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Relaxing the near-surface assumption in estimating 3C receiver orientations: azimuth-stack power optimization of reflected PS data

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Summary

In land multi-component (MC) data processing, the orientation of each receiver's horizontal components in the field (H1 and H2) is seldom known accurately. Methods that try to derive the orientations from the recorded data are in common use. They work by assuming a homogeneous, isotropic near-surface earth model and derive an orientation using P-wave first arrival amplitudes on the horizontal components. These methods aim to find a solution that maximizes the P-wave first-break energy on the radial component and are known to work very well on marine OBC/OBN data and downhole VSP data. For land data, the near-surface is often strongly inhomogeneous and anisotropic. The P-wave first break methods can therefore fail due to near-surface scattering, anisotropy etc. Further, the estimated orientations derived from such methods may not be close to the true orientations. We show examples that clearly illustrate the deviation of the P-wave first break amplitudes that are recorded on the horizontal components from what is expected from a homogeneous near-surface earth.

Estimating receiver orientations from the analysis of reflected PS data may be less influenced by the near surface than methods that analyze first-breaks because of the near vertical ray path of reflections near the surface. We present a new method for obtaining orientation estimates that analyses reflection data on the horizontal components. This method allows either the presence or absence of HTI anisotropy. The method is based on maximizing the azimuthal-stack power of radial component reflection data and/or minimizing the azimuthal-stack power of the transverse component. We test this method on real 3C/3D dataset where the true orientation of the H1 component is known.

Introduction

Conventional MC processing requires estimating the orientation of the horizontal components of the receivers from the data. These estimates are used to rotate the horizontal components to radial and transverse directions for further processing. Most methods of estimating the orientations assume a homogeneous isotropic earth model. They use first-break analysis of the P-wave first arrivals that are measured on the horizontal components to determine the respective orientations using vector decomposition. It can be shown that for simple earth models the P-wave first break waveform follows a radiation pattern whose amplitudes change polarity at a specific source-receiver azimuth depending on the orientation of the horizontal component sensor. Analytical methods can be used to determine the orientation estimates for each source-receiver pair and then to determine a statistical average (mean or median) to obtain the best fit measure (e.g. Dellinger *et al.* (2001); Bale *et al.*(2012)). Hodogram analysis of each shot-receiver pair followed by a best fit value over all shots for a given receiver is also proposed (Guevara & Stewart (1998), Burch *et al.* (2005)). More recently, a projection method that scans a range of angles to obtain the maximum objective function followed by global analysis of the objective function was proposed (Grossman & Couzens (2012)). After orientation estimation and rotation to radial and transverse components, one expects to observe maximum P-wave first-break energy on the radial and minimum P-wave first-break energy on the transverse component.

Burch *et al.* (2005) have discussed at length why the assumption of a simple earth model such as that used by first-break methods does not necessarily hold. They have shown that near-surface complexities can change the apparent source-receiver azimuth and affect the behavior of P-wave first arrival amplitudes considerably. In addition, near-surface anisotropy may be changing the polarization of P-wave arrivals. Thus it seems that using a criterion that maximizes the P-wave energy on the radial component may fail to give reliable receiver orientations.

In this abstract, we start with examples showing when first-break methods do work well and when they do not work well. Then, we propose the azimuth-stack power method that obtains the orientation estimate from reflected PS energy rather than from P-wave first-breaks. This new method finds a solution that maximizes the power of the stack over azimuth of the NMO-corrected PS reflections on the radial component. This is equivalent to minimizing the azimuth-stack power on the transverse component. The potential advantage of this method is that, since the reflected PS events have nearly vertical raypaths near the surface, they should not be affected as much by the near-surface variations that affect the first-break methods.

