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Waveform similarity for quality control of event locations, time picking and moment tensor solutions

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Summary

Waveforms generated during hydraulic fracturing treatments provide a plethora of information. We demonstrate how waveform similarity can be used at different stages of microseismic processing and interpretation for quality control purposes. We show that a plot of crosscorrelation values as a function of inter-event distances can reveal location errors due to mispicks or missing picks. By using histograms of differential times between highly correlated events (doublets), time picking errors can also be detected. We also suggest that doublets should fall within similar regions in the Hudson source-type plots even for events with large non double-couple components. These procedures can also be used in other settings such as geothermal studies, mining projects, reservoir monitoring and earthquake seismology, providing an innovative and fast approach to assess microseismic detection/location uncertainty as well as confirm/reject the interpretation and internal consistency of moment tensor solutions (MTS). This contributes to a better understanding of underground processes and increases our confidence during interpretation.

Introduction

Microseismic monitoring has become an extensively used geophysical technique to monitor projects in unconventional resources such as hydraulic fracturing treatments and enhanced oil recovery. Compared to seismic reflection surveys, this passive method involves different challenges such as noisy waveforms, weak signals, unanticipated velocity structures and inadequate or restricted acquisition geometries (Vavryčuk, 2007). It is imperative to include quality control procedures during data processing and interpretation that can help optimize stimulation programs and production by ensuring more internally consistent results.

In this work we take advantage of the plethora of information that can be obtained when detecting highly-similar events through crosscorrelation, in order to highlight quality control procedures during key stages of processing and interpretation of microseismic data. The use of crosscorrelation methods is justified since although microseismic events can occur anywhere, in most cases, they tend to occur in the same zone (Poupinet et al., 1984; Arrowsmith and Eisner, 2006; Castellanos and Van der Baan, 2013), especially in hydraulic fracturing treatments.

Theory

Waveform Similarity

We expect events with similar waveforms to originate from similar source regions and have nearly-identical source mechanisms (Geller and Mueller, 1980). Thus, we define a doublet as two highly-correlated events and a multiplet as three or more; following the methodology by Arrowsmith and

Eisner (2006) (see Figure 1). First, we crosscorrelate all events with each other at each common station to detect all doublets and multiplets. We weight each component based on their S/N ratio and take the average over all stations. If events have a correlation higher than a pre-defined threshold, events are considered similar. Every event is strongly linked (high crosscorrelation) to one another in each multiplet group to assure stability during the QC procedure.

QC on P- wave time picks

When two microseismic events i and j are doublets, their corresponding time picks at the kth station should be at the same time onset. Following Kocon and Van der Baan (2012) and Castellanos and Van der Baan (2013) the quality-control methodology consists of extracting two time windows that encompass both P-wave phases based on their time picks and perform crosscorrelation. Then, the time lag corresponding to the maximum peak of the crosscorrelation function reveals the internal consistency (null delay) or inconsistency (non-zero delay) in picking between both events. This is done in all three components and weighted by each crosscorrelation value. This can also be used to assess S-wave time picks independently. By applying this method to all similar events, time picks (from either P- or S-wave) are refined and also subsequent location errors given a velocity profile can be obtained.

QC on event locations

Crosscorrelation measurements are known to decay as inter-event distances increase, since waveforms from distant events are affected by velocity heterogeneities and ray paths differently and may also have different moment tensors (Baisch et al., 2008; Kummerow, 2010). Hence, we can assume that for a sufficiently high correlation value, events should have small inter-event distance (Kocon and Van der Baan, 2012; Castellanos and Van der Baan, 2013). Geller and Mueller (1980) argue waveforms are identical for events with separation distances up to a quarter of a wavelength λ. Therefore, event pairs with nearly-identical waveforms but estimated separation distances larger than λ/4 indicate location errors.

QC on Moment Tensor Solutions

Moment tensor inversion has become a key factor in understanding the fracturing processes in the vicinity of the source (Baig and Urbancic, 2010). A Hudson source-type diagram is useful to identify different modes of failure by plotting the T (shear component) and k (volume change component) values (Hudson et al., 1989). If two events show nearly-identical waveforms (Figure 1) their T and k values are expected to fall within similar regions in this diagram; otherwise, it is again indicative of possible errors in the moment-tensor solution due to incorrect picking, event mislocation, or non-unique inversions due to an insufficient solid angle.

