Investigation of azimuthal anisotropy in high-fold 3D multicomponent seismic reflection

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SUMMARY

3D P-wave seismic surveys can exhibit significant azimuthal variation in stacking velocities, and failure to allow for such variations can introduce smearing into the stacked volume. The problem is likely to be worse in the case of converted-wave (PS) reflection. Firstly, S-waves have lower velocities such that time variations are amplified. Secondly, PS rays are asymmetrical, such that anomalous features may be traversed by different wave-types (P or S), depending on the direction of travel.

Recently, a coal-scale 3D-PS trial was recorded in the Bowen Basin with the aim of providing a detailed investigation of such azimuthal variation. The survey was designed with extremely high fold (>500). This allowed good quality images to be constructed for data subsets having restricted ray azimuths. Target structures interpreted using different ray-azimuths exhibit significant timing variations (up to 30ms). The observed azimuthal variations may not necessarily indicate true azimuthal anisotropy. They can result from poor statics solutions, and PS imagery is notorious for difficult statics.

On the other hand, the observed variations may be indicative of true geological anisotropy. Based on shear-wave splitting models, our PS velocity variations have been modelled in terms of elliptical variation with azimuth, and this approach predicts the orientation of the horizontal stress field. It is interesting that a majority of our data zones indicate a consistent stress orientation. Furthermore, the interpreted horizontal-stress orientation is consistent with observed reverse faulting in the area.

Key words: PS wave, Azimuthal anisotropy, Fracture detection, 3D.

INTRODUCTION

The conventional P-wave seismic method is highly developed and has been very successful. However, theory suggests that S-waves should respond differently to subsurface variations, and hence could provide extra information about rock properties. This has led to the development of S-wave based seismic reflection surveying methods. Converted-wave (PS) reflection is an effective approach to obtaining S-wave information.

For PS data the processing stage is quite complex. One reason for this is the higher variability of S-wave seismic properties with ray-azimuth direction.

For example, in 2D-PS work it has been demonstrated (e.g. Velseis, 2007) that positive and negative offset data can yield different velocities and structural interpretations . This is an example of azimuthal variation of the geological environment and may be caused by diodic illumination (Thomsen, 1999), shear-wave splitting (e.g. Crampin et al, 1980 ,Crampin and Lovell, 1991) or azimuthal velocity variations that are inherent in the geological layers.

The orientation and amount of azimuthal velocity variation is often related to the localised stress field. There is some evidence that, at the deep petroleum-scale, variation in shear-wave velocity with azimuth may be of order 1-5%. For the shallower coal-scale environment surface-related stresses tend to lead to extensive fracturing, with suggestions that azimuthal velocity variations in excess of 10% might occur (Crampin, 1997).

Accommodating these effects is more difficult for 3D data than for 2D, since rays occur at all azimuths. A recently completed 3D-3C ACARP trial has been conducted to examine the feasibility of acquiring and processing 3D coal-scale PS-wave data. A core component of this investigation has been to explore the problem of azimuthal imaging variation. This was expected to be particularly severe at the coal scale, due to the highly asymmetric nature of shallow PS rays, coupled with potentially strong velocity variation.

The trial consisted of a 1200m x 500m 3D multi-component (3C) survey. This survey was designed to give a very high reflection fold (an average of 500 reflections per CCP/CMP bin). (The Common Conversion Point (CCP) is the PS-wave equivalent of the Common Mid Point (CMP) defined in P-wave reflection.) This high fold allows the data to be divided into separate subsets based on source-receiver azimuth while maintaining reasonable final stack fold for each subset. The purpose of this was to be able to examine the azimuthal variations in the data at every stage of processing.

In this investigation we have examined the azimuthal velocity variations of the PS data to determine if azimuthal anisotropy exists, and to what extent it will affect the stacked volume. We have also considered whether any additional geological information, such as fracture orientation, can be obtained from the azimuthal anisotropic results.

