Quality assessment of microseismic event locations and traveltime picks using a multiplet analysis

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The proliferation of hydraulic fracturing (frac) stimulation and other enhanced oil recovery techniques in unconventional plays has spurred interest in microseismic monitoring. Changes in stress in the subsurface produced by hydrocarbon production may induce brittle failure events. Many enhanced oil recovery techniques such as hydraulic frac stimulation or cyclic steam stimulation involve injecting large volumes of fluid at high pressure into a reservoir. Microseismic events, hereafter events, may illuminate the reach and effectiveness of enhanced recovery techniques within a reservoir. When array configuration is favorable, advanced analysis of microseismic data may provide additional information. For instance, seismic moment tensor inversion (Eaton and Forouhideh, 2010) may estimate the failure mode of an event. The aforementioned failure modes may include fracture-opening, shear, or fracture-closing events. Knowledge of the failure modes allows a detailed analysis of the effects of changing parameters such as steam injection temperature or well spacing.

Microseismic analysis begins by locating events. Events are most commonly located by finding the event hypocenter, which minimizes the difference between picked and modeled P- and S-wave traveltimes (Waldhauser and Elsworth, 2000). As a result, event location accuracy is directly tied to the accuracy of arrival picks and the subsurface velocity model used to calculate modeled P- and S-wave traveltimes. The onset of energy for an event is often obscured by random noise or coherent noise because of poor tool coupling or bad cement jobs. As noise and wavelet size increase, it becomes increasingly difficult to identify an event's "true" arrival time. For complex waveforms, phases may be misidentified entirely. Backscattered arrivals may appear as coherent phases, and shear-wave splitting may create the illusion that two events are present. When multiple overlapping events are observed on a single seismogram, it is often unclear which phase is associated with which event. In summary, picking issues include (1) large time errors in picks, (2) misidentification of various arrivals, or (3) missing picks caused by ambiguous or noisy waveforms.

In this article, we present a strategy to use microseismic multiplets to assess the quality of P- and S-wave arrival picks, and the resulting event location accuracy. We then present a methodology to examine event location error introduced by sparse velocity information, and how to mitigate the aforementioned error using multiplet analysis.

Methodology

Multiplet analysis. Multiplet analysis presents an opportunity to analyze arrival picks and the resulting event locations. A doublet is a repetition of a microseismic event. Poupinet et al. (1984) define a doublet as "a pair of microearthquakes that have nearly identical waveforms and the same hypocenter and magnitude but occur on different dates." A group of three or more events with nearly identical waveforms are referred to as a multiplet. The concept of a multiplet is illustrated in Figure 1 where brittle failure occurs in a hydrocarbon reservoir. At a later time, the same failure is observed in the same location creating a dupli-

