The effect of location error on microseismic mechanism estimation: synthetic and real field data examples

Michael Kratz[1] and Michael Thornton[1] present an issue that is of primary concern for all basins and imaging techniques.

The decomposing of the full moment tensor of microseismic events observed during hydraulic fracture stimulations into double couple (%DC), compensated linear vector dipole (%CLVD), and isotropic (%ISO) components has been shown to be useful for making more complete characterizations of these events (Williams-Stroud, 2008). While this information about the nature and geometry of a fracture is important and very telling, any source of potential error in these decompositions must be taken into account. One source of particular importance to microseismic monitoring is the effect of location error on the full moment decomposition. With this type of analysis becoming more prevalent, there is concern as to whether the effect of location error on potential interpretations and recommendations based on microseismic fracture geometry is thoroughly understood.

Moment tensor inversion of microseismic data is an immensely powerful interpretation tool. An understanding of the nature of the rock failure supports the development of discrete fracture networks (DFN), reservoir simulation models, and stimulated reservoir volume estimates. Such interpretations are a large part of the driving force behind the growth in microseismic monitoring. Furthermore, a proper characterization of the event mechanism is necessary in full waveform imaging of microseismic data to properly account for the radiation pattern of the signals (Duncan, 2010).

While determination of event strike, dip and rake can provide the geometry of the fracture plane, full moment inversion and decomposition provides insight into the shear versus tensile nature of the fracture planes. Historically, this has been presented through source component plots (Hudson, 1989) and tensile parameter analysis, which is commonly displayed in global earthquake seismology (Vavryčuk, 2001). However, interpretations are often made without considering possible sources of error in the decomposition itself. Given the non-unique nature of the deviatoric component of the moment tensor, it is important to include possible sources of noise in the moment tensor to ensure a reliable solution. The idea of errors and noise being introduced into moment tensor decomposition has been assessed in detail in earthquake seismology (Vavryčuk, 2001; Vavryčuk, 2002), but remains mostly dismissed in microseismic analysis. While many sources of error are cited in such seismology studies, this paper will focus on event location error as this is a primary calibration concern for all basins and imaging techniques.

Method

The automatic moment tensor solution, shown below, computes an estimated tensor via waveform fitting of the recorded data. Given an estimate of the event location and origin time, the vertical ground motion at a receiver ($u_i(t)$) can be modelled as (Aki and Richards, 1980):

$$u_i(t) = G'_{ij}\, m_j * s(t)$$

where $\boldsymbol{m}_j$ is the vector of six unique moment tensor elements, and $s(t)$ is the source time function. G'_{ij} is a matrix of the spatial derivative of the Green's function which captures the effects of source receiver geometry and wave propagation.

An estimate of the source function can be derived from the recorded data (d_i) and the event location and origin time ($x0$, $y0$, $z0$, $t0$) via the beamforming operator:

$$\hat{m} = \arg\min \sum_i \left(d_i(t) - G'_{ij}\, m_j * \hat{s}(t) \right)^2$$

where $G_i^{-1}(x_0, y_0, z_0, t_0)$ is the approximate inverse Green's function for receiver i and a source at the estimated event position and origin time, and the summation is taken over all (N) traces in the array. Thus, the source function is represented by the stack of data traces move out, which is corrected for the eaten source location and origin time.

The estimated source time function is used to determine the estimated moment tensor by minimizing the squared difference between the recorded data trace at each receiver and the modelled data trace (Sipkin, 1982; Song and Toksov, 2011):

$$\hat{m} = \arg\min \sum_i \left(d_i(t) - G'_{ij}\, m_j * \hat{s}(t) \right)^2$$

