# VSP IN CRYSTALLINE ROCKS - FROM DOWNHOLE VELOCITY PROFILING TO 3-D FRACTURE MAPPING

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## ABSTRACT

VSP surveys have been carried out at several potential nuclear waste disposal sites in Finland since the mid 80's. To date, more than 200 three-component profiles have been measured. The main purpose of the surveys was to detect fracture zones in the crystalline bedrock and to determine their positions.

Most seismic events could be linked to zones of increased fracturing observed in the borehole logs. The more pronounced seismic reflectors could be correlated with hydro-geologically significant zones, which have been the main targets in the investigations.

Processing and interpretation methods have been developed specifically for VSP surveys in crystalline rocks:

- Weak reflections from thin fracture zones are enhanced by multi-channel filtering techniques based on the Radon transform.
- The position and orientation of the fracture zones are determined by polarisation analysis and by combining data from several shot points.
- The compilation of the results from several boreholes gives a comprehensive image of the fracture zones at the scale of the whole site.

The discussion of the methodology is based on examples from the Olkiluoto site, in SW Finland.

# 1. INTRODUCTION

Vertical Seismic Profiling has routinely been used as a means of improving the interpretation of the surface reflection surveys in sedimentary basins, [1]. Since the late 80's, VSP also became a favoured methodology for deep seismic imaging, especially in crystalline rocks. The basic reasons for this development are as follows:

- With VSP, the source and the detectors can be placed within the bedrock itself, the loss of resolution due to near-surface signal absorption being largely avoided.
- 3-component detectors allow the polarisation of the signals to be used as an indication of the orientation of the reflectors. Even if 3-component receivers were used with surface profiling, most of the polarisation information would be lost due to near surface refraction, which causes all signals to arrive at the detectors on nearly vertical paths.
- The arrays of receivers placed in vertical or steeply inclined boreholes provide a favourable geometry for mapping, in depth, steeply dipping fractures.
- VSP is, generally, a more economical solution than a 3D surface seismic survey.

The capabilities of the VSP imaging method include:

- obtaining accurate velocity estimates in depth,
- determining rock mass anisotropy,
- mapping fracture zones and lithological contacts in 3-D.

Several authors reported good results with the first two topics above [2], [3], [4], [5]. The third topic is complex and includes the first two, among others. So far, most of the references to this topic relate to Radioactive Waste Management, e.g. [6].

The Site Investigation Programme for the Final Disposal of Spent Nuclear Fuel in Finland started in 1983 and the preliminary site investigations begun in 1987. Since then, more than 200 three-component VSP-surveys were carried out at several sites, often to depths approaching or exceeding 1000 m. The main objective of these surveys was to detect fracture zones in the crystalline bedrock and determine their position and orientation.

New processing and interpretation techniques were needed to turn VSP into a tool for mapping fracture zones. The reflections from fractures in crystalline rock are generally less pronounced than those from the boundaries of sedimentary formations, while scattering is stronger. Moreover, unlike reflections from sedimentary formations, in crystalline rocks the reflecting boundaries can have any orientation and 2-D analyses are not applicable.

Currently, the rock models of the sites investigated and in particular the deeper sections rely strongly on the results of the VSP surveys.

## 2. METHODOLOGY

### *2.1 Data acquisition*

The deep boreholes drilled during the investigations in crystalline rocks are often slim, even when the depth exceeds 1000 m. The combined requirements of small size, wide frequency band, 3-D directional sensitivity, high data production rate and relatively low cost were difficult to meet with existing seismic exploration equipment.

A multi-level 3-component receiver chain, with an outside diameter of 43 mm, was designed and built for surveys in slim boreholes. The optimum number of levels allowing manual handling is 8, but it can be increased to 16 for higher data production. Each module is equipped with geophones or accelerometers and preamplifiers. The modules clamp to the hole by side arms activated by DC motors (*Figure 1*).

