Fast Shear Azimuths in the Marcellus Shale from VSP and Crossed Dipole Sonic Data*

Steve Horne[1], David Rampton[2], and John Crowe[3]

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[1]Chevron Energy Technology Company, London, England (S.Horne@Chevron.com)
[2]Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, USA
[3]Consultant, Pittsburgh, USA

Abstract

The Marcellus Shale is a commercially important unconventional shale gas play. It has been suggested that a contributing factor to the success of the Marcellus Shale is the presence of natural fracture systems. At least two sets of joints are commonly reported to exist in the Marcellus Shale, commonly referred to as the J1 and J2 systems. The earlier J1 system is reported to be confined to the lower Marcellus black shales and coincidentally aligned with the contemporary stress direction in an ENE-WSW direction. The later J2 fracture system occurs in the upper section of the Marcellus Shale and is described to result from gas expulsion from the underlying organic shales. If such fracture systems are present in the Marcellus Shale, it is likely that they will need to be taken into account for optimal well planning and stimulation. For this reason, it would be useful to remotely map any fracture systems for exploration and production purposes.

To investigate whether seismic techniques could be used to characterize any fracture systems in the Marcellus Shale, walkaround VSP surveys were acquired to determine if fracture induced azimuthal anisotropy could be detected. A robust statistical approach was developed to process walkaround VSP data to measure shear-wave splitting resulting from fracture-induced anisotropy. We found a low degree of fracture induced anisotropy aligned in an ESE direction. This direction was surprising as the expectation was to find a fast shear azimuth aligned with the contemporary ENE stress direction. Based on this finding we expanded our analysis to review the fast shear azimuth measured over the Marcellus Shale interval from high quality crossed dipole sonic logs. We found that in most cases the fast shear azimuth tracks the J2, rather than the J1, fracture system. A second observation from this study is that the degree of azimuthal anisotropy observed in the seismic data is greater than that observed in the sonic data. This observation supports the idea that fracture induced anisotropy is frequency dependent and suggests that upscaling observed azimuthal anisotropy from sonic logs may lead to underestimating lower frequency wave propagation effects as observed in borehole and surface seismic data.

Introduction

The Marcellus Shale is an extensive Middle Devonian organic marine shale extending over the states of New York, Pennsylvania, Ohio, Maryland, and West Virginia. The Marcellus Shale is of commercial interest due to the presence of hydrocarbon gas with estimated proved reserves of 84 TCF (Energy Information Administration, 2015).

The Marcellus Shale has long been known to contain large quantities of gas because of the publicly funded Eastern Gas Shales Project conducted from 1976 to 1992. Interestingly, this study identified the presence of several fracture systems and suggested that these may play an important role in any future commercial production (Evans, 1994). However, at the time of the project the gas could not be recovered economically due to a combination of low commodity prices and a lack of production technologies. This latter problem was resolved by adopting lessons learnt from the Barnett Shale, Texas where the combination of horizontal drilling and hydraulic fracture stimulation allowed the commercial recovery of hydrocarbons.

It has been suggested that a contributing factor to the success of the Marcellus Shale is the presence of natural fracture systems (e.g. Engelder et al., 2009; Inks et al., 2014). At least two sets of joints are commonly reported to exist in the Marcellus Shale commonly referred to as the J1 and J2 systems. The earlier J1 system is reported to be confined to the lower Marcellus black shales and coincidentally aligned with the contemporary stress direction in an ENE-WSW direction. The later J2 fracture system occurs in the upper section of the Marcellus Shale and is described to result from gas expulsion from the underlying organic shales. The J2 system is approximately orthogonal to the Allegheny Structural Front so that the J2 system rotates from an ESE-WNW direction to a SSE-NNW direction moving from the southeast to the northern parts of Pennsylvania. If such fracture systems are present in the Marcellus Shale it is likely that they will need to be taken into account for optimal well planning and stimulation. For this reason it would be useful to remotely map any fracture systems for exploration and production purposes.