Theory and Method

We have observed the radiation pattern of P-wave first break amplitudes on H1 and H2 components in many datasets and found that it is not always close to the expected. We use the Blackfoot 3C/3D dataset for illustration since the orientation of the H1 component of the receivers is reliably known. We observed that for most receiver gathers, the radiation pattern deviates from the expected radiation pattern moderately to significantly (Figures 1 and 2), despite good quality first-break picks. In Figure 1, vertical component data is shown for two receiver gathers. The blue line identifies the first break times. The first breaks were picked on trough maxima. It can be seen that the quality of first break picks is reasonable. In Figure 2, data from the horizontal components for the same two receiver gathers are shown. At the vertical component's first break times, the amplitudes were extracted on corresponding H1 and H2 components. The two receiver gathers are shown in Figures 2c and 2d with the first break times as indicated by the blue line in each. A map of amplitudes for the corresponding two receiver gathers is shown in Figures 2a and 2b. In the map display, each amplitude value is plotted at the corresponding shot location relative to the receiver location. The positive amplitudes are identified by red squares and blue squares identify negative amplitudes, with the receiver location identified by a triangle. The quality of the P-wave amplitudes on the H1 and H2 components appears reasonable. However the radiation pattern in Figure 2a is close to the expected while the one in Figure 2b is suggesting that the first breaks are significantly affected by near surface heterogeneities. This observation is consistent with the findings of Guevara and Stewart (1998), Burch et al. (2005) and Bale et al. (2012). In general, we find that the statistical average of the orientations estimated from all receivers in the survey corresponds very well with the actual receiver orientation, but the deviation of individual receivers from the average value that is indicated by the first-break methods is untrustworthy, regardless of which first-break method is used for the analysis. This finding is inconsistent with the findings of Grossman and Couzens (2012). In our estimation, a more reliable method of estimating the receiver orientations is needed.

The effect of anisotropy (vertically aligned fractures) on radial and transverse components is discussed by Cary (2002). The traveltime of a PS-wave reflection event that passes through a single anisotropic medium of vertically aligned fractures varies with azimuth. On the radial component, the reflections follow a sinusoidal pattern. On the transverse component, the reflection amplitudes undergo an abrupt polarity change every 90 degrees, so the stack over azimuth of the transverse component is small in magnitude when the receiver orientation is correctly estimated. If the receiver orientation is incorrectly estimated, then the true radial energy partly appears on the estimated transverse component and the expected abrupt polarity change every 90 degrees becomes smeared. In this case, the magnitude of the azimuth-stack of the transverse component will be larger in magnitude than with the correct receiver orientation. So the azimuth-stack power of the transverse component is a minimum at the correct receiver orientation. In the absence of vertical fractures, the power of the azimuth-stack is also a minimum on the transverse component. Therefore an objective function that minimizes the azimuth-stack power of the transverse component should work in the absence of anisotropy or in the presence of a single anisotropic layer. Furthermore these objective functions should be less affected by scattering in the near-surface than the first-break methods.

The azimuthal-stack power on the transverse and radial components can be written as;

$$Et(\tau) = \sum_t[\sum_i(H1_i(t)\sin(\propto - \theta_i) + H2_i(t)\cos(\propto - \theta_i))]^2 \qquad (1)$$

$$Er(\tau) = \sum_t[\sum_i(H1_i(t)\cos(\propto - \theta_i) - H2_i(t)\sin(\propto - \theta_i))]^2 \qquad (2)$$

Where *Er* and *Et* are the power of the radial and transverse stacks respectively over a time window centred at τ, *H*1 and *H*2 are the measured horizontal component amplitudes at time *t* within the time window, α is the test angle, θ is the shot-receiver azimuth and the subscript *i* is the trace index. The summation over traces of variable azimuth and over time *t* is as shown in equations (1) and (2). To prevent the well-sampled azimuths from biasing the calculation over the poorly-sampled azimuths, partial stacking into discretely sampled azimuths can be done before calculating equations (1) and (2).

To determine the best fit α and thus the orientation, we used the objective function that maximizes the stack power on the radial component. Equivalent results are obtained if one chooses to minimize the power of the transverse stack or to maximize the difference between stack power of radial and transverse components.

Examples

We performed our tests on the Blackfoot 3C/3D dataset where the orientation of the H1 component of each receiver is reliably known to be 90 degrees clockwise from North. NMO and statics corrections were applied to the H1 and H2 components before analysis. A window of reflection data in an offset range with reasonable signal quality was selected. The proposed method was applied to the data. The best fit orientation estimate was obtained for each receiver gather and a statistical average of all receiver gathers was also obtained. The statistical average of the estimated orientations corresponds to the true orientation of 90 degrees from North for the H1 component. There are also instances of individual receivers that are estimated to have significant deviations from the true orientations. The source of these deviations is still being investigated. A significant limitation of the azimuth-stack power method is the fact that quite a limited number of traces within each receiver gather are available for the analysis of shallow reflectors, so the method is limited by the noise.

