MULTI-AZIMUTH VSP METHODS FOR FRACTURED ROCK CHARACTERIZATION

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ABSTRACT: VSP has lately extensively been used for mapping fractures and fracture zones with various hardrock applications. Fracture zones in hardrock display weak seismic contrast and reflected wavefields are easier identified by increased coherency along time-depth paths corresponding to possibly real reflection events than by amplitude standout. With the IP transform, stacking is performed along hyperbolic paths corresponding to the time-depth functions of possible reflectors. Due to this ”natural” choice of the stacking paths, the coherency can be used effectively to enhance the weak reflections. Polarization analyses of hardrock data may be unstable because of crisscrossing reflection events and non-coherent scattering noise. The stability increases in the IP space because the energy reflected on interfaces with different orientations accumulates in different regions of the IP space. The orientation estimates obtained by polarization analysis are improved by concurrent processing of several profiles. Based on ample direct and indirect verifications of results, the multi-azimuth multi-offset VSP can be considered an effective method for mapping fracture zones in hardrock.

1 INTRODUCTION

VSP (Vertical Seismic Profiling) has extensively been used for mapping fractures and fracture zones with various applications, from nuclear waste disposal, to ore delineation, to rock engineering. The VSP method has been found particularly suitable for surveys in hard rocks, where receiver arrays placed in boreholes and sources spread on the surface at diverse azimuths around the borehole provide a favourable geometry for mapping both steeply and gently dipping features. Receivers located in the bedrock minimize the loss of resolution due to near-surface signal absorption.

Recent surveys have been carried out with a time-distributed swept-impact source [1, 2] instead of explosives. With this source, the seismic signals are produced as rapid series of impacts, the impact intervals being monotonically increased to achieve a non-repeatable sequence. As the energy is built up from a large number of relatively low-power impacts, the high frequency components of the seismic signal are maintained.

Faults, fracture zones, dissolution features and lithological contacts may all reflect seismic waves. The fracture zones display a relatively weak seismic contrast and extensive processing is needed to retrieve the reflected wave field from the seismic profiles and the information on the position of the reflectors. The data processing focuses first on eliminating tube-waves and direct P and S onsets. Median and band-pass filters are used for this purpose. The amplitudes are then equalised. The second stage of processing consists mainly of Image Point (IP) filtering techniques [3], aimed at enhancing the reflected wavefields and at separating events generated by reflectors with different orientations.

When all the profiles have been processed and the reflection events emphasized by IP filtering, the positions and 3-D orientations of the reflectors are determined. Automatic interpretation procedures are used in order to diminish, whenever possible, the subjectivity of the interpretation.

Examples are given from work carried out during years 2000 and 2001 in the Finnish and Swedish site investigation programmes for the final disposal of spent nuclear fuel [4, 5]. A related method, HSP (Horizontal Seismic Profiling) has also been used in Finland, at the Olkiluoto site, with receivers laid on the bottom of an artificial pond and sources located around the pond. A 3-component geophone chain has been used for VSP and a hydrophone chain for HSP measurements.

2 THE VIBSIST SEISMIC SOURCE

With the VIBSIST seismic source the seismic signals are produced as rapid series of impacts (normally 100 to 1000), maintaining a monotonic variation of the impact rate. The monotonicity controls effectively the non-repeatability of the impact intervals and the seismograms are obtained by cross-correlating the swept impact sequence with pilot signal recorded near the source.

Following [6], a seismic time series can be written as: $s_1(t) = s(t)\text{Ä}e(t)$, where $s(t)$ is the source signature, $e(t)$ is the earth impulse response, and Ä is the convolution operator. With a VIBSIST source the signature is $s_2(t) = y(t)\text{Ä}\, s_1(t)$, where $y(t)$ is the VIBSIST time impact sequence. The recorded sequence is $r_c(t) = s_2(t) + n(t)$, where $n(t)$ represents wide-band noise.

