Are double-couples over-represented in microseismic focal mechanism studies?

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Monitoring microseismicity induced by fluid injection in hydraulic fracturing processes, geologic sequestration of carbon dioxide and geothermal fields facilitates understanding the fracture process and optimizing reservoir production (Lumley 2001; Shoham 2001). Characteristics of the source time functions and moment tensors can be inferred from studying seismic waveforms. Moment tensors can provide information about the inducing mechanisms and the size and orientation of fractures, the connectivity of fracture systems (Maxwell and Urbancic 2001; Fougler et. al. 2004), and whether the fracture is opening or closing (Kirkpatrick, et al. 1996).

The non-randomly distribution of microseismic events provide real-time information that can facilitate the delineation of the reservoir structure and fracture network. Characterizing the fracture system in a reservoir is done by performing moment tensor inversion on microseismic events. In general, multicomponent P- and S-wave amplitudes are employed in determining the moment tensors through a least-square inversion approach. In order to define the reservoir in terms of the three modes of fracture propagation (Figure 2), geophysicists typically decompose the obtained moment tensor into isotropic (ISO), compensated linear vector dipole (CLVD) and double-couple (DC) components using its eigenvalues and eigenvectors (Vavryčuk 2007).

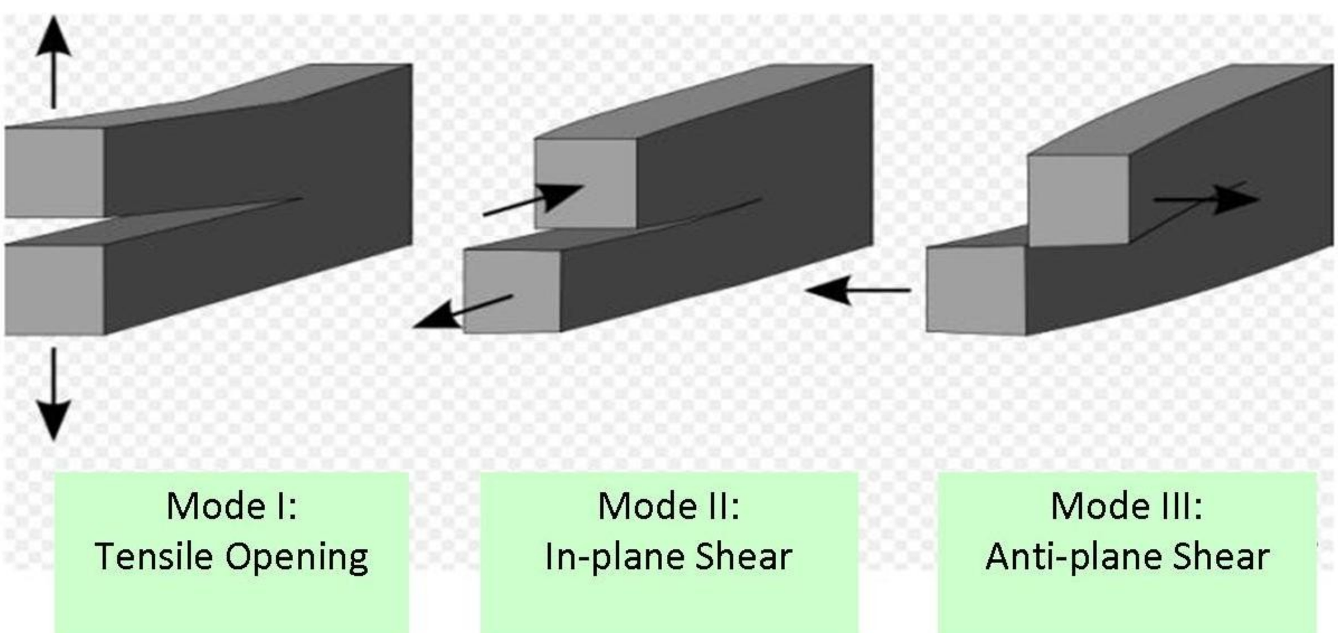


Fig. 1. Three modes of fracture propagation. Mode I: Tensile opening in which the displacement is normal to the crack or fracture plane; Mode II: In-plane shear in which displacement is in the plane of fracture plane and perpendicular to the fracture edge; and Mode III: Anti-plane shear in which the displacement is in the plane of the fracture and parallel to the fracture edge (Modified from Gibowicz & Kijko, 1994, pp225).

