

## 2D body-wave seismic interferometry as a tool for reconnaissance studies and optimization of passive reflection seismic surveys in hardrock environments

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## 1 **2D body-wave seismic interferometry as a tool for reconnaissance studies and** 2 **optimization of passive reflection seismic surveys in hardrock environments**

### 3 ABSTRACT

4 Despite the unrivalled spatial resolution and depth penetration of active-source seismic methods  
5 used for mineral exploration in hardrock environment, economic and environmental restrictions  
6 (e.g., source permitting) may preclude its full-scale application. In such a case, 2D passive  
7 reflection seismics can be considered a cost-effective way to perform reconnaissance-type  
8 survey and provide body-wave structural imaging using ambient-noise seismic interferometry  
9 (ANSI). This is, however, conditional to the presence of noise sources in the subsurface, for  
10 example produced by underground mining activity. Here, we propose a 2D ANSI workflow as  
11 an intermediate step prior to a full-scale 3D ANSI survey and an affordable tool in brownfield  
12 exploration, e.g., when trying to update current geological models beyond the drilled area. We  
13 test the applicability of this approach by analysing selected receiver lines from a 3D passive  
14 dataset acquired over the Kylylahti mine in Finland. Our methodology aims at choosing the  
15 optimal processing strategy at possibly lowest acquisition (2D geometry) and computational  
16 (small amount of data) cost. We address the fundamental questions in ANSI, i.e., (i) how much  
17 AN should one record and (ii) which SI processing approach should one choose. Therefore, we  
18 test different processing steps necessary to produce virtual shot gathers (VSG): preprocessing,  
19 selection of the ambient-noise portion, and selection of the method for retrieving the impulse  
20 responses between the receivers (crosscorrelation - CC, crosscoherence - CCh,  
21 multidimensional deconvolution - MDD). We conclude that trace energy normalization and  
22 high-pass filtering are the preferred preprocessing steps, while the best imaging is obtained  
23 when VSGs are retrieved using MDD applied in the noise-volume approach or CC in the event-  
24 driven approach. An event-driven approach may significantly reduce the acquisition time: for  
25 the Kylylahti dataset, using 10 events with energetic body-wave arrivals, extracted from one

26 hour of data, was enough to provide results comparable to the results from the noise-volume  
27 approach using the complete one hour of noise.

## 28 1. INTRODUCTION

29 The most comprehensive method to fully resolve the structural complexity characterizing  
30 highly deformed crystalline rocks hosting mineralization (referred to as ‘hardrock  
31 environment’, Eaton et al., 2003) are the 3D seismic surveys (e.g., Malehmir et al., 2012a).  
32 However, such surveys are not always the method of choice (Koivisto et al., 2012). Economic  
33 and environmental restrictions, source permitting, and challenging terrain conditions might  
34 significantly reduce the feasibility of a full-scale 3D survey at a given site (Cheraghi et al.,  
35 2012). Thus, 3D surveys are mainly conducted at well-recognized sites with ongoing  
36 exploration/production (brown-field exploration) with the aim to expand the knowledge about  
37 subsurface/reserves beyond the current geological models’ boundaries (Malehmir et al., 2012b;  
38 White et al., 2012; Singh et al., 2019). In such cases, a 3D passive survey based on the principles  
39 of ambient-noise seismic interferometry (ANSI) offers a cost-effective solution.

40 The successful applications of seismic interferometry (SI) in reflection imaging, and in  
41 particular the possibility of using ambient noise (AN) instead of active (controlled) sources  
42 (Draganov et al., 2013), eventually brought the concept of SI to the mining industry (Cheraghi  
43 et al., 2015). Recent applications demonstrated the feasibility of ANSI to support imaging in  
44 operating mine environments using surface waves (Olivier et al., 2015b; Czarny et al., 2016)  
45 and body waves (Cheraghi et al., 2015; Roots et al., 2017; Polychronopoulou et al., 2020).  
46 These experiments involved both underground (Olivier et al., 2015a) and surface measurements  
47 (Cheraghi et al., 2015).

48 2D seismic reflection projects aim at reconnaissance and initial exploration at a regional scale  
49 (Cheraghi et al., 2011; Calvert and Li, 1999). However, when dealing with a complex 3D

50 medium, only limited information of the true orientation of reflectors can be obtained from 2D  
51 surveys (Malehmir et al., 2012a, White et al., 2012). Ideally, one should combine both 2D (for  
52 higher resolution and lower acquisition cost) and 3D surveys (for wider azimuthal illumination  
53 and proper reflection positioning) (e.g., Hajnal et al., 2010).

54 Both 2D and 3D seismic surveys face the same problems typical for hardrock environments:  
55 strong scattering of seismic waves, low velocity gradients and small impedance contrasts  
56 between the rocks (with a notable exception of the massive sulphide mineralization), resulting  
57 in the inherently low signal-to-noise ratio (SNR), which is additionally degraded by the  
58 presence of anthropogenic noise (e.g., due to the mine infrastructure) (Eaton et al., 2003). All  
59 these factors impact negatively the reflections present in the 3D active-source data and decrease  
60 the overall SNR (compare the top and middle rows in Figure 1a).

61 Lower fold of the 3D surveys (and hence necessity of using wider bins and resulting lower  
62 resolution) is dictated by the source cost/effort. In the conventional, orthogonal design, shot  
63 lines are spaced between 1 to 2 receiver line spacings. In this regard, SI allows to obtain virtual-  
64 shot gathers (VSGs) at every receiver position, thus the dense array of receivers theoretically  
65 suffices to obtain high-fold 3D coverage and thus reflectivity similar to the active data (see  
66 bottom row in Figure 1a). The limitation though is related to the necessity of placing additional  
67 receivers to maintain the crossline fold.

68 As compared to the active acquisition, when designing a 3D passive survey, one should  
69 additionally consider, e.g., recording time, array geometry and its orientation with respect to  
70 the dominant noise sources, and number of receivers and their spacing (note again that sources  
71 will be retrieved at receiver positions). In such cases, the 2D geometry provides the minimal  
72 array configuration required for evaluating the dominant AN events present in the study area.  
73 Observations derived from processing steps of 2D ANSI regarding basic AN characteristics  
74 (periodicity and location of noise-sources activity and body-to-surface wave content) can help



75 estimate the length of the recording time and location of the array. Another advantage of 2D  
76 ANSI is that for distant sources (i.e., the distance to a source is much larger than the length of  
77 the array), the plane-wave approximation allows one to treat the arriving energy as separate  
78 plane waves with small ray parameters corresponding to body waves (Ruigrok et al., 2010).  
79 Thus, as compared to 3D ANSI, the 2D approach allows broadening the effective stationary-  
80 phase region and utilizing more AN sources, as long as their phases are consistent and in-plane  
81 with the array.

82 Acknowledging the aforementioned limitations of 2D imaging and differences between passive  
83 and active surveys, we evaluate the 2D ANSI method as an intermediate step prior to a full-  
84 scale 3D ANSI survey, as well as a cost-effective solution for brownfield exploration. Towards  
85 this end, we use passive seismic data acquired over the Kylylahti mine in Finland and synthetic  
86 data simulated using the geological model of the mine area. The methodology we develop in  
87 this study might be used to: (i) evaluate the acquisition parameters for a potential follow-up 3D  
88 seismic survey (both active and passive), (ii) estimate the length of the recording time and  
89 selection of SI processing steps for 3D ANSI, (iii) mapping the general structural framework in  
90 the area of interest, and (iv) constructing 3D geologic model from a network of seismic profiles.

91 We investigate the whole 2D ANSI processing flow, including data preprocessing, up to the  
92 VSGs retrieval (Figure 2). We put special emphasis on the choice of (i) an SI technique used to  
93 retrieve the impulse responses between the receivers and (ii) segments of recorded AN used for  
94 retrieval of VSGs, providing best-quality imaging. With the latter, we address the fundamental  
95 questions related to ANSI: (i) how much noise one should use (acquisition time), (ii) whether  
96 one should process continuous recordings (i.e., AN volumes) or noise panels containing events  
97 from separate sources (i.e., event-driven approach; Draganov et al., 2013).

98 Since the imaging part, i.e., selection of a migration algorithm, is not the scope of this study,  
99 we choose a conventional approach used in hard-rock data processing and mining applications

100 (e.g., Adam et al., 2003, Malehmir et al., 2012) of dip-moveout (DMO) stack and post-stack  
101 time migration to qualitatively compare the results of various SI approaches.

102 Note that our processing workflow can be evaluated at three different levels of details. At the  
103 level of ‘General procedure’ (Figure 2a), it contains all the steps we believe must be investigated  
104 in 2D ANSI. At the level of ‘Recommended approach’ (Figure 2b), we gather all the tools that  
105 should be used to address the ‘General procedure’. At the final level of ‘Variables specific for  
106 Kylylahti’ (Figure 2c), we summarize our case-specific selection of tools and processing  
107 parameters.

108 We first describe the methodology used in this study: SI methods, selection of AN segments  
109 using illumination diagnosis, different stacking approaches and semblance analysis. Next, we  
110 briefly introduce our 2D ANSI workflow followed by the description of the dataset used in this  
111 study (Kylylahti array). To provide the basis for verification of the 2D ANSI results, we further  
112 perform numerical tests and investigate the overall feasibility of reflection retrieval with active  
113 and passive seismic methods using a simplified geological model representative for our study  
114 area. For the passive case, we additionally investigate the role of illumination imposed by one-  
115 sided AN source localization. Subsequently, the 2D ANSI workflow is applied to the field  
116 recordings to assess the performance of every processing step. We further compare VSGs  
117 retrieved using all 9 approaches (3 VSGs retrieval techniques vs. 3 segments of AN data). We  
118 evaluate the reflectivity retrieved in VSGs by visual inspection and an automatic quantitative  
119 measure (semblance). Then, we compare migrated sections for all 9 configurations. Finally, we  
120 show 2D ANSI processing results with the preferred workflow applied to three adjacent  
121 receiver lines from the Kylylahti array. The migrated sections consistently show repeatable  
122 reflectivity patterns, which were previously identified in the synthetic data.

## 2. METHODOLOGY

Our 2D ANSI processing workflow (Figure 2) builds upon and combines experiences from previous SI experiments for both oil and gas exploration and mining-industry applications (Draganov et al., 2013; Cheraghi et al., 2015) as well as studies analyzing the performance of different SI methods: crosscorrelation (CC), crosscoherence (CCh), and multidimensional deconvolution (MDD) (Snieder et al., 2009; Nakata et al., 2011; and Wapenaar et al., 2011). We start with a brief description of the specific challenges faced when adapting ANSI to hardrock environments, as well as justification of the 2D approach in case of the available 3D passive data and complex geology.

### 2.1 Challenges of adapting ANSI to hardrock environments

The complex hardrock environment is very challenging for active-source seismics, and thus poses a big challenge for ANSI as well, as the changes in temporal and spatial stationarity of noise sources may cause destructive interference of potential reflection events during stacking (compare rows in Figure 1b). It means that results from stacking smaller amounts of data might exhibit higher SNR than those obtained from more data (see top row of Figure 1b, where stack for one day exhibits different coherent events than those obtained for more AN). This counterintuitive observation is even more evident for weak reflectivity observed in 3D passive data (see bottom row in Figure 1a), which might be very easily hindered during the stacking process (in the Kylylahti data such reflections exhibit low SNR and are observed only along 20-30 neighbouring traces out of all 994 traces). Therefore, contrary to the conventional approach used in ANSI, i.e., recording as much noise as possible and then stacking all the noise panels (e.g., Cheraghi et al., 2015; Chamarczuk et al., 2018), one needs to be more selective in the stacking process. It applies both to the noise-volume and event-driven approach. As a remedy, we propose to include novel illumination-diagnosis techniques in the ANSI workflow, allowing to (i) assess the temporal and spatial stationarity of noise sources (useful for designing

148 the 3D survey orientation and minimum recording time) and (ii) stack the periods of data  
149 containing body-wave illumination (useful in designing the processing workflow).

## 150 [2.2 Value of the 2D approach at initial stages of processing of 3D data](#)

151 When analyzing a full 3D passive dataset, the 2D ANSI approach seems to be a necessary  
152 intermediate step allowing to test the performance of an SI processing flow (SI techniques, AN  
153 segmentation, and preferred illumination-diagnosis techniques) at much lower computational  
154 cost. For example, the results shown in the bottom row of Figure 1a were obtained using an  
155 event-driven approach combined with CC (one of our preferred approaches) in a full 3D manner  
156 and visual inspection of hundreds of VSGs. Computing this collection of VSGs took  
157 approximately 60 hours on graphical processing units (GPU), and was preceded by several  
158 preprocessing steps (requiring analysis of the whole dataset, i.e., 600 hours of AN) necessary  
159 for the event-driven approach (which was only one of the possible solutions). Without initial  
160 testing using the 2D workflow (i.e., considering a representative receiver line), choosing the  
161 optimal combination of preprocessing, noise-panel selection, evaluating methods to retrieve  
162 impulse responses and the actual responses (e.g., choosing between causal and acausal part)  
163 and finally the stacking itself, would have been a daunting task.

## 164 [2.3 Impulse-response retrieval: transient vs diffuse fields](#)

165 Ambient noise can originate from a diffuse wavefield caused by multiple scattering in a  
166 heterogeneous medium and/or energy from transient sources in a deterministic medium  
167 (Wapenaar et al., 2004). From a practical point of view, it means that the reflection response of  
168 a medium can be obtained using SI either by correlating long recordings (possibly overlapping  
169 in time) of uncorrelated noise sources (diffuse-wavefield case) or by stacking correlations from  
170 separately acting sources (deterministic-wavefield case). In this study, we refer to those two  
171 cases as noise-volume and event-driven approach, respectively. To indicate the relevance of  
172 evaluating the influence of different segments of AN, we follow Wapenaar et al. (2006) and

173 describe the retrieval of the impulse response (i.e., Green's function) by CC for the case of  
 174 transient and uncorrelated noise sources.

175 The transient-source case relates to the situation when a noise panel contains the wavefield  
 176 resulting from a single seismic source. In such a case, we can write the wavefields  $u$  recorded  
 177 by receivers at  $x_A$  and  $x_B$  in the frequency domain as

$$178 \quad u(x_A, x_S, \omega) = S(x_S, \omega)G(x_A, x_S, \omega), \quad (1)$$

$$179 \quad u(x_B, x_S, \omega) = S(x_S, \omega)G(x_B, x_S, \omega), \quad (2)$$

180 where  $G(x_A, x_S, \omega)$  and  $G(x_B, x_S, \omega)$  are the Green's functions recorded by receivers at  $x_A$  and  
 181  $x_B$ , respectively, and  $S(x_S, \omega)$  denotes the source time function.

182 Then, the correlation of those two wavefields is given by

$$183 \quad C(x_B, x_A, \omega) = \oint_{S_{src}} |S(x_S, \omega)|^2 u(x_B, x_S, \omega) u^*(x_A, x_S, \omega) dx_S$$

$$184 \quad (3)$$

185 where superscript asterisk  $*$  denotes complex conjugation. Hence, the correlation function  
 186  $C(x_B, x_A, \omega)$  is proportional to the Green's function between  $x_B$  and  $x_A$ ,  $G(x_B, x_A, \omega)$ ,  
 187 convolved with the averaged transient-source wavelet.

188 In the case of recording uncorrelated noise sources characterized each by source time function  
 189  $N(x_S, \omega)$ , the responses at  $x_A$  and  $x_B$  are defined as

$$191 \quad u(x_A, \omega) = \oint_{S_{src}} N(x_S, \omega)G(x_A, x_S, \omega) dx_S \quad (4)$$

190

192 and

193 
$$u(x_B, \omega) = \oint_{S_{src}} N(x'_S, \omega) G(x_B, x_S, \omega) dx_S, \quad (5)$$

194 respectively.

195 The assumption of uncorrelated noise sources invokes processing of continuous recordings of  
 196 simultaneously acting passive sources. In this case, the summation over the sources is replaced  
 197 with time averaging. We assume that two noise sources  $N(x_S, \omega)$  and  $N(x'_S, \omega)$  are mutually  
 198 uncorrelated for any  $x_S \neq x'_S$  and have an equal power spectrum. The ensemble average  $\langle \quad \rangle$   
 199 taken over them is equal to

200 
$$\langle N(x'_S, \omega) N^*(x_S, \omega) \rangle = S(\omega) \delta(x_S - x'_S), \quad (6)$$

201 where  $S(\omega)$  is the autocorrelation of the AN source.

202 Then, the correlation of equations 4 and 5 is defined as

203 
$$C(x_B, x_A, \omega) = \langle u(x_B, \omega) u^*(x_A, \omega) \rangle. \quad (7)$$

204 The above discrimination between AN considered as originating from transient and  
 205 simultaneously acting sources is our motivation to investigate the influence of different  
 206 segments of the AN recordings on the reflection retrieval in crystalline environments. Equations  
 207 3 and 7 state that the correlation function yields the Green's function between  $x_B$  and  $x_A$   
 208 (Wapenaar et al., 2011). Considering practical applications, the characteristics of the AN  
 209 wavefield at a given site determine the eventual preponderance of either approach.

210 The imprint of a source signature  $S(\omega)$  on the correlation result  $C(x_B, x_A, \omega)$  is removed by  
 211 applying a wavelet deconvolution per every correlated trace. The deconvolution operator is  
 212 estimated by extracting a short segment around  $t=0$  s from the correlation result  $C(x_B, x_A, \omega)$   
 213 for  $x_A=x_B$ , i.e., the trace autocorrelation (AC).

214 The important parameter to establish before the actual correlation is the length of the noise  
 215 panels to be used as the input for SI (Draganov et al., 2007; Almagro Vidal et al., 2014;  
 216 Cheraghi et al., 2016). Regardless of transient sources or volumes of noise, the minimum length  
 217 should be greater than or equal to the two-way traveltime (TWT) to the deepest reflection event  
 218 of interest. To capture possible surface-related multiples of that event (as well as multiply  
 219 scattered contributions), this length should be further extended to at least double that TWT.  
 220 Furthermore, because our processing is specific for a situation in which seismic events are  
 221 induced by underground mine activity, the record length should account for the maximum depth  
 222 of mining operations (~1000 m depth). Taking these factors into account, for all the analyses  
 223 shown in this study, we use a window length of 10 s for both the noise-volume and event-driven  
 224 approach.

#### 225 2.4 Impulse-response retrieval: SI methods

226 Further part of the comparison analyzed in this study relates to the application of the three main  
 227 SI methods to retrieve impulse responses (Wapenaar et al., 2011).