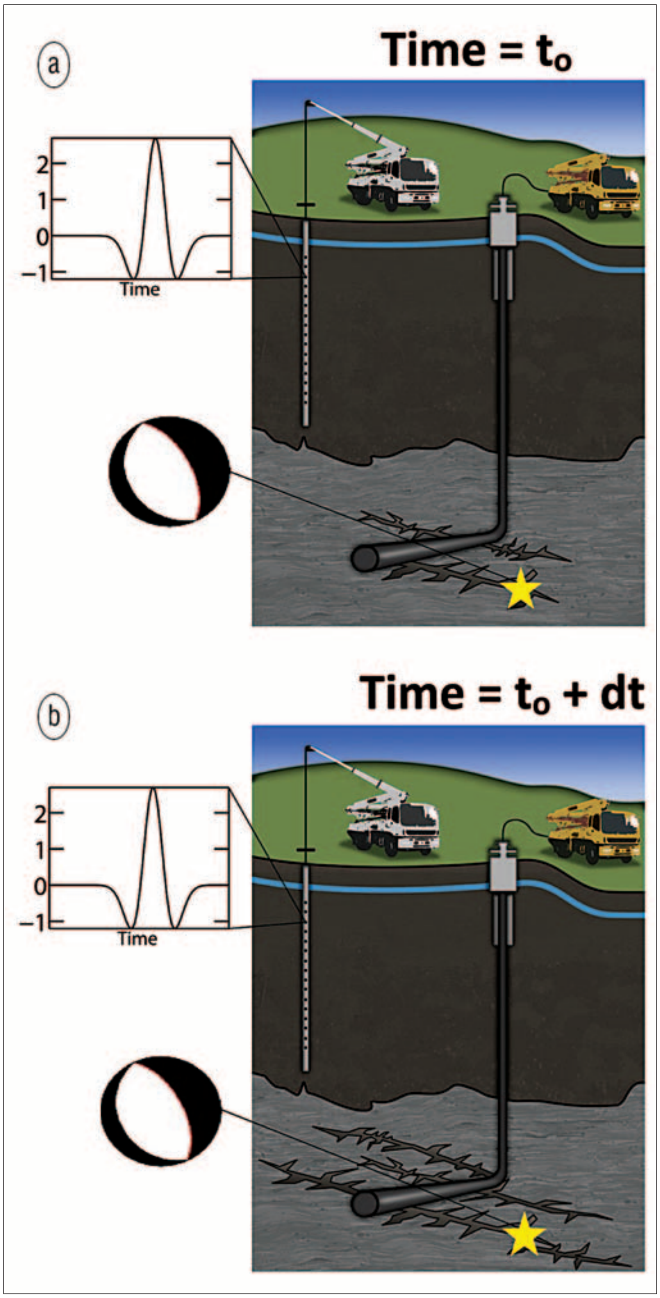

Figure 1. A multiplet is a repetition of a microseismic event. (a) Shear failure occurs at time $t = t_o$ in a hydrocarbon reservoir at the location denoted by a yellow star. (b) At a later time $t = t_o + dt$, the same shear failure occurs at a similar location. Consequently, the same waveform is recorded allowing data quality assessment.

cate waveform. An example of a multiplet recorded in a heavy oil field is shown in Figure 2. Multiplets were first observed by Geller and Mueller (1980) and have since been used for a number of applications including monitoring crustal velocity variations (Poupinet et al.), and event relocation (Got et al., 1994; Waldhauser and Ellsworth 2000; De Meersman et al., 2009).

When two events with the same hypocenter and same source mechanism create two waveforms with the same raypath, the recorded waveforms for both events are identical except for additive random noise. Multiplets may thus be identified by waveform cross-correlation (Poupinet et al.; Arrowsmith and Eisner 2006).

Arrowsmith and Eisner note that in a heterogeneous medium, for the waveforms produced by a pair of events to be highly correlated, event hypocenters can be separated by no more than "one-fourth of the dominant wavelength" of the waveforms. In other words, highly correlated events are likely to be closely located in space. Crossplotting waveform correlation coefficients versus event separation for each doublet provides an estimate of event location uncertainty as most location algorithms locate events independently without considering waveform correlation. A significant number of highly correlated waveform pairs showing a large hypocenter separation distance is indicative of a systematic event location problem.

We begin our analysis by identifying multiplets following the methodology of Arrowsmith and Eisner. For an event pair, sensors which have picks for both events are identified. If an event pair has less than three common sensors, it is discarded. For each common sensor, we cross-correlate all components and combine the correlation coefficients for each components in a signal-to-noise weighted average. P-waves and S-waves are correlated separately. We then calculate the correlation coefficient for the event pair by averaging all the correlation coefficients of all common sensors. The correlation coefficient for every event pair is then stored in an N × N cross-correlation matrix where N is the number of events. Events pairs with a large correlation coefficient are