One fracture mapping technique is to use seismic techniques that measure the directional response of elastic waves propagating through the rock with the idea that aligned small scale features impart a measurable directional response. Such directional responses are referred to as anisotropy. Conceptually, the presence of aligned open fractures can be thought of as slowing wave propagation perpendicular to the fractures. In the case that the fractures are smaller than the seismic wavelength the host rock will be anisotropic, that is, its elastic response will be directionally dependent. The simplest anisotropic scenario can be constructed by inserting an aligned system of fractures into a rock where the average geometry is invariant around the fracture normal direction. Since all the fractures are aligned and on average are rotationally invariant the composite rock’s behavior will be directionally dependent when measured from the fracture normal direction. However, if the rock is measured at a fixed angle with respect to the fracture normal direction then the response does not change, i.e. the rock appears to be isotropic when measured in this ‘transverse’ direction. For this reason, this form of anisotropic behavior is referred to as being Transversely Isotropic. Since sub-surface fracture systems are generally near vertical so that the fracture normal direction lies close to the horizontal plane. As a result, the rock will appear to be anisotropic with respect to the vertical direction and thus the response changes with azimuth. For this reason fracture induced anisotropy caused by aligned vertical fractures is referred to as being azimuthally anisotropic. The elastic anisotropy can be manifested by the directional variation of compressional and shear body waves but a key characteristic is the observation of two shear-waves. This phenomenon is referred to as shear-wave splitting or shear-wave birefringence and can be observed in crossed dipole sonic logs and seismic surveys.

To investigate whether seismic techniques could be used to characterize any fracture systems in the Marcellus Shale walkaround VSP surveys were acquired to determine if fracture induced azimuthal anisotropy could be detected. Furthermore, crossed dipole sonic data were also acquired which are also analyzed for azimuthal anisotropy effects.

Data Description

A walkaround VSP was acquired in south west Pennsylvania using vertical vibroseis units deployed at a nominal radius of 2800 m at 22 locations around a downhole receiver array deployed at approximately 2300 m (Figure 1). The receiver array comprised 12 3-component receivers spaced 15m apart resulting in a depth aperture of 165 m spanning the Tully Limestone, Upper and Lower Marcellus Shale. Over this depth interval the well is effectively vertical with a maximum deviation of 2.4°.

The walkaround VSP data was subject to conventional pre-processing steps of geometry loading, shot stacking, first break picking and geophone rotation to the inline-crossline-vertical co-ordinate system. At this point processing techniques specifically designed to measure subtle azimuthally anisotropic wave propagation effects were applied. After time aligning the data on the first breaks seismic attributes are generated over a sliding window for all the sources generating seismic attributes as a function of azimuth and time relative to the first break. These observed data attributes are then fit to the expected azimuthal variations due to azimuthal anisotropy appropriate to the attribute.

Two of the most useful seismic attributes are the Transverse to Radial RMS ratio and the horizontal ellipticity (Horne, 2003). These seismic attributes exhibit similar azimuthal variations for wave propagation through horizontally layered rocks containing a single set of sub-seismic aligned vertical fractures. In such a situation four nulls will be observed aligned in the fracture strike and fracture normal directions, i.e. every 90 degrees. Such behavior is related to shear-waves generated by down-going P- to S-wave conversions. In the fracture normal and fracture strike directions a down-going P-wave can only excite the shear-wave mode whose polarization is aligned in that direction and so in these directions only one of the two possible shear-modes can be excited. In other words, in these directions there is no shear-wave splitting as only one shear wave, either the fast or slow shear, can be excited. However, for other azimuths the down-going P-wave can excite both a fast and a slow shear-wave which will separate with propagation distance away from the conversion point. Since these shear-modes are not aligned with the incoming P-wave aligned in the radial direction the result is energy on the transverse component. Furthermore, because the two shear-modes propagate with different wave speeds and polarizations a time delay accumulates between the two resulting in a nonlinear hodogram.

These effects are quantified using the Transverse to Radial RMS ratios and ellipticity seismic attributes (Horne, 2003) which are fit to the following expression:

$$D(A_0, \phi_0) = A_0 \, sin^2 \, 2(\phi - \phi_0) \qquad \text{Equation 1}$$

where A_0 is the amplitude of the azimuthal variation and ϕ_0 is the direction of either the fast or slow shear-wave. These two fitting parameters are then determined using a grid search minimizing the difference between the observed seismic attributes and the modelled data given by Equation 1.

The fitting procedure described above is applied to the Transverse to Radial and ellipticity seismic attributes for all 12 receiver levels over a sliding time window commencing at the picked first break. Results of the analysis are shown in Figure 2. The left column shows estimated azimuthal angles ϕ_0 for the 12 receivers (grey lines) along with the median result (red line). These results are summarized in the rose plots in the rightmost column where the black petals indicate the results from the attribute analysis (including the complementary solutions) and the slowness anisotropy weighted fast shear azimuth from the crossed dipole sonic logs over the Marcellus Shale interval (cyan petals). The middle column shows the estimate magnitude of the azimuthal variation, A_0. Whilst the Transverse to Radial results (Figure 2a) are noisy the median result is quite stable at $\phi_0 \approx$ N25E or N115E. A similar picture is observed for the ellipticity attribute analysis (Figure 2b). In this case however, the level of scatter between the twelve receivers appears to decrease with analysis time so that for times later than 300 ms the estimated fast shear azimuth is $\phi_0 \approx$ N30E or N120E. The similarity of the results for the two attributes supports the interpretation that the effect is related to shear wave splitting and not due to some other effect e.g. geophone misorientation which would have distorted the transverse to radial analysis but would have had no effect on the linearity attribute.