The key idea of the Swept Impact Seismic Technique (SIST) is to retrieve the decoded signal $r_d(t) = y(t) \otimes r_c(t) = ACF\{y(t)\} \otimes s_1(t) + y(t) \otimes n(t)$ where ACF is the autocorrelation operator.

One should note in the expression above that the second term $y(t) \otimes n(t)$ tends to zero, as random noise tends to get cancelled through correlation. It follows that, if $ACF(t)=1$ at $t=0$ and $ACF(t)=0$ elsewhere, $r_d(t)= s_1(t)$. In other words, the VIBSIST and the single-pulse signals will become similar, with the noise cancellation benefit of the VIBSIST.

The VIBSIST-1000 source shown in Figure 1, uses a tractor-mounted hydraulic rock-breaker, powered through a computer controlled flow regulator and delivers 500-1000 J/impact at a rate of 7-15 impacts/second. Sweeps of 20 s are recorded and typically five sweeps are stacked bringing the total energy to approximately 1000 kJ.

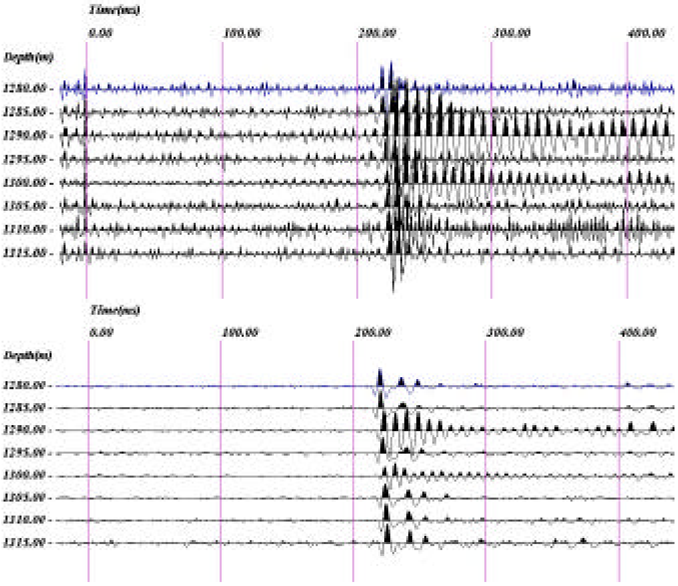
Figure 1. The VIBSIST-1000 seismic source.

2.1 Noise Suppression with the VIBSIST Source

A comparison between the VIBSIST-1000 source and explosive charges was made at Laxemar, Sweden, in 2000 [5]. The records shown in Figure 2 were obtained with the VIBSIST source acting on the ground surface and a 75g explosive charge placed in a shot hole. The thickness of the overburden was several meters. The signal-to-noise ratio has been significantly better for the SIST source while the frequencies have been slightly lower, due to the overburden. However, the VIBSIST signals display less ringing and therefore a better separation of adjacent reflectors can be achieved.

Figure 2. Records obtained with the VIBSIST-1000 on loose overburden (above) and 75g of dynamite in a 1m deep hole.

3 PROCESSING OF THE VSP DATA



A preliminary data conditioning sequence focuses on eliminating the direct P, direct S, tube-waves and ground-roll, so that the weaker later events, e.g. reflections, become visible. The signal levels are adjusted by an AGC (automatic gain control) operator.

A raw profile and its preconditioned version are presented in Figure 3. In the raw profile, of Figure 3a, a slope break of the direct P-onsets can be noticed at a depth of 440 – 460 m, associated with three up-going events, marked **A**, **B** and **C**. Events **B** and **C** are P-wave reflections. Event **A** is a PS-converted wave from the same interface that generates event **C**. The data preconditioning did not make other events to emerge convincingly from the noisy background. This non-coherent noise pattern is typical for the seismic response of hardrock and is generated by scattering on inhomogeneities with dimensions comparable to the wavelength. Secondary wave fields are therefore more likely to be identified by examining the coherency along time-depth paths corresponding to possibly real events than by looking for amplitude standout.