Conclusions

Reliable orientation estimation of H1 and H2 sensors is necessary for maximizing the potential of shear waves. Current standard methods assume a homogeneous isotropic earth and can then use vector decomposition of refraction data to obtain the orientation estimate. Near surface complexities due to scattering or anisotropy often change the behaviour of wave propagation and thus the standard methods can fail.

We have proposed a method that maximizes the stack power over azimuth on the radial component PS reflections. This method promises to work when the medium is isotropic or in the presence of a single anisotropic layer and is less affected by the near surface. Thus the method may be better suited for orientation estimation than methods that assume a homogeneous isotropic near-surface.

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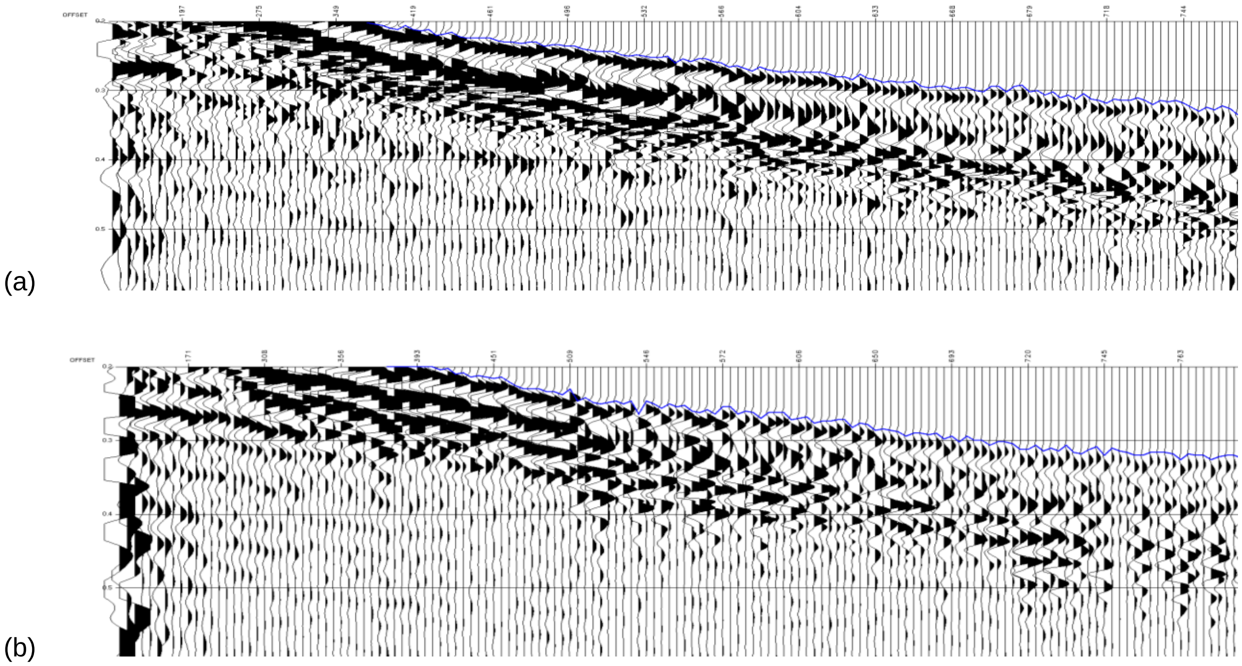

Figure 1. The vertical component data for two receiver gathers. The first break was picked on trough maximum and the quality of first break picks (blue line overlaying the gather) appears reasonable.

