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Fault activation and induced seismicity in geological carbon storage – Lessons learned from recent modeling studies

Jonny Rutqvist[a,*], Antonio P. Rinaldi[a,b], Frederic Cappa[a,c], Pierre Jeanne[a], Alberto Mazzoldi[a,d], Luca Urpi[b], Yves Guglielmi[a], Victor Vilarrasa[a,e]

[a] *Energy Geosciences Division, Lawrence Berkeley National Laboratory (LBNL), Berkeley, USA*
[b] *Swiss Seismological Service, Swiss Federal Institute of Technology (ETHZ), Zürich, Switzerland*
[c] *GéoAzur, University of Nice Sophia-Antipolis, Côte d'Azur Observatory, Nice, France*
[d] *UMSNH-IIM, Instituto de Investigaciones en Ciencias de la Tierra, Morelia, Mexico*
[e] *Institute of Environmental Assessment and Water Research (IDAEA), Spanish Council for Scientific Research (CSIC), Barcelona, Spain*

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A B S T R A C T

In the light of current concerns related to induced seismicity associated with geological carbon sequestration (GCS), this paper summarizes lessons learned from recent modeling studies on fault activation, induced seismicity, and potential for leakage associated with deep underground carbon dioxide (CO_2) injection. Model simulations demonstrate that seismic events large enough to be felt by humans require brittle fault properties and continuous fault permeability allowing pressure to be distributed over a large fault patch to be ruptured at once. Heterogeneous fault properties, which are commonly encountered in faults intersecting multilayered shale/sandstone sequences, effectively reduce the likelihood of inducing felt seismicity and also effectively impede upward CO_2 leakage. A number of simulations show that even a sizable seismic event that could be felt may not be capable of opening a new flow path across the entire thickness of an overlying caprock and it is very unlikely to cross a system of multiple overlying caprock units. Site-specific model simulations of the In Salah CO_2 storage demonstration site showed that deep fractured zone responses and associated microseismicity occurred in the brittle fractured sandstone reservoir, but at a very substantial reservoir overpressure close to the magnitude of the least principal stress. We conclude by emphasizing the importance of site investigation to characterize rock properties and if at all possible to avoid brittle rock such as proximity of crystalline basement or sites in hard and brittle sedimentary sequences that are more prone to injection-induced seismicity and permanent damage.

1. Introduction

Fault activation and induced seismicity associated with geological carbon sequestration (GCS) have in recent years become an intensively studied topic (Rutqvist, 2012). Concerns are mostly related to the potential for triggering notable (felt) seismic events and how such events could impact the long-term integrity of a carbon dioxide (CO_2) repository, as well as how they could impact the public perception of GCS (Fig. 1). The issue of induced seismicity has received broader attention among GCS stakeholders since 2012 when two high-profile publications appeared. First, in a study requested by the U.S. Government, The National Research Council (2012) concluded that projects involving large net volume of fluid injection and/or extraction of over long periods of time (such as GCS) may have the potential to induce large seismic events, though there was not sufficient information for understanding this potential for GCS, because no large-scale projects were yet in operation. Second, Zoback and Gorelick (2012) warned for the high probability that earthquakes would be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. They concluded that large-scale GCS would be a risky and likely unsuccessful strategy for significantly reducing greenhouse gas emissions to the atmosphere, because even small-to moderate-sized earthquakes could threaten the seal integrity of CO_2 repositories. These views have since been debated and

* Corresponding author.
E-mail address: Jrutqvist@lbl.gov (J. Rutqvist).
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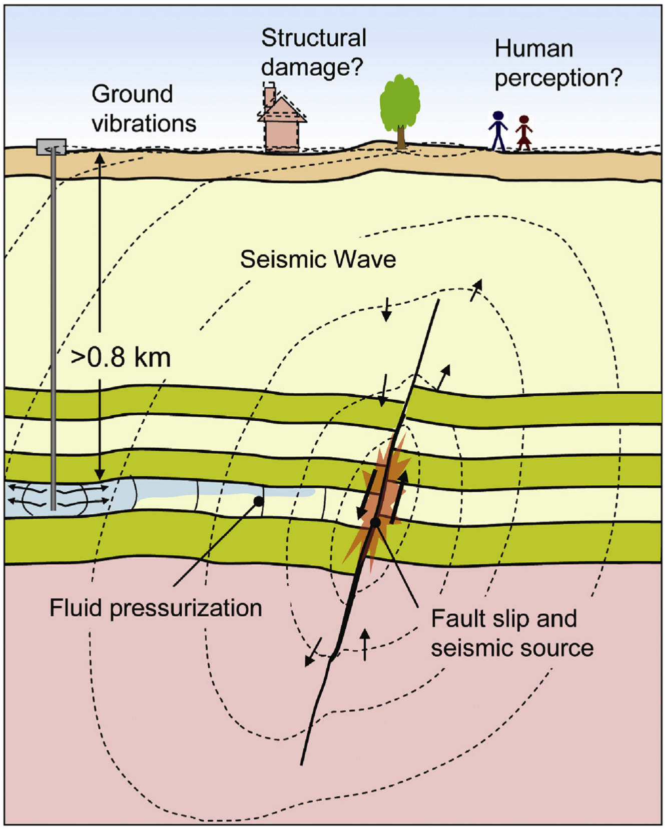

Fig. 1. Schematic of CO_2-injection-induced fault reactivation and potential impact on surface structures and human perception (Rutqvist et al., 2014).

questioned by some other researchers such as Juanes et al. (2012) and Vilarrasa and Carrera (2015).