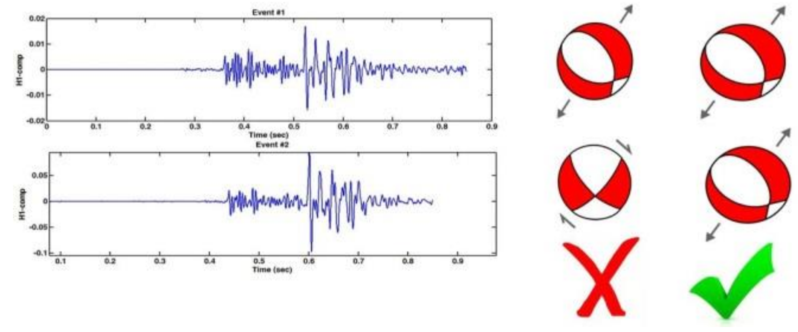

Figure 1: Two microseismic events with highly-similar waveforms should originate from the same source region and have similar source mechanisms.

Application to a dataset

We have applied this approach to a subset of 126 microseismic events during a single stage of a hydraulic fracturing treatment and recorded by two 11-receiver deviated boreholes. The microseismicity has a dominant frequency of 125 Hz (bandwidth 50-200 Hz) and an average velocity of 4000 m/s in the source-receiver vicinity. Thus invoking the argument by Geller and Mueller (1980) we can expect near-identical events to be separated by up to approximately 20 m. Nevertheless, in Figure 2 we observe most highly-correlated events are separated by up to approximately 100 m. There is a dense corridor above correlation values CC of 0.9, which gives an indication of the existing location uncertainty in the data (in this case around 70 m). Furthermore, there are some highly-correlated events with large separation distances between 100 m and 200 m, which suggest larger potential location errors due to mispicks or missing picks.

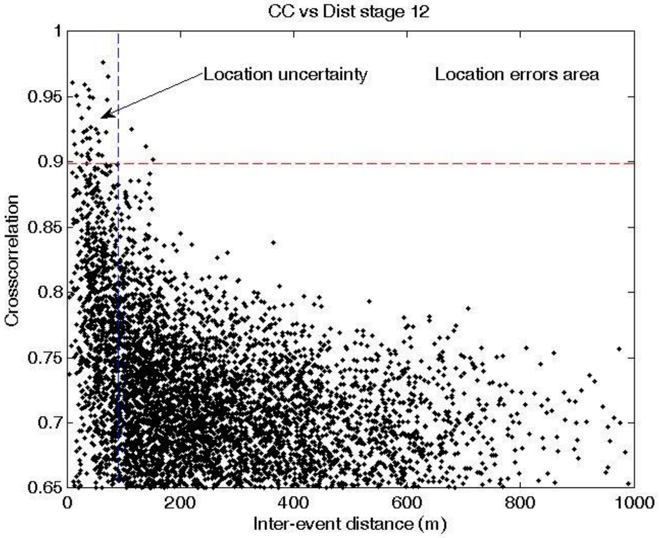

Figure 2: Correlation values (CC) versus distance between events used for QC purposes. Highly-correlated events with large separation distances suggest location errors due to mispicks or missing picks (red dashed line). The location uncertainty in the dataset can be estimated using a minimum correlation threshold of 90% (blue dashed line).

Using a correlation level of 90%, Figure 3 shows how consistent P-wave times are picked. They exhibit inconsistencies of approximately ±6 ms; thus using the mentioned average velocity, we can estimate location uncertainty of approximately 24 m only due to time picking errors. The symmetry in the picking histogram is due to the arbitrary numbering of the doublets. It does not reveal if first arrivals are systematically picked to early, late or biased in any sense. It simply reveals internal consistency. The chosen correlation threshold obviously influences the estimated location uncertainty, in that higher correlation thresholds will honor the assumption of truly co-located events better, but fewer events will be taken into account in the estimation, increasing the uncertainty in the estimate.

