottom, obtained with velocity and depth calibration on all available wells, presents a similar relief, with structures of 10–15 m of about 1–2 km diameter. The gentle dipping trend from GGR1 and over the GGR5 deviated and subhorizontal sections are down dip towards NE.

Remark: the reliability of the small observed structural dip is insured by the long-term experience of the CDP-consulting method of medium to long wavelength statics determination based on shallow layer geological modeling from numerous uphole datasets. The interested reader can access the instructive publications on this basic issue for the Paris Basin structural imaging, namely Hanot *et al.* [19, 20, 22], Becalotto *et al.* [21], Nosjean *et al.* [23].

Field recording parameters for the 85 OR18 2D line, vibroseis type: SN348 telemetric recorder with real time Correlator-Stacker CS2502 (with automatic edition of spurious noises of any kind), 4 Mertz-22 vibrators, Split spread 120 traces 40 m intertrace and inter source position, fold 60, linear upsweep (14–85 Hz), 4 sweeps per record with alternate polarity, a field trick aimed to kill even order harmonics generated by the vibrator; 36 (SENSOR SM4U 10 Hz) geophones per trace, deployed in-line.

Processing summary (iterative for some operations): Geometry, label, edition, data formatting, phase correction of recording chain to minimum phase, $T^{*1.2}$ divergence recovery, spiking deconvolution in three successive time windows (operator length 160 ms, 1% whitening). Initial static correction from geologic model of shallow layers (CDP consulting in-house method), followed by 3 passes of automatic static correction, 3 pass velocity analysis, cross line adjustments, time-variant filter, AGC, Final STACK, AGC, display of labelled plates, PSTM migration, velocity calibration on borehole information, depth conversion, map display of several Key horizons of good lateral coherency from above Dogger aquifer to deeper than Dogger, SEG-Y output.

The stack time section of Figure 34 restitutes coherent reflecting horizons down to 1.25 s twf. The top basement is expected around 1.27 s; the target Dogger horizon is

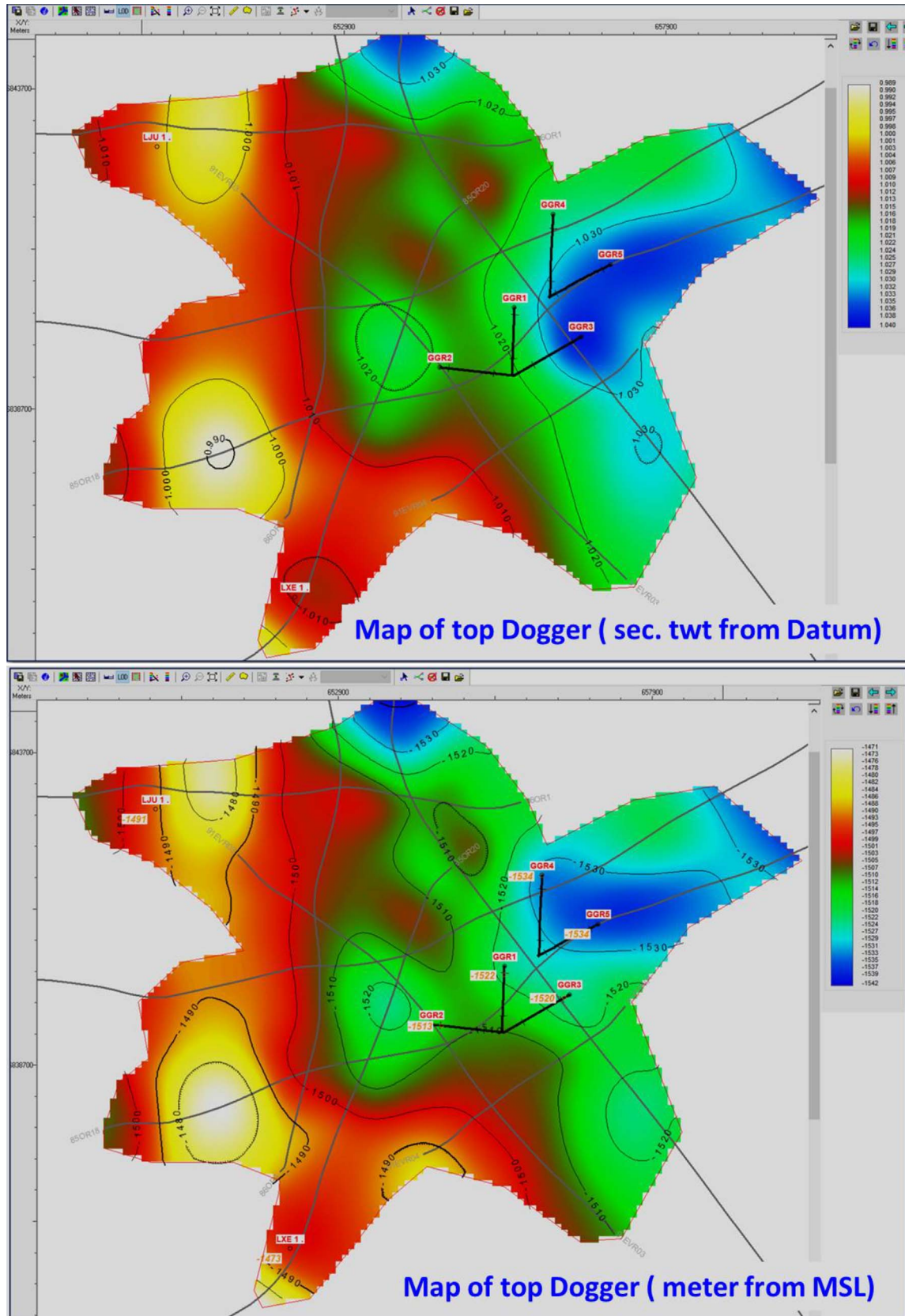


Figure 33. Map of top Dogger horizon, in time scale (top), and depth scale (bottom). Figure reproduced from Figures 34 and 36 of Vicelli et al. [16].

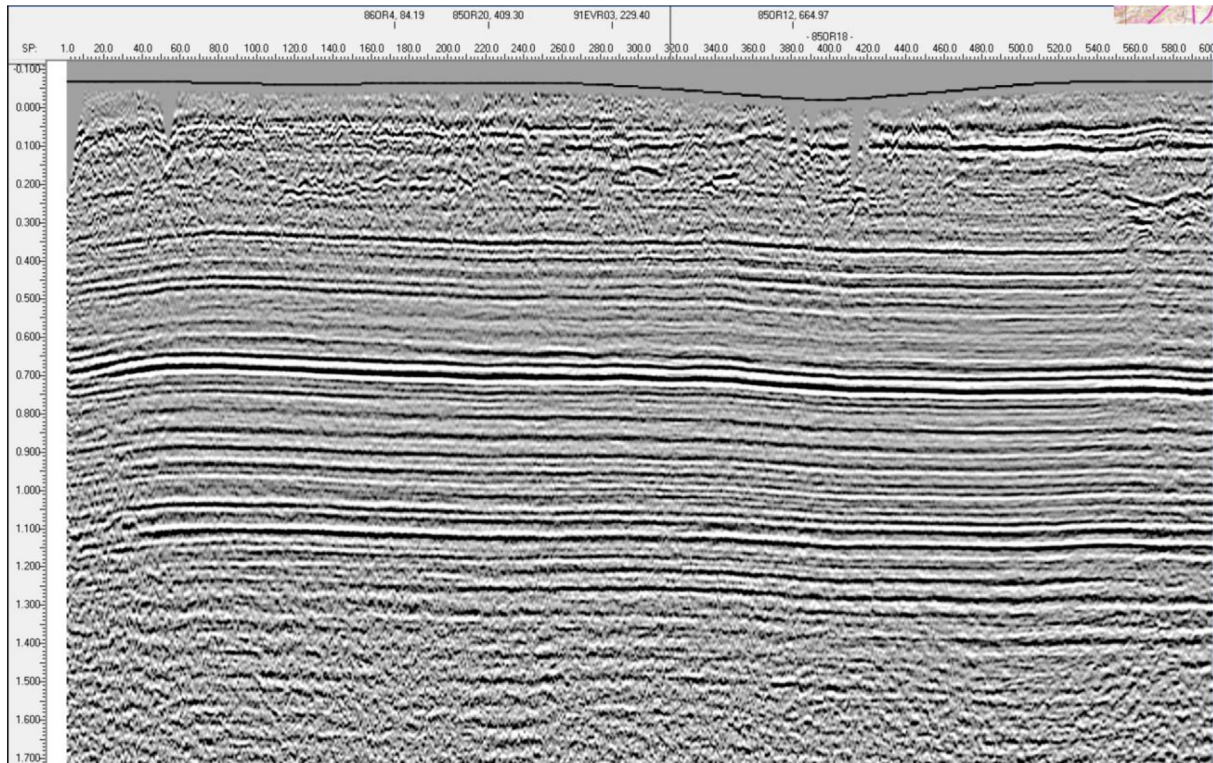


Figure 34. Stack section 85OR18. Figure reproduced from the presentation of Vicelli *et al.* [16].

around 1.0 s. Twt times are displayed from the origin zero seconds taken from a datum plane initially chosen at 50 m elevation, and the actual ground level is marked by a solid line called Floating Datum plane (FDP) located at -50 ms, above the zero-time origin. VSP times from the Ground level generally fit ± 5 ms with the FDP. In the present case, the time fit is less than 3 ms (Fig. 31), which translates the reliability of the shallow geological layer model of long-range static correction, including when crossing the Seine valley centered around CDP 410. For technical reasons, 2D-time migration is executed from the Zero-time origin of the datum plane.

All reflector horizons look quite coherent, down to 1.2 s. The top basement is estimated around 1.22 s–1.25 s from neighboring wells and does not constitute a marked reflector. All remaining reflectors below 1.26 s are deemed to be land multiple residuals, most probably generated between the strong Purbeckien-Kimmeridgien reflectors and the base of the weathered zone and/or the surface.

Note the intra-chalk diffractions around 0.2 s, a well-known source of undesired noise blurring the seismic reflection images in the Paris basin.

