REFLECTION SEISMIC METHODS APPLIED TO LOCATING FRACTURE ZONES IN CRYSTALLINE ROCK

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Abstract

The reflection seismic method is a potentially powerful tool for identifying and localising fracture zones in crystalline rock if used properly. Borehole sonic logs across fracture zones show that they have reduced P-wave velocities compared to the surrounding in-tact rock. Diagnostically important S-wave velocity log information across the fracture zones is generally lacking. Generation of synthetic reflection seismic data and subsequent processing of these data show that structures dipping up towards 70° degrees from horizontal can be reliably imaged using surface seismic methods. Two real case studies where seismic reflection methods have been used to image fracture zones in crystalline rock are presented.

Two examples using reflection seismics are presented. The first is from the 5354 m deep SG-4 borehole in the Middle Urals, Russia where strong seismic reflectors dipping from 25° to 50° are observed on surface seismic reflection data crossing over the borehole. On vertical seismic profile (VSP) data acquired in the borehole, the observed P-wave reflectivity is weak from these zones, however, strong converted P to S waves are observed. This can be explained by the source of the reflectors being fracture zones with a high P wave to S wave velocity ratio compared to the surrounding rock resulting in a high dependence on the angle of incidence for the reflection coefficient. A high P wave to S wave velocity ratio (high Poisson's ratio) is to be expected in fluid filled fractured rock.

The second case is from Ävrö, SE Sweden, where two 1 km long crossing high resolution seismic reflection lines were acquired in October 1996. An E-W line was shot with 5 m geophone and shotpoint spacing and a N-S one with 10 m geophone and shotpoint spacing. An explosive source with a charge size of 100 grams was used along both lines. The data clearly image three major dipping reflectors in the upper 200 ms (600 m). The dipping ones (to the South, East and Northwest) intersect or project to the surface at or close to where surface mapped fracture zones exist. The South dipping reflector correlates with the top of a heavily fractured interval observed in a borehole (KAV01) at about 400 m. 3D effects are clearly apparent in the data and only where the profiles cross can the true orientation of the reflecting events be determined. To properly orient and locate all events observed on the lines requires acquisition of 3D data.

1 Introduction

Reflection seismics have served as a useful tool for imaging and mapping of fracture zones in crystalline rock along 2D lines in nuclear waste disposal studies. (Carswell and Moon 1989; Juhlin 1995; Mair and Green 1981). This also applies to mineral exploration where the targets have been the general structural setting of the ore deposits or the ores themselves (Juhlin et al., 1991; Milkereit et al., 1996; Milkereit et al., 1994; Milkereit et al., 1992; Spencer et al., 1993). Although the primary targets on many of these lines can be approximated as 2D structures it has been evident that there exists numerous out of the plane reflections in the acquired data. This is to be expected in crystalline rock which has been subjected to several phases of deformation and/or metamorphism. In addition, strong P- to S-wave conversions may be expected from fracture zones if they contain significant amounts of fluids. These converted S-waves and the variation of amplitude with angle of incidence for the P-wave reflection coefficient can cause further problems in processing and interpreting seismic reflection data. However, the potential for better characterising the reflectors, and hence the fracture zones, is also possible if both P-wave and S-wave data can be acquired, processed and interpreted properly.

A major concern in the localisation of a nuclear waste site is the presence of hydraulically sub-horizontal fracture zones since these may have a major impact on water circulation patterns once waste has been deployed underground. These sub-horizontal to gently dipping fracture zones are difficult to detect using geological mapping methods since they generally do not intersect the surface in the area being mapped. In addition, drilling and hydraulic testing often give data which are difficult to interpret resulting in that borehole to borehole correlations may be poor. Reflection seismics provides a tool for integrating surface studies with borehole results in locating sub-horizontal to gently dipping fracture zones, some which may be hydraulically conductive. Reflection seismics can also constrain the geometry at depth of more steeply dipping known fracture zones which intersect the surface. Since there are numerous factors to consider in choosing a nuclear waste disposal site it is important that the seismic image obtained is as accurate as possible. The presence of sub-horizontal events on a seismic line need to be confirmed as truly being sub-horizontal by shooting either several cross lines or, preferably, by acquiring 3D data.