[1] *MicroSeismic Inc.*

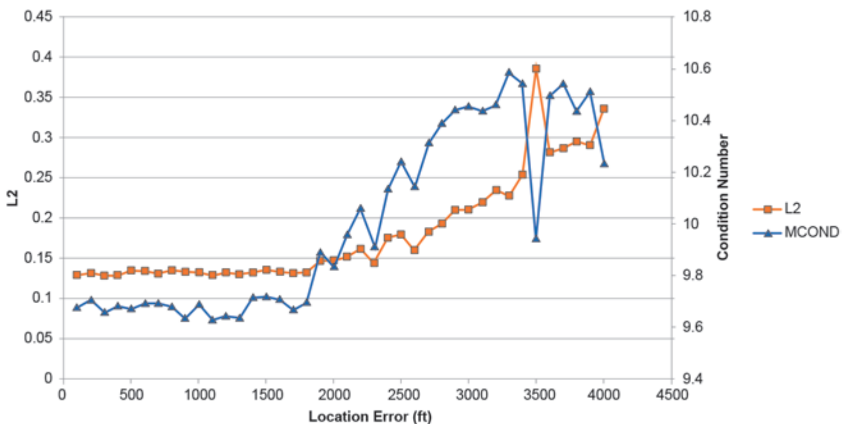

Figure 1 *Stability of moment tensor solutions by location error as measured by L2 misfit and condition number.*

In principle, this is a straight forward linear inversion that is easily computed using the recorded data and other parameters used in the event location process. However, when dealing with real data it is necessary to implement some additional preconditioning criteria to ensure that the best data is being used. These preconditioners typically limit the input traces to a subset of the entire array, using metrics such as instantaneous signal-to-noise ratio as well as similarity between the trace and estimated source wavelet to exclude noisy receivers from the inversion. Additionally, it is necessary to allow some velocity corrections within the algorithm, as erroneous locations will change the move out within the beamforming operator. This can cause the resultant move out to become incorrect before stacking out the source term estimate, as opposed to the stack of a properly corrected move out. This increased error during the move out is corrected by allowing the cross-correlation window to slide up and down the trace by a pre-determined amount in order to find the maximum cross-correlation value if the wavelet is not precisely aligned on the origin for that trace.

The main advantage to the waveform fitting approach is that it does not rely on accurate phase picks for the amplitudes input to the inversion; rather it looks at the overall scaling of the entire source function. This flexibility lends itself to an automated process by which robust moment tensors can be derived as soon as an event is located.

Results

A catalogue of 3600 synthetic events was created for a surface monitoring configuration in order to study the relationship between location error and moment tensor decomposition. Each event in the catalogue was modelled with the same hypocentre and with the same pure shear (100% DC) mechanism (strike=90°, dip=90°, rake=90°). A systematic location error was introduced to cover a radius of 1800 ft in a regular grid of location errors in XY. A limit of 1800 ft was chosen because this is the maximum distance at which the moment tensor solutions remain reasonably stable as illustrated in Figure 1.

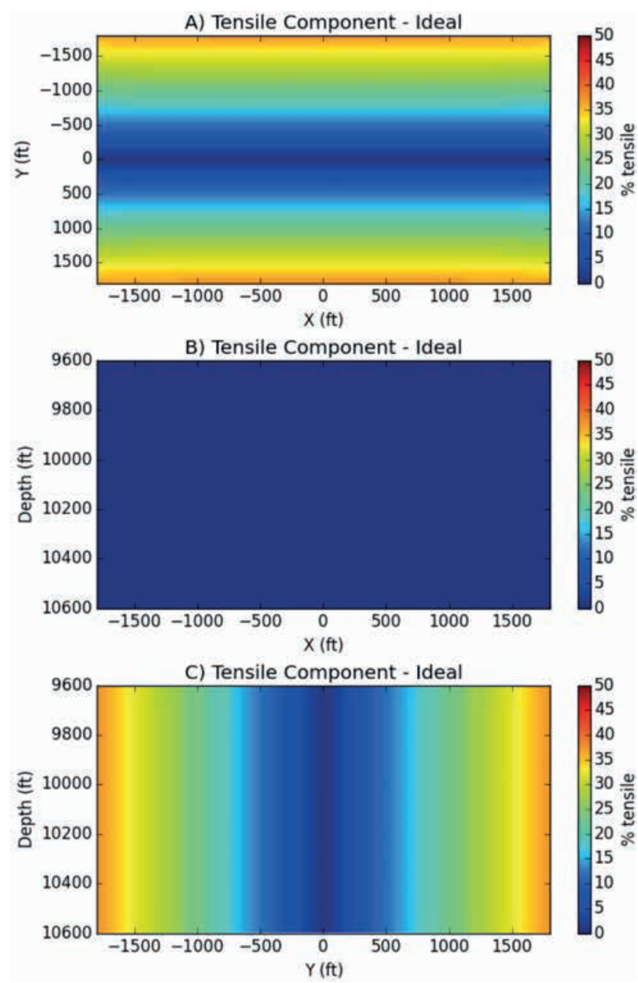

Figure 2 *3D surface plots showing the increase in tensile component of the full moment tensor decomposition with location error covering an 1800 ft radius around the epicentre in map view (Figure 2a) and 1000 ft of depth spread around the hypocentre in depth slice.*

