Reservoir characterization using microseismic facies analysis integrated with surface seismic attributes

Aamir Rafiq¹, David W. Eaton¹, Adrienne McDougall¹, and Per Kent Pedersen¹

Abstract

We have developed the concept of microseismic facies analysis, a method that facilitates partitioning of an unconventional reservoir into distinct facies units on the basis of their microseismic response along with integrated interpretation of microseismic observations with 3D seismic data. It is based upon proposed links between magnitude-frequency distributions and scaling properties of reservoirs, including the effects of mechanical bed thickness and stress heterogeneity. We evaluated the method using data from hydraulic fracture monitoring of a Late Cretaceous tight sand reservoir in central Alberta, in which microseismic facies can be correlated with surface seismic attributes (primarily principal curvature, coherence, and shape index) from a coincident 3D seismic survey. Facies zones are evident on the basis of attribute crossplots, such as maximum moment release rate versus cluster azimuth. The microseismically defined facies correlate well with principal curvature anomalies from 3D seismic data. By combining microseismic facies analysis with regional trends derived from log and core data, we delineate reservoir partitions that appear to reflect structural and depositional trends.

Introduction

During the past few decades, the focus of exploration activity within the Western Canada Sedimentary Basin, and more broadly within North America, has shifted toward unconventional low-permeability reservoirs that are exploited by horizontal wells and multi-stage hydraulic fracture technology (Heffernan and Dawson, 2010; Clarkson and Pedersen, 2011). Microseismic monitoring of hydraulic fracture stimulation has played a significant role in these developments. Interpretation of microseismic data often focuses on the spatial and temporal distribution of microseismic events to estimate stimulated reservoir volume and, in some cases, to infer the character and geometry of discrete fracture networks (DFNs; e.g., Warpinski, 2009; Cipolla et al., 2011). For example, magnitude and b-value (slope of frequency-magnitude distributions) are useful attributes to delineate rock fabric (e.g., Haege et al., 2013), including preexisting zones of weakness and hydraulic fractures that may result in fault activation (Maxwell et al., 2010).

We introduce a novel approach, microseismic facies analysis, to extract additional information from microseismic event clusters. Magnitudes of microseismic events due to hydraulic fracturing in a layered medium can be strongly influenced by the scale-length of layering (Eaton and Maghsoudi, 2015), in particular, where only weak mechanical coupling exists between adjacent stratigraphic layers, thus giving rise to stratabound fracture networks (Odling et al., 1999). In these circumstances, the distribution of event magnitudes may deviate significantly from the commonly assumed power-law distribution implied by the Gutenberg-Richter relation from earthquake seismology (Eaton et al., 2014c).

We present a case study based on the interpretation of a microseismic data set recorded during an open-hole hydraulic fracture completion of two horizontal wells within a Late Cretaceous Glaucocitic tight sand reservoir in western Canada. More than 1660 microseismic events were recorded and located during this 24-stage treatment, including 259 post-pumping events (Eaton et al., 2014a). A 3D seismic survey was acquired after well completion, providing an opportunity for crossvalidation and integrated interpretation of both data sets. The purpose of this study is to correlate event characteristics observed using microseismic data with surface seismic attributes, with the objective of delineating distinct reservoir zones. Through this integrated interpretation, we develop the concept of microseismic facies analysis as first proposed by Eaton et al. (2014b) for elucidation of lithofacies units for characterization of unconventional reservoirs.

¹University of Calgary, Department of Geoscience, Calgary, Alberta, Canada. E-mail: aamir_rafiq@hotmail.com; eatond@ucalgary.ca; aemcdougall@shaw.ca; ppkeders@ucalgary.ca.

Manuscript received by the Editor 10 July 2015; revised manuscript received 9 November 2015; published online 21 March 2016; Pagination corrected 27 April 2016. This paper appears in Interpretation, Vol. 4, No. 2 (May 2016); p. T167–T181, 11 FIGS., 2 TABLES.

http://dx.doi.org/10.1190/INTERPRET-2015-0109.1. © The Authors. Published by the Society of Exploration Geophysicists and the American Association of Petroleum Geologists. All article content, except where otherwise noted (including republished material), is licensed under a Creative Commons Attribution 4.0 Unported License (CC BY-SA). See http://creativecommons.org/licenses/by/4.0/. Distribution or reproduction of this work in whole or in part commercially or noncommercially requires full attribution of the original publication, including its digital object identifier (DOI). Derivatives of this work must carry the same license.
Geologic setting

The study area is located within the Hoadley Field in central Alberta, a giant gas-condensate field that was discovered in 1977. The field is situated within the Hoadley Barrier complex in the Alberta foredeep basin (Figure 1). The main reservoir of the field is the Glauconitic Formation of the Lower Cretaceous Upper Mannville Group, a lithologically diverse shallow-marine and nonmarine clastic wedge that prograded northward along the axis of the developing foreland basin (Hayes et al., 1994).

This Glauconitic sandstone member contains shallow-marine sandstone deposits that are interpreted to have formed as an extensive barrier-bar complex, extending northeast–southwest for approximately 210 km along strike. The barrier-bar complex is more than 25 km wide and covers an area of approximately 4000 km² and marks the northern limit of continental to marginal marine depositional environment (Hayes et al., 1994). Modern examples of this type of depositional environment include Galveston Island (Texas Gulf Coast) and the north shore of Prince Edward Island in eastern Canada (Reynolds et al., 2012).