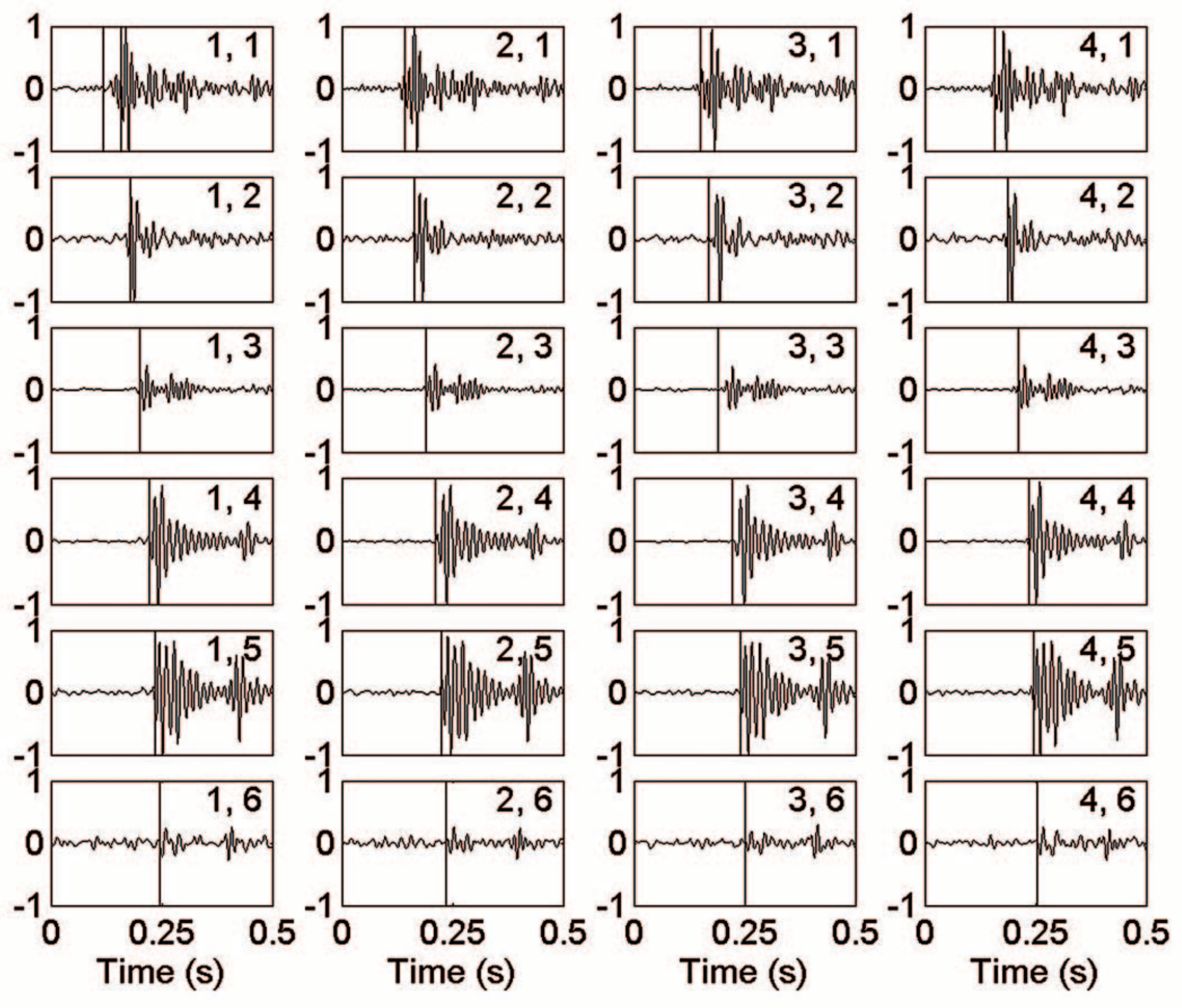

Figure 2. *Events recorded at four different times comprising a multiplet group; each column contains one event, each row illustrates one station. Note the waveform similarity across each row for the events occurring on separate dates. The event number followed by the station number is specified above each waveform.*

flagged as a doublet pair. Multiplet groups are then identified using a breadth-first search algorithm. A breadth-first search requires that an event in a multiple group be highly correlated with at least one other event in the said group. The search consists of two steps. First, we start with a group of events consisting of a single doublet pair. Second all other doublet pairs with at least one event present in the group are added to the group. The second step is repeated until no more events can be added to the current multiplet group. Both steps are then repeated for the remaining ungrouped events.

By definition multiplets are highly correlated waveforms and should thus be picked in a similar manner. Consider a sensor which has recorded a doublet pair. If the pair's waveforms are aligned to maximize their correlation, then the time separation between any common picks should be small. A large separation on the order of tens of milliseconds or more is diagnostic of a misidentified phase. By crossplotting correlation coefficient versus pick time offset, mispicked events are separated from consistently picked events. A corollary of the preceding argument is that if an event is accurately picked it may serve as a template to autopick any doublet of itself. The same argument applies directly to polarity picks when performing seismic moment tensor inversion. Polarity picks will be the same for both events in a doublet pair. An event with proper polarity picks may serve as a template to autopick any doublet of itself.

Relative relocation. After identifying multiplet groups, we use the double-difference method of Waldhauser and Ellsworth (2000) to relatively relocate each group. The double-difference method computes the difference between observed and modeled traveltimes for pairs of events. Assuming that two events have similar raypaths, both events will be equally affected by any unmodeled velocity heterogeneity. By definition, the raypaths must be similar for events in a doublet pair. By computing the difference in traveltimes between two events with similar raypaths, the velocity heterogeneities introduced by modeling errors will cancel. Using the traveltime difference between all doublet pairs,

