Seismic anisotropy in microseismic event location analysis

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Seismic velocity anisotropy has been known for many years to be an important factor in correctly imaging subsurface structures with reflection seismic methods (Alkhalifah et al., 1996). Fine vertical velocity layering naturally gives rise to VTI (vertical transverse isotropic) velocity in which seismic-wave velocity is faster in the horizontal direction than in the vertical direction. Similarly, vertically oriented natural fractures and stress fields influence seismic velocities in an azimuthal or compass direction which is described as HTI (horizontal transverse isotropic) velocity variation (Schoenberg and Sayers, 1995). HTI velocity analysis in seismic reflection imaging commonly has two main objectives: placing geologic features in the correct spatial location and characterizing fracture orientation and density to optimize oil and gas production strategy.

While others have shown the importance of including VTI corrections when locating microseismic events (Maxwell et al., 2010), we have found through our work in microseismic imaging that including both VTI and HTI seismic velocity anisotropy is necessary to correctly locate microseismic events associated with hydraulic fracture stimulation. The purpose of this paper is to discuss some fundamental elements of how HTI and VTI affect correct location of microseismic image points and show an example of the effects. The example that we show is for P-waves only as the method we use to locate microseismic events does not require the S-wave (Fuller et al., 2007). S-wave anisotropy, which is often more complicated than P-wave anisotropy because of the splitting of the wavefield into fast and slow modes, will certainly play a significant role when utilizing "earthquake location" type methods that require both P-waves and S-waves for microseismic event locations.

Wavefront particle motion plots for HTI media

In map view, a seismic wavefront expands away from a microseismic event location in a way that is similar to the wavefront that expands at the water's surface when a rock falls into a calm body of water. Figure 1 shows a map view sketch of sequential wavefront positions in a transversely isotropic medium in a 1D velocity field after a disturbance in the medium, such as a rock falling into a pond or a microseismic event. The expanding circles show where the wavefront would be at sequential times (t_1, t_2, etc.). The expanding circles also show the direction of the wavefront and the P-wave particle motion, which is normal to the wavefront as indicated by the red arrow. Seismic energy will have traveled perpendicular to the wavefront from the point of origin at the center of the circles to any point in the transversely isotropic medium. In a transversely isotropic medium, the raypath will be a straight line in the horizontal XY plane.

Figure 2 shows an expanding wavefront that is similar to Figure 1; however, the wavefront is expanding in an azimuthally anisotropic (HTI) medium. In this example, we represent

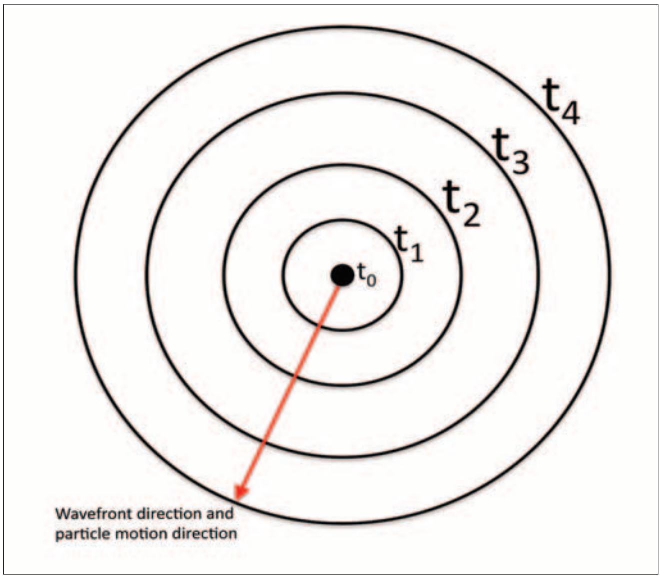

Figure 1. *Map view of the seismic wavefront expanding in a 1D isotropic velocity field. The wavefront is shown at sequential times (t_1, t_2, etc.). Particle motion is normal to the wavefront and raypaths are along a straight line in the XY (horizontal) plane.*

