MULTI-AZIMUTH VSP FOR ROCK CHARACTERISATION OF DEEP NUCLEAR WASTE DISPOSAL SITES IN FINLAND

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ABSTRACT

Multi-azimuth VSP surveys have been a part of The Finnish Site Investigation Programme for the Final Disposal of Spent Nuclear Fuel since the mid 80’s. The main objective of the surveys has been to detect hydraulically transmissive zones (normally fracture zones and faults) and to determine their geometry.

The receiver tool comprised eight three-component geophones, clamped to the borehole. Dynamite charges were used as sources. The high frequency content of the data allowed the mapping of fracture zones less than one meter thick.

The Image Point (IP) Transform forms the core of the processing scheme for enhancing weak reflected wave fields and for separating interfering reflections from boundaries of varying orientations. Polarisation analysis applied in Image Point space largely avoids problems caused by the interference.

The VSP layout demonstrated an outstanding capability of imaging both gently and steeply dipping features. Coverage analysis methods have been used to predict and identify possible blind zones.

Examples are given from two sites: Kuhmo-Romuvaara in Eastern Finland and Eurajoki-Olkiluoto in the SW. The orientations of the fracture zones Kuhmo-Romuvaara are diverse, resulting in a relatively complex case of seismic imaging. The major fracture zones at Eurajoki-Olkiluoto follow directional trends and a good correlation has been noticed between more pronounced seismic reflectors and hydrogeologically more significant zones, at both the local and the site scale.

As a result of the seismic work performed as part of the Finnish site characterisation programme for final disposal of spent nuclear fuel, conducted by Teollisuuden Voima Oy (TVO) and lately by POSIVA Oy, the VSP method, intended originally as a supportive technique for surface investigations of sedimentary formations, became an established tool for investigating deep regions of crystalline rockmass.
INTRODUCTION

The Finnish Investigation Programme

The Finnish Site Investigation Programme for the Final Disposal of Spent Nuclear Fuel started in 1983. Five sites were selected from a shortlist of potential candidate areas and preliminary investigations were conducted at these sites during 1986 – 1992. Subsequently, three areas were selected for detailed characterisation, concluded in 1999. The spent nuclear fuel is to be emplaced in the bedrock at a depth of 300 – 700 m, in canisters made of cast iron, enclosed in stainless copper shells (Posiva Oy, 1999). The bedrock is meant to act as one of several barriers preventing the migration of radioactive nuclides to the biosphere and providing a chemically stable environment around the disposal canisters. Both of these functions are related to the groundwater flowing through rock fractures.

The preliminary investigations were focused on rock features that could possibly jeopardise the use of a site for disposal purposes. These features would include extensive crush zones, fracture zones and faults. The objective of the detailed investigations was to detect also smaller scale hydraulically transmissive zones (normally fracture zones and faults) and to determine their geometry.

Multi-azimuth VSP surveys have been a part of the site investigation programme since its beginning in the mid 80’s. To date, more than 200 VSP-surveys have been carried out, to depths approaching or exceeding 1000 m. Examples of VSP surveys are given from Kuhmo-Romuvaara in Eastern Finland (Anttila et al., 1999b) and from Eurajoki-Olkiluoto, in the Southwest (Anttila et al., 1999a), where both preliminary and detailed investigations have been conducted. The rock types at the Kuhmo-Romuvaara are tonalities and gneisses (Figure 1). The orientations of the rock features are diverse. The bedrock at the Eurajoki-Olkiluoto site consists primarily of migmatitic mica gneisses (Figure 2).
Figure 1. The Kuhmo-Romuvaara test site in Eastern Finland. The positions of the seven shot points used for borehole KR2 are shown as blue circles.

Figure 2. The Eurajoki-Olkiluoto test site in SW Finland. The positions of the seven shot points used for borehole KR4 and of the six shot points used for KR6 are shown as blue circles.
Vertical Seismic Profiling in Crystalline Rocks

The VSP (Vertical Seismic Profiling) method uses survey configurations consisting of an array of detectors in a borehole and one or several out-of-the-hole source positions, at various distances from the borehole collar. VSP has widely been used as a means of improving the depth conversion of the surface reflection surveys in sedimentary formations. Many of the processing techniques used in this context rely on the separation of the direct and reflected wave fields by their slope, which is relatively easy to achieve in the case of semi-horizontal reflectors and near shot offsets. In crystalline rocks inclined reflectors are the rule rather than the exception and large shot offsets are needed for accurately determining the geometry of features with diverse orientations. Therefore, VSP has evolved into an independent tool for the 3-D mapping of structures.

The basic reasons for favouring VSP as a method for deep seismic imaging in crystalline rocks have been the following:

1. With VSP, both the source and the detectors can be placed within the bedrock, the loss of resolution due to near-surface signal absorption being largely avoided. Typically, frequencies of 500 Hz and more can be recorded at a kilometre scale, allowing features less than metre thick to be mapped throughout rock volumes exceeding 1 km$^3$.