In their article, Zoback and Gorelick (2012) mentioned reservoir-induced earthquakes associated with dam construction and water-reservoir impoundment as a good analog for the seismicity that potentially could be induced by large-scale CO_2 injection, because both activities cause pressure changes that act over large areas and are persistent for long periods. They also listed a number of recent small-to-moderate seismic events in the U.S. that seem to have been triggered by deep waste-water injection, referring to the critically stressed nature of the Earth's crust, which suggests that a subset of preexisting faults in the crust is potentially active in the current stress field almost everywhere in the continental interior (Zoback and Zoback, 1989). Because of the critically stressed nature of the crust, fluid injection in deep wells may induce earthquakes when injection increases the pore pressure in the vicinity of potentially active faults.

Since these two publications in 2012, concerns have been further amplified by the recent surge of injection-induced seismicity in the mid-continental U.S. as a result of waste-water injection (Ellsworth, 2013; Keranen et al., 2014; McGarr et al., 2015; Weingarten et al., 2015). In many of these cases, injected waste-water fluids seem to have communicated from the target formation to greater depth along preexisting faults, as evidenced by earthquake locations in the crystalline basement (Horton, 2012; Zhang et al., 2013; Verdon, 2014; Hornbach et al., 2015; McGarr et al., 2015). Vilarrasa and Carrera (2015) suggested that this higher rate of induced seismicity in the crystalline basement is a result of the deviatoric stresses that tend to be higher in the stiff basement rocks compared to the softer overlying sediments. Highlighted herein is also the critical importance of brittle-versus-ductile rock properties that could be decisive on whether fault activation induced by deep underground CO_2 injection could result in a felt seismic event and permanent damage to the CO_2 repository seal.

In the light of these concerns, this paper summarizes lessons learned from recently published modeling studies on fault reactivation associated with CO_2 injection into deep sedimentary formations. The model simulations were conducted using a coupled multiphase fluid flow and geomechanics numerical model (Rutqvist, 2011) applying deterministic modeling of a fault with evolving frictional coefficient that enables the simulation of sudden (seismic) fault rupture. In some cases, the modeling was extended to include the entire chain of processes of CO_2 injection, reservoir pressurization, dynamic fault-reactivation-induced seismic source, wave propagation, and ground motion. Finally, we summarize the results and lessons learned from modeling of injection-induced deep fracture zone responses at the In Salah CO_2 storage site, and conclude with recommendations to minimize the potential of induced seismicity and damaging geomechanical changes during a GCS operation.

2. Lessons learned from generic fault activation studies

In this section, we summarize lessons learned from generic (not site-specific) modeling studies on potential fault activation, induced seismicity and leakage associated with CO_2 injection into deep underground sedimentary formations. The model simulations were conducted using the TOUGH-FLAC simulator (Rutqvist et al., 2002; Rutqvist, 2011) which is based on linking the TOUGH2 finite-volume code for the simulation of multiphase fluid flow (Pruess et al., 2012) with the FLAC3D finite-difference code for the simulation of geomechanics (Itasca Consulting Group, 2011). The TOUGH-FLAC simulator was first applied for deterministic modeling of fault activation in Rutqvist et al. (2007) and in the modeling of the 1960s Matsushiro earthquake swarm by Cappa et al. (2009). Later, Cappa and Rutqvist (2011a) further tested the TOUGH-FLAC simulator with the deterministic fault activation model using different fault mechanical approaches, including representation of faults by slip interfaces or finite-thickness elements with isotropic or anisotropic elastoplastic constitutive models. Cappa and Rutqvist (2011a) then utilized the finite-thickness fault element approach coupled with a strain-permeability model to show the important role of shear-enhanced permeability in propagating fault instability and permeability enhancement through the overlying caprock. The TOUGH-FLAC simulator with such fault activation modeling approach has since been applied in a number of studies, in which the constitutive models for fault permeability and friction have been further developed, including slip-weakening and slip-rate dependent friction. In the following subsections, the main findings and lessons learned from these generic simulation studies are summarized.

2.1. Simulation of a felt seismic event on a major fault

Results from Cappa and Rutqvist (2011b) are presented as an example to illustrate what it takes to create a seismic event that might be felt by humans on the ground surface. Fig. 2a shows the model geometry and Fig. 2b the fault friction model. Details on the modeling input including material properties can be found in Cappa and Rutqvist (2011b). A strain-softening fault constitutive mechanical model was used as it enables modeling of sudden (seismic) fault slip. Using this approach in a quasi-static mechanical analysis in FLAC3D, discrete events of fault activation were modeled and the associated seismic moment magnitude was estimated