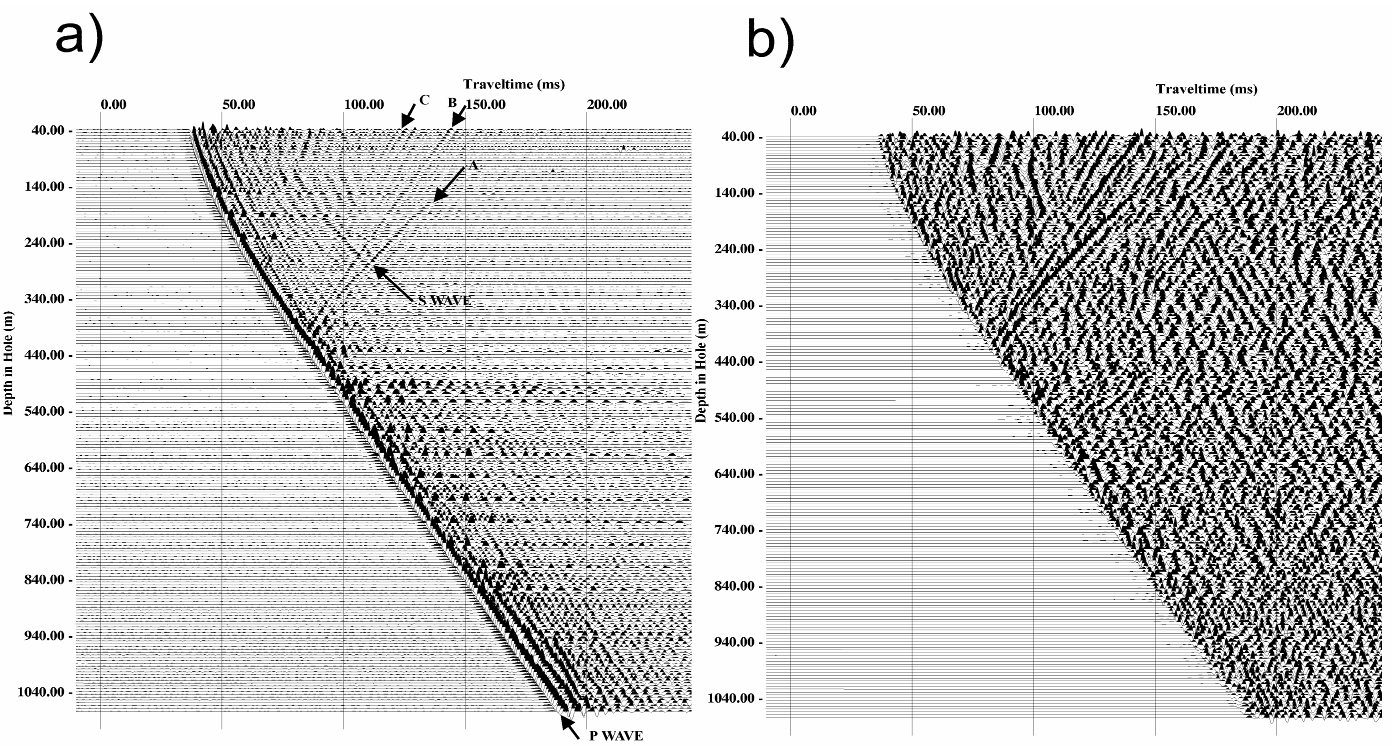


Figure 3. Raw and preconditioned VSP profiles.

3.1 Image Point Processing

The second stage of the processing sequence consists mainly of Image Space (IP) processing, aimed at enhancing the reflected wave fields and at separating reflection events originating at interfaces with different orientations. A description of Image Point technique can be found in [3].

With the IP transform, a reflective interface is divided in a series of planar elements, the mirror image of the source with respect to each element forming an Image Point. Stacking is performed along hyperbolic paths corresponding to the time-depth functions of possible reflectors. Due to this ”natural” choice of the stacking paths, the coherency can be used effectively to enhance the weak reflections.