2. Arrays of receivers placed in vertical or steeply inclined boreholes and multi-offset multi-azimuth shots provide a favourable geometry for mapping both steeply and gently dipping features.

3. Borehole 3-component detectors allow wave polarisation to be used as an indication of the orientation of the reflectors. With detectors placed on surface, the polarisation information tends to be lost due to near-surface refraction, which causes all signals to arrive at the detectors on nearly vertical paths.
DATA ACQUISITION EQUIPMENT

The basic requirements that a VSP receiver tool must meet with crystalline rock applications are wide frequency band, 3-component directional sensitivity and a relatively large operational depth combined with a small diameter. Practical aspects, such as portability in heavy terrain, high data production and low cost are also to be considered. An 8-level, 3-component receiver chain, with a diameter of 43 mm and an operational depth exceeding 2 km has been built to meet these requirements. The receivers are equipped with side arms for clamping, activated by DC motors, as shown in Figure 3. The distance between levels has been set to 5 m, which permits P-wave frequencies up to 500 Hz and S-wave frequencies up to 300 Hz to be recorded without spatial aliasing. Occasionally, higher frequencies were recorded; in which case, interlaced readings were taken, amounting to a level separation of 2.5 m. The frequency response of the tool equipped with 40 Hz miniature geophones is linear in the band 60 – 800 Hz. An accelerometer version has also been built, with a frequency band of 60 – 4000 Hz.

Dynamite charges of 35 – 225 g were detonated in water-filled percussion-drilled holes at depths varying between 5 m and 25 m. The boreholes were filled with water before each shot. A full round of shots was normally recorded before changing the depth of the receivers, to maintain similar coupling conditions. Seismographs with 21-bit and 24-bit resolution were used for data recording. The trigger signal was transmitted by radio and/or cable to the recording station placed close to the borehole collar.

Figure 3. The multi-level borehole seismic receiver chain for deep VSP surveys containing eight 3-component modules clamped to the borehole by a side arm mechanism.
The borehole KR2 at the Kuhmo-Romuvaara site (Figure 1) was drilled to a depth of 1100 m during 1994 (Anttila et al., 1999b). The drilling method was standard 56-mm core drilling. The VSP survey was carried out in 1995 from seven shot points (Cosma et al., 1995). The receiver interval was 5 m, between 40 m and 1075 m, amounting to 208 receiver stations. The survey layout was optimised by performing analyses of the coverage obtainable with various layout combinations.

**The coverage of VSP surveys**

The coverage analysis provides the means for choosing among the possible layouts a combination that will cover the site volume as evenly as possible. The following questions define the scope of the coverage analysis:

- What can be known about structures, which escape detection due to the unfavourable position with respect to the layout of the survey?
- Can the unfavourable positions be predicted?
- Can a volume be defined in which a structure, if it existed, would be detected with reasonable certainty?
- How to configure a group of surveys so that the region of reasonably certainty covers most of the investigation volume?

The primary purpose of the coverage analysis is to delimit the regions of space which cannot be probed with a given survey layout, whatever the capability of the apparatus and the complexity of the data processing schemes. This is essentially a geometrical problem. The analysis can be refined by adding conditions derived from the wave theory, but this tends to become a laborious task and is normally applied later in the processing/interpretation scheme, to selected classes of reflectors.

The coverage problem can be formulated as follows: Given a linear receiver array and a point source, can a reflection occur at a Point \( P(x, y, z) \) if the reflecting interface is a plane \( (D, \theta, \phi) \) containing \( P \) (\( D \) is the distance from the origin of the coordinates, \( \theta \) is the dip and \( \phi \) the dip direction).

On a plane reflector, the reflection points are distributed along a straight segment limited by the reflection points corresponding to the first and the last detector in the array or, if the reflection plane intersects the receiver array, by one of these points and the intersection of the plane with the array. If the azimuth \( \phi \) is left to vary, the reflection segments generate a surface like the one in Figure 4. If also the distance \( D \) varies, the locus of the reflection points is a volume. The shape and size of this volume depend on the dip \( \theta \). The coverage volume for a dip of 60° is presented in Figure 5. The region between the source and the receivers appears as a blind zone, as reflections are not defined with the source and the receivers on opposite sides of a reflecting plane. The outer boundary of the coverage volume is determined by the data length.
Figure 4. Locus of the reflection segments when only $\phi$ varies. The dip $\theta$ and the distance from the origin $D$ are fixed. The source point is marked with a black dot and the receiver array with a thick line.

Figure 5. The volume covered from one shot point when $\phi$ and $D$ vary and the dip $\theta$ is fixed to 60°. Cut view of the coverage volume. The light grey region between the shot point and the receiver array depicts the blind zone.

