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Similarities in characteristics of regional earthquakes and inferred long-period long-duration (LPLD) events

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Summary

Long-period long-duration (LPLD) events have been recently recognized as a new phenomenon of tremor-like signals that may occur during monitoring of hydraulic-fracture treatment programs in gas reservoirs. The current model of LPLD waveforms reflects slow deformation processes on fractures or faults that are mis-aligned for re-activation with respect to the present-day stress field. However, waveforms of small regional earthquakes could easily be mistaken for LPLD events, since both are characterized by similar frequency content (< 100 Hz) and time duration (~ 1 minute). Using data from a 10.5-month continuous downhole deployment of 15 Hz geophone array in a tight-sand gas field in western Canada, recordings of small earthquakes are compared with published LPLD events. In this study, we demonstrate that regional earthquakes show similar waveform characteristics to LPLD events, underlining the importance of distinguishing regional earthquake signals from LPLD events to ensure robust interpretation of reservoir deformation processes.

Introduction

Hydraulic-fracturing is widely used to enhance production from unconventional reservoirs (e.g. Rutledge and Phillips, 2003; Warpinski, 2009, Van der Baan et al., 2013). Microseismic events occur due to stresses and strains associated with fluid and pressure changes in the reservoir and may be related to activation of pre-existing fractures or the creation of new fractures (Maxwell and Urbancic, 2001). Long-period long-duration (LPLD) events have been recognized as a phenomenon observed during some hydraulic-fracturing programs. These signals are characterized by tremor-like waveforms that persist for up to 1 minute, dominated by frequencies in the range of 10-80 Hz (Das and Zoback, 2011, 2013a; Zoback et al., 2012). Based on polarization-based source localization, LPLD signals have been interpreted as a type of slow slip along fracture surfaces that are mis-aligned with respect to the main regional stress field (Zoback et al., 2012, Das and Zoback, 2013b). In this study, we document and describe waveforms of small regional earthquakes recorded during a long-term passive monitoring experiment in western Canada, the Hoadley Flowback Microseismic Experiment (HFME, Caffagni et al., 2015). The earthquakes considered are listed in the national catalog maintained by Earthquakes Canada with known locations, magnitudes and origin times. We show that the time duration, frequency content and apparent velocity of regional earthquakes recorded using typical microseismic downhole sensors (15 Hz geophones) are remarkably similar to previously published LPLD examples.

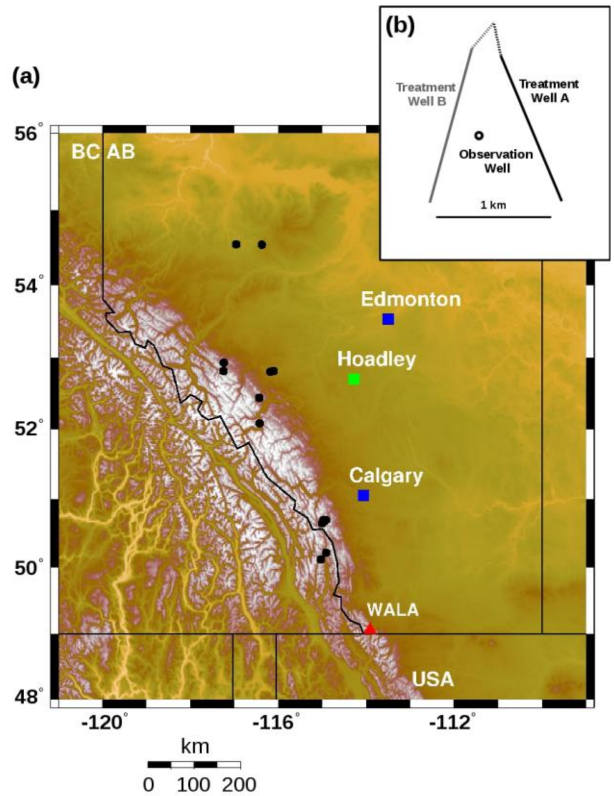

Figure 1. (a) Map showing locations of regional earthquakes, detected using a downhole geophone array at Hoadley. (b) Inset shows layout of the treatment and observation wells.