228 CCh is equivalent to the CC normalized in the frequency domain:

$$229 \quad C_{ch}(x_B, x_A, \omega) = \int_{S_{src}} \frac{u(x_A, x_S, \omega)u^*(x_B, x_S, \omega)}{|u(x_A, x_S, \omega)||u(x_B, x_S, \omega)| + \varepsilon}, \quad (8)$$

230 where  $u(x_A, x_S, \omega)$  and  $u(x_B, x_S, \omega)$  are the responses at  $x_A$  and  $x_B$  in the frequency domain,  $\omega$   
 231 denotes the angular frequency, and the asterisk denotes complex conjugate. In CCh, the  
 232 nominator is equal to the CC (equation 3) and is divided by the amplitude cross-power spectrum  
 233  $|u(x_A, x_S, \omega)||u(x_B, x_S, \omega)|$ . The regularization parameter  $\varepsilon$  is added to provide numerical  
 234 stability, and could be estimated for example by taking 1% of the cross-spectrum value per each  
 235 frequency component, averaged over many time windows. The spectral division in equation 8  
 236 removes any contributions related to noise-source wavelets. Thus, the estimation of  $S(\omega)$  and  
 237 wavelet deconvolution required by the CC approach is omitted in CCh processing.

238 Both CC and CCh are trace-by-trace operations and their definitions assume lossless medium,  
 239 isotropic illumination from the sources and regular source distribution (assumptions not  
 240 possible to meet in real data scenario).

241 There were many solutions proposed to account for directionally biased illumination (see  
 242 Bakulin and Calvert, 2006; Snieder et al., 2006; Mehta et al., 2007). However, most of them  
 243 are essentially deconvolution-based trace-by-trace operations which mostly account for source-  
 244 wavelet issues and do not address the asymmetric illumination of noise sources (Wapenaar et  
 245 al., 2011). Wapenaar et al. (2008) proposed a method in which deconvolution is performed on  
 246 all traces simultaneously thus allowing to account for assumptions limiting the validity of the  
 247 Green's functions retrieved using CC and CCh. In this multidimensional deconvolution (MDD),  
 248 an improved version of the frequency-domain Green's function  $G^S(x_B, x_S, \omega)$  is obtained by  
 249 deconvolving the raw correlation output  $C(x_B, x_A, \omega)$  by a 2D deconvolution operator  
 250  $\Gamma(x, x_A, \omega)$ :

$$251 \quad C(x_B, x_A, \omega) = \int_{S_{rec}} G^S(x_B, x, \omega) \Gamma(x, x_A, \omega) dx, \quad (9)$$

252 where  $G^S(x_B, x_S, \omega)$  is the scattered part of the Green's function (total Green's function minus  
 253 the direct wave) and  $\Gamma(x, x_A, \omega)$  is so-called point-spread function (PSF; van der Neut et al.,  
 254 2010, 2011). Equation 9 shows that the CC function is actually a blurred variant of the Green's  
 255 function  $G^S(x_B, x_S, \omega)$ , where the blur in time and space is quantified by the PSF and is  
 256 connected to source-related factors (source time functions, source distribution, relative strength,  
 257 etc.). The underlying assumption for MDD is that PSF be optimally obtained from CC (equation  
 258 3) such that it accounts for the source-related distortions. Note that the integration in equation  
 259 3 is performed along the source boundary  $S_{src}$ , while in equation 9 - over receivers, which  
 260 removes the requirement for regular source distribution. However, this also means that regular  
 261 receiver distribution is required. MDD is realized by solving for  $G^S(x_B, x, \omega)$  in equation 9 by



262 deconvolving  $C(x_B, x_A, \omega)$  with  $\Gamma(x, x_A, \omega)$ . To avoid ill-posedness, equation 9 is solved for  
263 each source position  $x_A$  and for each available source component at  $x_A$ , resulting in an ensemble  
264 of equations for  $G^S(x_B, x, \omega)$ .  $\Gamma(x, x_A, \omega)$ , as proposed by van der Neut et al. (2011), can be  
265 obtained by time windowing the CC output around  $t=0$  s (summed over sources for the transient  
266 case or over time instances for uncorrelated noise sources). This time windowing yields a  
267 butterfly-shaped seismic record with its thinnest part at  $x_A=x_B$  (Nishitsuji et al., 2016) and with  
268 slopes determined by the apparent slowness of the dominant events. In practice, MDD (equation  
269 9) is recast in a matrix form using a least-square approach or a singular value decomposition  
270 (see e.g., Nishitsuji et al., 2016 for the details of MDD discretization).

271 In this study, we approximate the PSF by extracting the butterfly-shaped seismic record from  
272 body-wave events captured in individual noise panels (in the event-driven approach). For the  
273 noise-volume approach, we extract the PSF from every correlated 10-s-long panel. For both  
274 approaches, we invert for  $G^S(x_B, x, \omega)$  using all noise panel simultaneously. For longer  
275 recordings, this becomes a computationally intensive task. As we are interested in the general  
276 performance of the noise-volume approach, we test MDD on an exemplary 1-hour-long  
277 recording.

278 The main difference between all three methods is related to the different type of deconvolution  
279 inherent in each of them. In CC, windowed AC of the master trace is used as a source-function  
280 estimate to divide each trace in the spectral domain. Deconvolution in CCh is done by dividing  
281 the CC output of two traces by the multiplication of the amplitude spectra of both traces, i.e., a  
282 cross-power normalization is actually performed. Compared to CC and CCh, the deconvolution  
283 in MDD is much more comprehensive, i.e., deconvolution is performed simultaneously for  
284 every trace in the currently analysed VSG. The theoretical improvements from applying MDD  
285 compared to CC are: (i) removing source signature(s), (ii) improved radiation characteristics of  
286 the retrieved source, (iii) relaxation of the assumptions of a closed surface of regularly sampled

287 sources (when directional illumination is present), and (iv) works correctly in dissipative  
288 medium. A disadvantage of MDD is that it requires a regular sampling of the receiver array.

289 From a theoretical point of view, CC should result in the correct phase and relative amplitude  
290 of arrivals, CCh - only the phase, and MDD - the absolute amplitude, phase, and correction for  
291 the unbalanced illumination. The robustness of CCh is useful when recordings contain  
292 unwanted instrument noise or poor-coupling effects. It could be appealing in case of surveys  
293 performed in hardrock environment, where the terrain conditions can vary quickly across the  
294 survey, yet the unwanted effect of CCh is data whitening, which can be harmful for retrieving  
295 weak reflectivity.

## 296 [2.5 Evaluation of preprocessing on virtual zero-offset data](#)

297 Reflection retrieval using ANSI involves correlating the separate body-wave sources or  
298 volumes of noise with dominant presence of body-wave arrivals. In such cases, the first aim of  
299 the preprocessing is to assure that the AN segments contain body waves with higher energy  
300 than surface waves. Additionally, the routine part of ANSI preprocessing is trace-energy  
301 normalization applied for each noise panel (Draganov et al., 2007, 2013). The energy  
302 normalization aims at equalizing the contribution of each correlated panel, i.e., fulfilling the  
303 assumption of equal energy of the different AN sources (Ruigrok et al., 2010; Nishitsuji et al.,  
304 2016). The inevitable consequence of applying CC to noise panels is enhancing the strongest  
305 event present in the given data segment (Almagro Vidal et al., 2014). As a consequence, the  
306 virtual-source function is determined by the strongest event in the pre-correlated noise panel.  
307 The illumination diagnosis method (Almagro Vidal et al., 2014) can be used to scan for panels  
308 with dominant presence of body waves. However, by providing appropriate preprocessing, even  
309 those noise panels which are dominated by surface waves might be turned into useful data.

310 In our 2D ANSI workflow, we use AC (Clearbout, 1968; Daneshvar et al., 1995) to obtain  
311 virtual zero-offset data and assess the influence of given preprocessing on the Green's function

312 retrieval. Analysing virtual zero-offset data allows for direct visual assessment of amplitudes  
313 and phases of waveforms in a time window of reflections indicated by simulated active-source  
314 data.

## 315 2.6 Selection of ambient-noise segments

316 The next step in the 2D ANSI processing workflow is the extraction of AN segments. The  
317 formulations of CC for transient sources (equation 3) and uncorrelated noise sources (equation  
318 7) indicate two possible approaches in processing AN data (Draganov et al., 2013): (1) an event-  
319 driven approach, where separate noise sources can be detected and extracted from the  
320 continuous AN recordings, or (2) a noise-volume approach, where long, continuous data are  
321 automatically separated into time windows of equal length with the assumption that most of the  
322 windows contains body-wave events that after stacking will not be masked by retrieved surface  
323 waves. For data extraction in the event-driven and noise-volume approaches, we apply  
324 dedicated illumination diagnoses. For the noise-volume approach, we apply a 2D illumination  
325 diagnosis (Almagro Vidal et al., 2014; Panea et al., 2014) to choose 1 hour of the AN recordings  
326 dominated by low-slowness arrivals. Note that, when using the noise-volume approach with all  
327 the noise, there is no need for illumination diagnosis. For selecting body-wave events in the  
328 event-driven approach, we use the two-step wavefield evaluation and event detection (TWEED)  
329 method (Chamarczuk et al., 2019).

330 In the event-driven approach, we aim to choose sources bounding the target area. According to  
331 Wapenaar et al. (2008, and 2011) even though the MDD approach can be carried out without  
332 assumptions with respect to the regularity of the source positions. The MDD results quality  
333 depends mainly on the source density (with a rule of thumb of average horizontal distance  
334 between sources being less than half of the dominant wavelength; see Wapenaar et al., 2008).  
335 Thus, during noise-panel selection we try to find events fulfilling this condition and located  
336 approximately on the contour outlining the main target (in this case Kylylahti ultramafic body).

337 Assuming high-frequency body-wave events with peak frequency around 50 Hz (see Figure 3b)  
 338 and background velocity of the host rock of 5000 m/s, the optimal source separation should be  
 339 less than 50 m. As the distribution of sources is constrained by the location of the noise sources,  
 340 the sources subset used in this study will only approximate the desired distribution.

341 In order to assure retrieval of reflections when applying the noise-volume approach to only 1  
 342 hour of AN, we have to make sure that this hour is characterized by a dominant body-wave  
 343 energy. To estimate the general body-wave energy content we use the aforementioned 2D  
 344 illumination diagnosis (Almagro Vidal et al., 2014; Panea et al., 2014). In this approach, we  
 345 use the slant-stack transform (Chapman, 1981) of the wavefield  $v$ ,  $\tilde{v}(p, \tau) = \int v(x, \tau + px)dx$ ,  
 346 where  $p$  is the ray parameter,  $x$  is the offset, and  $\tau$  is the intercept time at  $p = 0$ . The slant-stack  
 347 at  $\tau = 0$  for each correlated noise panel  $C^S$  can be described as

$$348 \quad \tilde{C}^S(x_A, p, \tau) = \int C^S[x_B, x_A, \tau + p \cdot (x_B - x_A)]dx_B, \quad (10)$$

349 where  $\tilde{C}^S$  is the representation of the virtual-source function of the transient source  $S$  in the  $\tau -$   
 350  $p$  domain. Therefore,  $\tilde{C}^S$  describes the dominant ray-parameter contribution from the transient  
 351 source to the virtual source located at  $x_A$  and recorded at  $x_B$ . Then, a discrimination test is  
 352 performed by comparing the dominant ray-parameter value  $\max(\|\tilde{C}_L^S(x_A, \mathbf{p})\|)$  with a  
 353 predefined ray-parameter threshold  $p_{limit}$  characteristic for the body waves in the recording  
 354 area.

355 For the event-driven approach, the number of used noise panels could be far lower than for the  
 356 noise-volume approach (which is the case for the Kylylahti data), thus if for the latter it is  
 357 sufficient to have the majority of the panels containing body-wave events, the event-driven  
 358 approach demands that every noise panel contains body-wave events. To assure this, we use  
 359 illumination diagnosis method extended to 3D, i.e., the TWEED method (Chamarczuk et al.  
 360 2019). TWEED was developed to overcome the insufficient crossline receiver spacing (i.e., no

361 receiver lines in the crossline direction deployed) by simultaneous analysis of the adjacent  
362 (parallel) receiver lines.

363 We use the illumination diagnosis for extracting two AN segments dominated by body-wave  
364 activity and surface-wave activity. Then, we apply the same SI processing to both volumes and  
365 compare the resulting VSGs.

## 366 2.7 Semblance analysis

367 Because of the inherent ambiguity in visual comparison of reflection patterns observed in pre-  
368 stack data, we propose to use a similarity measure. Similarity measures are commonly used in  
369 comparison of multiple datasets from various sources (Cooper and Cowan, 2008) and are well-  
370 known tools for analysing active-source seismic data (Neidell and Taner, 1971). Aiming to  
371 decrease the subjectivity of visual comparison of our passive results, we incorporate the  
372 semblance method, which enables comparison of time-series data in quantitative manner.

373 Semblance filtering compares two datasets on the basis of their phase as a function of frequency.  
374 The semblance is calculated using the continuous wavelet transform (CWT; e.g., Sinha et al.,  
375 2005). The CWT is defined as the correlation of the given time series  $h(t)$  with a scaled  
376 arbitrary wavelet  $\Psi$ :

$$377 \text{CWT}(u, s) = \int_{-\infty}^{\infty} h(t) \frac{1}{|s|^{0.5}} \Psi^* \left( \frac{t-u}{s} \right) dt, \quad (11)$$

378 where  $s$  denotes the scale,  $u$  is displacement, and  $*$  denotes the complex conjugate. Using the  
379 wavelet approach allows to account for temporal variability in the spectral character.  
380 Comparison of the two wavelet-transformed time series can be achieved using the cross-wavelet  
381 transform according to

$$382 \text{CWT}_{1,2} = \text{CWT}_1 \times \text{CWT}_2^*, \quad (12)$$

383 with the result being a complex quantity with an amplitude  $A = |CWT_{1,2}|$   
384 and local phase  $\theta = \tan^{-1}(Img(CWT_{1,2})/Re(CWT_{1,2}))$ .  $CWT_{1,2}$  is the relation between the  
385 imaginary and real part of the cross-wavelet transform and is valued between  $-\pi$  and  $+\pi$ . Then,  
386 the similarity between the two wavelet-transformed time series can be defined as semblance:

$$387 \quad S = \cos^n(\theta), \quad (13)$$

388 where  $n$  is a positive odd integer.  $S$  is a measure of the phase correlation between the two  
389 datasets and takes values between -1 and 1. In this study, we use the semblance value to compare  
390 the reflectivity patterns present in the VSGs retrieved with the 2D ANSI processing and in the  
391 synthetic active-source data.

## 392 [2.8 Imaging approach](#)

393 After applying our 2D ANSI workflow, we use the VSGs as input to standard time imaging to  
394 retrieve reflectivity sections. For simplicity, we use conventional constant-velocity Stolt f-k  
395 migration (Stolt and Benson, 1986) applied on DMO-corrected sections (with integral T-X  
396 DMO run on common-offset planes, Hale (1984)). Additionally, we apply a top mute to remove  
397 first arrivals and, in the case of the ANSI results, SI artefacts earlier than the first arrivals, and  
398 balance the amplitudes by dividing by the root-mean-square (RMS) value. We argue that the  
399 expected quality of the migrated sections can be already deduced from comparison of the VSGs.  
400 Since the scope of this study is limited to explaining and comparing different processing  
401 strategies for 2D ANSI in the mineral-exploration context, we focus on the SI methodology  
402 itself. Hence, selection of the imaging techniques for the recovery of the best-possible  
403 reflectivity image is outside the scope of this study. Despite the fact that considering the  
404 complexity of structures as in the Kylahti mine area, pre-stack depth migration was deemed  
405 the most-appropriate approach (see Heinonen et al., 2019; Singh et al., 2019), we prefer to use  
406 the above post-stack time migration approach. Since the potential of 2D ANSI is to use it as a

407 reconnaissance tool in mineral exploration, we assume that no detailed knowledge of the  
408 velocity structure is known prior to acquisition, which hampers application of pre-stack depth  
409 migration.

### 410 3. DATASET

411 The 2D passive data used in this study comprises a single receiver line (line 7) of the Kylylahti  
412 array (Chamarczuk et al., 2019). Additionally, lines 8 and 9 are used to show the consistency  
413 of the 2D ANSI processing results. Figure 3a shows the layout of the Kylylahti array,  
414 highlighting the lines used in this study and their relation to the known extent of the Kylylahti  
415 mineralization. The Kylylahti array was deployed as a part of the COGITO-MIN project tackling  
416 the cost-effectiveness of various novel seismic exploration technologies targeting high-  
417 resolution resource delineation (Riedel et al., 2018). The primary purpose of the Kylylahti array  
418 deployment was to advance the development of ANSI imaging techniques for mineral  
419 exploration and provide a baseline for testing novel array-processing techniques (see  
420 Chamarczuk et al., 2020).

421 The array was deployed over the active Kylylahti polymetallic mine (Outokumpu mineral belt,  
422 Eastern Finland) in the direct vicinity of the town of Polvijärvi. The array consisted of 994  
423 receiver stations distributed regularly over a 3.5 x 3 km area with 200 m line spacing and 50 m  
424 receiver spacing. Each receiver station was equipped with a bunched string of six 10-Hz  
425 vertical-component geophones and a wireless data logger, recording AN at 2 ms for 20 hours  
426 per day during 30 days, resulting in ~600 hours of passive seismic data. The Kylylahti mine  
427 was active during the whole recording period. Routine mining activities included, among  
428 others, drillings (surface and underground), transporting ore and waste rock (surface and  
429 underground), scaling (underground), mine ventilation (surface). Another source generating  
430 strong energy are the mine blasts which occurred daily at depths ranging from a few hundred  
431 meters down to approximately 800 meters below the surface. We expect all of these activities

432 to significantly contribute to the AN wavefield in the Kylylahti area and provide us the  
433 opportunity to record body-wave arrivals. In Figure 3b, we show the power-spectral-density  
434 (PSD) estimate for the whole array averaged over one day of recordings. The PSD analysis  
435 indicates a broad frequency content of AN in the Kylylahti area, with highest energy peaks  
436 between 10-15 Hz and 30-40 Hz. Areas in the direct vicinity of the mine (denoted with red  
437 dashed line in Figure 3b) exhibit PSD peaks also in the 65-80 Hz range.