Figure 4 shows Hudson diagram for all detected 16 multiplet groups during stage 12. In general they exhibit high double couple (DC) and deviatoric components but most events in each group are scattered, such as groups 1 (white), 3 (light orange), 12 (blue), indicating significant internal inconsistency between estimates. When tracing back the origin of the large discrepancies between some inferred moment tensor solutions, we found that in most cases this was caused by mispicks. In other words, inconsistent picking produced different event locations, leading to different inferred source radiation patterns, and thus different moment tensor solutions. This points to an accumulation of errors, when one inversion estimate is used to infer a second derived quantity. The described quality control strategies may help to reduce or at least detect inconsistencies in derived inversion results.

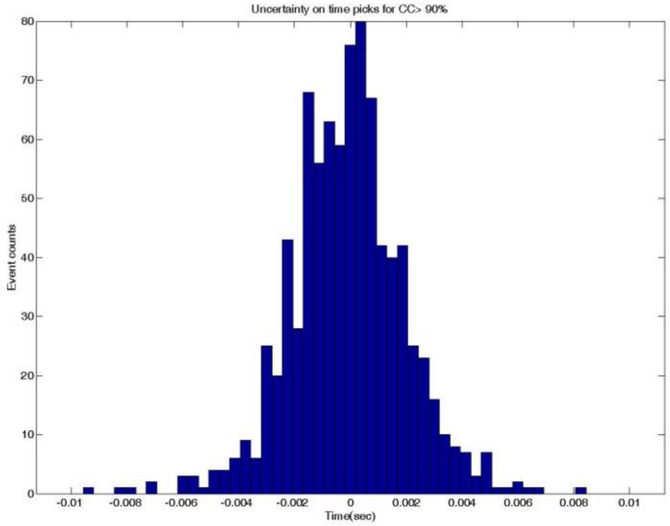

Figure 3: P-wave time pick uncertainty using 90% as minimum correlation level.

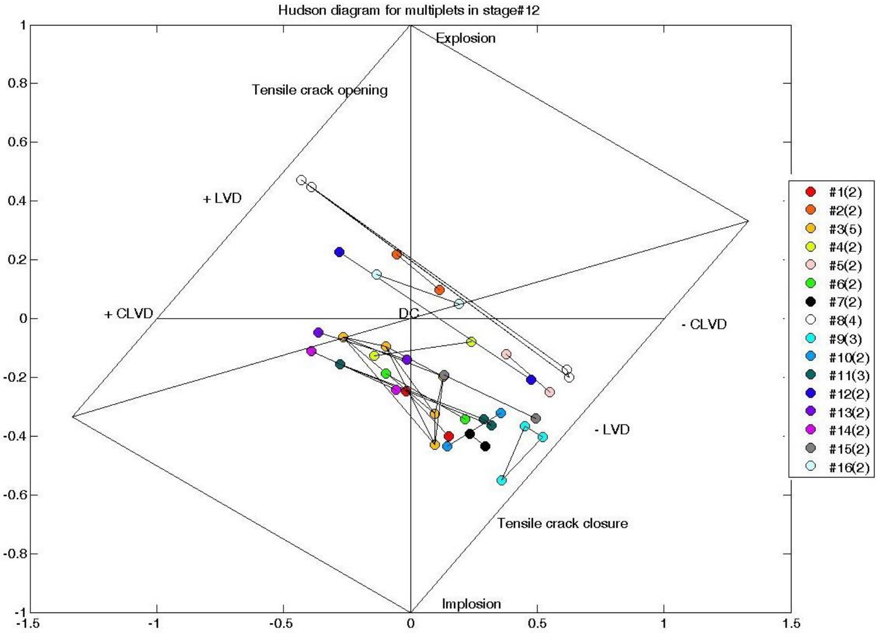

Figure 4: Hudson diagram for all 16 multiplet groups (the legend shows number of events per multiplet in parenthesis) found during stage 12. Most similar events (with identical colors) are located at different places. This suggests possible errors in the calculation of moment tensors. Lines connect events within the same multiplet group.

Conclusions

Waveform similarity offers a plethora of information in microseismic processing. It can be used for QC of time picking errors and hypocenter locations by assessing internal consistency of results. It also shows promising results as a QC strategy for moment tensor solutions. This technique based on waveform similarity is suitable not only for hydraulic fracturing treatments, but may also be applied to other datasets where repeating events are expected.

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