The seismic section excerpts assembled in Figure 35 evidence the resolution limitation at the Dogger level of the vintage surface seismic sections, in spite of the careful reprocessing operations and progress of the processing software: the small fault F1 detected by the VSP seems to be rooted deeper than Dogger formation down to basement, and may correlate with a 12 ms step fault (*i.e.* 20 m throw) seen on Rhetien level (1.23 s on Figs. 32 and 34 at GGR5 location). It looks quite chancy to be able to detect and

map such small faults on 2D seismic. Although high-resolution seismic lines (2D-HR) would help detect the presence of such small faults, only wide azimuth to full azimuth 3D-HR would enable mapping such faults: using the modern 3D seismic acquisition technology in urban areas, within acceptable costs, certainly remains a challenge for the geothermal industry in the Paris basin. Unfortunately, the VSP data was not processed deep enough to tentatively detect near basement reflections, if any...

Last, this gentle NE dip obtained by surface seismic is confirmed by the subhorizontal drain trajectory, Slide 17 of Naville *et al.* [17]. The surface seismic images have been obtained across the Seine River valley using the classical method of shallow layer velocity modeling developed and currently operated by CDP consulting, which provides a reliable deep structural image.

6 Additional VSP results

Since the seismic vibrator source of the VSP was located outside the vertical plane of deviation of the GGR5 well trajectory, an opportunity presented itself to determine the strike of a few clear small faults observed on the NMO corrected PP-up and PS-up deconvolved reflection wavefields, reproduced on Figures 36 and 37.

It should be noted that the VSP response obtained down to Sequanien depth (1200 m-GL) corresponds to a short offset VSP in a near vertical well, therefore the subhorizontal P-P reflectors observed in the 1200 m upper VSP levels correspond to true deconvolved reflectors at

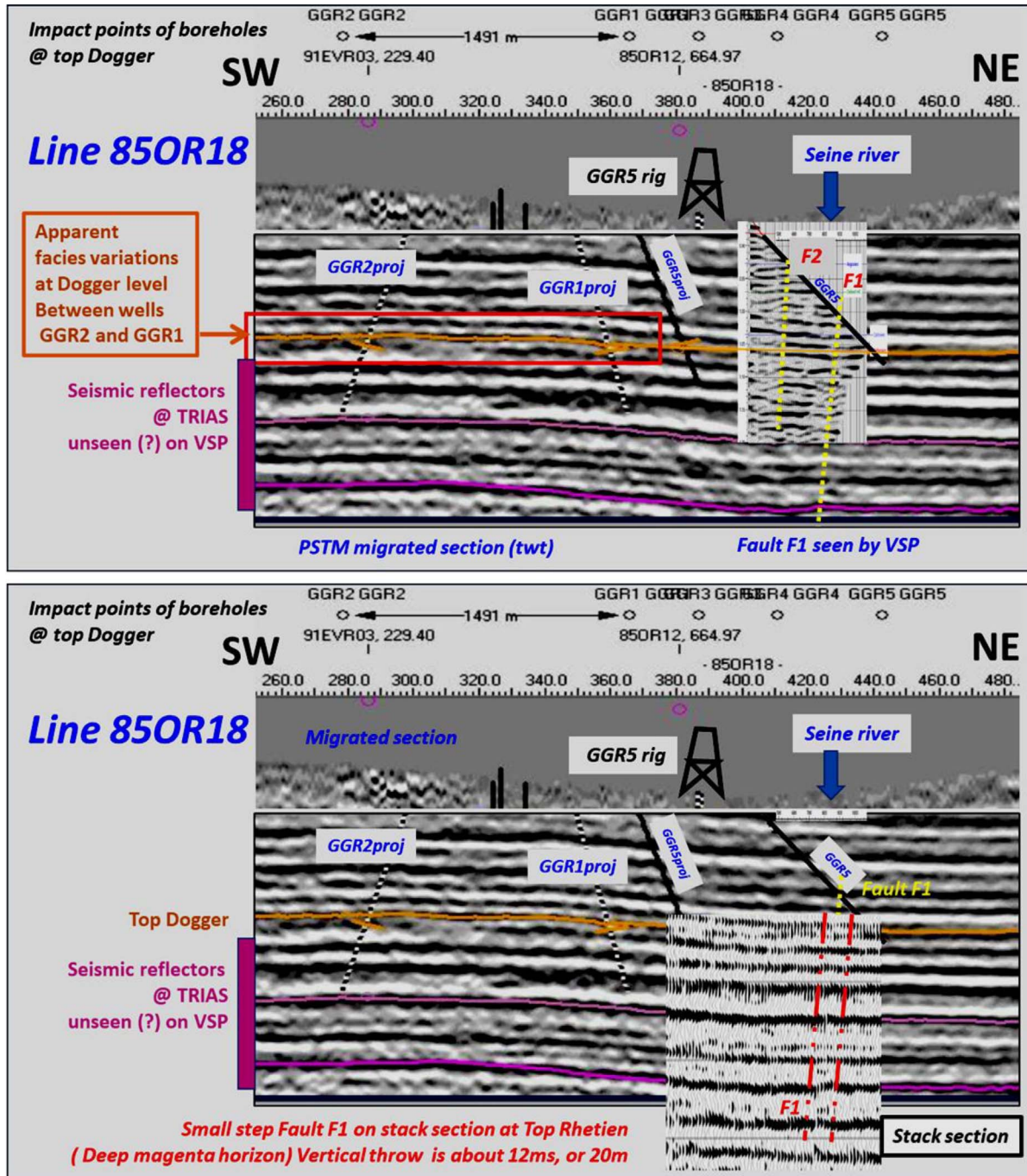


Figure 35. Top: Excerpt of the 85OR18 PSTM migrated section overlain with the VSP image below GGR5-deviated well section trajectory, with fault F1 underlined. Bottom: Same PSTM section overlain with unmigrated stack section below GGR5 well trajectory and fault F1 seen by the VSP. The migration smearing tends to smooth out the small step fault F1 on deep Rhetien level, near top basement. Figure modified from report presentation and .tiff stack section display of Vicelli et al. [16].

low incidence, especially in the deep interval below 1200 m, possibly down to the basement. In this respect, a limited VSP section is indicated in the blue edge box of Figure 36, in the western compartment of Fault F3, for comparison to surface seismic (Fig. 31).

In contrast, the P-S VSP image of Figure 37 is interfered with by S-S reflectors after the direct S-wave arrival, mainly in the near vertical incidence domain above Sequanien

depth, because high amplitude low-frequency downgoing S-wave are observed on the oriented raw VSP data (Figs. 12 and 14). Fault F3 cannot be defined at depth on this image, as P-S and S-S reflections cannot be separated in the yellow-colored S-wave domain of Figure 37.

It may appear surprising that a high amplitude, low frequency direct/downgoing shear (Sh) wavetrain is generated at near vertical incidence by a vertical vibrator

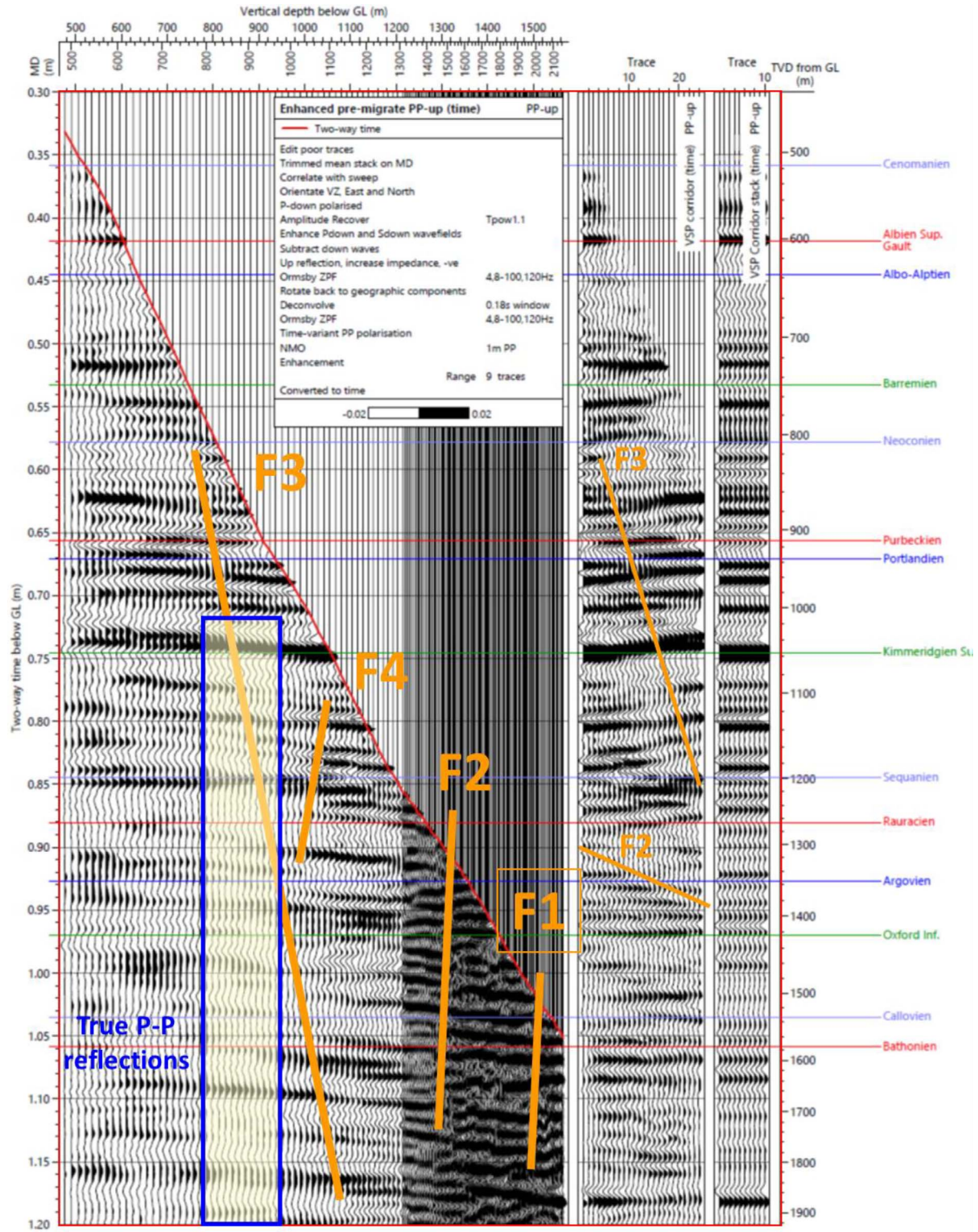


Figure 36. PP-up reflected wavefield, deconvolved, NMO corrected, at twt time scale. Clear faults are underlined. Subhorizontal events recorded down to Sequanien (1200 m-GL) are recorded in low incidence, thus are considered as non-interfered, reliable P-P reflections in the deep interval. The blue box on the left western side of fault F3 is retained for later comparison with surface seismic section. Fault F3 does not extend above Neocomien level (810 m-GL). Figure modified from Figure 4.2.1-PP of Bailey [8].