#### 438 4. NUMERICAL TESTS

439

440 To investigate the feasibility of 2D ANSI in a setting dominated by operating-mine activity, we  
441 perform 2D numerical tests including: (i) synthetic active-source data to provide a benchmark  
442 of the imaging quality expected from surface-seismic data (see Figure 4a); (ii) passive seismic  
443 simulation with regular source distribution to show the maximum achievable performance (in  
444 the case of the array deployed directly over the mine and assuming the AN sources to be  
445 generated by mine-related activities) of 2D ANSI (see Figure 5), and (iii) supporting test to  
446 evaluate the influence of the directional AN sources illumination breaking the omnidirectional  
447 AN distribution condition, which is a situation commonly encountered in field experiments (see  
448 Figure 6). The synthetic active-source data are our benchmark in this study for verifying the  
449 fidelity of reflections visible in the 2D ANSI. Furthermore, the synthetic active-source data  
450 juxtaposed with the 2D ANSI results from the field and synthetic data should indicate the  
451 potential deviations from desired imaging results, i.e., misplaced and/or flattened reflections,  
452 artifacts (near-surface noise, non-physical reflections), and general hints in terms of SNR. The  
453 velocity model used for modelling includes the ore body and is representative for one of the  
454 receiver lines of the Kylylahti array (receiver line 7 in Fig. 3).



#### 4.1 Synthetic model

For all synthetic tests, we use a 3D seismic impedance model based on a simplified geological model of the Kylylahti area (Riedel et al., 2018). The model is based on comprehensive drilling (i.e., the geology at this location is well known) and consists of the following four main rock units: (1) the sulphide-bearing schist (SULBS), (2) Outokumpu ultramafic rocks (OUM) – Kylylahti body, (3) Outokumpu altered ultramafic rocks (OME), and (4) massive to semi-massive sulphide (S/MS) mineralisation. The ore body is located at approximately 300 m depth (indicated by a yellow inclusion in Figures 4a and 5a). The petrophysical characterization of the targets indicates that S/MS should cause a strong reflected signal when in contact with any of the hosting rocks, mainly due to the notably higher densities of ore compared to those of the other rock types (Luhta, 2019). In Table 1, we provide the P-wave velocities, densities, and impedances of the units building the input model used for the acoustic modelling. The white dashed lines shown in Figure 4a indicate areas of expected reflectivity.

For the 2D synthetic modelling, we used a receiver spread mimicking the field acquisition geometry, i.e., a line of 29 sensors placed on the top of the model with 50 m spacing giving a total length of the line of 1400 m. For such a configuration, the theoretical maximum unaliased frequency is equal to  $f_{un} = V/(4B\sin(\theta))$ , where  $V$  is the average medium velocity,  $B$  is the bin size, and  $\theta$  is the geological dip. Assuming a dominant dip of the target of  $60^\circ$ , a common-depth-point (CDP) bin size of 25 m, and average P-wave velocity in the medium of 6000 m/s, the maximum unaliased frequency is approximately 58 Hz. The dominant frequency of the AN sources in the Kylylahti area is not higher than 60 Hz (see Figure 3b), thus we do not expect frequency aliasing for the passive results due to the steep dips.

The synthetic modelling was done using a 2D finite-difference acoustic modelling scheme (Thorbecke and Draganov, 2011). First, we test the performance of the 2D active-source seismic method using a linear array of sources deployed on the surface. To facilitate comparison with

480 data retrieved using SI, the synthetic shots are collocated with the receivers. We use a pressure  
481 source with a Ricker wavelet with centre frequency of 60 Hz and 40 Hz for the active and  
482 passive case, respectively. The synthetic active-shot gather is shown in Figure 4b. In Figure 4c,  
483 we show the migrated section obtained from all synthetic active-shot gathers. The reflectivity  
484 related to the main geological units (shown with dashed black lines) is visible both on the pre-  
485 stack (Figure 4b) and post-stack data (Figure 4c). We can distinguish three reflection packages  
486 (RPs) related to the velocity contrast between the host rock and the background (RP1), the S/MS  
487 mineralization (RP2), and the bottom of the Kylylahti body (RP3).

488 Next, we simulate the passive seismic survey. We use idealized regular noise distribution of  
489 underground sources. The rectangular polygon of sources together with the free surface form a  
490 surface enclosing the area of potential reflectivity. Theoretically, integrating over this surface  
491 (summing over separate sources) should provide a reliable estimate of the subsurface  
492 reflectivity (Wapenaar and Fokkema, 2006). The exemplary procedure to obtain Green's  
493 functions for the synthetic data by CC for a central receiver acting as a virtual source is as  
494 follows: for a fixed source position, we crosscorrelate the trace at the central receiver with the  
495 traces at all other receivers; we repeat this for all sources along the 'box'; the result is then  
496 summed per receiver over all sources. The erroneous amplitudes visible in the VSG obtained  
497 for the synthetic passive case (Figure 5b) are related to deviating from the far-field  
498 approximation of source boundary from the receivers and the assumption of smooth impedance  
499 contrast across the source boundary (see the 'Discussion' section for more detailed  
500 explanation). The migrated section in Figure 5c exhibits reflections in all the areas of expected  
501 reflectivity. We note, that it is very unlikely that AN sources in the actual field situation would  
502 appear with such a regular distribution and that serious deviations from this preferred  
503 illumination could be expected in actual field conditions; however, we want to examine the best

504 theoretically achievable performance of SI assuming preferable alignment of mine-induced  
505 seismic sources in the Kylylahti geological setting.

#### 506 4.1.1 Directional illumination test

507 To investigate the influence of directional distribution of AN sources, we investigate three  
508 scenarios with sources distributed along one of the three sides of the target area (distributions  
509 of sources shown as insets in Figure 6). We compare migrated images obtained using VSGs  
510 produced from pressure sources illuminating the target area from the left (Figure 6a), bottom  
511 (Figure 6b), and right (Figure 6c) side of the rectangle bounding the target area.

512 The migrated sections obtained from directionally biased source distributions are generally  
513 dominated by artifacts, but it is still possible to track the reflectivity in the expected areas  
514 (indicated with dashed black contours). Sources distributed underneath the target (Figure 6b)  
515 provide the clearest image of the three cases, in which each RP can be visually separated. The  
516 sources illuminating the target from the left side (Figure 6a) provide an image similar to the one  
517 from the bottom distribution, yet the presence of a strong dipping artifact stretching from the  
518 depth of 800 m until ~1000 m distorts the reflection related to the bottom of the OUM  
519 formation. The relatively worst image is provided using sources distributed along the right side  
520 of the target (Figure 6c), with a prominent horizontal artifact stretching for the whole section at  
521 the depth of 400 m and masking the RP related to part of the target with high-impedance  
522 inclusion (see RP2 in Figure 6c). On the other hand, the section shown in Figure 6c exhibits the  
523 highest level of SNR in the area between the RPs. Overall, the simulation results shown in  
524 Figure 6 aid the interpretation of the migrated field data by explaining artifacts related to  
525 directional source distributions.

#### 526 4.2 Validity of the 2D approach: 3D synthetic modelling

527 One may argue that the qualitatively good results of ANSI imaging applied to 2D synthetics  
528 might be misleading as we are ultimately aiming at imaging complex 3D structures. In order

529 to support the reliability of the 2D ANSI approach (Figures 5-6) we additionally performed 3D  
530 finite-difference acoustic modelling. We used SOFI3D open-source modelling code (Bohlen,  
531 2002) to simulate 648 separately acting AN sources and the full 3D model for the Kylylahti  
532 area (Riedel et al. 2018). The locations of those sources were obtained from the result of the  
533 InterLoc procedure (Dales et al., 2017a) applied to the events detected with TWEED  
534 (Chamarczuk et al. 2019, 2020) using the Kylylahti array data. In such a way, we used realistic  
535 3D distribution of passive sources. The sections shown in Figure 7 were obtained along the  
536 same receiver line as in the 2D synthetic case. Similar to the test of the directional illumination  
537 in 2D discussed above (Figure 6), we selectively stack sources on the left, bottom, and right of  
538 the target (Figure 7b, 7c, 7d, respectively). Additionally, we produce VSGs with all the sources  
539 included (Figure 7e) and a subset of sources mimicking the event-driven stacking (Figure 7f).  
540 When comparing the 2D results with those from the 3D approach, we can note that albeit the  
541 individual reflection packages are slightly shifted, structures inferred from the purely 2D  
542 approach agrees well with the synthetic model. Therefore, we conclude that the 2D ANSI can  
543 provide relatively robust imaging of 3D structures in the Kylylahti area.

## 544 5 FIELD DATA APPLICATION

545

### 546 5.1 Auto-correlations of traces

547 In this section, we evaluate the influence of the different AN preprocessing techniques by  
548 comparing virtual zero-offset traces. We obtain the zero-offset data by stacking the ACs of  
549 arbitrarily chosen one-hour-long AN segment. We focus on comparing the SNR in the time  
550 window of expected reflection arrivals and the general resemblance of the virtual data to its  
551 active counterpart. We compare zero-offset data for the 17th trace in the active-shot synthetic  
552 gather shown in Figure 4b and the corresponding trace extracted from line 7 of the Kylylahti  
553 array. Figure 8 shows the comparison of stacked zero-offset virtual traces retrieved using the  
554 various preprocessing schemes applied prior to AC. To facilitate the comparison between the

555 synthetic active-shot trace and virtual ACs, we show the zero-offset active-shot trace after  
556 concatenating its time-reversed variant (Figure 8a). In order to demonstrate the influence of  
557 each processing step, we show the raw AC result (Figure 8b). Applying time windowing (Figure  
558 8c) and filtering (Figure 8f and 8g) enhances the peaks in the time window not related to  
559 reflections (outside the grey shaded area shown in Figure 8) and the traces exhibit high-  
560 amplitude ringing noise. The high-amplitude event appearing between the pulse at  $t=0$  s and the  
561 grey shaded area (the expected arrival time of target reflections) in the AC traces suggests  
562 possible problems with the near-surface noise (caused by destructive interference of reflection  
563 and spurious events) retrieved in VSGs. On the other hand, peaks visible around the time  
564 window related to target reflections suggest the possibility of retrieving such reflections in the  
565 VSGs. The ‘ringing’ appearance of traces indicates possible problems due to overall low SNR  
566 in the retrieved VSGs. The auto-coherence (Figure 8e) exhibits a single positive peak, which is  
567 due to the spectral whitening performed intrinsically with this process (it is the AC normalized  
568 similarly to CCh). Energy normalization does not significantly affect the shape of AC (Figure  
569 8h). However, it has to be applied to assure equal contribution from separate stacks of correlated  
570 AN panels (Draganov et al., 2009). In general, applying one-bit and sliding-window energy  
571 normalization (Figures 8d and 8i, respectively) provides AC traces exhibiting highest  
572 amplitudes near the area of the expected reflections, while the ringing-amplitude effect visible  
573 in the raw CC (Figure 8b) is highly reduced. Based on those results, for the final processing of  
574 the field data we choose the routine time-windowing and energy normalization followed by  
575 high-pass filtering (Figure 8g) to further enhance the expected body-wave content.

## 576 [5.2 Noise-volume quality control and selection using illumination diagnosis](#)

577 In order to assure selection of high-quality AN segments for the 2D ANSI noise-volume  
578 approach, we apply illumination diagnosis to determine periods with the desired body-wave  
579 illumination. Subsequently, to show the relevance of illumination quality control (QC), we

580 investigate the consequence of applying CC to two different hours of noise. Towards this end,  
581 we extract two AN segments dominated by body-wave activity and surface-wave activity,  
582 respectively. We apply the same SI processing to both volumes and compare the resulting  
583 VSGs.

584 Figure 9 shows the illumination diagnosis panels for three adjacent receiver lines 7, 8, and 9  
585 (highlighted in Figure 3a). We obtain this plot by employing equation 10 for the whole day of  
586 recording (divided into 10-s-long noise panels) from those three lines and automatically picking  
587 the slowness characterizing the strongest event in each noise panel. We denote picks with green  
588 and black crosses for low- and high-slowness event, respectively. Note that line 7 contains the  
589 highest number of the low-slowness events, as it is located in the direct vicinity of the mine and  
590 the mine is expected to produce body-wave events. We select 1-hour-long recordings based on  
591 their illumination characteristics. Collating observations from all 3 receiver lines, we select the  
592 first 1-hour-long segment by choosing a period when at least several events with dominant  
593 slowness values fall into the limit of body-wave slownesses ( $< 0.2$  s/km) for all lines (see hour  
594 A in Figure 9). We choose a typical AN recording dominated by surface-wave energy as the  
595 second data segment. For that, we select an hour when zero low-slowness events occurred  
596 simultaneously on adjacent receiver lines (see Hour B in Figure 9). As indicated in the ACs of  
597 the zero-offset virtual traces (Figure 8), the most optimal preprocessing sequence is RMS  
598 energy normalization followed by a high-pass filtering. We apply this sequence to both selected  
599 hours and then retrieve VSGs using equation 7. The VSG retrieved using hour A (Figure 10b)  
600 has higher SNR compared to the VSG obtained using hour B (Figure 10c). Both VSGs exhibit  
601 the same reflection events, but the gather obtained from the low-slowness hour is characterized  
602 by less artifacts (see the events inside the blue rectangles in Figures 10b, c). To assure minimum  
603 number of artifacts, for further comparisons we select VSGs obtained using hour A.

### 604 5.3 Event-driven 2D ANSI

605 We evaluate the performance of the event-driven approach of 2D ANSI using body-wave events  
606 detected with the TWEED method. In order to construct the contour enclosing the target (see  
607 subsection 4.1), we use the InterLoc method (Dales et al., 2017a) to compute the location of  
608 every event captured with TWEED. Those locations were already used to calculate 3D  
609 synthetics (subsection 4.2). From these hypocenters, we select an ensemble of events  
610 mimicking the synthetic regular noise-sources distribution shown in Figure 5a. In Figure 11a,  
611 we indicate ten body-wave events selected for the event-driven approach considering the  
612 orientation of line 7 and the geological section shown in Figure 4a. In Figure 11b, we show the  
613 seismograms of those 10 events. Note that in order to detect and locate those events, we needed  
614 to scan the AN data over the whole recording period. Some of the selected events overlap with  
615 the low-slowness events from hour A (marked by dashed white circles in Figure 11a).  
616 Compared to the event-driven approach, body waves from the single hour are distributed  
617 directionally and illuminate the target area mainly from the right side. This suggests that the  
618 imaging using the event-driven approach should produce less artifacts related to directional  
619 illumination compared to the noise-volume approach.

### 620 5.4 2D ANSI methods applied to various segments of ambient noise

#### 621 5.4.1 Visual inspection

622 In this section, we apply CC, CCh, and MDD techniques to the AN segments consisting of (i)  
623 a single event, (ii) 10 events, and (iii) AN volume of 1-hour recording with the preferred  
624 illumination characteristics (hour A). In the subjective, visual comparison of the results  
625 described here we focus on: (i) resemblance to the synthetic active-source data, (ii) near-surface  
626 effects (up to 0.1 s TWT), (iii) general reflectivity content, and (iv) random noise on traces.

627 The VSG obtained with MDD (Figure 12 b, e, and h) exhibits the most prominent reflectivity  
628 for 1 hour (see the blue rectangle in Figure 12h). This result is also resembling the synthetic  
629 active-shot gather best. Generally, MDD exhibits the highest SNR of traces of all three 2D

630 ANSI techniques, and the first 0.1 seconds of the VSG exhibit distinguishable reflectivity. We  
631 also note that increasing the AN volume seems to have constructive influence on the quality of  
632 VSG retrieved with MDD.

633 The VSGs obtained using the CCh approach (Figures 12 c, f, and i) exhibit the lowest quality  
634 of all three applied SI techniques. The traces are noisy, almost no reflectivity is visible, and the  
635 near-surface artifacts seem to either dominate the whole gathers as in the case of 10 events and  
636 1 hour (see Figure 12f and 12i, respectively) or the whole gather is dominated by random noise  
637 (Figure 12c). The best result from the CCh appears to be achieved for the case of 1-hour-long  
638 recording (Figure 12i), in which the reflectivity is partially similar to the one obtained with  
639 MDD for 1-hour-long recording (Figure 12g). Note the lack of any coherent events in Figure  
640 12c.

641 The VSGs retrieved using CC (Figures 12d, g, and j) exhibit higher quality compared to the  
642 CCh results. The near-surface noise visible in the CCh results is not retrieved in all VSGs  
643 obtained using CC (note that some reflectivity in the first 0.1 s can be clearly tracked). The  
644 reflections in the green area expected from the synthetic active shot are best retrieved in case  
645 of 10 events (Figure 12g). Surprisingly, even the single-event CC (Figure 12c) allows to retrieve  
646 some reflectivity, yet clearly stacking over higher number of noise panels increases the SNR of  
647 most reflections and retrieves the new events. Generally, all VSGs (except the CCh for 1 event)  
648 exhibit more prominent reflectivity in the shallow parts of the data (first 0.1 s of TWT).

649 Another reflective feature retrieved with 2D ANSI and visible in the synthetic active-source  
650 data are the two events denoted with the shaded green colour in Figure 12. These are retrieved  
651 with all MDD approaches and CC for 10 events.

652 Apart from reflections expected from the synthetic active-source data, the VSGs contain some  
653 more coherent events. However, it is difficult to interpret them because their origin is uncertain.



654 Obviously, they are not predicted by our simplified geological model, but we should stress that  
655 it is hard to obtain shallow reflectivity from the real active-source data due to the shot-generated  
656 noise, muting, and low fold at shallow depths. Thus, they might be related to true geological  
657 features in the subsurface. The reflection events in the area of interest retrieved with 2D ANSI  
658 are shifted towards earlier times and exhibit less steeper dips compared to the synthetic active-  
659 source data.

#### 660 5.4.2 Semblance analysis

661 In order to compare reflectivity patterns retrieved with the synthetic active and field passive  
662 data in a more objective manner, we calculate semblances employing equation 11. CWT is  
663 calculated as both a function of scale and time, and, therefore, allows measuring the temporal  
664 change of the phase. We use part of the traces falling into the spatio-temporal window denoted  
665 with the blue rectangle in Figure 12 as input data. We calculate the semblance between every  
666 part of the trace falling in the analysed window and its corresponding trace in the synthetic  
667 active shot. As a result, we obtain a 2D matrix with phase and amplitude correlation coefficient  
668 for every trace. For comparison purposes, we average all results over amplitudes and obtain the  
669 mean phase-correlation value for every sample per each trace. In Figure 13, we show these  
670 average semblances calculated for VSGs obtained with the nine different processing  
671 approaches. To indicate the benchmark value, Figure 13a shows the part of the synthetic active-  
672 source used as base input for semblance calculation and Figure 13b shows its auto-semblance  
673 exhibiting maximum correlation represented with a red colour. The semblance plots in Figure  
674 13c to 13k are presented in the same layout as VSGs in Figure 12.