Two distinct sand units can be recognized within the Hoadley shoreface complex, called Lower (or basal) and Upper Glauconite sands, respectively (Chiang, 1984). These units represent distinct depositional environments. The Lower Glauconite sands were deposited during the southward marine transgression of the Clearwater Sea during Early Cretaceous time. The Upper Glaucnonte was deposited during the subsequent retreat of the Clearwater Sea, with a set of northeast–southwest sandbars marking marine transgressive pulses within an overall marine regression (Rosenthal, 1988). The series of northeast prograding marine bars were deposited into the shallow interior seaway in marinemto-subaerial depositional environments, with the number of distinct shoreline sand cycles comprising the Upper Glauconite varying with location along the barrier-bar complex (Chiang, 1984). Localized channels are incised into the bar at numerous locations, representing flow and sediment transport in a northwestward direction (Chiang, 1984; Rosenthal, 1988). Measurement of regional stress orientation indicates that maximum principal stress direction is parallel to the main bar trends, that is, northeast–southwest (Figure 2; Churcher et al., 1996).

The Lower Glauconitic sandstone is less permeable (approximately 0.5 mD) and is separated from the more permeable Upper Glauconitic sandstone (approximately 1–10 mD) by a muddy siltstone layer referred to as the middle Glauconite shale (Figure 3). Along strike, good-quality sandbars are separated by low-permeability interbar facies. Based on log and core data, the dominant facies observed in our study area is marine sandstone, which is comprised of mudstones interbedded with hummocky cross-stratified overain by planar laminated or massive shoreface sandstones with a high quartz content. In addition, Rosenthal (1988) notes the variability in lithology of the Upper Glauconitic sandstones, indicating that there may be a dual sediment source during this period of deposition. This supports the theory that tectonism may have been actively influencing deposition and may have influenced relative sea-level changes at the time (Rosenthal, 1988). Overall, due to the complex intercalation of facies, detailed geologic characterization of the Hoadley Field is necessary for identifying potential zones for hydrocarbon development. Consequently, there is potential of dual-permeability behavior within the reservoir (Sorensen and Little, 1993).

Data sets

Microseismic data for this study were acquired during a multistage hydraulic fracture treatment in two horizontal wells, undertaken as a research component of the Hoadley Flowback Microseismic Experiment (Eaton et al., 2014a). The downhole recording equipment consisted of a 12-sensor retrievable array of 15 Hz triaxial geophones. The geophone pods are installed at the end of multiconductor wireline of

Figure 1. Lower Upper Mannville depositional environments showing the location of the Hoadley barrier bar in south central Alberta, Canada (modified from Hayes et al., 1994).
Figure 2. Map view of the microseismic data recorded for the two horizontal treatment wells. Symbol color indicates different stages, and symbol size indicates magnitude. Inset shows the maximum horizontal stress direction (SHmax) from the World Stress Map (Reinecker et al., 2005). Blue symbols show stress measurements obtained from earthquake focal mechanisms, and $N_f$ and $N_p$ denote the number of events recorded during the fracture treatment and post-pumping periods, respectively.

Figure 3. Surfaces along the cross section from A–A’ using vertical well log data, along with MWD gamma ray log and directional survey data from well A. Note that well B is also in the same zone. Correlation of surfaces based on the gamma ray signature shows that there is a vertical offset in the location of the structural anomaly. The cross-section location is shown in Figure 10.
2057 m in length. Magnets were used to achieve coupling between pods and wellbore steel casing. Interpod spacing varied from 15.25 m for the bottom 8 units and 30.5 m for the top 4, having an array length of 229 m. The vertical observation well was situated between two horizontal treatment wells (Figure 2) to minimize observational bias for events in each well.

The hydraulic fracture treatment was performed as an open-hole completion, in which injection is isolated by packers into a series of distinct sections of the horizontal treatment wellbore, each approximately 100 m in length. Because the well completion was performed in 12 discrete injection stages in each treatment well, microseismic events are expected to exhibit strong spatiotemporal clustering characteristics. Indeed, the spatial extent of observed microseismic event clouds can be interpreted to represent stimulated rock volume (SRV), an important parameter for reservoir analysis (Mayerhofer et al., 2010). Event clusters may also provide diagnostic characteristics for interpreting fracture complexity (Cipolla et al., 2008).

Figure 4. Distribution of microseismic events with respect to stratigraphic layering. (a) True vertical depth (TVD)-magnitude crossplot showing complex distribution of low/high magnitudes along the depth of the reservoir. The concentration of events in the Medicine River Coal may be an artifact of the velocity model used to locate events, as a result of the low velocity in this layer (Pike, 2014). Magnitude values represent moment magnitude (Mw). (b) Microseismic event depth/time plot, showing events above and below the glauconite treatment zone (indicated by the red star). The receiver locations are indicated by blue triangles.

A total of 1660 microseismic events in the moment magnitude range $-2.58 \leq M_w \leq -0.76$ were recorded and located during this 24-stage treatment, including 240 post-pumping events after stimulation of well A and 19 post-pumping events after stimulation of well B (Figure 2), indicative of persistence of microseismic activity after treatment operations were finished. The distribution of microseismic events during the two days of treatment exhibits a complex fracture pattern. Based on the World Stress Map (Reinecker et al., 2005), the maximum horizontal stress direction ($SH_{max}$) in our study region is N49°E ± 8°. Some event clusters are aligned parallel with this direction (Figure 2), as expected for growth of simple tensile fractures (e.g., Bouroumand and Eaton, 2015), whereas other event clusters appear to be oriented in directions that form a high angle with the present-day maximum horizontal stress. Misaligned event clusters are interpreted to represent reactivation of preexisting fractures (Eaton et al., 2014a). Even in the case of microseismic clusters that are aligned approximately with the regional stress field, we observed subtle variability in the direction of fracture growth; for example, two subsets of the treatment stages in the northern part of well B show contrasting orientation along the length of the horizontal well (Figure 2).

There are significant differences in the microseismic response for the two treatment wells, despite the use of identical treatment parameters for both wells. Well A exhibits a greater persistence of post-pumping activity, and an inferred higher density of event clusters that are misaligned with the present-day stress field. These characteristics suggest that the microseismic response to fracture treatment may be partitioned into distinct zones, which could reflect variations in sedimentary facies, reservoir rock type, fluids, and natural fractures within the barrier-bar reservoir.

