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# Shear-wave splitting in shallow clays observed in a multi-offset and walk-around VSP

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## Abstract

Vertical seismic profiling using shear waves showed seismic anisotropy in the shallow 'Pot-Clay' sequence in the northern parts of The Netherlands.

Shear-wave splitting, a key identifier for anisotropy, was observed at various depth using a multi-offset/multi-azimuth data acquisition technique. For the first time in such investigations, a three-component geophone mounted in a penetration cone was used. This technique resulted in improved data quality.

A hodogram analysis of the shear wave data showed that fissures with strike and dip as specified by geological and geotechnical data cannot explain all observations of shear-wave splitting.

## Introduction

A shear wave entering an anisotropic medium, generally, splits up into a fast and a slow component. This phenomenon, called 'shear-wave splitting', is a key identifier of seismic anisotropy (Crampin 1985). Shear-wave splitting, however, not only identifies anisotropy, it may also be used to describe the internal structure of rocks. For anisotropic rock containing vertically aligned cracks, theoretical calculations (e.g., Crampin 1985) have shown that for a large range of directions of wave propagation the projection of the polarization vector (the vector indicating the direction of particle displacement during passage of the wave) of the first-arriving shear wave on a horizontal plane is parallel to the cracks. Moreover, the degree of shear-wave splitting (i.e., the time difference between both shear-wave components) increases with increasing crack density. Shear-wave splitting may thus have important applications in, e.g, enhanced oil recovery and geothermal experiments, where the orientation and intensity of fracturing are important parameters.

In the last decade many observations of shear-wave splitting have been reported (for an overview see Crampin 1987) in various types of rocks (e.g., igneous, metamorphic, and sedimentary rocks). In this paper shear-wave splitting is investigated in a shallow sequence (50–112 m) of clays. The clays were subjected to subglacial deformation and are locally fissured. In an earlier study (Douma et al. in press), hereafter called Paper 1, shear-wave splitting (and therefore anisotropy) has already been identified in these clays using a constant-offset shear-wave Vertical Seismic Profiling (VSP). In such a 'constant offset' VSP seismic waves generated by a source at a fixed distance from the borehole head are recorded by geophones at different depths in the borehole. It was shown that the observed anisotropy could be explained by aligned fissures in the clays. However, it was realized that for a thorough understanding of the anisotropy in the clays shear-wave splitting should be investigated at more source offsets and source azimuths than those used in the constant-offset VSP. The use of different offsets and azimuths means that the formation is observed under different directions of wave propagation. This results in a better definition of anisotropy (the dependence of seismic velocity on the direction of wave propagation).

Therefore, in June 1989 we returned to the same site and carried out a multi-offset shear-wave VSP and a 'walk-around' shear-wave VSP (the line through source and borehole head has different azimuths for different experiments). It was hoped that the additional source offsets and source azimuths would contribute to a better understanding and definition of the anisotropy in the shallow clays.

In this survey we used a new type of receiver. In the earlier experiment of Paper 1 the receiver was a three-component geophone that had to be locked in the borehole using a clamping device. In our latest experiment, however, a three-component geophone located in a cone (the 'Dutch penetration cone', a product of Delft Geotechnics) was used. This cone is pushed into the clays at the bottom of the borehole just above the depth to be studied using a system of rods. The better coupling of this receiver was expected to result in better data quality.

If the observation of shear-wave splitting in shallow VSP surveys provides information about fissuring in shallow clays, the technique might become an important diagnostic for geoscience disciplines such as glaciology (to study subglacial deformation phenomena) or geotechnical engineering (to study deformation and strength characteristics of clays in the shallow subsurface).

## Fundamentals on wave propagation through cracked media

A medium containing aligned inclusions (e.g., aligned cracks) that has an axis of rotational symmetry can be replaced by a homogeneous transversely isotropic medium, if the dimensions of the inclusions are small with respect to the seismic wavelength. Transverse isotropy (described by five independent elastic constants) is a special case of general anisotropy characterized by 21 independent elastic constants.

In an anisotropic medium there are in every direction of plane-wave propagation three body waves with different velocities and mutually orthogonal polarizations. Generally, none of the waves has a polarization parallel (longitudinal) or perpendicular (transverse) to the wave normal. In weakly anisotropic media, however, the polarizations are close to these directions. Therefore, the three waves are called quasi-longitudinal (qP) and quasi-transverse (qS1 and qS2), respectively.

Since the directions of polarization of the two (quasi-) shear waves are spatially fixed, an arbitrarily polarized shear wave entering an anisotropic medium generally splits up into a qS1- and qS2-component. In many papers (e.g., Crampin 1985) Crampin has shown that for cracked media such shear-wave splitting often results in a fast shear-wave component polarized parallel to the aligned cracks and a slow component polarized in a plane containing the normal to the cracks. The delay between the two components depends on the degree of anisotropy (i.e., the intensity of cracking) and the time of propagation.

