The impact of high-density spatial sampling versus antenna orientation on 3D GPR fracture imaging

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ABSTRACT

Three-dimensional Ground Penetrating Radar (3D GPR) surveys are necessary to reconstruct complex fracture geometries in the subsurface. Two of the most important factors controlling image quality are antenna orientation relative to fractures and density of acquisition grids. This study, conducted in the Madonna della Mazza quarry (Italy), compares two acquisition methods with the goal of optimizing the imaging of fractures and related 3D fracture networks. We acquired two very dense, orthogonal 3D GPR surveys with a 250 MHz antenna and 5 cm trace spacing on the same day, covering the same area of 20 x 20 m. By decimation of the original raw datasets, reduced survey densities of 10 cm and 20 cm spacing are simulated. The results show differences in the imaging quality of the two methods to depths of 75 cm, while for a depth of 130 cm and deeper, image quality is similar. At the same trace density/m², a single, unidirectional survey with a densely sampled grid is the preferred method rather than two surveys with orthogonal antenna orientations but larger profile spacing. The extra effort of conducting surveys with an acquisition grid of an eighth of wavelength of the antenna centre frequency guarantees that we can properly sample the high-frequency content of the GPR signal spectrum and results in optimum image quality regardless of fracture orientation. The simple survey design principle found in this study is universally applicable to any field condition, target geometry, and antenna frequency. Such high-density 3D GPR survey design enables the high-resolution characterization of 3D fracture networks on subsurface timeslices in near photographic quality.

INTRODUCTION

The use of Ground Penetrating Radar (GPR) to image fracture networks is documented in geological studies to distinguish undisturbed matrix from fractured areas (Granjean and Gourry 1996; Sigurdsson and Overgaard 1998; Jeannin et al. 2006; Denis et al. 2009), and engineering applications for structural integrity evaluations (Orlando 2007; Hugenschmidt et al. 2010). Fracture imaging is not a simple task because fractures are thin, steep, and non-planar targets ranging in aperture from a few millimetres to a few centimetres, and develop in complex three-dimensional networks crosscutting the subsurface.

The majority of the studies found in literature is based on the acquisition of a few two-dimensional (2D) profiles (Orlando 2007; Denis et al. 2009) or sparsely sampled three-dimensional grids (Granjean and Gourry 1996; Sigurdsson and Overgaard 1998, Jeannin et al. 2006; Orlando 2007). From a practical point of view, the 2D GPR method allows easy access to most survey areas and a relatively fast and simple acquisition with conventional GPR equipment. However, because 2D profiles contain off-line reflections, interpretation is often not sufficient to reconstruct fracture geometries, to measure fracture strike and dip, and to analyse the interconnectivity of complex 3D fracture networks. Three-dimensional (3D) surveys are required to achieve accurate frameworks of fracture location and azimuth in the shallow subsurface. Nevertheless, sparsely sampled 3D surveys fail to capture subtle discontinuities due to a high degree of interpolation between adjacent profiles. This leads to poor image quality and a high probability of interpretation errors. Capturing the full GPR wavefield requires 3D acquisition grids with a profile spacing of at least quarter-wavelength (Grasmueck et al. 2005).

Other works use multi-component GPR to compensate for asymmetric antenna radiation patterns and exploit the vectorial nature of the electromagnetic wavefield (Lehmann et al. 2000; Seol et al. 2001; Pipan et al. 2003; Streich et al. 2006; Tsofilas et al. 2006; Sassen and Everett 2009; Böniger and Tronicke 2012). Streich et al. (2006) explore the benefits of acquiring orthogonal 3D surveys and combining GPR signal components using a 3D vectorial migration algorithm. Tsofilas et al. (2006) investigate how polarization properties of GPR can help to detect the location and azimuth of thin, vertical fractures.

