Toward interpretation of intermediate microseismic $b$-values

Abdolnaser Yousefzadeh, Qi Li, Schulich School of Engineering, University of Calgary, Claudio Virues, CNOOC-Nexen, and Roberto Aguilera, Schulich School of Engineering, University of Calgary

Summary

It is expected from our knowledge of earthquake seismology that the logarithm of cumulative events’ frequency versus events’ magnitude in the Richter scale must result in a slope of about -1 which corresponds to a “$b$-value” equal to unity. Many studies show that the microseismic data recorded over hydraulic fracturing treatments have a $b$-value equal to about 2 or slightly larger. Microseismic events that are associated with fault re-activation may still be recognized with the $b$-value=1. However, there are many instances in which $b$-values range between 1 and 2, and this generates some difficulties in the interpretation. Assuming as valid the relationship between $b$-values and the source of microseismic events, we developed an algorithm that calculates intermediate $b$-values that are the result of the combination of stacked datasets of two pools; one from hydraulic fracturing and other one from fault activation in a highly fractured or faulted reservoir. This observation allows better interpretation of microseismic data for fault identification, stimulated reservoir volume (SRV) calculation, creation of discrete fracture network, reservoir simulation, and re-fracturing optimization. The proposed methodology is summarized in this paper.

Introduction

Microseismic monitoring provides valuable information on the extension and geometry of hydraulic fractures, fracturing mode, and reservoir characterization; valuable information that aids in the exploitation of unconventional hydrocarbon reservoirs, an important source of oil and gas that will help to meet future energy needs of North America and the world. Microseismic methods are developed based on earthquake seismology concepts and methods and allow detecting, in a smaller scale, the low amplitude sonic signals which are emitted from sudden fracturing of the reservoir rocks under high pressure fluid injection.

The frequency-magnitude distribution of earthquakes is commonly represented by the Gutenberg-Richter relation as (Ishimoto and Lida, 1939; Gutenberg and Richter, 1954),

$$\log_{10} N = a - bM$$  \hspace{1cm} (1)

where $N$ is the number of events with the magnitude equal to or larger than $M$ Richter, and $a$ and $b$ (called activity rate $a$ and $b$-value) are constant real numbers. Gutenberg-Richter relation simply states that the probability of occurrence of an earthquake with a specific magnitude is 10 times more than the possibility of one magnitude smaller event to happen in the earth crust. The value of $a$ is equal to the logarithm of the number of earthquake events with magnitude equal or larger than 0 Richter and is the indicator of seismic activity rate in an area. Estimation of $b$-value is important since it can be used as an indicator of the probability of larger earthquake occurrence after a period of seismic activities in a study area. To bring a prospective of $a$ and $b$-value, for example, $a$ varies between 3.91 and 5.93 and $b$ is between 0.58 and 0.91 in different regions of Iran (Ashtari-Jafari, 2008). It is widely accepted that for the most naturally happened earthquakes $b$-value is about 1. However, analyses of different sets of microseismic data from hydraulic fracturing treatments tend to give a $b$-values equal or slightly larger than 2. It is believed that the $b$-value is affected by reservoir elastic and geomechanical properties and treatment methods. The $b$-value analyses have been used to identify fault activation (mainly post-fracturing event) associated with hydraulic fracturing events (Maxwell et al., 2009; Maxwell and Norton, 2012). In reality, many clusters of microseismic events may show a $b$-value which lies between 1 and 2, which is called intermediate $b$-value in this text. Our
algorithm is used in this study to demonstrate how the stack of two pools of randomly distributed synthetic data with different $b$-values may result in intermediate $b$-values.

**Calculating $b$-value**

The method to correctly calculate $b$-value is important to seismologist. A Gutenberg-Richter logarithmic plot can cause a small error in the $b$-value calculation to result in a large predictability error of the larger earthquakes. For example in an area with $a = 5$ and $b = 0.9$, the possibility of having an earthquake with magnitude equal to or greater than 5 is three time more than when $b = 1$ at the same period of time. The most uncomplicated method to calculate $b$-value is to find the best data fit in a semi-log graph of cumulative number of events versus events magnitude in Richter scale using a least squares algorithm. Another method which is widely accepted and used is the maximum likelihood method of Aki (1965) who derived the following relation for $b$-value calculation:

$$
\beta = \frac{1}{\bar{m} - m_{min}},
$$

where $\beta = b \ln 10$ and $\bar{m}$ and $m_{min}$ are the average magnitude and the magnitude of completeness of the earthquake catalog in a certain area over a specified time period, respectively. The Aki method assumes that the magnitudes are continues random variables and therefore a large number of events is necessary to satisfy this assumption. A method by Kijko and Smit (2012), which we implement in this study, overcomes this requirement and permits working with an incomplete catalog with the use of the generalized Aki-Utsu method. In the generalized Aki-Utsu method, an earthquake catalog is divided into $s$ subcatalogs and $\beta$ is calculated for each subcatalog by the Aki method. The generalized Aki-Utsu value, $\hat{\beta}$, is

$$
\hat{\beta} = \left(\frac{r_1}{\beta_1} + \frac{r_2}{\beta_2} + \ldots + \frac{r_s}{\beta_s}\right)^{-1},
$$

where $r_i = n_i/n, n = \sum_i n_i$, and $\hat{\beta}_i$ is the Aki-Utsu $\beta$ in the $i^{th}$ subcatalog (Kijko and Smit, 2012).