This paper briefly reviews the seismic reflection method, discusses the need for 3D data, and shows how the amplitude of P- and S-waves may vary with angle of incidence. Two examples of real data are presented, one where P- to S- wave conversions are shown to be important and the other where 3D effects are clearly evident in 2D data.

2 Seismic reflection method

Seismic data are generally acquired by exciting a source (explosive, vibrator, etc.) on the surface or in a borehole and recording the waves emanating from this source on an array of receivers (geophones, hydrophones, etc.). Ideally, numerous sources are excited and the acquired data are processed in such a manner so that a subsurface image is obtained that can be interpreted. The method has been, and is, applied with great success in the petroleum industry on sedimentary rock based on the assumptions that interfaces are sub-horizontal and that only acoustic waves are propagating (no shear waves). In crystalline rock these assumptions are often not valid since some of the strongest variations in rock properties may be laterally and shear waves are often generated at interfaces. Even simple models may generate complex seismograms (Figure 2-1). Traditional processing (CDP sort, NMO, stack) of such data will give an image which is incorrect. However, if more advanced processing is applied (pre-stack migration and stack) then an image which resembles the subsurface may be obtained (Figure 2-2).

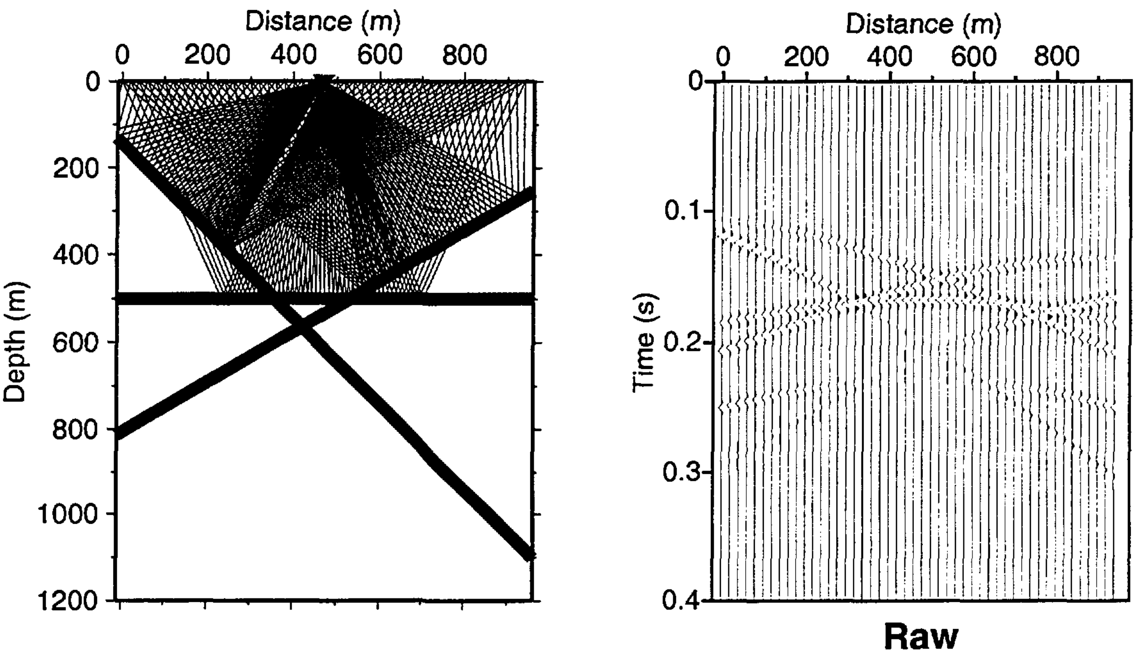

Figure 2-1 Ray paths and resulting synthetic seismogram. The background P-wave velocity and Poisson's ratio are 6000 m/s and 1.73, respectively. The reflectors are modelled as fracture zones having a P-wave velocity of 5000 m/s and a Poisson's ratio of 2.