The interference of both shear-wave components results in a signal that begins with the polarization of the first-arriving shear wave followed (after the time delay between both components) by an elliptical polarization. Such elliptical polarization (elliptical motion of a point of the medium in a plane) occurs if the two orthogonal shear components have a time delay. Only for propagation in special directions (or for isotropic media) the shear-wave splitting vanishes, i.e., the resultant signal becomes linearly polarized. These special directions in an anisotropic medium are called shear-wave singularities (Crampin & Yedlin 1981). There can be two types of singularity: first-order singularities (where the difference between the two shear-wave velocities decreases proportionally to the 'distance' from the singularity), and second-order singularities (where the difference decreases proportionally to the square of the 'distance'). First-order singularities are much more common.

If in a 'multi-direction experiment' the source-receiver line passes through a first-order singularity, splitting vanishes just for this direction, and polarization of the leading shear wave (the direction of the first motion) is different on either side of the singularity. At a second-order singularity splitting is very small in the vicinity, and the polarization of the leading shear wave is the same on either side of the singularity.

## Location and geology

Our VSP experiment was carried out in the northern parts of The Netherlands (Fig. 1) at almost exactly the same location as used in the experiment described in Paper 1. A detailed description of the geological sequence encountered in the borehole was already given in Paper 1, only a short summary will be given here. The geological sequence (Fig. 2) consists of a lower clay sequence (lacustroglacial clay) deposited at the end of the Elster glaciation. This clay with the local name 'Pot Clay' is the equivalent of the Lauenburger Clay, which is found in northern Germany.

The sand and clay layers overlying the Pot Clay were formed during the warmer Holstein period that followed the Elster glaciation. The deposits are mainly of fluviatile origin, except for the upper clay layer, which may have been deposited partly in an estuarine environment.

On top of these layers lies glacial till formed during the existence of the Saalian ice sheet, which at its maximum extension reached the present river Rhine in The Netherlands. This glacial till covered large parts of the northern and central Netherlands during that period. The 'Pot Clay' is over-consolidated, heavily sheared, and locally fissured due to subglacial deformation. Core samples have shown that these fissures are aligned with an average strike of N254°E and an average dip of 40° to the NNW. In contrast with the large degree of fissuring observed in the Pot Clay, almost no fissuring is reported in the upper clay layer.

*Fig. 1.* Map showing the location of the borehole in the northern part of The Netherlands.

## Data acquisition

### *Geometry*

Two types of VSP geometries were used to analyze wave propagation through the subsurface.

a) Multi-offset VSP: here we had three receivers in a borehole and ten sources at different offsets from the borehole head. The receiver depths were 30 m, 65 m, and 77 m. The first receiver depth lay within the upper clay layer, whereas the other two lay within the Pot Clay sequence. The sources were situated along a N-S line through the borehole head and had offsets ranging from − 20 m to + 80 m (see Fig. 3) with the minus- and plus sign indicating source offsets to the south and north, respectively, of the borehole. The nearest offsets to the borehole were − 10 m and + 10 m, because the truck responsible for our receiver system is located exactly above the borehole.

b) Walk-around VSP: here we had one receiver in the borehole at a depth of 77 m and six sources located at six different azimuths with respect to the borehole head (Fig. 4). All source offsets were constant (20 m).