Figure 6 illustrates how a site can be covered by ten offsets. The geometry of the shot point spread needs not to be exactly regular and locations with easy access, thin overburden and competent bedrock are preferred. One can note that some regions remain uncovered even with ten shot points. To resolve this problem, VSP surveys are normally conducted in several boreholes, with each subsequent survey partly overlapping with the previous ones but also contributing with new information, from other regions of the site, until a quasi-complete and iteratively validated coverage is obtained.
Preliminary Examination of the Data

The 3-component raw data shown in Figures 7, 8 and 9 were obtained in at Kuhmo-Romuvaara in borehole KR2 from shot-point L22 (Figure 1) (Cosma et al., 1995). The borehole KR2 dips 75° to West and shot point L22 has a South-Southeast offset of app. 200 m. The Z-component points upwards along the borehole, the radial R-component is perpendicular to Z pointing to the shot point and the transverse T-component completes a left-handed system.

The time-depth function of wave field propagating with the velocity \( c \), is the hyperbola \( r^2(\zeta) c^2 - \zeta^2 = r_p^2 \), with \((r_p, 0, z_p)\) the co-ordinates of the shot point, \( \zeta = z - z_p \) and the z-axis running along the borehole. The slope \( V = dz/dt \) is the apparent velocity and \( |V| = c \) for \( r_p = 0 \). Reflected wave fields generate similar hyperbolic time-depth functions, except that the source is virtual, as explained in “The Image Point Transform”.

One can notice in both Z- and R-component profiles from Figures 7 and 8 that the direct P-wave onsets follow closely the time-depth function for \( c = 5850 \text{ m/s} \), which indicates that the velocity variations throughout the profile are small. The P-wave direct onsets are weak in the T-component (Figure 9), as the P-wave is polarised in the \( T=0 \) plane.

A slope break can be noticed, at 440 – 460 m, associated with three up-going events, marked A, B and C. Event A cannot be a P-wave reflection because its apparent velocity is smaller in absolute value than \( c = 5850 \text{ m/s} \). In fact, it corresponds to an S-wave converted field on the same interface that generates event C, travelling with a velocity \( V_s = 3350 \text{ m/s} \). Without event A being recognised as the
associated $S$-conversion of $C$, the latter could be an $S$-conversion generated by a steeper reflector.

Although event $B$ has no apparent associated $S$-wave conversion, it can be interpreted as a $P$-wave reflection. As $B$ has an apparent velocity close to the limit $|V| = c$, the reflection occurs close to normal incidence and little or no energy is converted to $S$-waves. Further support of the above can be found in the $R$-component profile from Figure 8, where events $A$ and $C$ originate at the same depth, while event $B$ is slightly shallower. Forward converted $S$ energy (event $D$) is also noticeable, originating at the same depth with $A$ and $C$. Traces of events $A$, $B$ and $C$ can also be observed in the $T$-component, as virtual sources associated with reflectors are not confined to the $T = 0$ plane. This will be discussed in more detail in “Polarisation analysis in IP space”.

The absence of tube waves in Figures 7 - 9 is largely due to the clamped 3-component receivers. The relative scarceness of the direct $S$-wave field can be also noted. This has to do with the shot being fired sufficiently deep in the bedrock.

![Figure 7. Z-component raw data from Kuhmo-Romuvaara borehole KR2, shot point L22.](image)
Figure 8. R-component raw data from Kuhmo-Romuvaara borehole KR2, shot point L22.

Figure 9. T-component raw data from Kuhmo-Romuvaara borehole KR2, shot point L22.
Data Preconditioning

A preconditioning scheme is applied as the very first processing stage, consisting of the following:

1. *Band pass filtering* is applied to eliminate spectral components originating with instrumental and environment noise, including 50/60 Hz power line contamination. Filtering in the same band (or slightly wider) is repeated after each possibly noise-generating operation, e.g. median filtering, deconvolution.

2. *Median filters* are used to remove direct *P* and *S*-waves and tube-waves. The paths along which the median filters are performed are determined whenever possible by time picking. In other cases, time-depth functions are computed by assuming a velocity model.

3. *Deconvolution* is performed when deemed necessary, mainly to remove ringing.

4. *Trace equalization* is performed at the end of the pre-processing sequence to compensate for amplitude loss by geometrical spreading and attenuation. This is done either by TAR (True Amplitude Recovery) or by AGC (Automatic Gain Control). In both cases the equalization is done by the same operator for all three components, to conserve the polarisation information.

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

The effect of the preconditioning scheme is exemplified on the Z-component data from Figure 7. The result is presented in Figure 10.

![Figure 10. Z-component, preprocessed data from Kuhmo-Romuaara borehole KR2, shot point L22.](image_url)
The sequence of preconditioning operations did not make secondary wave fields to emerge convincingly from the non-coherent noise background. The reason is that the contrast of acoustic impedance of the fractures and fracture zones vs. the relatively competent crystalline rock is low. An alternative approach is to attempt to identify secondary wave fields by examining the coherency along time-depth paths corresponding to possibly real events. Fractures in crystalline rock appear as repetitions of similar patterns at various scales. Features with dimensions significantly larger than the mean wavelength would generate coherent events while features significantly smaller than the wavelength would produce an integrated null response. However, the network of fractures and joints with dimensions comparable to the wavelength is likely to produce non-coherent scattering. The non-coherent appearance is increased by the fractures having very diverse orientations, which causes even the fairly coherent events to intersect and interfere.

