Seismic while drilling with a diamond drill bit in project DIVE DT-1B borehole in the Ivrea-Verbano Zone (Western Alps, Italy)

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Abstract

A unique Seismic While Drilling (SWD) experiment, whereby a diamond coring drill rig as the seismic source has been conducted in the Val d'Ossola, Western Alps, Italy. For the SWD experiment 64 3C-sensors are employed in an array at the surface and the grinding action of coring the rock acts as an active seismic source within the borehole. The maximum offset of the sensor array is 480 m with non-uniform spacing that increases with distance. The drilling operation took place from early October until mid-December 2022 and reached a depth of approximately 580 m. The seismic sensors recorded at a sampling rate of 1 ms, which is more than sufficient for an expected frequency of up to 200 Hz. The proposed SWD experiment is to evaluate the potential and limitations of the SWD method for diamond core drilling commonly utilized in scientific drilling projects with a focus on fundamental developments of the methodology and data processing techniques. Ideally the drill-bit seismic record should produce a seismic image around the bore hole and ahead of the drill bit. First it is important to determine if a signal can be detected, and to what depth, from a diamond core drill bit. In contrast to percussion or reverse circulation drilling, the diamond core drilling method produces a very weak signal. The seismic data is also heavily contaminated by coherent and random noises generated at the drill site, including rig engines, generators and mud-pumps, vehicles, and the movement of equipment. Separation of theses coherent noises using radon transform has thus far failed and other wavefield separation methods are investigated. Using seismic interferometric methods for unknown source positions, we aim to detect the weak signal at known drill bit positions. This is promising especially at drilling depths where the drill-rig and drill-bit wave-fields are spatial or temporal separated from each other, due to their different origins and velocities. Interferograms are obtained using the cross-coherence method, which is applied to the recorded passive seismic data. These are computed from 30sec time windows of the continuous recordings and then stacked into the final interferogram to increase the signal-to-noise ratio. Instead of migration summation, semblance is measured for the interferometric migration process. For the migration process, a constant velocity model is sufficient in this hard-rock environment. The major noise sources that we image are the vibrations of the drill rig and power generator, which appear to mask the weaker signal from the drill bit. In an ongoing second experiment, we utilize grid power, reducing the noise sources to the mud-pumps, rotating string, and rig.

Introduction

Figure 1: The drill site an an early phase of the drilling operation.

The SWD is in essence a reverse Vertical Seismic Profile (VSP), where 3C-sensors are employed in an array at the surface and the grinding action of coring the rock acts as an active seismic source within the borehole. The proposed SWD experiment is to evaluate the potential and limitations of the SWD method for diamond core drilling commonly utilized in scientific drilling projects with a focus on fundamental developments of the methodology and data processing techniques. The initial step involves determining whether the notably very weak signal emitted by the drill bit is sufficiently strong to function as a source and whether this weak signal can be successfully detected.

Study Area

The steep topography of the Val d'Ossola and the proximity of the Toce river and local infrastructure restricted surface instrumentation, and a challenging 3D seismic array was installed (Fig. 2). 40 stations were placed within the hard rock (red, green, yellow & white triangles), whereas an additional 24 stations were placed on top of the sedimentary valley fill (blue triangles).

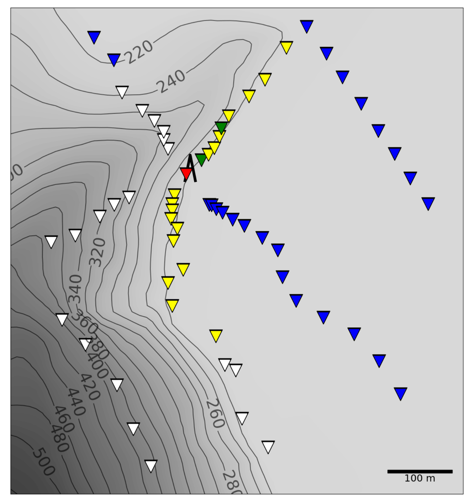

Figure 2: Geophysical survey site layout highlighting stations used for the common source gathers (yellow and red), stations used for the common receiver pair gathers (green) and stations on top of the sedimentary fill (blue).