675 The red patches visible in the semblance plots indicate areas of high correlation, while the blue  
676 colour denote high anti-correlated part of data (all values fall in the range between -1 to 1).  
677 Considering that the 2D ANSI results contain significant amount of noise (see Figure 12), we  
678 expect that areas outside the targeted reflection would be strongly uncorrelated, because the

679 synthetic active-source data do not contain noise. Thus, if the VSG contains a coherent  
680 reflection similar to the one observed in the synthetic active-source data, the semblance plot  
681 should display a broad continuous red patch extending over the whole plot with generally  
682 similar curvature as the reflection visible in Figure 13a. To some extent this feature can be  
683 observed in the MDD (Figures 13f, and i) and CC results (Figure 13h) and is highlighted with  
684 white arrows. A semblance anomaly appearing as scattered remnant of the above feature  
685 appears in Figures 13j, and 13k, possibly indicating the faded imprint of expected reflectivity.  
686 Another potentially significant feature is the red area visible in the top-right segment of Figures  
687 13 c, e, f, j, k, and g, possibly related to partial correlation with the direct wave shown in Figure  
688 13a. To facilitate distinguishing between semblance anomalies related to the direct wave and  
689 reflection event, we indicate the line separating both type of arrivals with the black dashed line.

690 The general orientation of positive anomalies in Figure 13 c-k is horizontal, implying that the  
691 coherent features are stretching across the receivers, yet the anomalies have a narrow temporal  
692 extent (usually up to several time samples). The semblance plots shown in Figures 13 c, d, e,  
693 and g exhibit relatively broad, scattered red patterns indicating similarity which is likely  
694 random. Thus, they are not related to credible reflectivity content in the synthetic active-source  
695 data and we qualify them as not-resembling the expected result. Overall, we interpret the  
696 semblance anomalies denoted with white arrows in Figure 13f, 13h, and 13i, as features related  
697 to part of the reflection shown in Figure 13a. This means that the VSG obtained with MDD on  
698 10 events and 1 hour (see Figure 12e and 12h, respectively) as well as the VSG obtained with  
699 CC applied on 10 events (see Figure 12g) exhibit a reflection event similar to the one in the  
700 synthetic active-source data.

#### 701 5.4.3 Imaging results

702 For all nine 2D ANSI configurations presented in Figure 12, we retrieve VSGs for every  
703 receiver position. Subsequently, we apply top-mute and amplitude scaling, common-offset

704 DMO with a constant velocity  $V=6000$  m/s, and normal CDP stack. The CDP stack is migrated  
705 using constant-velocity Stolt migration and time-to-depth-converted with a constant velocity of  
706 6000 m/s.

707 The resulting depth sections are shown in Figure 14 using the same layout as in Figure 12. As  
708 the quality of the imaged reflectivity differs significantly, we focus only on the general SNR of  
709 the retrieved images and quality of reflections retrieved with 2D ANSI in the areas of the  
710 reflectivity predicted by the synthetic model (see dashed black lines in Figure 14). The migrated  
711 sections obtained using the single-event approach (Figure 14 b-d) exhibit a similar, low-  
712 frequency blurred pattern of reflectivity for every tested method, with low SNR, where the  
713 target RPs are hardly distinguishable from the image noise. For the single-event approach, RP1  
714 is best retrieved using MDD (Figure 14b) and is to some extent visible in the CCh result (Figure  
715 14c). RP3 is best visible in the CC panel (Figure 14c). In the single-event case, all three sections  
716 (Figure 14b-d) contain reflectivity in the expected areas, yet they are difficult to interpret as  
717 they are masked by the reflection artifacts of similar order of amplitude. The RP2 retrieval is  
718 of the poorest quality.

719 The images obtained using 10 events (Figure 14e-g) are much clearer than those obtained from  
720 the single event. The lowest number of artifacts is obtained with the MDD approach (Figure  
721 14e), yet the reflectivity packages expected from the synthetic data are best visible in the CC  
722 section (Figure 14g). Again, RP2 is poorly constrained. The x-shaped reflection visible in the  
723 CC result (see Figure 14g, in the proximity of the RP3 area) is discernible also in the CCh result  
724 (Figure 14f), yet it is shifted towards shallower depths. The CCh section obtained for 10 events  
725 (Figure 14f) exhibits almost no coherent reflections in the shallower part (up to 750 meters) and  
726 the only recognizable feature is the x-shaped reflection related to RP3.

727 The reflectivity images obtained using the noise-volume approach (Figure 14 h-j) bring the  
728 highest quality image for the MDD and CCh case. Especially, the MDD with 1 hour of AN

729 (Figure 14h) enables retrieval of reflections related to all RPs expected from the synthetic data  
730 (Figure 14a). On the other hand, the CC result for 1 hour (Figure 14j) brings a relatively poor  
731 image where no expected reflections can be tracked, with the exception of an ‘x’-shaped  
732 reflection similar to the observed in Figures 14f and g, barely visible again in the RP3 area. The  
733 CCh results for 1 hour (Figure 14i) show RP1 and RP2; however, the ringing noise in the RP2  
734 area and broad, horizontal artifacts, visible at approximately 750 m depth, are most likely not  
735 related to any geological features.

736 From all the images shown in Figure 14, the image resembling best the synthetic migrated  
737 section is obtained for the MDD 1-hour approach (Figure 14h). The second-best image  
738 resembling the synthetic active-source data is obtained using the event-driven CC approach  
739 (Figure 14g). Based on the visual inspection and semblance analysis of VSGs, we select the  
740 most optimal 2D ANSI approach, which is MDD applied to 1 hour of AN (see Figure 12h and  
741 13h for the VSG and migrated section, respectively) and we use this approach to process the  
742 adjacent receiver lines. In Figure 15, we show migrated images for receiver lines 7, 8, and 9.  
743 Persistence of the imaged features across the receiver lines corroborates our findings.

## 744 6 DISCUSSION

### 745 6.1 Optimizing the array – inferences from synthetic modelling

746 The synthetic passive data obtained with a preferable, i.e., regular distribution of sources around  
747 the target, provide ANSI results similar to the ones from the synthetic active-source data, but  
748 also contain artifacts. The artifacts in the virtual-shot domain (Figure 5b) are represented with  
749 arrivals visible before the line of the first breaks. Furthermore, in the synthetic active shot, the  
750 reflection related to the target at 0.1 s at ~20-29th trace is stronger than the reflection on the  
751 opposite side of the gather, while the synthetic passive case exhibits a reversed tendency. These  
752 amplitude errors are related to the imperfect distribution of simulated sources, i.e., instead of a  
753 sphere with a large radius and/or sources in the far-field (Wapenaar et al., 2010), we used the

754 rectangular polygon of sources located in the direct vicinity of the target. Furthermore, because  
755 the location of the mine imposes inducing seismic events mostly in the direct vicinity of the  
756 Kylylahti body, the contour of sources is crossing a sharp contrast in impedances (see the left  
757 flank of sources in Figure 5a). Not complying with the required source assumptions results in  
758 Green's functions with a correct phase of the arrivals, but with distorted amplitudes, which is  
759 clearly visible in Figure 5b. Fulfilling these assumptions in the field conditions would require  
760 moving the recording array away from the underground mine infrastructure, to approach the  
761 far-field approximation, but at the expense of a one-sided illumination. As shown in Olivier et  
762 al. (2016), the mine tunnels can act as scatterers, hence approximating the inhomogeneous  
763 medium, where seismic energy is scattered back to the receivers. In such case, one-sided  
764 illumination might be sufficient (Wapenaar et al., 2006a).

765 The image obtained from migration of the passive synthetic source data (Figure 5c) contains  
766 RPs similar to those in the synthetic active-source data, yet we could see a strong horizontal  
767 artifact hindering the clear outline of RP2; this artefact is mainly arising due to the right flank  
768 of the subsurface sources (see Figure 6c).

769 The illumination test shown in Figure 6 allows us to investigate the consequence of directionally  
770 biased illumination, which is a common issue in field measurements. The important conclusion  
771 from the reflection patterns visible in Figure 6 is the possibility to image the target even using  
772 an irregular sources distribution. The relatively best image is retrieved with sources underneath  
773 the target (see Figure 6b); however, such distribution is difficult to achieve in field conditions.  
774 Depending on the noise-sources location, we could obtain a response of the same structures but  
775 represented with different reflectivity patterns. For this reason, if it is possible to estimate the  
776 AN sources distribution prior to deployment (e.g., from the locations of the dominant noise  
777 sources in the area), one could estimate what part of the target would be illuminated best and  
778 how to layout the recording array with respect to the dominant AN source locations.

779 In the active mining camps, most of the AN sources would be related to routine mining activities  
780 concentrated in one place. Thus, the array should be oriented in accordance to the mutual  
781 orientation of the target and the mine area, with the general requirement to obtain a recording  
782 geometry allowing to capture the sources which emit wavefronts with ray paths connecting the  
783 traces being crosscorrelated and the point to be imaged. In the case of an operating mine where  
784 most activities are vertically aligned under the surface, the spatial distribution of ambient-noise  
785 sources may be approximated by a situation, where the sources are distributed in the vertical  
786 flanks (as shown in Figures 6a and 6c). For instance, if the target of interest is a dipping  
787 reflector, then the recording array could be deployed: (i) at some distance from the mine area  
788 (such that the far offsets for sources located toward the dipping direction are obtained, or (ii)  
789 directly above the mine for the sources located in direction opposite to the dip of the target  
790 reflector (see e.g., Roots et al., 2017 for details of imaging the dipping reflectors with SI).

## 791 [6.2 Influence of data preprocessing](#)

792 We incorporated two well-established SI QC tools: virtual zero-offset traces (Claerbout, 1968)  
793 and illumination diagnosis (Almagro Vidal et al., 2014) as parts of our ANSI workflow.  
794 Analysing virtual zero-offset traces allows for computationally effective evaluation of the  
795 preprocessing at the initial stage of data analysis. The pitfall related to assessment of amplitudes  
796 in a reflection time window from AC traces relates to the estimation of the deconvolution  
797 operator in the CC case. The side lobes visible in the grey shaded areas in Figure 8 are possibly  
798 related to the reflectivity targets; time-windowing of ACs around  $t=0$  s might remove such  
799 events during the source-function deconvolution usually performed after stacking of all  
800 correlated panels (Draganov et al., 2009). This is a consequence of having relatively low  
801 frequency (causing broadening of the side lobes) in our data. Therefore, we additionally applied  
802 high-pass filtering. Out of all compared preprocessing techniques, the one-bit normalization is  
803 particularly effective solution for extracting coherent information from AN. By removing the  
804 amplitude information, it could potentially retrieve all coherent events travelling between the

805 two receivers (Väkevä, 2019). However, for body-wave retrieval, it requires preferential  
806 illumination from body-wave sources (like having a receiver line oriented inline towards a  
807 railway, see e.g., Quiros et al., 2016). Otherwise, the body-wave events may be hindered by  
808 interfering, and usually much stronger. surface waves. In the Kylylahti case, the mine area is  
809 located approximately perpendicular to the line orientation, and thus applying one-bit  
810 normalization could result in degrading the body-wave arrivals. However, as demonstrated by  
811 Väkevä (2019), one-bit normalization in conjunction with bandpass filtering, and f-k filtering  
812 can be effectively used for suppressing the dominant surface-wave content and reveal the  
813 reflectivity content in the Kylylahti area. The recent developments in autocorrelation studies  
814 using AN recordings (Clayton, 2020) indicate the potential to further improve the performance  
815 of the preprocessing step in the 2D ANSI workflow.

### 816 [6.3 Body-wave- vs surface-wave-dominated recordings](#)

817 We used illumination diagnosis to identify periods of AN dominated by body waves. Noise-  
818 volume selection (one-hour-long recording in this study) is an ambivalent choice and has  
819 implication in the resulting VSGs (see Figure 10 b, and c). We argue that even when stacking  
820 continuous data (noise-volume approach), it is beneficial to perform illumination diagnosis and  
821 scan for the noise panels dominated by low-slowness events. The VSGs shown in Figure 10b  
822 and 9c suggest that stacking over volumes of noise recorded during different periods (see  
823 illumination characteristics of these periods in Figure 9) bring generally similar results, yet  
824 varying in terms of SNR of the retrieved reflections and number of artifacts. Practically, it  
825 means that acquiring longer recordings does not necessarily bring better results, as  
826 improvement mainly depends on the eventual body-to-surface-wave content ratio. The potential  
827 pitfall of stacking an hour dominated by body waves is that despite capturing events with low  
828 slownesses, their distribution might be asymmetric as shown in Figure 11a. An event-driven  
829 approach allows directly to choose which sources we want to stack and, hence, overcomes the  
830 directional-illumination issue. However, the need for scanning more data and computing the

831 illumination direction of recorded sources makes this approach more computationally  
832 expensive. This process can be automated though with machine-learning tools (Chamarczuk et  
833 al. 2019, 2020). Furthermore, even scanning the whole available data volume does not  
834 guarantee proper illumination, i.e., the subset of the available sources to choose from is  
835 determined by the location of the sources comprising the AN at a given recording site, which  
836 in the case of the Kylylahti data is mostly limited to the extent of the mine infrastructure. The  
837 practical implication of choosing an event-driven approach over a noise-volume approach is in  
838 the required recording time, since theoretically a few body-wave events should bring equal  
839 results to stacking over long periods of noise, thus possibly reducing the necessary acquisition  
840 time if a number of events, deemed sufficient, is already detected.

#### 841 [6.4 Quality of the virtual shot gathers](#)

842 The main goal of applying 2D ANSI is to produce VSGs, which will allow to obtain structural  
843 imaging comparable to the one from the active-source surveys, but using ambient-noise sources  
844 (Draganov and Ruigrok, 2015). We rated the performance of SI processing strategies by  
845 comparing VSGs obtained using three different SI methods and benchmarking the results with  
846 the synthetic active-source data. In the case of the Kylylahti data, the CCh method yields the  
847 noisiest results, with relatively better performance for 1 hour of noise (see Figure 12 i). We  
848 argue that possibly many reflections are retrieved with CCh, yet they are buried in the noisy  
849 traces of the retrieved VSGs. A reflection in the target area is present (see blue rectangles in  
850 Figures 12f and i), yet it is hard to track as it exhibits low SNR. The poor performance of CCh  
851 is mostly related to the relatively low SNR of any reflection events in the noise panels, which  
852 further gets undermined in the correlated gathers. The consequence of applying CCh is bringing  
853 all recorded events to the same amplitude level. As a result, when the raw noise panels contain  
854 surface waves, the virtual shots after CCh will contain reflection events with amplitudes of the  
855 same magnitude as surface waves. The CC produces generally higher-quality results than CCh  
856 (Figure 12 d, g, and j). The best result is obtained for the event-driven approach (see Figure



857 12g). The CC result for 1 event (Figure 12d) is comparable for the result retrieved using 1 hour  
858 of noise (Figure 12j). Furthermore, the result for 10 events (Figure 12g) resembles to some  
859 extent the MDD result for 1 hour of noise (Figure 12h), exhibiting both reflectivity in the target  
860 area (denoted with blue rectangles in Figure 12) and also deeper reflections (denoted with green  
861 dashed colour in Figure 12) visible in the MDD result. The better performance of CC over CCh  
862 is related to the fact that the deconvolution operator in CC is derived from the data itself, and  
863 allows suppressing the ringing-amplitude pattern visible in the CCh results. Theoretically,  
864 MDD should bring better results than CC, as deconvolving by PSF should correct for varying  
865 noise-sources signatures, intrinsic attenuation, and irregular noise-source illumination.  
866 Accordingly, the MDD technique seems to produce VSGs resembling most the synthetic active-  
867 source data (see Figure 12b-h). Next to the reflections expected from the synthetic data, deeper  
868 reflectivity is also retrieved. The best result for the MDD case is achieved using 1 hour of AN  
869 (Figure 12h). Since MDD relies on deblurring the correlation output with PSF (equation 9), the  
870 main reason for differences observed in the virtual shots compared to the other two techniques  
871 is related to the PSF estimation. Deblurring the correlation function with PSF should eliminate  
872 the crosstalk from the correlation function and give the deblended virtual-source response. The  
873 potential distortions of the MDD result might be related to crosstalk contributions contained in  
874 PSF itself (Wapenaar et al., 2011), as well as incorrect extraction of the PSF. The exact  
875 influence of the PSF estimation on the reflection retrieval deserves a separate study, but is also  
876 thoroughly discussed, e.g., in Nishitsuji et al. (2016). On top of the shallow reflectivity, the  
877 MDD results brought also very clear reflections at  $\sim 1$  s (not shown here); however, their fidelity  
878 is yet to be verified and is outside the target depths for exploration (but such reflectors were  
879 present in the active-source imaging of Heinonen et al. 2019 and Singh et al. 2019).

880 Generally, all VSGs exhibit very prominent reflectivity at shallower depths. The differences  
881 between the three techniques are mostly related to the specific type of deconvolution implied

882 by them. The event-driven approach for MDD and CCh (Figure 12e and f) performs worse than  
883 the noise-volume approach. Nevertheless, these gathers still exhibit some reflectivity, which is  
884 promising in terms of similar SI applications with refined processing. For the MDD method,  
885 when adding more AN, both the deconvolution operator and the scattered field become updated,  
886 while for the CC only the raw correlation is stacked and the deconvolution operator is derived  
887 from the stacked correlogram, hence, theoretically, it cannot account for the whole complexity  
888 of the wavefield. For the CC method, the event-driven approach (see Figure 12g) performs best,  
889 and it could be potentially further enhanced by applying deconvolution per-event (Ruigrok et  
890 al., 2010).

## 891 6.5 Imaging

892 The general diversity of the retrieved reflectivity makes it hard to directly assess the quality of  
893 the processing approaches for selecting an optimal one using these migrated images. For this  
894 reason, and from the point of view of computational efficiency, the assessment of the  
895 effectiveness of the processing strategies should be carried out before migration, at the level of  
896 noise panels and VSGs (including e.g., the introduced semblance evaluation method). We leave  
897 it up to the reader to review the presented images and draw their own conclusions. Yet, based  
898 on both the visual similarity to the synthetic shots and semblance analysis, we think that the  
899 results from MDD with 1 hour of AN (Figure 14h) and CC with 10 events (Figure 14g) exhibit  
900 reflectivity resembling most the image obtained from the synthetic data. The results of imaging  
901 for adjacent receiver lines (Figure 15) suggest the redundancy of 2D ANSI imaging (provided  
902 the same processing sequence is applied to the data from every line). The reflectivity packages  
903 in the synthetic section are visible in line 7 collocated with the synthetic model, and the  
904 reflectivity patterns visible along the two adjacent lines deployed to the south of line 7 (Figures  
905 15 c and d) are persistent.