At the kilometre scale, the P-wave frequencies recorded can go up to 500 Hz. The corresponding S-wave maximum frequency is roughly 300 Hz. In both cases the minimum wavelength is approximately 12 m. Therefore, the distance between the levels in the receiver chain is 5 m, i.e. slightly less than the half of the minimum wavelength. This allows the detection of rock features with thickness of 1 metre, or even less. For surveys at smaller scales interlaced records are taken, e.g. at 2.5 m, to avoid spatial aliasing due to the possibly higher frequency content of the signals.

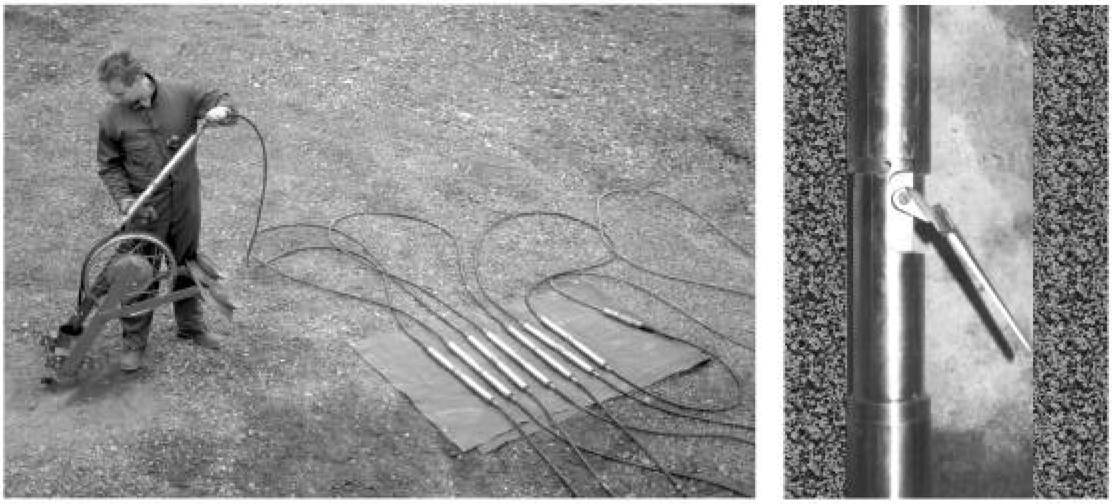


*Figure 1. The multi-level borehole seismic receiver chain for deep VSP surveys. It contains eight 3-component receiver modules clamped to the borehole by a side arm mechanism. The clamping arm is moved by an electric motor.*

In areas with thin overburden, a handy way to produce VSP signals is by placing small dynamite charges (35 - 70 g) in shallow holes drilled into the bedrock. Typically, a group of three holes are drilled at each shot point and the shooting is switched from one to another in case of collapse. This arrangement becomes uneconomical in areas covered by thick overburden where deeper holes are needed to reach the bedrock. In these situations engineered sources, e.g. borehole guns and hammers, are preferred, as the risk of collapse is much smaller than with explosives and one shot hole is normally sufficient for measuring a whole VSP profile.

With VSP, the angular coverage is more complete than with surface reflection profiling. Therefore, VSP will be more successful in determining the geometry of the rock features, especially of the steep ones. Conversely the positional coverage is less complete and only certain portions of these features can be imaged by any single VSP survey. To resolve this, VSP surveys are conducted in several boreholes, with each subsequent survey partly overlapping the previous ones but also contributing with new information, from other regions of the site, until a complete and iteratively validated model is obtained.

At the initial site description stage, the investigation area is of the order of 10 km$^2$. A fairly complete coverage was achieved at the Olkiluoto site, in SW Finland, with nine boreholes with depths ranging from 300 to 1000 metres. The average distance between the boreholes was 500 metres. A spread of six to nine shot points was set around each borehole, with offsets varying from 100 to 500 metres.