Although the migrated image in Figure 2-2 resembles the sub-surface there are some important differences. First, the dipping reflectors are not necessarily imaged below the points where the shots were fired, but are observed most clearly where the interfaces are at right angles to the source. This is because reflected waves obey Fermat's principle of taking the ray path which gives the shortest time of propagation. In order to image steeply dipping interfaces then requires that long profiles are shot even if the area of interest is relatively small. Secondly, there are artefacts in the stacked section between 600 m to 800m depth on the right hand side of the migrated image (Figure 2-2). These are P- to S- converted wave reflections which are not handled properly even when pre-stack migration is applied. In principle it is possible to migrate these waves correctly, but on real data it is difficult to discriminate between which waves are which when only one component of motion is recorded. Finally, note that exactly the same image would have been obtained if the subsurface geometry was rotated at an angle perpendicular to the direction of profile. That is, from 2D lines it is not possible to determine from what direction the reflected events are arriving at, a sub-horizontal event could just as well originate from a near-vertical interface from out of the plane of the profile.

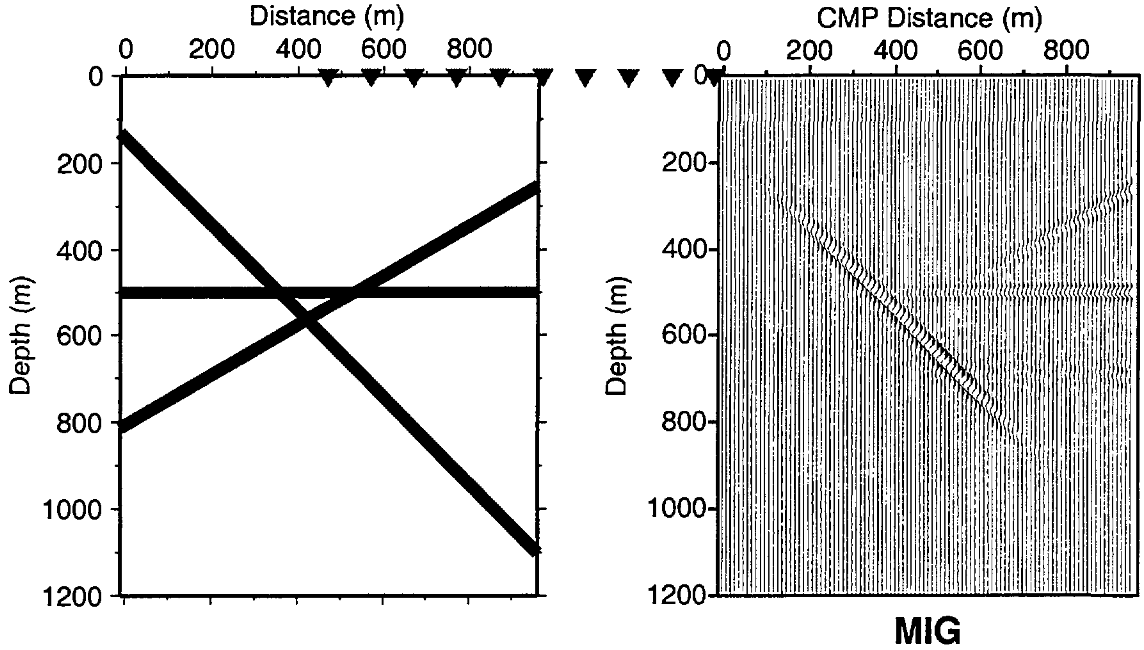

Figure 2-2 *Reflector model as in Figure 2-1 and the results from pre-stack migration and stacking 10 shots to obtain the image on the left. The position of the shots used in the migration are shown by inverted triangles along the top of the section.*