STACK ANALYSIS

Geological layers are generally not homogeneous and may be formed in an asymmetric nature (e.g. laminar bedding) or may be fractured due to local stress fields. In these environments the velocity of a seismic wave through an earth layer may be dependent on the wave type and the direction of travel. Another process, unique to converted waves, that also produces an azimuthal velocity effect is diodic illumination. This is caused by inhomogeneities of limited lateral extent occurring above the target reflector. For rays from different directions one ray path may pass through the body as a P wave and the other may pass through it as an S wave. This can result in differing travel times and therefore different moveout velocities.

If the subsurface is azimuthally invariant and all static errors have been corrected then we would expect the moveout velocity for all traces contributing to a CCP bin to be the same. Therefore, azimuth-limited stacks should have similar structures to the all-azimuth stack.

Figure 1 (last page) shows the relative difference between limited-azimuth horizon picks of Line 112 and the all-azimuth horizon picks. There appear to be strong azimuthal variations in the vicinity of a large fault which occurs about half way along the line (horizontal axis). This could be due to fault related diodic effects, or fracture related azimuthal behaviour. However, the errors in picking due to unmigrated diffractions are expected to be significant in this zone causing the degree of true azimuthal anisotropy to be difficult to determine. Away from the fault the image has less structural variation although it is still on the order of +/- 10ms. For a 25Hz wavelet this would correspond to shifts of +/- quarter of a wavelength. This would lead to significant smearing of the target horizon and a consequent reduction in the resolution of the stacked PS volume.

VELOCITY ANALYSIS

To examine the variation of the seismic velocity with azimuth, we have used a concept similar to automatic velocity picking via semblance. For each CCP bin the gathers are sorted into subsets based on azimuth ranges. For each subset a range of PS NMO parameters are trialled to determine which gives the best stack, for a window of data about the target horizon. For this trial a constant P-wave velocity of 3200m/s has been used and γ (Vp/Vs) has been varied between 1.5 and 3.0. Since this is an automated process it tends to generate some anomalous results. These are generally associated with noise and complexities in the shape of the seismic wavelet generated at the target. To improve the probability of a meaningful solution a number of CCP locations are averaged (Figure 2, last page). For this test 60m x 60m 'super bins' have been used. Each super bin combines 3 CCP locations in the cross-line direction by 5 locations inline, giving a total of 15 CCPs to average. The anomalies can cause the technique to return the maximum or minimum γ values. For our testing these are considered to be outliers and are removed prior to the averaging process.

Figure 2a shows the azimuthal velocity analyses corresponding to these super bins, whose locations are shown in Figure 2b. That figure also includes interpreted fault locations. The γ values range over the entire analysis window (1.5 – 3.0) with an average of 2.25. The mean and median values show very good correlation. There are some similarities between some of the plots. For example figures from the second bottom row have a similar shape and orientation.

Seismic velocities may be affected by distribution of stresses in the earth. Based on this concept, we might expect our γ plots to exhibit a dipolar distribution, with larger γ values at an azimuth and its polar opposite, and smaller γ values at azimuths that are offset by 90°. This expected dipole direction is difficult to quantify by direct examination of Figure 2, although a number of the figures show some general NW-SE elongation. One way to obtain a more objective interpretation is to fit an ellipse to each of the plots.

Figure 3 illustrates the concept where one of the analyses from Figure 5 (L102-G2; Row 3, Column 3) has been fitted with an ellipse. The nonlinear least-squares algorithm (Gander, et. al., 1994) returns the equation of the ellipse in terms of the ellipse centre, the semi-major axis, the semi-minor axis, and the direction of the semi-major axis. The ratio of the length of the semi-minor and major axes gives an indication of the amount of azimuthal anisotropy (1 = no anisotropy; close to 0 = large anisotropic effect). The flatness of an ellipse is equal to one minus this ratio, and in this case is indicative of the degree of anisotropy. The direction of the semi-major axis is equivalent to the azimuth exhibiting greatest γ.