## *2.2 Velocity Models and Anisotropy*

VSP is used in sedimentary formations for determining the 'interval velocities', which are required for depth-migrating surface reflection data. A similar approach can be used in crystalline rocks, if the shots are placed in the bedrock, as recommended in *Section 2.1.* In this case, it can be assumed that significant velocity variations occur only in the near-surface weathered zone, hence the velocity field can be considered one-dimensional (nonetheless, a ray tracing inversion approach is needed for determining the velocity-depth function for shots with significant horizontal offsets). *Figure 2* depicts the fracture density log, the acoustic log and the VSP interval velocity measured in the same borehole (KR4). One can see that the acoustic log is very indicative of the fracture density, while the thin fracture zones are not observed in the velocity function computed from the VSP data (the dashed line in *Figure 2*). The lack of a significant velocity contrast in depth makes the relevance of the interval velocity procedure questionable in crystalline rocks.

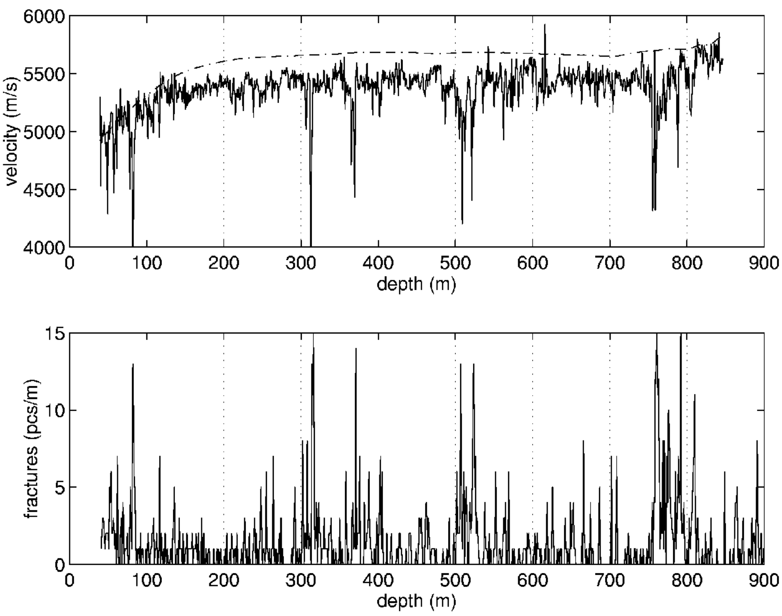



*Figure 2. The fracture density log (bottom picture), the sonic log and the VSP interval velocity (top picture) measured in borehole KR4 (Olkiluoto).*

A velocity model becomes essential when thick overburden prevents the shots from being placed in the bedrock. As the overburden-bedrock interface is not necessarily horizontal, a one-dimensional velocity model may not be always suitable and more intricate approaches must be devised. *Figure 3* presents a case where the determination of the velocity function has been derived by 3-D tomographic inversion using ray tracing. The survey layout consisted of 3 deep boreholes, with two shot points for each borehole. Ray tracing was applied. The tomographic velocity distribution is shown in the plane of the maximum dip of the overburden-bedrock contact. Although the 3-D VSP tomographic inversion shown in *Figure 3* provides no direct information on the structure of the bedrock, it determines the reliability of the geometrical model obtained as a final result.