The plot (Figure 1) shows the L2 misfit and condition number for solutions over a large range of location errors and serves as a preliminary guide to which errors are stable enough to yield reasonably accurate estimates of tensile

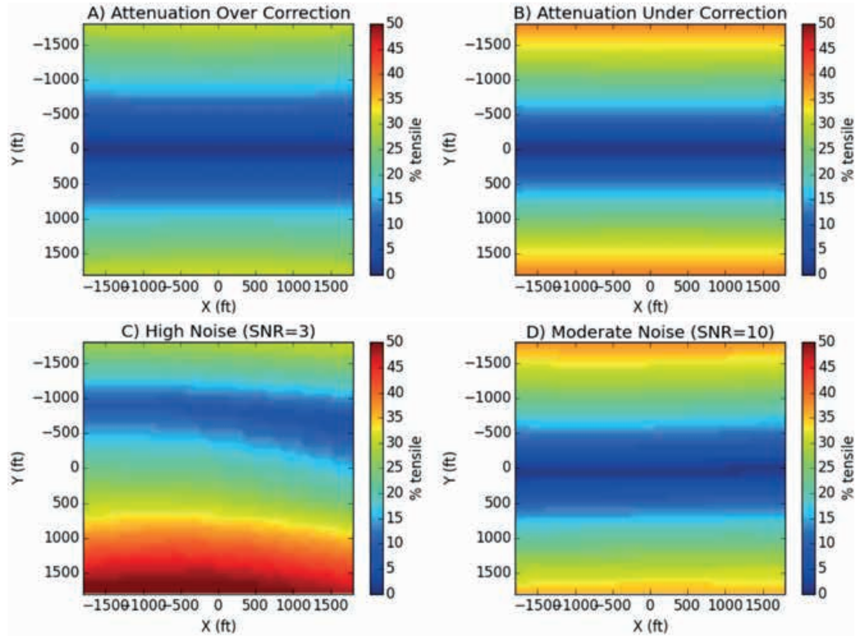

Figure 3 Tensile component error by location and attributes accounted for in the model. 3a – Model from Figure 2 with over correction of attenuation effects (Q=30). 3b – Same model but with an attenuation under corrected (Q=200). 3c – Ideal model with high level of random noise added (SNR=3). 3d – Ideal model with moderate level of noise added (SNR=10).

component. Modelled moment tensors that have poorly constrained solutions may be thrown out, on this basis, during quality checks preceding interpretation of these moment tensors. Constraining the synthetic model in this way will allow for a quantitative assessment of the relationship between %DC, %TENSILE, and location error to better understand how these factors can affect field data interpretations.

For this model, a high density, 20-arm, 2000-channel Fracstar geometry was used as an ideal case for synthetics. This set-up helps to acquire any acquisition footprint out of the resultant moment tensor decomposition. The synthetic data were built using ray trace forward modelling (Staněk, 2013). The initial synthetic model will look only at location in XYZ so attenuation and noise level were not considered. Similarly, the modelled media is homogenous and isotropic with constant velocity in an attempt to remove any effect on the moment tensor decomposition and preserve location error. A small amount of Gaussian noise was added to the data so that the effect on the solution was minimal. Additionally, since each event was modelled as a pure shear DC source mechanism, any reported tensile component from these decompositions is considered an artificial inflation of the true value.

The results from running the moment tensor algorithm on these data are plotted in Figure 2. Figure 2a shows the tensile component calculated from the same source mechanism with varying errors in location over an 1800-ft radius from the event's original location in XY. Figure 2b and Figure 2c show 1000 ft of depth spread in the XZ and YZ plots, respectively. These spectral plots show a clear pattern in XY showing a band of low DC component along the nodal plane indicating that not only is the amount of error an important consideration for anomalously high tensile components in the solution, but the azimuth of those errors is important as well. This is evident when observing tensile components of moment tensor decompositions at large errors of ~1800 ft, but also along azimuths sub-parallel to the nodal plane of the source mechanism. The values in these regions of the plot stay at zero regardless of the overall distance of the location error. The apparent relationship between tensile component inflation and location error is more of a function of the orthogonal distance to the nodal plane of the erroneous location than the distance vector itself. In the Z direction, (Figures 2a and 2b), it is clear that there is no definite structure or trend to the tensile component with depth. This is because of the nature of ray path travel times for the surface array model being used. The Z direction of the ray travel time is very large compared to XY, making errors in the Z direction a much smaller percentage of the overall travel time, reducing their impact on tensile component inflation. This effect on XYZ errors compared to overall travel times for XYZ will be a significant factor in downhole monitoring where small errors in all three dimensions will be a significant portion of the ray travel times. The implication of this effect in downhole monitoring warrants further research, but for the purposes of this analysis the current model we choose ignores effects of location error in the Z direction.