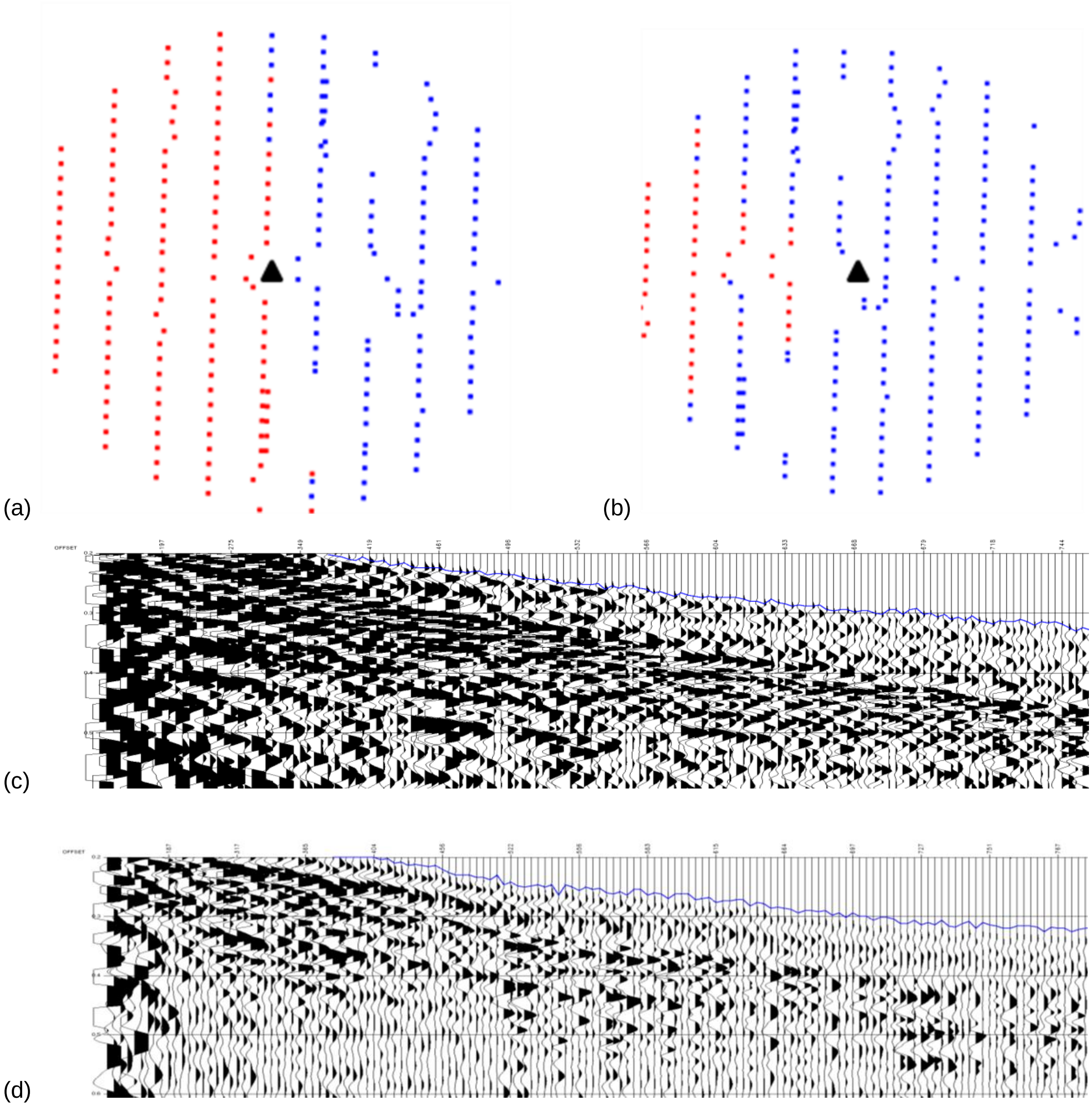

Figure 2. The P-wave radiation pattern on H1 component for two receiver gathers corresponding to those shown in Figure 1. (a) radiation pattern that is close to ideal, (b) radiation pattern that shows near-surface may not be isotropic, (c) receiver gather corresponding to map shown in (a), (d) receiver gather corresponding to map shown in (b). In the radiation pattern maps, the positive amplitudes are identified by red squares and the negative amplitudes by blue squares. The receiver location is shown by the black triangle.