906 The results shown in Figure 15 were obtained with only 1 hour of AN. The hour used for  
907 imaging was selected after thorough illumination diagnosis (see Figure 9 for illumination-

908 diagnosis QC panel). Note that even if the amount of data we used is not significant, we still  
909 needed to process the bigger dataset to increase the probability of capturing AN with satisfying  
910 illumination characteristics. Some of the RPs visible in the migrated sections might still be  
911 related to out-of-plane targets and the full-3D ANSI processing could address their geometry  
912 properly.

### 913 [6.6 Future developments and recommendations](#)

914 The core of the 2D ANSI methodology is the comparison of different SI processing techniques  
915 to determine the most optimal sequence of processing steps for a given case study. Practically,  
916 it means that it requires repeating the complete processing flows starting from extraction of the  
917 recorded passive data up to the generation of the VSGs. This idea is illustrated in Figure 16,  
918 where the 2D ANSI methodology is represented with parallel processing flowcharts allowing  
919 for the practical implementation of the comparison between various tools advocated in this  
920 study.

921 We believe that 2D ANSI is capable of imaging targets in a hardrock environment. However,  
922 the quality of the imaging, apart from the acquisition geometry and strength of the impedance  
923 contrasts and the complexity of the medium (e.g., dip angles), depends on the selected SI  
924 method and the selection of AN segments. The results obtained for the real-case scenario of the  
925 complex structure at the Kylylahti site are generally quite noisy, and most of the compared  
926 approaches differ significantly in the imaging quality. Therefore, when applying 2D ANSI, a  
927 comparison of different approaches should be an essential part of the processing workflow.

928 We recommend using 2D ANSI as a reconnaissance tool prior to the massive 3D deployments  
929 (either active or passive) as it allows to determine the cycle of body-wave event activity (related  
930 to the mine operations). As we show in Figure 9, some periods of AN exhibit higher density of  
931 body-wave events. For instance, receiver line 7, i.e., the line which is closest to the mine area,  
932 could serve as a good indicator of potential body-wave content in AN in the Kylylahti area.  
933 Knowing that the mine operations produce body-wave events in repeatable cycles could allow

934 reducing the recording time with a full array to periods when mine-induced sources with  
935 preferable illumination are likely to be recorded. Our results can be used to derive general  
936 recommendations in terms of planning future SI experiments for mineral exploration purposes:  
937 (i) orienting the acquisition array considering the location of the dominant noise sources and  
938 targets, and (ii) considering the possibility to reduce the continuous recording time to  
939 preselected time period, i.e., it is safe to assume that scheduled drilling and mine blasting  
940 occurring at several hundred meters below the surface would produce body-wave events. Each  
941 passive dataset would be recorded in a different AN setting, yet because we address active mine  
942 camps, the general characteristic of the AN wavefield would exhibit similar dominant features  
943 due to the dominance of mine-induced noise (Cheraghi et al., 2015; Oliver et al., 2016a,b; Dales  
944 et al., 2017a,b; Roots et al., 2017) and particularly unusually high ratio of body-to-surface wave  
945 energy with highly asymmetric distribution. In the Kylylahti case, for a single 3D virtual shot  
946 gather, reflection events are observed only along 20-30 traces out of all 994 receivers (top row  
947 in Fig. 1a) and are much less prominent than in the active 3D data (bottom row in Fig. 1a). The  
948 processing method aiming for automatic detection of such sparse, coherent events deserves  
949 dedicated tailored approach including scanning of hundreds of receivers for hundreds of virtual  
950 shots, which is not established yet and computationally not feasible. At this point we argue that  
951 prior to developing the 3D ANSI methodology, it is beneficial to know which combination of  
952 SI techniques and AN segmentation offers the highest probability for reflection retrieval and as  
953 such we need to develop 2D ANSI methodology first.

## 954 7 CONCLUSIONS

955 We introduced a 2D ambient-noise seismic interferometry (ANSI) processing workflow, which  
956 can be applied to passive seismic data acquired along a test profile to serve as a reconnaissance  
957 tool for AN evaluation and future more detailed seismic acquisition (passive or active) in active-  
958 mine environments. Using synthetic and field data from the Kylylahti mine (Finland), we

959 indicated the relevance of 2D ANSI in general structural delineation and optimization of both  
960 the acquisition design and AN recording parameters. The synthetic modelling indicated that the  
961 passive data can be used to reproduce similar details of the complex geological model as the  
962 active-source data. The differences are attributed mainly to AN sources illuminating the target  
963 from different angles than the active shots. The key point of our workflow was the comparison  
964 of the performance of SI by multidimensional deconvolution (MDD), crosscoherence (CCh),  
965 and crosscorrelation (CC) on various AN segments: single body-wave event, event-driven  
966 approach using 10 body-wave events, and a noise-volume approach using 1 hour of AN  
967 recordings. The primary general conclusion of the comparison is the necessity to recognize the  
968 spatial and temporal distribution of the AN sources in the recording area. Based on this  
969 information, synthetic tests should be performed and the 2D receiver line for passive acquisition  
970 should be subsequently oriented with respect to the expected dominant AN sources and the  
971 imaging target. After acquisition of 2D passive data, different processing schemes should be  
972 evaluated using the methodology we proposed in this study. We showed that the final outcome  
973 of the 2D ANSI workflow provides initial target delineation, which facilitates the decision about  
974 conducting follow-up 3D surveys (active or passive) or using a network of 2D lines. These  
975 future experiments should be designed with the acquisition parameters, length of recording  
976 time, and SI processing workflow indicated by the initial 2D ANSI assessment.

977 The application of the full processing workflow on 2D receiver lines extracted from a passive  
978 dataset recorded at the Kylylahti mine led to the following conclusions specific for this case  
979 study. (1) The effectiveness of the AN preprocessing could be evaluated on zero-offset data.  
980 For the Kylylahti dataset, the sequence of trace-energy normalization and high-pass filtering  
981 provided the highest amplitudes in the retrieved body-wave arrivals and minimized the artifact  
982 contribution. (2) The 2D illumination diagnosis applied to AN for the noise-volume approach  
983 increased the signal-to-noise ratio of the reflection events in the retrieved VSGs, and thus we

984 recommend it as a routine SI processing step. Illumination diagnosis applied for the event-  
985 driven approach provided results bearing similar quality, but obtained using significantly  
986 smaller amount of AN data. For the Kylylahti dataset, using 10 body-wave events, extracted  
987 from one hour of AN, was enough to provide results comparable to the results from the noise-  
988 volume approach using the complete one hour. (3) VSGs retrieval using the MDD method  
989 applied using the noise-volume approach and CC using the event-driven approach provided the  
990 highest quality data with reflection events resembling the active-source data the most. (4)  
991 Semblance analysis is an effective tool to aid the visual comparison of the passive and active-  
992 source data in selected spatio-temporal windows. (5) For the optimal selection of an SI  
993 technique and AN segment, the subsurface image can be obtained using a simple post-stack  
994 migration scheme, which requires only little knowledge on the velocity model. (6) The 2D  
995 ANSI processing workflow applied to the Kylylahti data provided images of the subsurface  
996 acceptable in terms of the general delineation of the target structures, as verified by comparison  
997 of results along adjacent receiver lines.

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## 1007 REFERENCES

1008

1009 Adam, E., G. Perron, G. Arnold, L. Matthews, and B. Milkeriet, 2003, 3D seismic imaging for  
1010 VMS deposit exploration, Matagami, Quebec, in D. W. Eaton, B. Milkereit, and M. H.  
1011 Salisbury, eds., *Hard rock seismic exploration*: SEG.

1012 Almagro Vidal, C., D. Draganov, J. van der Neut, G. Drijkoningen, and K. Wapenaar, 2014,  
1013 Retrieval of reflections from ambient noise using illumination diagnosis: *Geophysical Journal*  
1014 *International*, 198, 1572-1584, doi: 10.1093/gji/ggu164.

1015 Bakulin, A., and R. Calvert, 2006, The virtual source method: theory and case study:  
1016 *Geophysics*, 71, no. 4, SI139 SI150, doi: 10.1190/1.2216190.

1017 Balestrini, F., D. Draganov, A. Malehmir, P. Marsden, and R. Ghose, 2020, Improved target  
1018 illumination at Ludvika mines of Sweden through seismic-interferometric surface-wave  
1019 suppression: *Geophysical Prospecting*, 68, 200-213. doi:10.1111/1365-2478.12890.

1020 Bohlen, T., 2002, Parallel 3-D viscoelastic finite difference seismic modelling. *Comput.*  
1021 *Geosci.* 28, 887–899, doi:10.1016/S0098-3004(02)00006-7

1022 Calvert, A. J., and Y. Li, 1999, Seismic reflection imaging over a massive sulfide deposit at the  
1023 Matagami mining camp, Quebec: *Geophysics*, 64, 24 32, doi: 10.1190/1.1444521.

1024 Chamarczuk, M., M. Malinowski, Y. Nishitsuji, J. Thorbecke, E. Koivisto, S. Heinonen, S.  
1025 Juurela, M. Mężyk, and D. Draganov, 2019, Automatic 3D illumination diagnosis method for  
1026 large-N arrays: robust data scanner and machine learning feature provider: *Geophysics*, 84, no.  
1027 3, Q13 Q25, doi: 10.1190/geo2018-0504.1.

1028 Chamarczuk, M., Y. Nishitsuji, M. Malinowski, M. and D. Draganov, 2020, Unsupervised  
1029 Learning Used in Automatic Detection and Classification of Ambient-Noise Recordings from  
1030 a Large- Array: *Seismol. Res. Lett.*, 91, 370-389, doi: 10.1785/0220190063.

1031 Chapman, H., 1981, Generalized Radon transforms and slant stack: *Geophysical Journal*  
1032 *International*, 66, 445-453, doi: 10.1111/j.1365-246X.1981.tb05966.x.

1033 Cheraghi, S., A. Malehmir, and G. Bellefleur, 2011, Crustal-scale reflection seismic  
1034 investigations in the Bathurst Mining Camp, New Brunswick, Canada: *Tectonophysics*, 506,  
1035 55 72, doi: 10.1016/j.tecto.2011.04.011.

1036 Cheraghi, S., A. Malehmir, and G. Bellefleur, 2012, 3D imaging challenges in steeply dipping  
1037 mining environment: New lights on acquisition geometry and processing from the Brunswick  
1038 no. 6 seismic data, Canada: *Geophysics*, 77, no. 5, WC109, doi: 10.1190/geo2011-0475.1.

1039 Cheraghi, S., J. A. Craven, and G., Bellefleur, 2015, Feasibility of virtual source reflection  
1040 seismology using interferometry for mineral exploration: A test study in the Lalor Lake  
1041 volcanogenic massive sulphide mining area, Manitoba, Canada: *Geophysical Prospecting*, 63,  
1042 4, 833-848, doi: 10.1002/2015JB011870.

1043 Cheraghi, S., D. J. White, D. Draganov, G. Bellefleur, J. A. Craven, and B. Roberts, 2016,  
1044 Passive seismic reflection interferometry: A case study from the Aquistore CO2 storage site,  
1045 Saskatchewan, Canada, *Geophysics*, 82, no. 3, doi: 10.1190/geo2016-0370.1.

1046 Clayton, R., 2020, Imaging the Subsurface with Ambient Noise Autocorrelations,  
1047 *Seismological Research Letters*, 91, 2A, 930-935, doi: 10.1785/0220190272.

1048 Claerbout, J. F., 1968, Synthesis of a layered medium from its acoustic transmission response:  
1049 *Geophysics*, 33, 264 269, doi: 10.1190/1.1439927.

1050 Cooper, G.R.J., and D.R. Cowan, Comparing time series using wavelet-based semblance  
1051 analysis: *Computers and Geosciences*, 34, no. 2, 2008, 95-102, doi:  
1052 10.1016/j.cageo.2007.03.009.



1053 Czarny, R., H. Marcak, N. Nakata, Z. Pilecki, Z. Isakow, 2016, Monitoring velocity changes  
1054 caused by underground coal mining using seismic noise: *Pure and Applied Geophysics*, 173,  
1055 no. 6, 1907-1916, doi:10.1007/s00024-015-1234-3.

1056 Dales P., P. Audet, G. Olivier, and J.P. Mercier, 2017a, Interferometric methods for spatio-  
1057 temporal seismic monitoring in underground mines: *Geophysical Journal International*, 210,  
1058 731-742, no. 2, doi: 10.1093/gji/ggx189.

1059 Dales, P., P. Audet, and G. Olivier, 2017b, Seismic interferometry using persistent noise  
1060 sources for temporal subsurface monitoring: *Geophysical Research Letters*, 44, 10, 863-870,  
1061 doi: 10.1002/2017GL075342.

1062 Daneshvar, M., R., C. S. Clay, and M. K. Savage, 1995, Passive seismic imaging using  
1063 microearthquakes, *Geophysics*, 60, 1178-1186, doi: 10.1190/1.1443846.

1064 Draganov, D., K. Wapenaar, W. Mulder, J. Singer, and A. Verdel, 2007, Retrieval of reflections  
1065 from seismic background-noise measurements: *Geophysical Research Letters*, 34, L04305, doi:  
1066 10.1029/2006GL028735.

1067 Draganov, D., X. Campman, J. W. Thorbecke, A. Verdel, and K. Wapenaar, 2009, Reflection  
1068 images from ambient seismic noise: *Geophysics*, 74, no. 5, A63-A67, doi:  
1069 10.1190/1.3193529.

1070 Draganov, D., X. Campman, J. W. Thorbecke, A. Verdel, and K. Wapenaar, 2013, Seismic  
1071 exploration-scale velocities and structure from ambient seismic noise (>1 Hz): *Journal of*  
1072 *Geophysical Research: Solid Earth*, 118, no. 8, 4345-4360, doi: 10.1002/jgrb.50339.

1073 Draganov, D. S., and E. Ruigrok, 2015, Passive seismic interferometry for subsurface imaging.  
1074 In M. Beer, E. Patelli, I. Kougioumtzoglou, and I. Siu-Kui Au, eds., *Encyclopedia of earthquake*  
1075 *engineering*, 1-13, doi:10.1007/978-3-642-36197-5\_378-1.

1076 Eaton, D, B. Mikereit, and M. Salisbury, 2003, *Hardrock Seismic Exploration*, SEG.

1077 Hajnal, Z., D. White, E. Takacs, S. Gyorfi, I. R. Annesley, G. Wood, C. O'Dowd, and G.  
1078 Nimeck, 2010, Application of modern 2D and 3D seismic reflection techniques for uranium  
1079 exploration in the Athabasca Basin, in *Lithoprobe: Parameters, processes and the evolution of*  
1080 *a continent: Canadian Journal of Earth Sciences special issue*, 47, 761-782, doi: 10.1139/E10-  
1081 026.

1082 Heinonen, S., M. Malinowski, F. Hloušek, G. Gislason, S. Buske, E. Koivisto, and M. Wojdyla,  
1083 2019, Cost-effective seismic exploration: 2D reflection imaging of the mineral system of  
1084 Kylylahti, Eastern Finland: *Minerals*, 9, no. 5, 263, doi: 10.3390/min9050263.

1085 Koivisto, E., A. Malehmir, P. Heikkinen, S. Heinonen, and I. Kukkonen, 2012, 2D reflection  
1086 seismic investigations at the Kevitsa Ni-Cu-PGE deposit, northern Finland: *Geophysics*, 77, no.  
1087 5, WC149-WC162, doi: 10.1190/GEO2011-0496.1.

1088 Luhta, T., 2019, Petrophysical properties of the Kylylahti Cu-Au-Zn sulphide mineralization  
1089 and its host rocks: M.S. thesis, University of Helsinki.

1090 Malehmir, A., R. Durrheim, G. Bellefleur, M. Urosevic, Ch. Juhlin, D.J. White, B. Milkereit,  
1091 and G. Campbell, 2012a, Seismic methods in mineral exploration and mine planning: A general  
1092 overview of past and present case histories and a look into the future: *Geophysics*. 77, no. 5,  
1093 WC173-WC190, doi: 10.1190/GEO2012-0028.1.

1094 Malehmir, A., C. Juhlin, C. Wijns, M. Urosevic, P. Valasti, and E. Koivisto, 2012b, 3D  
1095 reflection seismic investigation for open-pit mine planning and exploration in the Kevitsa Ni-  
1096 Cu-PGE deposit, northern Finland: *Geophysics*, 77, no. 5, WC95-WC108, doi:  
1097 10.1190/geo2011-0468.1

1098 Mehta, K., A. Bakulin, J. Sheiman, R. Calvert and, R. Snieder, 2007, Improving the virtual  
1099 source method by wavefield separation: *Geophysics*, 72, no. 4, V79 V86, doi:  
1100 10.1190/1.2733020.

1101 Nakata, N., R. Snieder, T. Tsuji, K. Lerner, and T. Matsuoka, 2011, Shear wave imaging from  
1102 traffic noise using seismic interferometry by cross-coherence: *Geophysics*, 76, no. 6, SA97  
1103 SA106, doi: 10.1190/geo2010-0188.1.

1104 Neidell, N. S., and M. Turhan Taner, 1971, Semblance and other coherency measures for  
1105 multichannel data: *Geophysics*, 36, no. 3, 482-497, doi: 10.1190/1.1440186.

1106 Nishitsuji, Y., S. Minato, B. Boullenger, M. Gómez, K. Wapenaar, and D. Draganov, 2016,  
1107 Crustal-scale reflection imaging and interpretation by passive seismic interferometry using  
1108 local earthquakes: *Interpretation*, 4, no. 3, SJ29-SJ53, doi:10.1190/INT-2015-0226.1.

1109 Olivier, G., F. Brenguier, M. Campillo, P. Roux, N. Shapiro, and R. Lynch, 2015a, Investigation  
1110 of coseismic and postseismic processes using in-situ measurements of seismic velocity  
1111 variations in an underground mine: *Geophysical Research Letters*, 42, 9261-9269,  
1112 doi:10.1002/2015GL065975.

1113 Olivier, G., F. Brenguier, M. Campillo, R. Lynch and P. Roux, 2015b, Body-wave  
1114 reconstruction from ambient noise seismic noise correlations in an underground mine:  
1115 *Geophysics*, 80, no. 3, KS11-KS25, doi: 10.1190/geo2014-0299.1.