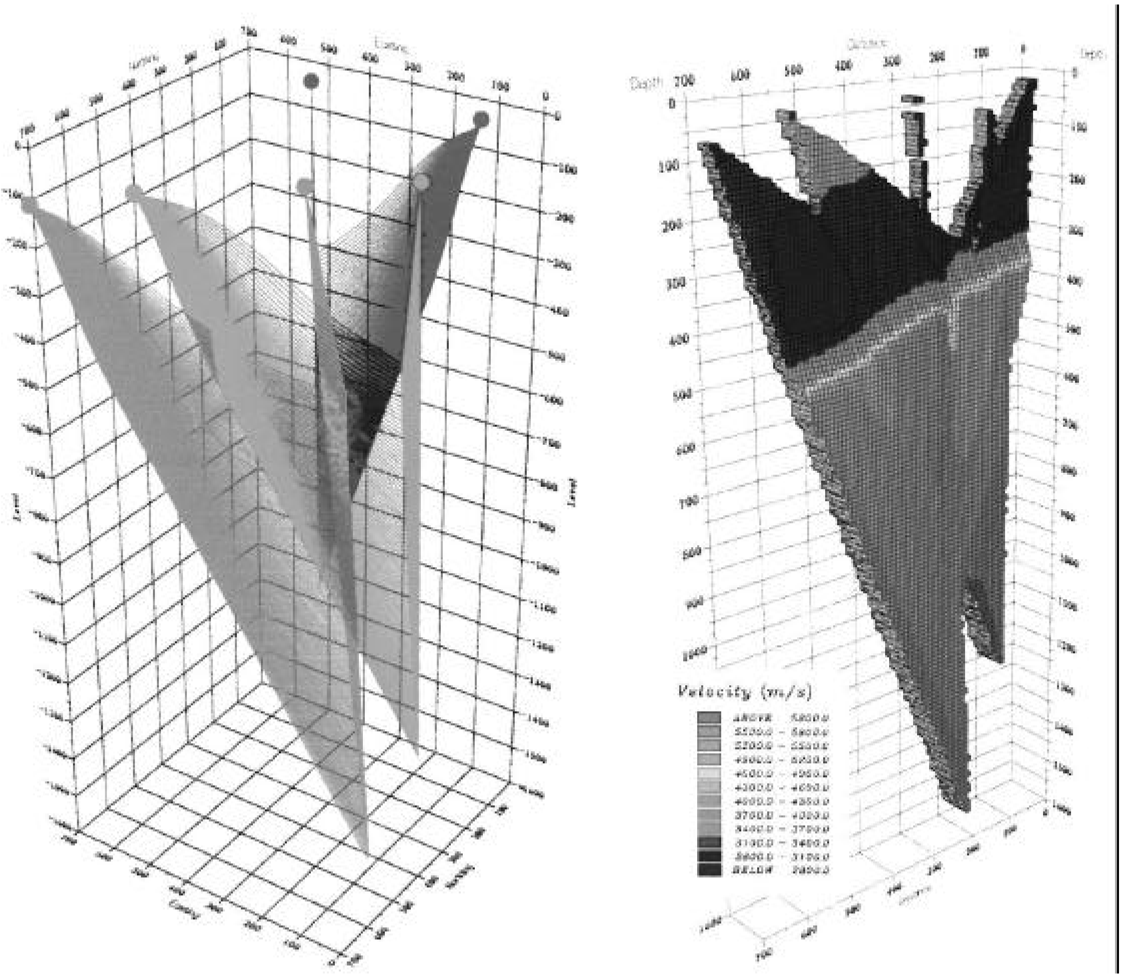



*Figure 3. 3-D velocity model, shown in the plane of the maximum dip of the overburden-bedrock contact.*

As shown in *Figures 2* and *3*, velocity variations within the rock mass due to local changes of the rock texture are generally small. However, anisotropy is quite common and is often related to trends in the orientations of the fractures.

As an example, *Figure 4(a)* shows the P-wave velocities determined from first arrivals as a function of the receiver depth, for the six profiles measured in borehole KR6 at Olkiluoto. It can be seen that the velocities vary considerably and it was not possible to construct an isotropic velocity model to account for the anomalous velocity-depth functions in all six profiles. The rockmass was therefore modelled as a transversely isotropic medium, in which the minimum velocity is normal to the dominant fracturing. With this approach, the velocity function can be described by the values of the maximum and minimum velocities and by the direction of the axis of minimum velocity.

*Figure 4(b)* presents the velocity-depth function for profile L22, which displays the most anomalous variation in *Figure 4(a)*. The velocity function corresponding to the transverse isotropy model is shown for comparison. The parameters of the model have the following values: minimum velocity 5.1 km/s, maximum velocity 6.1 km/s, and direction of the minimum velocity dipping approximately $20^o$ to N-NE. It is apparent that the velocity variation is overwhelmingly due to anisotropy. After subtracting the anisotropic component the velocity variation was reduced to less than +/- 100 m/s.