The optimum data acquisition approach for 3D GPR fracture surveys is often debated. In 3D survey design, two of the most

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important factors controlling image quality are orientation of the GPR antenna relative to fractures and trace spacing. In order to accurately image multiple fracture orientations in the same survey, two methods are possible: (1) acquisition of two orthogonal surveys; (2) acquisition of just one survey with increased trace density with only one antenna orientation. The same amount of line kilometres is acquired with both methods. Still, acquiring a 3D survey with a densely sampled grid or repeating the survey with orthogonal antenna orientations is time-consuming and significant effort needs to be made on the field campaign. The choice of acquisition parameters and antenna configuration is critical when designing surveys to image complex fracture networks. The survey design has an impact on the ability of imaging targets with accuracy and enough resolution, and on the cost/benefit balance of the study.

This study, conducted in the Madonna della Mazza quarry (Italy), compares the two 3D GPR acquisition approaches with the goal of optimizing the imaging of fracture patterns and related 3D fracture networks. We investigate whether a single survey with a very dense acquisition grid or two surveys with orthogonal antenna orientation and less dense grids is the most cost-effective and least time-consuming methodology to achieve the best possible visualization of fracture networks in terms of dimension, orientation, interconnectivity, and depth. The purpose of this acquisition experiment is to fill the gap between theoretical studies and field practice by providing practical guidelines for designing field data acquisition programs that ensure consistent image quality of complex fracture networks and reliable geological interpretation. The objective is to determine optimal acquisition parameters in terms of antenna orientation and grid density by acquiring two very dense, orthogonal surveys with less than quarter-wavelength trace spacing. Both surveys properly sample the full GPR signal spectrum including the high frequencies. Surveys with less dense acquisition grids are obtained by decimation, generating subsets of the original raw data.

After a brief description of the survey site, the 3D GPR acquisition strategy, and data processing, we present results from surveys acquired with orthogonal antenna orientation, comparing datasets with highly dense trace spacing versus datasets with less dense trace spacing.

STUDY AREA
The field site for this study is the Madonna della Mazza quarry (80 m long in E-W, and 50 m wide in N-S direction), cut into structurally deformed rudist grainstone strata situated on the inner part of the Majella mountain, southern Italy (Fig. 1). The stratigraphy of the quarry is characterized by prograding beds of massive grainstones, separated by thinner, mudstone layers slightly dipping to NE. The site is particularly suitable for this study and serves as an extraordinary natural laboratory to compare the two 3D GPR acquisition methods because of the presence of fractures with different strike, dip, and a high degree of 3D complexity of the resulting fracture network.

The quarry is characterized by two main types of fractures in the otherwise undisturbed rock matrix: deformation bands and open fractures. These features were described by previously conducted structural assessments of the entire quarry. Tondi et al. (2006) give a comprehensive meso- and micro-structural descrip-
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Grainstone units (shallower than 130 cm in the surveyed area) due to micro-mechanical grinding of grains and do not show surfaces of discontinuity (Fig. 2a). On the quarry floor the deformation bands appear lighter in colour than the surrounding rock, standing up like ribs because of higher resistance to erosion (Aydin 1978). Open fractures observed on the quarry floor are characterized by apertures varying from 0.5 cm up to 10 cm, filled with sandy debris, and colonized with grass and small bushes when exposed at the surface (Fig. 2b).

HIGH-DENSITY ORTHOGONAL 3D GPR SURVEYS

For this study we chose a 20 x 20 m survey area located in the central part of the Madonna della Mazza quarry floor where two clusters of deformation bands and open fractures intersect (Fig. 1). Datasets were collected using a ProEX GPR control unit (Mala Geoscience, Sweden) and a shielded GPR antenna with a centre frequency of 250 MHz. The GPR equipment was coupled to a 3D Rotary Laser Positioning System (RLPS) to achieve centimetre positioning precision. A LED-based guidance system mounted on the antenna showed the antenna operator how to follow the survey tracks without having to stake out survey tapes (Fig. 3a) (Grasmueck and Viggiano 2007).