1116 Panea, I., D. Draganov, C. A. Vidal, and V. Mocanu, 2014, Retrieval of reflections from  
1117 ambient noise recorded in the Mizil area, Romania: *Geophysics*, 79, Q31-Q42, doi:  
1118 10.1190/geo2013-0292.1.

1119 Polychronopoulou, K., A. Lois, and D. Draganov, 2020, Body-wave passive seismic  
1120 interferometry revisited: mining exploration using the body waves of local microearthquakes:  
1121 *Geophysical Prospecting*, 68, 232-253, doi:10.1111/1365-2478.12884.

1122 Quiros, A. D., L. D. Brown, and D. Kim, 2016, Seismic interferometry of railroad induced  
1123 ground motions: body and surface wave imaging: *Geophysical Journal International*, 205, 1,  
1124 301-313, doi: 10.1093/gji/ggw033.

1125 Riedel, M., C. Cosma, N. Enescu, E. Koivisto, K. Komminaho.; K. Vaittinen, and M.  
1126 Malinowski, 2018, Underground Vertical Seismic Profiling with Conventional and Fiber-Optic  
1127 Systems for Exploration in the Kylylahti Polymetallic Mine, Eastern Finland: *Minerals*, 8,  
1128 no.11, 538, doi: 10.3390/min8110538.

1129 Roots, E., A. Calvert, and J. Craven, 2017, Interferometric seismic imaging around the active  
1130 Lalor mine in the Flin Flon greenstone belt, Canada: *Tectonophysics*, 718, 92-104, doi:  
1131 10.1016/j.tecto.2017.04.024.

1132 Ruigrok, E., X. Campman, D. Draganov, and K. Wapenaar , 2010, High-resolution lithospheric  
1133 imaging with seismic interferometry: *Geophysical Journal International*, 183, 339-357, doi:  
1134 10.1111/j.1365-246X.2010.04724.x.

1135 Singh, B., M. Malinowski, F. Hloušek, E. Koivisto, S. Heinonen, O. Hellwig, S Buske, M.  
1136 Chamarczuk, and S. Juurela, 2019, Sparse 3D Seismic Imaging in the Kylylahti Mine Area,  
1137 Eastern Finland: Comparison of Time vs Depth Approach: *Minerals*, 9, no. 5, 305, doi:  
1138 10.3390/min9050305.

1139 Sinha, S., P. S. Routh, P.D. Anno, and J. P. Castagna, 2005, Spectral decomposition of seismic  
1140 data with continuous-wavelet transform: *Geophysics*, 70, no. 6, P19 P25, doi:  
1141 10.1190/1.2127113.

1142 Snieder, R., J. Sheiman, and R. Calvert, 2006, Equivalence of the virtual source method and  
1143 wave-field deconvolution in seismic interferometry: *Physical Review E*, 73, 066620,  
1144 doi:10.1103/PhysRevE.73.066620.

1145 Snieder, R., M. Miyazawa, E. Slob, I. Vasconcelos, and K. Wapenaar, 2009, A comparison of  
1146 strategies for seismic interferometry: *Surveys in Geophysics*, 30, 503-523, doi: 10.1007/s10712-  
1147 009-9069-z.

1148 Stolt, R. H., and A. K. Benson, 1986, *Seismic migration: Theory and practice*, handbook of  
1149 geophysical exploration, 5, Geophysical Press.

1150 Thorbecke, J. W., and D. Draganov, 2011, Finite-difference modeling experiments for seismic  
1151 interferometry: *Geophysics*, 76, no. 6, H1-H18, doi: 10.1190/geo2010-0039.1.

1152 Väkevä, S., 2019, *Using Three-Component Data for Seismic Interferometry Studies at the*  
1153 *Kylylahti Mine, Eastern Finland*: M.S. thesis, University of Helsinki.

1154 van der Neut, J., E. Ruigrok, and K. Wapenaar, 2010, Retrieving the earth's reflection response  
1155 by multidimensional deconvolution of ambient noise: 72nd Annual International Conference  
1156 and Exhibition, EAGE, Extended Abstracts, P406, doi: 10.3997/2214-4609.201401259.

1157 van der Neut, J., J. Thorbecke, K. Mehta, E. Slob, and K. Wapenaar, 2011, Controlled-source  
1158 interferometric redatuming by crosscorrelation and multidimensional deconvolution in elastic  
1159 media: *Geophysics*, 76, no. 4, SA63, doi: 10.1190/1.3580633.

1160 Wapenaar, K., J.W. Thorbecke, D. Draganov, and J. T. Fokkema, 2002, Theory of acoustic  
1161 daylight imaging revisited: 72nd Annual International Meeting, SEG, Expanded Abstracts,  
1162 2269-2272, doi: 10.1190/1.1817165.

1163 Wapenaar, K., J.W. Thorbecke, and D. Draganov, 2004, Relations between reflection and  
1164 transmission responses of 3-D inhomogeneous media: *Geophysical Journal International*, 156,  
1165 179-194, doi: 10.1111/j.1365-246X.2003.02152.x.

1166 Wapenaar, K., and J. Fokkema, 2006, Green's functions representations for seismic  
1167 interferometry: *Geophysics*, 71, no. 4, 1JA-Z75, doi: 10.1190/1.2213955.

1168 Wapenaar, K., J. van der Neut, and E. Ruigrok, 2008, Passive seismic interferometry by  
1169 multidimensional deconvolution: *Geophysics*, 73, A51-A56, doi: 10.1190/1.2976118.

1170 Wapenaar, K., E. Slob, R. Snieder, and Andrew Curtis, 2010, Tutorial on seismic  
1171 interferometry: Part 2 — Underlying theory and new advances: *Geophysics*, 75, no. 5, doi:  
1172 75A211-75A227, doi: 10.1190/1.3463440.

1173 Wapenaar, K., J. van der Neut, E. Ruigrok, D. Draganov, J. Hunziker, E. Slob, J. Thorbecke,  
1174 and R. Snieder, 2011, Seismic interferometry by crosscorrelation and by multidimensional  
1175 deconvolution: a systematic comparison: *Geophysical Journal International*, 185, no. 3, 1335  
1176 1364, doi: 10.1111/j.1365-246X.2011.05007.x.

1177 White, D. J., D. Secord, and M. Malinowski, 2012, 3D seismic imaging of volcanogenic  
1178 massive sulfide deposits in the Flin Flon mining camp, Canada: Part 1 — Seismic results:  
1179 *Geophysics*, 77, no. 5, WC47, doi: 10.1190/geo2011-0487.1.

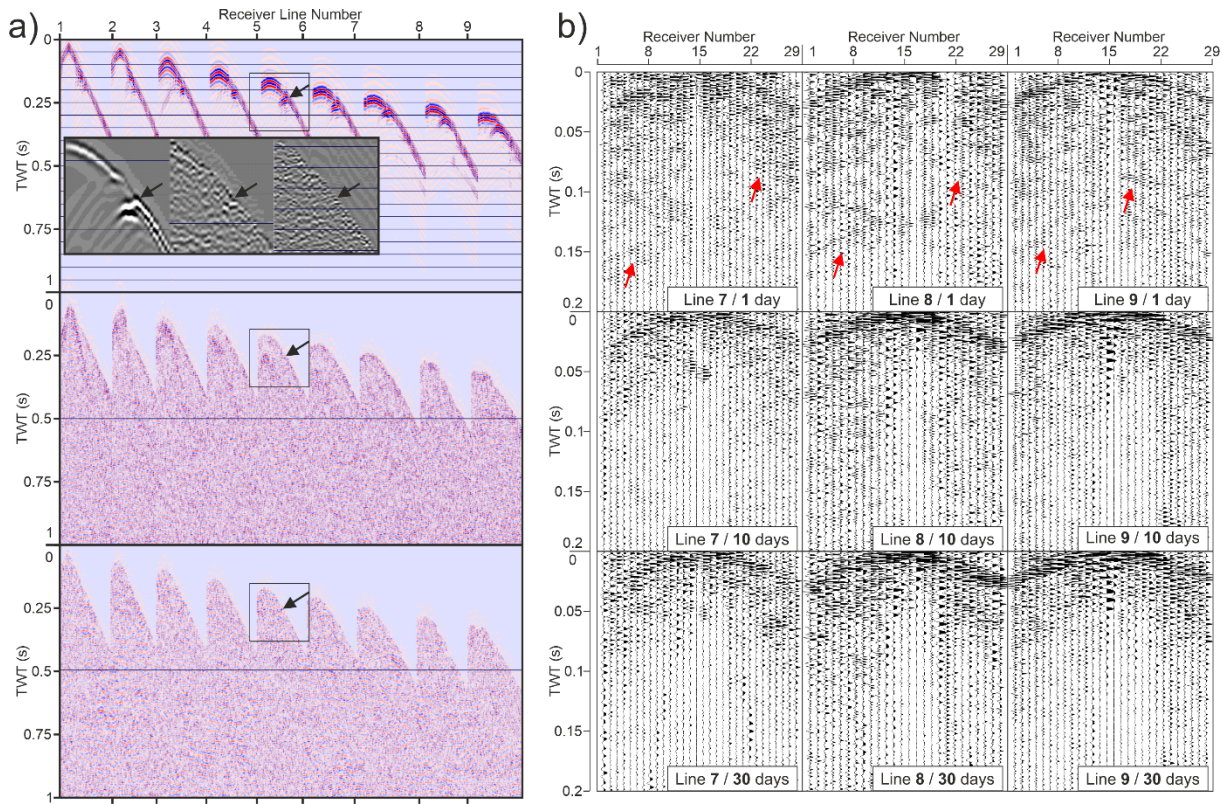
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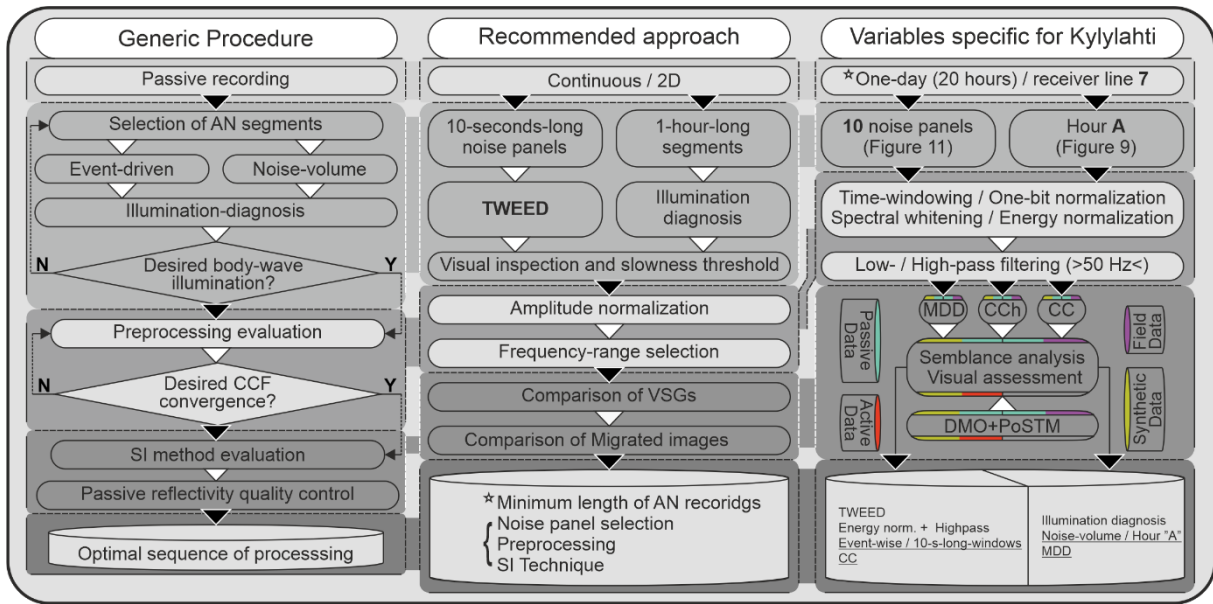
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1188 Figure 1 (a) Comparison of exemplary collocated shot gathers illustrating performance of 3D  
 1189 imaging in the Kylylahti mine area, (top row) synthetic active-shot gather, (middle row) field  
 1190 active-shot gather, and (bottom row) field virtual shot gather. Insets show zoomed part of shot  
 1191 gathers indicated with black polygons. (b) Influence of using more ambient-noise (AN) data for  
 1192 retrieval of virtual shot gathers (VSGs) without accounting for temporal and spatial stationarity  
 1193 of noise sources (blind stacking). Each row represents three VSGs obtained for three adjacent  
 1194 receiver lines. Each column represent VSGs obtained at the same master-trace position for  
 1195 increasing AN volumes. TWT stands for two-way travelttime.

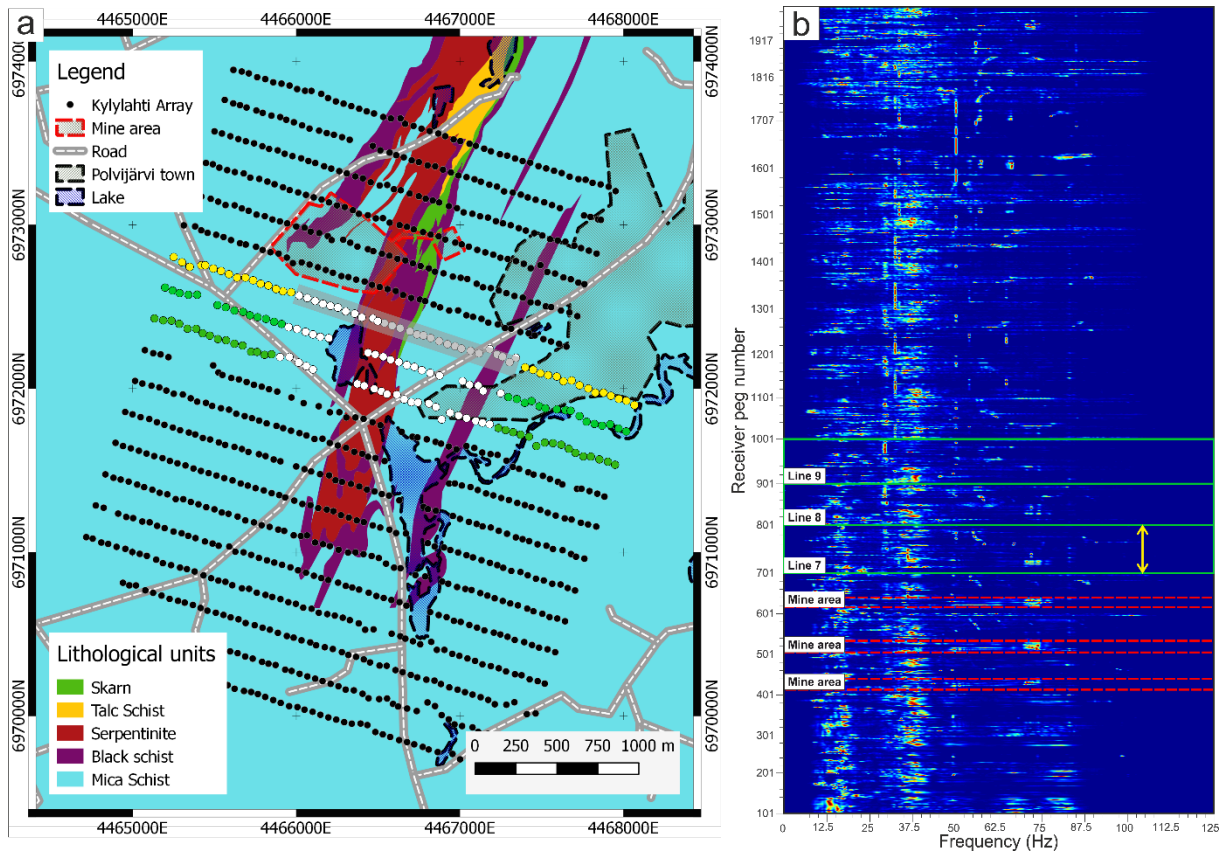


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1197 Figure 2. 2D ANSI processing workflow developed in our study. At the ‘Generic procedure’  
 1198 level, it contains all the important steps (grey-scale coloured) and their ingredients to be  
 1199 investigated. Under the ‘Recommended approach’, we list all the tools/procedures that can be  
 1200 used at each step. The parameters specific for the case of the Kylylahti data we investigate are  
 1201 listed in the ‘Variables specific for Kylylahti’ flowchart.

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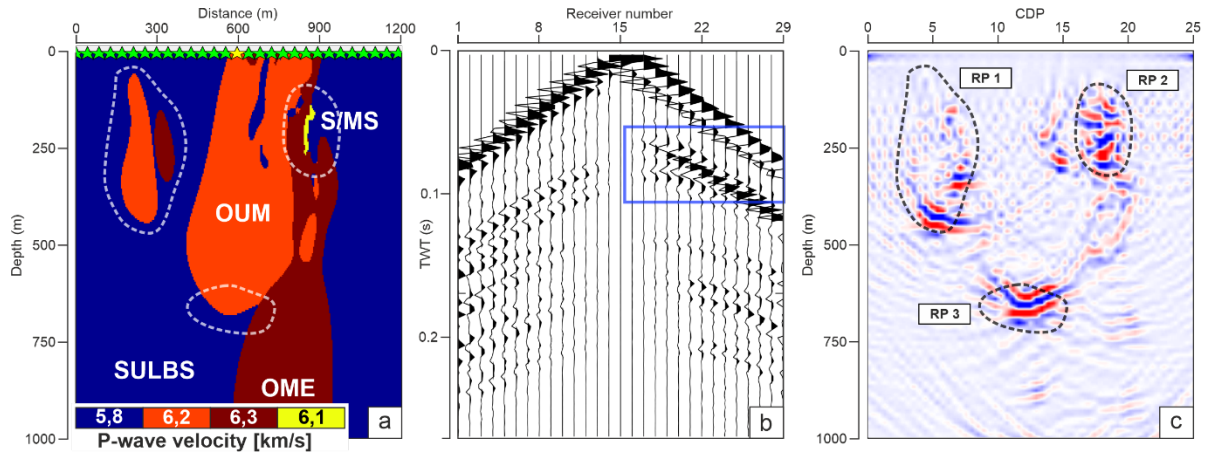


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1204 Figure 3. Layout of the Kylylahti array. Receiver line 7, selected for evaluation of the 2D ANSI  
 1205 processing strategy, is shown with yellow dots. Receiver lines used for illumination diagnosis  
 1206 and testing of results redundancy are denoted with green dots. Grey transparent stripe denotes  
 1207 the horizontal extent of the velocity model used for modelling; white dots indicate the part of  
 1208 the selected lines we use for 2D ANSI data processing. (b) Power Spectral Density averaged  
 1209 over one day of recording for the Kylylahti array. The green solid lines denote the receiver lines  
 1210 selected for analysis (as in (a)), the yellow arrow shows the spatial extent of receiver line 7, and  
 1211 the red dashed lines indicate the receivers located in the operating mine site.