When the direct and the inverse transform are applied, one gets a time-depth profile where the coherent reflections are enhanced. The filtering effect of the IP transform results from the use of the actual propagation velocity in the computation of the stacking paths. The data shown in Figure 4 are derived from the profile from Figure 3.

Figure 4a depicts the 2-way IP transform for all reflector orientations. Event **B** became overwhelmingly clear, while event **C** remained visible but considerably diminished. Other events became clearer, including down-going events like **E**, which is a secondary surface reflection.

The IP transform can also be used to enhance or suppress subsets of reflectors with given orientations. The surface reflection **E**, which is not relevant to the rock structure, has been suppressed in Figure 4b.

With the HSP layout, both sources and receivers are at the surface and velocity variations are likely to become more important than at large depths. Static corrections and refracted wave paths are in this case computed by tomography. The forward IP transform is then computed by taking into account the influence of the varying velocity field. The mean velocity of the rock at larger depth is used in the inverse transform, which amounts to a consistent 3-dimensional model driven static correction procedure.

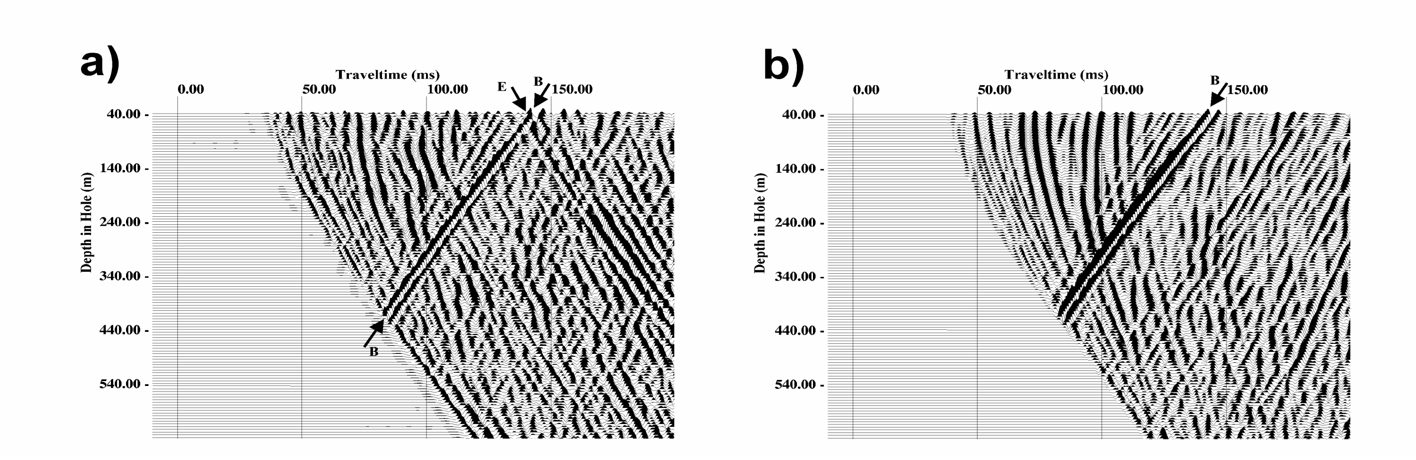


Figure 4. Complete and dip-filtered 2-way IP transformed data of the profile from Figure 3.

4 POLARISATION ANALYSIS IN IP SPACE

Both the depth-time and the IP representations of a single VSP shot gather define two of the three parameters needed to determine the 3-D position of a reflector. The reflected waves travel on nearly straight paths to the 3-component receivers placed within the bedrock, which allows the wave polarization to be effectively used to determine independently the azimuth of the reflectors.

The method relies on solving an eigenvector problem to determine the direction and degree of polarization within a certain window. The horizontal axes are then rotated so that one of them points in the direction of the main eigenvector. A filtering effect is achieved by multiplying the rotated components by $L(t)=1-(\lambda_2(t)/\lambda_1(t))^2$ where $\lambda_1(t)$ and $\lambda_2(t)$ are the largest and the second largest eigenvalues computed in the respective window [7].