As shown in Figure 4, microseismic activity stimulated by the hydraulic fracture treatment occurs at a range of depths that extends into strata above and below the treatment zone, indicated by the red star symbol. Reported microseismic location uncertainty varies from approximately 5 to 20 m, both laterally and in depth. Caution should be exercised in the interpretation of these event depths, however, because they may contain artifacts related to the large velocity change at the overlying Medicine River Coal. Nevertheless, it is evident from Figure 4 that fracture height growth above and below the reservoir level is likely to have occurred.

In addition to microseismic observations, this study makes use of 3D seismic data recorded approximately four months after completion of the hydraulic fracture treatment program. The seismic survey used 1.5 kg dynamite as a source, with 2016 geophone channels and 60 m source and receiver intervals. The processed 3D seismic data used in this study underwent poststack time migration, with spectral whitening applied to enhance data resolution.
Interpretation workflow

Our interpretation workflow was carried out in a stepwise fashion. First, we analyzed microseismic data acquired during the hydraulic fracture treatment of two horizontal treatment wells in Glauconitic tight sandstone reservoir in central Alberta. Next, we interactively classified microseismic events into distinct clusters, from which we computed numerous microseismic attributes, for example, azimuth, net seismic moment, length, and duration. We then organized clusters with similar information into zones having similar characteristics. As elaborated below, we call these characteristics microseismic facies.

The next step in our interpretation workflow involves calculating different attributes from the available poststack 3D seismic data. We computed numerous poststack attributes such as geometric, stratigraphic, and frequency attributes. Out of the set of computed attributes, we find that incoherence, most-positive curvature and most-negative curvature attributes provide the most clearly interpretable association with the microseismicity. Finally, we integrated microseismic results with surface seismic attributes. These methods are discussed in detail below.

Microseismic facies analysis

Identification of event clusters is the first step in microseismic facies analysis. Each microseismic event cluster reflects brittle deformation processes associated with hydraulic fracturing, such as tensile opening or shear slip on fractures. In practice, the time windows of treatment stages are typically used as a convenient proxy for establishment of clusters. This approach, illustrated in Figure 2, is less effective if temporal overlap exists between deformation activities within several distinct spatial regions. This is especially problematic for open-hole hydraulic fracture completions, in which the time interval between stages is relatively short compared with the duration of each individual stage. This rapid transition between stages can lead to misidentification of microseismic events that are spatially associated with a previous stage. Moreover, in some cases clusters may be difficult to resolve for some treatment stages and/or generate clouds of events that are indistinguishable between stages.

To overcome these difficulties, we use an interactive approach to define microseismic clusters by selecting a polyhedral region around a spatially coherent cloud of microseismic events. Application of this process may result in either grouping of events from multiple stages or elimination of spatial or temporal outliers. Multiple stages are grouped together in cases in which there is significant overlap in event locations between stages, such as persistence of activity after the treatment time window for a given stage.

The next step in the procedure is to obtain estimates of microseismic attributes, each of which is a quantitative measure of a property or characteristic that can be extracted from microseismic data. The following list gives definitions for representative microseismic attributes (Eaton et al., 2014a), examples of which are provided in the next section:

1) Azimuth: direction of the best-fitting line obtained by linear regression through the easting and northing coordinates of points within a given cluster.
2) Length: distance between end points obtained by projection of events from a given cluster onto the linear-regression line.
3) Height: difference in elevation between the shallowest and deepest events in a cluster.
4) Volume: 3D volume of the smallest convex set containing all of the points in a cluster, a construct known as the convex hull (Barber et al., 1993). The convex hull is formed from triplets of points and thus creates a tessellated volume comprised of triangular surface elements. Informally, a convex hull can be viewed as a shrink-wrapped surface around the exterior of the point cloud.
5) Duration: time difference between the earliest and latest events in a cluster.
6) Magnitude statistics: mean and standard deviation statistics of the magnitude (M) distribution in an event cluster. Due to stratabound fracture systems (Eaton et al., 2014c), a regular layered bed-set might be expected to produce a magnitude distribution with a small standard deviation, whereas a bed-set with a large range of thicknesses due to complex depositional environment may exhibit a large standard deviation in magnitude.
7) b-value: slope of the frequency-magnitude distribution from the Gutenberg-Richter relationship (e.g., El-Isa and Eaton, 2014):

\[
\log N = a - bM. \tag{1}
\]

where \( N \) is the total number of microseismic events with magnitudes \( \geq M \). Intercept \( a \) describes the productivity, whereas slope \( b \) describes the relative size distribution of events.
8) Net seismic moment: sum of the seismic moments of individual events within a cluster, computed from the moment magnitude using the following expression (Stein and Wyssession, 2003):

\[
M_0 = 10^{0.5(M_w+5)} \tag{2}
\]

9) Seismic moment density: net seismic moment normalized by the volume of an event cluster (Eaton et al., 2014a).
10) Maximum moment release rate (MMRR): maximum seismic moment release rate per hour, computed numerically in six-minute time windows over the duration of a cluster (Eaton et al., 2014a).
11) Transience: ratio of the net seismic moment for a fixed time interval (e.g., a one-hour time window starting at the onset of injection for a given stage),
to the net seismic moment for the entire event cluster (Eaton et al., 2014a).

This proposed set of attributes is intended to be representative but not exhaustive because numerous other useful characteristics can be measured from microseismic data. In principle, determination of microseismic attributes facilitates identification of subtle stratigraphic details, structural deformation, fracture orientation, SRV, and stress compartmentalization within a reservoir (Eaton et al., 2014a). Similarly, the term microseismic facies is defined here as a body of rock with distinctive characteristic properties that can be extracted from microseismicity. The suite of microseismic attributes listed above provides examples of empirical characteristics that can be extracted directly from most microseismic observations. By analogy with lithofacies analysis, microseismic facies can be interpreted effectively on the basis of combinations of attributes. Moreover, as elaborated below, a complete set of all such attributes is not necessarily required to support a facies-based microseismic interpretation and useful results can be obtained using a subset of observed attributes.