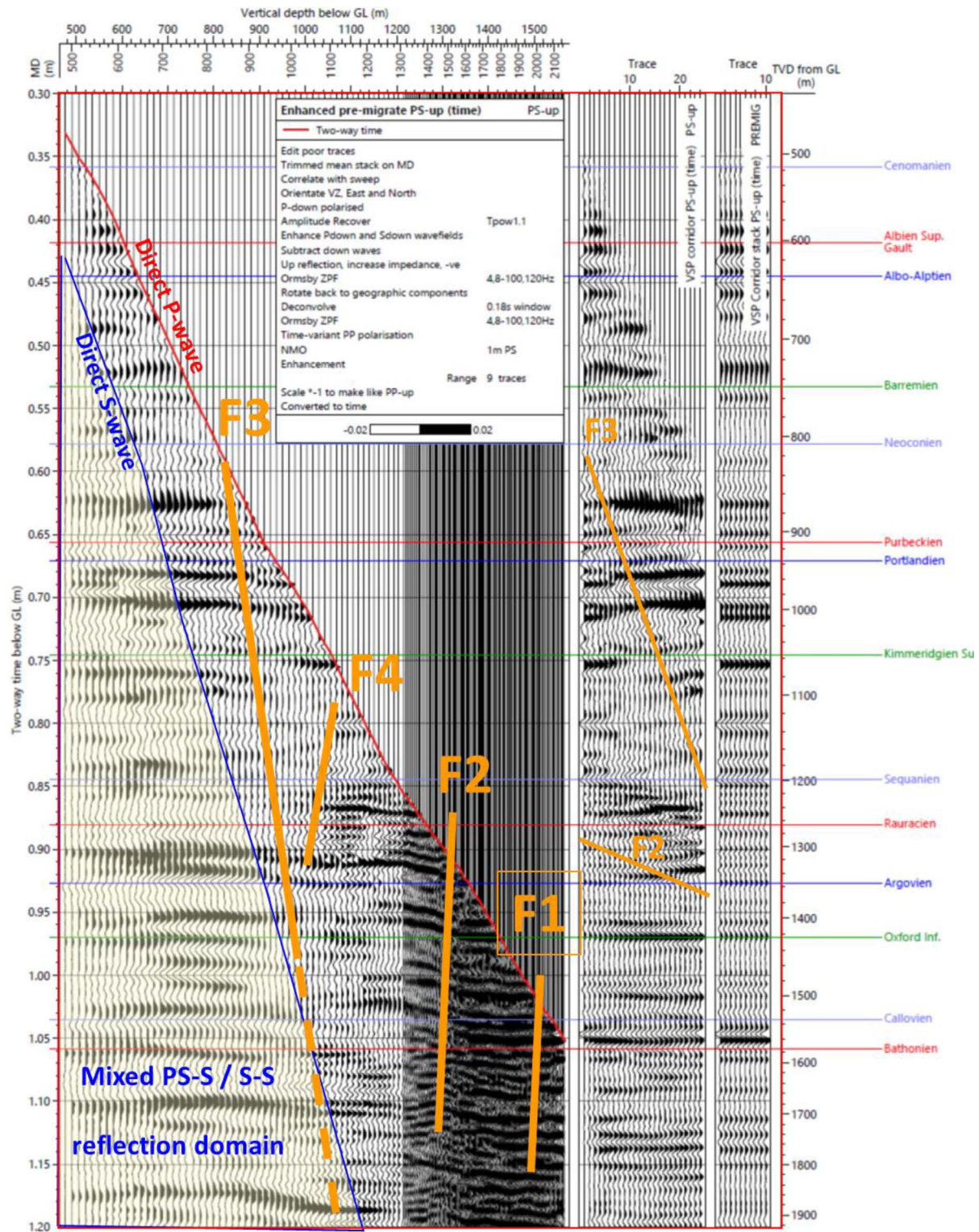


Figure 37. PS-up reflected wavefield, deconvolved, NMO corrected, at P-wave mode twt time scale. Clear faults are underlined. Interferences of inseparable P-S and S-S reflections after the direct S-wave arrival prevent accurate interpretation. Figure *modified from Figure 4.2.1-PS of Bailey [8]*.

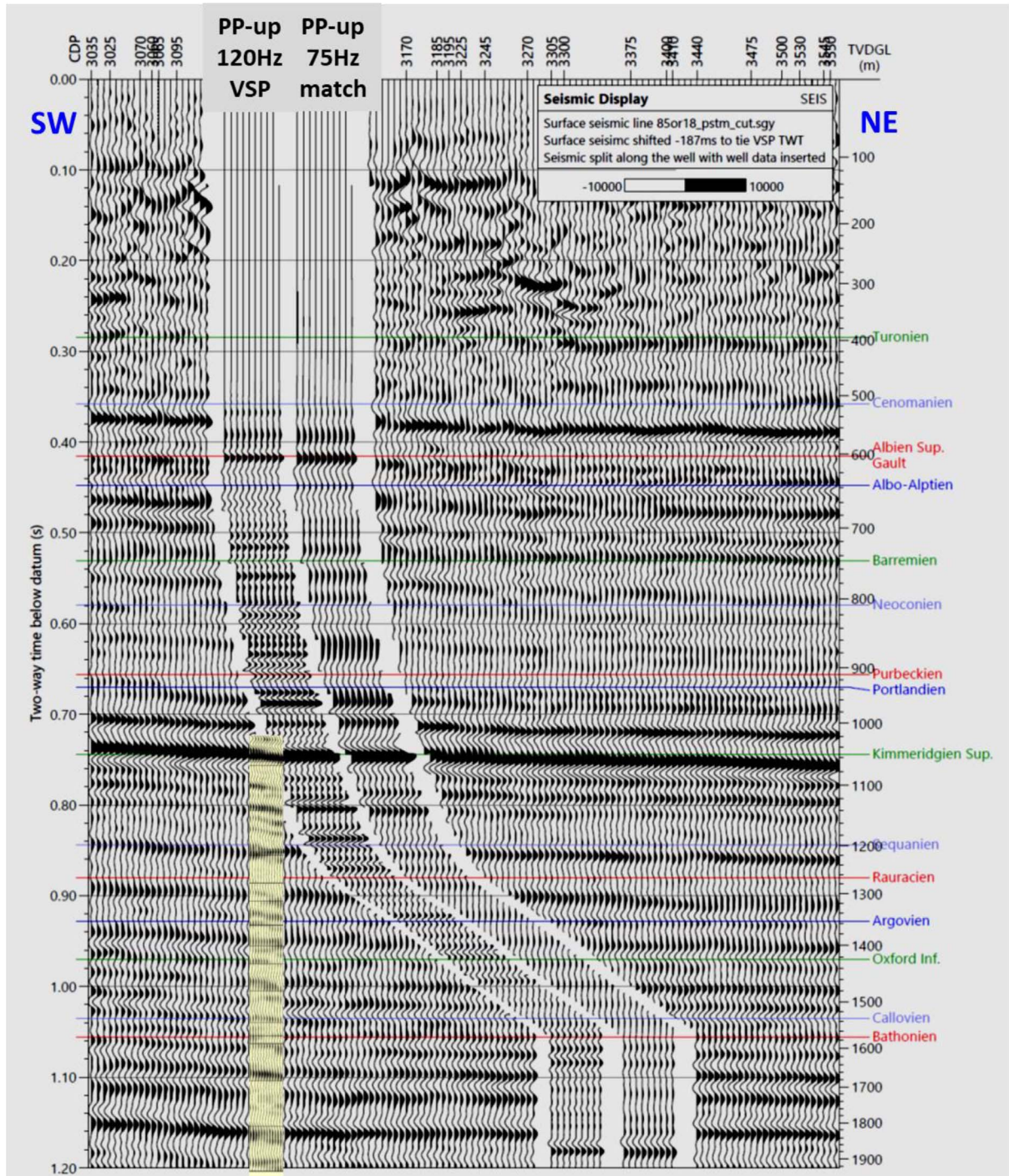


Figure 38. Well tie with surface seismic, in time scale from Ground level. Figure augmented from Figure 31, reproduced from Figure 7.4.1 of Bailey [8].

(Fig. 12 and 14), resulting in the strong, low frequency S-S (Sh-Sh) reflections observed on Figure 37. The main reason lies in the ground heterogeneity right below the vibrator, consisting of backfill of earth, recycled road gravel, and unknown material (?), disposed above uncompacted Seine valley natural alluvion. Luckily it did not notably alter

the emission of HF P-waves. Strong direct S-wave residuals are not uncommon in land VSP datasets.