Profile spacing equal to quarter-wavelength is the minimum requirement to produce spatially non-aliased images of the subsurface. Spacing between adjacent profiles in 3D GPR surveys is usually calculated taking into account the centre frequency of the GPR antenna (Grasmueck et al. 2005). In this study, for an electromagnetic wave velocity of 9 cm/ns, the quarter-wavelength spacing at 250 MHz would be 9 cm. However, the signal spectrum also contains higher frequency components. For the purpose of this acquisition experiment we decreased the profile spacing to 5 cm, corresponding to an eighth-wavelength of the antenna centre frequency, in order to properly sample the full signal spectrum. Trace spacing along profiles was maintained at a constant and equal to 5 cm for every dataset acquired in this study.

We conducted the first high-density 3D survey in E-W direction at a speed of about 1 m/s, walking forward and backward without turning the antenna at profile ends. Acquiring a single 3D GPR survey covering the 20 x 20 m area, consisting of 401 profiles with a total length of 8 km, took 3 hours. Immediately after the first survey we acquired a second, equally dense 3D survey on the same 20 x 20 m area in N-S direction rotating the antenna orientation by 90 degrees (Fig. 3b). The square survey geometry, symmetric sampling, and centimetre precise positioning allows us to maintain the same acquisition grid for both E-W and N-S direction surveys and to exactly match the two resulting GPR volumes.

DATA PROCESSING

The two raw, high-density surveys (5 cm profile spacing) are decimated to obtain simulations of 3D GPR surveys with 10 cm and 20 cm profile spacing, resulting in a total of six 3D GPR volumes. Decimation is performed by progressively halving the
DATA ANALYSIS

We interpreted GPR volumes to a maximum depth of 10 m, with focus on the shallow portion (< 130 cm) where crosscutting relationships between deformation bands and fractures are abundant. The comparison between the aerial photograph of the survey area (Fig. 4a) and a shallow horizontal GPR slice (Fig. 4b, 25 cm in depth) shows an excellent match. The GPR data clearly image the crosscutting relationships between stratigraphy, fractures (with N-S and E-W strike), and a cluster of curved deformation bands on the western part of the survey area with NW-SE strike. The deformation bands are not visible on the aerial picture and are difficult to map on the quarry floor. Shallow 3D GPR slices offer the clearest image of the deformation bands. Figure 4c shows the geological interpretation of the survey area highlighting the locations of Fig. 5, Fig. 7, Fig. 8, Fig. 9, and Fig. 10.

All six 3D GPR volumes are processed using identical parameters and workflow. Data processing with 3DGPR Software (Grasmueck and Viggiano 2007) includes: (a) regularization, which populates a 5 x 5 cm bin grid selecting the nearest available trace; (b) data detrend, to compensate for long-term instrument drift; (c) dewow, to remove the DC offset in the waveforms; (d) time-zero adjustment; (e) the same gain curve for all traces, to preserve relative amplitudes; (f) background removal; (g) normal move-out correction, to compensate for the distance between GPR transmitter and receiver; (h) vertical and horizontal dynamic signal-to-noise (DS/N) filtering, to reduce random noise and enhance the lateral coherency of data (Canales 1984); (i) 3D phase-shift migration with a constant velocity of 9 cm/ns, to focus the diffractions and correctly position reflections from dipping layers. Landmark ProMAX 3D is used for processing steps (h) and (i). Before interpretation, the six volumes are equalized to the same amplitude range. The resulting GPR volumes are imported as SEGY files into Landmark GeoProbe seismic interpretation software using a display scale correspondence of 0.1 m = 1 m and 100 MHz = 100 Hz (Grasmueck 1996).
widths of signatures are narrower and contrast is slightly enhanced for the dominant N-S fracture and deformation bands direction when perpendicular to the acquisition direction (Fig. 5a). As a consequence, image quality of features striking parallel to the acquisition direction appears less sharp. Interpretation of all features is shown in Fig. 6a. At 10 cm profile spacing (quarter-wavelength), stepping patterns are generated due to spatial undersampling and image quality is more degraded when the acquisition occurs in the N-S direction (Fig. 5b, e). Some N-S oriented features are not properly imaged: for example, in Fig. 5e, the intersection between deformation band D1 and fracture F3 (Labels shown in Fig. 6a) at x = 5 m, y = 12 m is not resolved. The difference in image quality observed in the two surveys conducted with orthogonal antenna orientation (Fig. 5b, e) is due to sampling bias and not because of polarization effects. With 10 cm profile spacing, proper imaging of features widths of signatures are narrower and contrast is slightly enhanced for the dominant N-S fracture and deformation bands direction when perpendicular to the acquisition direction (Fig. 5a). As a consequence, image quality of features striking parallel to the acquisition direction appears less sharp. Interpretation of all features is shown in Fig. 6a. At 10 cm profile spacing (quarter-wavelength), stepping patterns are generated due to spatial undersampling and image quality is more degraded when the acquisition occurs in the N-S direction (Fig. 5b, e). Some N-S oriented features are not properly imaged: for example, in Fig. 5e, the intersection between deformation band D1 and fracture F3 (Labels shown in Fig. 6a) at x = 5 m, y = 12 m is not resolved. The difference in image quality observed in the two surveys conducted with orthogonal antenna orientation (Fig. 5b, e) is due to sampling bias and not because of polarization effects. With 10 cm profile spacing, proper imaging of features is shown in Fig. 6a.