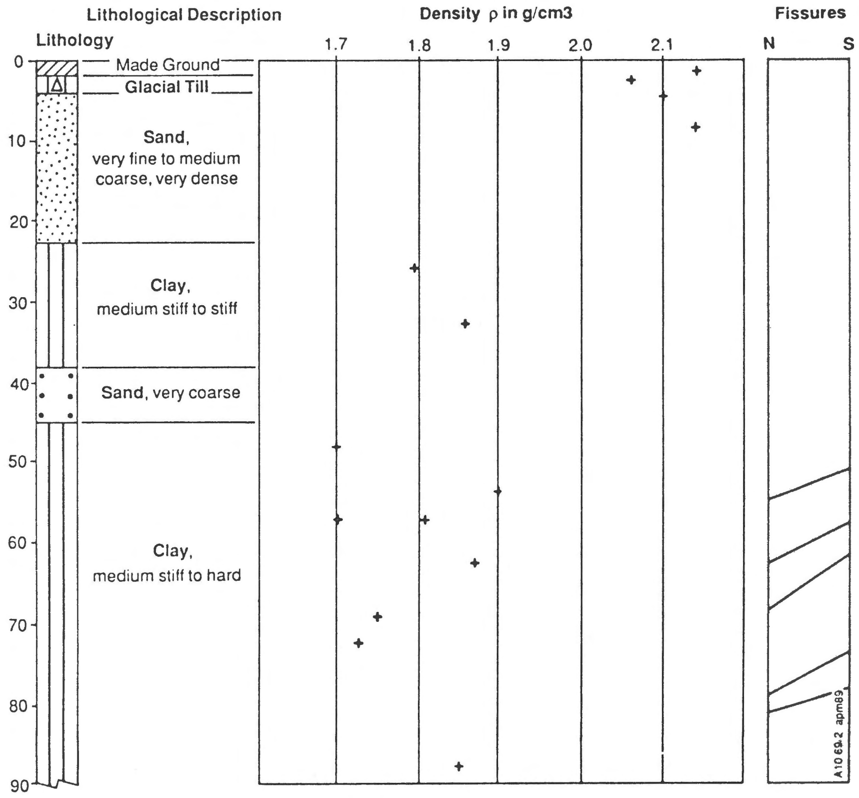

*Fig. 2.* Geological sequence of Noordbergum borehole showing lithology, density and fissuring of the layers. Depth in metres. (After Douma et al. 1990.)

### *Receiver*

A three-component geophone located in a cone (the 'Dutch penetration cone') was used as a receiver. Since the cone is pushed (using a system of rods) into the subsurface, the geophone is expected to have a good coupling with the surrounding medium. This device is different from the one used in the experiment of Paper 1, where a three-component geophone was clamped in the borehole. Problems with the clamping mechanism sometimes noticeably affected the data of Paper 1. Therefore, it is interesting to find out whether such problems can be reduced using the penetration cone.

A serious drawback of the penetration cone (in its present version) is the lack of an orientation device. Every time the cone is pushed down 1 meter a new rod has to be attached to the existing string of rods. This may easily cause some rotation of the receiver (especially for large receiver depths where many rods are necessary). The problem is aggravated by 'tripping': The cone cannot stay longer than a few hours in the hole, since setting of the clay might make retrieval impossible.

In our experiment the problem of orientation was solved by comparing the data at 20 m offset with corresponding data from our previous experiment (Paper 1).

In a large-scale borehole investigation the orientation of the tool is measured with a magnetic or gyroscopic compass combined with a device that measures the deviation from the vertical. This is primarily done to obtain (by integration of the orientation data) the location of the tool in deviated boreholes, but for surveys that require angular information the orientation data themselves are

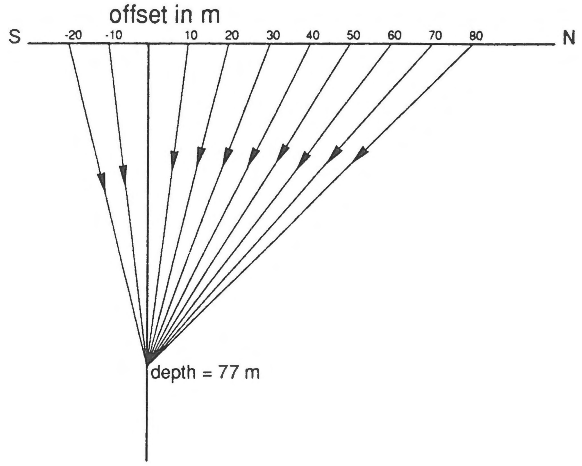

*Fig. 3.* The geometry of our multi-offset VSP, where the sources are located along a S-N profile crossing the borehole head. Straight ray paths are given to one of the receivers (at a depth of 77 m).

significant. For shallow investigations one generally has to make do without orientation sensors. This does not matter much for locations, but is critical for azimuth-sensitive investigations such as those described in this paper. The only recourse is then to try to minimize the uncertainty in the orientation. In the first experiment, the geophone was lowered by a train of rods with rigid linking, in the second experiment rods were screwed together. Slack in individual links and small deviations in tightening the rods can sum to measurable mis-orientation with both systems.

Normally, one has no control over the mis-orientation. In this respect, the repetition of the experiment with a different emplacement technology at virtually the same location was fortuitous, since in this way we got confirmation that the errors, though discernible, were small. However, the orientation is the weakest link in the chain of arguments, and in future surveys the orientation mechanism should be improved.

### Sources

In our VSP experiments a beam positioned under the wheels of a Landrover was used as shear-wave source. Shear waves were generated by hitting one side of the beam with a hammer. In the multi-offset experiment the beam was hit in an eastward direction, perpendicular to the source-borehole line. In the walk-around experiment the beam was placed perpendicular to the source-borehole lines (which had, of course, different azimuths).