Work Plan

- Velocity profile and structural imaging from passive seismic observations of
  - vibrations from drill bit
  - drilling operation induced impulse sources

Problem

- Very weak signal from drill bit (Fig. 3)
- Multiple noise sources
  - Pump
  - Generators
  - Drill rig

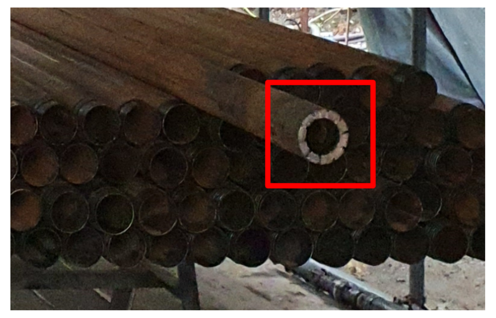

Figure 3: The drill pipes with the diamond impregnated drill bit emphasized by a red square

Data

For the measurements we used 64 Sercel-Unite acceleration 3C-sensors, which were recording autonomously. The sensor units were orientated towards the drill rig. The Micro-machined Electro-mechanical Sensors (MEMS) measure acceleration with a flat amplitude response function. Continuous measurement was conducted from October 4 to December 10, 2022, with a sampling interval of 1 ms. The acceleration data was then converted to velocity. In three out of the four example spectrograms (Fig. 4), the drilling operation (marked with black arrows) is clearly visible. The amplitudes at the station within the soft sediments are predominantly due to the drill rig, and the operation is also noticeable at distant offset stations within the sediments. Stations within hard rock have significantly more high frequencies, and ground vibrations are rarely observed in the distant station's spectrogram. Transparent arrows indicate the drill bit signal (Fig. 4b).

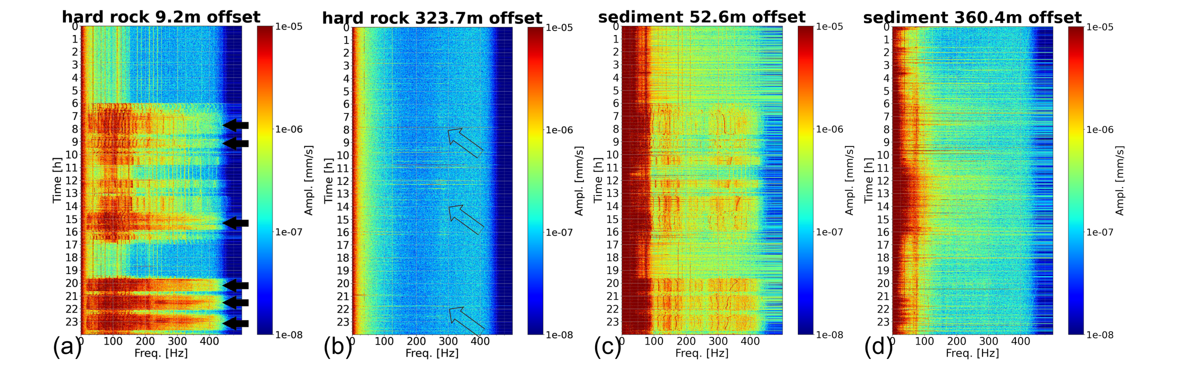

Figure 4: One day spectrograms of four representative seismic stations placed in hard rock (a,b) and placed in soft soil (c,d). Black arrows (a) highlight times of active drilling operations and transparent arrows indicate the drill bit signal (b).

Method

Figure 5a shows the most important seismic phases that are emitted by the drill bit and drill rig. Figure 5b and c show hypothetical travel time differences that illustrate Matched Field Processing (MFP). MFP is an algorithm that migrates the amplitude of the correlogram of stations A and B at lag time Δt to the subsurface points with the corresponding time difference (Fig. 5d). The migration velocity must be known and is assumed to be 5.5 km/s in this work.

