Long-term assessment of reservoir integrity utilizing seismic source parameters as recorded with integrated microseismic-pressure arrays

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Summary

In this paper, we investigate how an integrated approach to long-term reservoir monitoring utilizing pressure and micorsiemic data can be used to identify changes in reservoir behaviour leading to compromises in reservoir integrity. In particular, we examine the observations related to a cyclic steam operation and subsequent loss of steam containment. Based on these observations, we suggest that the integration of real-time microseismic monitoring provides an opportunity to investigate reservoir integrity over long-term field development.

Introduction

As field operations mature, interest in obtaining continuous information on reservoir response has resulted in the addition of long-term monitoring programs. Often referred to as “Smart Field” completions, these programs have focused on providing distributed pressure and sometimes temperature measurements in near real-time thereby allowing operators to assess reservoir performance and optimize production. More recently, the addition of microseismic monitoring has been considered to provide additional information on the effectiveness of stimulation related programs, such as Steam ‘Huff and Puff’ operations. Of particular interest, is the combined interpretation of microseismic and pressure data to identify sudden changes in reservoir behaviour, related to activities such as buffer zone and reservoir integrity. By integrating pressure and temperature data with microseismics, it is postulated that the spatial and temporal behaviour of the observed microseismicity can provide more details on where possible excursions or anomalous behaviour is occurring in the reservoir.

As a first approximation, the observed event distribution can be used to map the extent the reservoir is undergoing deformation. To identify possible compromises in reservoir integrity, the most direct approach is to determine if events are occurring outside the formation of interest. Moreover, examination of the recorded event waveforms provides additional information on the seismic source responsible for the generation of the event as well as the surrounding rock conditions leading to failure. By examining these waveforms, information on the strength, energy and stress release associated with each individual event can be obtained. In this paper, we go beyond the first-order approach and utilize observed changes in source characteristics along with associated pressure and temperature measurements to identify a response to the treatment and subsequent loss of containment of steam in a cyclic steam operation. Based on these observations, we suggest that the integration of real-time microseismic monitoring provides opportunities to probe reservoir integrity over the long-term field development.

Seismic Source Parameters

The seismic moment, which is directly related to moment magnitude, is a measure of the strain induced by the event, and is related to the seismic waveforms through the low frequency behaviour of the displacement (Brune, 1970). However insightful the moment is as a measure for how large an event is, what it does not tell us is how energetic the failure is. This parameter is governed by seismic energy, E_S, and relates to how quickly the fracture slipped and gives more information about the style of fracturing. It should be noted, that seismic energy is only the fraction of the energy budget of the fracturing process expressed as seismic waves; typically an order of magnitude more energy is involved with the friction of the fault surface and initiating the fracture (Aki and Richards, 2002). Nevertheless, there is usually a large degree of correlation of seismic energy, E_S, with moment magnitude, M_W. Since the energy is related to the integral of the waveforms over the entire frequency range, as opposed to the moment, which only concerns itself with the low-frequency part of the spectrum, the deviations from exact correlation are indicative of different types of faulting. To quantify this effect, the Energy Index, EI (van Aswegen and Butler, 1993; Mendecki, 1996), is defined as:

$$EI = \frac{E_S}{\overline{E_S}(M_W)}$$

Where, $\overline{E_S}$ is determined by a least squares fit of the scatterplot of moment magnitude versus seismic energy, as in Figure 1. Therefore, regions with high energy index are undergoing deformation more energetically than usual.

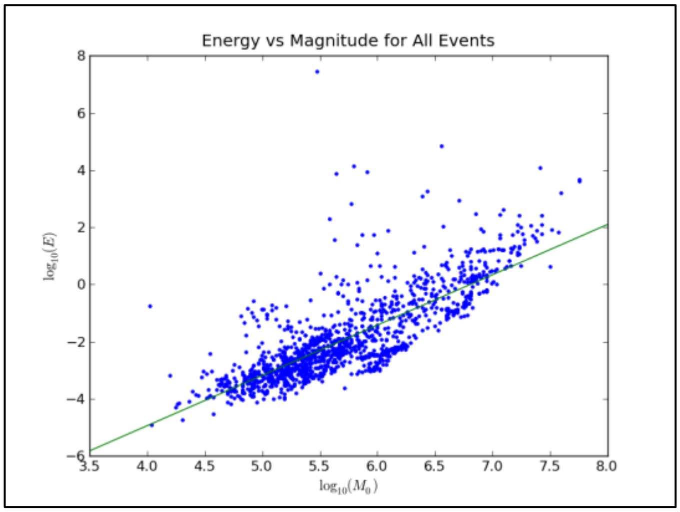

Figure 1: *Log-log scatterplot of seismic moment versus seismic energy for the events over a several month period*