FIGURE 5
GPR horizontal slices extracted from 25 cm depth covering a subset of the entire 3D GPR survey area (Fig. 4c). Comparison of profile spacing of 5 cm, 10 cm, and 20 cm and antenna orientation. Red arrow and antenna dipoles indicate acquisition direction. Trace spacing is constant and equal to 5 cm along each profile. The geological interpretation highlighting the locations of deformation bands and fractures is shown in Fig. 6a.

FIGURE 6
The geological interpretation of the portion of survey area as shown in Fig. 4c, Fig. 5, Fig. 8, Fig. 9, Fig. 10 highlighting the locations of deformation bands and fractures for depths of 25 cm (a), 75 cm (b), and 130 cm (c).
b). The top depth is 25 cm. Figure 7c is the geological interpretation of the GPR sub-volumes with stratigraphic column.

Figure 7 shows a corner cut through the two orthogonal, high-density (5 cm profile spacing) 3D GPR volumes (Fig. 7a, b). The top depth is 25 cm. Figure 7c is the geological interpretation of the GPR data including a stratigraphic column correlated from an outcrop wall at 30 m distance from the 3D GPR survey area. Data show that, as with timeslices, also vertical cross-sections extracted from orthogonal surveys acquired with 5 cm profile spacing produce comparable image quality for both acquisition directions. Deformation bands and thin fractures, inclined fracture planes, and stratigraphic boundaries are clearly imaged with both antenna orientations. As already seen in horizontal slices, the signatures of the deformation bands and fractures striking N-S are slightly clearer when perpendicular to the acquisition direction (Fig. 7a). However, despite this observation, acquiring a high-density 3D
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with orthogonal antenna orientation are very similar: both are equally degraded compared to 5 cm profile spacing but still sufficient to define the fracture offset at x = 2 m and the main stratigraphic boundaries (Fig. 9b, e). At this depth of about three wavelengths, the effect of denser profile spacing has less impact on the image quality when compared to the shallower portion of the GPR volumes (Fig. 5, Fig. 8). The benefit of sampling the higher frequencies above the antenna centre frequency becomes smaller. Data with a profile spacing of 20 cm are only adequate to define main stratigraphic interfaces without fracture interpretation. Genuine fracture offsets are indistinguishable from stepping patterns due to spatial undersampling of the antenna centre frequency (Fig. 9c, f).

DISCUSSION

In this study we test two 3D GPR acquisition methods to produce images of deformation bands and open fractures, one based on very densely spaced profiles and one based on orthogonal orien-
tation of GPR antennas. The purpose is to determine optimal parameters and the most practical acquisition method to achieve the best image quality and reliable structural interpretation.

