Self-Consistency in Scaling Relations for Seismicity Induced during Hydraulic Fracture Stimulations*

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Abstract

Understanding whether large and small earthquakes have the same physics is a major question in seismology and plays a role in understanding the development of discrete fracture networks associated with hydraulic fractures. S it is becoming evident, it is possible to generate larger magnitude events (M > 0) during hydraulic fracture stimulation under different circumstances, such as increasing injection rates that cause changes in local stress conditions. In order to examine the scaling relationship of larger events (M>0) and small magnitude events (M<0), microseismic data from fully integrated passive seismic monitoring programs were used. In this study, we identify that even if small magnitude events are generally lower in stress release compared to those observed for the larger events; over all scales of observation, the events follow a self-similar behavior. The differences for small and large magnitude events can be explained by the observed failure mechanisms where smaller events tend to be driven by shear-tensile failures of pre-existing discrete fractures (joints) whereas the larger events appear to be dominated by shear driven failure processes associated with pre-existing faults. Our investigation in failure mechanisms show that the larger-magnitude data have in general a much stronger shear component compares to the lower-magnitude data, which have much smaller shear associated with them. We also notice that slip is not a dominant mechanism in lower-magnitude events.

Introduction

To understand whether the behavior of small and larger magnitude events is self-similar, we examine the scaling relationship. By considering how event seismic moment scales with the source radius and utilizing Brune's penny-shaped crack fault model (Brune, 1970) we can identify whether events follow a self-similar behavior (follow lines of constant stress drop) or nonsimilar behavior (increasing seismic moment with constant source radius). In either case, the analysis through spectral analysis has to account for bandwidth limitations, propagation, and site effects before underlying differences can be explained in terms of source behavior.

Numerous examples in the literature have looked into scaling behavior. For hard-rock excavation-induced events, nonsimilar scaling relationships have been observed for weakly structured rock masses with reduced clamping stresses, whereas self-similar behavior has been found for heavily fractured zones under stress confinement (Urbancic et al., 1993). Overall, the interaction of stresses with pre-existing fractures and fracture complexity, initially thought as a second-order effect, appears to significantly influence source characteristics of excavation induced seismic events with $M < 0$ and consequently favors a nonsimilar earthquake generation process. It has also been considered that excavation-induced events contain a significant volumetric component of failure and as such result in significantly lower stress drops as compared to pure shear sources. For reservoir-induced events, it has been shown that these events typically have on average ten times lower stress drops than natural tectonic earthquakes, suggesting that reservoir-induced seismicity can occur with a lower stress drop due to the high pore pressures of the underground medium (Goertz-Allmann et al., 2011). Similarly, in hydraulic fracture stimulations, lower average stress drops have also been reported and have thought to be related to heterogeneous slip along less well-developed or previously nonexistent fractures (Fehler and Phillips, 1991).

For this study we consider data sets recorded downhole and close to the surface (within 50 m) in order to provide for effective monitoring of induced seismicity ranging in magnitude from $-4 < M < +4$. The combination of instrumentation also reduces possible magnitude-saturation issues and frequency band limitations and their influence on scaling behavior. Additionally, we consider whether the underlying mechanisms of fracture development over all scales are self-consistent.

Example

Two data sets consisting of events recorded during hydraulic fracture stimulations are discussed in this paper (Figure 1). The first data set is containing events recorded during hydraulic fracture stimulations at a depth of approximately 2.5 km. Around 800 events with $M > 0$ were detected by a near-surface seismic network, over a period of a few weeks. To properly characterize the positive magnitudes that can be easily observed from a distance of 1.6-5 km; each station consisted of a force-balanced accelerometer deployed with a 4.5-Hz geophone. The second data set contains downhole events, which were recorded in the same field but over a different time interval, comprise one stage of data from the completion of a lateral well, and were monitored from a number of wells around the stage of interest. For this stage, over 400 events were located. For both sets of events, we calculated source characteristics such as seismic moment, magnitude, source radius, energy release, and stress release utilizing a time-domain spectral equivalent approach. Additionally, to indicate whether the event mechanisms can be determined, all events were assessed for condition number; those events with a good condition number were used in the determination of failure components through moment tensor inversion.