The second parameter we will discuss is the apparent volume of an event. Many zones of permanent deformation and complex geometry are accompanied by a local volume change. Apparent volume can be used to provide insight into the rate and the distribution of co-seismic deformation and/or stress transfer in a rockmass.

Data

A cyclic steam operation was monitored from a number of observation wells continuously over a three week period. During the injection, a number of events appeared above the reservoir indicating a potential breach of integrity. These events are shown in depth view in Figure 2, where the events are coloured by moment magnitude. In a nearby well, this breach correlates to observed increases in pressure. This pressure curve, shown in Figure 3a, roughly corresponds to the behaviour of the reservoir. There is an initial increase in the pressure as the steam treatment begins, followed by an inflation one week later. During this inflation period, the pressure increases steadily until it begins to spike, corresponding to a loss of steam containment.

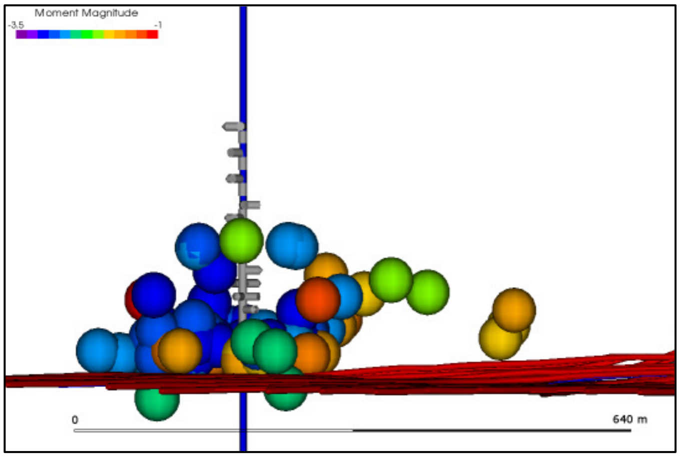

Figure 2: *The distribution of events created during the three weeks of steaming, coloured my moment magnitude.*

The overall inflation is reflected well in the plot of cumulative moment with time, shown in Figure 3b. The cumulative moment is calculated both for reservoir level events and for above reservoir, mid-level events. Here the moment can be taken to be a measure of the strain in the reservoir, and it very well mirrors the smooth trend of the pressure curve plotted in Figure 3a. In contrast, the pressure spikes revealing a loss of containment of the steam does not appear to feature a discernable signature in the moment of the events.

Figure 3c shows the curves of cumulative apparent volume with time. In contrast to the moment curves in Figure 3b, there is a clear response in the mid-level events to the containment breach as the cumulative apparent volumes for these events are very large. This would indicate, when taken with the fact that the moment for these events are relatively modest, that the deformation induced here is very different. In particular, the co-seismic deformation accompanying these events is very large and much of the strain induced by the reservoir level events is inducing a transfer of stress above.

The energy index plot, shown in Figure 3d, completes the picture of the seismic deformation in the reservoir and above it. Here the reservoir-level events show a large decrease in energy index corresponding to the initiation of the inflation of the reservoir. This drop would indicate that these events are putting more energy into the reservoir and less into seismic radiation than expected given their moments. The mid-level events show a moderate decrease in energy index after the containment breach, which would indicate that a similar pattern with not as much energy being radiated away but potentially being stored as deformation

Conclusions

The seismic waveforms contain much more information about the type of deformation and the state of the system than is most frequently used from just magnitudes and locations. Additional source parameters give higher-order insight into how the rockmass deforms and the states of stress and strain in the reservoir. In the example we discuss, the inflation and subsequent breach of containment in the reservoir which is mirrored in the cumulative moment and apparent volume, and the initiation of these processes can be seen in the energy index plots. For long-term 'Life of Field' monitoring, the integration of microseimic monitoring with pressure provides opportunities for identifying and responding to reservoir integrity issues, as well as assessing reservoir performance and optimizing production.