As for shallower data, the antenna orientation at a depth of 130 cm with 5 cm profile spacing does not affect image quality. Both surveys with 5 cm profile spacing appear smooth while the fracture offset at x = 2 m, y = 11–13 m and stratigraphy boundaries are equally well defined (Fig. 9a, d). Interpretation of all features is shown in Fig. 6c. With 10 cm profile spacing, surveys with orthogonal antenna orientation are very similar: both are equally degraded compared to 5 cm profile spacing but still sufficient to define the fracture offset at x = 2 m and the main stratigraphic boundaries (Fig. 9b, e). At this depth of about three wavelengths, the effect of denser profile spacing has less impact on the image quality when compared to the shallower portion of the GPR volumes (Fig. 5, Fig. 8). The benefit of sampling the higher frequencies above the antenna centre frequency becomes smaller. Data with a profile spacing of 20 cm are only adequate to define main stratigraphic interfaces without fracture interpretation. Genuine fracture offsets are indistinguishable from stepping patterns due to spatial undersampling of the antenna centre frequency (Fig. 9c, f).

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Concerning image quality to a depth of three wavelengths, the acquisition of a single, denser survey with profile spacing 5 cm (eighth-wavelength, based on a centre frequency of 250 MHz) is the preferred approach rather than repeated surveys with orthog-
nal antenna orientation and increased profile spacing of 10 cm (quarter-wavelength). Surveys acquired with profile spacing of an eighth-wavelength produce good image quality for fractures in any orientation and depth. With such dense profile spacing the acquisition direction is irrelevant and independent of field site conditions. On the contrary, results show that, at a profile spacing equal or larger than quarter-wavelength, image quality is strongly biased by the profile orientation and spacing. Image quality degrades significantly for fractures striking parallel to the acquisition direction on surveys acquired with 10 cm and 20 cm profile spacing. In this scenario, both surveys with orthogonal antenna orientation are needed to fully interpret the fracture network. The samplewise arithmetic sum of the two orthogonal surveys neither increases the image quality at eighth-wavelength profile spacing (Fig. 10a), nor compensates for sampling bias at quarter-wavelength profile spacing (Fig. 10b). The effect of this operation is actually counterproductive, resulting in overall amplitude weakening, as shown also in Lehmann et al. (2000). At half-wavelength profile spacing, the addition of orthogonal surveys results in noise generated by spatial undersampling (Fig. 10c).
By reducing the profile spacing to 5 cm, the high-frequency content of the signal spectrum is properly sampled (Fig. 11): this leads to sharper fracture signatures and allows us to image shallow and thin features (shallower than 130 cm) with optimum quality regardless of their strike. The clearer image obtained with a profile spacing equal to an eighth of wavelength facilitates the mapping of deformation bands and fractures in 3D GPR volumes. Crosscutting relationships are easy to follow in 3D visualization. The effect of the enhanced image quality achieved with eighth-wavelength profile spacing decreases with depth. The benefit of sampling the higher frequencies of the signal spectrum reduces because of attenuation of high frequencies due to longer GPR signal propagation paths. At a depth of 130 cm (approximately three wavelengths) features are equally well imaged with 5 cm and 10 cm profile spacing.

The densely sampled datasets produce almost identical images regardless of antenna orientation. When sampling is dense enough, deformation bands and thin fractures of any orientation are equally well imaged. The small differences in signature and contrast between the two surveys conducted with orthogonal antenna orientation are the result of antenna polarization, only observable at 5 cm profile spacing. The polarization effect is surprisingly little at 5 cm spacing and all the features are fully interpretable. On the contrary, in images produced with 10 cm profile spacing some features are better interpretable on one survey than on its orthogonal counterpart, and differences are due to sampling bias and not a polarization effect.

From a practical point of view, while the total profile length and the trace density/m² are identical, acquiring a single, denser survey is faster and logistically easier than acquiring two surveys with orthogonal antenna orientation and double the profile spacing. The presented acquisition experiment shows that a single survey with eighth-wavelength profile spacing results in a simple survey design in which any acquisition direction will provide good results.