The azimuthal analysis of the Transverse to Radial and ellipticity attributes suggests the fast shear azimuth, and the fracture strike, is aligned N30E or N120E. To resolve this ambiguity the seismic data are usually rotated into one of these directions and the fast and slow directions determined by picking on the two geophone components. In this case the time delays were too small to unambiguously resolve the fast and slow directions. Instead we compared the walkaround VSP results with crossed dipole sonic logs through the Marcellus Shale. This comparison is shown as a rose plot of the fast shear azimuth weighted by the magnitude of the slowness anisotropy (slowness weighting reduces the scatter in intervals of low anisotropy where fast shear azimuth estimates become erratic). The crossed dipole sonic log suggests that the dominant fast shear azimuth over the Marcellus Shale is in the ESE direction, close to the N120E solution observed in the walkaround VSP analysis. For this reason, the fast shear direction results from the walkaround VSP are interpreted to be N120E.

It is observed that there is an increase in the ellipticity attribute with time. This increase in ellipticity can be related to the increasing separation of the fast and slow shear-waves in time. This effect is explained with the help of Figure 3 which shows a down-going compressional arrival (green, solid line) and down-going fast and slow (red dashed and blue dotted lines respectively) shear wave conversions generated at 3 different depths. If we consider the deeper receivers, then the first set of split shear waves will have originated at a point just above the receiver and will have travelled a relatively short distance such that the shear waves will have had little chance to separate. The later arriving split shear-waves correspond to conversions occurring at shallower depths and thus will have travelled further and experienced greater separation.

Ellipticity is related to the time delay between the two shear waves. This implies that time delays can be estimated from the ellipticity attributes under certain assumptions, e.g. fast and slow shear waves are of equal amplitude, monochromatic and orthogonally polarized. Under these conditions the time delay can be estimated by considering the equations of an ellipse written as:

$$e = \frac{1 - \cos\beta}{1 + \cos\beta}$$ Equation 2

where β is a phase shift parameterizing the non-linearity of the ellipse such that when $\beta=0$ the ellipticity is zero and when $\beta=\pi/2$ the ellipticity is 1 and the ellipse is circular. The phase shift β can be interpreted in terms of the time delay between the fast and slow shear waves as

$$\beta = 2\pi f_0 \Delta t$$ Equation 3

where f_0 is the shear-wave's frequency and Δt is the time delay between the fast and slow shear waves. In the case that there is no shear wave splitting there is no time shift $\Delta t=0$ and the ellipticity is zero (i.e. linear particle motion), $e = 0$. When the time delay between the split shear waves is equal to ¼ of the period then $e = 1$ and there is circular particle motion. Using Eqns. 1 and 2 we can estimate the time delay between the split shear waves as

$$\Delta t = \frac{T_0}{2\pi} \cos^{-1}\left(\frac{1 - e}{1 + e}\right)$$ Equation 4

Note that this equation is applicable only in the case of small time delays where the time delay is less than ¼ of the period.

Using the approach outlined above we estimated the time delay from the ellipticity attribute analysis results. The estimated time delays are shown as a function of fast shear wave travel time after the first break in Figure 4. Furthermore, an estimate can be made for the Thomsen's splitting parameter γ_s subject to the assumption that both shear-waves are travelling near vertically

$$\gamma_s \cong \frac{1 - \left(1 + \frac{\Delta t}{T_F}\right)^{-2}}{2}$$ Equation 5

where Δt is the time delay between the fast and slow split shear waves and T_F is the arrival time of the fast shear-wave. Using the approximation above yields an estimate for Thomsen's γ_s to be 0.02 over the Marcellus Shale interval.

The cumulative time delay can be computed from the crossed dipole sonic logs by integrating the measured fast and slows shear-slownesses with respect to depth and taking their difference assuming a constant fast shear azimuth. The cumulative time delay predicted from the crossed dipole sonic log is shown in Figure 4 as the blue line.

The sonic logs describe a lower rate of shear-wave splitting compared with the walkaround VSP. Such an effect is consistent with previous observations which are attributed to scale dependent anisotropy where higher frequency measurements appear to measure a lower degree of anisotropy compared with lower frequency measurements (e.g. Liu et al., 2003). Such an effect is consistent with the idea that the fracture-induced anisotropy observed with the higher frequency dipole sonic data correspond to smaller scale fractures which are less compliant than larger scale fractures that would contribute to the longer wavelength measurements obtained from seismic measurements (Hobday and Worthington, 2012).