There are several ways in which lithofacies or stress environment can manifest in microseismic facies. A possible link between microseismic facies and reservoir properties was suggested by Eaton et al. (2014c), who showed that mechanical layering in a reservoir could result in stratabound DFNs that could, in turn, lead to preferred scaling behavior of microseismic magnitudes.

**Seismic attributes**

Seismic attributes have long been used by interpreters to map subtle stratigraphic details and structural deformation that are not otherwise readily observable on seismic data (Chopra and Marfurt, 2007). A multitude of seismic attributes are in common use. In this study, attributes derived from the 3D seismic cube were converted to the depth domain to enable correlation with microseismic events.

Perez and Marfurt (2014) show a correlation between curvature and microseismic events in the Barnett Shale. Chopra and Marfurt (2007) define curvature as a 3D property of a quadratic surface that quantifies the degree to which the surface deviates from being planar. Curvature can be determined from a grid of measurements by fitting a quadratic surface, \( z(x, y) \), (Roberts, 2001):

\[
z(x, y) = ax^2 + by^2 + cxy + dx + ey + f.
\]

The mean curvature and the Gaussian curvature can be computed from this quadratic surface. The mean curvature is given by

\[
k_{\text{mean}} = \frac{[a(1 + e^2) + b(1 + d^2) - cde]}{(1 + d^2 + e^2)^{3/2}},
\]

and the Gaussian curvature is given by

\[
k_{\text{Gauss}} = \frac{(4ab - c^2)}{(1 + d^2 + e^2)^2}.
\]

The most-positive and most-negative principal curvatures can be written in terms of these two curvature parameters as follows:

\[
k_1 = k_{\text{mean}} + (k_{\text{mean}}^2 - k_{\text{Gauss}})^{1/2},
\]

and

\[
k_2 = k_{\text{mean}} - (k_{\text{mean}}^2 - k_{\text{Gauss}})^{1/2}.
\]

Subject to the horizontal and vertical resolution limits of seismic data (Widess, 1973; Chen and Schuster, 1999), zones of high principal curvature identified in seismic data may be indicative of faults or other localized structural or stratigraphic deformation. Conversely, seismic coherence measures the continuity between seismic traces in a specified window along a picked horizon and tends to exhibit relatively low values near a fault or area of structural complexity (Bahorich and Farmer, 1995). Thus, coherence is a measure of similarity between waveform features and traces.

Chopra and Marfurt (2007) define the shape index as:

\[
s = \frac{2}{\pi} \tan^{-1} \left[ \frac{k_2 + k_1}{k_2 - k_1} \right],
\]

where \(k_1\) and \(k_2\) denote the most-positive and most-negative curvatures, respectively. This attribute highlights the morphological structure of a surface. For example, the shape index of a dome is 1, 0.5 for an antiform, 0 for a saddle, −0.5 for a valley, and its value is −1 for a bowl (Chopra and Marfurt, 2007).

Because attributes are sensitive to input data quality, the input data were pre-conditioned to reduce random noise and the effects of acquisition/processing footprint. For this purpose, we have applied \(f - x\) deconvolution (FX-decon) and structure-oriented median filter on time migrated 3D poststack seismic data (Chopra and Marfurt, 2007, 2008, 2012) to suppress noise and to enhance lateral continuity, respectively. A comparison of our data before and after preconditioning is shown in Figure 5. FX-decon is a predictive deconvolution filter that is applied spatially across seismic spectral traces along constant time levels, to attenuate random noise and retain coherent seismic signal. FX-decon is usually applied in areas of low to moderate geologic complexity, as was the case here. The seismic traces reconstructed from this filter are characterized by a more coherent signal relative to random noise,
as shown in Figure 5b. A structure-oriented median filter was subsequently applied to remove acquisition/processing footprint patterns and to enhance lateral seismic continuity while preserving subtle geologic features. Median values are selected from traces in inline and crossline directions, where the size of the median filter is adjusted to optimize data quality without attenuation of true signals. In this case, we used a $3 \times 3$ median filter, which has a relatively mild filtering effect (Figure 5c).

**Results**

Based on the interactive clustering approach described above (i.e., user selection of a polyhedral region around a spatially coherent cloud of microseismic events), discrete clusters were identified. A total of 94% of microseismic events are contained within 17 event clusters, as shown in Figure 6a. The remaining 6% of events are outliers with respect to the clusters and can be observed in Figure 2, which shows all of the microseismic events.

Selected attributes of the 17 event clusters are summarized in Table 1. In our proposed new approach for microseismic interpretation, a suite of attributes with distinctive properties is used to identify and characterize microseismic facies. The basic size characteristics of the clusters, as represented by length and height attributes, exhibit ranges of 349–535 m (average 429 m) and 63–151 m (average 99 m), respectively. Information of this type is sometimes used for assessment of treatment design and stimulated reservoir volume (Mayerhofer et al., 2010). The cluster azimuth shows considerable variability, with a range from N34.6°E to N140.3°E and an average value of N72.6°E. This average cluster azimuth is oblique to the local SHmax direction derived from the World Stress Map (N49°E). Cluster duration varies over an even greater relative range, from 0.6 h to a maximum value of 17.1 h, which is significantly longer than the treatment stages (1–2 h) and reflects persistence of post-pumping events. This variability is similarly reflected in the unitless transient attribute, which ranges from 0 (quiescence during the first hour of the nearest treatment stage) to unity (all events occurred within the first hour). The net seismic moment depends upon the moment of individual events and the number of events (productivity) of a cluster; in this study, it ranges from $0.49 \times 10^8$ N-m to $4.56 \times 10^8$ N-m, with an average value of $1.72 \times 10^8$ N-m. The moment density, on the other hand, also considers the volume of a cluster. One cluster (#6) exhibits an anomalously large value of $332.4$ N-m/m$^3$, owing mainly to its relatively compact volume. Finally, the MMRR varies from 0.08 to 1.23 GJ/hour; as elaborated below, this parameter is diagnostic for recognition of microseismic clusters.

