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Magnitude, scaling, and spectral signature of tensile microseisms

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Summary

The spatial dimensions and rupture characteristics of microseismic events are encoded in the spectra of radiated seismic waves. Compared with the determination of seismic moment tensors, source spectral analysis can be performed with limited aperture coverage around the source region. Provided that wave attenuation is well constrained, P- and S-wave spectral corner frequencies can be used, in principle, to estimate rupture velocity, source radius and stress-drop, but these paramaters are strongly model dependent. In addition, the ratio of S/P amplitudes may be used to distinguish between shear and tensile events, since tensile events are characterized by $S/P < 5$ whereas for shear events S/P is generally > 5. Several models are available to calculate seismic moment from the low-frequency displacement spectrum. In the case of tensile rupture, there is less ambiguity and source radius (a) can be related to moment magnitude (Mw) and internal fluid pressure within the fracture (P) by a recently discovered scaling relation: $\log_{10}(a) = [9-\log_{10}(2)]/3 + 0.5Mw - \log_{10}(P)/3$. Source spectra may also contain notches that are diagnostic of rapid opening and closing of tensile fractures – so-called “clapping” mechanism – during hydraulic fracture treatment. Finally, slow rupture mechanisms may give rise to distinctive low-frequency tremor or long-period long-duration (LPLD) events that are typically overlooked during routine processing of microseismic data. By analogy with low-frequency phenomena that characterize volcanic and earthquake fault systems, such features may be indicative of gradual tensile opening, fluid resonance or slow slip on fractures that are misaligned with the present-day stress field.

Introduction

Moment tensors offer a potentially powerful tool to determine microseismic source characteristics (Baig and Urbancic, 2010). A limitation of this approach, especially for downhole microseismic monitoring, is the limited observational aperture, or solid angle, that is provided by the monitoring array (Eaton and Forouhideh, 2011). As a consequence, the moment tensor is often not well resolved.

An alternative approach for determining microseismic source characteristics, less constrained by small aperture, is based on source spectra. For example, the popular Brune model (Brune 1970, 1971) predicts the shape of far-field spectra due to rupture on circular cracks. Based on this model, the measured low-frequency plateau amplitude of the displacement spectrum can be used to compute the seismic moment, M_0 (and the moment magnitude, Mw), and the corner frequency can then be used to estimate parameters such as source radius and stress drop. If both P and S corner frequency are measured, it may be possible to infer the source rupture velocity (Walter and Brune, 1993). The relationship between these parameters and the seismic moment is often referred to as seismic scaling relations. In practical applications, considerable care is required to ensure that the spectral effects of P- and S-wave attenuation are compensated to ensure that meaningful source parameters are determined (Eaton et al., 2014). In addition, significant parameter trade-offs exist and should be taken into account (Beresnev, 2001).

The purpose of this paper is to review and describe several new developments in the application of source spectra to the analysis of microseismic sources, including tensile sources, spectral notches associated with opening and closing of fractures (Eaton et al., 2014), and low-frequency signals that may reflect slow rupture processes (Das and Zoback, 2013; Eaton et al., 2013).