Discussion

We extended our analysis away from the location of the walkaround VSPs by analyzing high quality crossed dipole sonic data from 11 wells over the Marcellus Shale interval. Rose plots showing the fast shear azimuths weighted by the slowness anisotropy in Figure 5. In this figure the J1 joint system is represented by the dotted green lines aligned ENE-WSW parallel to the contemporary stress direction. The maximum horizontal stress directions are also shown in Figure 5 (lower right) as a rose plot generated from 25 data points extracted from the World Stress Map project database (Heidbach et al., 2008). The J2 joint system is perpendicularly aligned to the Allegheny Structural Front (the solid black line in Figure 5) and changes orientation from ESE-WNW to a more NW-SE direction moving in a NE direction across Pennsylvania. Thus it can be seen that towards south west Pennsylvania the joint systems are more obliquely oriented to each other whereas to north Pennsylvania they become more orthogonal. The fast shear azimuths observed in the Marcellus Shale generally track the J2 directions. This result was surprising as the canonical expectation and general observation is that open fractures and the fast shear azimuth are generally aligned in the maximum horizontal stress direction. However, these fast shear wave azimuths suggest that the J2 fractures are sufficiently compliant to result in azimuthal anisotropy. This hypothesis is supported by a recent review of the Marcellus Shale subsurface fracture system (Wilkins et al., 2014) where the J2 fractures (referred to as Cross Strike Veins due to the mineralization in the fractures) were found to be partially open due to the presence of euhedral/blocky minerals. However, in 4 other wells the fast shear azimuth was more consistent with the J1 direction thus it is likely that lateral variability exists within the Marcellus Shale that leads to changing fracture properties and any resulting anisotropy.

The presence of a partially open fracture system that follows the J2 system may partially explain the presence of increased productivity in southwest Pennsylvania. In this area, the J2 fractures are aligned obliquely to the contemporary stress and as a result may be more easily reactivated by shear slip during hydraulic fracture stimulations compared with the fractures located to the north where the stress field and fractures are more orthogonal.

Conclusions

A robust statistical approach has been developed to process walkaround VSP data. We found a low degree of fracture induced anisotropy aligned in an ESE direction. This direction was surprising as the expectation was to find a fast shear azimuth aligned with the contemporary ENE stress direction. Based on this finding we expanded our analysis to review the fast shear azimuth measured over the Marcellus Shale interval from crossed dipole sonic logs. We found that in most cases the fast shear azimuth appeared to be tracking the J2 fracture system rather than the J1 fracture system which coincidentally is aligned ENE with the contemporary stress direction. This suggests that the J2 system is partially open and may explain the increased productivity observed in south western Pennsylvania.

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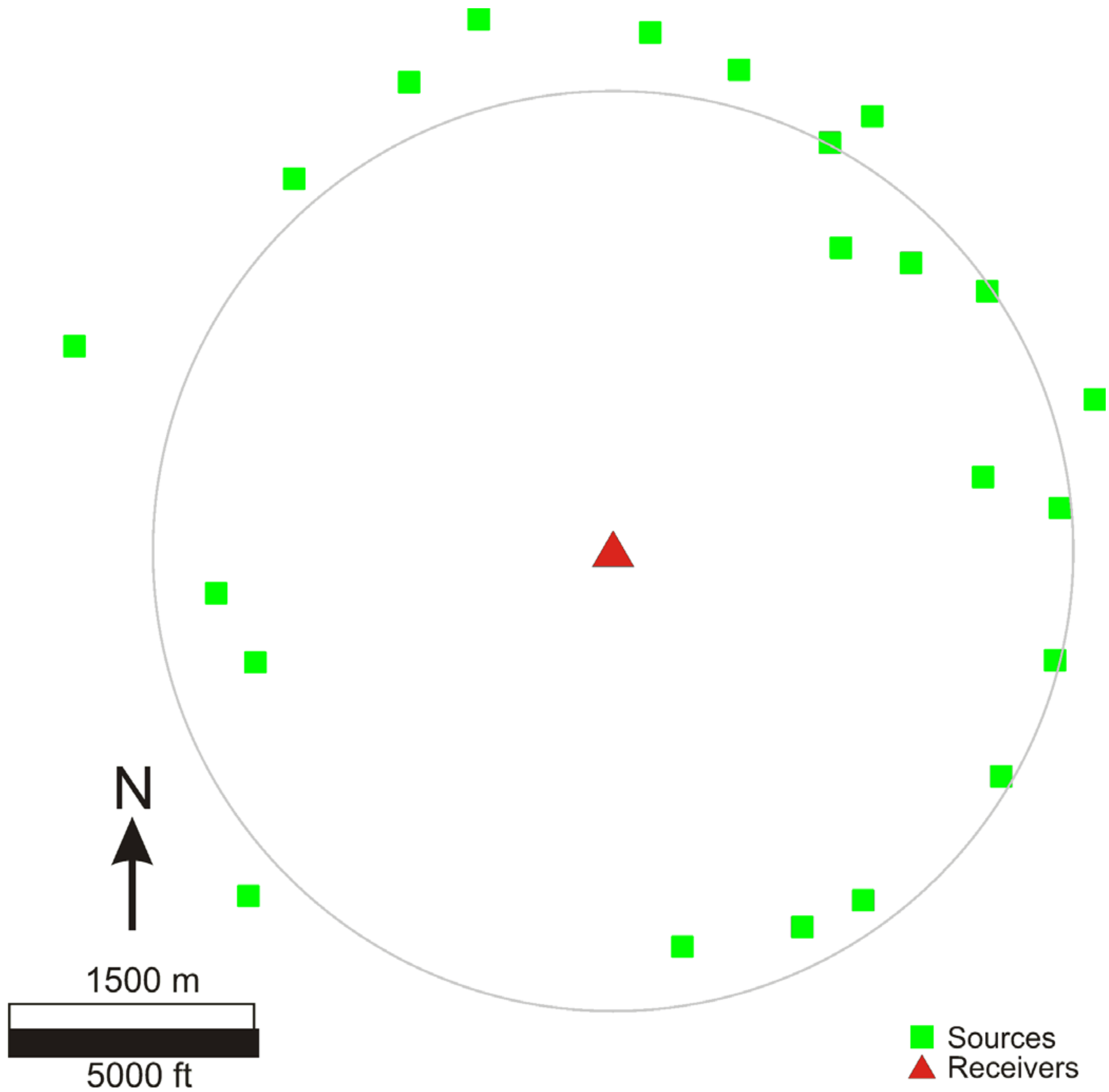