In order to study the effect of simultaneous hydraulic fracturing and fault activation during a fracturing treatment on the resulting microseismic $b$-values, we have developed an algorithm to create randomly distributed synthetic microseismic magnitudes for given $a$ and $b$-values. The events from two data sets are combined and the $b$-value is calculated for the combined data set.

**Examples and Results**

Table 1 shows $b$-values results of stacking events from two pools of magnitude with the $b$-values equal to 1 and 2 and different level of activity when data are complete and the magnitude of completeness is the lowest magnitude in both data sets.

Table 1: Calculated $b$-values for data from stacking two sets of events with $b$-values equal to 1 and 2 and different $a$-values without considering the data incompleteness and -2.5 minimum magnitude.

<table>
<thead>
<tr>
<th>$b$-value=1</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$-values 2</td>
<td>-1</td>
<td>2.0</td>
<td>1.9</td>
<td>1.6</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.6</td>
<td>1.2</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.6</td>
<td>1.2</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 1 shows that if the activity rate ($a$-values) for both pools is equal, the $b$-value of the combined data is approximately equal to 2 due to larger number of events from the pool with the $b$-value=2. The combined $b$-value will get very close to unity when the activity rate of the data set with $b$-value=1 is about 4 units larger than the activity level of the data set with $b$-value=2. In microseismic monitoring, the activity level of the events related to fault activation and events related to hydraulic fracturing may be estimated from magnitude-frequency relationship in the area where there are other evidences to confirm the uniqueness of the data origin (Yousefzadeh et al., 2015).
In reality, the limitation in detecting low magnitude events may eliminate more events from the pool with higher b-value, increasing the effect of data from the pool with b-value=1, and slightly reducing the total b-values, if both pools have relatively low level of activities as shown in Table 2. With high level of activities, the effect of detection limit is different and may increase the total b-values.

<table>
<thead>
<tr>
<th>b-value=2</th>
<th>a</th>
<th>b-value=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>1.8</td>
<td>1.3</td>
</tr>
<tr>
<td>0</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>1</td>
<td>2.0</td>
<td>1.9</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>2.0</td>
</tr>
</tbody>
</table>

We used microseismicity front curves based on the diffusivity equation (Shapiro et al., 1997; Yu and Aguilera, 2012; Yousefzadeh et al., 2016) to distinguish hydraulic fracture events from fault activation-related events in two stages of hydraulic fracturing treatments which showed some degree of spatial anomaly in their patterns. Figs. 1 (a) and (b) show the microseismic events for hydraulic fracturing stage 12 in well D. The calculated b-value for this data is equal to 1.3. Figs. 1 (b) and (c) illustrate data after separation of hydraulic fracturing from fault activation events. Our study shows that the b-value for data in Fig. 1 (b) increases slightly to about 1.4. We interpret this low b-value as an indication of faulting activation at the stage location since it cannot be distinguished from hydraulic fracturing events. Fig. 2 (a) illustrates stage 9 microseismic events in well I. The b-value in this stage is 1.4. Figs. 2 (b) and (c) show the separation of hydraulically fractured and fault activated events. The b-value for data shown in Figs. 2 (b) and (c) are 2.2 and 1.2, respectively. These distinct b-values show that events in Fig. 2 (b) are mostly hydraulic fracturing events, and events shown in Fig. 2 (c) are mainly fault activation related events. It is notable that events which are recognized as fault activation and shown in Fig. 2 (c) are mostly at the same location as events in Fig. 1 (c) which had a b-value equal to 1.4. This observation is in agreement with our explanation on low b-value for data in Fig 1 (c). It must be mentioned that stage 9 in well I was hydraulically fractured before stage 12 in well D. Additional information about activity rates in the area would be required in order to calculate the percentage of the events in Fig. 1 (c) that contribute to the corresponding SRV.

Conclusions

Assuming the validity of b-value being equal to unity for fault (re)activation events and about 2 for hydraulic fracturing events, we have shown that the intermediate events could be an indicator of simultaneous fault activation and hydraulic fracturing. However, quantification of an intermediate b-value for determining the portion of events that are related to each hydraulic fracturing and fault (re)activation require consideration of additional parameters including the detection limits and the activity rates of the data in the study area. The analyses may provide additional confirmation for fault detection or activation when combined with other anomalies in microseismic data such as spatially linear events that do not follow other general microseismic trends in the area and may be related to faulting; events that happen after termination of fluid injection, event clusters that are not well-connected to the hydraulic fracturing points, and high magnitude events. A large number of microseismic events and a good estimation of the magnitude of incompleteness are required to avoid any bias in calculation and interpretation of b-values.

Acknowledgements

The support CNOOC Limited and Nexen, the Schulich School of Engineering at the University of Calgary and Servipetrol Ltd. of Calgary, Canada is gratefully acknowledged. We also thank the GFREE research team [GFREE refers to an integrated research program including Geoscience (G); Formation Evaluation (F); Reservoir Drilling, Completion, and Stimulation (R); Reservoir Engineering (RE); and Economics and Externalities (EE)] at the University of Calgary for their continued help and support.
Fig. 1: Microseismic data from stage 12 in well D: a) map view, b) section view, c) events related mostly to hydraulic fracturing, d) events related to fault activation.

Fig. 2: Microseismic data from stage 9 in well I: a) map view of all microseism events. These events are separated to the b) events related mostly to hydraulic fracturing, and c) events related to fault activation.
References


Ashtari Jafari, M., 2008, The distribution of b-value in different seismic provinces of Iran: 14th World Conference on Earthquake Engineering, International Association for Earthquake Engineering (IAEE).