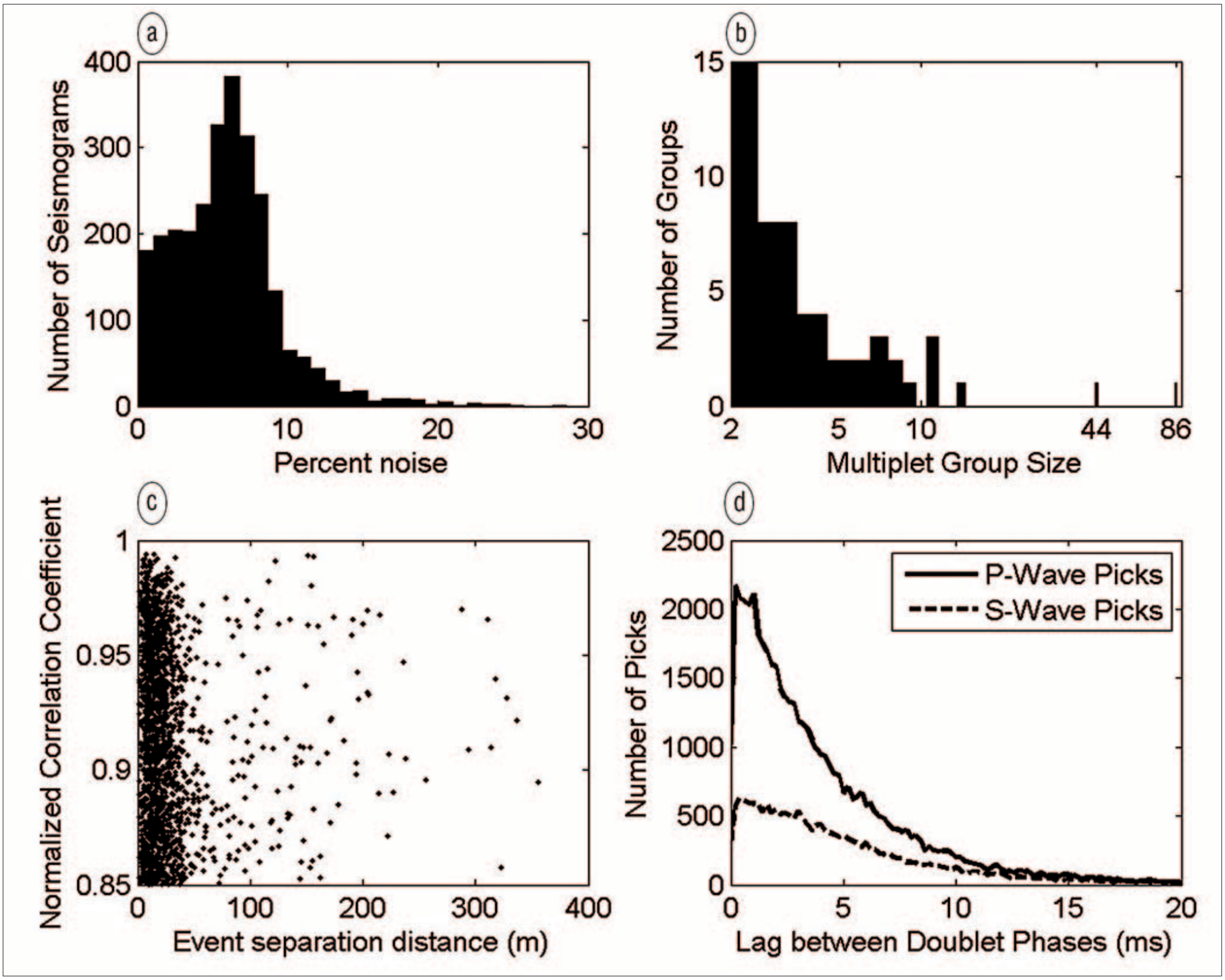

Figure 3. *Overview of microseismic multiplets recorded in a western Canadian heavy oil field. (a) Postfiltering noise contamination histogram. The noise percentage is defined as the standard deviation of the pre-event noise to the maximum amplitude after the first arrival. On average, multiplets contain 9.0% noise. (b) Histogram of the multiplet groups identified via cross-correlation; 86 groups containing 373 events were identified. Note the x-axis is logarithmic. (c) Normalized correlation–hypocenter separation for all doublet pairs. Most doublet pairs locate in close proximity. (d) Lag between phases picked on common sensors for doublet pairs.*

