Passive-seismic methods provide an effective surveillance technology for monitoring the growth and activation of fracture networks during hydraulic-fracture (HF) stimulation of unconventional reservoirs, since microseismic events occur as localized brittle-failure processes that accompany tensile fracture growth (Warpsinski, 2009; Maxwell, 2010). A number of acquisition geometries are used for microseismic monitoring (e.g., Eisner et al., 2010), including downhole geophone arrays installed in a deep wellbore close to the injection zone as well as deployment of surface and/or near-surface arrays. Downhole acquisition within a single monitor well is a commonly used configuration; although it is subject to a number of limitations that stem from limited observational apertures (Eaton and Forouhieh, 2011), this approach provides some distinct advantages by virtue of proximity of the sensors to the treatment zone (Maxwell et al., 2010). This paper introduces a novel correlation-based method for detection, location and analysis of microseismic events, tailored for a downhole recording geometry.

In the case of downhole microseismic acquisition, hypocentre locations are generally determined by picking P and S arrival times to estimate hypocentral distance, followed by polarization analysis of the P wave to estimate back-azimuth to the event (Oye and Roth, 2003). Typically, this process requires a significant level of user interaction and is prone to missing weak events for which only a single phase (e.g. the S-wave) is readily discernible and (Akram, 2014). In earthquake studies, template-based methods (also known as Matched Filtering Analysis, or MFA) have been developed for automated detection of weak events based on one or more reference signals (Skoumal et al., 2015). The MFA approach has been employed for microseismic monitoring (Goertz-Allmann et al., 2014) and has significant potential to overcome some of the limitations of traditional downhole microseismic processing methods.

The MFA method is based on cross-correlation of the raw continuous time series with a template event, herein referred to as a ‘parent’. This approach is based on the principle that for a pair of microseismic events observed at a given location, strongly correlated waveforms imply similarity in both focal mechanism and hypocentre location. For an array of three-component geophones, waveform cross-correlation depends on the moveout characteristics of P- and S-wave arrivals as well as the polarization of each phase. Figure 1 shows an example of a parent microseismic event together with three other events, herein referred to as ‘child’ events, which were detected based on a correlation analysis technique that is described below. Although there is a considerable level of background noise in these recordings, there is evident similarity in moveout and polarization of the child and parents events.

In this paper, we augment the basic MFA approach with a new procedure to estimate the relative location and magnitude of child events, by exploiting both the beam-forming capabilities and directional sensitivity of the downhole array. This new approach enables automated detection and analysis of microseismic events that might otherwise be difficult to locate using standard processing techniques. Our methodology requires a set of well-located template parent events that are selected on the basis of high signal-to-noise (S/N) ratio. The effectiveness of our technique is illustrated with a case study from microseismic monitoring of a multi-stage slickwater HF treatment of a tight sand reservoir in western Canada.

**Method**

The MFA workflow is summarized in Figure 2 and briefly described below; for additional details of the methodology, the reader is referred to Caffagni et al. (2015). Our approach requires a set of accurately located parent events with good S/N, which are each used as template signals for cross correlation with the raw data. Preconditioning is required for both parent events and raw data to avoid spurious detections and to ensure that low S/N child events are recovered. We have found that suitable signal preconditioning is obtained by normalization of parent events by their maximum 3-C amplitude, together with application of automatic gain control (AGC) to the raw data in a manner that preserves the relative amplitudes of each receiver component, using a window length similar to the event duration (Caffagni et al., 2015).

The first step in the event-detection procedure is based on three-component cross-correlation, given by

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**Enhanced downhole microseismic processing using matched filtering analysis (MFA)**

David W. Eaton\(^1\) and Enrico Caffagni\(^1\) present a new procedure to estimate the relative location and magnitude of child events, by exploiting both the beamforming capabilities and directional sensitivity of the downhole array.

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For each parent event, one of the three phases (P, S\textsubscript{fast}, and S\textsubscript{slow}) is selected as a reference phase for stack optimization for the detected child events. The reference phase is chosen on the basis of S/N and typically the S\textsubscript{fast} phase is selected. The use of a reference phase in our MFA procedure enables location and magnitude estimation for child events for which only a single phase is discernible in the data, as illustrated in Figure 3d.