Polarization analyses performed on hardrock data are generally unstable because of crisscrossing reflection events and strong non-coherent scattering. The analyses become more stable in the IP space because the energy reflected on interfaces with different orientations accumulates in different regions.

Figure 5 displays two polarization-filtered profiles computed from the horizontal components associated to the vertical component profile discussed above. Polarization-filtered profiles were computed with a 10^{o} azimuth increment. Event **F** displays a maximum amplitude at an azimuth of 150^{o}. Without polarization filtering the reflection event **F** would be barely visible.

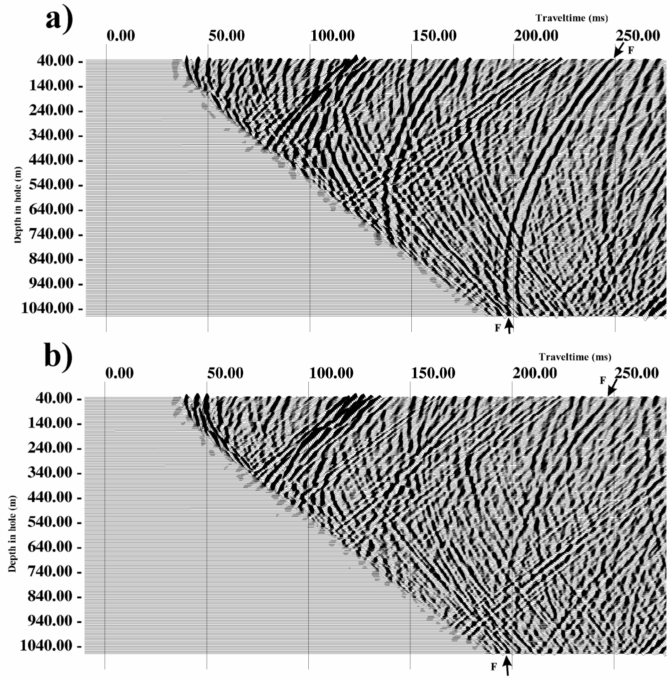


Figure 5. Polarisation-filtered profiles.
(a) Azimuth 150°. (b) Azimuth 160°.

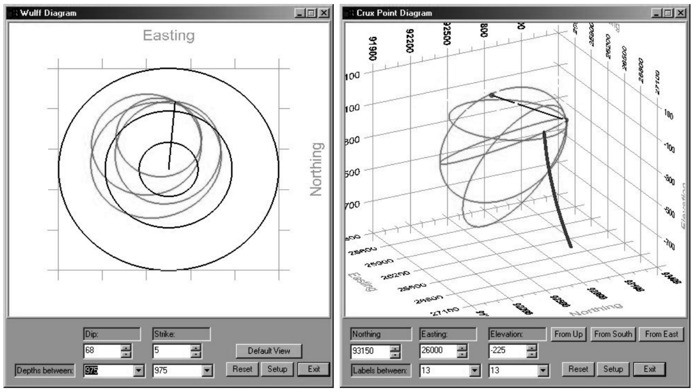
5 INTERPRETATION

5.1 VSP / HSP Multi-Profile Reflector Fitting

VSP & HSP investigations are normally conducted in several boreholes and along several surface layouts at the same site, each layout comprising typically ten or more offsets. The azimuth estimates obtained by polarization analysis are improved by the concurrent processing of all profiles. To facilitate the consistent interpretation of the considerable number of reflection events, an attempt is made to link the ones likely to represent the same feature in different profiles. However, this reduction procedure cannot easily be done interactively, as the gap between layouts is often large and the site features are not necessarily planar. Solving the problem requires the use of statistical methods, e.g. clustering analysis.