Figure 5. Segments of 3D seismic depth volume from (a) input post-stack seismic amplitude data, (b) data after FX-decon filter applied to remove random noise, and (c) data passed through the structural-oriented $3 \times 3$ median filter, applied to enhance lateral continuity. Notice the improvement in lateral continuity in the highlighted portions.
To interpret microseismic facies, we begin by considering the spatial distribution of attributes. As noted above, some clusters show a clear misalignment with respect to the regional SHmax direction. Referring to Figure 6b, clusters are shaded so that those that are strongly misaligned are shown red. This reveals that some event clusters are nearly orthogonal to SHmax; in the absence of local deflections in stress direction due to stress heterogeneity in the reservoir, tensile opening and shear slip on fractures-oriented parallel to these clusters are energetically unfavorable in this orientation. Consequently, this analysis implies the existence of either local perturbation to the stress field to enable slip or tensile opening on a misoriented fracture, or fracture complexity wherein microseismic events occur on surfaces that are oblique to the general trend of the cluster.

The variability in cluster height distribution does not reveal any clear systematic patterns (Figure 6c); however, it is noteworthy that the cluster with the maximum height growth is cluster 8, located in the southeast corner of the map area. Based on the marked deviation from SHmax orientation (Figure 6b), this cluster is inferred to be a natural fracture system, which may thus extend above the reservoir zone. The distribution of cluster duration is shown in Figure 6d. A pattern is evident in which longer-duration event clusters are concentrated in the southeast and northern parts of the map area, including several clusters that are strongly misaligned with SHmax. Because the treatment parameters were uniform through the treatment program, this pattern is suggestive of partitioning of the reservoir into discrete regions with different stress and/or petrophysical characteristics that influence the microseismic response.

Although cluster magnitude and duration attributes are measured independently, the mean magnitude distribution for the event clusters (Figure 7a) shows a general similarity to the duration distribution in Figure 6d. In the case of fluid injection into stratified rocks, event magnitude may be linked to mechanical bed thickness defined by stratabound fracture networks (Eaton et al., 2014a). Thus, the areas of relatively high and low magnitude may be indicative of regions of relatively higher or lower...

Figure 6. (a) Spatial clustering of microseismic events from all stratigraphic levels. A total of 94% of microseismic events are contained within the 17 inferred event clusters. The black dot shows the observation well, yellow dots show the centroids of the treatment stages. (b) Misalignment of the cluster azimuth with respect to the regional direction of SHmax (N49°E). Clusters that are strongly misaligned are shown in red. (c) Cluster height distribution. (d) Cluster duration. Groups of longer-duration clusters are observed in the southeast and north parts of the map area.
mechanical bed thickness, respectively. A map of net moment release highlights significant differences between the two treatment wells (Figure 7b). Clusters along well A, on the east side of the map area, show a significantly higher net moment release. Because treatment parameters were the same for both wells, this difference in net moment release most likely reflects intrinsic differences in stress conditions or geomechanical characteristics of the rock mass for the two treatment wells.

Transience, a measure of the fraction of seismic moment released within one hour of initiation of the treatment stage, is plotted in Figure 7c. This distribution also reveals a significant variation between well B on the west and well A on the east. In the case of well B, the bulk of seismic moment release occurs during the treatment stages, whereas for well A, the microseismic moment release persists for a number of hours after the treatment. Distribution of the maximum seismic moment release rate shows that clusters in the west along well B are characterized by a relatively low maximum rate (Figure 7d). In contrast, microseismic clusters in the central and southern parts of well A are characterized by a delayed response and short bursts of high-rate activity.

According to our proposed method, distinct combinations of microseismic attributes can be used for classification of microseismic facies. Figure 8 shows a crossplot of MMRR versus azimuth for the 17 clusters of microseismic events, highlighting a number of distinct groupings of events that provide a basis for microseismic facies classification. Microseismic facies A is characterized by relative high MMRR together with azimuth that is close to the SHmax direction (N49°E). This microseismic facies includes a substantial number of events that plot above the level of the treatment zone (Figure 4a). Microseismic facies B also has an azimuth that is close to the SHmax direction but with significantly lower level for MMRR. Progressively increasing misalignment with SHmax is characteristic of microseismic facies C to E. It should be noted that microseismic facies D applies to one cluster of events (#6) that has an anomalously high moment density (Table 1). Microseismic facies E is comprised of event clusters that are almost orthogonal to SHmax and interpreted as possible reactivated fractures (Eaton et al., 2014a). Microseismic facies A and E are predominantly from well A, located on the east side (Figure 2); collectively, these define an apparent linear trend with respect to MMRR and azimuth attributes. One of the three microseismic facies E clusters of events is from well B, and microseismic facies C and E collectively define a different apparent linear trend for well B.