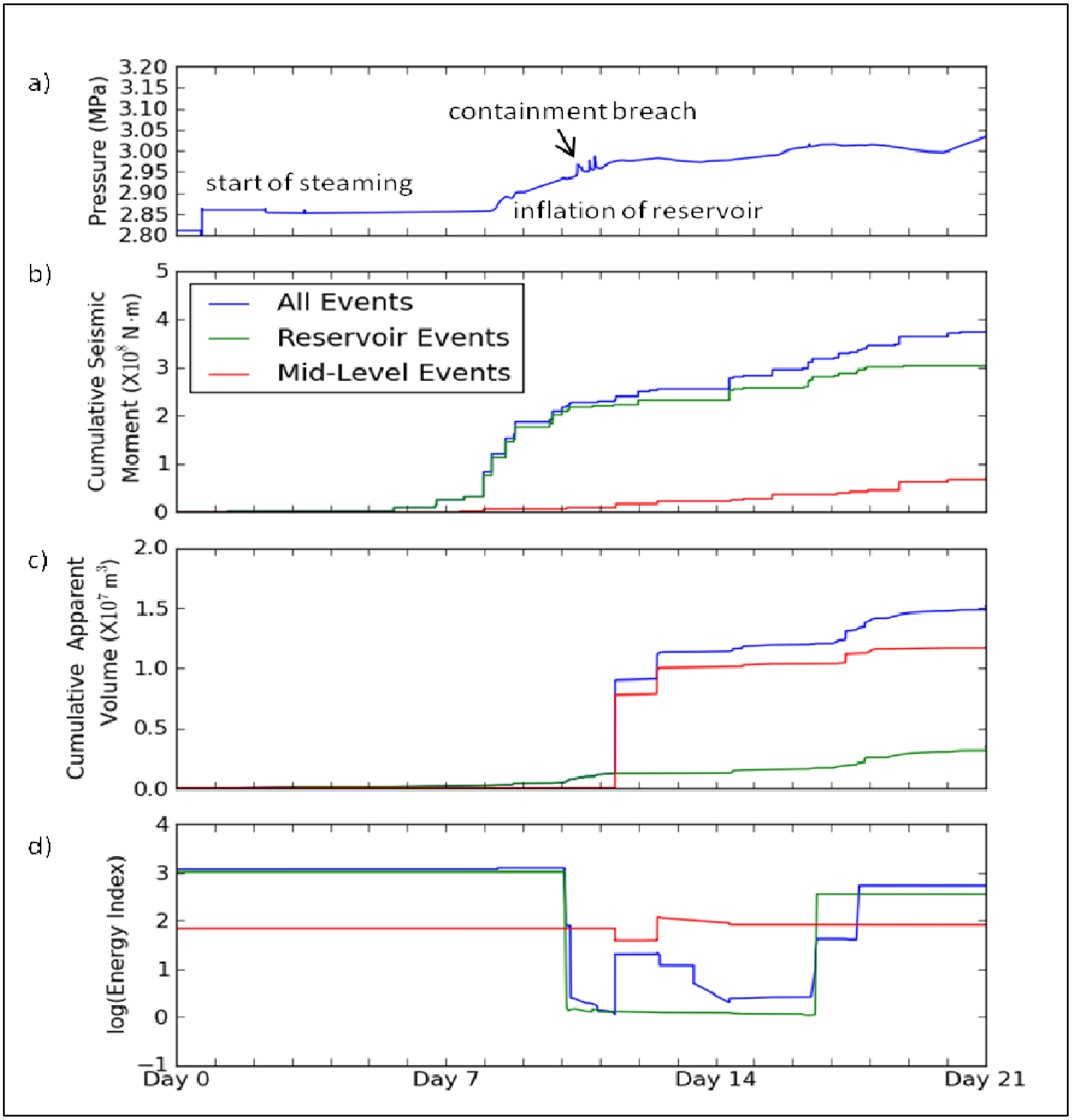

Figure 3: *Time histories of a) pressure in a neighbouring wellbore compared to the source parameters of b) cumulative moment of microseimicity, c) cumulative apparent volume, and d) energy index smoothed over a 50 event sliding window. In each source parameter plot, there are three curves: green for reservoir level events, red for mid-level events, and blue for both datasets.*

EDITED REFERENCES

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