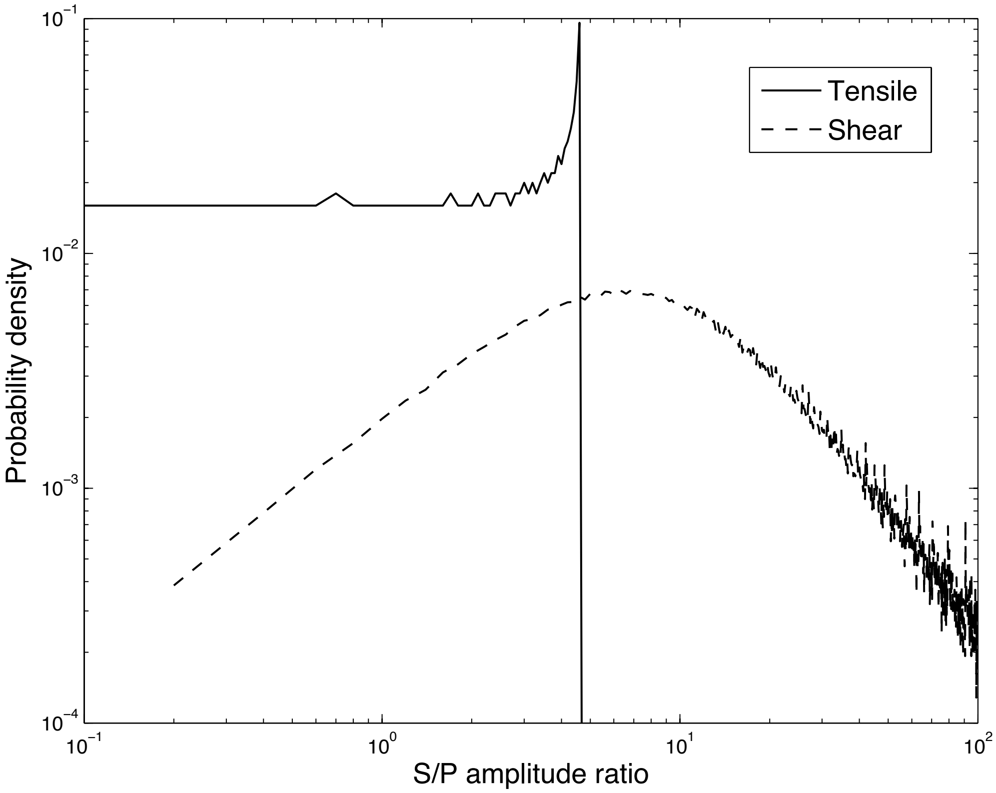

Figure 1. Normalized probability density for S/P amplitude ratio, based on uniform sampling of the focal sphere. For a random source-receiver direction there is 9.1% probability of S/P < 4.617 for shear events, versus 100% probability in this range for tensile rupture. From Eaton et al. (2014).

Magnitude of tensile sources

In principle, models such as the Brune source model can be used to provide estimates of the source radius and stress drop. In simple terms, smaller events produce spectra with higher source radius, due to the reduced time required for the rupture to occur, whereas stress drop provides a crude proxy for frictional strength of the fault. In the case of shear slip on a fault surface, associated with classic double-couple mechanisms, significant trade-offs exist (Beresnev, 2001) and the corner frequency may be strongly influenced by the effects of attenuation. In the case of tensile failure, however, Eaton et al. (2014) showed that source radius (a) is related to moment magnitude (Mw) and internal fluid pressure within the fracture (P) by the scaling relation:

$$\log_{10}(a) = A + 0.5Mw - \log_{10}(P)/3 \quad , \tag{1}$$

where $A = [9-\log_{10}(2)]/3$. For hydraulic fracturing, it may be possible to obtain an estimate of the internal fluid pressure within tensile fractures that is independent of the microseismic observations. Consequently, this formula provides a way to estimate source radius of tensile events, without the inherent tradeoffs for shear failure.

Discrimination between shear and tensile (or non double-couple) sources is problematic for small-aperture arrays, since in these circumstances it is often not possible to estimate the seismic moment tensor in a robust fashion. For the binary model of shear and tensile rupture, Eaton et al. (2014) showed that the S/P amplitude ratio may be used as a discriminator. As shown in Figure 1, in a probabilistic sense a S/P ratio of 5.0 can be used to separate tensile events, which have lower S/P ratios, from shear events, which have predominantly higher S/P amplitude ratios. An important prerequisite for this discriminator is

