Near-Surface Correction for Nine-Component VSP

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SUMMARY
Nonlinear source effects and the wave properties of the near-surface layers affect the anisotropic interpretation of a subsurface target zone using multicomponent data. Nine-component VSP are processed to correct for these effects using a non-linear deconvolution operator. The depth at which the operator is applied is determined by the unitary property of the subsurface wave propagation. The results appear encouraging.

INTRODUCTION
It has been common to correct for the near-surface response in shear wave data by assuming it to be uniformly anisotropic (Winterstein and Meadows 1991) or anisotropic with changes in the direction of the symmetry axis (MacBeth, Li, Crampin and Mueller 1992). These corrections rely upon a downgoing transmission response for the subsurface $M(\omega)$ for which the unitary product $M^{\ast T}(\omega)\cdot M(\omega)$ equals a unit or diagonal matrix. Here, $\omega$ represents the temporal frequency, with the asterisk representing complex conjugation, and the superscript $T$ a transpose matrix. It is unlikely that this assumption will be generally applicable for low velocity heterogeneous near-surface layers, or layers which are laterally varying, dipping, attenuative and possess large joints or open fractures. In an attempt to re-address this problem, Zeng and MacBeth (1992) used a four-component general non-unitary deconvolution operator to account for non-anisotropic wave behaviour in VSP data from the Romashkino reservoir. The present work extends and applies this deconvolution operator to a full nine-component VSP dataset.

CONVOLUTIONAL MODEL
A so-called nine-component dataset is obtained by grouping together the three-component displacement vectors, $d_y(t), d_z(t)$ and $d_x(t)$, recorded at depth level $i$ from three orthogonal source motions which are usually two horizontal shear and one vertical compressional wave source, into a 3x3 matrix of traces $D_{ij}(t)$. This grouping facilitates a compact convolutional matrix notation for analysing near-offset VSP data (Zeng and MacBeth 1993):

$$D_i(\omega) = a_i(\omega)M(\omega)S(\omega);$$  \hspace{1cm} (1)

$a_i(\omega)$ is the $q^P$ (anisotropic P-wave) scalar amplitude and time-shift, so that the transmission response for downgoing waves $M(\omega)$ can be defined in terms of the relative amplitudes and time-shifts between the three anisotropic arrivals $q^P, q^S$ (fast shear-wave) and $q^S$ (slow shear-wave). $S(t)$ is a matrix of vector source functions. Each constituent matrix of Equation (1) is defined for a common right-handed orthogonal coordinate frame (X-Y-Z) for which geophones and source motions are aligned along each axis. Z points downwards and X and Y are in-line and cross-line directions respectively.

Figures 1(a) and (b) show the downgoing wavefield $D_i(t)$, derived from nine-component VSP field data acquired at the Conoco borehole test facility in Kay county, OK. The data have been recorded between 2950’ (900m) and 500’ (153m) in increments of 50’ (15m). The shear sources are at near-offsets between 99’ (30m) and 128’ (39m) and the P-wave sources between 134’ (41m) and 163’ (50m), with a common azimuth of N279’ E relative to the well. The horizontal components of the displacement vectors have been rotated to allow for tool spin using additional far-offset P-wave data. The data in Figures 1(a) and (b) have been bandpass filtered so that the response is over a common bandwidth of 5 to 45Hz. The traces of Figure 1(a) have been normalized to a common vector amplitude for the entire matrix, whilst those for Figure 1(b) are normalized for each separate matrix component so that the finer details of the off-diagonal components may be inspected.

For anisotropy with a horizontal plane of symmetry, resulting from vertical microcracks or fine layering, or a combination of these, it is expected that there will be negligible shear-displacements (on X or Y geophones) due to the P-wave (Z) source, or vertical (Z) displacement due to the shear-sources (X and Y). The off-diagonal components $d_{iX}(t)$, and $d_{iY}(t)$, of the matrix do appear to conform to this model, but $d_{iXZ}(t)$ and $d_{iYZ}(t)$ show large compressional wave arrivals and a shear-wave arrival. All of the sections display evidence of an extended wavefield apparently propagating into the subsurface, which could be attributed to scattering, source process, or the correlation of the vibrator signal. The large off-diagonal shear-components $d_{iYX}(t)$ and $d_{iXZ}(t)$ imply a substantial birefringence in the shallow layers. As these anomalies all arise from the source and near-surface interaction, we separate the medium response $M_i(t)$ into the near-surface and subsurface effects, so that $M_i(\omega)$ becomes $L_i(\omega), N(\omega)$, where $L_i(\omega)$ is a linear anisotropic subsurface
operator acted upon by a general non-linear forcing function $N(w)$ combining the source interaction with the near-surface and which may include the effects of differential amplitude due to radiation pattern, non-dipolar sources and natural directivity. Our intention is to deconvolve the non-linear function $N(w)$ to reveal the changes in the multicomponent wavefield due to the medium.