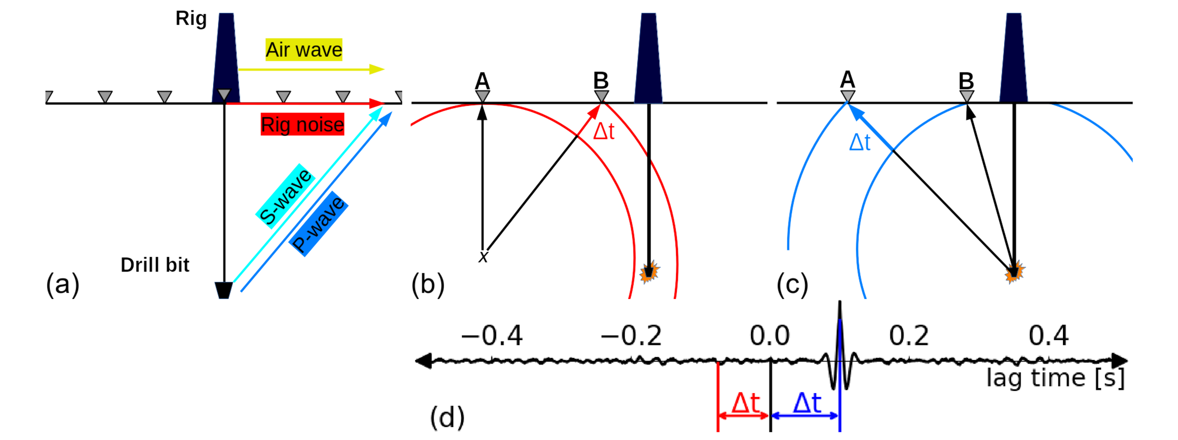

Figure 5: Scetch of seismic phases observed from active source (a), the ray path from a hypothetical source position (b), the ray path if hypothetical source position matches the actual source position (c), and a simplified correlogram (d) with the lag times from figures (b) and (c).

Cross-Correlation

The cross-correlogram is calculated in spectral domain by cross-coherence:

$$\phi_{A,B}(\omega)=\frac{A(\omega)B^{*}(\omega)}{|A(\omega)|\cdot|B(\omega)|+\epsilon} \quad (1)$$

$A(\omega)$ and $B(\omega)$ are the spectral densities and ϵ is a water level regularisation. The result provides the phase of the Green's function, but differs in amplitude [1]. The cross-correlations were performed in 30-second time windows, and to enhance the signal-to-noise ratio, the final cross-correlogram is derived by stacking a number of cross-correlograms within a time window corresponding to the "same depth" of the advancing drill bit.

Common Source Gathers

Seismic stations, highlighted in yellow on map (Fig. 2), are used to plot the common source gather. The stations were cross-correlated with the nearest station, indicated in red on the map. In the cross-correlogram (Fig. 6), the drill bit is at a depth of 200 m. The cross-correlograms, which include low frequencies, mainly show the unwanted surface waves generated by the drill rig (Fig. 6b,c). A 150 Hz high-pass filter removes those unwanted surface waves (Fig. 6d).

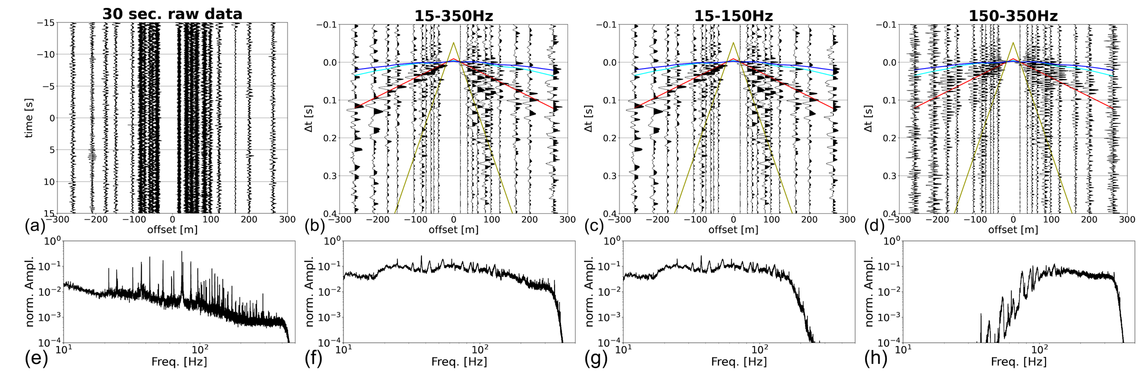

Figure 6: Raw data over 30 seconds (a), along with three distinct bandpass-filtered cross-correlograms (b-d). The red, yellow, blue, and cyan lines represent the hypothetical direct surface wave, air wave from the rig, and the P-wave and S-wave originating from the drill bit at a depth of 200 meters, respectively. The corresponding average amplitude spectra of the data are shown in (e-h).

Common Receiver Pair Gathers

For the common receiver pair gather we used stations 1 and 5, highlighted in green on the map (Fig. 2). Events originating from stationary sources always have the same travel time, whereas events generated by the moving drill are expected to show a move-out. The events are indicated by the hypothetical lines in Figure 7a and 7c, following the color scheme of Figure 2a. Despite the application of an FK-filter (Fig. 7d) the drill bit signal is not visible in the data (Fig. 7c).