The task of retrieving secondary wave fields from seismic profiles in crystalline rocks can therefore be approached by either increasing their amplitude or by enhancing their coherency. Attempting to increase the amplitude by increasing the energy of the source may meet with only moderate success, as the scattering noise is shot-generated and therefore likely to increase proportionally with the coherent signal. Emphasising coherency is likely to be a more rewarding approach. Multi-channel filters based on the Image Point transform have been developed and are currently used for enhancing weak reflections and for separating interfering events.

The Image Point Transform

The IP (Image Point) transform is a version of the Radon transform and forms the core of the technique that we have developed for filtering crystalline rock VSP data. The Radon transforms have been applied to seismic data in many ways. In most cases a slant stack $\tau$-$p$-transform is used, the apparent velocity limits being varied according to the predicted travel times of reflections. Radon-transforms where stacking paths are not straight have also been used (Miller et al., 1987). Unlike with the $\phi$-$p$, with the IP transform the stacking is done 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. Other advantages of the IP transform include the efficient separation of interfering reflections and the possibility of using directly the IP transformed profiles as interpretation tools.

In a constant velocity medium, a reflection plane is completely defined by the mirror image of the source $S$ with respect to that plane, i.e. the Image Point, as shown in Figure 11. Therefore, one can generate any time-depth function associated with a planar reflector by computing the distance from the Image Point to each detector and divide by the velocity. Therefore, the IP transform turns the hyperbolic reflection patterns of the time-depth space into points in the IP space.
A cylindrical co-ordinate system \((i, \alpha, \phi)\) has been used in Figure 11, where the \(\alpha\)-axis lies along the borehole (assumed to be straight), the \(i\) axis contains the source \(S\) and the angle \(\phi\) is the azimuth relative to the \(\alpha\)-axis. All image sources with the same \((i, \alpha)\) coordinates produce identical time-depth functions because the distances from the image source to all receivers are independent of the relative azimuth \(\phi\). This property allows most of the computations to be performed in two dimensions. The third dimension is regained at a later stage, when the polarisation of the data is examined. It should be noted that the relative azimuth \(\phi\) in \((i, \alpha, \phi)\) is different from the dip direction \(\phi\) in \((D, \theta, \phi)\) from “The coverage of VSP surveys”. Both representations define uniquely a plane and can be derived from each other.

The time-depth function of a reflected event in a time-depth profile is

\[
t_r = \sqrt{\xi^2 + (z - \zeta)^2} / c = \sqrt{\xi^2 + \zeta^2 + z^2 - 2z\zeta} / c
\]  \( (1) \)
where $t_r$ is the travel time to the receiver placed at depth $z$, $c$ is the constant propagation velocity and $(\tilde{\xi}, \zeta)$ are the co-ordinates of the Image Source.

Equation (1) becomes

$$t_r = \sqrt{\rho^2 + z^2 - 2z\tilde{\xi}} / c$$

(2)

by replacing the variable $\hat{\rho}$ with

$$\rho = \sqrt{\tilde{\xi}^2 + \zeta^2}$$

(3)

If the distance $\rho$ from the origin is used instead of the offset $\tilde{\xi}$, the transformed representation will not be stretched and easier to use as an interpretive tool. The travel time does not depend on the relative azimuth $\tilde{\alpha}$, i.e. the locus of possible image points forms a circle centred on the borehole.

The Image Point transformed profile $\Gamma(\tilde{n}, \alpha)$ is obtained by stacking in the time-depth profile $g(z, t)$ along paths corresponding to all $(\tilde{n}, \alpha)$ pairs within a selected domain $\tilde{n}_{\min} \leq \tilde{n} \leq \tilde{n}_{\max}, \alpha_{\min} \leq \alpha \leq \alpha_{\max}$, thus covering all possible positions and orientations that a reflecting plane may have:

$$\Gamma(\zeta, \rho) = \int_{z_{\min}}^{z_{\max}} dz \ g(z, t = t_r(\zeta, \rho; z))$$

(4)

where $t_r(\zeta, \rho; z)$ is the arrival time corresponding to the planar reflector specified by $\rho$ and $\zeta$, to the detector at depth $z$.

The inverse transform is constructed by integrating along each path that received the contribution of $g(z, t)$ in the direct transform:

$$g(z, t) = \frac{1}{2\pi e^{-i\tilde{\xi}}} \frac{\partial}{\partial \tilde{\xi}} \int_{\tilde{\xi}_{\min}}^{\tilde{\xi}_{\max}} d\tilde{\xi} \ Gamma(\tilde{\xi}, \rho = \rho_r(z, t; \zeta))$$

(5)

where

$$\rho_r = \sqrt{c^2 t^2 - z^2 + 2z\tilde{\xi}}$$

(6)

The Hilbert transform $H$ and the derivation with respect to time are used to restore the original signal shape, similarly as with the $\hat{\alpha}$-$p$ transform.