Figure 3 uses the same style of map view plot, used in Figure 2, which shows the effect on tensile component generated with attenuation effects and noise added to the ideal model. Figures 3a and 3b illustrate the additional effects of over- and under-correction of attenuation on tensile component inflation. For this model, a Q value of 100 was assumed for the forward modelling, values of Q=30 were used to over-correct the data, and a value of Q=200 was used to under-correct it. Over-correction, shown in Figure 3a, reduces the overall level of inflated tensile component, while under-correction increases the overall level of inflation. In both cases, the pattern of increased apparent tensile component with distance orthogonal to the nodal plane remains. Figures 3c and 3d show the effects of noise level and location error on the apparent tensile component. In both figures, a single realization of Gaussian noise was added to the input data and the moment tensors estimated and decomposed as before. In Figure 3c, a relatively high level of noise was added, such that the average signal-to-noise ratio (SNR) was 3. In this case one can see that the apparent tensile component is significantly increased, and that the symmetry of the response about the focal plane is broken. Smaller levels of noise (Figure 3d with SNR=10) show a similar increase in tensile component and a disruption of the focal plane symmetry. The specific shape of the non-symmetric response appears to be driven by the distribution of the random noise, as different noise realizations produce different non-symmetric patterns.

However, what is important is that all four have the same general shape of tensile changes relative to the true origin. This indicates that the effect of location error is consistent and could be considered independently from other sources of error. Thus, tensile inflation should be predictable given the location error and should scale as its orthogonal distance to the nodal plane (ϕ). Figure 4 shows a scatter plot of data from the initial ideal model of the inflated tensile component of the moment tensor decomposition vs ϕ. A steady and definite increase of tensile component with distance (ϕ) is obvious until approximately 1400 ft when some scatter in data points becomes prominent. This gives a reasonably good relationship between tensile component inflation and location error distance and azimuth simultaneously, following the relationship:

$$T_i = 0.0005 * \phi^{0.95}$$

where T_i is the tensile component inflation in per cent.

This relation works well for synthetic data but becomes problematic for field data since both direction and distance of the location error is needed and the actual location of microseismic events is unknown. It is possible to estimate the total distance of the location error from statistical methods in the locating algorithm. However, the definite direction of said error cannot be estimated. In order to test this effect on field data, it must be assumed that the imaged location is correct, with known errors both in distance and direction, and then one can predict the increase in tensile component between the initial solution and erroneous solution. If the increase can be accurately predicted using phi for known errors in field data, it should hold true that this relationship applies to the tensile inflation caused by location error for the majority of field examples. This can be accomplished by shifting all field points from their assumed true location by arbitrary ϕ distance of 300 ft and recalculating the moment tensors. If the relationship holds for field data this would produce a consistent increase in the tensile component of ~11%.

The field point data were transformed by location error ϕ=300 ft and the predicted tensile component of the same events using the tensile inflation relationship determined from synthetic testing in field data, acquired in the Eagle Ford play (Figure 5). The data suggests a strong correlation between the actual and predicted tensile components, confirming the synthetic relationship also applies to field data. The correla-