Figure 1. Plan view of the Walkaround VSP acquisition geometry. Green squares denote source positions and red triangles denote receiver positions. The grey circle indicates the average source receiver offset.

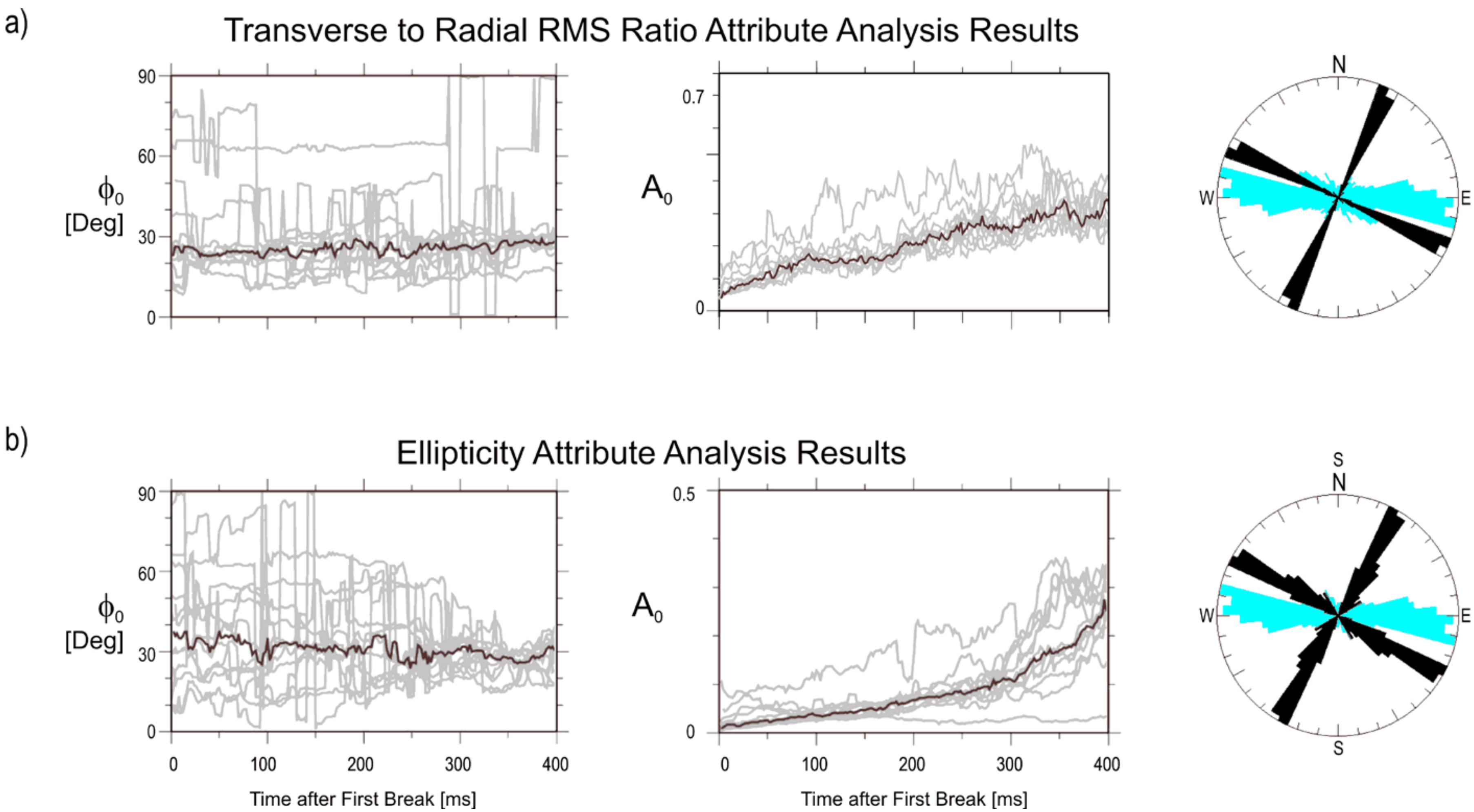

Figure 2. Azimuthal analysis results as a function of time after the first break for the (a) Transverse to Radial attribute, and (b) the ellipticity attribute. Rose plots to the right show a summary of the estimated ϕ_0 (black petals) compared with the slowness weighted fast shear azimuth over the Marcellus Shale interval (cyan petals).