The envelope of the IP transformed $Z$-component profile from Figure 10 is presented in Figure 12. The triangular shape is due to the $(\rho, \alpha)$ representation, as $|\zeta| \leq \rho$.

One can notice the concentration of amplitude to certain regions of the IP space. Higher amplitudes in the IP space can be generated by higher amplitudes and/or higher coherency along the integration path. Both phenomena are indicative of the probable presence of a true reflector.
When the inverse transform is applied, one gets a time-depth profile where the coherent reflections are enhanced, with respect to the original profile. Non-coherent noise as well as coherent events corresponding to other wave types are suppressed because of their lack of coherency along the integration paths computed for \( c = 5850 \text{ m/s} \). The two-way transformed Z-component profile is presented in Figure 13. The disappearance of the S-conversion event (event A discussed in section “Preliminary examination of the data”) can be noted. Several up-going events appear, following the same trend as event B, along with other coherent patterns with different orientations.

Figure 12. The envelope of the IP transformed Z-component profile from Figure 10.
Figure 13. Two-way transformed Z-component profile. The original profile before the transform is presented in Figure 10. The envelope of the IP-space representation of the same profile is shown in Figure 12.

Non-linear enhancement of reflectors

The general filtering effect of the Image Point transform results from the use of the actual propagation velocity in the computation of the integral paths. The filtering effect can be increased by following a non-linear approach instead of the linear integral in the inverse transform. For example, the amplitudes along each stacking path can be ordered and the sum be performed only for a chosen subset. A less computationally demanding method is to compute the envelopes in the IP transformed space and weight the sum by the maximum of the envelope along each integration path. The optimum weight to be used with the filter depends on certain characteristics of the data and is to be decided upon on a case-by-case basis. Large weights of the envelope maxima would result in well defined but fewer events, the fainter reflections being filtered out along with the noise. Small weights would let through more events but the coherency would improve only slightly. A fairly safe procedure for preventing over-processing consists of randomly rearranging bits and parts of the IP transformed profile so that causal coherency is destroyed. The dummy profile is then run through the same processing scheme as the real profile. Coherent events seeming to emerge in the dummy profile indicate that the power of the filter must be turned down.

The method described above has been applied to enhance the coherency of the profile presented in Figure 13, the result being displayed in Figure 14. It can be noted
that event $B$ became overwhelmingly clear, while event $C$ was diminished. Other events seemingly parallel to $B$ also became clearer, together with several down-going events with opposite slopes. Note that wave fronts with low apparent velocities (in absolute value) would be reflected at nearly normal incidence. The relatively small offset of shot point L22 would make them semi-horizontal and appearing preponderantly in the Z-component. Event $E$ is interpreted as a secondary surface reflection of $B$ (were it a real reflection, the reflector would have to be above ground surface). The suppression of this kind of events shall be discussed in the following section.

Figure 14. Non-linear inverse of the Image Point transform presented in Figure 12

**Dip filtering in IP space**

The IP transform can also be used to enhance certain subsets of reflected events, e.g. by forming dip classes. The relative dip in the IP space is defined as $\zeta/p$. As noted in section “The Image Point transform”, the IP transform turns the time-depth hyperbolic reflection patterns into isolated vicinities and reflectors with different orientations are imaged in different regions of the transform space. Filtering is achieved by muting selected areas of the IP transform space. For example, secondary surface reflections, like event $E$ from Figure 8, have their image points above the $\zeta = 0$ axis (negative $\zeta$ values) and can be suppressed by blanking the region $\zeta < 0$. This dip-filtered version of the profile in Figure 14 is presented in Figure 15.
Figure 15. Dip-filtered version of the profile in Figure 14 where all events with $\zeta < 0$ in the IP representation from Figure 12 were muted.

Another example of simple IP filtering is the suppression of the up-going semi-horizontal events, thus allowing a clearer view of the inclined features. The profile from Figure 16 has been obtained for $0 < \zeta/\rho < 0.71$. More elaborate filters, e.g. with folded boundaries can be applied with the same easiness to emphasise or suppress individual or classes of reflection events. The intuitive representation offered by the IP transform representation greatly helps in designing the filters.
Figure 16. Dip-filtered version of the profile in Figure 14 where all events with 0 < ζ/ρ < 0.71 in the IP representation from Figure 12 were muted.

Polarisation analysis in IP Space

The (ρ, ζ) co-ordinates of the Image Point space define two of the three parameters needed to determine the 3-D position of a reflector (as noted in section “The Image Point transform”, the azimuth ō relative to the ζ-axis plays no role in the IP transform).