Dataset

The dataset In this study was recorded during the HFME experiment (Eaton et al., 2014). Continuous passive seismic data were acquired over 295 days using a downhole array of 12 triaxial 15 Hz geophones at a depth range from 1605 m to 1835 m. The vertical monitor well was located between two horizontal treatment wells. Figure 1 inset shows the layout of the treatment and observation wells for the experiment. Different types of seismic sources have been observed, including interpreted regional earthquakes, Instrument frequency response and its effects on earthquake characteristics are discussed in Caffagni et al. (2015).

The harvested microseismic data was GPS time synchronized, then archived and backed up to a processing/archival system. Automatic event detection using the Short Term Average Long Term Average technique (STA/LTA) analysis (Trnkoczy, 2002) and interactive inspection of the continuous data were used to scan the raw data for events. A short time series of closely spaced triggers (10 seconds to 3 minutes) identified potential long duration events, along with relatively low dominant frequency (< 100 Hz) and trace-to-trace coherency of the raw waveforms. Based on origin times and hypocentre locations in the national earthquake catalog maintained by Earthquakes Canada, these potential events were confirmed as naturally occurring earthquakes following a simple crustal velocity model with a Moho depth, fixed at 36 km and Vp (Vs) = 6.2(3.57) km/s and 8.2(4.7) km/s respectively in the crust and mantle. A location map of these interpreted regional events is shown in Figure 1 with full black circles. The epicentral distances (~200km) to Hoadley array imply that these events are unrelated to hydraulic fracturing.