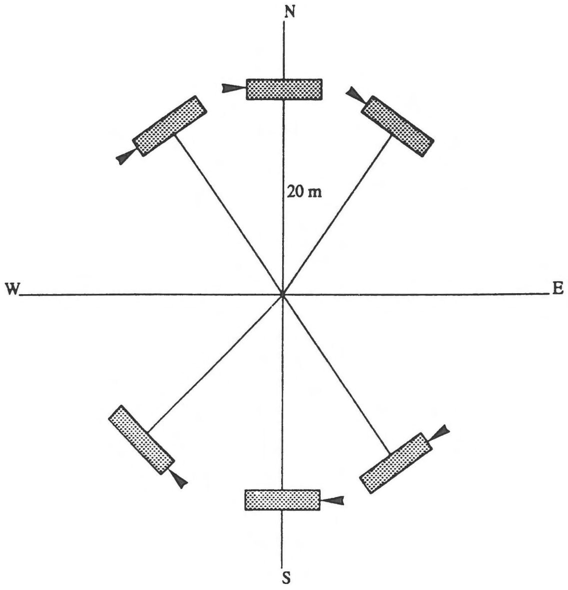

*Fig. 4.* A plan view of the source positions in the walk-around VSP. All sources have a constant offset (20 m) from the borehole head. The arrowheads indicate in which direction the beam under the Landrover was hit.

## Results

### The data

The results of the VSP experiments are presented using hodograms. In such hodograms the particle displacement during a seismic arrival is projected on reference planes; a hodogram is thus a record of the direction of particle motion. The polarization of shear-waves traveling through anisotropic media is constrained to specific directions, and from a study of these directions information on the anisotropy and its cause may be derived.

In Figs 5a, b, and c the results of the multi-offset

VSP are presented for the depths 30 m, 65 m, and 77 m, respectively. The three geophone components are rotated in processing, so that after the rotation there is one vertical (V) component and two horizontal (H1 and H2) components, that are positive upward, eastward, and northward, respectively. In Fig. 5 hodograms are presented for the horizontal (H1, H2) reference plane and for the vertical (V, H1) reference plane. The hodograms have been normalized with the maximum of the amplitudes in the V, H1, and H2 directions. For the hodograms belonging to one particular combination of geophone depth and source offset the (normalized) particle displacements are given for a time interval that includes the shear-wave arrival.

At a depth of 30 m (Fig. 5a) almost no shear-wave splitting is observed. Most of the hodograms show a linear polarization. Only at the source offsets 10 m, 20 m and 70 m a small tendency towards elliptical polarization in the horizontal plane can be noticed. Since there is but little shear-wave splitting, any direction of a first-arriving shear wave is difficult to determine at these offsets. Close inspection of the particle motion in the horizontal reference plane reveals that for source offsets increasing from 10 or 20 m to 70 m a change in particle motion (indicated by arrowheads on the polarization curves) from clockwise to anticlockwise can be noted. Finally, it is noted that the particle motion in the vertical reference plane is almost horizontal for all source offsets.

At a receiver depth of 65 m (Fig. 5b) shear-wave splitting can easily be identified. At the source offsets − 20, 20, 30, 40, and 50 m the H1, H2 hodograms show elliptical polarization preceded by a clear polarization of the first-arriving shear wave (indicated by an arrowhead lying off the polarization curve). At source offsets − 10, 10, 60, 70, and 80 m shear-wave splitting, however, almost vanishes. Increasing source offsets from − 20 m to 20 m results in a change of the particle motion (in the horizontal reference plane) from anticlockwise to clockwise. Moreover, the polarization of the leading shear wave changes drasticly from NW to SW at these offsets. Just as for 30 m depth the particle motion in the vertical reference plane is almost horizontal for all offsets.

At 77 m depth (Fig. 5c) almost the same type of results are obtained. However, the shear-wave splitting is even more pronounced than at 65 m, so that even clear elliptical polarization in the vertical plane can be observed now. Moreover, shear-wave splitting can also be noted now at source offsets 60, 70, and 80 m.

In Fig. 6 the results are shown for the walk-around VSP. The hodograms only show clear shear-wave splitting for the source azimuths N0°E and N180°E. Elliptical polarization is noticeable in the horizontal reference plane at these azimuths. At other azimuths the horizontal polarization is almost linear. The polarization in the vertical reference plane is almost linear at all azimuths.

### *Interpretation*

The shear-wave splitting observed in the data clearly indicates the presence of anisotropy in the geological sequence encountered by the borehole. The degree of shear-wave splitting observed at 30 m depth (i.e., in the upper clay layer), however, is noticeably less than at 65 m and 77 m depth (i.e., in the Pot Clay). This may be explained by a difference in the degree of anisotropy of the upper clay layer and the Pot Clay. Such a difference might indicate that the upper clay layer is less fissured than the Pot Clay. This agrees with geological information on the fissures in both layers. However, the difference in shear-wave splitting might also be explained by the distance the shear wave travels through an anisotropic medium. If it is assumed that only the clay layers are anisotropic, a shear wave arriving at the receiver at 30 m depth can only build up shear-wave splitting from a depth of ± 21 m (where the upper clay layer starts) till 30 m. Although it is realized that most ray paths are probably oblique, so that the actual ray path would be longer than 9 m (the vertical distance between the upper boundary of the upper clay layer and the receiver) this distance is much smaller than the distance a shear wave travels through the Pot Clay to the receiver at 65 or 77 m. This distance is of the order of 20 or 32 m for the receiver depths 65 and