3 Reflection coefficients

In elastic media the strength of a reflected wave will be dependent upon the angle of incidence of the incident wave. In addition, a P-wave which impinges on an interface at non-normal angles of incidence will give rise to reflected S-waves as well as P-waves. The strength of these reflected waves (the reflection coefficients) are dependent upon the P-wave velocity (Vp), the S-wave velocity (Vs), and the density (ρ) of the media above and below the interface. If the reflection is due to lithological contrasts in the two media there will be a tendency for the P-wave energy to increase with increasing angle of incidence (Figure 3-1) and for the P- to S-wave energy to gradually increase in magnitude. In contrast, if the reflections is from a fluid filled fracture zone the P-energy will be expected to decrease with angle of incidence and the P- to S-wave energy to increase rapidly (Figure 3-2). The greater the Vp/Vs ratio in the fracture zone the more pronounced this effect will be.

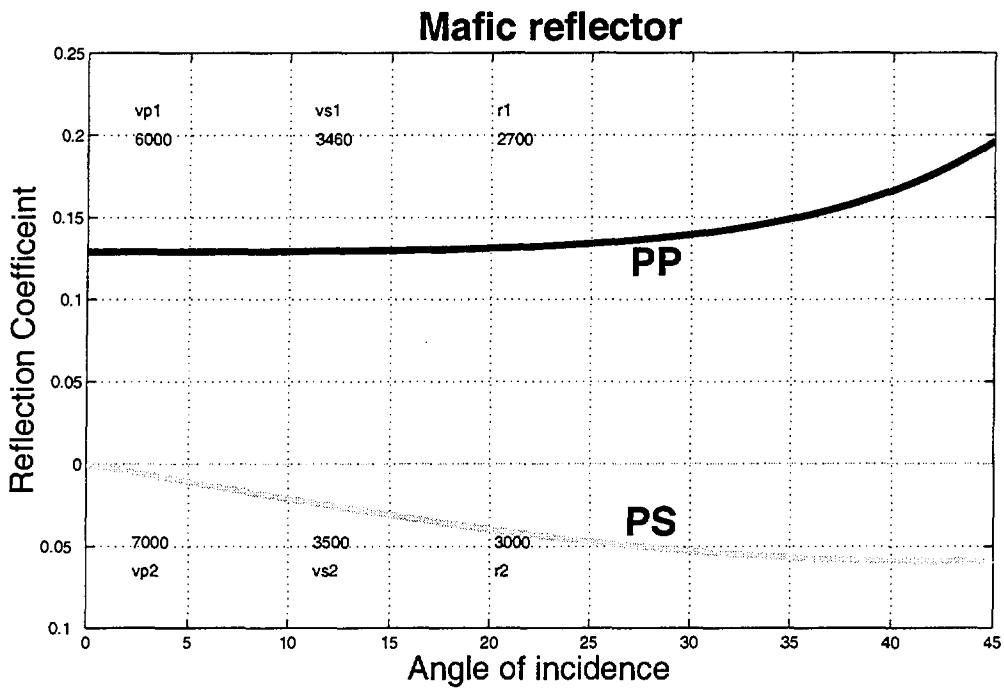

Figure 3-1 Reflection coefficient vs. angle of incidence for a granitic/mafic interface.