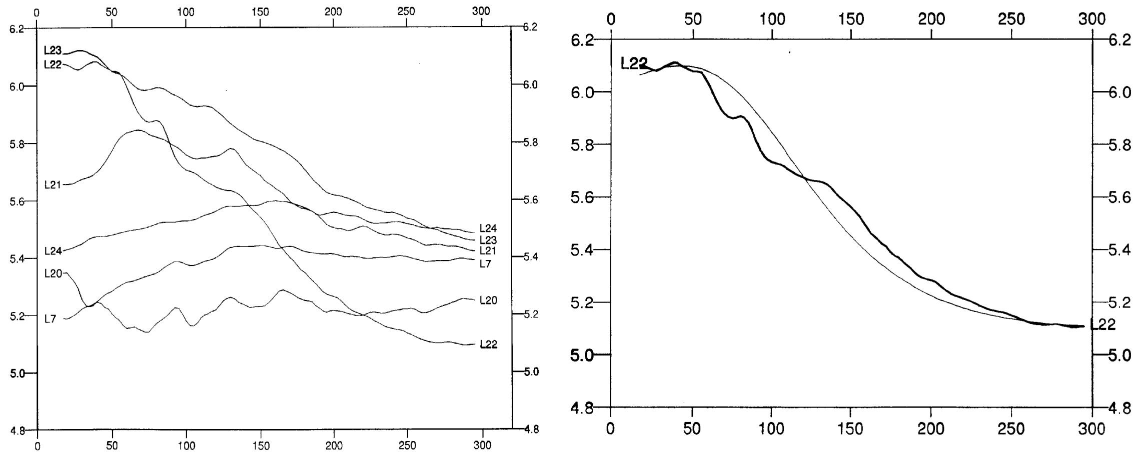



*Figure 4a (left). P-wave velocities determined from first arrivals as a function of the receiver depth, for the six profiles measured in borehole KR6 at Olkiluoto.*

*Figure 4a (right). The velocity-depth function for profile L22.*

## *2.3 Modelling the 3-D Fracture Geometry*

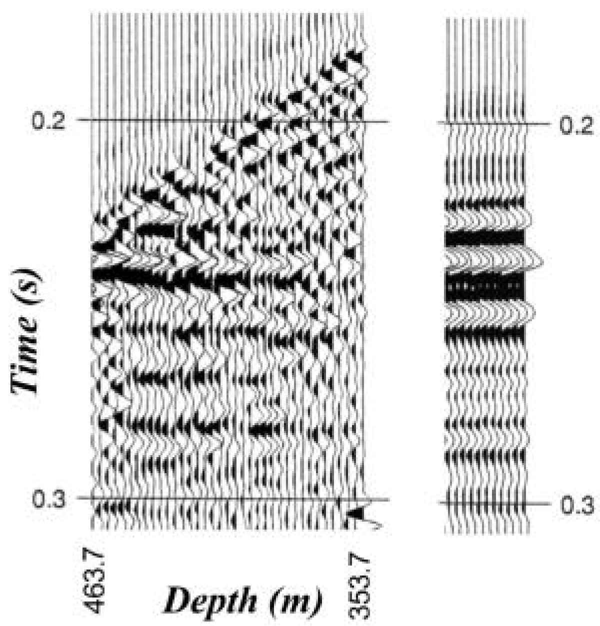
The preliminary processing consists of a series of fairly standard procedures aimed at emphasising the reflected field. The typical steps of the preliminary processing stage are the following:

- indexing the traces and synchronising the traces with the survey coordinates,
- picking arrival times,
- rotating the horizontal components to the radial (R) and transversal (T) directions,
- band-pass filtering,
- removing direct P-waves, S-waves and tube-waves by median filter,
- deconvolution,

- amplitude compensation using the same AGC-operator for all three components.

A thorough checking of the data is performed during this stage and, where needed, other means of signal conditioning are also applied, e.g. static corrections based on heterogeneous and/or anisotropic velocity models, as discussed in *Section 2.2*.