If the profiles are measured in the same borehole (or along the same surface layout), the mean orientation of a reflector can be found in a stereographic representation (Wulff diagram) at the intersection of the dip-azimuth curves computed for each profile, as shown in Figure 6a. Each dip-azimuth curve describes the possible orientations associated with the same time-depth function in a given profile. As fracture zones develop more or less along planes, their images in profiles measured with the same receiver layout are assumed to have the same intersection position along the layout and the stereographic projection is computed at this specific position. The intersection, the dip and the azimuth determine completely the position and orientation of a reflector. The stereographic representation method is not applicable to profiles measured in different boreholes because the intersection positions vary widely due to lateral extrapolation. The 3D fitting procedure exemplified in Figures 6b and Figure 7 is applied instead. Each curve is the locus of a ‘Crux Point’, defined as the foot of the perpendicular descended on a given reflection plane from an origin common for all profiles. The Crux Points from Figure 7 have been computed for profiles measured in four different boreholes, the curves described by their loci being more complex than the ones from Figure 6b.

Figure 6. (a) Wulff diagram. (b) Crux point diagram.



Dip: 68

Strike: 5

Depths between: 975 975

Northing 93150

Easting: 26000

Elevation: -225

Labels between: 13 13

Figure 7 displays also the segments of the reflecting interface actually covered by the four profiles.

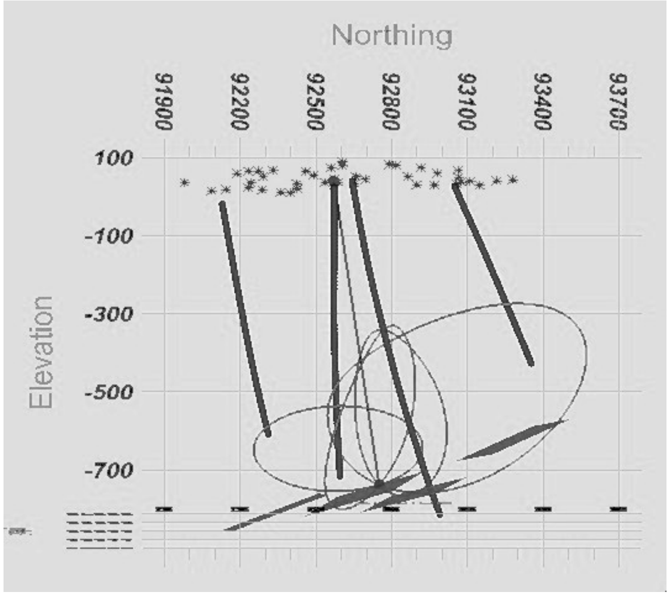


Figure 7. Crux point diagram for reflector fitting among VSP profiles measured in different boreholes.

5.2 *IP Migration*

In addition to the geometry, the amplitude of the reflected wave field bears useful indications of the character of the seismic features. With VSP in hardrock, the reflected wave amplitudes are generally difficult to operate with because of the very diverse orientations of the reflectors, which translates into different distributions of energy amongst transmitted, reflected and converted waves. If the profiles are migrated along the dip directions of the dominant fracture sets, the relative amplitudes in each migrated profile are more stable, as reflections occur at nearly normal angles. CMP 3-D migration and the IP transform are used concurrently to filter out events associated with other orientations than the one for which the migration is performed. Migrated sections help classifying reflectors mapped by the fitting procedure outlined above according to the magnitude of their responses.

Two IP-Migrated sections from the HSP profiles measured at Olkiluoto in 2001 are shown in Figure 8. They emphasize reflectors dipping E-W.