this wavefront as an ellipse rather than a circle as in Figure 1. The elliptical shape of the wavefront is because of the wavefront having travelled farther in the fast velocity direction than in the slow velocity direction over the same amount of time. While it has been shown that wavefronts in HTI are elliptical only for small angles of incidence, we have found that using an elliptical approximation is acceptable for our applications. Figure 2 also shows arrows perpendicular to the wavefront at various locations. The arrows indicate the direction of P-wave particle motion at those locations. Particle motion direction is a critically important measurement in locating microseismic events when using three-component downhole geophones because the particle motion information provides the direction from which the microseismic event wavefront arrives at the geophones. Figure 3 shows one of the key points of this paper by demonstrating how a microseismic event can be incorrectly located if an isotropic velocity field is assumed in the presence of actual anisotropic velocities. Figure 3 is a close-up map view of the elliptical wavefront in Figure 2 and it is assumed that an observation well contains three-component geophones at the point P. The arrival angle of the P-wavefront in the anisotropic medium from a microseismic event shown as the red arrow perpendicular to the wavefront while the arrival angle of a wavefront assuming a homogeneous isotropic medium is shown as a black arrow. If the microseismic data are processed assuming an isotropic velocity field, then the microseismic event will be mapped as having occurred along a straight line in the trajectory of the anisotropic raypath, which is incorrect. If anisotropy is correctly accounted for in microseismic mapping, assuming a correct velocity field, then

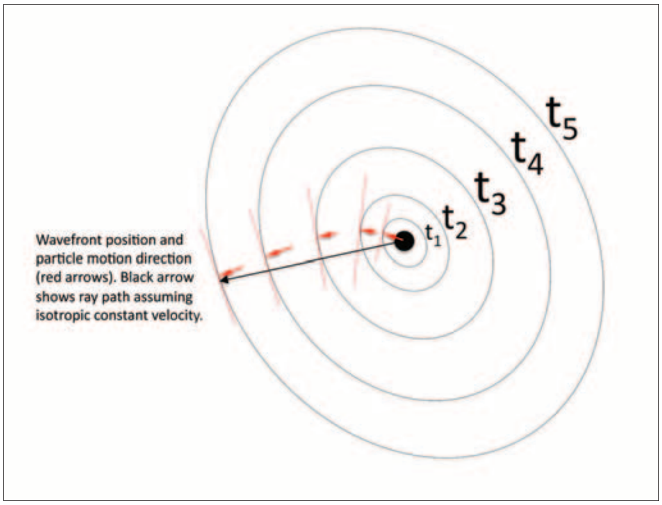

Figure 2. *Map view of the seismic wavefront expanding in a 1D anisotropic velocity field. The wavefront is shown at sequential times (t_1, t_2, etc.). Particle motion is normal to the wavefront. The ellipse shown has a major axis length of 1.0. The minor axis has a length of 0.8. This represents an anisotropy value of about 0.2 which is large but within the range of measured HTI values. The large anisotropy value was chosen to make the figure easy to see. The red straight lines are tangents to the ellipse. Red arrows show the wavefront position and particle motion. Black arrow shows the raypath for constant isotropic velocity.*

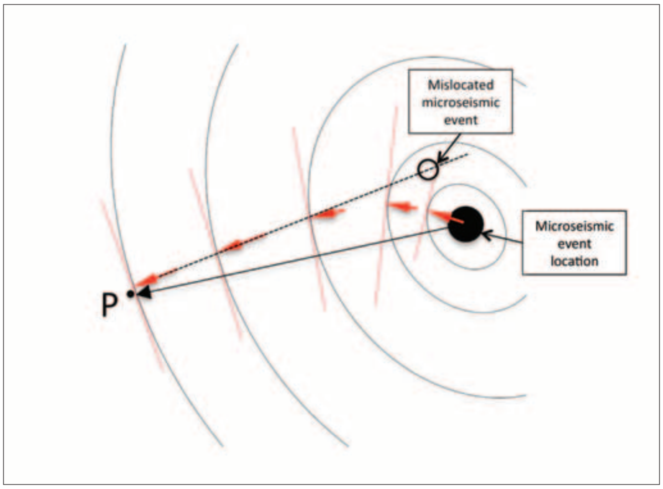

Figure 3. *Close-up view of particle motion for isotropic (black) and anisotropic (red) velocity fields arriving at point P. Particle motion measured by a three-component geophone at point P would be the particle motion of the red arrow. If an isotropic velocity model is assumed in the data processing, then the microseismic event location will be projected back along the direction of particle motion of the red arrow (along the black dotted line) which will place the event in the wrong location. Correct location of the microseismic event can be determined only if the particle motion due to the anisotropic velocity field is accounted for.*

the particle motion direction in the XY plane will lead to a correctly located microseismic event.