A straightforward method to estimate the azimuth is to rotate incrementally the R and T components and observe at which angle reflection patterns disappear. This angle would give the perpendicular direction to the actual signal polarisation. A more elaborate technique relies on solving the eigenvector problem to determine the direction and the degree of polarisation in a time window /n/. A filtering effect is achieved by projecting the instantaneous particle motion at the time t on the average polarisation direction determined in a time window centred on t. Multiplying the projected components, with $L(t) = 1 - \left(\frac{\lambda_2(t)}{\lambda_1(t)}\right)^2$, where $\lambda_1(t)$ and $\lambda_2(t)$ are the largest and the second largest eigenvalues determined in the respective window, would enhance the polarised events.

A problem encountered when attempting to apply polarisation analysis to crystalline rock VSP data is the intermingling and criss-crossing of events arriving from diverse directions. In fact, there would be very few, if any, time windows in a time-depth profile where a reflected arrival is unaffected by interference with other arrivals and noise. The result is that the polarisation estimated in the time-depth space is, generally, extremely unstable. Polarisation analysis performed in Image Point space largely avoids such problems because the hyperbolic patterns from the time-
depth profiles collapse to separate vicinities in IP space. However, the polarisation is not conserved if non-linear filtering has been performed independently on each component, as presented in section “Non-linear enhancement of reflectors”. If non-linear filtering is to be applied, it has to be done after polarisation analysis. Dip filtering applied simultaneously to the three components does not alter their relative amplitudes and can therefore be applied before polarisation analysis.

Figures 17 to 19 are polarisation-filtered Z-, R- and T-component profiles. The polarisation filtering was performed in the IP space by solving the eigenvector problem in a window sliding along ρ and multiplying the projected components with $L(\rho) = 1 - (\lambda_2(\rho) / \lambda_1(\rho))^2$. The linear inverse transform, described in section “The Image Space transform”, was applied and dip filtering was performed to suppress the surface multiples.

Figure 17. Polarisation-filtered Z-component profile.
Figure 18. Polarisation-filtered R-component profile.

Figure 19. Polarisation-filtered T-component profile.
Figures 15 and 17 depict the results of two filtering techniques, one based on non-linear coherency enhancement, the other on polarization. Both figures present the Z-component. The non-linear filtered profile from Figure 15 displays a higher level of continuity of the stronger events, at the expense of the weaker events. The polarisation filtered profile from Figure 17 appears as less resolved, but the ratio between strong and weak events is better preserved. Furthermore, the amplitude ratio of the three components is also conserved by the polarisation filter, which allows reflections arriving from specific azimuths to be enhanced by looking for their maximum amplitude while rotating the components. However, the amplitudes are relatively insensitive to simple rotation, e.g. at $+/- 30^\circ$ off-target the amplitude of an event would still be 0.87 of its maximum. It is therefore difficult to estimate with sufficient precision the azimuth where a certain event would attain its maximum. To avoid this difficulty, azimuth slices are taken in the IP space and back-transformed independently to the time-depth space.

To demonstrate the merit of the polarisation filtering, we shall focus on a reflection event difficult to identify due to its low amplitude and interference with stronger events. Such a barely visible event is marked as $F$ in Figure 18 (the R-component) and in Figure 19 (the T-component). The azimuth slicing procedure is exemplified in Figures 20 to 24.

The horizontal components were rotated with a $10^\circ$ increment and a cosine bell was applied with an aperture of $+/- 30^\circ$. The amplitude of events arriving from other azimuths, as determined by polarisation analysis, was reduced to 20%. One can notice that event $F$ displays a maximum amplitude at $150^\circ$, which demonstrates that the azimuth can be estimated at least with a precision of $+/- 10^\circ$.

The eigenvector approach does not resolve the polarisation of events arriving from azimuths differing by $\pi$. With VSP, a relatively simple solution exists to this problem, as the shot points are generally placed above the receivers and the sign of the cross-correlation with the Z-component profile will differentiate between opposite azimuths.
Figure 20. Polarisation-filtered profile. Azimuth 130°.

Figure 21. Polarisation-filtered profile. Azimuth 140°.
Figure 22. Polarisation-filtered profile. Azimuth 150º.

Figure 23. Polarisation-filtered profile. Azimuth 160º.
COMBINING THE INFORMATION OF SEVERAL SHOT POINTS

The azimuth estimate obtained for each reflector by polarisation analysis can be further improved by comparing profiles from several shot points. To fully determine position and orientation of a plane, one needs three independent parameters, e.g. the \( (D, \theta, \phi) \) triplet from section “The coverage of VSP surveys”. One plane reflector must therefore be identified in three non-coplanar profiles. Theoretically, seven shot points, forming non collinear triplets, are needed to insure that a plane reflector does not fall in the blind zone of at least three profiles. The number of shot points can be reduced to five, if the case of a shot point being contained in a reflector plane is dismissed as improbable. However, a survey with a reduced number of shot-points may fall short of correctly determining the geometry of the site because one has also to insure that the three determinations refer in deed to the same plane, which becomes increasingly difficult with the increasing number of reflectors. A practical approach to resolving the site geometry by multi-offset multi-azimuth VSP relies on the simultaneous interactive fitting among several profiles.