Earthquakes that are resulted from a shear or slip on a fault may be modeled by a double-couple (DC) seismic source with no volume change involved. However, there are some earthquakes that are caused by shearing combined with tensile faulting and therefore, comprise some volume changes (Vavryčuk, 2001). Examples of these events are microearthquakes induced by hydraulic fracturing and CO_2 sequestration. In order to find the extent of the volume, it is essential to find the percentages of ISO and CLVD components of the moment tensor in addition to the one of DC component. The ISO and CLVD components, which are known as the non-double-couple mechanisms, are a measure of deviation of faulting or fracturing from pure shearing or DC mechanism (Vavryčuk, 2001). Isotropic component corresponds to an explosion or an implosion event and involves volume changes. CLVD represents an opening and closing in perpendicular directions so that there is no volume change occurred (Kirkpatrick, et al. 1996). Figure 2 illustrates some selected moment tensors and their associated focal mechanisms (beach ball diagrams) for various seismic sources.

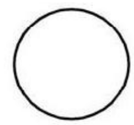
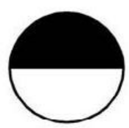
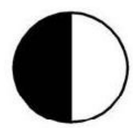
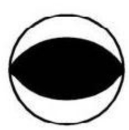
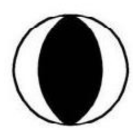
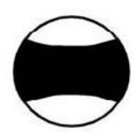
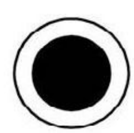
Moment tensor	Beachball	Moment tensor	Beachball
$\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$-\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&-1\\0&0&0\\-1&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&-1\\0&-1&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}-1&0&0\\0&0&0\\0&0&1\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&-1&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$		$\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$		$-\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$	

Fig. 2. Selected moment tensors and their associated focal mechanisms. The first row indicates an isotropic source (explosive source on the left and implosive source on the right). Rows 2 to 4 corresponds to different DC or shearing sources. The last two rows represent CLVD sources (Modified from Stein and Wysession, 2002).

We have conducted a synthetic seismogram study using an assumed borehole acquisition geometry modeled on an actual field program. For a given source at depth of 2 km and receiver array composed of 12 geophones with 11.5 m spacing (Fig. 3), we have generated the synthetic seismograms for 90 source mechanisms with random combinations of ISO, CLVD and DC components. We have then used the synthetic waveforms to invert for the moment tensors and decompose them into the ISO, CLVD and DC components. As a result of the narrow observation aperture, the inverse problem is ill-posed (Eaton 2009); consequently the least-squares inverted solutions differ from the input mechanism.

The results of this synthetic study are illustrated on the ternary diagrams in Figure 4. In general, we find that the distribution of inverted focal mechanisms maps to a sub-region of the parameter space that is close to the double-couple (DC) end member. This result is consistent with previous studies showing that a necessary condition for the moment tensor to be fully resolved is that the receiver array subtends a nonzero solid angle viewed from the source (Eaton 2009). This condition is not met in the case of a single observation well.

Our findings suggest that caution should be exercised in the interpretation of moment-tensor solutions from microseismic field experiments. Least squares solutions that are based only on P- and S-wave amplitudes tend to be biased toward double-couple mechanisms. Possible strategies to alleviate this concern could be to ensure a nonzero solid-angle aperture (Eaton 2009) or to incorporate other types of data, such as a priori knowledge of fracture orientation, to constrain the solutions.