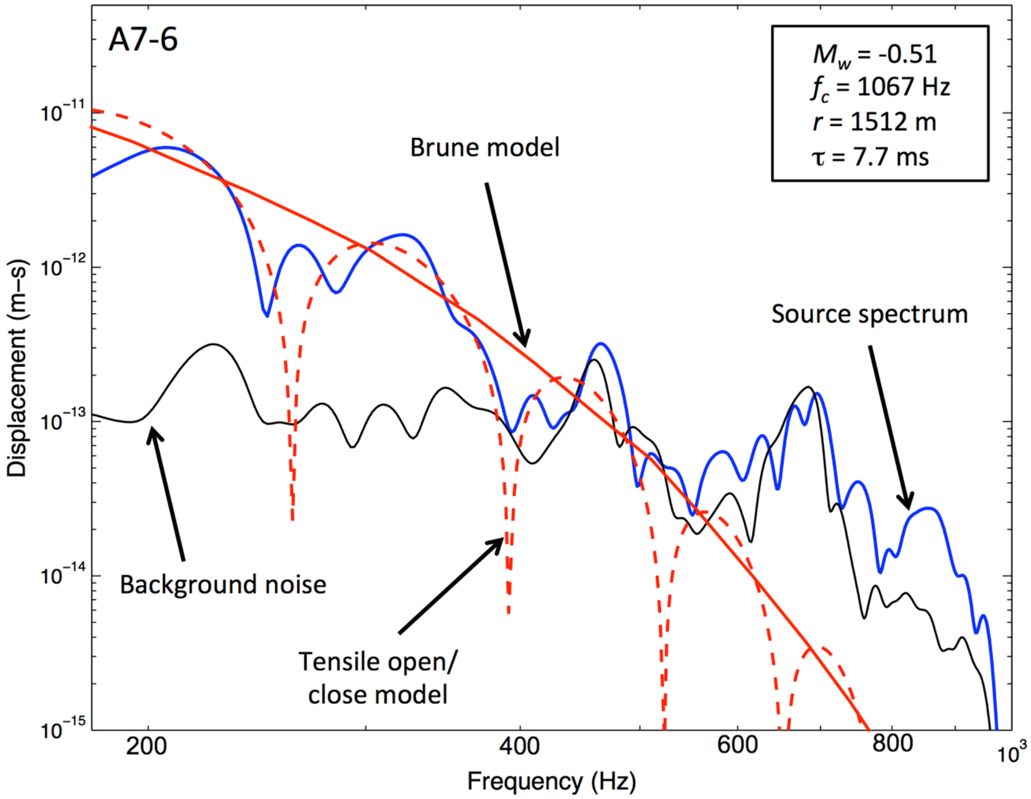

Figure 2. Example of source-spectrum for a “clapping” mechanism. Blue curve shows the displacement spectrum for the S-wave arrival. Dashed red curve shows the best-fitting tensile opening/closing model, with parameters summarized in the inset box. Solid red curve shows the best-fitting standard Brune model. Black curve shows background noise based on a pre-event noise window.

accurate compensation for differential attenuation of P waves and S waves. It is necessary to account for the differential attenuation in order for the S/P amplitude ratio to be meaningful.

Opening/closing cracks

If a crack opens and then quickly closes with an equal but opposite seismic moment, the spectrum of the composite event can be obtained from the spectrum of the first event by applying the following filter in the frequency domain (Water and Brune, 1993)

$$F(\omega) = 2 - 2\cos(\omega\tau) \quad , \qquad (2)$$

where τ is the time separation between the two subevents. This filtering process creates a diagnostic series of notches in the source spectrum. Figure 2 shows and example of a source spectrum with modulating amplitude that has been interpreted as spectral notchs of this type (Eaton et al., 2014). In the case of tensile mechanisms, this process can occur due to mode I opening be followed by closure due to a pressure drop in the crack that occurs when +fluid flow is not as fast as the fracture propagation, resulting in formation of a metastable crack opening (Julian et al., 1996). Although such notches could theoretically occur from a back-and-forth shear motion on a fault surface, there is no simple mechanism to explain such retroshear motion. This model for opening and closing of tensile fractures is referred to as a “clapping” model and may thus represent a spectral diagnostic of tensile failure.

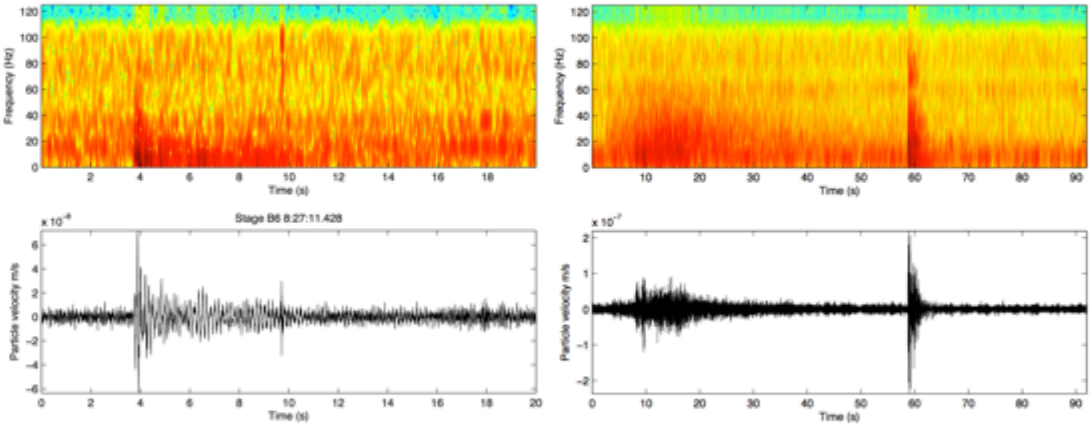

Figure 3. Two examples low-frequency tremor followed by a high-frequency event. From Eaton et al. (2013).

Low-frequency tremor signals

Eaton et al. (2013) reported a number of cases of tremor-like low-frequency signals (Figure 3) during a Montney treatment in northeastern BC and suggested that these signals could reflect low-frequency deformation processes. Similarly, Zoback et al. (2012) have argued that long-period long-duraction (LPLD) events reflect slow slip on pre-existing fracture surfaces, much like slow slip that has recently been recognized to occur on natural earthquake fault system.

Conclusions

The spectrum of microseismic sources conveys important information about the nature of the underlying rupture processes. Recent innovations have revealed that:

1. The source radius for fluid-induced tensile events can be calculated based on seismic moment without knowledge of the corner frequency, provided that the internal fluid pressure is known.
2. The S/P amplitude ratio can provide capability to discriminate between shear and tensile failure, even for limited aperture geophone arrays.
3. Periodic notches in the source spectrum may be indicative of rapid opening and closing of a tensile crack – the so-called “clapping” mechanism.
4. Ongoing studies provide evidence for slow deformation processes that may be detectable using microseismic systems as low frequency tremore.

Acknowledgements

Sponsors of the Microseismic Industry Consortium are sincerely thanked for their support.

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