The procedure consists of fitting a time-depth function with an observed reflector e.g. in profile \( P_1 \). As discussed in section “The Image Point transform”, each time-depth function is paired with a \((\rho, \zeta)\) point in the IP space, which in turn determines the corresponding reflection plane up to the relative azimuth \( \phi \). A guess
value for \( \varphi \) is prompted by polarisation analysis, thus defining the reflector plane as \((r, \zeta, \varphi)\). Subsequently, time-depth functions are derived for profiles \( P_1, P_2, \ldots, P_n \). Note that the co-ordinates \((r, \zeta, \varphi)\) are relative to the shot point and the transfer between profiles must be done through a more general representation, e.g. \((D, \theta, \phi)\) from section “The coverage of VSP surveys”. The azimuth \( \varphi \) is then gradually modified, while examining the simultaneous fit between the time-depth functions and candidate reflection events in all profiles. If recognised as such, converted \((P\text{-to-}SV)\) events are also used. Conversions have a different variation with dip and azimuth than \(P\)-wave reflections and therefore add additional information.

The structures presented in Figure 25 were inferred by the procedure outlined above. The reflectors were classified in three categories: certain (I), probable (II) and possible (III). Three class (I) features were found, one intersecting the borehole at 425 m, the second intersecting the borehole at 1015 m and the third intersecting the extension of the borehole at 1380 m. The dips of all three are between 35° and 45° and the dip directions between 240° and 260°. Reflectors with slightly different orientations were observed at roughly the same depths, interpreted as sub-structures of the same main features. Events belonging to this set were discussed in sections “Preliminary examination of the data”, “Data processing”, “The Image Point transform”, “Non-linear enhancement of reflectors” and “Dip filtering in IP space”. Steeply dipping class (II) events were also identified, e.g. the ones examined in “Polarisation analysis in IP space”.

In Figure 25 reflectors seem to converge towards the borehole. This is an effect of the limited coverage of the VSP layout, as explained in section “The coverage of VSP surveys”. The limited coverage problem is avoided by conducting surveys in several boreholes. The interpretation is done by a simultaneous fitting procedure, similar to the one presented above for multiple offset profiles measured in the same hole. A site area of the order of 10 km² is usually covered with five to nine boreholes, arranged so that groups of 3 – 4 boreholes fall roughly in the same plane. The average distance between the boreholes is 500 metres.

The example from Figure 26 is from Eurajoki-Olkiluoto (Figure 2) (Anttila et al., 1999a) and combines the results from two deep holes, KR4 and KR2 and two shallow boreholes, KR8 and KR6 (Cosma et al., 1996). The measurements were done during 1995. The deep holes were measured at 5.0 m intervals to 900 – 1000 m depth. The shallow holes were drilled to a depth of 300 m and were mainly used to provide a direct validation of the orientation of the structures predicted by the long holes. Seven shot points were used for each long hole and six for the short ones.

Two sets of reflectors dominate the site, one dipping South-Southeast with dips 20°-30° and another dipping more to Southeast with dips from 45° to 60°. A set dipping in the opposite direction appears at shallow depths in the proximity of KR8 but has not been detected through the rest of the site. Five seismic structures meet the class I criteria, all belonging to one of the two main sets. Their mean orientations are outlined in Figure 26. Based on the independent analysis of the data for each borehole, the other reflectors presented in Figure 26 were interpreted as class II, but their consistency with the general model tends to increase the reliability of the interpretation.
We can conclude that the prediction of the site structures by VSP finds a strong support in the continuity of features inferred independently from different surveys. However, the final proof of relevance of the VSP results has been given by the good correlation of the more pronounced seismic reflectors with the hydrogeologically significant zones and the geochemical models.

A 3-D model of the total salt content of the ground water at the Olkiluoto-Eurajoki site has been built as part of the detailed investigation stage (Posiva Oy, 1996). The model has been based on the electric resistivity of the rock and ground water, inferred from electric and electromagnetic surveys, the saline content of the ground water measured on water samples and the porosity of the rock determined by logging.

Beneath the meteoric and sweet water layer, three regions were identified, with increasing TDS (Total Dissolved Solids) content. A section roughly following boreholes KR8, KR4, KR2 and KR6 is presented in Figure 27. The depth of the layers varies strongly through the section and the general trend follows the direction of the fracture zones. The positions and orientations of the rock features superposed on the salinity model in Figure 27 have been determined mainly by VSP and cross-checked by examining their match with zones of increased fracturing observed in boreholes across the site. The fracture zones controlling the salinity model appear to be the more extensive and continuous seismic reflectors from Figure 26.