The relationships between moment and source radius are plotted against lines of constant stress drop for the data sets considered in Figure 2. Although there is some scatter, each individual data set appears to follow a self-similar distribution, as shown by their tendency to follow lines of constant stress drop. However, the two data sets are not self-similar with each other, as the average stress drop for the smaller magnitude events detected downhole is about an order of magnitude lower than the large-magnitude events observed from the near surface. This observation suggests that the generating mechanisms for these data are fundamentally different.

In order to investigate the differences in source behavior, we take advantage of the favorable source-array geometries in the data sets to do seismic moment tensor inversion. The mechanisms for the events are directly related to the radiation patterns of P- SV-, and SH-waves. Observations of these waveforms from a distribution of sensors that sufficiently span the volume allows for the amplitudes and polarities of these phases to be back-projected along raypaths back to the focal sphere, reconstructing the radiation patterns. In practical terms, this provision on sensor geometry for downhole observation of microseismic events usually translates to the need for the signals to be detected across multiple receiver arrays deployed in nearby wells. For surface or near surface monitoring of larger-magnitude seismicity, this restriction is not practically as strict. So long as waveforms are observed from a sufficient number of azimuths, the moment tensor can be robustly determined.

The orientations of the strain axes for fracture-related events can be related to the orientation of the fractures. For double-couple events, this particular problem has been the subject of much attention in the geophysical literature since any particular DC moment tensor results in two equally valid solutions. In order to resolve this ambiguity, a group of related DC events can be inverted for a best-fitting state of stress, which will make one solution more likely than the other will. The situation is much simpler for events closer to opening and closures, as the fracture planes for these cases will be normal to the outward and inward strain axes, respectively.

Moment Tensor Results

The contribution from the double-couple component of two data sets associated with both smaller and larger magnitude events are plotted in Figure 3. As seen in this plot, there is a very notable shift in the style of the mechanisms between the downhole and surface data sets, in that the larger-magnitude data have in general a much stronger shear component. The lower-magnitude data have much smaller shear associated with them, suggesting that slip is not a dominant mechanism in these events, in line with the opening and closing mechanisms observed during hydraulic fracture stimulations (see Baig and Urbancic, 2010). These differences in behavior further suggest that a mechanistic difference exists between the event source sizes and could be the underlying reason as to why the differences in scaling behavior are observed.

With help of rosette diagram for the orientations of the fracture planes, the dominant fracture orientations of large and small magnitude events are illustrated in Figure 4. While the fracture orientation for the large-magnitude events tend to follow to the maximum horizontal stress in the region of NE-SW, the smaller events have varied fracture orientations, which are dominated by movement along the pre-existing fracture network as, identified through core and downhole imaging data. These data further suggest that the downhole-recorded data are activating different features than the data seen on the near-surface arrays.

Conclusions

By considering these results, we can speculate on the underlying process responsible for the observations. The prevalence of double-couple-dominant events for the larger-magnitude events is indicative of stress-driven processes that are generating these events. The smaller-magnitude events, showing significant deviations from double couple, necessitate fluid involvement in the failure process. Furthermore, although the larger- and smaller-magnitude data sets are themselves self-similar, these events follow different scaling-relations paths. The events themselves are responding to different generating mechanisms, the smaller events, tensile in nature, are the likely the response of the joint sets and other lineations in the reservoir to the fluid injection. The events of larger magnitude that are seen from the near-surface network are necessarily activating larger-scale features, greater than 100-m source radii. These features are likely pre-existing faults, previously unidentified, in the formations at and below the reservoir. In general, these differences can be explained by the observed failure mechanisms where smaller events tend to be driven by shear-tensile failures of pre-existing discrete fractures (joints) whereas the larger events appear to be dominated by shear driven failure processes associated with pre-existing faults.