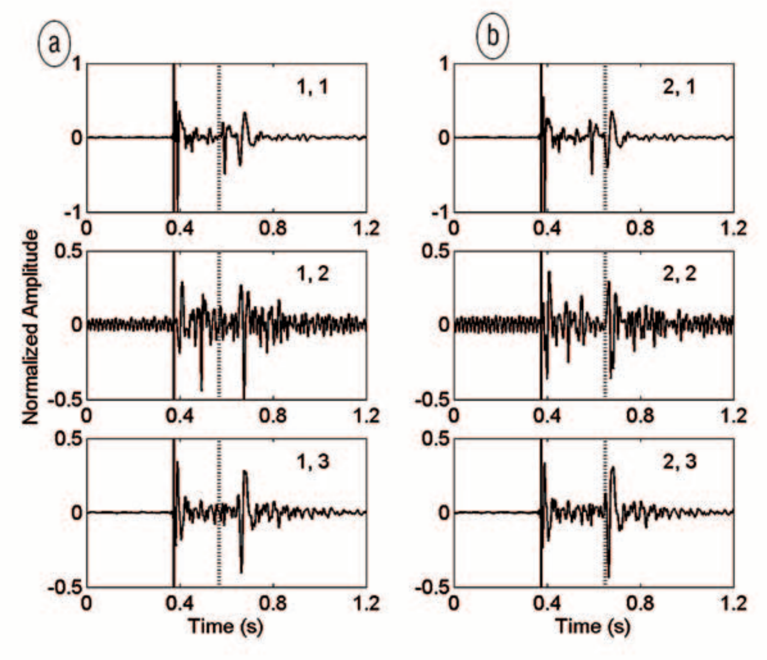

Figure 4. *A mispicked doublet pair. Event number followed by channel number are shown above each waveform. The P-wave picks (solid vertical lines) are consistent within the doublet pair. However, different phases have been picked as the S-wave (dashed vertical lines) for each event.*

high-resolution event location corrections are calculated and applied to the doublets.

Before applying the double-difference method to a doublet pair, arrival picks must be inspected to ensure the relative traveltime differences are because of the spatial offset between both events. Inspection is an important tool for any postprocessing technique, especially if the assumptions made by a postprocessing technique are challenged by the data. The role of inspection is examined in more detail in the discussion section.

Results

We perform multiplet analysis on a data set acquired in a western Canadian heavy oil field. We analyze a total of 2692 microseismic events recorded by multiple observation wells. A total of 164 geophones are used to detect and locate seismicity. P- and/or S-waves for microseismic events are typically identified on 12 geophones; however, some events are detected on as few as three or as many as 74 geophones.

Seismograms are sampled at 4000 Hz. Prior to cross-correlation, we filter the data with a trapezoidal band-pass filter with corner frequencies of 0 Hz, 10 Hz, 85 Hz, and 115 Hz to reduce noise. We then decimate our data by a factor of four to decrease computing times during waveform cross-correlation.

The correlation coefficient of a doublet pair depends on several factors. For instance, random noise or temporal variations in elastic medium properties will reduce the correlation observed between a doublet pair. S-waves often have higher amplitudes and longer wavetrains than P-waves; thus many weighting schemes are plausible for combining separate S- and P-wave correlations. We use the threshold for identifying doublet pairs based on noise level presented in Arrowsmith and Eisner.

We identify a total 373 multiplets in 86 groups. Figure 2 shows an example of an identified multiplet group. For our purposes, we define the signal-to-noise ratio of an event as the ratio of the standard deviation of the pre-event noise to the maximum amplitude observed after the first arrival. A histogram of filtered event signal-to-noise ratios is presented in Figure 3a. On average, an event is contaminated by 9% noise; we thus use a correlation threshold of 0.85. Any waveform pair that is at least 85% correlated is flagged as a doublet pair. The size of the identified multiplet groups is summarized in Figure 3b. The separation distance and correlation between each doublet pair is shown in Figure 3c, and time lag between common doublet picks is shown in Figure 3d. We define the zero time lag as the position where common pick pairs are collocated. The peak at 2 ms in Figure 3d represents arrival time uncertainty; arrival pick uncertainty is examined in further detail in the discussion section. For the identified doublet pairs, 1.1% of correlated P-wave pairs and 1.7% of S-wave pairs exhibit a large lag exceeding 20 ms. Such a large lag is diagnostic of a mispick. An example of a mispick that adversely affects event location accuracy is presented in Figure 4. Event location uncertainty due to pick uncertainty is illustrated in Figure 3c by a cluster of doublet pairs around a separation of 40 m. Several poorly located outliers with separation distances in excess of 300 m are also seen in Figure 3c.

The initial locations of all multiplets are shown in Figure 5. Two major seismicity clusters are immediately apparent. This first cluster is observed at a depth of 200 m while the second cluster is observed at a depth of 450 m. The two main clusters seem to be linked by a chain of events. The link between clusters suggests some kind of stress communication. Multiplet locations following a double-difference relocation are shown in Figure 6. By comparing Figures 5 and 6, it is clear that scatter in the event cloud has been reduced as theoretically expected. Multiplets in the chain that initially linked event clusters have collapsed into a much tighter group of events inside the upper cluster. The two clusters which originally appeared to be in communication emerge as separate entities following relocation. This example clearly illustrates the potential for event location error to lead an erroneous interpretation.

