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Preface

With the growing concern in climate change, governments and industries are intensifying their efforts to plan excess CO_2 storage in geological traps located at several kilometers below the surface. A successful implementation of CCS relies on storing a large amount of CO_2 in multiple storage sites while maintaining storage safe over the long term. Geological faults that are ubiquitous throughout the earth's crust display an extremely complex and large variety of structures and evolutions through time. It is reasonable to imagine that, given the scale of the future CO_2 storage efforts, among a majority of silent faults some will rupture, causing earthquakes and CO_2 flow by-pass the geological traps.

Fault rupture requires sophisticated concepts that were developed from different research disciplines such as Hydrogeology, Mechanics and Seismology. In addition, it appears that several concepts must be combined with each other to best figure the multiple interacting hydromechanical and chemical processes of fault rupture. Beyond the concepts, fault rupture spans over a broad range of time scales, from a few seconds for an earthquake to several days and years for a slow rupture.

All this complexity in the fault physics makes it difficult for the choices to simplify the problem of estimating the fault risk associated to CO_2 storage. The first motivation of this book is to put together key research results on fault mechanics, hydrogeology and induced seismicity that are relevant to CO_2 storage. The second motivation is to provide in the same book a detailed enough physics of fault leakage and induced seismicity, by confronting relevant theories on fault rupture with experimental results from laboratory scale and from mesoscale field experiments.

For the above reasons, we expect this book to be considered as useful by students, scientists and engineers in their attempts to better consider fault zones at CO_2 storage scales.

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Introduction

After decades of research on carbon capture and storage (CCS), the world needs to finally move from pilot tests and demonstration experiments to industrial-scale implementation (Birkholzer et al., 2015; Shu et al., 2023). In different countries, CCS deployment over the coming years and decades will likely create multiple large storage projects (or clusters of integrated projects, or hubs) across selected sedimentary basins. These projects will involve the injection of substantial volumes of CO_2, leading to large-scale pressure increases, accompanied by associated stress perturbations within the subsurface (Nicot, 2008; Birkholzer and Zhou, 2009; Zhou et al., 2010). These activities may potentially cause unwanted geomechanical effects, such as the formation of leakage pathways in the caprock or the seismic reactivation of critically stressed faults (Rutqvist et al., 2012; Rutqvist et al., 2016; Zoback and Gorelick, 2012; Ellsworth, 2013; Vilarrasa et al., 2019).

Fault reactivation can be a concern even if the large-scale pressure changes are smaller than the pressure thresholds (i.e., fracturing pressure) typically employed to ensure that local injection pressures do not cause geomechanical damage in the reservoir and the confining units (Rutqvist et al., 2007). It follows that large-scale pressure buildup can be a limiting factor for sequestration capacity (Thibeau et al., 2014), because the possibility of pressure-related impacts of individual projects needs to be considered. Furthermore, in a future world with CCS being a fully deployed technology, sedimentary basins with interconnected reservoirs might host multiple storage sites between which pressure interference can be expected (Birkholzer and Zhou, 2009; Zhou et al., 2010), potentially adding a further concern for storage security and further constraints on storage capacity.

In this review, we explore how the complexity of the rheological heterogeneity of faults is considered in generating permeable pathways for brine or CO_2 to flow out of the storage reservoir along the faults. We focus on the potential for flow paths to grow along fault zones and trigger the loss of integrity of caprocks sealing the storage reservoir. We define this as the fault leakage risk. We also explore how building pore pressure while storing supercritical CO_2 into a reservoir layer can generate seismicity around and far deeper from the storage volume in the basement of the sedimentary basin. We define this as the seismic risk induced by CO_2 storage. We focus on fault zones affecting sedimentary basin and their upper basement limit, i.e., the behavior of faulted layered lithostratigraphic systems between the surface and perhaps 6–8km depth. We first provide an overview of the current workflows and concepts used to estimate both leakage risk through faults across caprocks and changes in seismicity rates caused by fluid injections (Chap. 1). We discuss how these workflows integrate simplified fault zones physics based on clay content, friction and stress or stress rates to describe the seismic activation and leakage of faults.

In Chap. 2, we go deeper into the geomechanics of basin faults and on the implications for CO_2 storage at scale. One key question is the potential effect of brittleness and of brittle-ductile limits on faults within basins. We discuss how the presence of faults within clay-rich caprocks affects their frictional dilatant properties, which in turn alters their leakage and seismogenic potentials. We furthermore explore various constitutive relationships for the plastic deformation of faults and how to relate contraction/dilation with softening/hardening leading to stable/unstable fault slip. Specifically, we propose that a Cam-Clay model may provide a more general mechanical framework compared to a Coulomb model for describing a large variability of fault activation scenarios.

Chapter 3 is a review of all factors influencing permeability change at fault rupture. This chapter is focused on the complex coupling between fault mechanics and permeability. We first review different laboratory-scale experiments and compare these to fault permeability measurements from field-scale experiments. We observe that fault permeability tends to drastically decrease with shear at laboratory scale while a much smaller-to-no decrease is observed in the field. We finally propose a new conceptual model for the fault permeability evolution with slip and discuss how it can be considered in constitutive relationships for the coupled hydromechanical behavior of faults.

Chapter 4 is dedicated to induced seismicity. It appears that induced seismicity is currently modeled using one dominant approach based on the physics of rate-and-state friction (Dieterich, 1972, 1979; Marone, 1998). We review the key hypotheses and concepts of this theory and describe how it has been applied to model changes in natural seismicity rates related to seismicity rates due to CO_2 injections at basin scale. Then, we compare this physics based on friction with another model one based on plastic instability, referred to as Cam-Clay model. This plastic approach is relatively new and has never really been tested for basin scale injections. Based on an extension of the Cam-Clay model to dynamic processes, we particularly explore how slow slip initiated on a fault away from a CO_2 storage project can accelerate with time into an earthquake rupture. We use existing codes from the literature to estimate if this is possible when considering a basin fault initially mechanically stable and relatively far from critical state of stress.

We conclude this review by asking what the hydromechanical behavior of faults as discussed above means for carbon storage management at basin scale. We propose a general framework for assessing these impacts which we hope will help unify leakage and induce seismicity workflows in the future.