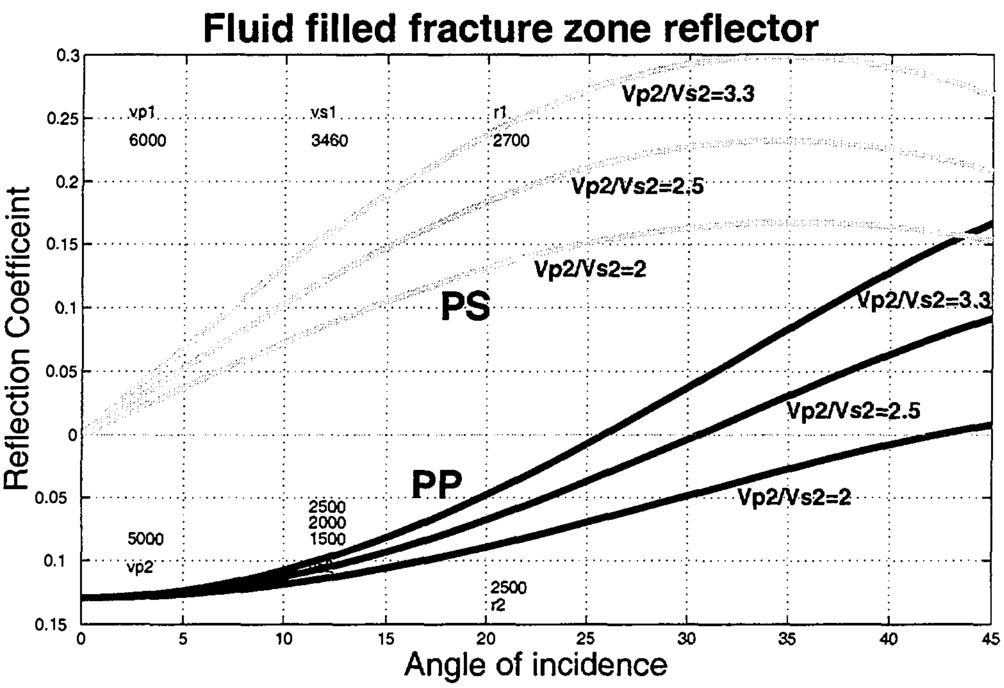

Figure 3-2 Reflection coefficient vs. angle of incidence for a granitic in-tact/fracture zone interface.

4 SG-4 example

4.1 Data acquisition

The SG-4 borehole is located in the Tagil Synform of the Middle Urals in Russia and had reached a depth of 5354 m as of August 1995. The final depth is targeted to 15000 m. The penetrated rocks are of island-arc origin and have been proven to contain clear strong reflectors (Juhlin et al., 1997). A particularly strong reflector is imaged at about 3000 m depth close to where a seismic line crosses the SG-4 borehole. The geological structure strikes mainly north-south and surface observations along with seismic data indicate that lithological boundaries and thrust faults dip at about 30-50° to the east. However, near-vertical fracture zones cut at angles across the geological strike. Vertical seismic profile (VSP) data have been acquired to image the surface seismic reflectors and determine the source of reflectivity. Data were acquired in two campaigns in the cased part of the borehole within the depth interval 520 m to 3940 m with shots offset from the wellhead by as much as 1840 m. The presence of dipping geological structure and sub-vertical faults is consistent with the complex wavefields recorded on the VSP data.

4.2 Data processing and interpretation

Downgoing waves are strong in VSP data and generally need to be removed before clear upoing or reflected waves can be observed. On shots offset greater than 400 m to the north of the wellhead a clear upoing reflected wave is observed (Figure 4-1). Processing steps were kept to a minimum and include bandpass filtering (10-20-60-90 Hz), removal of downgoing P-waves, removal of downgoing S-waves and coherency filtering. Other shots record reflected waves from steep interfaces (dips up 85°).

The apparent velocity of the reflected wave in Figure 4-1 is too low for it to be a P-wave which implies that it must be either a reflected S-wave or a converted P- to S-wave reflected wave. Synthetic data were generated to match the traveltimes and amplitudes of the reflected event (Figure 4-2). Excellent traveltime agreement between the synthetic and real data is achieved for both the reflected P-wave arrival (the earlier event arriving at 0.65 s at 1120 m and at 0.56 s at 2120 m) and the reflected S-wave arrival (the later event arriving at 0.9 s at 1120 m and at 0.61 s at 2120 m). The strong event on the N-S component on the real data which arrives about 0.1 s after the first reflected S-wave is probably a multiply reflected wave. It is difficult to judge the amplitude agreement of the reflected waves since in the real data there are numerous additional reflected waves which interfere with the main events. However, the qualitative amplitude agreement is good. If the reflector is modelled as a mafic interface then the traveltime agreement is the same since no changes were made in layer 1, however, the qualitative amplitude agreement is poorer. In addition, polarity studies indicate the reflected S-wave to be from a negative impedance interface. These observations strongly suggest that the reflected arrivals are from a fracture zone.