In above Figure 38, the yellow-colored near zero offset P-P VSP earth response of the upper western compartment of Fault F3 seen on the VSP wavefield (Fig. 36) has been added as a projection on surface seismic section 85 OR

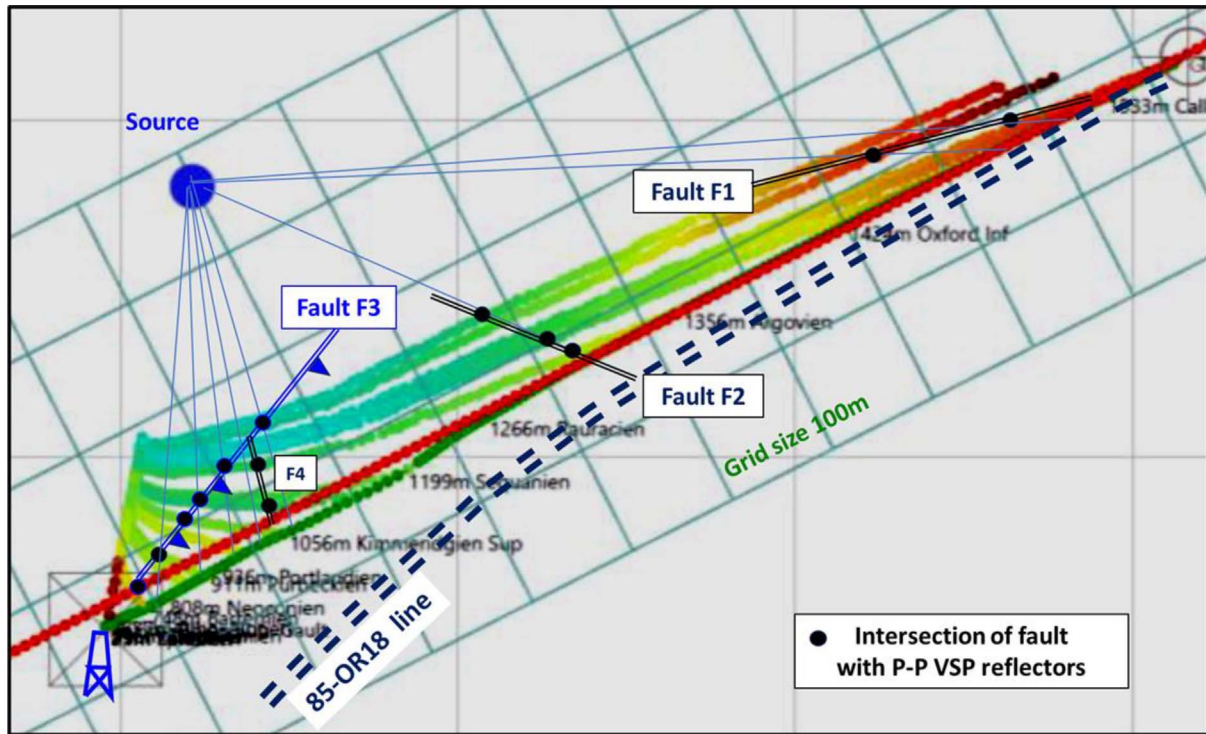


Figure 39. Position and strike of faults clearly seen on VSP images. The incidence angle for the intra Bathonien reflections extends from 15° (light green), to 23° (yellow), up to 37° (dark red) near the NE intermediate TD. Figure modified from Figures 4.3.1 and 7.3.1 of Bailey [8].

18: it can be observed the intra-Sequanien VSP reflector (0.85 s twt) and the well-defined deep VSP reflectors intra-Bathonien (1.08 s) and (1.15 s) fit better with the surface seismic section than the VSP corridor stack: this observation confirms the complex structural GGR5 borehole environment.

The 3D ray tracing routine developed by VSPROWESS yields the spatial position of the illuminated mirror points for each of the velocity contrast surfaces introduced, resulting in plan view Figure 39, modified from Figure 23. Therefore, the reflector interruptions corresponding to faults can be positioned with fair precision and provide interesting 3D structural information in the immediate borehole vicinity.

The position of faults F1-F3 may slightly change with the reflectors tracked:

The strike of fault F1 is close to the well deviation plane direction, which is coherent with the interfering aspect of the reflectors across this fault on the VSP image of Figure 24.

The strike of fault F2 is close to the source-receiver direction for many reflectors showing an abrupt lateral interruption on the VSP image of Figure 24.

Fault F3 extends vertically from Neocomien possibly to the basement, its strike is nearly parallel to the surface seismic line 85 OR18. Fault F3 appears as a clear step fault (~10 m vertical throw at Portlandien depth, 18 m at Kimmeridgien) and its seismic response looks interfered at all depths as the strike differs from the orthogonal to the source-receiver radial azimuth. The interference is due to

mixed reflections from both fault compartments, and possible diffraction from sharp fault edges (the VSP image must be interpreted as a “single fold” image, in reference to the surface seismic denomination...). Similar fault image patterns are observed on 2D reflection seismic sections and in long-range head wave refraction seismic.

Fault F4 looks like a secondary accident marked by abrupt lateral reflector interruptions.

7 Discussion

7.1 On the field seismic operations

Good exchanges were held in 2021 between downhole seismic hardware engineers and GEOFLUID drillers to prepare the SISMOSUB project and evaluate its feasibility, especially with the downhole sparker operation, which had to be canceled due to the extremely high amplitude of undesirable tube Stoneley wave. Gas injection in the borehole fluid might be a feasible solution in the future, with slightly underbalanced fluid conditions in a downhole section of the well to be planned and prepared by the drilling team.

Operating a long downhole seismic string of VSP tools in the 65° GGR5 open hole deviated section had to be cancelled, for safety reasons. Operating the downhole sparker tool alone in an open hole section still seems feasible, with the receiver toolstring inside the cased second hole of the geothermal well doublet.

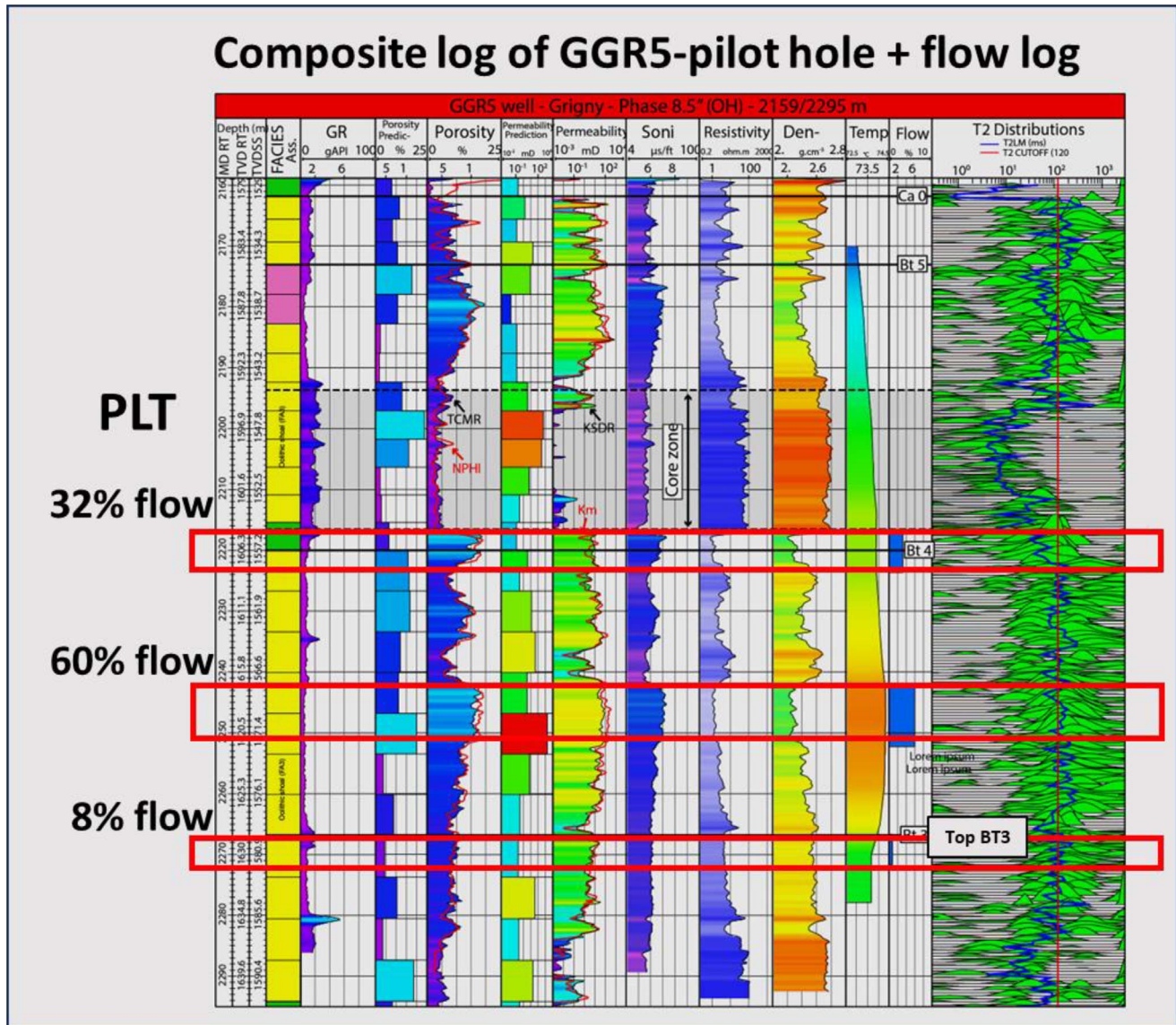


Figure 40. Composite log of GGR5 pilot hole, displayed below casing shoe (top of Dogger carbonates). MD Depth scale = MDRT/ from Rotation Table, 10 m above GL (first track on the left). TVD-SS = True vertical Depth from Sea level (50 m below RT). TVD-GL = TVDSS + 40 m (third track from left). Lithological units: CA-0 = Top of carbonates near base-Callovian. Btn = top of Bathonian transgressive-regressive sequence of order « n ». Red boxes = permeable oolite beds, corresponding to high porosity values and low velocity ($V = 1/\text{sonic}$) and density values, except for the deepest bed on top of Bt3.

Permitting issues for the VSP vibrator source need to be addressed very early for VSP operations in urban areas.

VSP Prediction below the borehole trajectory, or “ahead of the bit”, is best achieved with low seismic incidence. Therefore, it would have been appropriate to envisage using an airgun/G-gun source in the Seine River, or in a dedicated water pit prepared in advance, as soon as the GGR5 well trajectory was defined. In any case, operational constraints request to address defining the seismic source type and source field accommodation as soon as possible in urban and suburban areas.

Using a multilevel VSP receiver toolstring is highly recommended to accelerate the borehole seismic operations, especially when high frequencies are looked for.

The vibrator emission was extremely repeatable over the whole sweep frequency range, which ensures the reliability of geophysical and geological conclusions after analysis and processing.