Discussion

Microseismic event locations are determined primarily by inverting traveltime data. Thus uncertainty in the velocity model and in event arrival times will result in many plausible event location models. When comparing two plausible event location models, it is often not clear which model is more accurate. However, events in a multiplet group should be tightly clustered and a model perturbation which collapses a diffuse multiplet cloud has likely improved event locations. Multiplets thus provide a means for gauging the effectiveness of a relocation technique or model perturbation.

We compare a set of event locations before and after running a double-difference analysis. The double-difference method assumes interevent distance is small relative to event-receiver separation distance. The aforementioned assumption is often challenged in a microseismic setting, suggesting the double-difference method may fail to improve event locations. We assess the effectiveness of the double-difference relocation by comparing doublet separation before and after relocation.

By comparing Figures 5 and 6, it is clear that scatter in event clouds has been reduced. This is illustrated best by the chain of events between both clusters in the original event locations. The chain contains doublets that are separated by as much as 197 m. The separation of all doublet pairs in the chain before and after relocation is shown in Figure 7. Relocation significantly reduces both average and maximum doublet separation, strongly suggesting a successful relocation.

The reliability of any location optimization will depend strongly on pick quality. For multiplets, mispicks in the data can be found using cross-correlation and then corrected. For a doublet pair, the lag between picks for similar phases should be small. Arrival-time separation for each phase on the same sensor for every doublet pair at peak correlation is shown in Figure 3d. Figure 4 shows an example of a mispick for a doublet pair. In Figure 4, the time lag between the picked P- waves is 3 ms while the lag between picked S-waves is 56 ms. The time lags clearly indicate that the P-wave has been consistently picked while at least one of the S-waves has been mispicked. Unfortunately, the cross-correlation analysis does not indicate the true S-wave arrival. The modeled arrival time predicted from the event location and assumed velocity model may illuminate which pick is correct.

An alternative strategy to identify and correct mispicks is by using a modified form of the approach by De Meersman et al. (2009). They stack and correlate waveforms to reduce arrival-time uncertainty for an event recorded by several sensors in a borehole array. The same principle can also be applied on waveforms for all events in a multiplet group recorded by one sensor (that is, a row in Figure 2). Waveforms are first aligned based on arrival time. The moveout-corrected traces are then stacked to create a pilot trace. Separate pilot traces are created for P- and S-waves. Next, each trace is crosscorrelated with the pilot trace to correct the arrival time at each station. This process is repeated until arrival-time shifts become negligibly small. If a picked