The large events mostly occur because of a stress transfer due to the stress changes or transfer resulting from the occurrence of smaller-magnitude events in the volume. Based on these observations, we suggest that there is a sufficient stress transfer and stress buildup resulting from the smaller events to allow for pre-existing faults to slip in shear. The presence of these faults, which can be activated by the stress-shedding effects during hydraulic fracture treatments, can have profound effects on the understanding of the fracture propagation in the reservoir and create potential pathways that can lead to either enhanced or ineffective stimulations.

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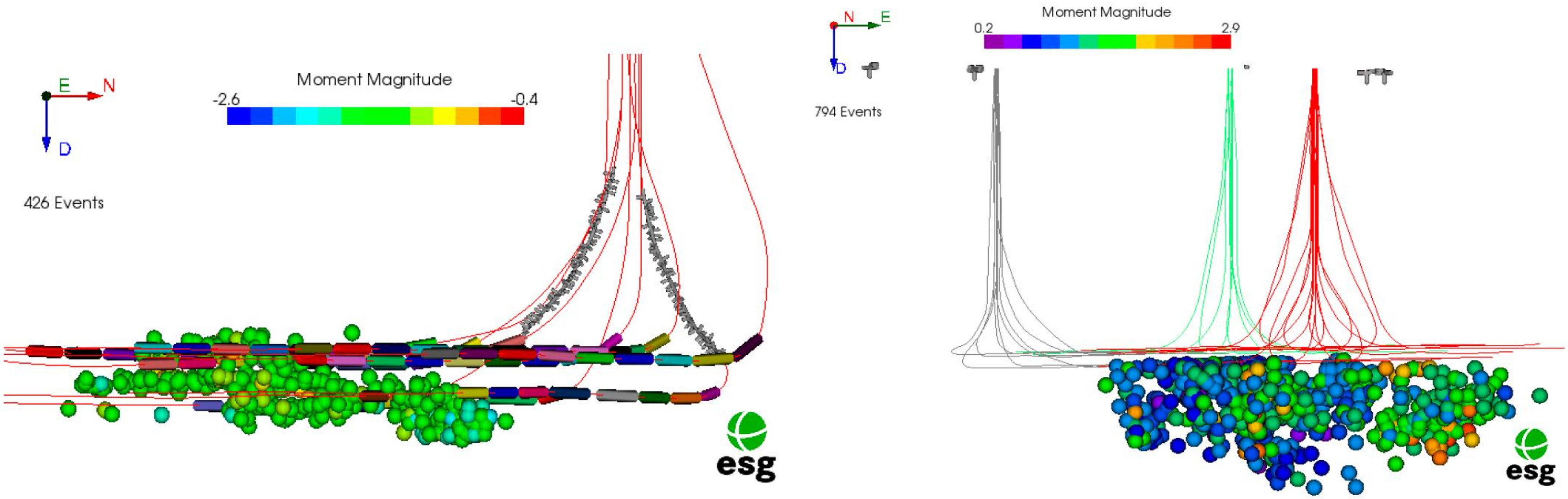

Figure 1. Left: depth view of the event distribution from a hydraulic fracture detected by a hybrid seismic network comprised of surface and downhole components. Right: depth view of one-stage downhole events, monitored by a number of wells around the stage. Where the treatment wells are displayed in red and the events are coloured by moment magnitude.