7.2 On the VSP impedance prediction results confronted to pilot hole logs

The processing of VSP data focused on predicting low impedance thin beds below the deviated well trajectory, with seismic frequency as high as possible, was performed with the 3-component recorded VSP signals, and the results are partially successful, although the depth resolution of predicted low impedance thin beds have been impaired by

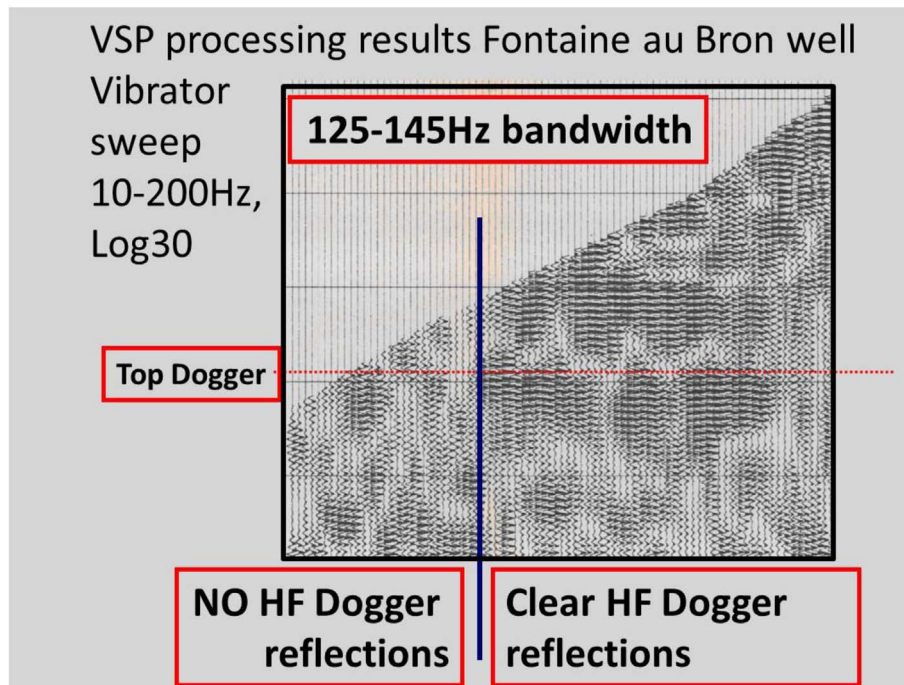


Figure 41. Deconvolved Dogger reflected wavefield, in the 125–145 Hz frequency band, figure modified from [Figure 3](#) of *Naville et al.* [3].

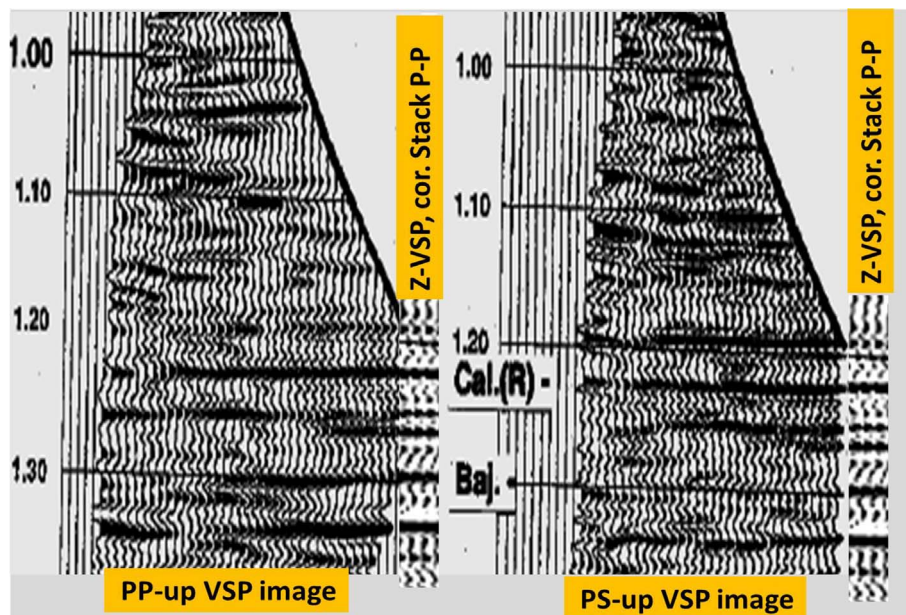


Figure 42. Deconvolved PP and PS VSP images from rig source VSP, in same PP twt scale, with corridor stack from second vibrator source near the vertical of Total Depth. Note the intense lateral variations from heterogeneous reflectors between 1.05 s to 1.2 s (Top Dogger). These heterogeneities located right above the Dogger reservoir platform alter the lateral frequency content of the Dogger interval reflections, thus may bias the results of fine reservoir studies and reduce their resolution. Figure modified from [Figure 9](#) of *Mougenot et al.* p. 464 [2].

the drastic wave attenuation encountered in the GGR5 well area, attributed to the presence of many faulted (and slightly tilted ?) blocks revealed by the VSP images produced. Indeed, drastic attenuation of high frequencies beyond 120 Hz occurs in the geologically reworked formation material in the vicinity of faults, clearly evidenced on the first P-wave arrivals.

Furthermore, VSP information was used for more detailed formation evaluation by using direct and converted downgoing S-waves, allowing measurement of shear wave velocities above Top Dogger as well as inversion of P-S converted reflected arrivals with even higher depth resolution than P-P VSP reflections.

The inversion in impedance of the P-wave reflections of VSP (Fig. 25) fits correctly with the low velocity, resistivity and density logs measured in the pilot hole (Fig. 40) in the 1596–1611 m TVDGL interval indicated by the two shallow permeable beds indicated in the red boxes, but the deepest productive interval does not correspond to a lower acoustic impedance nor to a lower resistivity (no indication of rock fracturation is available). Luckily, the pilot hole is located about 100 m away laterally from the location of the low VSP impedance interval in Figure 25, and fast lateral variations of reservoir characteristics have been observed while drilling the subhorizontal drain, which encountered no more permeability in the top permeable 2 m thick bed at 150 m laterally to the NE of the pilot hole (the geometry of the subhorizontal drain along thin porous carbonate beds is indicated in Naville *et al.* [17]).

7.3 On the results of reprocessed vintage surface seismic lines

The platform geometry of the Dogger geothermal reservoir formation appears in rather low vertical resolution but with excellent lateral coherence as a gentle, smooth surface, without major fault in the Grigny area. The Bathonien formation is nearly horizontal over the whole extent of the subhorizontal drain, on the NE side of the pilot hole: this geometry is confirmed by the image produced from the array of sonic data recorded in the subhorizontal GGR5 ST-1 drain (Fig. 1 of Naville *et al.* [17]). Nevertheless, the lateral coherency of the Dogger reflector response seems to vary between Grigny wells GGR1 and GGR2 (Fig. 35), and it is difficult to attribute these variations to facies variations or alternatively to the presence of numerous small faults, as suggested by the GGR5 VSP images. Definite progress should be made in surface seismic acquisition and processing, preferably with nothing less of a high fold/high resolution and full azimuth 3D seismic survey in order to become useful as a pre-drilling technique for geothermal development in the Paris area.

7.4 On the unexpected attenuation of seismic frequencies above 100 Hz on GGR5 VSP, attributed to the seismic propagation through small step faults

The seismic attenuation of the High frequencies is drastic on the first arrivals of GGR5 VSP, much higher than what was observed on a zero-offset VSP in the vertical cased test well

of Marolles en Hurepoix, located 5 km to the south of GGR5: this latter VSP was recorded in 1989 with different Log upsweeps, and up to 200 Hz, as related in Figure 8, reported by CGG's authors Michon [18], then Mougenot and Meunier [4]. The VSP corridor stacks on Figure 8 have been obtained with only the 12 VSP stations, 15 m apart, between 1400–1565 m, or 0.95–1.95 s twt interval in Figure 8, with a reliable high frequency look ahead prediction response beyond 1.05 s when compared to the 10–200 Hz synthetic seismogram, track 3 in Figure 8.

In contrast, the Fontaine au Bron HF VSP recorded by CGG in 1991, related in Mougenot *et al.* [2] and [6], and Naville *et al.* [3], 1996), using a Log30, 10–200 Hz upsweep vibrator emission shows HF amplitude fluctuations and extinctions of the Dogger reflections above 105 Hz on the VSP levels located in the 200 m depth interval right above the targeted Dogger reservoir, while VSP receivers located farther above reconstitute the desired HF Dogger reflections with good amplitudes, as illustrated by Figure 41. This fluctuating HF VSP reflection response may be plausibly explained by lateral rock formation variations in the immediate Dogger overburden, between 1.05 s to 1.2 s on the rig source VSP images of Figure 42: the PP and PS VSP images underneath the deviated well trajectory both express these lateral variations, although the target top Dogger reflections at 1.2 and 1.22 s are continuous monoclines.

In this respect, the GGR5 VSP images and the Fontaine au Bron VSP images equally evidence hectometric lateral variations of reflection response in the immediate Dogger overburden interval, which can be quite abrupt at seismic frequencies above 100 Hz. Unfortunately, there is no log measurements in the overburden to potentially confirm a spatial compartmentation of mechanical and acoustical formation parameters.

8 Way forward

Within the SISMOSUB project, the GGR-5 VSP dataset has been transferred to Christophe Barnes, geophysicist and academic researcher, for application of Full Wave Inversion (FWI) VSP processing technique with 2D elastic modeling, which would take AVO effects in account. A separate publication will be prepared using this alternative technique.

In the future, the difficulty of operating VSP acquisition with a vibrator source staying for many hours in a fixed position in an urban environment will remain.

VSPs acquired in deviated geothermal boreholes of the Grand Paris area would benefit from downhole 3C VSP tools implemented with Roll angle measurements to facilitate the 3C signal orientation and resulting 3D structural imaging (Wills *et al.* [24, 25]).

Running VSPs in old geothermal wells can be performed during the regular maintenance work over operations about every 5 years. 3C geophone and 3C fiber optic downhole sensors are preferred to single-axis DAS (Distributed Acoustic Sensors).