A direct validation of the model inferred by VSP has been obtained from pumping tests undertaken in the open holes KR7 and KR8 (Posiva Oy, 1996). Good hydraulic connections have been observed between the deeper part of KR8 and the upper part of KR4 and between the upper part of KR7 and KR4 at a depth of 350-400 m, as shown in Figure 28. The same directional trend continues towards KR2 and KR6, with a downwards step, as predicted by the VSP model of Figure 26. A deeper transmissive feature has also been identified, with a slightly larger dip, again, as predicted by VSP. The deepest features presented in Figure 26 lie beneath the bottom of the boreholes and thus cannot be validated directly by hydraulic measurements.

Figures 27 and 28 illustrate that the fracture model inferred by the VSP surveys performed, as part of the Finnish Site Investigation Programme for the Final Disposal of Spent Nuclear Fuel, is relevant for predicting the possible paths of radionuclide migration within the ground water and the geochemical conditions in the vicinity of a planned repository.
Figure 25.

Figure 26.
Multi-azimuth VSP for Rock Characterisation

Figure 27

Figure 28.
DISCUSSION AND CONCLUSIONS

Based on the large number of surveys performed and on the ample direct and indirect verifications, the multi-azimuth multi-offset VSP can be considered an effective method for determining the positions and orientations of fracture zones in crystalline rock. The main difficulties to overcome have been the low contrast of acoustic impedance of the fractures and fracture zones vs. the relatively competent crystalline rock and the diversity of the orientations of the targets. Conversely, the task has been alleviated by the nearly constant seismic velocity throughout the rockmass and by the planarity of the targets. Moreover, the VSP method has been found effective for identifying and locating those features that control the groundwater flow and for predicting the distribution of the groundwater salinity. The main objectives of the VSP surveys as part of the Finnish Site Investigation Programme for the Final Disposal of Spent Nuclear Fuel have thus been fulfilled.

The VSP layout provides a favourable geometry for mapping both steeply and gently dipping rock features. The main drawback is the existence of blind zones that can prevent the detection of significant features in the very vicinity of the survey set-up. The extent and shape of the blind zones depend on the layout design but also on the feature geometry itself. The survey layout was optimised by performing analyses of the coverage obtainable with various layout combinations. The coverage analysis provided the means for choosing multi-borehole layout combinations that cover the site volume as evenly as possible. The interpretation was then done by a simultaneous fitting procedure of all data collected. The final result has been a comprehensive geometrical model of the fracture zones throughout the site.

The first stage of processing consisted of data enhancement procedures commonly used with VSP in sedimentary formations. Several well-established techniques, e.g. corridor stacking, f-k and $\delta$-p filtering were dropped as unsuitable for enhancing reflectors with a wide diversity of orientations. In general, common VSP processing routines were deemed insufficient for mapping fracture zones in crystalline rock, as they did not succeed in making reflected wave fields to emerge convincingly from the noise background.

New tools and methodologies had to be developed. A 3-component multi-level receiver chain was built to meet both the needs of the processing/interpretation schemes in terms frequency and directional sensitivity and the practical requirements of operation in slim deep holes, a small survey crew and deployment locations with difficult access. High frequency data can also be obtained with borehole hydrophone strings, which are also easy to deploy and provide a higher data production rate than 3-component clamped geophones. The initial surveys of the site characterisation programme were performed with hydrophones. However, besides the lack of directional sensitivity, which deprived the analyses of the possibility of using polarisation as a filtering and interpretative tool, the hydrophone data contained disturbingly high amounts of tube waves. The low velocity of the tube waves required small receiver intervals, to avoid spatial aliasing, which invalidated the assumption of
high productivity. The quasi-total absence of tube waves from the data presented here is largely due to the clamped 3-component receivers.

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 transform, the stacking is done along the time-depth functions corresponding to wave fields travelling with a given velocity. The IP transform turns the hyperbolic reflection patterns into points in the IP space. Non-coherent noise and coherent events corresponding to wave types travelling with other velocities are suppressed, which produces a filtering effect even when the two-way linear transform is applied. The filtering effect can be increased by following a non-linear approach instead of the linear integral. The IP transform can also be used to enhance certain 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 accumulates in closed vicinities, greatly helps in designing the filters.

The main reason for using 3 component receivers is the possibility of performing polarisation analysis to determine the azimuth of the reflectors. A problem encountered when attempting to apply polarisation analysis to crystalline rock data is the intermingling and criss-crossing of events arriving from diverse directions. Polarisation analysis applied in IP space largely avoids such problems, allowing the reflector azimuths to be estimated with a precision of $\pm 10^\circ$. The azimuth estimates are further improved by simultaneous interactive fitting among several profiles.

The continuity and consistency of the features inferred independently from several VSP constitutes an internal verification of the validity of the model. However, the final proof of relevance of the VSP results is given by the good correlation of the more pronounced seismic reflectors with the hydrogeological and the geochemical models.

REFERENCES