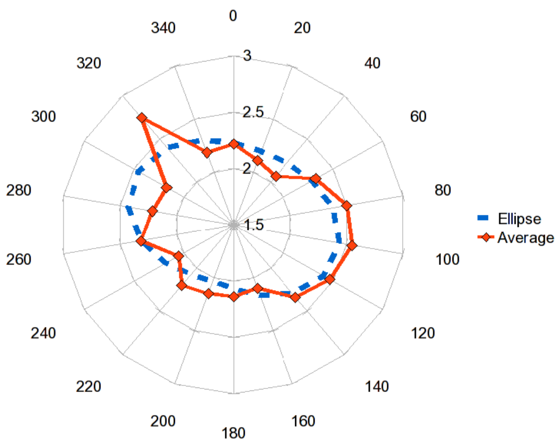

Figure 3: Localised stress fields might be expected to produce dipolar azimuthal variations. Fitting an ellipse to γ/azimuth data can give an indication of the most likely direction of any such stress field. This figure shows a representative γ/azimuth image (taken from Figure 5) and its corresponding best fit ellipse.

Figure 4 summarises the direction and flatness response for each of the CCP groups. Initial investigation of this image alone implies that the angle of the maximum γ value is distributed over many azimuths for the survey. If we also take into account the position of the CCP groups we see that they divide into two main sets. Those more toward the top and bottom of the survey have loose north/south distribution with the maximum gammas occurring in the ranges -20 to 25° and 160 to 205°. The other set consists of CCP groups having a tighter WNW/ESE distribution occurring in the ranges 120 to 135° and 300 to 315°.

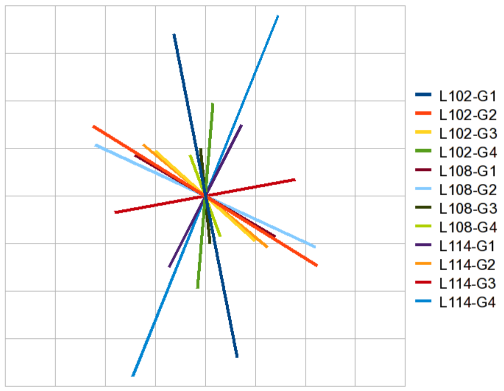

Figure 4: Spider plot of the ellipse parameters for each CCP groups marked on Figure 5. The direction of each line represents the direction of semimajor axis and corresponds to high γ values and therefore lower S-wave velocity. The length of each line indicates the flatness of the ellipse and is proportional to the degree of anisotropy.

Figure 5 shows that WNW/ESE trending group tend to be located in the vicinity of the central faulting. Note also, that the interpreted ellipse major axes tend to be orientated close to the strike of the faulting in this region.

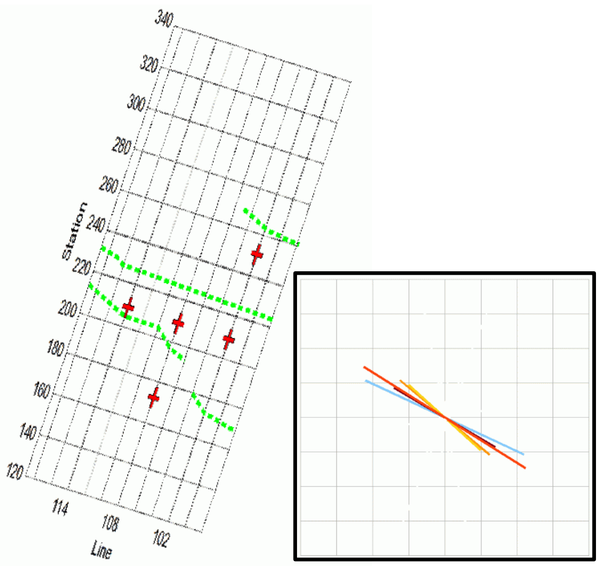

Figure 5: Close to the region of faulting the semi-major axes of velocity ellipses tends to align with the strike direction of the faulting. The image on the left gives the ground location of velocity analysis bins, and the image on the right gives the corresponding ellipse responses.