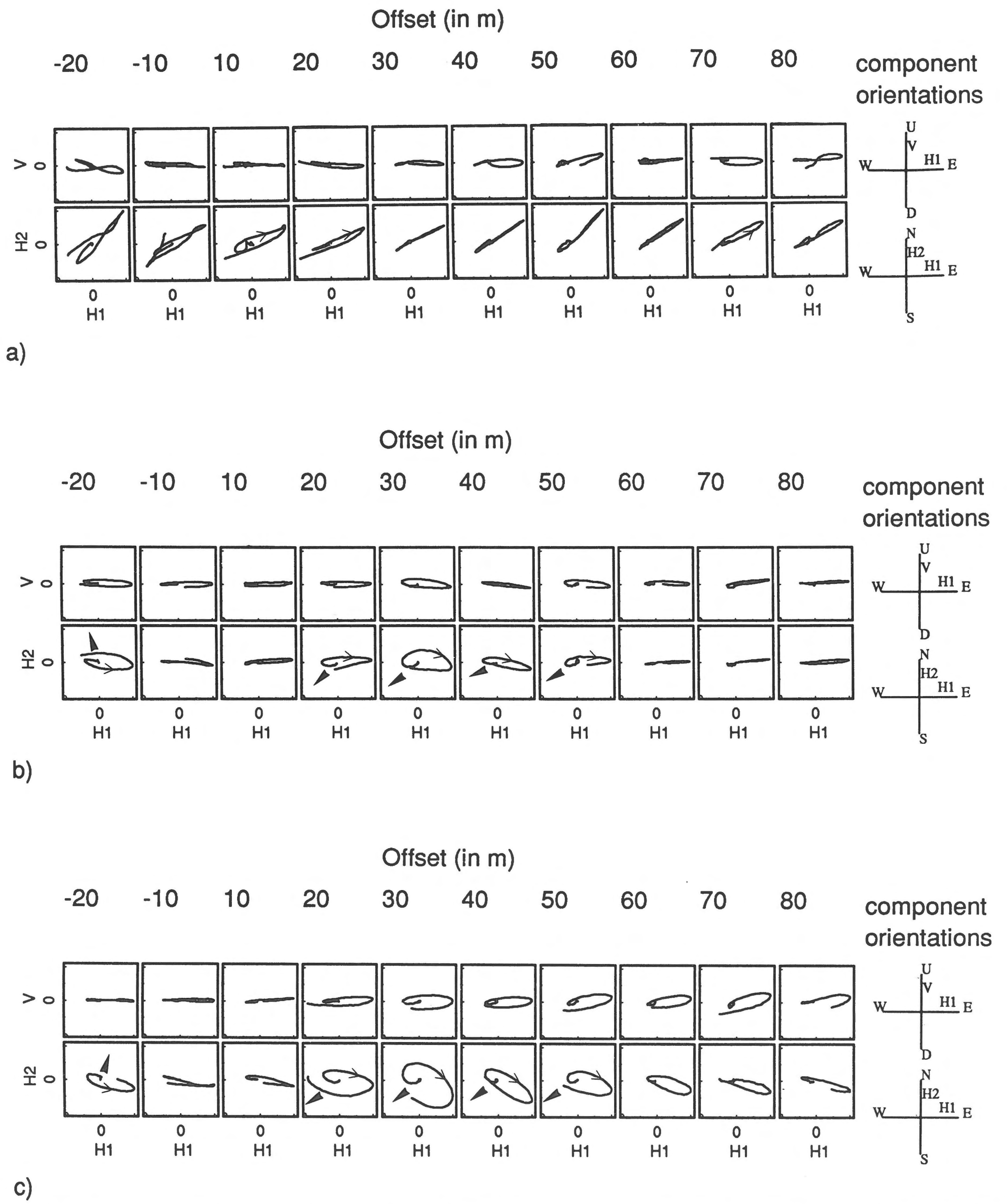

*Fig. 5.* The shear-wave arrivals observed in our multi-offset VSP at three geophone depths: (a) 30 m, (b) 65 m, and (c) 77 m. For each depth the shear-wave arrival is presented, from top to bottom, by the hodograms of the displacements in the vertical (V, H1) and horizontal (H1, H2) plane. These results are given for each source offset. The arrowheads lying off and on the displacement curves in the hodograms show the polarization of the leading shear wave and the displacement direction of the shear wave, respectively. The spatial orientations of the three geophone components (V, H1, H2) are given at the right of the hodograms.