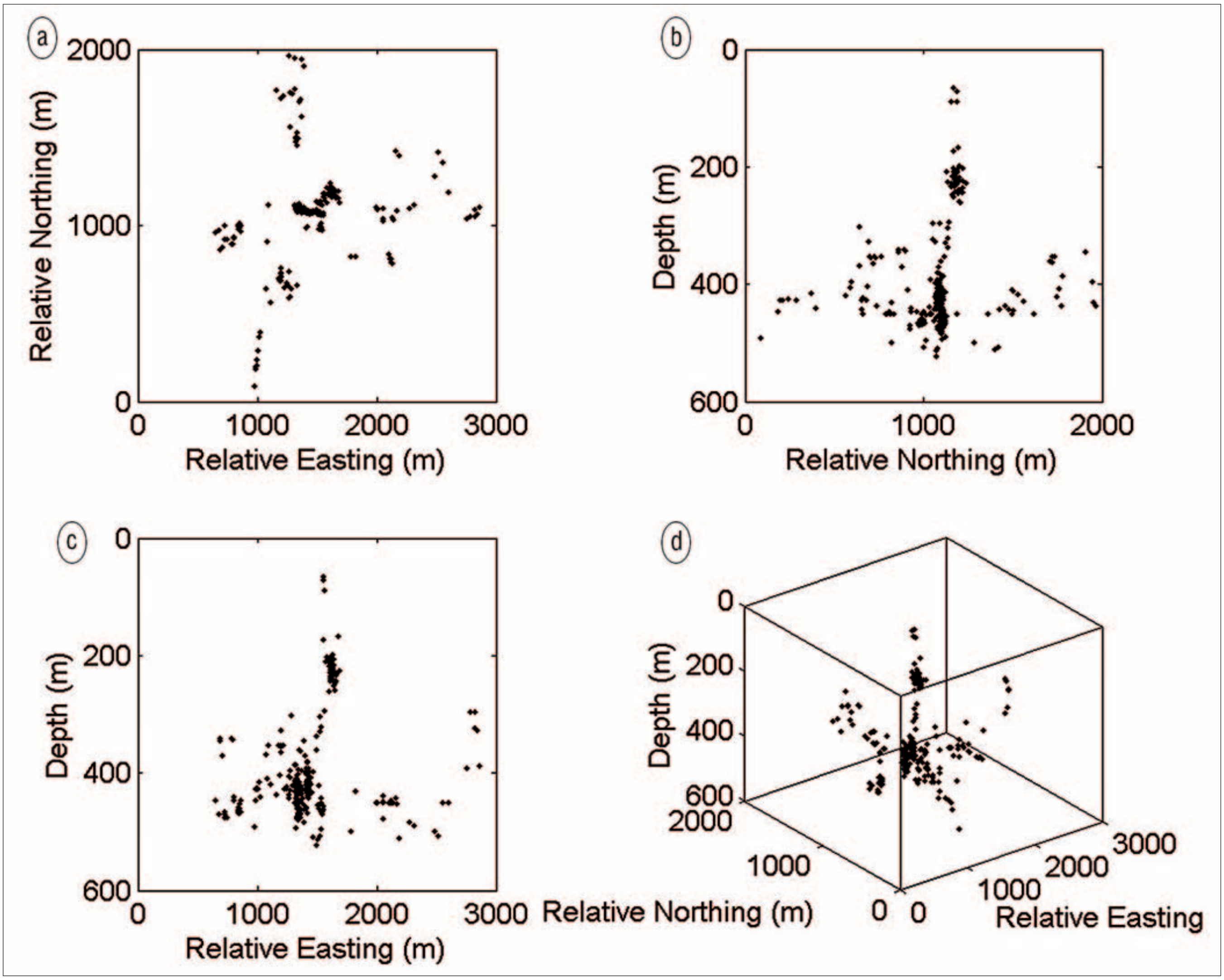

Figure 5. *Multiplets before relocation shown in x-y (a), y-z (b) and x-z (c) planes, as well as a 3D view (d). Note the two seemingly linked seismicity clusters at depths of 200 and 450 m (cf Figure 6).*

