

## Breakdown of the Gutenberg-Richter relation in layered media

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### Summary

Variants of the Gutenberg-Richter (G-R) relation, which express scale-independent behavior of earthquakes over a range of values, are almost universally used to describe magnitude-recurrence statistics for microseismic observations. The  $b$  value, which is the slope derived from classic G-R plots, is a particularly important parameter that effectively measures the abundance of large-magnitude events relative to small events. Hydraulic fracture monitoring programs often yield apparent  $b$  values of 2.0 or greater. These values are exceptionally high compared to earthquake fault systems, which typically exhibit  $b$  values close to 1.0. In some reports, a sudden reduction in  $b$  value during treatment has been attributed to unintended activation of a pre-existing fault. An alternative model is developed here to describe magnitude statistics of microseismic events that occur on steeply dipping to vertical fracture surfaces in horizontally layered media. Termination of fractures at mechanical layer boundaries imposes a size-dependent scaling relationship and results in a stratabound fracture networks, which are well described in a number of field studies. In the case of constant stress drop, microseismic magnitude distributions will mimic bed-thickness distributions under these circumstances. A lognormal distribution of mechanical bed thickness, which provides a good fit for three examples considered here from various parts of North America, leads to a Gaussian distribution of microseismic magnitudes that readily explains apparent observed  $b$  values of close to 2.0. This model is consistent with a sudden reduction in  $b$  value arising from unintended triggering of a pre-existing fault, and also implies that subtle changes in  $b$  value during a treatment program may be indicative of spatial variations in reservoir facies.

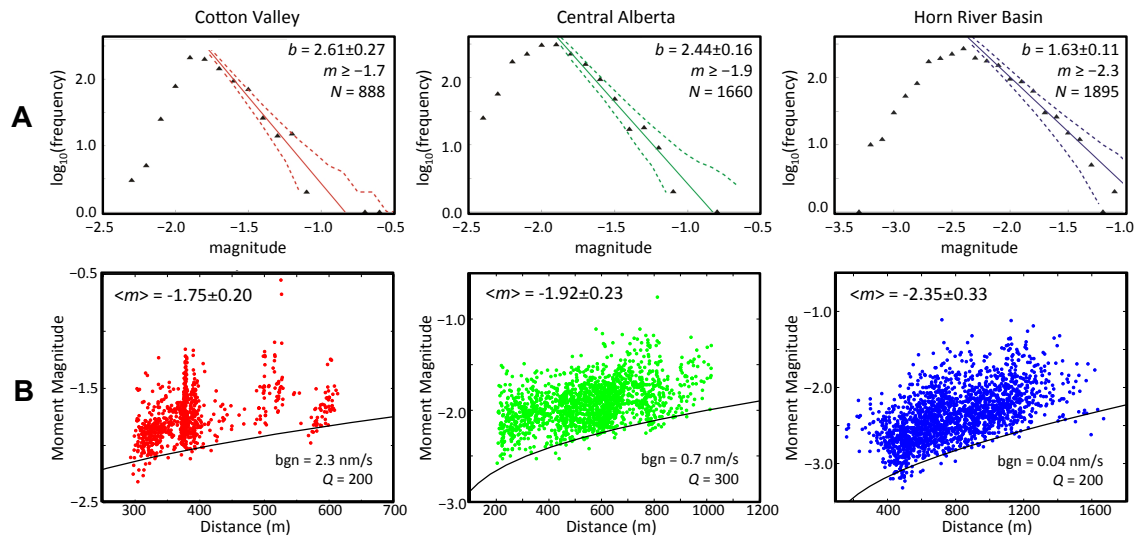
### Introduction

The Gutenberg-Richter (G-R) relation, proposed independently by Ishimoto & Iida (1939) and Gutenberg & Richter (1944), can be written using a cumulative distribution magnitude distribution as

$$\log N(m) = a - b(m - m_t) , \quad m > m_t \quad , \quad (1)$$

where  $N$  is the total number of earthquakes with magnitude  $\geq m$  and  $m_t$  corresponds to the threshold magnitude value above which an earthquake catalog can be considered complete. The intercept  $a$  denotes the productivity of a given region in space and time, whereas the slope  $b$  describes the relative size distribution of earthquakes. The  $b$  value is strongly influenced by the stress environment of the fault system (El-Isa & Eaton, 2013 and references therein). The G-R relation can also be expressed as a binned probability distribution, rather than a cumulative distribution, with no change in the  $b$  value.