Turning now to 3D seismic attributes, Figure 9 shows a summary of depth-horizon slices of various attributes at the treatment level (glauconite). The seismic amplitude value (Figure 9a) is dominated by regional trends that mask some important details of the reservoir that

<table>
<thead>
<tr>
<th>C2</th>
<th>S3</th>
<th>Facies zone</th>
<th>Length (m)</th>
<th>Height (m)</th>
<th>Azimuth (degrees)</th>
<th>Duration (hours)</th>
<th>mean Mw</th>
<th>M0 (10^8 N-m)</th>
<th>Net Moment density (Pa)</th>
<th>Max release rate (GJ/hour)</th>
<th>T4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>B</td>
<td>500</td>
<td>100</td>
<td>57.1</td>
<td>11.6</td>
<td>-1.74</td>
<td>1.15</td>
<td>29.2</td>
<td>0.23</td>
<td>0.58</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>A</td>
<td>418</td>
<td>107</td>
<td>56.0</td>
<td>14.5</td>
<td>-1.63</td>
<td>4.56</td>
<td>225.0</td>
<td>0.93</td>
<td>0.62</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>A</td>
<td>432</td>
<td>97</td>
<td>34.6</td>
<td>16.2</td>
<td>-1.89</td>
<td>2.85</td>
<td>202.8</td>
<td>1.23</td>
<td>0.52</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>A</td>
<td>352</td>
<td>127</td>
<td>57.1</td>
<td>4.9</td>
<td>-1.93</td>
<td>1.11</td>
<td>134.6</td>
<td>0.87</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>A</td>
<td>368</td>
<td>102</td>
<td>64.1</td>
<td>7.9</td>
<td>-1.98</td>
<td>3.78</td>
<td>99.6</td>
<td>0.72</td>
<td>0.45</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
<td>D</td>
<td>349</td>
<td>71</td>
<td>94.7</td>
<td>4.3</td>
<td>-1.92</td>
<td>2.51</td>
<td>332.4</td>
<td>0.30</td>
<td>0.81</td>
</tr>
<tr>
<td>7</td>
<td>9</td>
<td>B</td>
<td>350</td>
<td>74</td>
<td>53.8</td>
<td>16.1</td>
<td>-1.97</td>
<td>1.74</td>
<td>143.5</td>
<td>0.17</td>
<td>0.57</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>E</td>
<td>386</td>
<td>151</td>
<td>127.7</td>
<td>17.1</td>
<td>-1.74</td>
<td>1.18</td>
<td>162.0</td>
<td>0.34</td>
<td>0.41</td>
</tr>
<tr>
<td>9</td>
<td>11</td>
<td>E</td>
<td>386</td>
<td>114</td>
<td>117.4</td>
<td>14.0</td>
<td>-1.76</td>
<td>1.72</td>
<td>137.2</td>
<td>0.32</td>
<td>0.03</td>
</tr>
<tr>
<td>10</td>
<td>13</td>
<td>B</td>
<td>445</td>
<td>95</td>
<td>52.4</td>
<td>1.8</td>
<td>-2.05</td>
<td>0.58</td>
<td>27.9</td>
<td>0.10</td>
<td>0.75</td>
</tr>
<tr>
<td>11</td>
<td>15</td>
<td>B</td>
<td>535</td>
<td>112</td>
<td>47.5</td>
<td>2.2</td>
<td>-2.12</td>
<td>0.66</td>
<td>21.3</td>
<td>0.14</td>
<td>0.49</td>
</tr>
<tr>
<td>12</td>
<td>16</td>
<td>B</td>
<td>521</td>
<td>119</td>
<td>45.1</td>
<td>9.4</td>
<td>-2.08</td>
<td>2.33</td>
<td>86.8</td>
<td>0.29</td>
<td>0.27</td>
</tr>
<tr>
<td>13</td>
<td>18</td>
<td>B</td>
<td>447</td>
<td>88</td>
<td>48.5</td>
<td>6.4</td>
<td>-1.95</td>
<td>0.58</td>
<td>38.0</td>
<td>0.13</td>
<td>0.70</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
<td>C</td>
<td>447</td>
<td>87</td>
<td>81.2</td>
<td>2.0</td>
<td>-1.88</td>
<td>1.44</td>
<td>67.1</td>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>15</td>
<td>22</td>
<td>A</td>
<td>447</td>
<td>91</td>
<td>77.1</td>
<td>0.6</td>
<td>-1.83</td>
<td>1.54</td>
<td>120.3</td>
<td>0.83</td>
<td>1.00</td>
</tr>
<tr>
<td>16</td>
<td>24</td>
<td>C</td>
<td>451</td>
<td>63</td>
<td>79.8</td>
<td>16.5</td>
<td>-1.93</td>
<td>1.09</td>
<td>95.9</td>
<td>0.27</td>
<td>0.49</td>
</tr>
<tr>
<td>17</td>
<td>19</td>
<td>E</td>
<td>451</td>
<td>90</td>
<td>140.3</td>
<td>2.5</td>
<td>-1.92</td>
<td>0.49</td>
<td>70.9</td>
<td>0.08</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Average 429 99 72.6 8.7 -1.90 1.72 117.3 0.42 0.54

2Cluster number.
3Nearest treatment stage.
4Transience (unitless).
are enhanced through the use of a number of attributes, such as incoherence (Figure 9b), most-positive curvature, and most-negative curvature (Figure 9d and 9e). In addition to individual seismic attributes, multiattribute images are co-rendered using red–green–blue (RGB) and red–green–blue-gray (RGBGray) scales to enhance the contrast between the features of interest and their corresponding stratigraphic and structural details (Figure 9f and 9g). In the case of the RGB scale, red represents the most-positive curvature, green represents the most-negative curvature, and blue represents the incoherence attribute, whereas in the case of the RGBGray scale, red is the most-positive curvature, green is the shape index, blue is the most-negative curvature, and gray represents the incoherence attribute.