A stacking process is used to obtain the relative location of the child event within a search region around the parent hypocentre. The stacking function is defined as

\[ S(t, r, z, \theta) = \sum_{j=1}^{N} A_j(t, r, z, \theta), \]

where \( A \) is a positive-valued function given by

\[ c_i(t) = p_i(t) \otimes u_i(t) = \int_{-\infty}^{\infty} p_i(\zeta)u_i(\zeta + t) d\zeta, \]

where \( u_{ij}(t) \) represents continuous raw three-component data after preconditioning, for the \( i \)th component and the \( j \)th receiver level, and \( p_{ij}(t) \) is a preconditioned parent event containing P and S wave arrivals. Event detections are obtained by selection of local maxima of the stacked cross-correlation function

\[ s(t) = \sum_{i=1}^{3} \sum_{j=1}^{N} c_i(t), \]

An important part of the preconditioning procedure involves polarization analysis of the parent events and rotation of 3-component traces into ray-centered co-ordinates (Cerveny, 2001), thereby isolating P, S\textsubscript{fast}, and S\textsubscript{slow} signals. Our procedure also makes use of an iterative refinement of the picked times that incorporates static shifts and polarity checking (De Meersman et al., 2009). Once the ray-centered co-ordinates for the parent event have been determined, the three-component recordings for the child events are transformed into the ray-centered co-ordinate system for the corresponding parent (Figure 3). This step has the effect of approximately isolating the P, S\textsubscript{fast}, and S\textsubscript{slow} phases on to mutually orthogonal waveform components.

**Figure 1** Unfiltered record sections showing a representative parent event (A) and a set of children events (B-D) that were detected with 3-C cross-correlation. Calculated magnitudes are indicated in the lower-right corner of each panel. Receiver levels are independently normalized. Trace colours denote pre-rotation geophone orientations: blue = vertical, red = horizontal 1, green = horizontal 2.

**Figure 2** Workflow for the MFA method.
\[ A_i(t, r, z, \theta) = R_\theta (a_i(t, r, z)) , \]

In this expression, \( R_\theta \) is an operator that applies a clockwise rotation through an angle \( \theta \) in ray-centered co-ordinates and \( a_i \) is the three-component amplitude envelope for the \( i \)th receiver level. An envelope-stacking procedure is used here, rather than direct waveform stacking, to accommodate slight variations in radiation patterns and location that may exist between the parent and child events (cf. Figure 3). After searching within a specified region around the parent hypocentre, the relative hypocentre location for the child is obtained by selecting values of \( \Delta r, \Delta z \) and \( \theta \) that maximize the peak value of \( S(t) \). As a final screening process, child event detections are omitted if they do not yield a maximum of \( S(t) \) within a user-defined search region around the parent event. In the examples below, the search region is confined to ± 100 m in depth and radial distance and ± 5 degrees in azimuth around the parent hypocentre.

As detailed by Caffagni et al. (2015), the relative magnitudes of child events, \( M_{\text{child}} \), are estimated based on the ratio of child/parent amplitudes and distances, according to

\[ M_{\text{child}} = M_{\text{parent}} + dM = M_{\text{parent}} + \frac{2}{3} \log_{10} \left[ \frac{d_{\text{child}}}{d_{\text{parent}}} \cdot \frac{c Q A_{\text{child}}}{\Delta d A_{\text{parent}}} \right] , \]

where \( d = (r^2 + z^2)^{1/2} \) is the minimum distance from the receiver array to the hypocentre, \( \Delta d \) is the difference in minimum hypocentral distance for the parent and child events, \( f_0 \) is the corner frequency of the source spectrum, \( c \) is the average wave velocity corresponding to the reference phase along the path from the hypocentre to the receiver, \( Q \) is the quality factor corresponding to the reference phase and \( A = \max(S(t)) \) denotes the peak value of the beam-formed amplitude envelope function.

