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Linking microseismic event observations with geomechanical models to minimise the risks of storing CO_2 in geological formations

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ABSTRACT

For carbon capture and storage (CCS) in geological formations to be scientifically viable, we must be able to model and monitor the effects of geomechanical deformation on the integrity of the caprock. Excess deformation may open fractures, providing pathways for CO_2 leakage from the reservoir. An acceptable geomechanical model must provide a good match with field observations. Microseismic activity is a direct manifestation of mechanical deformation, so it can be used to constrain geomechanical models. The aim of this paper is to develop the concept of using observations of microseismic activity to help ground truth geomechanical models. Microseismic monitoring has been ongoing at the Weyburn CO_2 Storage and Monitoring Project since 2003. We begin this paper by presenting these microseismic observations. Less than 100 events have been recorded, documenting a low rate of seismicity. Most of the events are located close to nearby producing wells rather than the injection well, a pattern that is difficult to interpret within the conventional framework for injection-induced seismicity. Many events are located in the overburden. Without geomechanical simulation it is difficult to assess what these observations mean for the integrity of the storage formation. To address these uncertainties we generate numerical geomechanical models to simulate the changes in stress induced by CO_2 injection, and use these models to predict the generation of microseismic events and seismic anisotropy. The initial geomechanical model that we generate, using material properties based on laboratory core measurements, does not provide a good match with either event locations or S-wave splitting measurements made on the microseismic events. We find that an alternative model whose reservoir is an order of magnitude softer than lab core-sample measurements provides a much better match with observation, as it leads shear stresses to increase above the production wells, promoting microseismicity in these areas, and generates changes in effective horizontal stresses that match well with S-wave splitting observations. This agreement between geophysical observations and a softer-than-lab-measurements reservoir model highlights the difficulties encountered in upscaling lab scale results. There is a strong need to link geomechanical models with observable manifestations of deformation in the field, such as induced seismicity, for calibration. Only then can we accurately assess the risks of leakage generated by mechanical deformation.

1. Introduction

Storage of CO_2 in deep geological formations such as saline aquifers and mature hydrocarbon reservoirs is a strategy that can immediately reduce mankind's greenhouse gas emissions while continuing to meet the world's energy needs. As we consider the development of large scale storage sites – the EU has proposed that at least 12 CCS sites should be in operation by 2015 – it is clear that monitoring programs will be required to demonstrate that CO_2 is safely stored, and also that effective modelling tools should be developed to predict the fate of injected CO_2 (Bickle et al., 2007). It is necessary not just to model the flow of CO_2 through the subsurface, but also the mechanical deformation that CO_2 injection can induce. There is a host of uncertainties that beset the accurate modelling of subsurface processes, which means that models can only be trusted when they provide a good match with observations made at the site. This is why the Directive 2009/31/EC of the European Parliament, on geological storage of CO_2, states that 'the minimum conditions for site closure and transfer of responsibility includes […] the conformity of the *actual* behaviour of the injected CO_2 with the *modelled* behaviour' (E.U. Parliament and Council, 2009). For reservoir flow modelling, the accuracy of a model is confirmed by history matching with known wellhead pressures, CO_2 breakthrough at observation wells

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(Giese et al., 2009), and matching the plume shape with that inferred from 4D seismic monitoring (Arts et al., 2004; Bickle et al., 2007).

Injection of CO_2 will increase the pore pressure in the reservoir, deforming both the reservoir and sealing caprocks. Excess deformation can compromise caprock integrity through the formation or reactivation of fractures or faults. It is therefore important to model the geomechanical impact of CO_2 injection. Geomechanical models can also be used to help design CO_2 injection programs that do not risk inducing earthquakes on nearby faults. Just as fluid flow models are matched with observations, so we must do so with geomechanical models to ensure that they are accurately representing reality. There are several techniques that can be used to constrain geomechanical models, such as surface deformation, 4D seismic observations and microseismic activity. At In Salah, Algeria, CO_2 injection has produced surface deformation, which has been imaged using satellite based InSAR methods (Onuma and Ohkawa, 2009). The magnitude and geometry of the surface deformation provide a constraint to guide geomechanical models (Rutqvist et al., 2009). Increases in P-wave travel time detected during 4D seismic surveys have been used to image deformation in the overburdens of depleting reservoirs (Hatchell and Bourne, 2005). However, this technique has yet to be applied to a CO_2 storage site, where, presumably, the expansion of the reservoir would compress the overburden, reducing P-wave travel times (e.g., Verdon et al., 2008b).