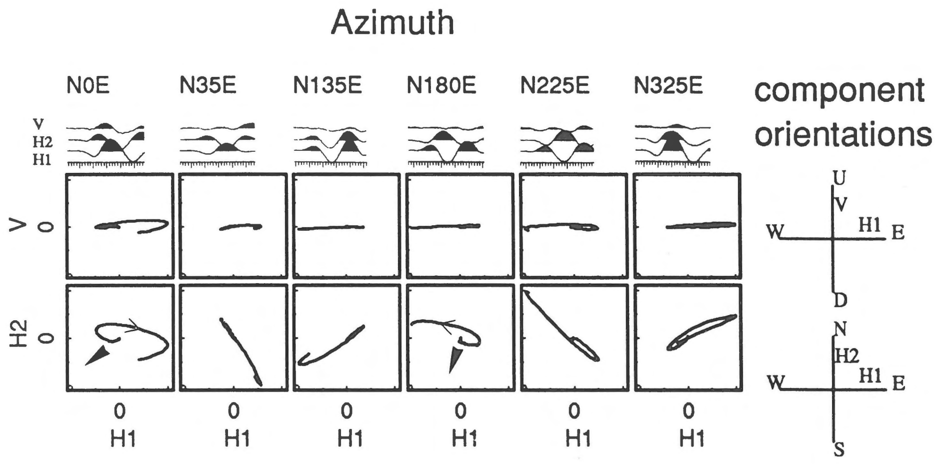

*Fig. 6.* The same as for Fig. 5, but now for the shear-wave arrivals observed in our walk-around VSP. The results are given for different source azimuths at one geophone depth (77 m).

77 m, respectively, since the Pot Clay sequence starts at about 45 m.

The difference in ray path to the receivers at 65 and 77 m in the Pot Clay certainly contributes to the difference in shear-wave splitting observed at 65 and 77 m. However, a changing degree of anisotropy within the Pot Clay may also contribute to this difference.

From the multi-offset VSP data (Fig. 5) shear-wave singularities can be identified at all three receiver depths. This can easily be done for the receiver depths 65 and 77 m, where a clear polarization change of the first arriving shear wave can be noted around source offsets −10 m and 10 m. This would imply a singularity at an almost vertical direction of shear-wave propagation. Moreover, at 65 m depth another shear-wave singularity seems to exist for source offsets around 60, 70, or 80 m. If straight ray paths would be assumed this would imply a singularity of shear-wave propagation at an angle of about 50° with the vertical. The same singularity is not noticeable for the receiver depth of 77 m. This is probably due to the fact that shear-wave propagation for this depth takes place at smaller angles with the vertical than for the same offsets at the depth of 65 m.

For the receiver depth of 30 m the offset VSP data (Fig. 5a) also indicate a singularity. Although a changing polarization of the first-arriving shear wave is difficult to identify, the change in particle motion from clockwise to anticlockwise (observed for offsets changing from 10 to 70 m offset) means that such a polarization change may have occurred. However, since there is but little shear-wave splitting at 30 m depth, it is difficult to identify the exact direction of this point singularity. Moreover, this small degree of shear-wave splitting prevents us from investigating the anisotropy of the upper clay layer in more detail. Therefore, we concentrate on the interpretation of the anisotropy observations in the Pot Clay layer.

The results of Figs 5b and c show two singular directions for the depth region corresponding to the Pot Clay: a first-order (point or line) singularity for vertical wave propagation (the polarization changes when this singularity is crossed) and another singularity for wave propagation at about 50° with the vertical (this angle may be larger when refraction is taken into account). The character of this last singularity is unknown because the combination of source offsets and receiver depths used in the experiment makes it impossible to cross this singularity.

If we assume that the anisotropy of the Pot Clay is caused by aligned fissures in an isotropic background material, these singularities together with the directions of the leading shear wave can be used to investigate the orientation of the fissures. Characteristic features of wave propagation in media containing aligned cracks are presented in Fig. 7 (after Crampin 1985). It is assumed that anisotropy caused by aligned fissures is identical to the anisotropy caused by aligned cracks, so that Fig. 7 can be used to study the anisotropy induced by fissures. In Fig. 7 the equal area projection of the polarization of the leading shear wave on the horizontal reference plane is given for a large range of directions of shear-wave propagation for vertical, dipping, and horizontal orientations of the inclusions. First-order singularities can be identified in Fig. 7, and some of them have been indicated by stars. Note the drastic change of the polarization of the leading shear wave at these singularities. 'Kiss singularities' (second-order singularities) are indicated in Figs 7a, b, and c by filled circles. These kiss singularities generally lie on the axis of rotational symmetry of the medium.