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1215 Figure 4. Synthetic active-source data tests. (a) Velocity model used as an input for the forward-  
 1216 modelling study, green stars denote the source distribution, while the yellow star denotes the  
 1217 location of the active shot used to record the shot gather shown in (b). The blue rectangle marks  
 1218 the part of data with a reflection arrival from the massive to semi-massive sulphide (S/MS)  
 1219 mineralisation; this reflection is also used in the semblance analysis. (c) Post-DMO (post dip  
 1220 moveout) migration of the synthetic active-source data. RP1-RP3 are the group of reflectors  
 1221 discussed in the text. CDP stands for common depth point.

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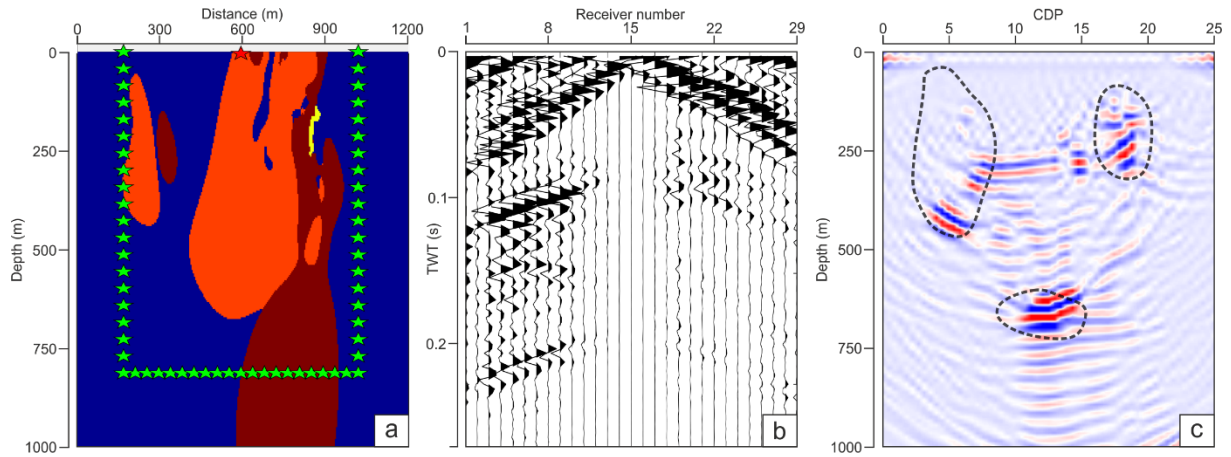
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1233 Figure 5. Synthetic passive data tests. (a) Same velocity as in Figure 3a used as an input for the  
 1234 forward-modelling study, green stars denote the regular passive-source distribution, while the  
 1235 red star denotes the location of the retrieved virtual shot used to record the VSG shown in (b).  
 1236 (c) Post-DMO migration of the synthetic VSGs.

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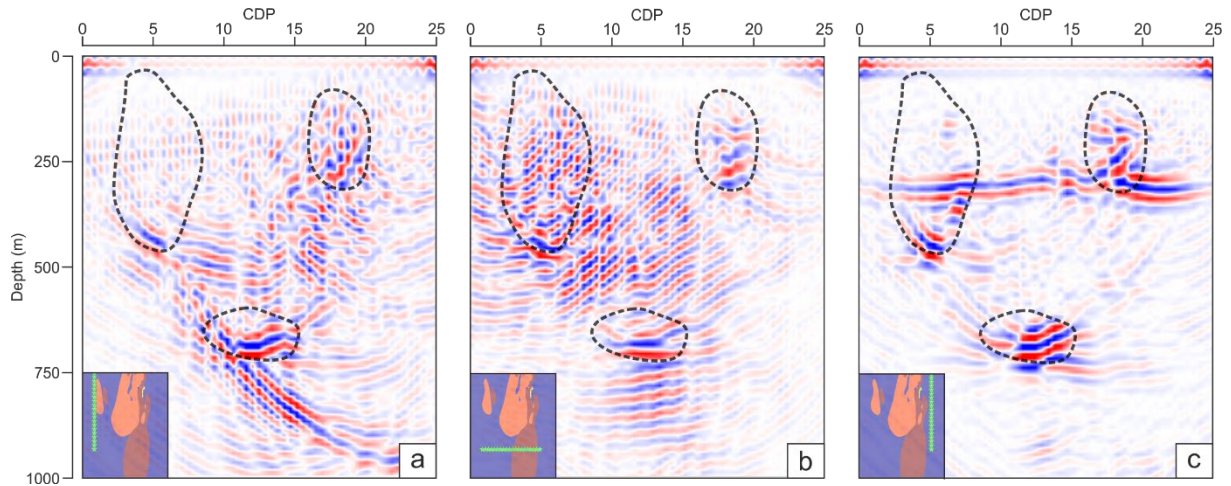
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1248 Figure 6. Post-DMO migration of the synthetic passive data obtained from simulating  
 1249 directional illumination with passive sources. Depth images obtained using sources distributed  
 1250 along a line (a) to the left of the geological target, (b) underneath the geological target, and (c)  
 1251 to the right of the geological target.

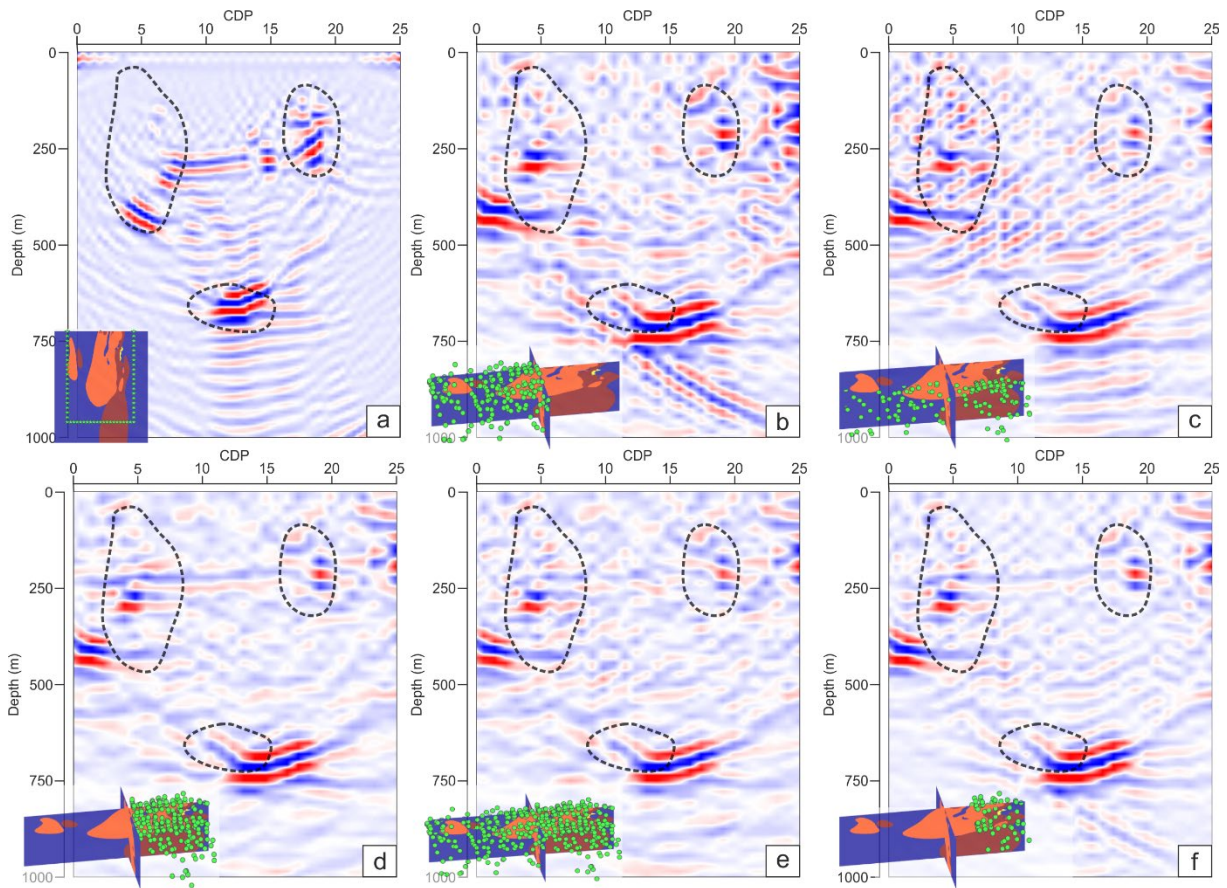
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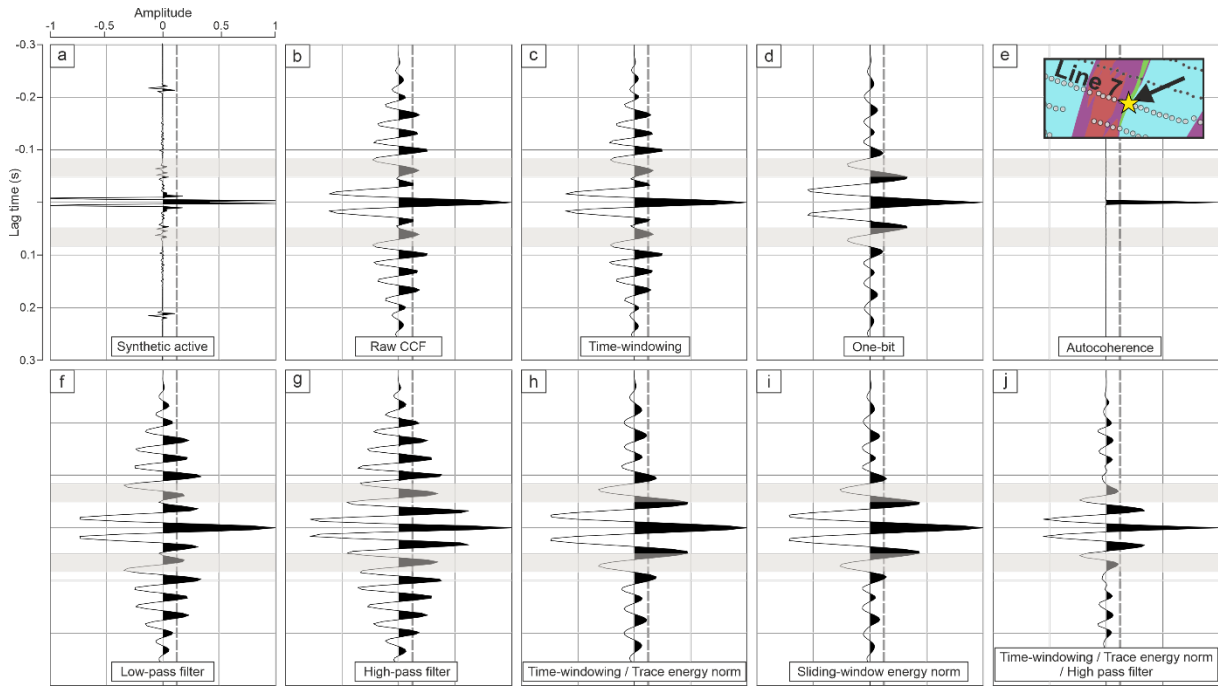


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1258 Figure 7. Comparison of Post-DMO stacks of the 2D synthetic passive data (a), and 3D  
 1259 synthetic passive data using various approaches of stacking the passive sources (b-f). The  
 1260 migrated images for the 3D scenario are obtained using VSGs produced from sources  
 1261 illuminating the target area from the left (b), bottom (c), right (d), all 648 modelled sources (e),  
 1262 and subset of sources mimicking the event-driven approach (f).

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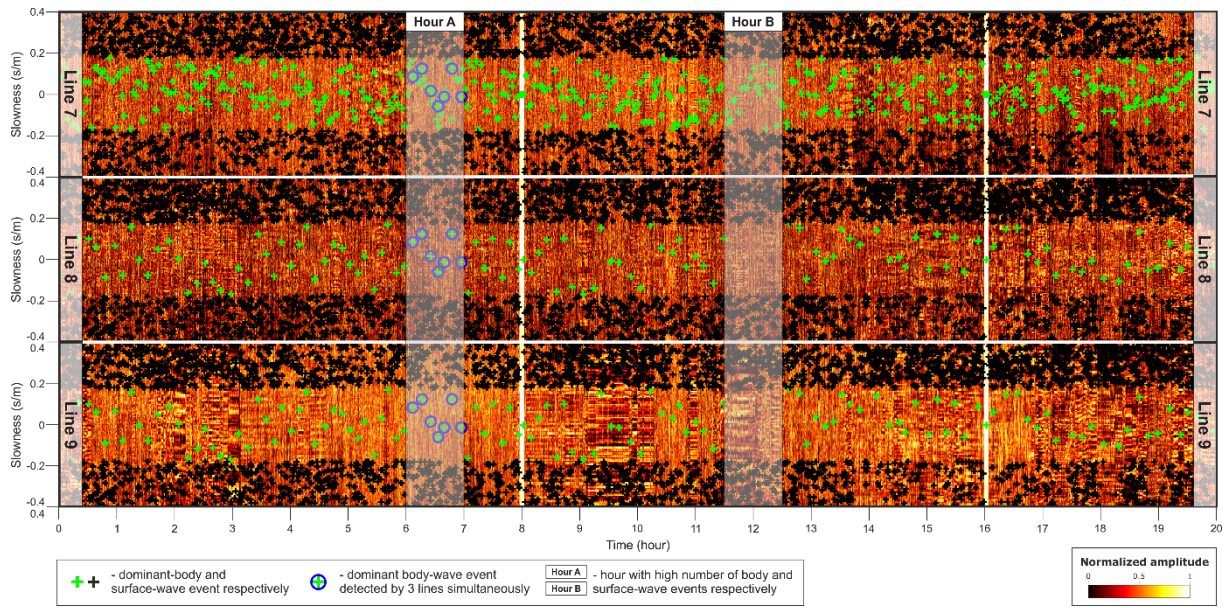
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1265 Figure 8. Influence of basic preprocessing procedures on the retrieval of zero-offset virtual  
 1266 traces. Synthetic active-shot trace concatenated with its time-reversed version (a) and (b) zero-  
 1267 offset trace without any preprocessing are show for reference. Virtual zero-offset traces are  
 1268 retrieved using: (c) windowing in the time domain, (d) one-bit normalization, (e) auto-  
 1269 coherence, (f) low-pass filtering, (g) high-pass filtering, (h) time windowing followed by trace  
 1270 energy normalization, (i) sliding-window energy normalization, and (j) sequence of time  
 1271 windowing, trace energy normalization, and high-pass filtering. The inset in (e) indicates the  
 1272 location of the zero-offset trace with respect to the synthetic velocity model and receiver line  
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1278 Figure 9. Illumination diagnosis panel obtained from the TWEED method (Chamarczuk et al.  
 1279 2019) showing a distribution of normalized slant-stack values for every noise panel recorded  
 1280 by three receiver lines during a whole day of passive acquisition.

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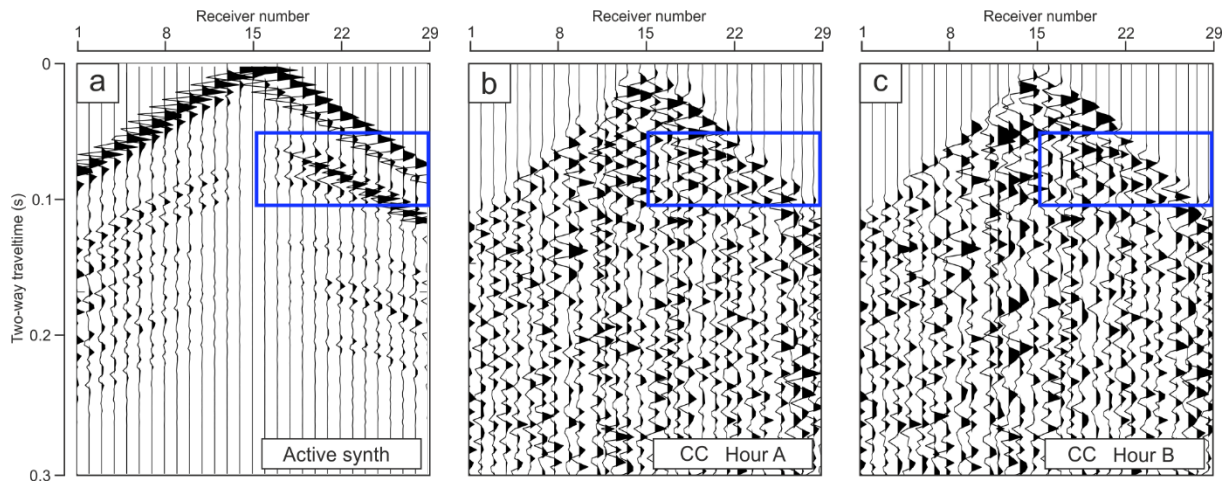
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1291 Figure 10. Comparison of (a) an active-shot gather and VSGs retrieved with CC using one hour  
 1292 of AN dominated by (b) body-wave events and (c) surface-wave events. Blue rectangles mark  
 1293 the part of data selected to compare the reflectivity content and used in the semblance analysis.