Obtaining optimum image quality with a single, high-density, unidirectional GPR survey is not limited to fracture imaging but can also be applied, for example, to subsurface utility detection or design of GPR arrays for automatic target detection and tracking. Reliable mapping of pipes and cables oriented in any direction can be achieved with a single, unidirectional survey as long as a very dense acquisition grid is used. The profile spacing should be at least quarter-wavelength of the highest signal frequency transmitted by the GPR antenna for optimal imaging quality to provide easy data interpretation. The same principle can be also applied to GPR antenna array design for automatic target tracking where a denser layout antenna configuration is more beneficial to image quality than sources and receivers with orthogonal or oblique orientations.

Repeated surveys with orthogonal antenna orientations are still useful for distinguishing targets of different materials, metallic versus dielectric (Radzevicious and Daniels 2000). However, despite observations concerning the fact that sparsely sampled surveys with orthogonal orientation might be suitable for detection of linear and homogeneous targets (e.g. metallic rebars), a denser grid in acquisition should be still the preferred approach in order to detect and image crosscutting relationships of any orientation at sub-wavelength scale.

Polarimetric techniques do not compensate for sparse spatial sampling bias and should be applied only to 3D datasets spatially sampling the full GPR spectrum in all directions. Lehmann et al. (2000), Streich et al. (2006), and Sassen and Everett (2009) provided a summary of 3D GPR acquisition parameters from Lehmann et al. (2000), Streich et al. (2006), Sassen and Everett (2009), and comparison with this paper.

<table>
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<th>Frequency</th>
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<th>λ/4 Limit</th>
<th>IL Spacing</th>
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FIGURE 11
Frequency spectra calculated for all traces in high-density 3D GPR volume with profile spacing of 5 cm. Solid line shows the spectrum generated for the shallower portion of the volume (10 cm – 75 cm depth). Dashed line shows the spectrum generated for the portion of the volume from 76 cm to a depth of 130 cm. The spectrum of the shallower portion of the volume is shifted towards the higher frequencies of the GPR signal bandwidth.
do not simply add datasets, but develop methods to extract partial components of Electric (E) and Magnetic (H) field from co- and cross-polarized datasets to improve imaging quality. Combining GPR datasets acquired with orthogonal orientation requires the use of polarimetric algorithms, which is beyond the purpose of this paper. Moreover, about acquisition density, all three studies rely on undersampled datasets. Table 1 shows a brief summary of acquisition parameters from the three studies and compares them with this paper. Polarimetric data acquisition and processing is an opportunity for quantitative fracture analysis (Sassen and Everett 2009). From this perspective, past works based on sparse 3D datasets should be re-assessed because what had been described as polarization differences could easily be the effect of spatial undersampling.

As GPR and seismic are both wave-based imaging methods, a similar outcome can be expected for seismic data. For unbiased imaging of any fracture orientation, the 3D geophysical survey grid should be equally dense in all directions.

CONCLUSION
This study provides a guideline to design field data acquisitions for optimal imaging quality of fractures. Fractures are thin, steep, and non-planar targets difficult to image. 3D GPR data show that a single, unidirectional survey with a densely sampled grid is the preferred method rather than two repeated surveys with orthogonal antenna orientations but larger profile spacing. When sampling dense enough, fractures of all orientations are clearly imaged by any GPR acquisition direction. A profile spacing equal to eighth-wavelength of the antenna centre frequency is necessary to image all fractures and deformation bands with optimum image quality. If the target depth is three wavelengths or more, the spatial sampling interval can be increased to the usual quarter-wavelength of the antenna centre frequency due to attenuation of the high frequencies. Such high-density, unidirectional 3D GPR survey design enables the high-resolution characterization of 3D fracture networks on subsurface horizontal slices in near photographic quality. This translates into a universal, simple GPR survey acquisition design applicable to any antenna frequency and target orientation. Any acquisition direction will provide good imaging results. From a practical point of view, outcomes from this study are not only valid for fracture imaging, but also for other applications and can be adjusted to the survey site for optimal access with 3D GPR equipment.

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