The stronger reflections can generally be pinpointed in the pre-processed data. A common attempt to make them more visible is exemplified in *Figure 5*. The procedure consists of shifting the traces along the time axis by an additional interval equal to their respective travel time and stacking them. In zero-offset sections, horizontal reflectors appear as synchronous and are emphasised by stacking (*Figure 5(b)*). The technique is hardly of any use in crystalline rocks, where horizontality has no particular meaning and large shot offsets are the rule, rather than the exception. *Figure 6(b)* shows a corridor stack for data acquired in a crystalline rock environment and this illustrates that this is a rather poor means of enhancing reflectors.




In crystalline rocks, reflectors are generally masked by scattering, surface multiples, converted waves, tube-waves and stronger reflections. Multi-channel filters based on a version of the Radon transform - the Image Point transform - are used for enhancing weak reflections and for separating the interfering events [6]. The effect of the technique is exemplified in *Figure 6(c)*.

*Figure 5. Zero-offset and stacked sections.*

The filtering capabilities of the Image Point transform result from the fact that reflectors with different orientations are imaged in different regions of the transform space and that the actual propagation velocity is used instead of the apparent velocity, as the case is e.g. with the $\tau$–p transform. Enhancing reflectors with different orientations is reduced to simple editing of the transform space.

## 3. 3-D MODELLING

A notable characteristic of the Image Point approach is that polarisation filters applied in Image Point space avoid the problems appearing in the time-depth representation caused by noise and interference among coherent events with different origins. By using the polarisation of the signal in the Image Point space, it is possible to enhance reflections arriving from specific azimuths and thus estimate the dip direction of the corresponding reflecting interfaces.

The travel time function associated with a planar reflector gives a relation between the dip and the dip direction and, with the dip direction already estimated independently by polarisation, the dip can be computed. The travel time function also determines the distance from the reflector to the borehole. Therefore, all the three parameters needed to completely determine the position and orientation of a planar reflector are resolved.

*Figure 6* shows the pre-processed section and the same section after polarisation filtering, from the zero-offset shot point of borehole KR8. The reflectors dipping to South are enhanced. Polarisation filters applied in the Image Point space help in determining the orientations of the reflectors and also enhance the reflected signals, making the determination of their travel-time functions easier.