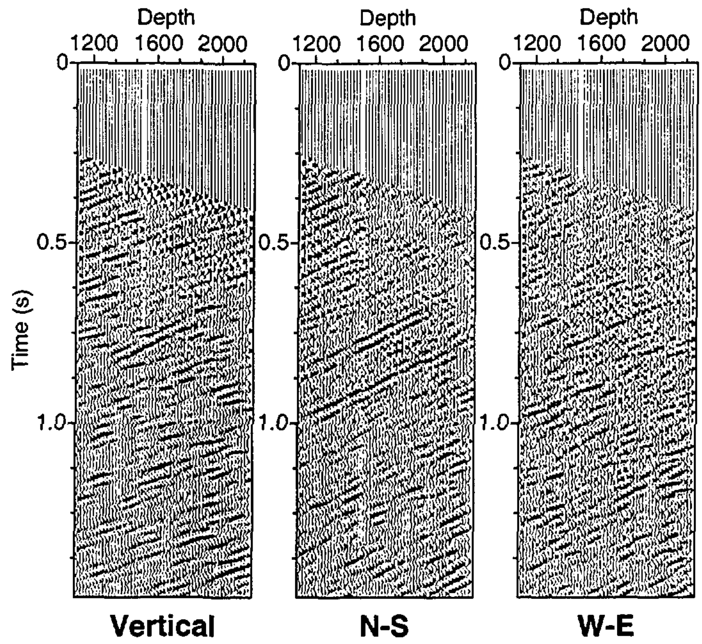

Figure 4-1 *Three component data from the SG-4 borehole showing a clear dipping P- to S- wave converted reflection. The source was offset from the wellhead by 31 m to the east and 839 m to the north.*

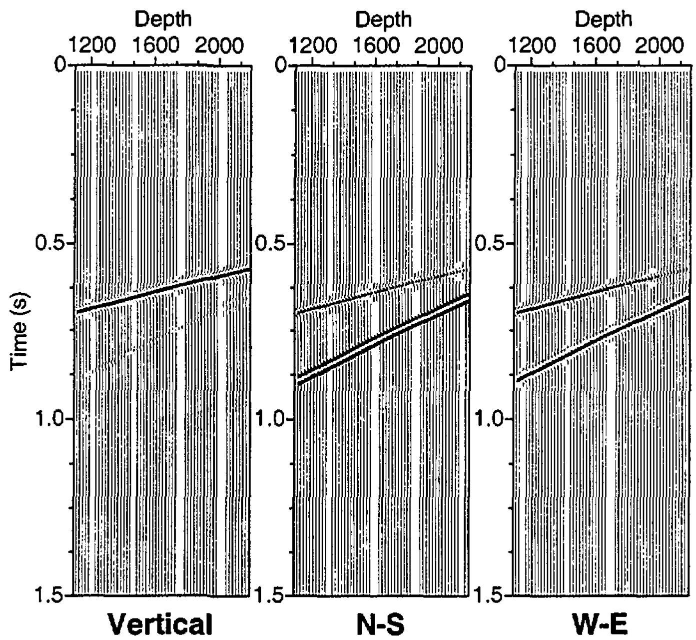

Figure 4-2 *Synthetic data from simple modelling of the P- to S-wave converted event in Figure 4-1. The model consists of an interface dipping 30° to the east, striking N-S, and intersecting the borehole at 2900 m. The elastic parameters were Vp=6100 m/s, Vs=3500 m/s, ρ=2700 kg/m³ for layer 1 and Vp=5500 m/s, Vs=2500 m/s, ρ=2500 kg/m³ for layer 2.*