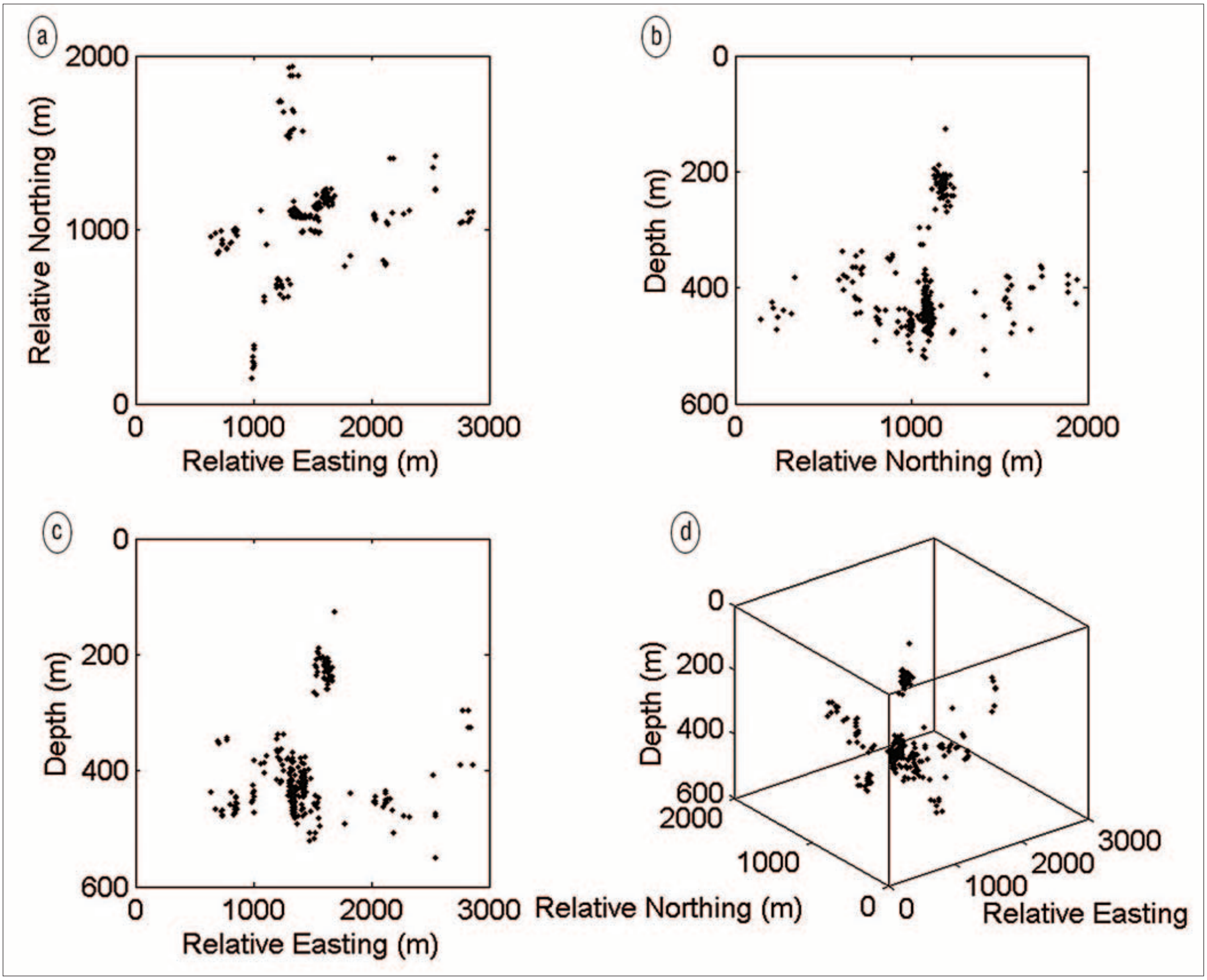

Figure 6. Multiplets after relocation shown in x-y (a), y-z (b) and x-z (c) planes, as well as a 3D view (d). Note the two seismicity clusters at depths of 200 and 450 m are separate (cf Figure 5).

phase has a low correlation with the pilot trace, the event in question is cross-correlated with the pilot trace to find a phase which has a high correlation with the pilot trace. A new pick is then placed to maximize the correlation and minimize the lag of the event with the pilot trace.

This approach assumes that the majority of picks are correct within a multiplet group but will identify mispicks, for instance because of misidentification of an arrival (Figure 4).

A different approach is required to identify missing picks. Often, either the P-wave or the S-wave will have significantly higher amplitude than the other.

We observe multiplet groups where the S-wave is consistently and clearly visible; however, the P-wave is masked by background noise. To estimate missing picks in multiplets, the methodology of De Meersman et al. can be modified as follows. For a multiplet group, we use any available P-wave picks, complemented by modeled P-wave arrival times, to align P-wave arrivals. Next, traces are stacked to create a pilot trace which is then used to obtain fine-tuned arrival

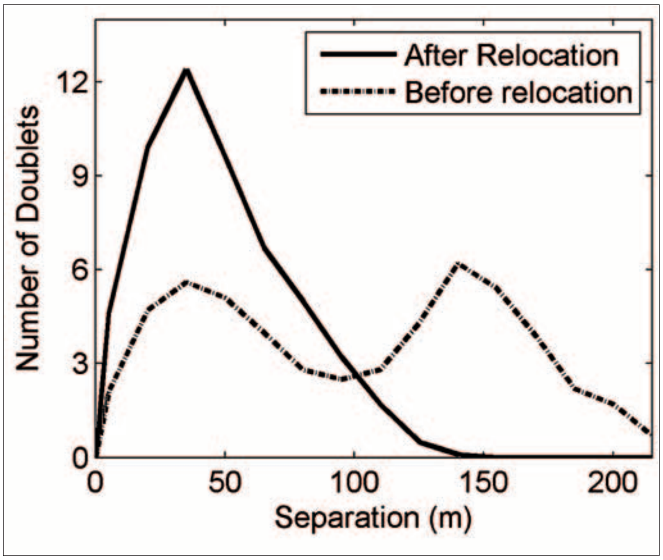

Figure 7. Hypocenter separation distance for all doublet pairs within a multiplet group before and after a double-difference relocation. Postprocessing decreases both average and maximum doublet hypocenter separation suggesting a successful relocation.

times as before. This procedure will reduce missing picks as long as the P-wave arrivals are weak but above the noise floor.

Conclusions

Event groups with highly correlated waveforms known as multiplets illuminate event location quality before and after undergoing postprocessing. To produce a pair of highly correlated waveforms in a heterogeneous medium, a pair of events must be nearly colocated. Most location algorithms do not consider interevent waveform correlation; thus location issues are highlighted by highly correlated, widely spaced event pairs.

Missing or mispicks will reduce event location quality. Inconsistent picking within a multiplet group is highlighted by a large time lag at peak cross-correlation. Where picks are absent because of data quality, multiplets may be stacked to improve signal-to-noise ratio.

A multiplet analysis performed on a microseismic data set recorded in a heavy oil field reveals the importance of postprocessing quality control. Event locations are significantly improved by a double-difference analysis that collapses diffuse multiplet clouds as demonstrated by comparing Figures 5 and 6. In excess of 99% of arrival picks display a small time lag on the order of milliseconds, suggesting that the 1D velocity model originally used to locate events may be inadequate. In the absence of sufficient data to construct a 3D velocity model, postprocessing is essential for obtaining accurate event locations. Multiplets analysis is an ideal tool to gauge if a postprocessing technique has successfully improved event locations. TLE

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