High γ (Vp/Vs) values in the strike direction correspond to lower S-wave velocities (Vs) in the strike direction and higher velocities perpendicular to the strike of the faulting. The fact that faulting in this region is reverse does suggest horizontal compressive stress perpendicular to the strike. These observations are consistent with the theoretical velocity stress model given by Crampin (1997). That is, the observed azimuthal anisotropy in S-wave velocity near the fault zone is consistent with the expected stress orientation. This suggests that azimuthal analysis of the type described here might provide a tool for prediction of stress and fracture orientation.

The flatness values, and therefore the degree of anisotropy, for all the CCP groups range from 0.05 to 0.2 although those above about 0.13 (L102-G1 and L114-G4) may be irregularities. This suggest that the difference between γ values are generally in the range of 5-13%. This matches well with the expected shallow-environment variation suggested by Crampin (1997).

CONCLUSIONS

This investigation has shown that both interpreted structures and moveout velocities appear to vary based on the azimuth of PS seismic rays. In the vicinity of the faults, the velocity analysis appears to suggest a faster S-wave velocity perpendicular to the faulting. This could be an indication of local fracturing. These results are consistent with theoretical stress / velocity models, and appear to have direct practical application. However, further research is needed to be certain that these effects are not due to extraneous factors, such as variations in processing or errors in the correction of weathering statics.

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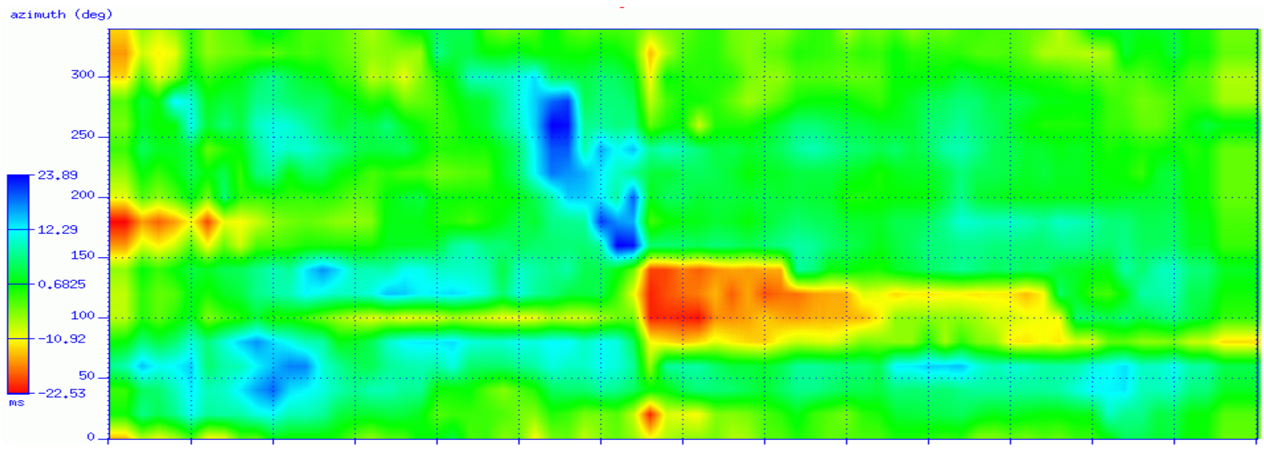

Figure 1: Relative difference in horizon time (colour coded), as a function of position along Line 112 (horizontal axis) and ray azimuth (vertical axis). The largest anomalies appear close to a known fault (centre of line) and could be the result of diffraction effects. Ignoring these, the azimuthal variation may be on the order of +/- 10ms.