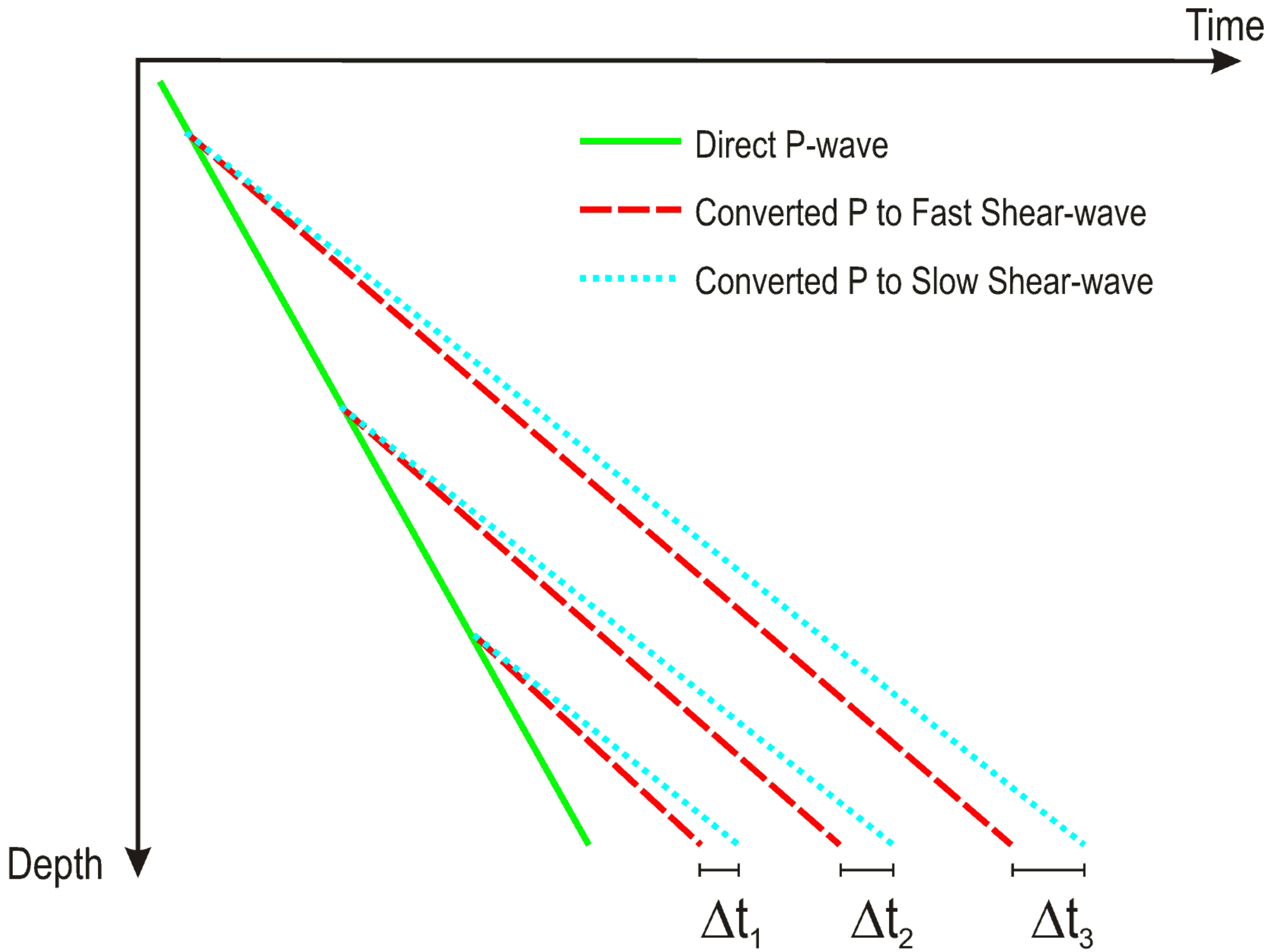

Figure 3. Schematic illustration showing how shear wave splitting can be expected to increase with time after the direct arrival.

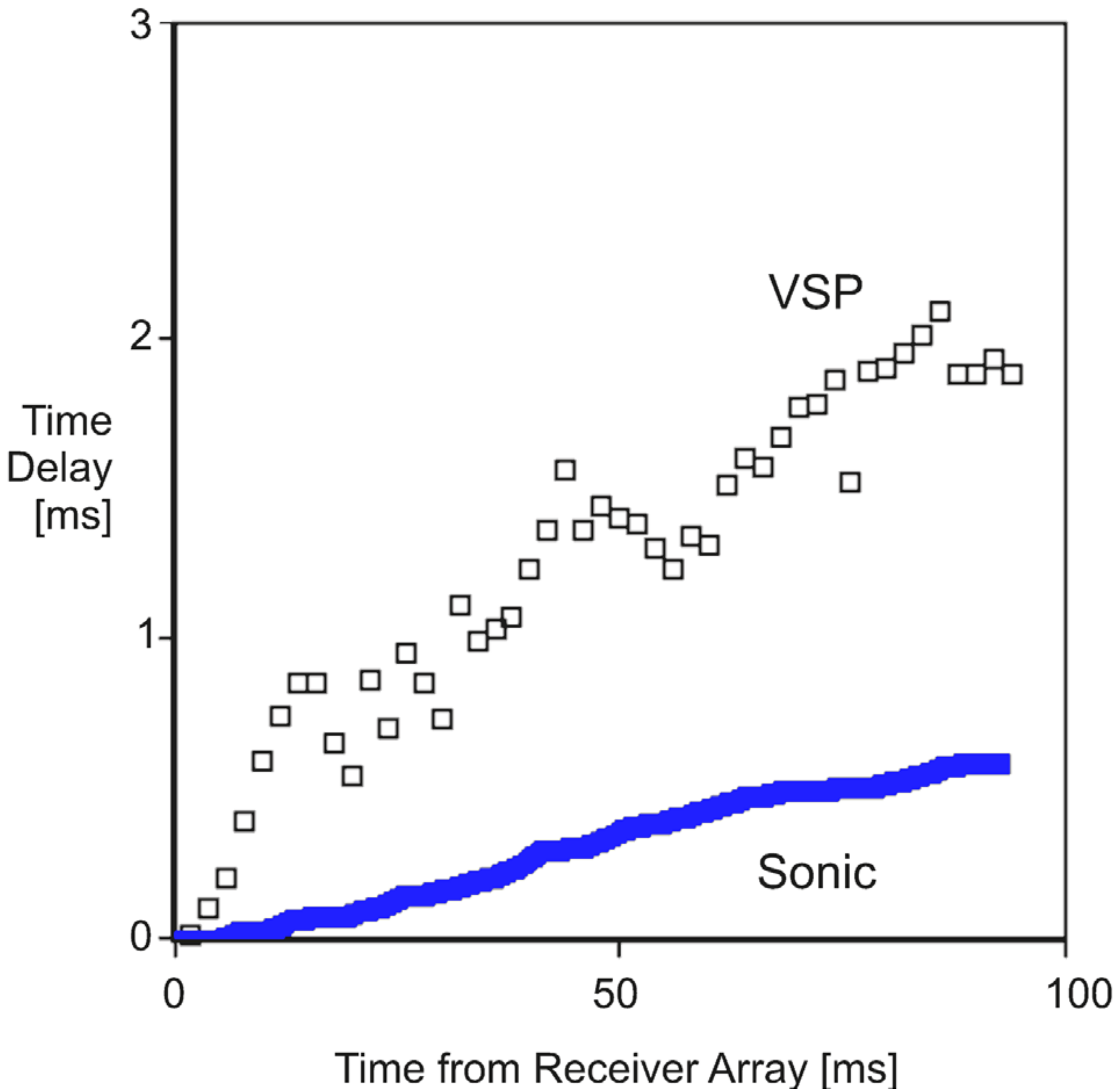

Figure 4. Cumulative time delays estimated from the walkaround VSP ellipticity analysis (black squares) and from the crossed dipole sonic data (blue line) measured as a function of fast shear-wave time computed relative to the center of the receiver array.