Understanding the underlying statistical distribution of magnitudes is important for fundamental studies of geomechanical processes associated with fracturing, including energy balance, as well as for forecasting hazards associated with anomalous large microseismic events. The G-R relation has been used to characterize microearthquakes induced by hydraulic fracturing (Grob and van der Baan, 2011; Vogelaar et al., 2013). In some studies, a sudden drop in  $b$  value has been attributed to fault reactivation (Maxwell et al., 2009). In this study, three microseismic catalogs from different geologic settings from North America (Figure 1) are used to evaluate if the G-R relation, or some other distribution, best describes fracture-induced microseismicity.

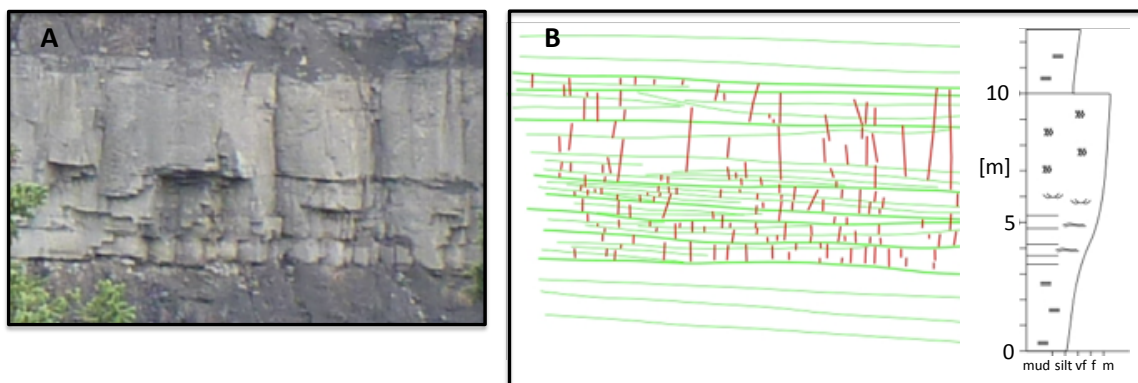


**Figure 1.** Gutenberg-Richter (G-R) plots for three hydraulic fracture monitoring datasets, expressed as probability distributions. Dashed lines show 95% confidence limits for the fitted  $b$  value, obtained using a maximum-likelihood method (Aki, 1965). b) Magnitude-distance scatter plots. Curved black lines show magnitude-detection threshold derived from the raw waveform data. Mean magnitudes,  $\langle m \rangle \pm$  one standard deviation are given for comparison with synthetic catalogs. From Eaton et al. (2014).