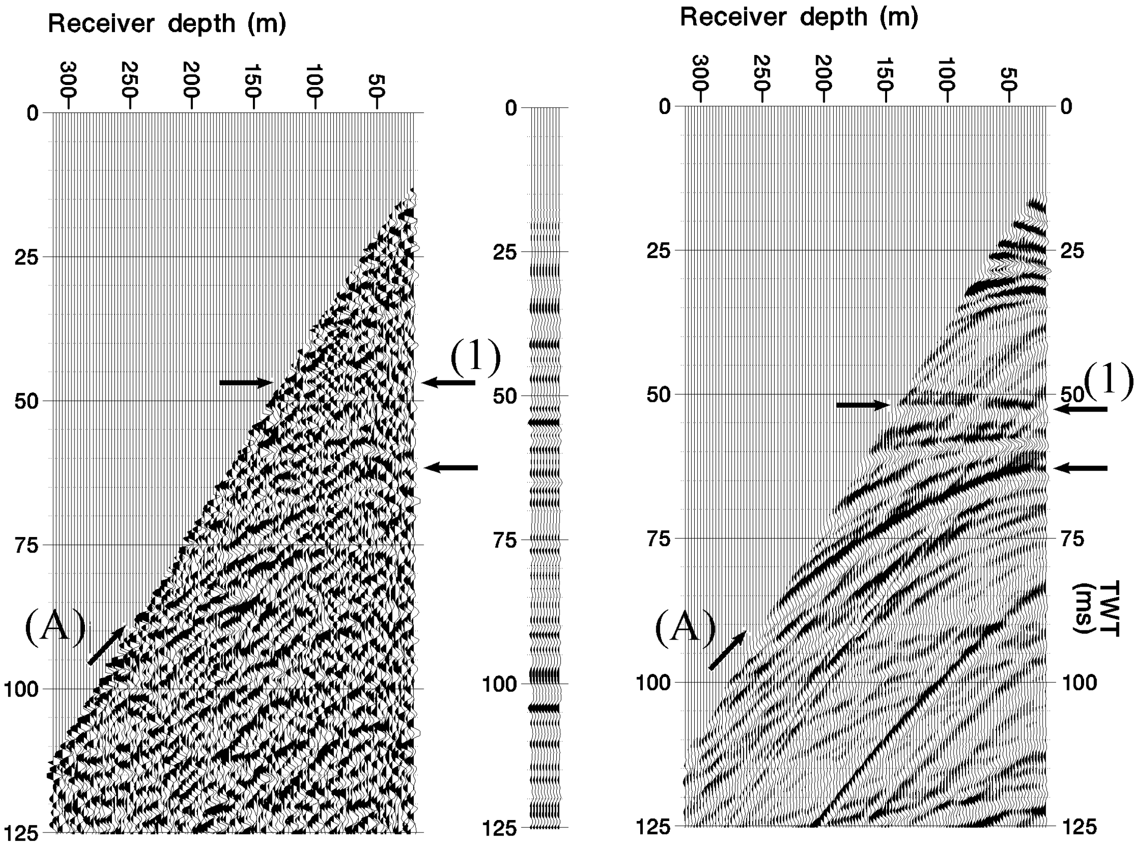



*Figure 6. Pre-processed section and the same section after polarisation filtering, from the zero-offset shot point of borehole KR8. The middle section represents a corridor stack.*

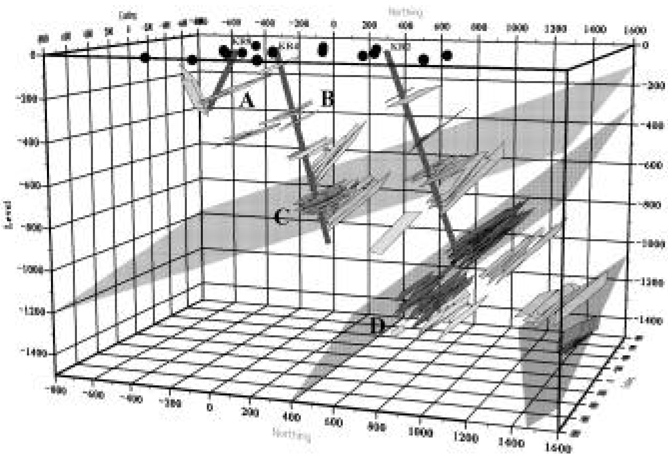
The orientation estimated by polarisation analysis is usually no better than +/- 10° but the results is very robust. The estimate can be significantly improved by combining the results from several shot points and in some cases, by using the converted (P-to-SV) reflections. In the far-offset sections conversions have a different variation with dip and dip direction than the P-wave reflections. Due to the sparseness of the coverage offered by small number of shot-points, this procedure is carried out by statistical analysis, rather than by linear integration. This makes it relatively unstable, meaning that small errors in the input may produce large changes in the model. After determining the average position and orientation of a reflector, those regions actually mapped can be computed.

## 4. APPLICATION OF 3-D FRACTURE MAPPING

Most of the reflectors detected by VSP in crystalline rock can be interpreted as fracture zones, appearing in the borehole logs to be from 2-3 m to 30-50 m thick, with a typical fracture density of 10 pcs/m. The velocity change resulting from the presence of such fracture zones is of the order of 10 %, or more. Within a signal frequency range of 200-600 Hz, it is possible to image fracture zones less than 2 m thick. Fracture zones more than 30 m apart, i.e. 2-3 wavelengths, can be positively resolved as separate reflectors.

These conclusions are confirmed by the results from Olkiluoto. The three strong reflections (A, B and C) from *Figure 7(b)* can be correlated with fracture zones seen at the depths 85-90 m, 320-380 m and 760-800 m in the P-wave acoustic and fracture logs in *Figure 2.* The fracture zones at the depths 520 m and 650 m are better imaged from other shot points. A closer examination of the section in *Figure 7(b)* reveals that the event B consists of two reflections, corresponding in the logs in *Figure 2* to 3-5 m thick fracture zones, at 320 m and 360 m depth.