DAS VSP surveying in deviated geothermal wells in the Grand Paris area could be tested after implementing an

appropriate fiber optic cable inside the chemical inhibitor lines which are permanently installed into the Dogger geothermal producer wells of the Paris area.

Basic information on the VSP technique and seismic resolution from VSP surveys is suggested to interested readers in Campbell *et al.* [26], Al-Rahim *et al.* [27] and Hardage [15].

9 Conclusion

The present experimental study of borehole seismic in the Grigny GGR5 hole is a multidisciplinary technical success as far as VSP seismic acquisition, processing, and interpretation are concerned, resulting from the enthusiastic collaboration of many service companies with the reservoir and drilling engineers of GEOFLUID and GPCIP. However, the “so-called” 1D geological structure initial assumptions have been challenged by the reliable, fine-faulted structures highlighted by the GGR5 VSP images. The VSP technique is mostly efficient for imaging below the deviated section of boreholes and can be used to evaluate the quality of surface seismic images.

Even if VSP processing can be achieved within 24 h for prediction below the hole trajectory, the resulting image and impedance prediction may be different at a hectometric distance beyond the top Dogger casing shoe.

AVO effects may effectively alter the normal incidence inversion results, however, the numerous structural faults and the high HF attenuation observed considerably reduce the effectiveness of the present HF/HR VSP for the prediction of a thin, porous layer below the deviated well trajectory.

Locating the VSP source outside the vertical plane of borehole deviation allows to delineate of fine geological faults in 3D, using oriented 3-component VSP data.

Therefore the VSP technique, and the crosswell seismic technique when applicable, are clearly useful for revealing detailed geological structures between the well trajectories of a geothermal doublet, with a higher resolution than 2D surface seismic. Nevertheless, high-frequency VSP surveys in the Paris Basin seem to be reasonably limited to 140 Hz, for the Dogger reservoir, to avoid squandering the seismic source energy and field acquisition time.

The present study confirms that the VSP method mainly provides a detailed glimpse of the subsurface locally to the well vicinity, improving the spatial image resolution from a reduced Fresnel zone relative to surface seismic imaging.

Full azimuth 3D surface seismic surveying using high-resolution parameters is necessary to reach a finer description of the Dogger aquifer over large areas, using modern recording technology with thousands of surface receivers in an urban context: this remains a technical and economical challenge, to be tested in places where infill geothermal drilling is considered and where reservoir interferences between neighboring geothermal doublets are suspected. Modern, fine 3D surface seismic surveying can indicate subtle fault lineaments at Dogger depth that are unattainable with 2D surface seismic, as shown in the last 3D images

of Mougenot D. and Layotte P.C. [5] obtained in 1991 in the Villeperdue oil field, eastern Paris basin.

Last and by chance, small, sub seismic faults and natural fractures are prone to enhance the Dogger carbonate permeability when encountered by drilling, without affecting the sealing quality of the shaly Callovien cover.

Acronyms

ADEME:	Agence de l'environnement et de la maîtrise de l'énergie (French Agency for Ecological Transition)
VSP:	Vertical Seismic Profile
OVSP:	Offset Vertical seismic Profile (Surface source distant from well head)
HF/HR:	High Frequency/High Resolution
3C:	Three component (for seismic receiver or seismic signals)
DAS:	Distributed Acoustic Sensors
PP or PP-up:	P-incident to P-reflected wavefield
PS or PS-up:	P-incident to S converted-reflected wavefield
1D, 2D, 3D:	One, Two, or Three Dimensions (characterizes the Earth's geometry)
PH:	Pilot Hole
CS:	Casing Shoe
TD:	Total Depth (bottom of borehole, vertical or deviated)
TVD:	Total Vertical Depth
TVD-GL:	Total Vertical Depth from Ground Level origin
FDP:	Floating Datum Plane (seismic time of surface level in land surface seismic)
POOH:	Pull Out Of Hole
DLS:	Dog-Leg Severity
RHOB:	Rock formation density (log)
NPHI:	Neutron porosity (log)
ASL:	Avalon Sciences Ltd
SLB:	Schlumberger
CGG:	Compagnie Générale de Géophysique

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The authors appreciate the technical exchanges with colleagues of different disciplines which occurred during the SISMOSUB project, as well as the valuable comments from anonymous experienced exploration geologists and experienced VSP practitioners who reviewed the present paper.

Data availability statement

Access to surface seismic, VSP, and borehole data. The data used in the SISMOSUB project can be transferred to R&D researchers and VSP training centers for further studies, upon request to M. Antics in GEOFLUID.

Author contribution statement

Charles Naville, Mary Humphries: Conceptualization, Preparation, Global Supervision. **Sebastien Soulas:** Hardware, Field operation management, Field supervision. **James Bailey:** Borehole seismic processing, Software, Investigation. **Josephine Vicelli, Frank Hanot:** Surface seismic re-processing & structural mapping, Methodology and Software. **All authors:** Integration, Interpretation, Writing, Validation. **Charles Naville:** Technical project administration, Global Analysis, Review.

References

- Naville C., Soulas S., Antics M., Ungemach P. (2024) *Illustration of a land VSP field operation with vibrator source around the drilling site, Grand Paris area, France in Researchgate*. <https://doi.org/10.13140/RG.2.2.10611.09765>.
- Mougenot D., Layotte P.C. (1996) Imagerie sismique d'un réservoir carbonaté: le Dogger du Passin Parisien, *Revue Institut Français du Pétrole* **51**, 4, 451–496. (in French) <https://ogst.ifpenergiesnouvelles.fr/articles/ogst/pdf/1996/04/vol51n4p451.pdf>
- Naville C., Serbutoviez S., Mougenot D. (2002) Borehole calibration of the high frequencies filtering and attenuation in the Paris Basin, in: *64th EAGE Conference & Exhibition*, cp-139-00032. <https://doi.org/10.3997/2214-4609.201405761>. Presentation link: <https://www.researchgate.net/search.Search.html?query=%E2%80%A2Borehole+Calibration+of+the+High+Frequencies+%&type=publication>.
- Mougenot D., Meunier J. (2002) High resolution vibroseis in the Paris Basin, in: *64th EAGE Conference & Exhibition*, cp-139-00031. <https://doi.org/10.3997/2214-4609.201405760>, or: https://www.researchgate.net/publication/341014541_High_Resolution_Vibroseis_in_the_Paris_Basin.
- Mougenot D., Layotte P.C. (1996) *Seismic imaging a carbonate reservoir: The Paris Basin Dogger*. https://www.researchgate.net/publication/291961353_Seismic_imaging_a_carbonate_reservoir_The_Paris_Basin_Dogger.
- Humphries M. (2022) *VSProwess Synthetic GGR1-2-3-final report for GEOFLUID*.
- Rozemond J.H. (1996) *Slip-sweep acquisition, SEG Abstract ACQ 3.2. Initial Slip-sweep field test history*. https://wiki.seg.org/wiki/Justus_Rozemond.
- Bailey J. (2023): SISMOSUB GGR5-VSP_Processing report for GEOFLUID, 24-08-2024.
- Newman P. (1973) Divergence effects in a layered earth, *Geophysics* **38**, 3, 481–488.
- Naville C., Rivet A., Lesnikov V. (2017) *Extracting more information from rig source 3CVSPs, OA02, Fourth EAGE Workshop on Borehole Geophysics, 19-22 November 2017, Abu Dhabi, UAE*. Online Presentation slides: https://www.ifpenergiesnouvelles.com/sites/ifpen.fr/files/inline-images/NEWSROOM/Actualit%C3%A9s/OA02-more-info-from-VSP_0.pdf.
- Smidt J.M., in First Break (1989) VSP processing with full downgoing-wavefield deconvolution applied to the total wavefield, *First Break* **7**, 6, 247–257.
- Naville C., Serbutoviez S. (2003) Method for absolute preserved amplitude processing of seismic well data, US patent 2003/0086335 A1 <https://patents.google.com/patent/US20030086335A1/en>, or: <https://www.ifpenergiesnouvelles.com/sites/ifpen.fr/files/inline-images/NEWSROOM/Actualit%C3%A9s/US-Patent-2003-0086335-A1.pdf>.
- Serbutoviez S., Naville C., Throo A., Bruneau J. (2003) *3C VSP Processing and Interpretation in IFPEN*. Online presentation, November 2003, revised July 2020: <https://www.ifpenergiesnouvelles.com/sites/ifpen.fr/files/inline-images/NEWSROOM/Actualit%C3%A9s/2020-True%20Amplitude%203C-VSP-method.pdf>.
- Kunetz G. (1961) Essai d'analyse de traces sismiques, *Geophys. Prospect.* **9**, 3, 317–341. <https://doi.org/10.1111/j.1365-2478.1961.tb01514.x>.
- Hardage B.A. (1983) Fresnel zones and horizontal resolution. Handbook of geophysical exploration, in: *Section 1. Seismic Exploration, Vertical Seismic Profiling, Vol 14A: Principles*, Geophysical Press, London-Amsterdam, 286–295.
- Vicelli J., Nagy I., Miquelis F., Hanot F. (2023) Processing and interpretation report of vintage 2D seismic lines in Grigny area, Essonne, France, for GEOFLUID, June 2023.
- Naville C., Ungemach P., Antics M., Sarda D., Jocker J., Dalhaus L., Kumar R., Wielemaker E., Hamon Y., Souque C., Vincent B. (2023) Imaging the vicinity of a subhorizontal (SH) drain into the carbonate Dogger geothermal aquifer using the 3D Far Field (3DFF) processing of a dipole sonic array dataset; results and perspectives, in: *Presented in SPWLA 2023 Fall Topical Conference "See and hear the formation: exploring the synergies between borehole imaging and borehole acoustics"/ looking beyond the wellbore, November 8–9th 2023*. https://www.researchgate.net/publication/377983629_Imaging_the_vicinity_of_a_subhorizontal_SH_drain_into_the_carbonate_Dogger_geothermal_aquifer_using_the_3D_Far_Field_3DFF_processing_of_a_dipole_sonic_array_dataset_results_and_perspectives.
- Michon D. (1991) La sismique haute résolution dans la bassin de Paris, Pétrole et Technique, *Geologie-Geophysique* **365**, 5–15.
- Hanot F., Renoux P. (1991) Petrophysical variations in the Senonian chalk of the Paris Basin in their influence on static corrections, *First Break* **9**, 11, 515–526.
- Hanot F., Thiry M. (1999) Anomalies sismiques dans la craie et déformations superposées dans les formations tertiaires du sud-est du bassin de Paris, *Bull. Soc. Géol. France* **170**, 6, 915–926.
- Beccalotto L., Hanot F., Serrano O., Marc S. (2011) Overview of the subsurface structural pattern of the Paris Basin (France): insights from the reprocessing and interpretation of regional seismic lines, *Mar. Petrol. Geol.* **28**, 4, 861–879. <https://doi.org/10.1016/j.marpetgeo.2010.11.006>.
- Hanot F., Vicelli J., Miquelis F., Olivero G. (2012) Diagenèse de la craie du Bassin Parisien. Hypothèse d'un biseau salé d'âge éocène. Couplage des données industrielles et géologiques, *Bull. AGBP* **49**, 2, 6–24.
- Nosjean N., Hanot F., Gruffeille J.-P., Miquelis F. (2017) Statics: from imaging to interpretation pitfalls and an