(a) **(b)**

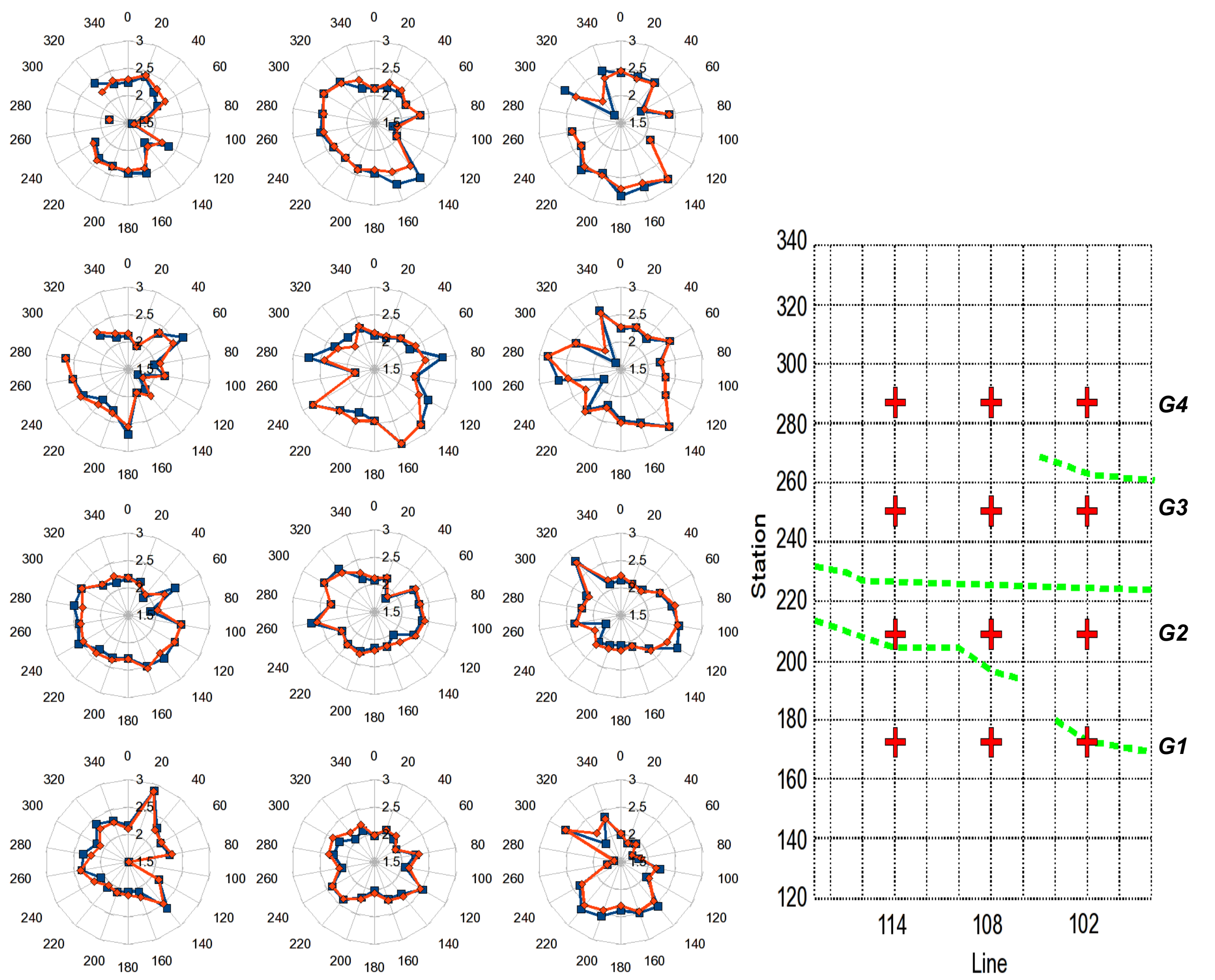

Figure 2: (a) Optimum γ (radial axis) versus azimuth corresponding to each of the CCP groups (locations indicated by red crosses in (b)) . Both the mean (red) and median (blue) values are displayed. A number of the locations exhibit general azimuthal trends, although some of the analyses appear to be contaminated by spurious points. The map in (b) also includes the location of possible faults for reference.