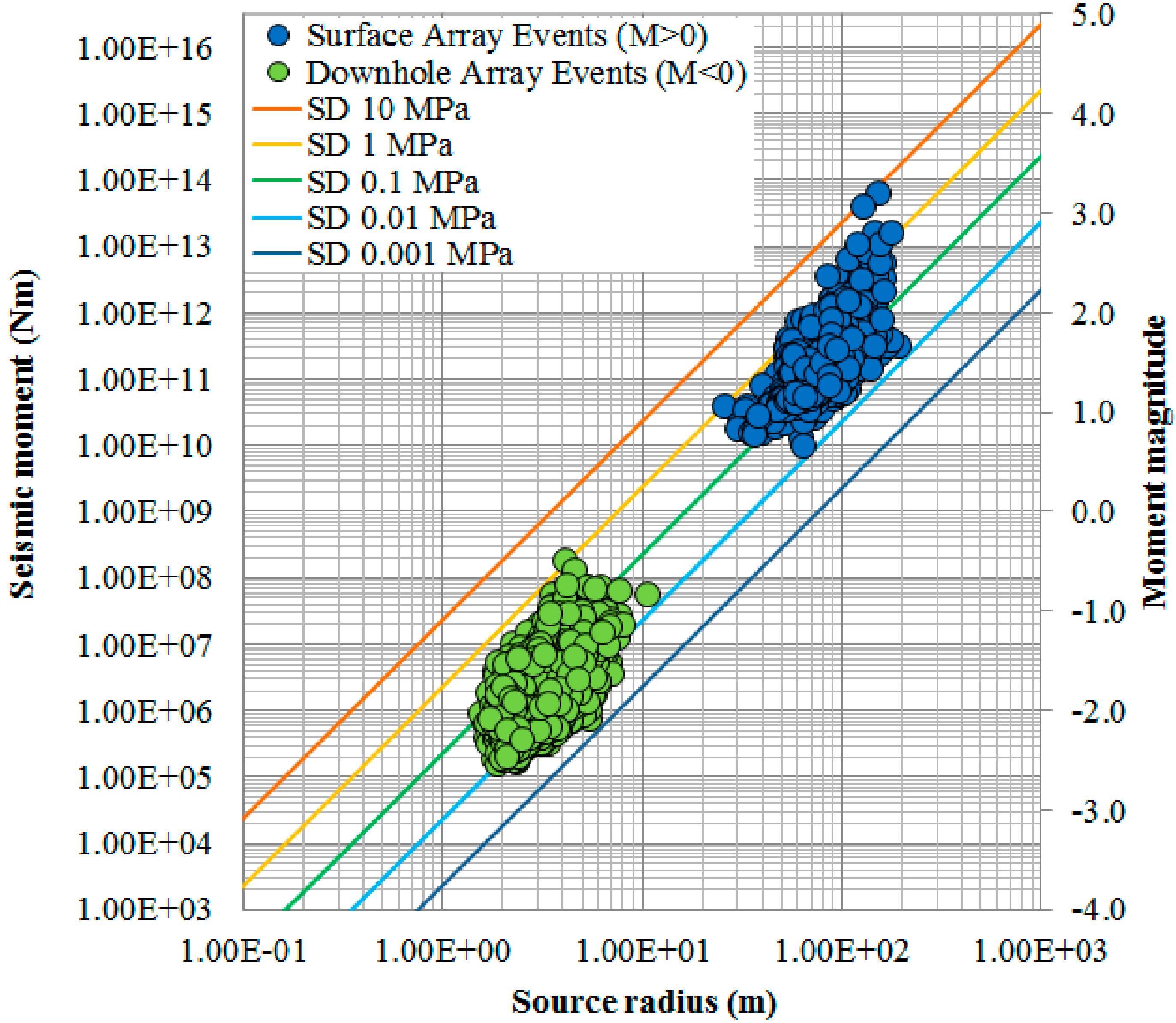

Figure 2. Observed scaling relations between source radius and seismic moment (and therefore moment magnitude), with lines of equal static stress drop for the larger-magnitude events detected with the near-surface array (in blue) and smaller-magnitude downhole recorded data set (in green).