- efficient way to overcome them, *First Break* **35**, 1, 1–8. Jan 2017. <https://doi.org/10.3997/1365-2397.35.1.87383>.
- 24 Wills W., Naville C., Nott-Bower M., Tubridy G., (2017) Orientation of a 3-C VSP dataset acquired by integrated geophone sensor and MEMS inclinometer devices, in: *3C orientation field QC, fourth EAGE Workshop on Borehole Geophysics, Nov. 2017, PO04, Abu Dhabi, UAE Proceedings*, pp. 1–6. <https://doi.org/10.3997/2214-4609.201702497>.
 - 25 Wills W. (2019) *A guide to orientating 3-C Geochain data using HSI devices*. https://avalonsciences.com/wp/wp-content/uploads/2014/05/HSI-Datasheet_v1.3.pdf.
 - 26 Campbell A., Fryer A., Wakeman S. (2005) Vertical seismic profiles—more than just a corridor stack, *Lead. Edge* **24**, 7, 694–697. <https://doi.org/10.1190/1.1993259>.
 - 27 Al-Rahim A.M., Doohee O.S., Iskandar A.Z. (2017) Simple processing sequence to VSP-seismic data matching in Sindbad oil field, south of Iraq, *Int. J. Adv. Eng. Res. Sci.* **4**, 10, 237283. <https://dx.doi.org/10.22161/ijaers.4.10.21>, or: https://www.researchgate.net/publication/320803004_Simple_Processing_Sequence_to_VSP-Seismic_data_matching_in_Sindbad_oil_field_south_of_Iraq.
- Gap in DT_BHC is filled with DT_POR (DT from NPOR) between 2040 m and 2055 m MD.
 - Spikey DT_BHC is replaced by DT_POR between 2087 m MD and 2089 m MD, as shown on the blue curve of Figure A1.1.
 - Where the density RHOB values are not recorded (ex: above 1510 m, ref Fig. A1.2), density is calculated from Gardner equation: $RHOB = 0.31 * (Velocity)^{0.25}$.

Synthetic seismograms are generated in GGR1, GGR2, GGR3 (example: Fig. A1.3).

Then a range of filters are applied to the reflection coefficients to simulate different seismic techniques. The filtered reflection coefficients are then inverted to impedance to ease comparison with recorded logs.

The results show that seismic data should contain frequencies up to 150 Hz to clearly see all the high porosity zones. However, seismic techniques use small variations in the shape of the seismic wavelet that make it possible to interpret the small changes with lower frequency, to a certain extent.

Appendix 1: Excerpts of synthetic seismogram construction on deviated wells GGR1, GGR2, and GGR3, drilled from GRIGNY-2 platform

A.1.1 Summary

Geothermal wells GGR1, GGR2, and GGR3 are investigated to ascertain whether seismic methods could distinguish different reservoir zones in the Dogger formation.

Synthetic seismograms are created from velocity and density logs. Synthetic seismograms are used to calibrate surface seismic sections with well data and to determine whether surface seismic might be able to detect any lateral variations in the reservoir characteristics.

GGR3 contains a full suite of logs for synthetic seismogram generation (compression velocity and bulk density). Velocity logs were not recorded in GGR1 and GGR2, but porosity logs are available in those wells and GGR3. Velocity and density logs are recorded in GGR3 and cover formations above and below the geothermal reservoir which will be useful in calibrating the surface seismic data.

Cross-plots of GGR3 logs NPOR (neutron porosity) and DT_BHC (borehole compensated velocity) supply conversion factors and those factors are used to convert NPOR logs to compression velocity logs in GGR1 and GGR2 (Fig. A1.1).

A.1.2 Synthetic seismogram

Log editing prior to synthetic seismogram construction:

The following edits are applied to logs in GGR3:

- Gap in DT_BHC logs is filled at 90 μ s/ft between 2024.8 m MD and 2040 m MD.
- The filled gap appears on the GGR3 logs of Figure A1.2, as a vertical segment around 1500 m in Vertical depth scale.

A.1.3 Conclusions on synthetic seismogram construction

Velocity data in GGR1 and GGR2 was successfully converted from Neutron Porosity NPOR logs using conversion factors calibrated in GGR3. Reflection coefficients from the synthetic seismogram were filtered at various frequencies and then inverted to acoustic impedance.

The results show that noise-free seismic data must contain frequencies up to around 150 Hz to clearly see all the high porosity zones inside the carbonate Dogger formation.

For future geothermal wells in the Paris Basin, starting with GGR4 and GGR5, it would be desirable to record the Neutron log above the top Dogger casing shoe up to the double casing section. In this way a sonic log could be inferred from the NPOR log up to about the Kimmeridgien level and overlap with the DT_BHC sonic log recorded before setting the casing. Such a logging procedure would catch the top Dogger limestone acoustic impedance contrast in every well, and build a synthetic seismogram over a much larger depth interval than over the Dogger aquifer interval only. This could be done without altering the common drilling-logging procedures and operations.

Appendix 2: Geophysical estimation of the spherical divergence amplitude loss from VSP in 1D medium. Choosing the signature length for VSP deterministic deconvolution

A.2.1 Principle

The value of the divergence amplitude in a horizontally layered medium (also called 1D medium, or Vertically Transverse Isotropic/VTI medium), for the near vertical incidence propagation, has been expressed by Newman [9] and can be estimated from the rms velocity V and vertical two-way time T derived from VSP: an example of such

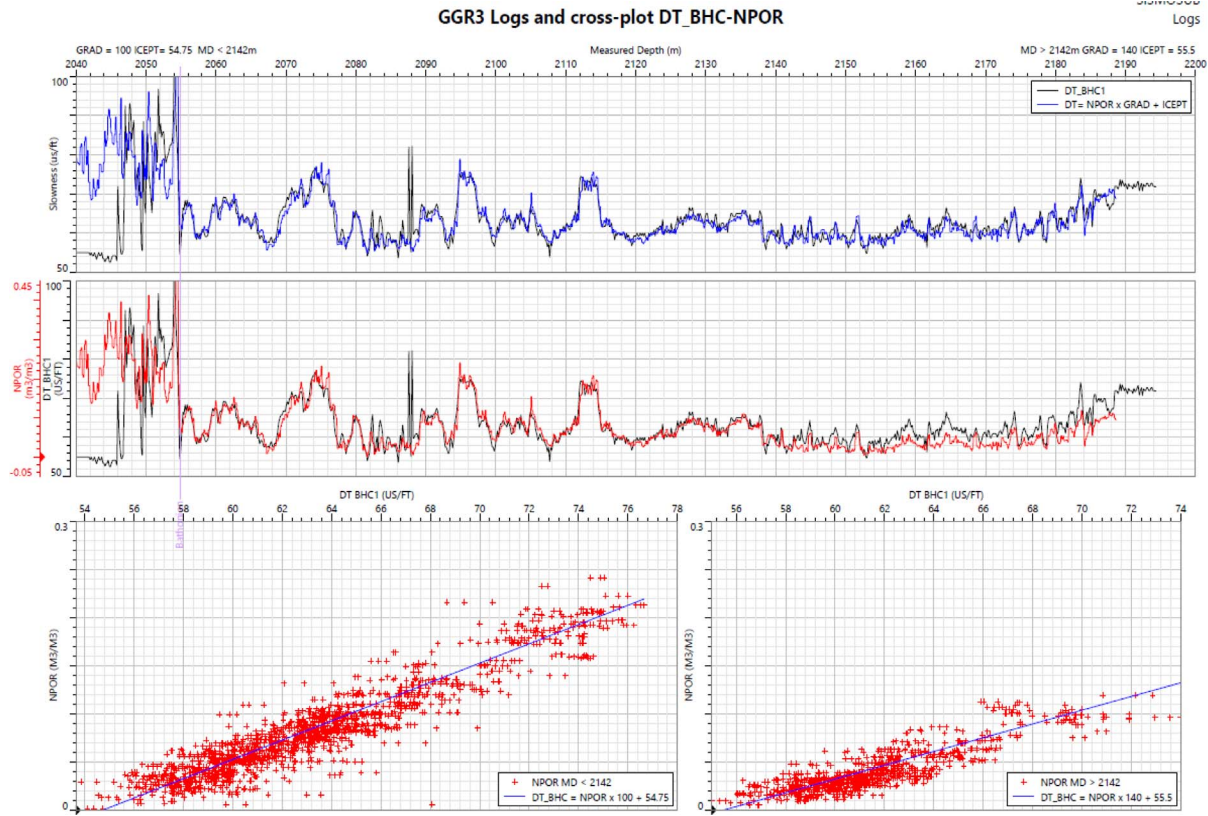


Figure A1.1. GGR3 Logs within the reservoir and cross-plot (DT_BHC, NPOR). The equations used for regression appear in the cross-plot boxes. Figure reproduced from *reproduced from Figure 3.1 in GGR3 TWT-Synthetic of Humphries* [6].