**Case Study**

We illustrate the application of our MFA procedure using a monitoring dataset recorded during the first four stages of an open hole, slickwater HF treatment of the upper Cretaceous Cardium formation within the Garrington field in Alberta, Canada (Figure 4). Commercial processing of this dataset yielded a complex spatial distribution of microseismicity (Duhault, 2012), with 346 microseismic events in stages 1-4 ranging in magnitude from −4.01 to −1.29. The initial velocity model used to locate the microseismic events was constructed using well-log data from the vertical monitor well. The final velocity model was obtained by adjusting the initial model to ensure that calibration sleeve opening events were located to their correct positions. Four events from each treatment stage were chosen here as parent events, based on criteria of high \( S/N \) and avoidance of pairs of parent events in close mutual proximity. The locations and magnitudes of the parent events in this case are based on the original contractor processing of the data.

After removal of duplicate events and child events that did not produce a local maximum within the search region around its parent hypocentre, we detected and located 1316 child events. In Figure 5, histograms showing the microseismic event rate are compared with the treatment
curves. The event rate for the MFA results is plotted using blue bars, whilst the event rate from the original catalog is mirrored beneath it using red bars. Although both catalogs exhibit approximately similar relative trends in microseismicity, the MFA results are more easily interpreted due to the higher event rate and greater range of values. There is a clear, time-varying correspondence between event rate and the treatment parameters for individual treatment stages. In stage 1, the highest event rate occurs near the beginning of the stage, roughly synchronous with the highest treatment pressure levels during initiation of the hydraulic fracture at the wellbore. In contrast, the highest rates of microseismicity during stages 2 and 3 occur near the end of each treatment stage. The seismicity rate histograms suggest overlapping activity during stages 3 and 4. For this reason, rather than using treatment stages for interpretation, we define event clusters whose start and end times are marked along the event rate time axis. A final burst of microseismic activity, identified here as cluster 4, coincides with a pressure transient that immediately follows stage 4 of the treatment.

Locations of the microseismic events using different methods are compared in Figure 6. The original catalog contains 346 events that are primarily located on the north side of the treatment well, which may reflect either an observational bias in the direction of the monitor well or stress-gradient effects (Caffagni et al., 2015). In cross-section, based on the original locations, the events occur mainly within the treatment zone (Cardium sand) but some events occur both above and below the zone. The distribution of the 1332 events (parents + child events) determined

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**Figure 4** Location map of the study area showing Garrington and other Cardium pools in western Canada.

**Figure 5** Comparison between pump curves (upper panel) with seismicity rate (lower panel) determined using both the MFA approach (blue) and the original catalog (red).
Figure 6  A) Perspective view (looking WNW) of microseismicity from the original catalog. Clusters 1-4 are plotted in red, blue, green and magenta, respectively. Sleeve opening event locations are indicated by stars. B) As in (A), side view looking north. C) Perspective view (looking SSW) of microseismicity from the MFA catalog, with clusters plotted using the same colours as in (A). Parent events are indicated with plus symbols. D) As in (C), side view looking north. Formation names: W = Wapiti, C = Cardium, B = Blackstone, 2WS = Second White Specks.

Figure 7  A) Map view of microseismicity from the original catalogue, showing clusters 1 (red) and 2 (blue). Event symbol size is scaled by magnitude. B) Map view of microseismicity from the MFA catalogue, clusters 1 and 2. C) Interpretation of (B). Although the overall trend of the microseismic clouds is close to the direction of Shmax, several event lineations that extend between clusters suggest activation of natural fractures with an ENE strike, oblique to Shmax. D) Map view of microseismicity from the original catalog, clusters 3 (green) and 4 (magenta). Events from clusters 1 and 2 are plotted in grey. E) As in (D) for the MFA catalog. F) Interpretation of (D). Cluster 4 contains events that reactivated a distal part of cluster 3 during a pressure transient that occurred after stage 4 (Figure 6).
using the MFA approach are more concentrated both in map and cross-sectional views (Figure 6, lower panels). Notably, the depth extent of the microseismicity appears to be more densely concentrated within the target horizon. This has important implications for evaluation of the effectiveness of the stimulation programme.