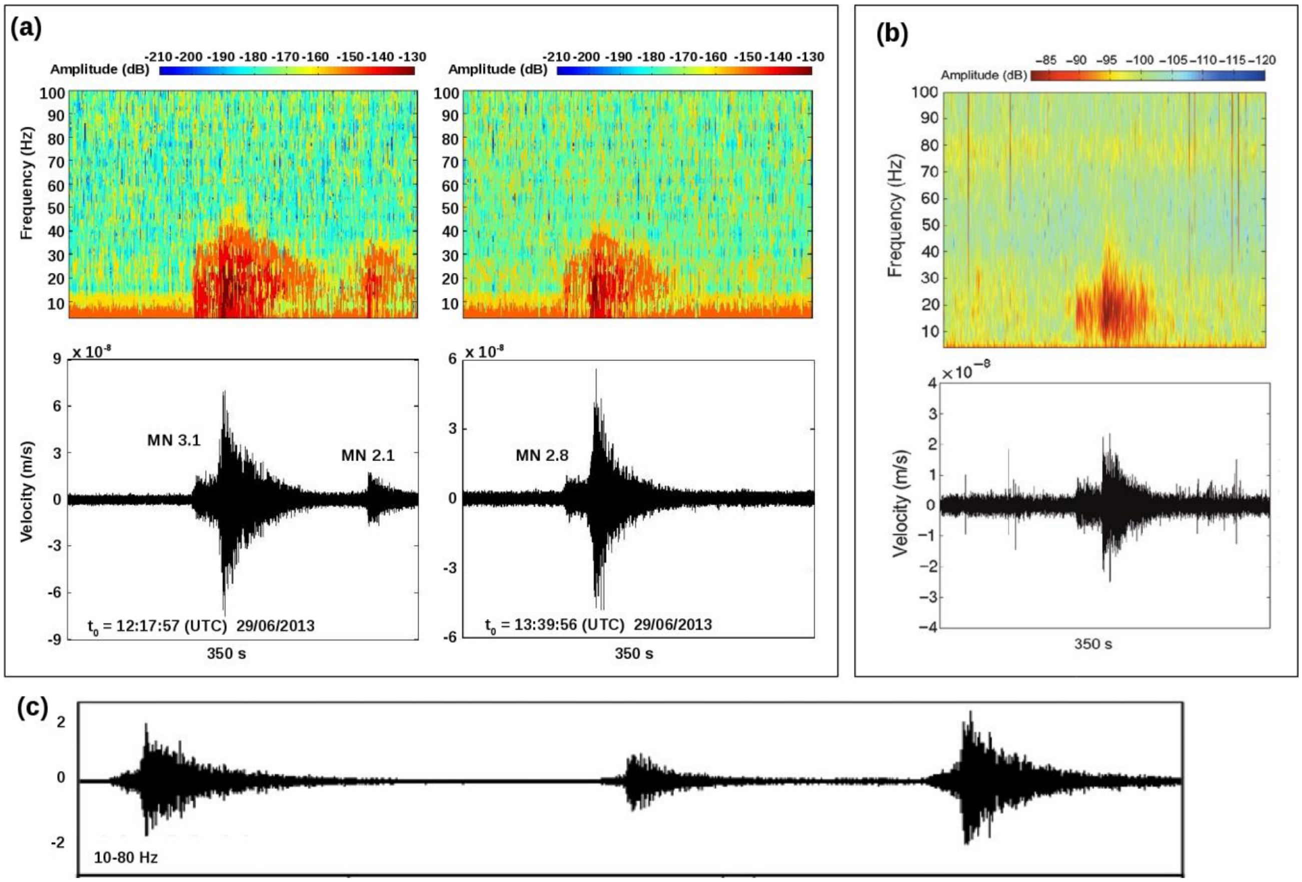

Figure 2. (a) Spectrograms (upper panels) and horizontal h1-component filtered traces (10-80 Hz) (lower panels) of a sequence of small regional earthquakes, on June 29, 2013, MN (Nuttli magnitude) 3.1 mainshock (left), and MN 2.1 (left), 2.8 (right), recorded during the HFME. Time windows are 350 s and the spectral amplitudes are referenced to 1 m/s. (b) Spectrogram (upper panel) and filtered traces (10-80 Hz) for an interpreted LPLD event from western Canada. (c) Examples of filtered waveforms from a sequence of LPLD events from the Barnett. Parts (b) and (c) are from Das and Zoback (2013a).

LPLD or Regional earthquake?

Figure 2a (Caffagni et al., 2015), shows an example of a regional earthquake sequence (mainshock + aftershocks) recorded by Hoadley downhole geophone array in western Canada and listed by the national earthquake catalog. This sequence includes a small (MN 3.1) main shock with two aftershocks (MN = 2.1, 2.8) recorded on June 29, 2013 at an approximate distance of 225 km from the monitoring array (MN is Nuttli Magnitude, see Nuttli (1973)).

The earthquake signals have a duration of about 1 minute and are characterized by dominant frequencies in the range of 8-35 Hz. Distinct onsets of P-wave and S-wave are clear, and are followed by visible codas that are characterized by complex waveforms due to scattering from crustal heterogeneities along the source-receiver path, resulting in a roughly exponential amplitude decay (Aki and Chouet, 1975). For comparison, Figure 2 shows examples of interpreted LPLD events (Das and Zoback, 2013a), which have very similar characteristics including signal duration, dominant frequency content, occurrence of two distinct arrivals and an approximately exponentially decaying amplitude response that is characteristic of S-wave coda for regional earthquakes. For the described sequence, we expect individual phases with different apparent velocity across the vertical array and we obtained apparent velocity values of ~ 5.0 and ~ 2.1 km/s. Das and Zoback (2013a) indicated discrete phases with similar apparent velocities (4.9 km/s and 2.9 km/s, respectively) using microseismic data from the Barnett shale.

Naturally, the potential to record earthquake signals during the recording time window for a microseismic program depends on the rate of the local regional seismicity. In the case of the Barnett area investigated by Das and Zoback (2013a), it is noteworthy that a high level of induced seismicity such as earthquakes activity, has been reported more recently in north Texas-Oklahoma (Frohlich, 2012; Keranen et al., 2014).

Conclusions

LPLD events are a promising indicator of potential slow-deformation processes occurring during hydraulic fracturing. However, a potential unappreciated pitfall in the interpretation of LPLD is that regional earthquakes can easily be mistaken for LPLD events, since both have similar frequency content (< 100 Hz) and duration (~ 1 minute). Using data from a 10.5-month continuous deployment of a downhole 15 Hz geophone array, we identified regional earthquakes at epicentral distances of ~200 km from the array. The earthquakes signals are characterized by similar frequency content and duration as LPLD events and therefore pose a potential pitfall for mis-interpretation. Based on the observations presented in this paper, we suggest that identified LPLD events must be checked in regional earthquake catalogs including quarry blasts if available, to enable a correct discrimination based on arrival timing.

This study clearly demonstrates that a borehole array in a environment where energy operations by hydraulic fracture stimulation is conducted, is able to detect ~200 km distant regional earthquakes. Because the Barnett Shale has relatively sparse permanent seismic monitoring, and because regional seismicity has increased in recent years, we cannot rule out the possibility that some or all of the documented Barnett Shale LPLDs are misidentified regional earthquakes. It is therefore important to distinguish LPLD events from regional earthquake signals, in order to ensure reliable interpretation of reservoir deformation processes.

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