From the first-order singularities observed in the Pot Clay (Figs 5b and c) important conclusions concerning the orientation of the fissures can be drawn. Since a point singularity was observed at (almost) vertical wave propagation, the plane of the fissures can not be vertical of horizontal: Figs 7a and c show that these orientations do not result in first-order singularities close to the vertical direction of wave propagation. Therefore, the direction of the first-order singularity in the Pot Clay indicates dipping fissures (see Fig. 7b).

We have tried to determine strike and dip of the fissures from the VSP data. According to geological information the fissures have an average strike of N254°E and an average dip of 40° to the NNW. In Fig. 7d the horizontal projection of the polarizations of the leading shear wave for NNW (45°) dipping cracks is given. These have to be compared with the VSP data. The encircled area within Fig. 7d indicates the range of ray directions expected for the waves involved in the multi-offset VSP experiment. Within this area the 'theoretical' horizontal polarization changes from SW at angles corresponding to source locations to the south of the borehole, through W at source locations just to the north of the borehole, to SW again at source locations far away to the north of the borehole. The shear-wave singularity is crossed for almost vertical directions of wave propagation.

Except for the crossing of the shear-wave singularity, these theoretical results do not agree very well with the experimental results of the multi-offset VSP. As shown by Figs 5b and c the horizontal projection of the polarization of the leading shear wave changes from NNW (or about N) for source locations to the south of the borehole to SW immediately to the north of the borehole. Only if the shear waves originated at source offsets to the north of the borehole would be seriously refracted, so that the shear waves would arrive at the borehole receiver at a large angle with the vertical, the SW directions observed for the leading shear wave would correspond with the theoretical polarization. However, the NNW (or N) direction of the leading shear wave for source offsets to the south of the borehole would still not agree with the SW direction of the theoretical polarization at these locations. Therefore it is concluded that the variation of the polarization of the leading shear wave observed in the multi-offset VSP experiment can not be explained by the orientation of the fissures obtained from geological information.

In Fig. 7e theoretical 'horizontal' polarizations are presented for a crack configuration with a strike SW/NE and a dip (45°) towards the SE. As in Fig. 7d the area of theoretical horizontal polarizations of the leading shear wave for the multi-offset VSP experiment is indicated by a circle. A change in direction from NW to SW is predicted for variation of the source position from south of the borehole to north of it. Since this polarization behaviour has been observed in the multi-offset VSP experiment, it is concluded that the data in the Pot Clay can be explained by a configuration of fissures with a SW-NE strike and a dip of about 45° towards the SE. Although this strike and dip are almost identical to the values obtained from geological information, the dip direction is opposite to what is (geologically) observed.

The results of the walk-around VSP show only clear shear-wave splitting for source positions on the N-S line through the borehole. At all other azimuths this splitting is almost negligible. Thus

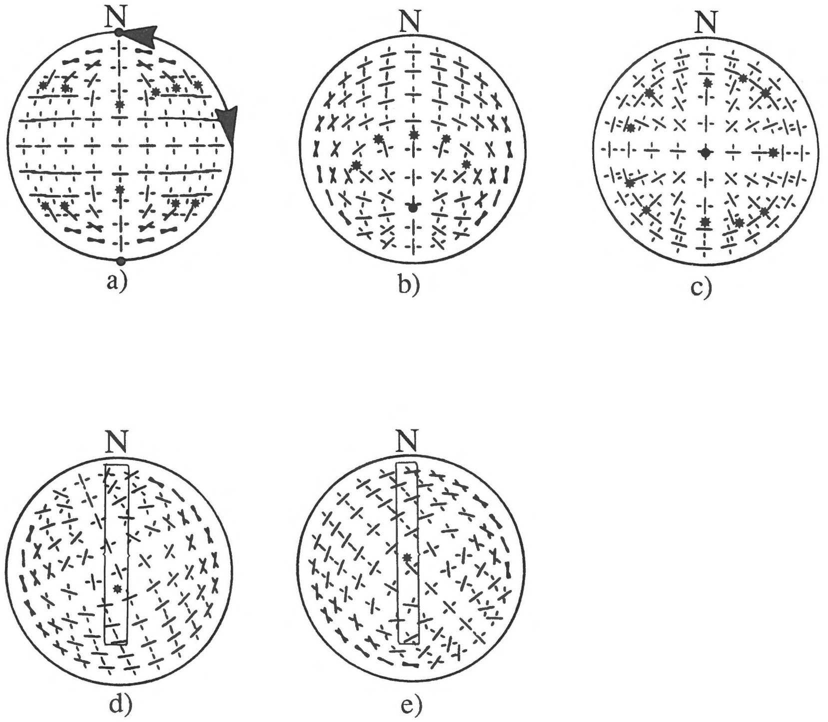

*Fig. 7.* Equal-area projections of the horizontal polarizations of the first-arriving shear wave for propagation through upper-hemispheres containing aligned cracks (from Crampin 1985). The solid line is the horizontal projection of the polarization of the faster shear wave, the broken line that of the slower shear wave. The arrows in Fig. 7a have no meaning in this paper. The orientations of the cracks are (a) vertical and E-W striking, (b) dipping 45° to the south and E-W striking, (c) horizontal, (d) dipping 45° to the NNW and WSW/ENE striking, and (e) dipping 45° to the SE and SW/NE striking. Several first-order and 'kiss singularities' are indicated with stars and filled circles, respectively. In (d) and (e) the range of angles of wave propagation that is assumed to be involved in our multi-offset VSP is encircled.