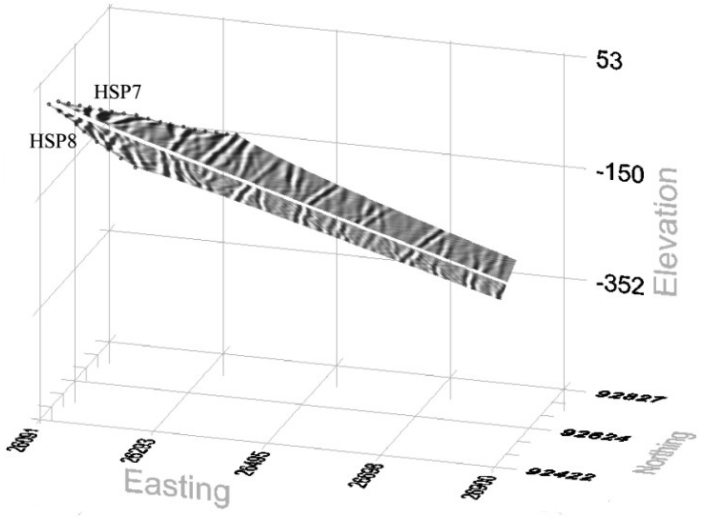


Figure 8. IP filtered and migrated shot gathers. The IP filter was designed to emphasize the steeply dipping reflectors.

5.3 3D Fracture Models

After having determined their geometry and classified them according to the magnitude of their seismic response, reflectors are presented in a 3-D perspective as in *Figure 9*, which is begotten by combining individual reflector analyses like the one presented in Figure 7.

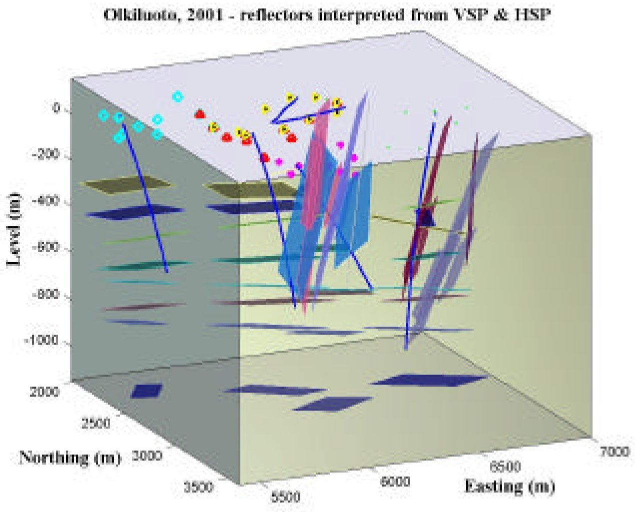


Figure 9. 3D fracture model derived from VSP and HSP data at Olkiluoto, Finland.

6 CONCLUSIONS

The main difficulties experienced with VSP surveys in hardrock have been the diversity of the orientations of the targets and the low reflectivity of the fracture zones. Moreover, networks of fractures and joints with dimensions comparable to the wavelength produce non-coherent scattering.

Established techniques used for VSP in sedimentary formations; e.g. corridor stacking, f-k and τ-p filtering had to be dropped as unsuitable for enhancing reflectors with a wide variety of orientations. In general, common VSP processing routines have been deemed insufficient for mapping fracture zones in hardrock. The Image Point (IP) transform became the core of the processing scheme for enhancing weak reflected wave fields and for separating interfering reflections from boundaries of varying orientations. With the IP technique, non-coherent noise and coherent events corresponding to wave types traveling with other velocities are suppressed, which produces a filtering effect even when the two-way linear transform is applied. The IP transform can also be used to enhance subsets of reflected events, e.g. by forming dip classes. The intuitive representation offered by the IP transform, i.e. the fact that the reflected energy is concentrated in a small area, greatly helps in designing the filters.

Three-component receivers offer the possibility of using polarization analysis to determine the azimuth of the reflectors. Problems with intermingling and crisscrossing of events arriving from different directions are avoided in IP space, allowing the reflector azimuths to be estimated with a precision of approximately +/- 10°.

The reflector location determinations based on azimuth estimates are further improved by simultaneous fitting of data from several profiles. The reflectors are classified according to the magnitude of their responses by migrating the profiles along the fracturing directions found as dominant. The final interpretation is then done by combining all of the data collected in different boreholes at the site. The continuity and consistency of features inferred independently from several VSP surveys constitutes an internal verification of the model. The result is a comprehensive model of the fracture zones throughout the site.

Based on the large number of surveys performed and the ample direct and indirect verifications, the multi-azimuth multi-offset VSP is considered an effective method for determining the positions and orientations of fracture zones in crystalline rock.

7 REFERENCES

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