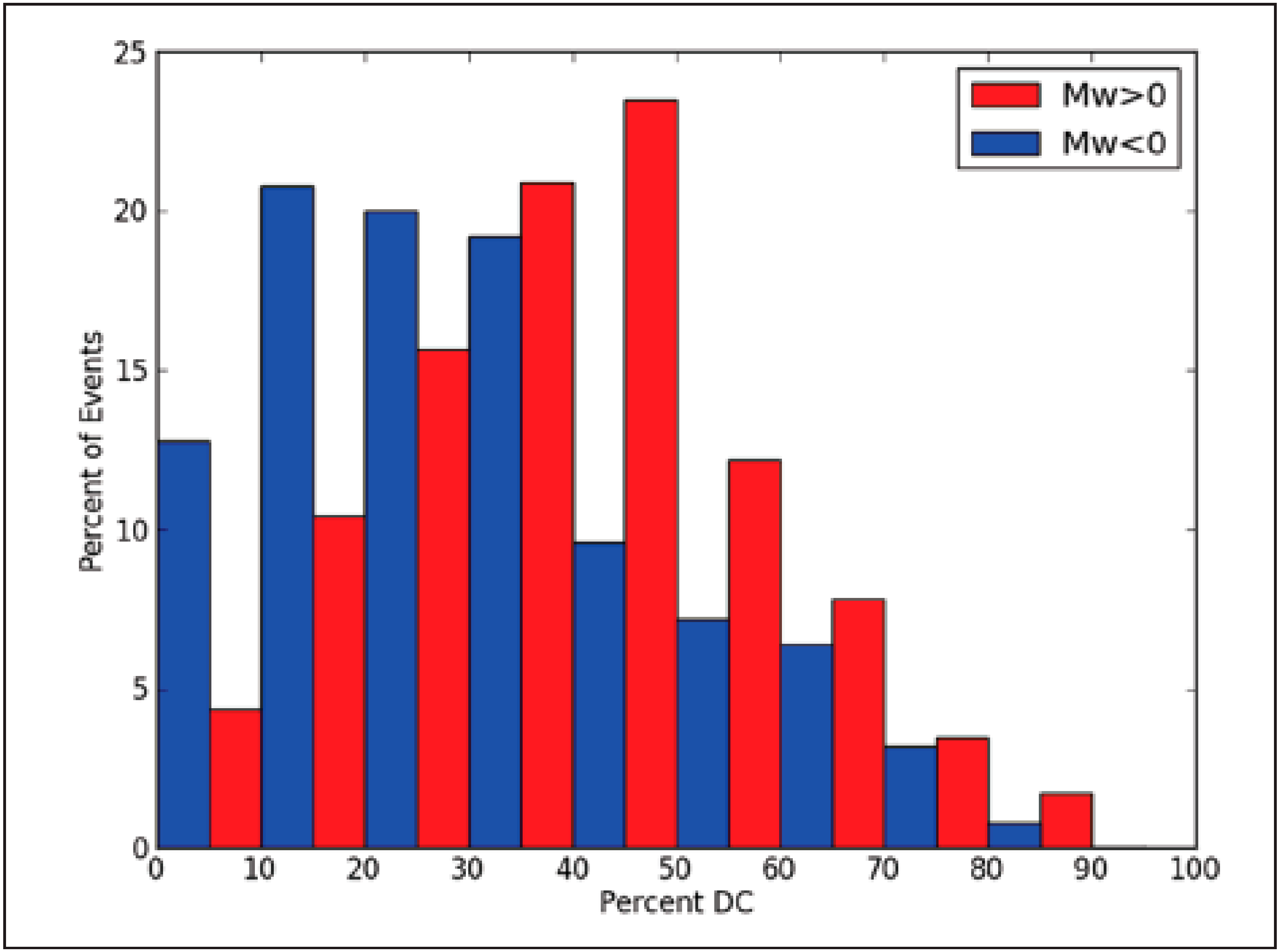

Figure 3. Histogram comparing the percentage contribution from the double-couple component from both the surface-recorded Mw > 0 and downhole Mw < 0 data sets.