Several seismic attributes exhibit prominent curvilinear anomalies that trend northeast–southwest and north–south, subparallel to the regional depositional trend of the Hoadley barrier-bar complex. Another set of features exhibits an orientation that is transverse to the main

![Figure 7](image-url)  
**Figure 7.** (a) Mean magnitude distribution. The black dot shows observation well, and yellow dots show the centroids of the treatment stages. (b) Distribution of net seismic moment release. Clusters on the east side along well A exhibit a significantly greater net moment release than those on the west along well B. (c) Transience, which measures the fraction of seismic moment released within one hour of initiation of the treatment stage. Well B, on the west side, is characterized by a large fraction of the seismic moment release during the treatment stages, in contrast to well A on the east side. (d) Maximum seismic moment release rate. The high rate for well A on the east side is indicative of short bursts of microseismic activity.

![Figure 8](image-url)  
**Figure 8.** Crossplot of MMRR versus cluster azimuth for 17 interpreted microseismic clusters, showing microseismic facies groupings.
depositional trend. These conjugate (northwest–southeast-trending) anomalies terminate against northeast–southwest-trending anomalies in various ways, as shown in Figure 9. RGB and RGBGray scaled multiatributes in Figure 9f and 9g show a better view of north–northwest/south–southeast and north–south trending anomalies and reservoir compartments. Taken by itself, the shape index is more difficult to interpret (Figure 9c); however, it provides additional information for interpretation when corendered with principal curvature and incoherence, in which it is inferred to quantify the deformation morphology and delineate reservoir compartments, as illustrated in Figure 9f and 9g.

Discussion

Anomalies observed in seismic attributes may be interpreted as either depositional or structural in origin or some combination of these factors (Newbert and Trick, 2015).

Figure 9. Seismic attributes for a depth slice at the glauconite level (reservoir) (a) amplitude; (b) incoherence; (c) shape index; (d) most-positive curvature ($k_1$); (e) most-negative curvature, ($k_2$); (f) most-positive curvature corendered with most negative curvature and incoherence ($I$) on RGB scale; (g) most-positive curvature corendered with shape index (SI), most-negative curvature and incoherence on RGBGray scale. Locations of treatment and observation well are indicated for reference. Arrows indicate anomalies that are considered in the interpretation.
Most-positive curvature anomaly (Figure 9). To further hinge, along strike to the southwest correlates with a feature, possibly a minor fault or which terminates within horizontal well pairs A and B. Extrapolation of this feature, in which case, the roughly orthogonal set of features may be viewed as conjugate structures. Finally, in the case of a hybrid model, development of structural elements within the barrier-bar complex may have occurred preferentially along depositional trends, due to response of the rock mass arising from juxtaposition of units with contrasting mechanical properties.

Structural mapping based on well log data across the study area reveals anomalous structural highs oriented in a northeast–southwest direction (Figure 10), one of which terminates within horizontal well pairs A and B. Extrapolation of this feature, possibly a minor fault or hinge, along strike to the southwest correlates with a most-positive curvature anomaly (Figure 9). To further elucidate structural details in the vicinity of the hydraulic fracture treatment, characteristic gamma ray signatures were inspected in the measurement-while-drilling (MWD) gamma ray log in lateral well section, and the depth at which this gamma ray signature was intersected (Figure 3). The top of the Lower Glaucinite, top of the Upper Glaucinite, and the base of the Medicine River Coal are easily discernible in the gamma-ray logs. These gamma-ray signatures and associated depths were also observed in nearby vertical-type wells. Correlation of these picks (Figure 3) suggests that well A may have intersected a minor fault with a vertical offset of approximately 5 m, or a sloping depositional surface (clinoform) with 5 m of relief. This feature can be clearly seen on the most-positive curvature anomaly running northeast–southwest (Figure 9d), providing independent evidence to support interpretive partitioning of the reservoir.

In addition to local stress variations and heterogeneity of the reservoir rock, zones of weakness and preexisting faults/fractures are expected to play a major role in developing complex fracture patterns (Haege et al., 2013). Significant variations and complex geometry in fracture evolution are observed in short intervals along the lateral path of the wells A and B in our study area. Because the hydraulic fracture treatment was undertaken using an open-hole completion methodology with essentially the same parameters for each stage, it is expected that if the reservoir properties and stress state were uniform then the microseismic response for every stage should remain similar (Reynolds et al., 2012). However, our results exhibit a complex distribution of magnitudes indicating variability in rock fabric (preexisting zones of weakness) within the reservoir, as shown in Figure 6d. In particular, we observe a variable depth distribution and variable density of microseismic events consisting of a mix of relatively low- and high-magnitude events.

Wells A and B exhibit significant differences in apparent fracture height growth through the aerially extensive Medicine River Coals. In Figure 4, the distribution of microseismic events near well A shows that most occur above the reservoir zone, that is, within Medicine River coal and upper Mannville. In contrast, microseismic event clouds near well B indicate that microseismicity occurs within and below the reservoir zone. It is also evident that saturation of events and apparent “blunting” of the event distribution occurred near the interface of Medicine River Coal, at a depth of 1865 m. As rock mechanical properties of coals generally tend to reduce vertical fracture propagation, bedding-plane slippage may have occurred at the interface (Reynolds et al., 2012; Pike, 2014). We attribute this difference in microseismic event distribution in wells A and B to heterogeneity and varying rock fabric throughout the reservoir, in addition to the overlying coals and shale section. Based on a comparison of these results with surface seismic attributes shown in Figure 9, we interpret the reservoir to be compartmentalized; wells A and B are thus interpreted to have distinct facies with varying rock fabric.