Suppose that there is only a 4° difference between the isotropic and anisotropic raypath angles in Figure 3. If the event occurs 1500 ft from the observation well, then the component of horizontal location error due simply to ignoring anisotropy will be in excess of 100 ft in the transverse direction, which is in addition to other radial positioning errors caused by incorrect velocity assumptions. While this angle difference depends on many factors, the real data example we show below indicates that errors of this magnitude may result from HTI values of only a few percent. In practice, we find that HTI anisotropy ranges from values of 0.0 to as high as 0.20 (defined at the ratio of the difference between the fast and slow horizontal velocity divided by the fast horizontal velocity). The use of string shots and perforation shots at known locations over a range of azimuths is the most certain way to measure and account for HTI velocity variations. There is often a good agreement between the seismically derived anisotropy direction and that obtained from sonic logs, provided the sonic log is in close proximity to the microseismic survey. While it is common in the industry to produce a new isotropic velocity model for each fracture stimulation stage in a project, including anisotropy in the model allows us to derive a single model that correctly images all known events for all stages.

VTI media

The vast majority of, if not all, sedimentary rock volumes in nature exhibit VTI velocity behavior. VTI is particularly pronounced in shale formations, which includes a majority of economically important geologic formations under hydraulic stimulation today. Accounting for VTI in microseismic event locations from downhole 3C geophone data is as important as correctly accounting for HTI factors and for the same reason—accuracy of the microseismic event location. In addition, the increasing use of long 3C receiver arrays or multiple shallow 3C arrays make this even more significant because it effectively increases the range of angles of incidence recorded. The arguments shown above in Figure 3 for HTI are largely applicable to VTI arguments except that in the VTI case we are concerned with vertical positioning of the microseismic event location. Because the VTI arguments are so similar to the HTI case, we forego a significant discussion of VTI for purposes of this paper. In our imaging methodology, we use the Thomsen anisotropy values of epsilon and delta to describe the velocity variations in the vertical plane (Thomsen, 1988).

Real data example: velocity models and event locations

Figure 4 (left panel) shows a map view of microseismic event locations recorded in the marked observation well. The treatment well (marked with multiple colored dots at perforation and sliding sleeve points) is a horizontal well with multiple perforation points in the Bakken Formation in North Dakota. The perforations were generated with explosives that also provide an excellent seismic signal from a known location. The P-wave events received from perforation shots and sliding-sleeve closures were used to orient horizontal geophone components and build a velocity field for microseismic event imaging. The bandwidth of these events was approximately 65–250 Hz. The initial isotropic velocity model was derived from a nearby P-wave sonic log. Perforation events from a range of horizontal source-receiver azimuths and vertical in-