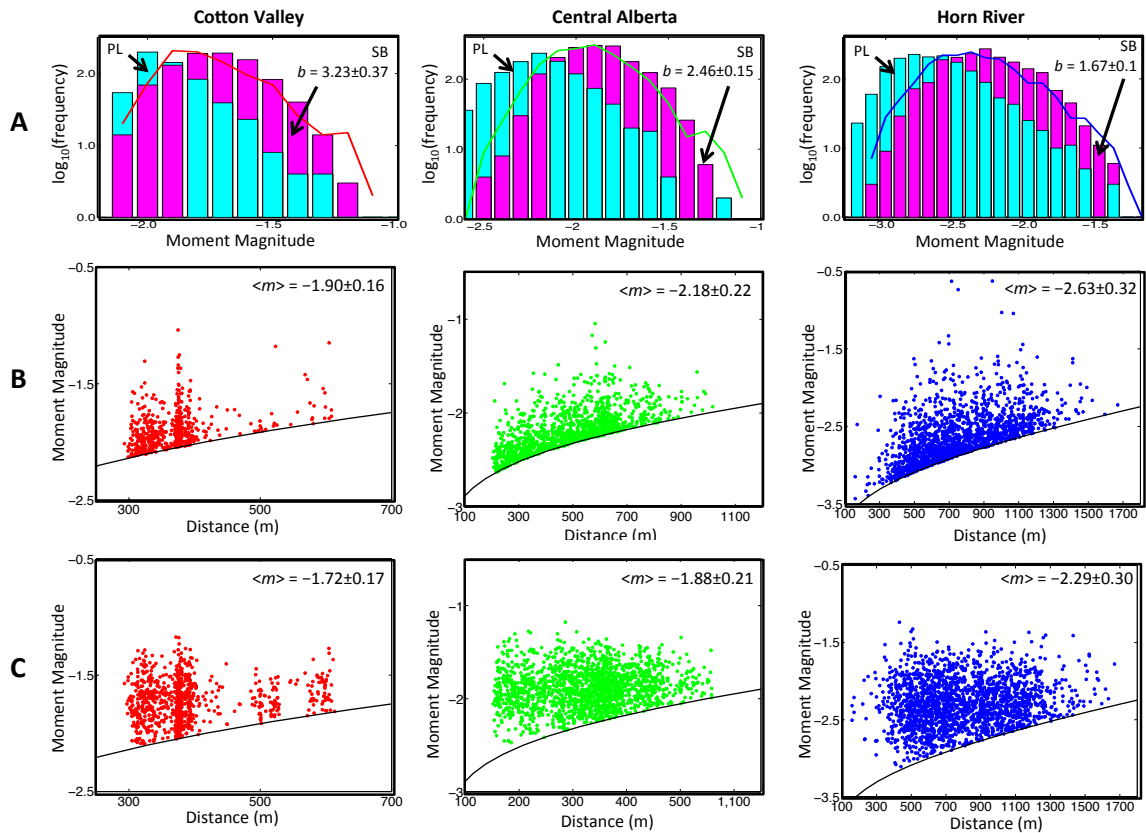
## Results

Figure 1 shows G-R plots and magnitude distance graphs for three microseismic catalogs that sample different geologic environments in North America. Each of the microseismic monitoring programs was processed by a different company or research group, thus mitigating processing methodology as a potential source of bias in the calculation of magnitudes (Shemata & Anderson, 2010). In all cases, hypocentres were located using P- and S-wave traveltimes coupled with P-wave particle motion data and moment magnitudes were determined based on the Brune model.

Figure 2 shows a naturally fractured outcrop that is stratigraphically correlative with the reservoir unit from central Alberta. The outcrop illustrates stratabound fractures, in which fractures terminate at mechanical layer boundaries.



**Figure 2.** a) Outcrop photograph of a shoreface sandstone of the Moosebar Formation, correlative the reservoir in central Alberta. Height of section is 10 m. b) Interpretative drawing, showing fracture arrest at mudstone interbeds (from Eaton et al., 2014).



**Figure 3.** Top panels (a): Magnitude-frequency plots for observed and synthetic catalogs, showing computed  $b$  value for stratabound (SB) models fitted with the same lower magnitude limit as in Figure 1. Power-law (PL) and SB models are presented as histograms, whereas the observed distribution is indicate by a solid line. Centre panels (b): Magnitude-distance scatter plots for synthetic distributions computed with a power law model based on the observed  $b$  values (Figure 2). Curved black lines show inferred magnitude-detection threshold. Mean magnitudes,  $\langle m \rangle \pm$  one standard deviation, are given for comparison with observed data. Lower panels (c): As in (b), but computed with for the stratabound model with mechanical bed thickness derived from well logs, and a fixed stress drop of 1.0 MPa.

Figure 3 shows G-R plots and magnitude-distance distributions for two types of synthetic catalogs. One set of synthetic catalogs was computed by assuming a power law model for magnitudes that is described by equation (1). The second set of synthetic catalogs was computed using a stratabound model, in which the Brune source diameter distribution is assumed to be the same as the mechanical bed thickness distribution derived from well logs (Eaton et al., 2014). For the latter model, a constant stress drop of 1.0 MPa is assumed, consistent with the observed stress drop for very small earthquakes (Abercrombie, 1995).

Due to the rapid decay in probability of occurrence with increasing magnitude, the power-law magnitude models exhibit tight clustering of events near the detection threshold. Consequently, the power-law models systematically underestimate observed magnitudes. In contrast, the stratabound models produce a spread of magnitudes extending well above the detection threshold. Moreover, the stratabound hypothesis based on the mechanical bed-thickness distribution gives rise to an effective  $b$  value over the range of observed magnitudes that coincides remarkably well with the observed  $b$  value. In view of the simplicity of the stratabound fracture model and the independence of its derivation from microseismic observations, the similarity between the observed and synthetic magnitude distributions is striking.

## Conclusions

For three widely separated hydraulic fracturing field examples, microearthquake magnitudes are not well represented by the classic Gutenberg-Richter relation that describes earthquake occurrence on active fault systems. A more satisfactory fit is obtained assuming that the magnitude distribution represents activation of stratabound fracture networks. The size distribution of microearthquakes induced by hydraulic fracturing in oil and gas development may thus reflect an intrinsic preferred scale length, which is fundamentally different from scaling of earthquake fault systems. Our model implies that statistical characteristics of fracture networks may be determined using observed microearthquake magnitude distributions, with important ramifications for incorporation of microseismic observations in reservoir models.

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