In this paper we will demonstrate how microseismic activity can be used to constrain geomechanical models. Movement of faults and/or fractures will generate seismic energy. Although analogous to earthquakes, event magnitudes in and around reservoirs are significantly lower, so they are termed *microearthquakes* or *microseismic events*. The

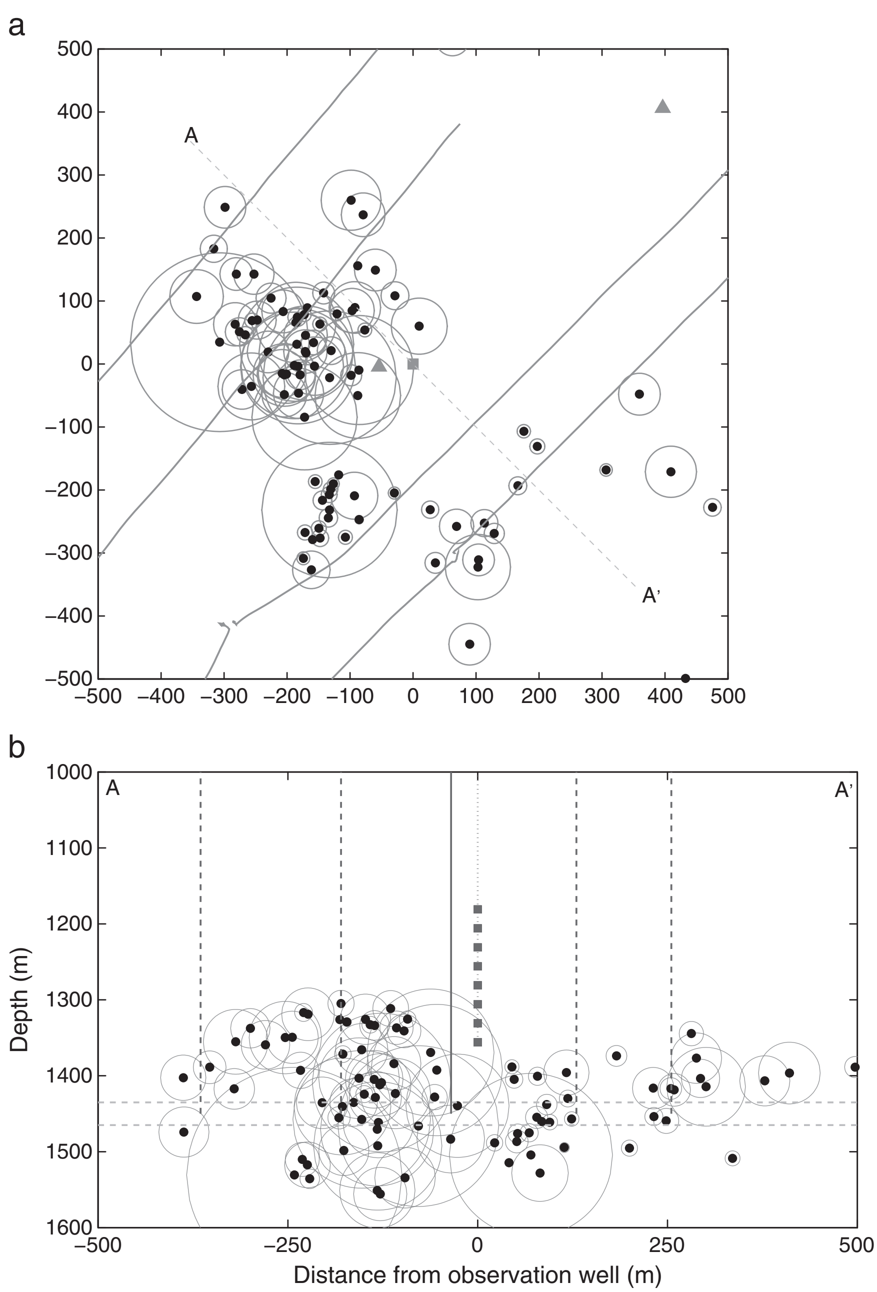

Fig. 1. Microseismic event locations in map view (a) and in cross section perpendicular to the horizontal well trajectories (b). Gray ellipses mark 95% confidence limits. In (a) the horizontal production wells are marked by gray lines, the injection wells by gray triangles, and the observation well by the gray square. The limits of the cross-section (A–A′) are also marked. In (b) the geophones are marked by gray squares, the injection well by the solid vertical line, and the approximate positions of the producing wells by the dark gray vertical dashed lines. The reservoir interval is marked by the light gray horizontal dashed lines.