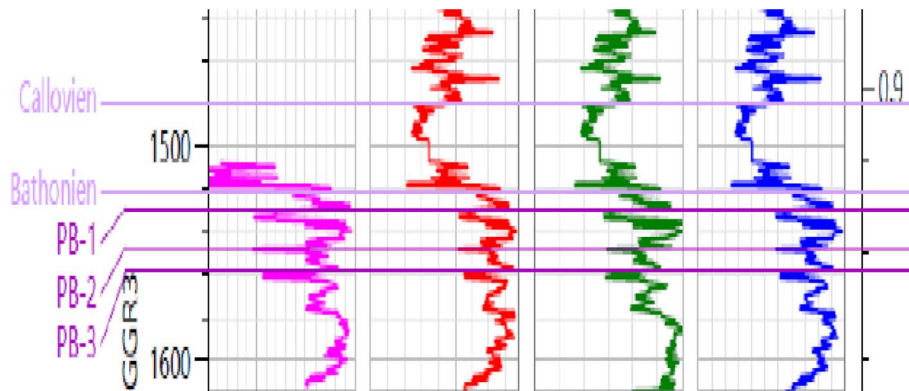


Figure A1.2. GGR3 Logs (NPOR-magenta, Sonic-red, Density-green, impedance-blue) in the 1440–1620 vertical depth interval. Tops of Porous Beds are noted: PB-1, PB-2, PB-3. This figure is modified from *Figure 4.2 of Humphries* [6].

VSP derived divergence is given in [Figure 1](#) of Naville *et al.* [10], reproduced in the same workshop presentation, slide 6, by the same authors.

For the deviated GGR5-VSP, the time exponent of the divergence function has been visually estimated to **1.08**

from the display [Figure A2.1](#). This significant time exponent is in good agreement with the spherical divergence independently determined for surface seismic processing in the Paris basin sedimentary interval with basement overlap (**exponent 1.2**).

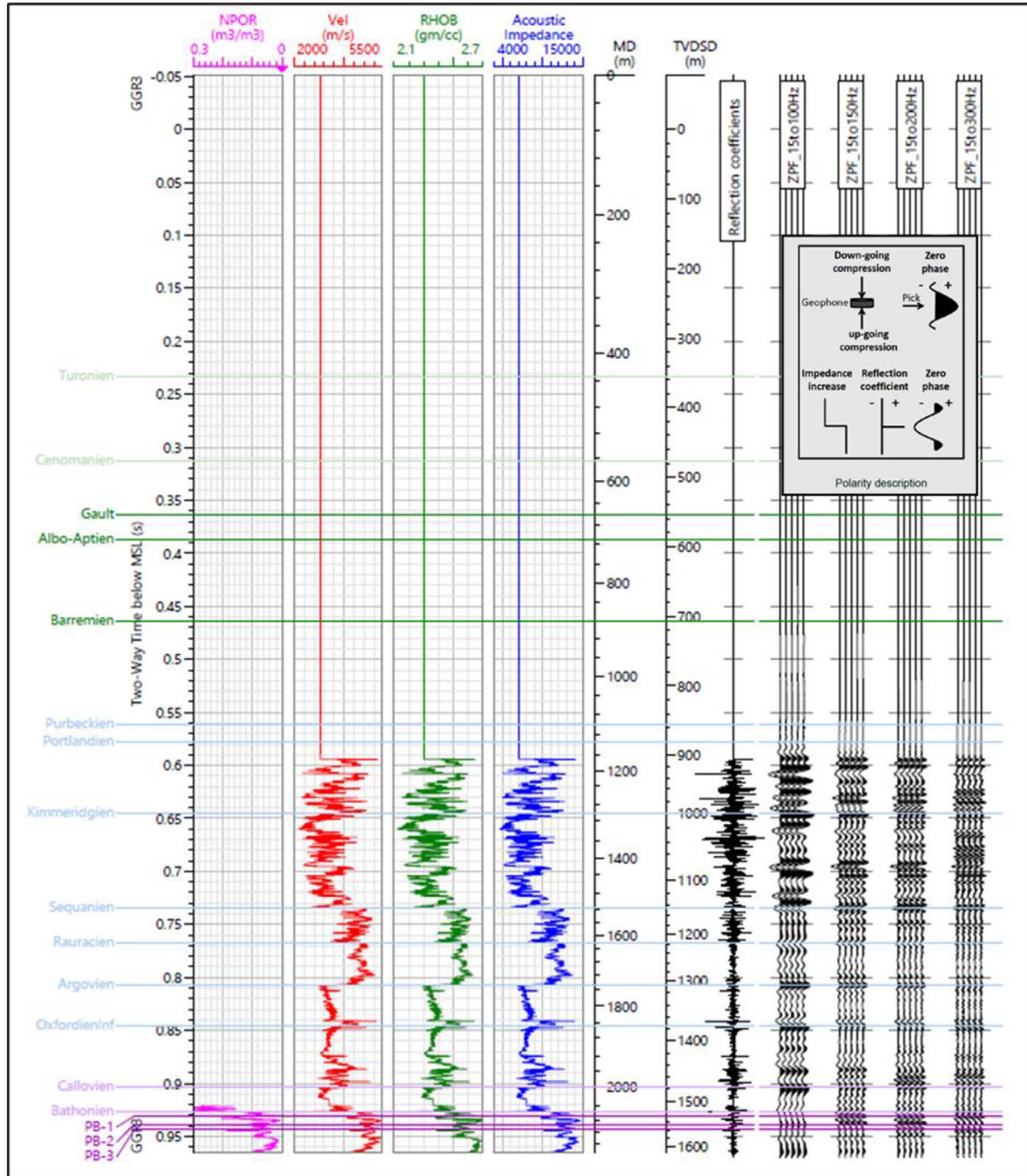


Figure A1.3. Synthetic seismogram construction on GGR3, in two-way time scale (left). MD depths and TVDSD vertical depths from Ground level appear at the center. The Reflection coefficients are filtered in 4 frequency ranges, with zero phase wavelets, on the right side. The polarity description of these filtered seismic responses appears in the upper right box. Figure modified from *Figure 4.1 of Humphries [6]*.

A.2.2 Consequence on the signature length used for VSP deterministic deconvolution

- First, the conventional zero offset VSP processing route starts with isolating the P-down wavetrain from all other wave modes using a velocity filter of some sort (median filter, FK filter, parametric separation, etc.)

- Then, a deterministic deconvolution is applied using a time-windowed signature on the head of the P-down wavetrain, in which the signal holds most of the seismic energy.

The above operations are correct, except that an amplitude compensation ramp in the form of T^{**n} is applied on the

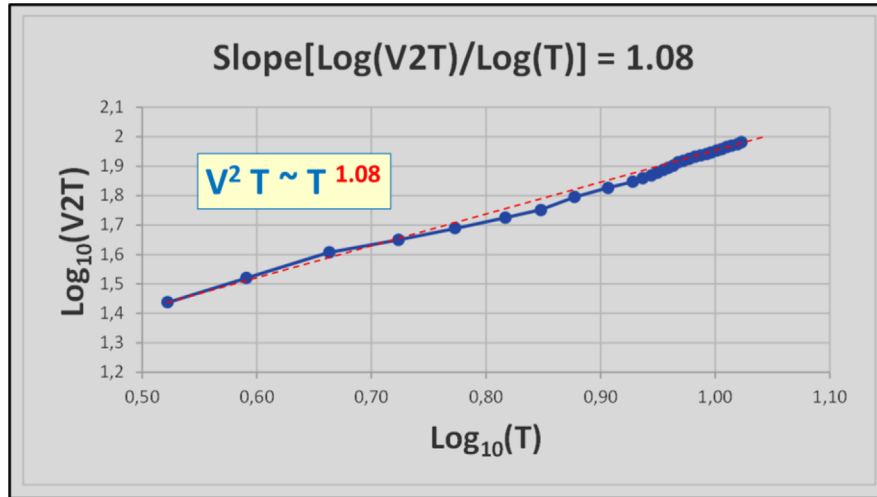


Figure A2.1. Geometrical spreading computed from GGR5 VSP depth and times, from surface to top Dogger depth. A straight-line regression yields a time exponent value of 1.08.

raw VSP dataset BEFORE wavetrain separation. The initial application of spherical divergence compensation is inherited from surface seismic processing practice where the signal spiking deconvolution procedure assumes quite short source wavelets (typically 100–250 ms), and short operator lengths (often < 200 ms), although the computation window is much larger. Nevertheless, the surface seismic processor has enough seismic imaging clues to fairly estimate the spherical divergence while building surface seismic images. In contrast, the VSP processing geophysicist does not have much seismic data in hand, and he may inappropriately define a too-long signature signal (from 600 ms to 1 s or even longer) by overcompensating the raw VSP data amplitudes prior to deconvolution.

Additionally, deconvolution routines are linear operations, while an amplitude compensation ramp versus time is not, therefore these two types of operations cannot validly commute in a strict mathematic viewpoint, especially when the time window defining the source signal wavelet on the downgoing P-wavetrain is long. Overcompensating amplitudes of raw VSP data can lead to altering the amplitudes of the desired deconvolved deep VSP reflections. In these conditions, it is recommended to estimate the time exponent of the geometrical spreading from the VSP data and minimize the signature length retained for the VSP deterministic deconvolution, keeping in mind that

the highest frequencies of a direct P-wave arrival are in the head of the direct arrival rather than in a late pegleg...

An alternate approach is to deconvolve the VSP dataset before applying any divergence amplitude compensation, which has been investigated by very few authors: deconvolving the total VSP wavefield was tested in vertical component offshore VSP by Smidt [11], to study the potential differences in the processed VSP results relatively to the conventional VSP route, mentioning the potential data distortion by non-linear processes of divergence correction and wavefield separation. Oriented 3C VSP processing in true amplitude has been developed and tested by Naville [12], and Serbutoviez *et al.* [13], to improve the accuracy of deep seismic reflector amplitudes from VSP and to better identify the observed seismic events on VSP datasets, namely reflection, diffraction, and wave type. “Deep” VSP seismic events pertain to the time delay between the incident’s first arrival and seismic events, typically beyond 200 ms. Of course, deconvolving the total field of a VSP dataset requires carefully estimating the coherency and stability versus depth of the P-Down re wavelet considered for deterministic deconvolution. Trace-to-trace deconvolution versus single-operator deconvolution procedures is a matter for the processing VSP geophysicist to adapt, and so is the order of application of divergence compensation and deconvolution.