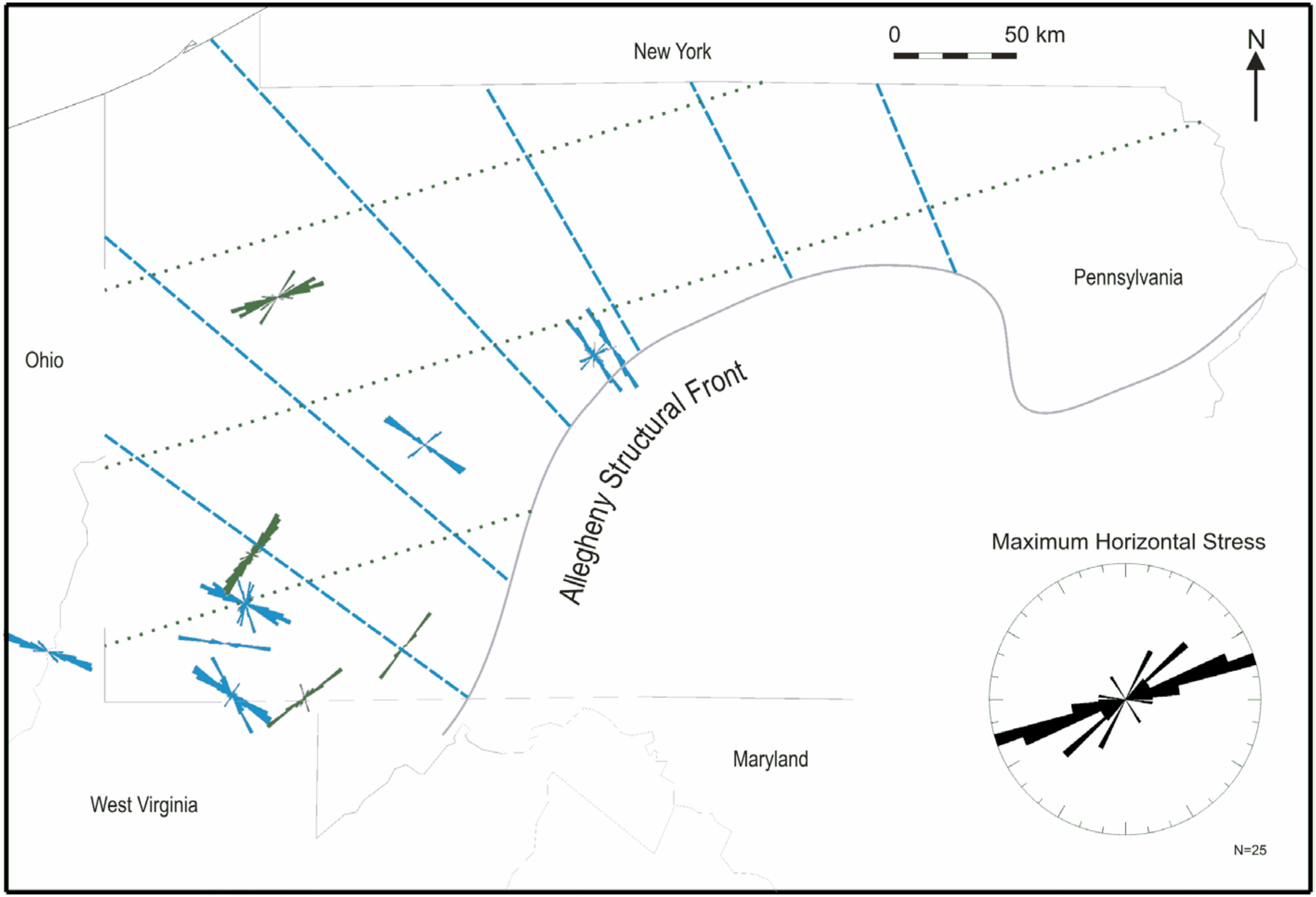

Figure 5. Schematic representation of the J1 and J2 directions (dashed blue and dotted green lines) overlain with rose plots of the slowness anisotropy weighted fast shear azimuths from crossed dipole sonic logs over the Marcellus Shale interval. The rose plots are colored blue if closer to the J2 direction and green if closer to the present day maximum horizontal stress direction. The rose plot shown in the bottom right is a rose plot of maximum horizontal stresses from the World Stress Map project (Heidbach et al., 2008).