shear waves generated by sources lying off the N-S line seem to travel at directions close to shear-wave singularities. This result does not seem to disagree with the results of Fig. 7e which show that shear-wave propagation at different azimuths, but close to the vertical directions (as expected for in the walk-around VSP) is close to a shear-wave singularity. That shear-wave splitting was observed despite being close to a singularity for sources on the N-S line may be due to rapid changes in the degree of splitting in the immediate vicinity of the vertical. Compare Fig. 5c, where small changes in source location (−20 m to 10 m, 10 m to 20 m) cause a rapid change in splitting.

We want to point out that at the two receiver depths 65 and 77 m the direction of the horizontal polarization of the leading shear wave is almost SW for the 20 m source offset. At identical receiver depths and almost identical source offset in the previous constant-offset VSP (described in Paper 1) this direction, however, was almost W. We believe that this discrepancy can be explained by the difference in the coupling between the receiver and its surroundings. The receiver used in the experiment described in this paper is pushed into the clays and, therefore, is expected to result in a better coupling with its surroundings than the receiver used in Paper 1, which is clamped in the borehole. Due to this different coupling the (sometimes small) polarization of the leading shear wave could be better identified. This discrepancy, however, does not affect the results of the previous survey significantly, since the prime goal was to identify anisotropy as a function of depth.

## Conclusions

The multi-offset and walk-around shear-wave VSPs described in this paper confirm earlier observations of anisotropy in the Pot Clay sequence. The key identifier of this anisotropy is shear-wave splitting that is observed at three-component geophones located in the clay sequence. This shear-wave splitting is much stronger than the splitting observed in the upper clay layer, which may mean that the upper clay layer is less anisotropic.

The shear-wave splitting has also been used to study the cause of anisotropy. If the anisotropy in the Pot Clay is assumed to be only due to aligned fissures (i.e., the material is assumed to be transversely isotropic) shear-wave singularities observed in the multi-offset VSP indicate that the fissures must dip. This is also confirmed by the variation of the horizontal projection of the polarization of the leading shear wave in the multi-offset VSP as a function of the source offset. This variation corresponds well with theoretical calculations of this variation for SE dipping fissures that have a strike SW/NE. Moreover, the results of the walk-around VSP agree with this result. The SE dipping fissures, however, do not agree with geological information that indicates that the fissures dip towards NNW. This discrepancy may mean that the assumptions made in this paper are not correct. For instance, the anisotropy of the Pot Clay may be more complex (have a lower degree of symmetry) than the transverse isotropy (induced by aligned fissures) assumed here. This might be the case if additional to the aligned fissures there are other phenomena (e.g., horizontal bedding, preferred particle orientations, etc.) that contribute to the anisotropy. Another assumption that may be invalid is the assumption that the aligned fissures in the Pot Clay can be modelled by aligned cracks. If this would be the case the theoretical polarizations of the leading shear wave (that are based on alignments of cracks) can not be used to model the polarization behaviour caused by aligned fissures.

To find out whether the anisotropy in the Pot Clay is more complex than assumed here we suggest that shear-wave propagation through the Pot Clay should be analyzed at more directions. If we would go on using VSP experiments this could be realized by using much more source offsets and source azimuths. However, it could also be realized, e.g., by using a different geometry such as cross-hole experiments in which wave propagation at a large range of directions can be studied. Such additional data would result in a much better angular coverage of information on the polarization of the leading shear wave. This is expected to lead eventually to a better understanding of the anisotropy observed in the Pot Clay.

The excellent data quality obtained in this experiment is due to the use of the penetration cone. The coupling between the geophone and its surroundings is much better with this cone than with the geophone used in the experiment described in Paper 1.

The improved coupling has substantially reduced the noise level in the data. Winterstein (1989) has pointed out that hodogram analyses rely on a low-noise time window before the first arrival. Geophone emplacement with a penetration cone has significantly lowered the noise level and thus should be regarded to be more accurate than the clamped borehole geophone.

It is not likely that a similar low-noise window can be found in reflection seismic data (Winterstein 1989). The hodogram method discussed here thus may be only useful for the direct arrivals in VSP data.

## Acknowledgements

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