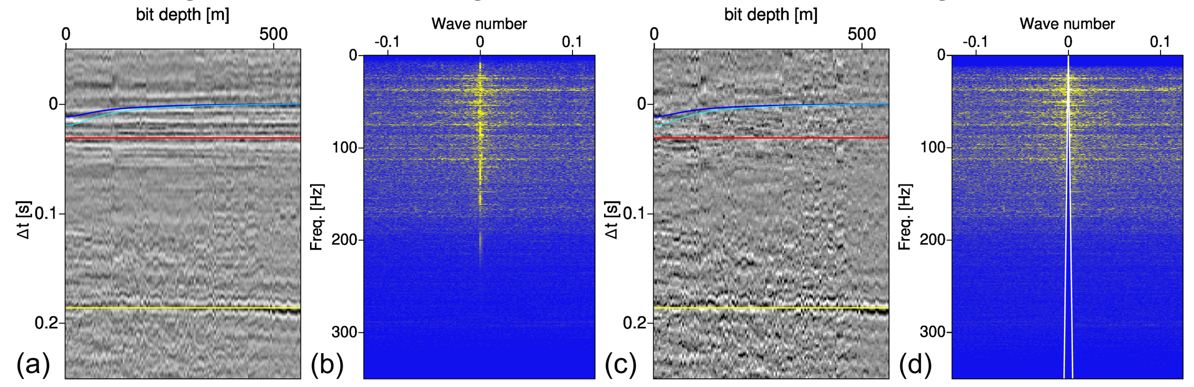

Figure 7: Common receiver pair gather of cross-correlogram of station 1 and station 5, before (a) and after FK-filter (c), with their respective FK-spectrum (b,d). The red, yellow, blue, and cyan lines represent the direct surface wave and air wave from the rig, as well as the P-wave and S-wave originating from the drill bit.

Source Location Imaging

Source location imaging is typically employed to identify the positions of unknown sources. In our experiment, we aim to localize the drill bit signal. To find an unknown source position the migration kernel $e^{-i\omega(t_{xB}-t_{xA})}$ is applied [2]. The travel time t between a hypothetical position x (Fig. 2b) and the receivers (A,B) is calculated with a simple constant velocity model, which is sufficient for our hard rock environment.

$$m(x)=\sum_{\omega}\sum_{A,B}e^{-i\omega(t_{xB}-t_{xA})}=\sum_{A,B}\phi_{A,B}(t_{xB}-t_{xA}) \quad (2)$$

If the position x matches the source (Fig. 2c), we get a constructive response from equation 2.

Semblance

Instead of summing the traces along the move-out we use semblance, which is particularly useful for identifying coherent signals across multiple seismic traces, making it beneficial for applications like detecting the drill bit signal in noisy environments [3].

$$S=\frac{\sum_{\tau=-\mathrm{w}}^{\mathrm{w}}\left(\sum_{A,B}\phi_{A,B}((t_{xB}-t_{xA})+\tau)\right)^{2}}{M\sum_{\tau=-\mathrm{w}}^{\mathrm{w}}\sum_{A,B}\phi_{A,B}^{2}((t_{xB}-t_{xA})+\tau)} \quad (3)$$

M is the number of cross-correlations, of the trace A with trace B, w is the the window width and τ represents the time time shift within the window over which the semblance S is calculated

Numerical example

The numerical example (Fig. 8) demonstrates that semblance is a powerful tool for visualizing signals in very noisy traces, which are not directly observable in the data. The cross-correlogram was created for a source at a depth of 300 m in a constant velocity model (v=5500 m/s), and noise was added to decrease the signal-to-noise ratio to 0.25. Due to the receiver geometry, there is poor vertical resolution (Fig. 8c).

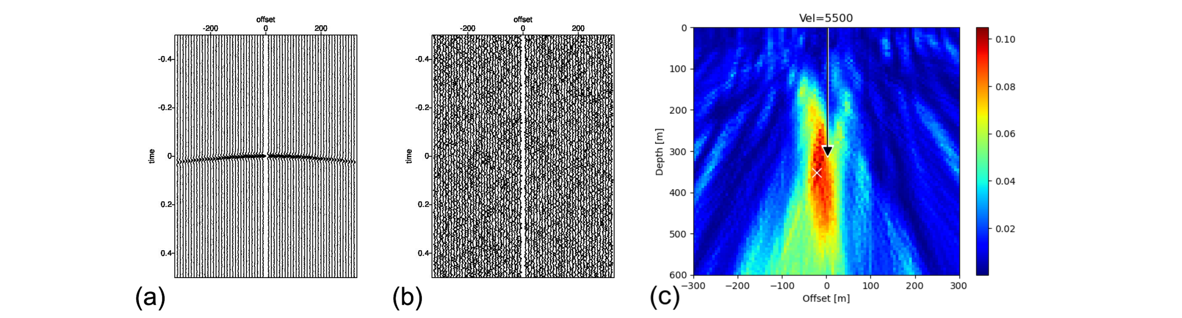

Figure 8: Cross-correlogram of source at 300 m depth (a), the same Cross-correlogram after adding noise (b) and the semblance plot for the source position (c). The black triangle marks the drill bit position and the white cross marks the global maximum.