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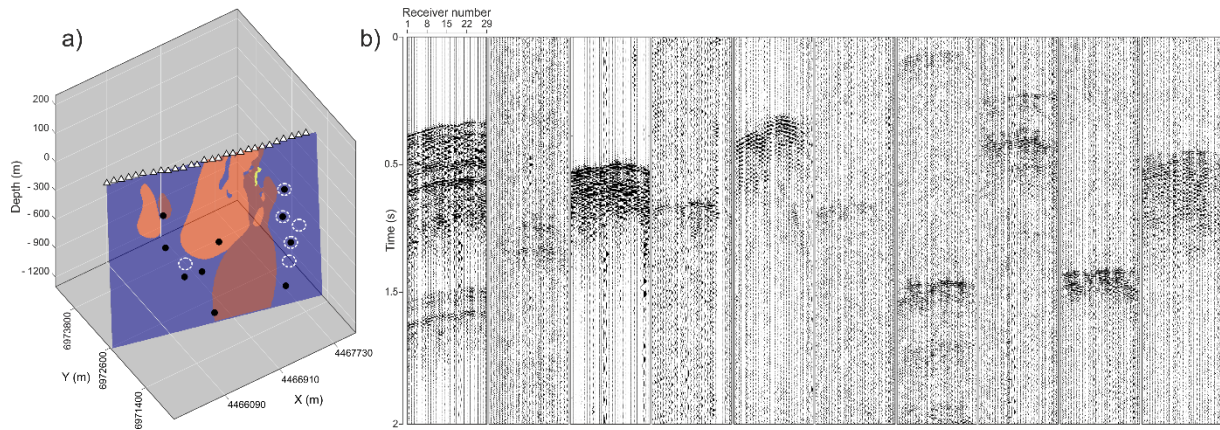
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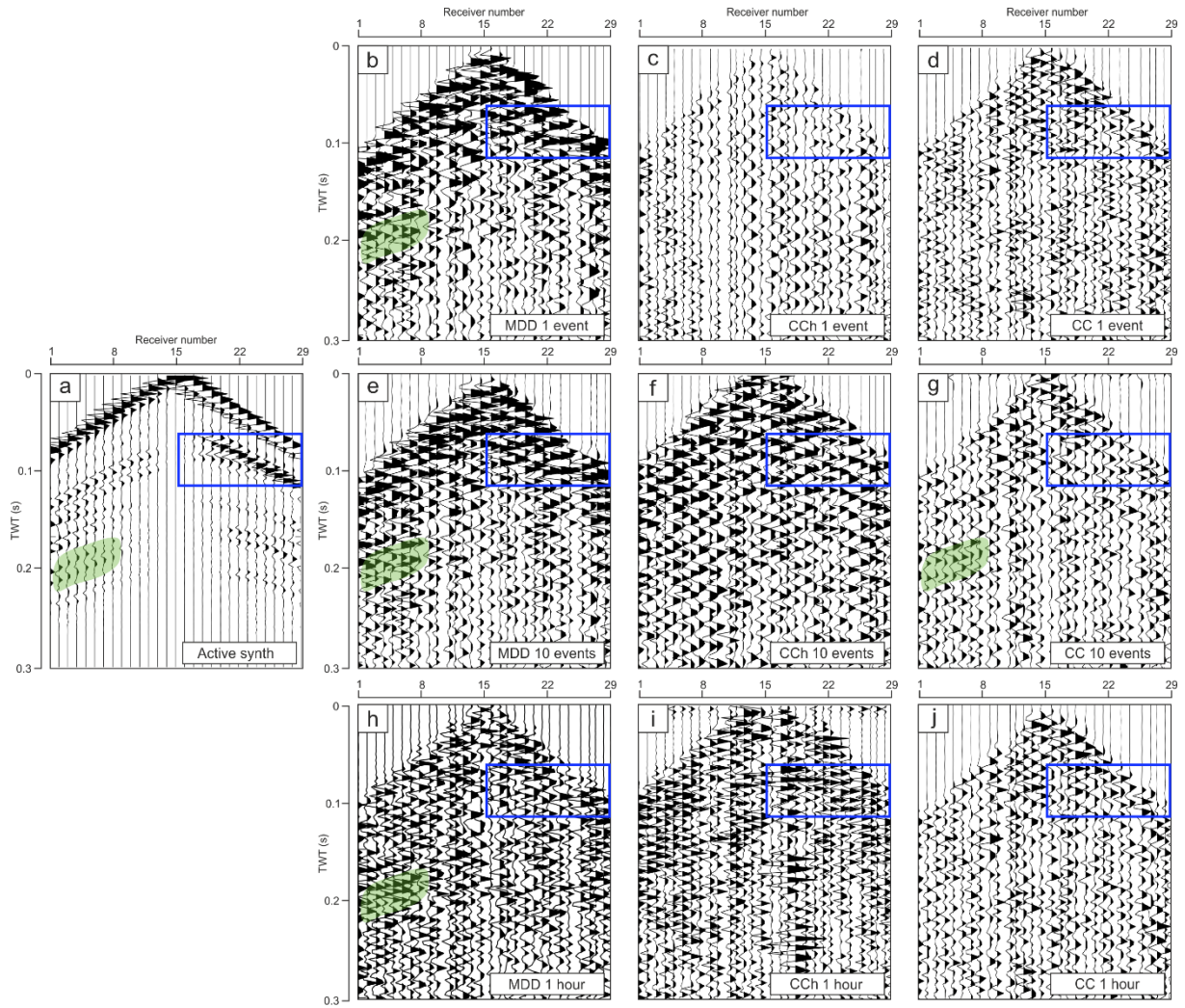


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1307 Figure 11. (a) Location of recording line 7 with respect to the velocity-model section used for  
 1308 the forward-modelling study. Location of the body-wave events detected during hour A  
 1309 indicated in Figure 7 is denoted with white circles, body-wave events selected for the evaluation  
 1310 of the event-driven 2D processing and enclosing the target area are shown with black dots. (b)  
 1311 Seismograms of body-wave events recorded by receiver line 7, and selected for the evaluation  
 1312 of the event-driven 2D processing.

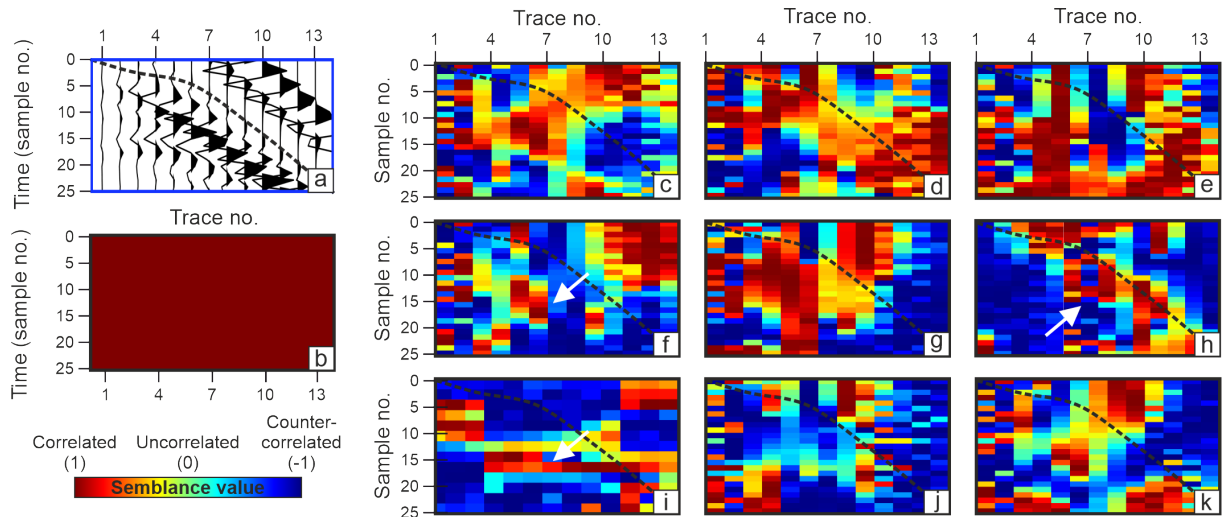
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1316 Figure 12. VSGs obtained from applying 2D ANSI on different segments of AN recordings  
 1317 selected on the basis of illumination diagnosis characteristics. (a) Synthetic active shot; (b, e,  
 1318 and h) VSGs obtained using MDD on a single event, 10 body-wave events, and 1 hour of AN,  
 1319 respectively; (c, f, and i) VSGs obtained with CCh using a single event, 10 body-wave events  
 1320 and 1 hour of AN, respectively; (d, g, and j) VSGs obtained with CC using a single event, 10  
 1321 body-wave events, and 1 hour of AN, respectively. Blue rectangles mark the part of the data  
 1322 selected to compare the reflectivity content and used in semblance analysis. Green shaded areas  
 1323 indicate part of the data, where deeper reflectivity appears on both active-shot gathers and  
 1324 VSGs, and are discussed in the text.



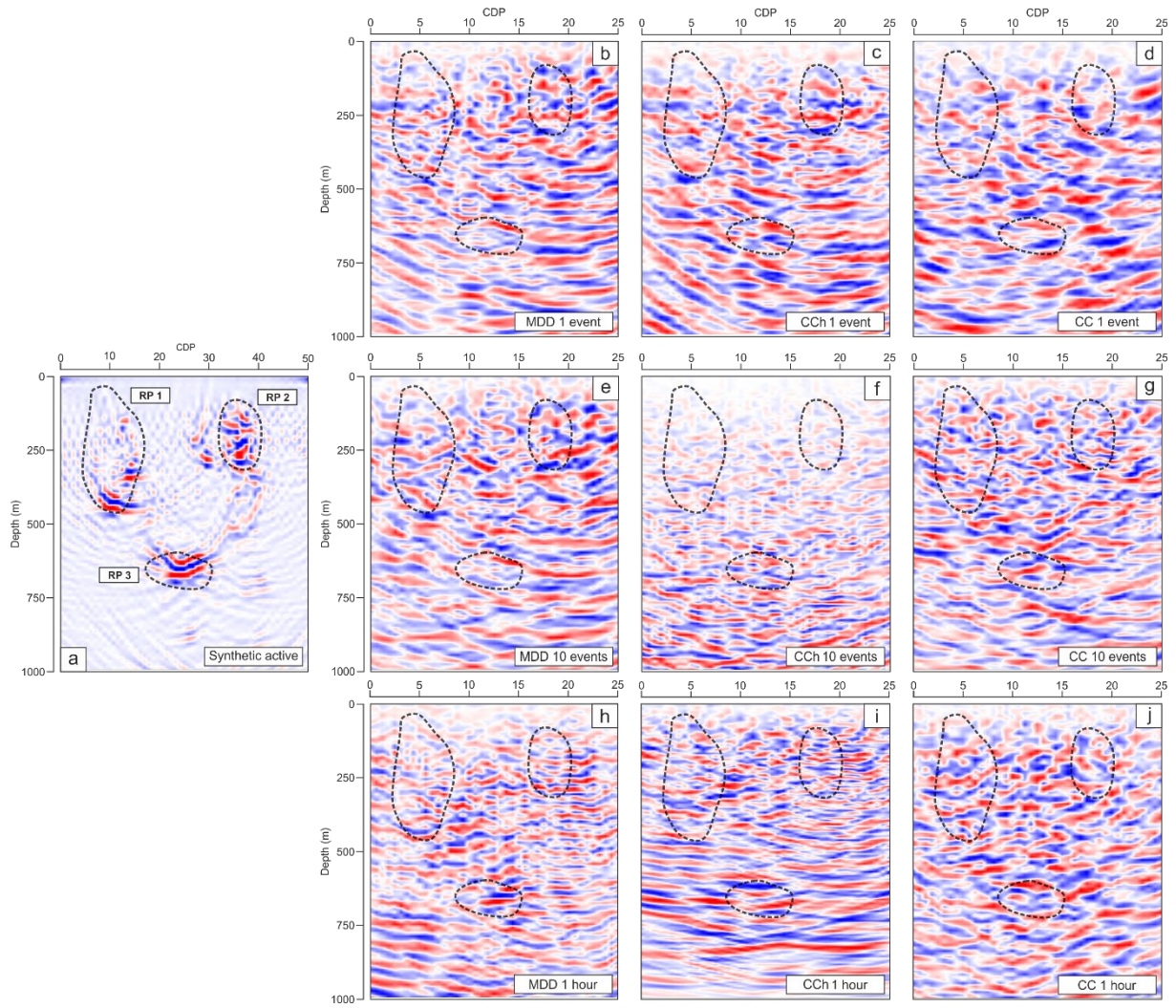
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Figure 13. Semblance analysis of the virtual shots retrieved using 2D ANSI. The results are calculated in the spatio-temporal windows denoted with the blue rectangles shown in Figure 10. (a) Extracted part of the synthetic active-source data used for comparison with the passive data; (b) auto-semblance output calculated for the data shown in (a); (c, f, and i) semblance results for the reflection event obtained using MDD on a single event, 10 body-wave events, and 1 hour of AN, respectively; (d, g, and j) semblance results for the reflection event obtained using CCh on a single event, 10 body-wave events and 1 hour of AN, respectively; (e, h, and k) semblance results for the reflection event obtained using CC on a single event, 10 body-wave events, and 1 hour of AN, respectively. The black dashed line indicates the separation between the direct wave and the reflection event.

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1338 Figure 14. Comparison of migrated depth sections obtained from the nine different 2D ANSI  
 1339 processing strategies. The sections in a) to j) correspond to the order of the VSGs in Figure 12.

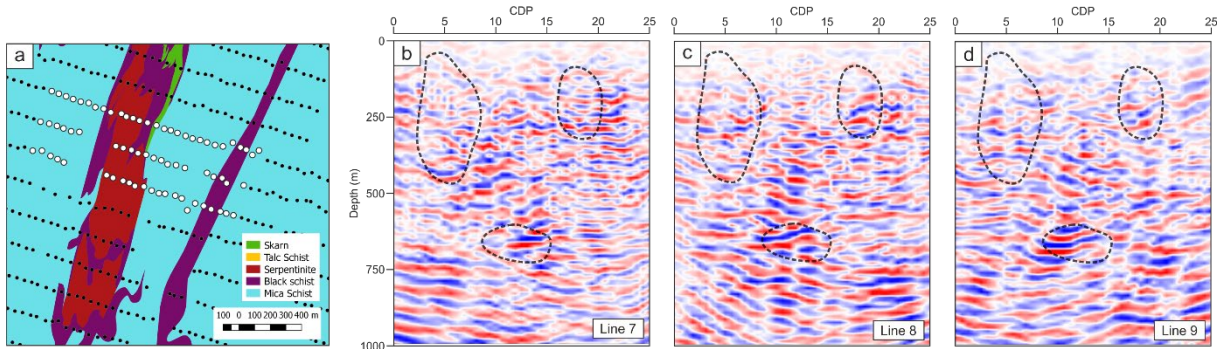
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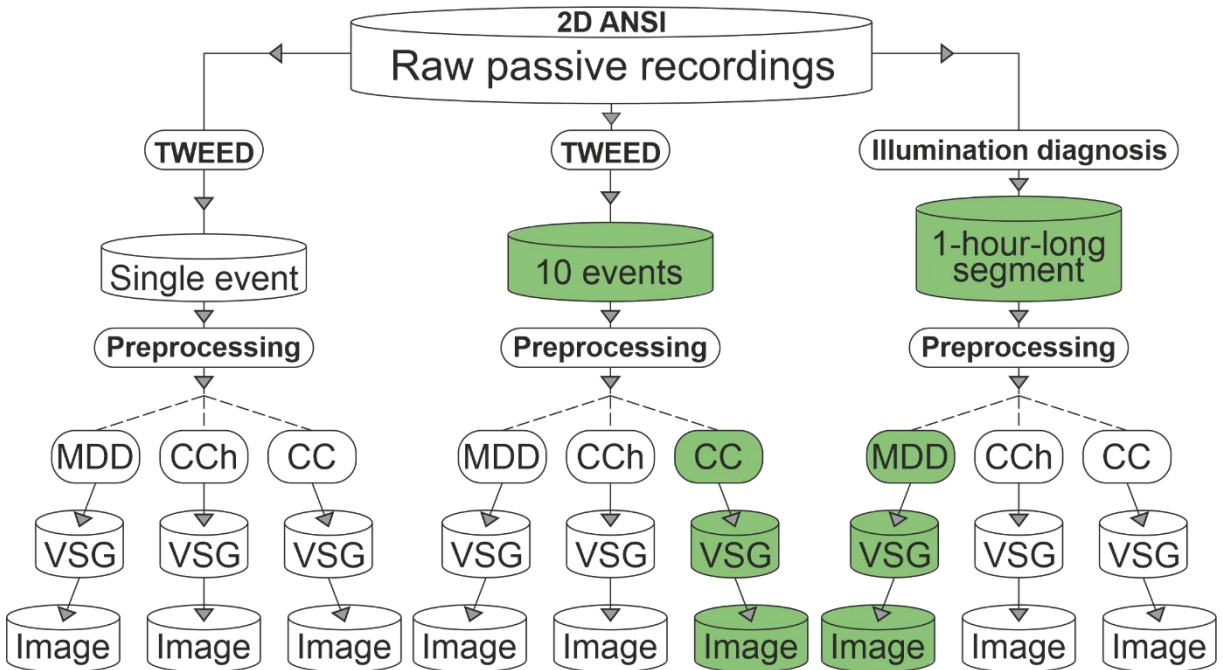
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1346 Figure 15. Images using the MDD results obtained from 1 hour of AN recordings for 3 adjacent  
 1347 recording lines denoted with white circles in (a). Depth sections are shown for the following  
 1348 receiver lines: (b) line 7, (c) line 8, and (d) line 9. Consistent reflectivity can be observed in  
 1349 areas where reflections in the synthetic active (Figure 4c) and synthetic passive (Figure 5c)  
 1350 migrated sections are visible.

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1353 Figure 16. Summary of the 2D ANSI methodology and comparison strategy. The core of the  
 1354 comparison is represented by parallel flow diagrams. The optimal SI processing sequences  
 1355 selected for the Kylylahti data are denoted with green colour. Parts of the workflow in bold  
 1356 denote processing steps implicit for a given processing route.

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	SULBS	OUM	OME	S/MS
P-wave velocity (km/s)	5,8	6,2	6,3	6,1
Density (g/cm <sup>3</sup> )	2,9	2,9	3,1	3,8
Impedance (km/s g/cm <sup>3</sup> )	16,82	17,98	19,53	23,18

1360 Table 1. Average elastic rock properties of the geological units in the synthetic model

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1375 LIST OF ACRONYMS

1376	AC	autocorrelation
1377	AN	ambient-noise
1378	ANSI	ambient-noise seismic interferometry
1379	CC	crosscorrelation
1380	CCh	crosscoherence
1381	CDP	common-depth-point
1382	CWT	continuous wavelet transform
1383	DMO	dip-moveout
1384	GPU	graphical processing units
1385	MDD	multidimensional deconvolution
1386	OME	Outokumpu altered ultramafic rocks
1387	OUM	Outokumpu ultramafic rocks
1388	PSD	power-spectral-density
1389	PSF	point-spread function
1390	QC	quality control
1391	RMS	root-mean-square
1392	RP	reflection packages
1393	S/MS	massive to semi-massive sulphide
1394	SI	seismic interferometry
1395	SNR	signal-to-noise ratio
1396	SULBS	sulphide-bearing schist
1397	TWEED	two-step wavefield evaluation and event detection
1398	TWT	two-way traveltime
1399	VSG	virtual shot gathers