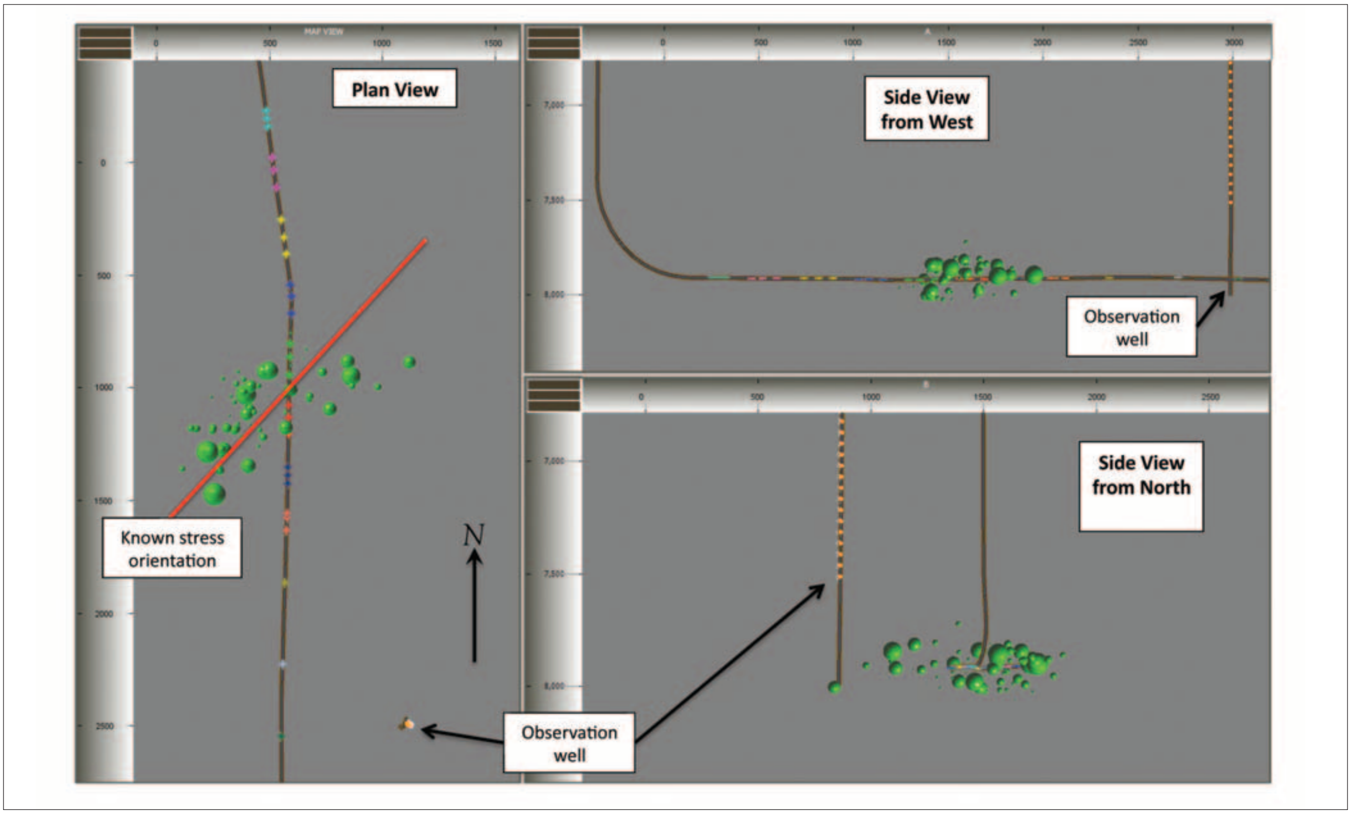

Figure 4. *Views from perspective points above (left), from the west (top right) and the north (bottom right) of microseismic event locations. These events are from a fracture stimulation stage in the Bakken Formation of North Dakota. The events were located using the anisotropic velocity field that correctly located the perforation shots and sleeve-closing events at their known locations. A dominant stress field is annotated on the map view. The HTI anisotropy value was 0.07 and VTI (epsilon) values varied between 0.0 and 0.18, depending on rock type and depth of the velocity field. The observation well is indicated with orange dots showing the location of the receivers. The multicolored crosses show the locations of the perforation points within the treatment well.*

clinations were then used to determine P-wave HTI and VTI velocity parameters. The specifics of this operation are beyond the scope of this paper. The range of source-receiver azimuths for the example in Figure 4 covers a horizontal angle of more than 100°. The vertical range of inclination angles for these perforation events into the 45-level receiver array is more than 60° (i.e., near vertical to about +70°).

Among the criteria used to determine a complete velocity field for 3D microseismic event location is that correct event locations must be obtained for all known events (perforation shots, string shots, and sliding sleeves) using a single velocity field. The velocity field can be fully 3D with structural constraints provided by 3D seismic and well control. Anisotropic parameters must generally be derived from the recorded borehole seismic data including perforation events, string shot events, and other seismic sources including surface seismic sources. Surface sources, however, do not typically provide the resolution needed for this level of analysis and will include the cumulative effects of the overburden anisotropy.

To demonstrate the importance of including anisotropy in the velocity field, we perturbed the best velocity field that correctly located all perforation shot events. The perturbations included changes only in the HTI and VTI anisotropy parameters. The original velocity model had an HTI anisotropic percentage of 0.07 with the fast direction trending in the direction N15E and VTI anisotropy (epsilon) between 0.0 and 0.18, depending on rock type in the vertical section. Delta was held constant at 0.001. The perturbation set the HTI and VTI (epsilon) value to zero (i.e., isotropic) without changing the underlying velocity values. We then located the cluster of events in Figure 4 using the perturbed (isotropic) velocity field and observed the change in event locations.

Figure 5 shows that the contribution of anisotropy to the overall velocity model is significant in that the perturbed velocity field moved the microseismic events hundreds of feet in the horizontal plane and approximately 100 ft vertically.

While this perturbed velocity field would not have been used to locate microseismic events, the demonstration shows the sensitivity of event locations to the correct HTI and VTI parameters. Recall that the base velocity field did not change at all for this demonstration; only HTI and VTI parameters were changed.