Figure 10. Structure map at the glauconite formation (derived from well log data), overlain by most-positive curvature attribute in the vicinity of the hydraulic fracture treatment (derived from 3D seismic data). The interpreted fault based on the structure mapping is outlined in blue. Standard symbols are used to indicate the well locations.
Based on the microseismic event clusters in Figure 8 and microseismic facies zones in Table 1, we have overlain microseismic clusters onto most-positive curvature ($k_1$) attribute in Figure 11. A large fraction of the event clusters in wells A and B is aligned subparallel to the regional maximum horizontal stress (SHmax) direction, which is northeast–southwest, as shown in Figures 6 and 7. Event clusters that are oblique to this trend (microseismic facies E) are interpreted as reactivation of preexisting zones of weakness (Eaton et al., 2014a). These inferred preexisting zones of weakness are not discernible in any of the seismic attributes (Figure 9), possibly because they represent features that are below the resolution of the seismic data. However, as evident in the two insets (Figure 11), microseismic facies E clusters appear to occur in close proximity to abrupt termination of distinct anomalies that are evident in the most-positive curvature seismic attribute. Thus, these inferred zones of weakness (fractures) may be manifested indirectly in the seismic data as anomaly cutoffs, rather than directly as anomalies per se.

Conclusions

Integrating microseismicity with surface seismic data can provide valuable insight for delineating unconventional reservoirs that may aid in development of unconventional resources. We introduce microseismic facies analysis as a new approach for interpretation of microseismic data in terms of characteristic attributes obtained for clusters of events. In the case study presented here, microseismic events exhibit a complex spatial distribution, with approximately 50% spatially oriented in the direction of SHmax, that is, northeast–southwest. The remaining events are oblique to SHmax and are inferred to represent reactivation of preexisting fractures. Correlation of principal curvature anomalies extracted from 3D seismic data with microseismic facies zones reveals a set of attributes that are interpreted to be indicative of specific sedimentary depositional environments. In particular, principal curvature anomalies evident from surface seismic attributes may delineate hinge lines associated with potential depositional features or structural features. Taken together, attribute analysis, magnitude statistics, and well log analysis are integrated here to characterize reservoir heterogeneity, rock fabric, and compartments in the reservoir. These reservoir characteristics may, in turn, reflect variations in depositional environment, structural deformation, and lithofacies.

In summary, based on our interpretation of microseismic facies coupled with comparison with surface seismic attributes and well log data, we interpret the reservoir to be compartmentalized: Wells A and B intersect distinct facies with varying rock fabric. This compartmentalization may reflect different depositional environments, with lithofacies varying from porous sandbars to silty interbar facies and/or the effects of conjugate structural hinges or subtle faults.

Acknowledgments

Sponsors of the Microseismic Industry Consortium and Tight Oil Consortium are sincerely thanked for their support of this initiative. The authors particularly wish to thank ConocoPhillips Canada for their support of the Hoadley Flowback Microseismic Experiment. The 3D seismic data were provided by Arcis Seismic Solutions, and the initial processing of the microseismic data was carried by ESG Solutions and interpreted using software from Transform (Drillinginfo). Comments from five reviewers helped to improve the clarity of this manuscript.

References


Figure 11. Most-positive curvature ($k_1$) attribute at the glauconite level, overlain with microseismicity and microseismic facies zones. Symbols for microseismic events represent facies, as shown in Figure 8. Northeast–southwest-trending anomalies (green) are parallel to the strike of the barrier-bar complex.


Chopra, S., and K. J. Marfurt, 2007, Seismic Attributes for prospect identification and reservoir characterization: SEG.

Chopra, S., and K. J. Marfurt, 2008, Gleaning meaningful information from seismic attributes: First Break, 26, no. 9, 43–53.


Clarkson, C., and P. K. Pedersen, 2011, Production analysis of western Canadian unconventional light oil plays: Canadian Unconventional Resources Conference.


tology: Surface and subsurface: Canadian Society of Petroleum Geologists Memoir, 15, 207–220.


Aamir Rafiq received an M.S. (2015) in geophysics from the University of Calgary’s Microseismic Industry Consortium, and he is currently working as a reservoir geophysicist at 3DGeo Exploration Ltd. Canada. He began his professional career as an exploration geophysicist at Pakistan Oilfields Limited and later worked with Cenovus Energy, where he specialized in inversion, attribute analysis, and reservoir characterization. In 2013, he joined Microseismic Industry Consortium to pursue his graduate studies at the University of Calgary under the supervision of David Eaton. His research focused on the integration of microseismic data with surface seismic attributes, combining the main aspects of his diverse educational background and industry experience. He has also taken several leadership and volunteer positions within industry, campus, and community groups. He served on the executive board for the university and was a big proponent of student engagement within the industry.

David Eaton received a B.S. (1984) from Queen’s University and an M.S. (1988) and a Ph.D. (1992) from the University of Calgary. He rejoined the University of Calgary in 2007 after an 11-year academic career at the University of Western Ontario. His postdoctoral research experience included work at Arco’s Research and Technical Services (Plano, Texas) and the Geological Survey of Canada (Ottawa). He is presently codirector of the Microseismic Industry Consortium, a novel, applied-research geophysical initiative dedicated to the advancement of research, education, and technological innovations in microseismic methods, and their practical applications for resource development. In addition to microseismic monitoring and induced seismicity, his current research is also focused on the lithosphere-asthenosphere boundary beneath continents. He has written more than 115 peer-reviewed publications. He is currently working as NSERC/Chevron Industrial Research Chair in Microseismic System Dynamics, Department of Geoscience, University of Calgary.

Adrienne McDougall received a B.S. (2015) in geology from the University of Calgary and is a geologist I.T. She is currently working at an E&P company in Calgary, Alberta, working in oil sands petrophysics. She has had multiple work terms in the energy industry, with experience in exploration geology, oil sands, shale gas, and petrophysics. She is an active volunteer with the Canadian Society of Petroleum Geologists (CSPG). She is a member of APEGA and CSPG, and also has a bachelor’s degree in kinesiology.

Per Kent Pedersen received a Ph.D. (1999) in geology from Aarhus University, followed by positions with academia, government, and several oil and gas companies before he joined the University of Calgary in 2008. His research interests include geologic reservoir characterization from pore to basin scale of unconventional clastic reservoirs integrating outcrops, cores, core analysis, and well logs.