The reflector C also consists of two branches, representing fracture zones at the depths of 760 and 790 m. The event D does not intersect the borehole, but can be correlated with a fracture zone found in the nearby hole KR2, as seen in *Figure 7(a)*.



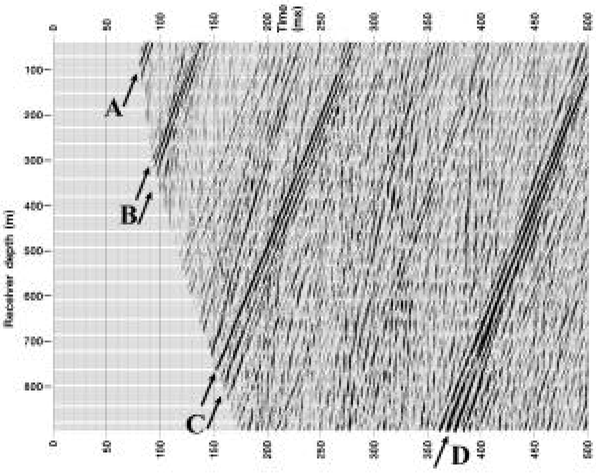




*Figure 7a (left). The major fracture zones determined from VSP from boreholes KR4, KR2 and KR8 at Olkiluoto. The fracture zones are marked with A-D.*

*Figure 7b (right). The polarisation-filtered section from shot point L25, borehole KR4. Reflections dipping to the South are enhanced. The strongest reflections (A-D) come from the fracture zones marked in Figure 7a.*

When the reflector position estimates based on polarisation analysis are improved by combining the results from several shot points, the spread of the dips and dip directions is, usually, a few degrees. As the reflections from different shot points map different areas of the reflecting boundaries, the consistency of the reflector attitudes indicate that the fracture zones are quite planar at least over an area a few hundreds of metres.

Once the geometry of the reflectors has been established, determined as best fitting planes, the areas where the reflections actually occur for different shot points can be computed. *Figure 7(a)* displays the major fracture zones interpreted from the VSP surveys performed in boreholes KR4, KR2 and KR8 in Olkiluoto [7]. The areas actually mapped by VSP data are shown as small rectangles and the average position of the reflecting planes as grey shaded planes. As seen in *Figure 7(a)*, most of the reflecting boundaries can be correlated from one borehole to another. The major fracture zones at the Olkiluoto site seem to form a system of zones dipping gently (10°-30°) to south.

This observation is also confirmed by hydraulic studies [8]. The upper boundary of the saline groundwater and the hydraulic flow patterns in the holes were shown to be controlled by the fracture zones. The flow studies also indicate that the fracture zones observed in the two adjacent boreholes (KR4 and KR2) are connected as indicated by the VSP results.

## 5. CONCLUSIONS

The multi-offset three-component VSP can be successfully used in determining the 3D positions of thin fracture zones in crystalline rock, as shown by the results of the VSP measurements at the potential radioactive waste disposal sites in Finland. VSP also images the zones accurately at depths difficult to reach by other methods. The rock fracture zones interpreted from VSP surveys in several boreholes can be combined into a comprehensive site model.

Compared with surface seismic methods, higher frequencies can be used with VSP, which leads to higher resolution. This is due to the fact that both the sources and the receivers can be directly placed in the hard rock.

Due to the relatively high signal frequency, most of the VSP reflectors in crystalline rock can be correlated with fracture zones, with fractures as narrow as 1-2 m being detected and zones separated by 20-30 metres can also be resolved as individual reflectors, within an investigation range of 1-2 km.

The standard VSP processing and interpretation routines are not sufficient for mapping fracture zones in crystalline rock. A more efficient technique is the Image Point transform, which, used in conjunction with polarisation analysis, gives the possibility to enhance weak reflections from thin fracture zones and, simultaneously, to determine their 3D orientation, thus extending the imaging range of the VSP method from the vicinity of the borehole to the site scale.

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