5 Ävrö example

5.1 Data acquisition

As part of the Swedish Nuclear Waste Management Companay's (SKB) research program, reflection seismic measurements were carried out on the island of Ävrö in South-eastern Sweden. Ävrö island is situated just to the Southeast of Äspö island, the location of the Äspö Hard Rock Laboratory (Hammarstöm and Olsson, 1996). The main objectives of the seismic measurements were (1) to test the method for future site investigations in other areas (2) to map a known hydraulically conductive fracture zone that intersects a borehole between 400 and 600 m measured depth and (3) to add to the database of reflection seismic studies on the shallow crystalline crust in Sweden. In order to obtain 3D control of the known fracture zone two ~1 km long crossing high resolution seismic lines were shot (Juhlin and Palm, 1997). The W-E one (Line 1) had a station spacing of 5 m on average and the N-S one (Line 2) had a station spacing of 10 m on average (Figure 5-1). The profiles cross one another close to the ~740 m deep borehole KAV01. Shot and geophone points were placed, to the greatest extent possible, on bedrock. Drillers of shotholes were instructed to drill at the closest suitable location to a staked point where bedrock outcrop was present, but not further than 1 m parallel and 2 m perpendicular to the profile from the staked point. If no bedrock was found within this area the hole was drilled at the staked point. Geophone holes (8 mm diameter, 50 mm deep) were later drilled following the same instructions, but were not necessarily drilled close to the shotpoints. Weather conditions were excellent during the one week period it took to acquire the data.

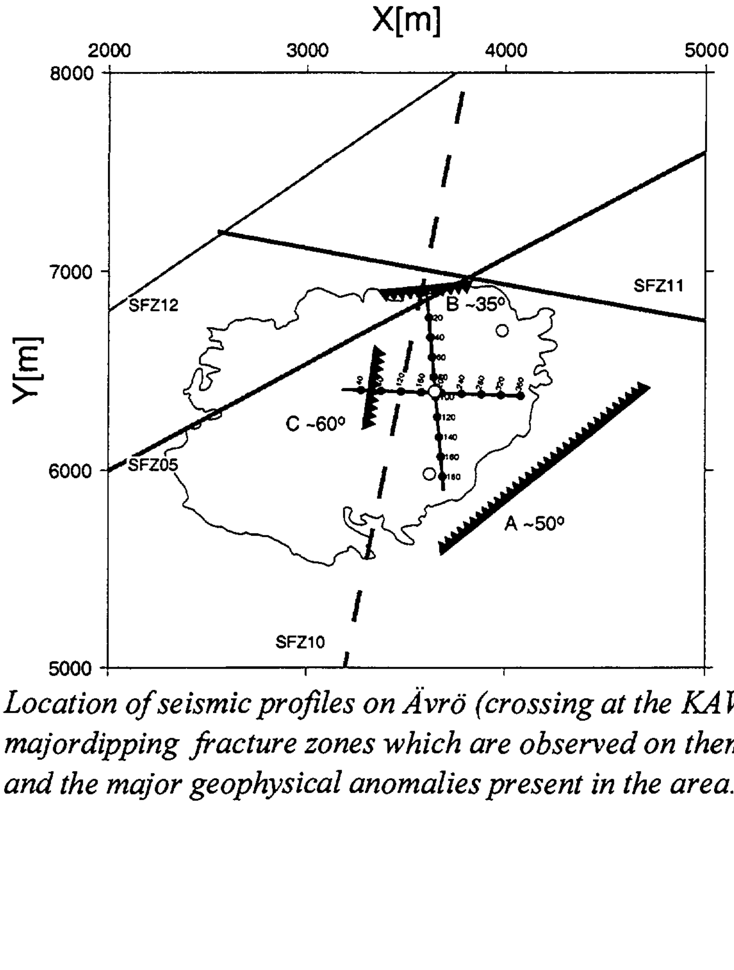

Figure 5-1 Location of seismic profiles on Ävrö (crossing at the KAV01 borehole), the majordipping fracture zones which are observed on them (A, B and C) and the major geophysical anomalies present in the area.