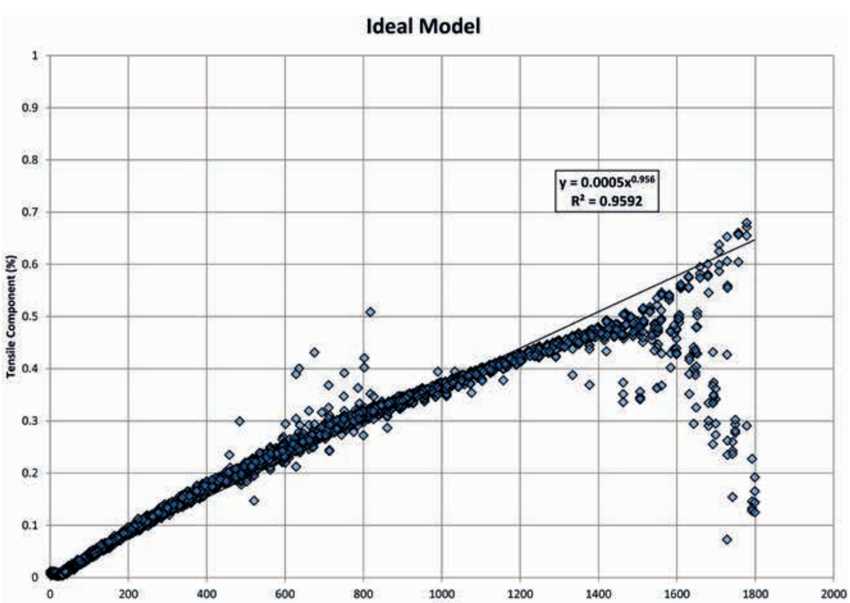

Figure 4 *Scatter plot of tensile component increase vs distance ϕ for ideal model.*

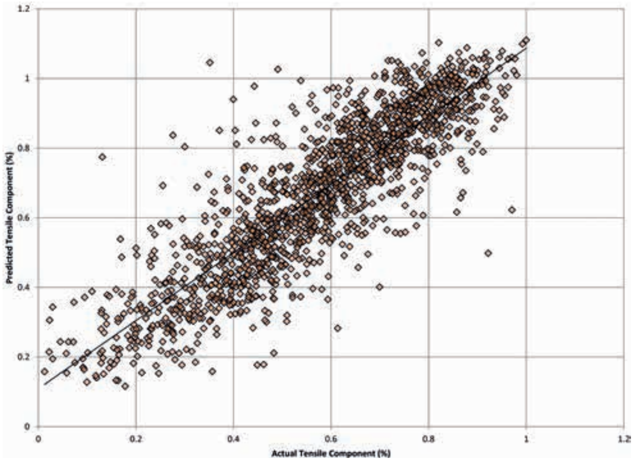

***Figure 5** scatter plot of the linear regression between actual and predicted tensile components for field data with known error introduced.*

tion is not flawless, however, background noise, spherical divergence, attenuation, and anisotropy are not specifically accounted for in this regression.

Discussion

Traditional thinking in microseismic interpretation says that tensile events are not observable, mostly because from an empirical sense, we do not observe them. In the past, events recorded during microseismic surveys have been dominated by shear failure mechanisms yet better imaging techniques and more advanced moment tensor analysis are revealing a more complex picture of hydraulic fracture geometry. This complexity shows that fracture events are shear dominated but can also have significant CLVD and volumetric components to them. The presence of these components in moment tensor solution shows a tensile nature to the fracture event and is being used to categorize observable events into opening and closing mode cracks based on the decomposition of the moment tensor (Baig, 2011). While this interpretation of tensile opening fractures can be a valid conclusion in principle, any possible source of error in the tensile component can lead to incorrect interpretations of opening and closing events. The computed tensile component can be affected by many factors inherent to the microseismic process and these must be eliminated as a possibility before one can say whether or not a hydraulic fracture is truly an opening or closing mode crack. The ability to evaluate entire catalogues of moment tensors is a big step towards identifying unrealistic classifications of fractures as the scale of the measurements will reveal trends that make these errors more apparent. While such sources of tensile component inflation are quantifiable, it is undeniably difficult to calculate these in the field since true locations and origin times are not known. Knowing what the relationship is and taking it into consideration goes a long way to determining whether tensile component values are valid.

Conclusions

Synthetic modelling of moment tensor decomposition with introduced location error shows a significant and quantifiable relationship between the location error ϕ and inflated tensile components for moment tensors. This relationship holds true for a field data example and should to be considered when looking at moment tensor decompositions from production acquisitions. While it is impossible to know the precise tensile inflation in field data, as the direction of location error for any event cannot be estimated, it is important to consider the maximum amount of inflation possible for a given location error before interpreting any tensile component to the moment tensor as being significant. Realistic microseismic location errors of 50-300 ft can possibly yield inflation values of up to 5-15%, therefore any tensile component of 10% or less should be considered with some scrutiny.

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