Details of the microseismic event distributions are presented in Figure 7, where clusters 1 and 2 are highlighted in the top panels and clusters 3 and 4 are highlighted in the lower panels. Unlike the diffuse distribution apparent in the original catalogs, the MFA results appear to show well-defined linear trends. Elongated clouds of microseismic events occur along azimuths that are oblique to the maximum horizontal stress direction, the direction in which hydraulic fractures are expected to grow. This mis-orientation with respect to Shmax may represent reactivation of natural fracture systems within the target zone during the treatment programme (Eaton et al., 2014).

For cluster 1, the event distribution defines a possible set of en echelon fracture trends, some of which appear to be aligned with dense microseismicity that occurred during cluster 2 (Figure 7). A dense cloud of microseismicity that is subparallel to the cluster 2 events is evident for cluster 3. The width of the event cloud is slightly greater for cluster 3 than for the previous clusters, suggesting a possible increase in fracture complexity. The majority of events that occur during cluster 4 are located near the distal part of cluster 3. This spatiotemporal pattern suggests that a pressure transient that occurred after stage 4 (Figure 5) led to reactivation of a distal part of the region that was active during cluster 3. Due to the diffuse distribution of events in the original processed results, none of these details is evident in the original catalog (Figure 7), hindering detailed interpretation of the results.

Discussion

The MFA approach developed here has a number of potential advantages over conventional processing of downhole microseismic data. Conventional approaches require detection and time picking of both P and S wave arrivals for all events, which is prone to errors from time-picking uncertainty as well as missed events where only a single phase (typically the S wave) is visible (Akram, 2014). To ensure high quality of event locations, the picking and location process is usually interactive and can be time consuming and subjective. For the MFA approach described here, only a few select parent events need to be geo-located. Since the parent events have high S/N, the picking process is less error prone and is expected to produce more accurate locations and magnitudes. Since the relative locations and magnitudes of child events are obtained automatically this enables interactive processing effort to be focused on only the highest-quality events.

As noted by Caffagni et al. (2015) there are a number of distinct challenges for the MFA approach. Among these, the selection of a suitable set of parent events is critical. In principle, these events should form a complete basis for all of the detectable microseismicity; in practice, this level of completeness is difficult to verify. In the present study, we selected four parent events from each of the four treatment stages considered, for a total of 16 parent events. The criteria used in the selection process were both high S/N together with an attempt to choose parent locations that span the expected spatial extent of microseismicity for each treatment stage (i.e. parents with proximal locations and similar waveforms are avoided). Ongoing research is focused on the elucidation of practical guidelines for optimal selection of parent events.

A number of interpretational advantages of the MFA approach are evident from the case study presented here. We find that the higher abundance of locatable events, which is mainly enabled by the inclusion of single-phase events that would otherwise be discarded, allows for more robust correlation of microseismic event rate with treatment curves. Hypocentres for child events are anchored to the absolute locations of parent events; our results suggest that relative locations obtained using this approach provide more easily interpretable spatiotemporal patterns of the distribution of microseismicity, which can then be incorporated into the assessment of the stimulation programme.

Conclusions

We have developed a Matched Filtering Analysis (MFA) method that is tailored for application to downhole microseismic monitoring using an array of multi-component sensors within a single monitor well. Our procedure is based on cross-correlation between reference events (‘parent’) and continuous raw data, generating additional (‘child’) events. A new technique based on projection of child events on to ray-centered coordinates of the corresponding parent facilitates estimation of relative magnitudes and locations, including single-phase events. Hypocentre locations of child events are obtained by maximizing the amplitude of stacked envelope functions within a user-defined region surrounding the parent hypocentre.

Application of our MFA procedure to four stages from a hydraulic-fracturing treatment in western Canada has yielded promising results, with a roughly four-fold increase in the number of located events relative to recently processed (~2 years) data. On the basis of comparison with hydraulic-fracture treatment curves, we divided the microseismicity into temporal clusters, thus obtaining a more reliable interpretation of their spatiotemporal evolution using the MFA results and insight on HF completion efficiency. Our method provides a more efficient approach than conventional downhole microseismic processing,
since interactive analysis including P- and S-wave picking are limited to a relatively sparse distribution of parent events and the majority of events are picked and located automatically.

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