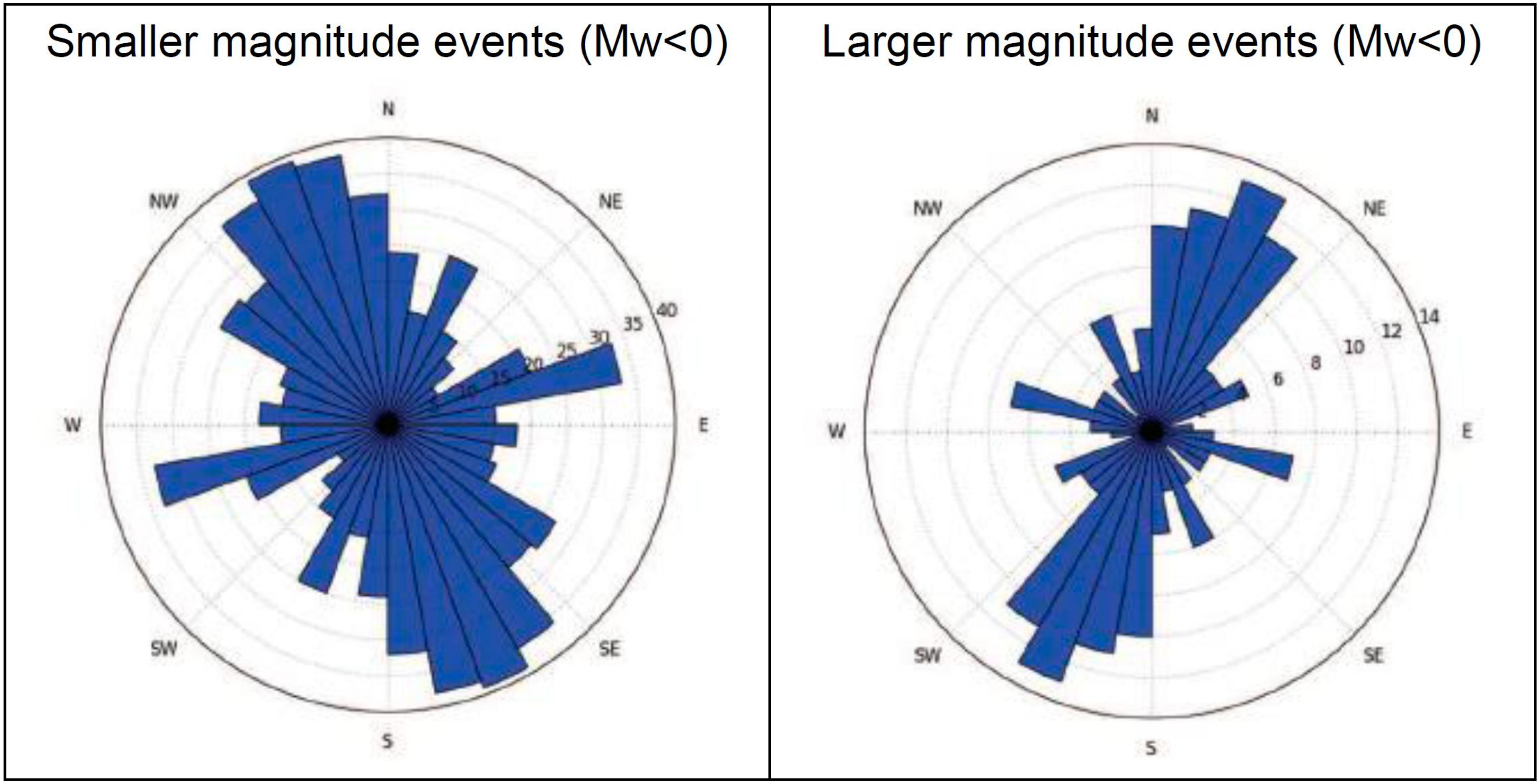

Figure 4. Rosette diagrams of the fracture orientations determined from the two data sets.