Conclusions

The mechanisms and importance of anisotropic velocity fields have been shown regarding the accuracy of microseismic event locations. Anisotropy parameters can be estimated from the downhole source data that is usually acquired during a microseismic monitoring project. This can be done through string shots, perforation shots, crosswell surveys, and even surface seismic sources from a range of

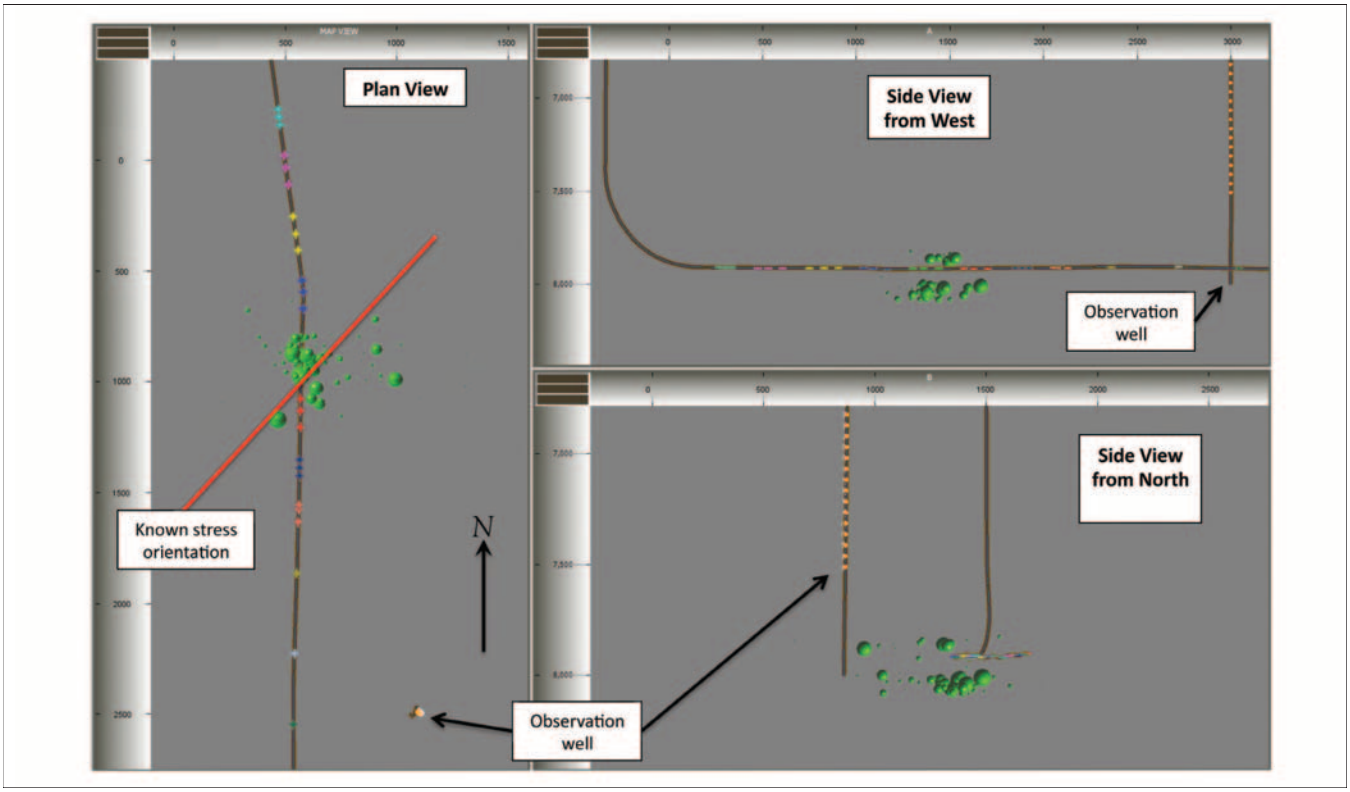

Figure 5. *The same microseismic events shown in Figure 4 but with the anisotropic terms removed from the velocity field prior to locating the microseismic events. The events move many hundreds of feet horizontally and as much as 100 ft vertically from the locations determined using the correct anisotropic velocity field. This demonstrates that the anisotropic terms are important, particularly given that there was no isotropic velocity model that correctly positioned all the perforation shot and sliding-sleeve events and therefore could not have, in general, correctly positioned the microseismic events.*

azimuths. These parameters can and should be included in the final velocity model in order to produce more accurate event locations. Given these results, it is apparent that part of the design criteria for microseismic surveys should include measurement of anisotropic parameters. Consumers of microseismic results can use this outcome as an indicator of questions to ask microseismic service providers as part of the quality control process. TLE

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