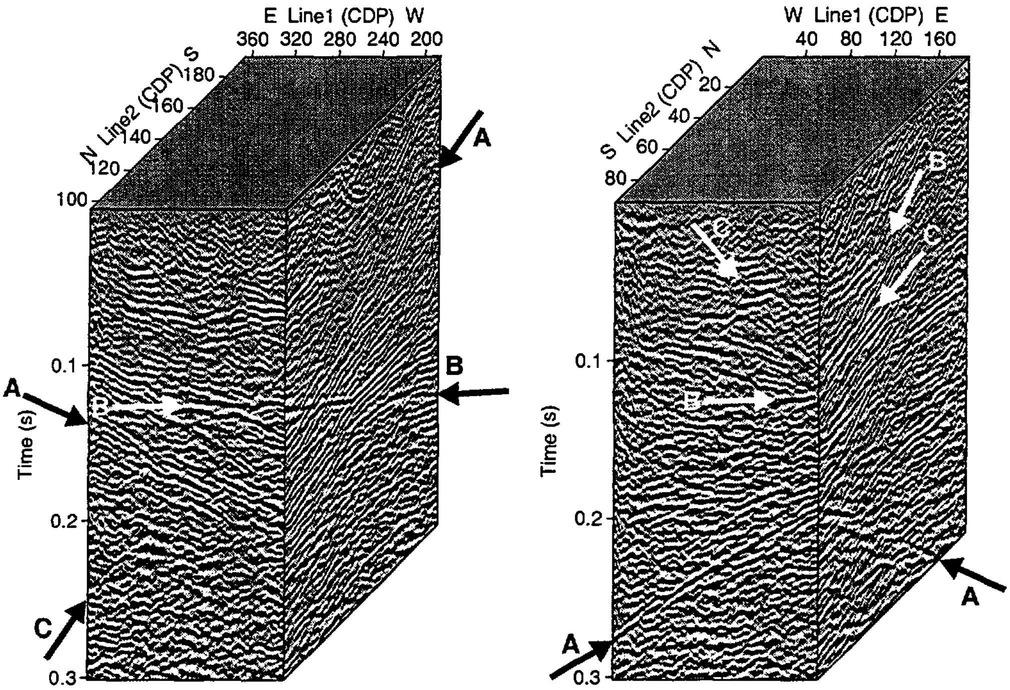

Figure 5-2 N-S and W-E seismic profiles merged where they cross and viewed from the NW (left) and SE (right).

5.2 Data processing and interpretation

Standard processing was applied to the two seismic lines including DMO. After merging the two lines where they cross (Figure 5-2) several clear reflections are observed (labelled A, B and C). Event A dips at an angle to both profiles and strikes about 60° to Line 2. It projects to the surface along the Southeast coast of Ävrö. Event B on Line 1 appears to be sub-horizontal, but has a true dip to the South and projects to the surface close to CDP 1 on Line 2. Event C dips steeply to the East and projects to the surface close to CDP 60 on Line 1. Other sub-horizontal events away from the intersection point may also come from out of the plane, but this cannot be proven without further data acquisition.

Events A, B and C on Lines 1 and 2 can be projected to the surface (Figure 5-1). Their strike and dip are constrained by their apparent dip on Lines 1 and 2. Reflector A projects to the surface Southeast of Ävrö and dips ~50° to the Northwest. It is observed on both seismic lines, however, the KAV01 borehole does not penetrate it. If the hole were to be deepened, reflector A would be expected to be penetrated at about 1000 m depth. Reflectors B and C strike approximately perpendicular to Line 2 and Line 1, respectively, and can, therefore, be subjected to 2D migration. After migration, reflector B dips at about 35° to the South and the top of it intersects the borehole at about 400 m. Reflector C is much steeper, about 60°, and the point where it intersects the borehole is not clearly imaged. However, the projection of the reflector downwards implies the top of it intersects the borehole somewhat below 500 m. The hydraulic conductivity in borehole KAV01 increases significantly between 400 and 600 m. It is probable that this increase is due in part to reflectors B and C intersecting the borehole in this depth interval.

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