Observed Data

Drill rig detection

The detection of the strong clear signal of the drill rig serves as a test for the method. The origin of the noise can be detected within meter of accuracy (Fig. 9). All stations depicted in Figure 9 were cross-correlated with each other, excluding neighbouring stations in the cross-correlation process.

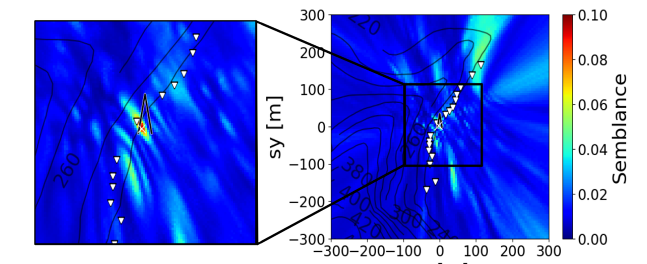

Figure 9: Semblance calculated at the surface. The white triangles show the positions of the seismic stations and the white cross marks the global maximum.

Drill bit detection

For drill bit detection, a 150 Hz high-pass filter was applied to the data prior to cross-correlation. A migration velocity of 5500 m/s was chosen. Multiple depth slices within specific depth ranges of the drill bit were stacked together to improve the signal (Fig. 10a-d). The drill bit can be located at various depths within the profile (Fig. 10e-h).

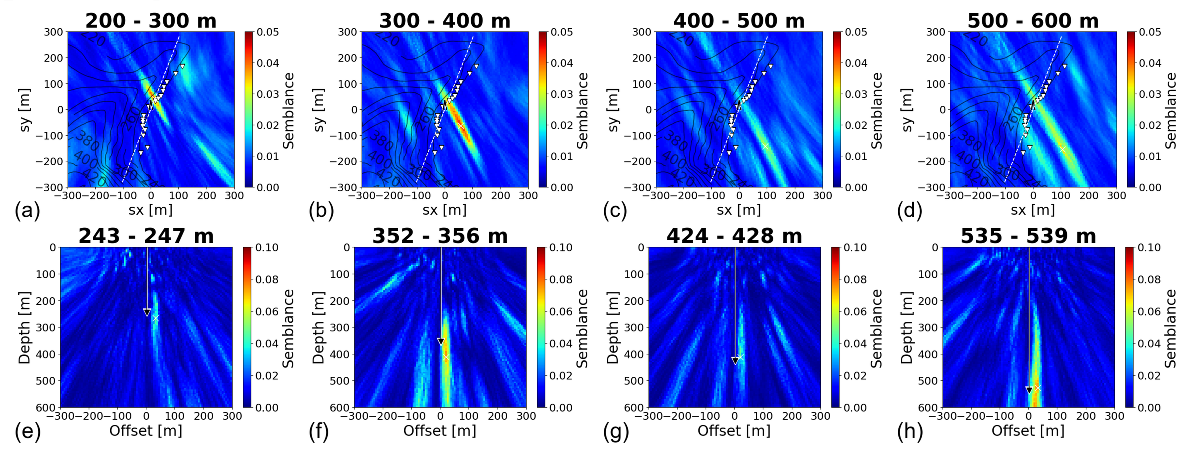

Figure 10: Semblance of multiple depth slices, stacked within depth intervals (a-d). White triangles mark the seismic stations, and the dashed line shows the position of the vertical profile (e-h). The black triangle shows the position of the drill bit, and the white cross marks the global maximum.

Conclusions

In our innovative Seismic While Drilling (SWD) experiment within the Ivrea-Verbano Zone, Western Alps, Italy, we explore the potential of using the grinding energy from a diamond coring drill bit as a seismic source. Despite the challenges posed by weak signal strengths and significant noise interference from the drilling process, the application of cross-coherence, source location imaging, and semblance measures for detecting a signal in a noisy environment has yielded promising results. Our findings demonstrate the feasibility of detecting drill bit signals in hard rock environments, marking a significant step forward in real-time drilling operation monitoring. Previous attempts to isolate the bit signal by removing surface waves through Radon transformation and FK-filtering on the raw data were unsuccessful due to the receiver geometry. The next step involves applying an FK-filter to the common receiver pair gathers to enhance the signal in the common source gather.

References

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[3] Sun, B., Bona, A., King, A., and Zhou, B. A comparison of coherency measurement using semblance and multiple signal classification, from a seismic-while-drilling perspective. *Geophysics 80*, 3 (2015), KS27–KS39.