**ESTIMATING NEAR-SURFACE RESPONSE**

It is assumed that after transmission through complicated near-surface layers, a wavefield propagates through an effectively anisotropic subsurface which contains the target zone. The incremental anisotropic operator $\Delta L(\omega)$ which connects closely spaced geophone levels is unitary (relatively lossless after compensation for absolute amplitude changes), and the ith recorded data matrix $D_i(t)$ may be expressed by a modified Equation (1):

$$D_i(\omega) = a_i(\omega)\Delta L(\omega)^{-1} N(\omega);$$

(2)

A group of VSP levels for determining the near-surface response can now be chosen using the unitary product $D(\omega)^*T \cdot D(\omega)$ (multi-component cross-power spectrum). If the subsurface is unitary then Equation (2) gives a constant value of $N(\omega)^*T \cdot N(\omega)$, which becomes the diagonal matrix of source function autocorrelations if the near-surface layers are also unitary. This should be independent of depth for recording levels where Equation (2) holds. This gives an indication of the depth to apply corrections for the near-surface operator based upon this equation. The time-domain expression of this product is shown in Figure 2(a), together with two unitary indices in Figure 2(b) giving the ratio of off-diagonal to principal-diagonal components (curve A) and the deviation of the principal-diagonals from unity (curve B). The unitary product appears reasonably consistent with depth (except for a washout zone), but starts to change below 2100’ (640m) and again below 2500’ (763m). The second of these depths coincides with a region of intense fracturing, where it is likely that excessive attenuation will cause a breakdown of the unitary assumption. Therefore, it appears that the data are suitable for deconvolution based upon the shallowmost traces.

**NEAR-SURFACE CORRECTION**

Firstly a least-squares estimate is obtained for the local transfer function $\Delta L(\omega)$, and then $N(\omega)$ is obtained by minimizing the error between the recorded data matrices $D(\omega)$ and the estimates $\{\hat{\Delta L(\omega)}\}^{-1} \cdot \hat{N(\omega)}$. Deconvolution can now be applied by post-multiplying the recorded data matrix with this estimate of the inverse overburden operator. It is applied to the data of Figure 1 and is shown in Figure 3. The extended waveforms for the shallowest levels have now been collapsed, some of the energy on the off-diagonal components has reduced, and there now appears to be a prominent arrival emanating from the 1200’ (366m) level. The deconvolution breaks down for the deepest traces from within the highly fracture zone. The off-diagonal wavefield for the shear-wave sections now slowly evolves with depth indicating a weak anisotropy in the layers below 500’ (153m). Anisotropic analyses of the shear-waves give identical polarization azimuths and birefringences to those obtained by interval measurements (Lefeuvre et al. 1992), and confirm that the deconvolution does not distort the shear data.

**CONCLUSIONS**

Near-surface correction using a general non-unitary matrix operator appears to provide a satisfactory way of deconvolving nine-component VSP data. We suggest that this procedure is particularly useful for analyses where we seek to correlate target zone birefringence with fractures and production rates, but may also be used for highlighting strong subsurface anomalies. A unitary product of multicomponent trace matrices may be indicative of fracturing (or any other at tenuative process). The present work will be extended to include full-wave modelling results of the dataset.

**REFERENCES**


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Figure 1. Nine-component downward transmission response derived from a VSP shot at the Conoco test facility, Kay County, OK. Data are bandpass filtered between 5 and 45Hz, and corrected for tool spin, so that the three geophones and source motion are aligned along in-line (X), cross-line (Y) and vertical down (Z) directions. The trace notation IJ gives the geophone along the J-axis recording the source motion along the I-axis. (a) the traces are normalized to the maximum vector amplitude; (b) the traces are individually normalized so that the off-diagonal behaviour may be seen.
Figure 2. (a) Time-domain expression of nine-component unitary product of data matrices $D^T D$. The principal diagonal gives the three autocorrelation functions of the displacement vectors. (b) Depth dependence of unitary indices indicating closeness of each trace set to a diagonal unitary product. Curve A gives the ratio of off-diagonal to principal diagonal amplitude, curve B is the deviation from a unit matrix.

Figure 3. Nine-component data from Figure 1 corrected by a general non-unitary near-surface operator based upon the shallowest traces.