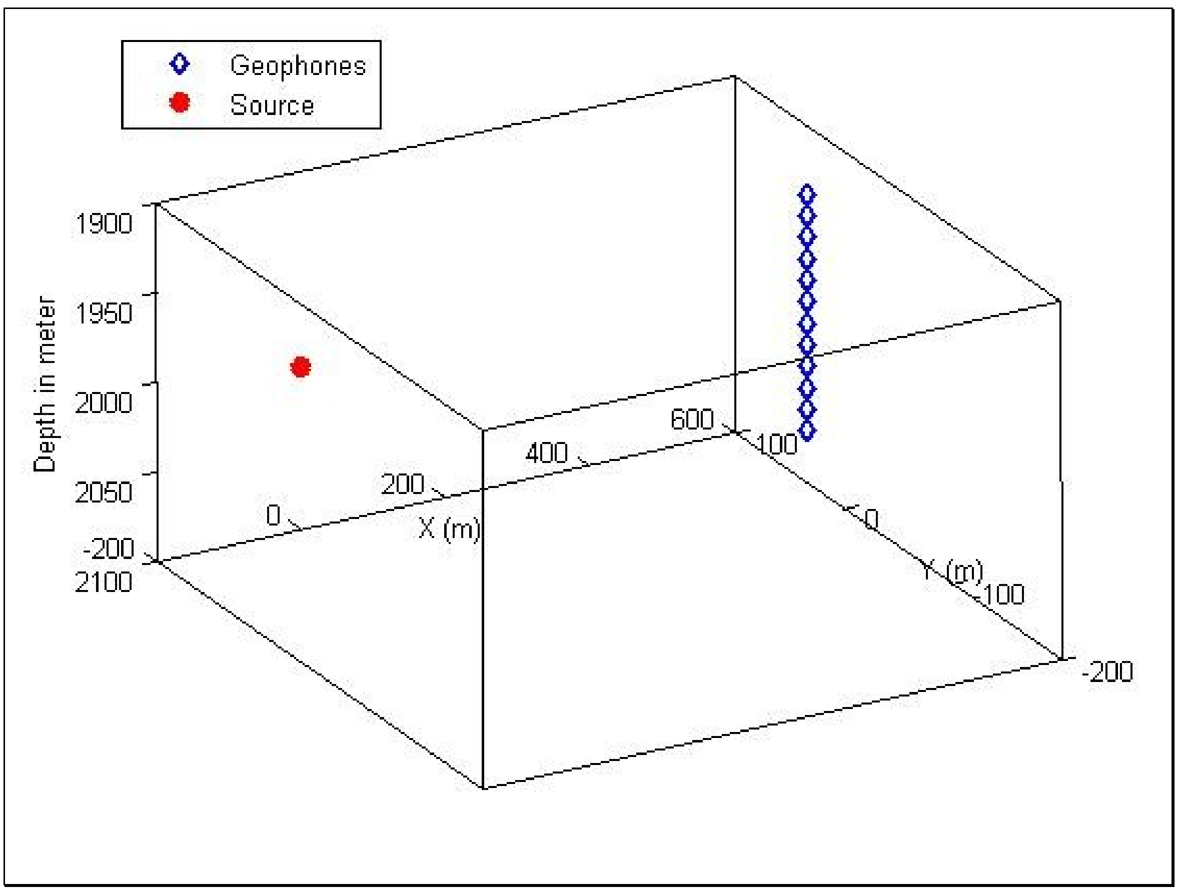


Fig. 3. Source and receiver geometry. Source is a located at depth of 2 km and the geophone array contains 12 geophones with 11.5 meter spacing.

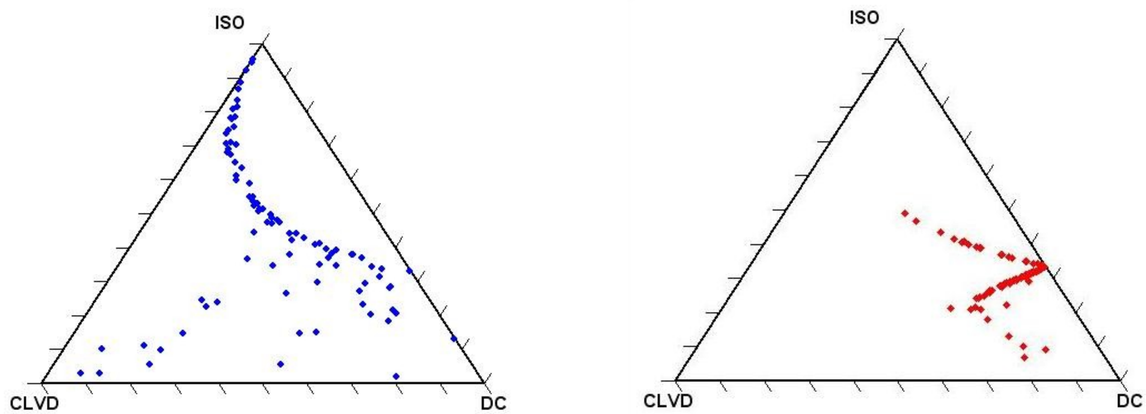


Fig. 4. Left: Decomposed moment tensors used in forward modeling. The apexes demonstrate the end member models, ISO, CLVD and DC, each indicates 100% proportions; Right: Moment tensors obtained through inversion, decomposed into ISO, CLVD and DC components. Note the over-representation of the DC component in the decomposed moment tensor.

Acknowledgements

We gratefully thank the sponsors of μ-SIC (micro-Seismic Industry Consortium) for their financial support of this project.

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