The Seismicity at the Castor Underground Gas Storage, Spain, was Induced by Pressure Buildup, Buoyancy, Aseismic Slip, Shear Slip Stress Transfer and Slip-Driven Pressure Changes

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Abstract

The Underground Gas Storage (UGS) project of Castor, Spain, was strategically conceived to guarantee the Spanish gas demand during 50 days. Yet, the project did not enter into operation because it was cancelled as a result of a sequence of felt earthquakes induced after cushion gas injection. The project cancellation implied an investment compensation to the operating company that may cost up to 4.73 billion euros to Spanish citizens. The sequence contained the three largest earthquakes (M4.08, M4.01 and M3.97) ever induced by any of the more than 640 UGS facilities around the world. The largest earthquakes were induced some 20 days after stopping injection, which lasted for 15 days. The focal depth of these earthquakes was between 4 to 10 km, far deeper than the 1.7 km injection depth. To understand the causes of this induced seismicity, we have performed coupled two-phase flow and geomechanical numerical simulations and we have employed Okada's solution to analyze the shear slip stress transfer. We analyzed four seismicity-inducing mechanisms (pore pressure build-up, stress transfer, destabilizing buoyancy, and recovery of pressure drops that ensure transient stability in regions that are mechanically destabilized after a microseism). We found that the onset of seismicity was induced by gas injection, which reactivated the critically stressed Amposta fault through pore pressure buildup and buoyancy. The Amposta fault, a mature fault bounding the storage formation, crept, accumulating aseismic slip. Destabilization of the fault continued even after the stop of injection because of the permanent effect of buoyancy caused by the low density of the injected gas. The progressive accumulation of slip perturbed the stress around the rupture area of the Amposta fault and eventually reactivated a critically stressed unmapped fault located in the crystalline basement. Once this deep fault was reactivated, the sequence of earthquakes was induced by shear slip stress transfer, with transient slip-driven pore pressure changes likely controlling the delay between earthquakes. We contend that an analysis of fault stability prior to gas injection would have identified the high risk of inducing seismicity at Castor.

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PRESENTED AT:

INTRODUCTION

The Underground Gas Storage (UGS) project of Castor, Spain, was strategically conceived to guarantee the Spanish gas demand during 50 days. Yet, the project did not enter into operation because it was cancelled as a result of a sequence of felt earthquakes induced after cushion gas injection. The project cancellation implied an investment compensation to the operating company that may cost up to 4.73 billion euros to Spanish citizens. The sequence contained the three largest earthquakes (M4.08, M4.01 and M3.97) ever induced by any of the more than 640 UGS facilities around the world. The largest earthquakes were induced some 20 days after stopping injection, which lasted for 15 days. The focal depth of these earthquakes was between 4 to 10 km, far deeper than the 1.7 km injection depth. These three features, i.e., To understand the causes of this induced seismicity, we have performed coupled two-phase flow and geomechanical numerical simulations and we have employed Okada's solution to analyze the shear slip stress transfer. This video (https://www.youtube.com/watch?v=A6OoEqsQjyk&fs=1&modestbranding=1&rel=0&showinfo=0)explains the causes of the induced seismicity.

BUOYANCY

The density contrast between the injected natural gas and the resident salty water is very large, around 900 kg/m^3. As a result, the injected gas exerts a vertical force due to buoyancy, modifying the initial stress of state. In particular, the vertical stress increases and the horizontal stress decreases above the storage formation. Consequently, the deviatoric stress increases for the stress regime at Castor, a normal faulting/strike slip, and thus, stability decreases. Therefore, the Amposta fault became and remains destabilized above the storage formation because buoyancy acts permanently. This persistent destabilization gave rise to the accumulation of aseismic slip even after shut-in, which built up shear slip stress transfer until a deep fault was reactivated.

SHEAR SLIP STRESS TRANSFER

The accumulation of aseismic slip in the Amposta fault changed the stresses around it. In particular, at the location of the deep fault, the vertical stress increased and the horizontal stresses decreased, which increased the deviatoric stress and eventually led to the reactivation of the deep fault that induced the largest earthquakes. This deep fault is located in the crystalline basement, which is more seismogenic than sedimentary rock and thus, explains the high magnitude of the induced earthquakes.

Once the deep fault was reactivated, the sequence of felt earthquakes that nucleated in this fault can be explained with shear slip stress transfer.

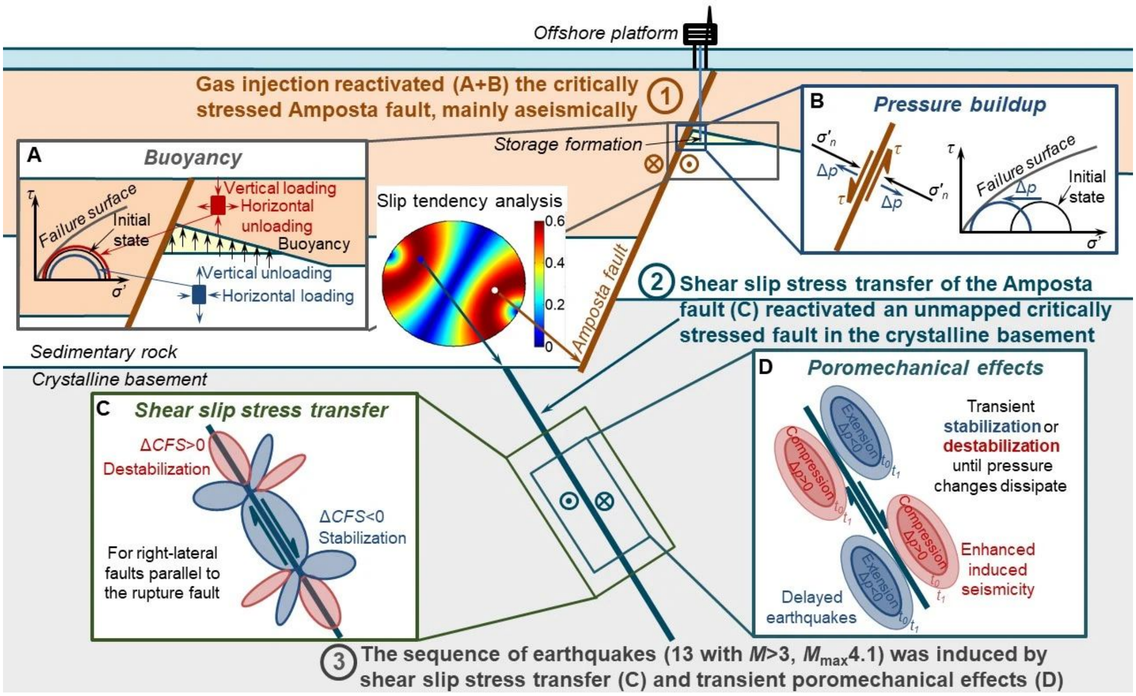
SLIP-DRIVEN PRESSURE CHANGES

Slip of a fault causes compression in front of the slip patch and extension behind it. This deformation induces undrained pore pressure changes, causing pressure buildup where compression occurs and pressure drop where extension takes place. These pore pressure changes are transient and the dissipation time is proportional to the rock matrix permeability. As a result, a transient destabilization occurs where pore pressure builds up, promoting further induced seismic events; and a transient stabilization occurs where pore pressure drops, delaying induced seismicity. This mechanism could explain the delay of hours to days between earthquakes within the sequence.

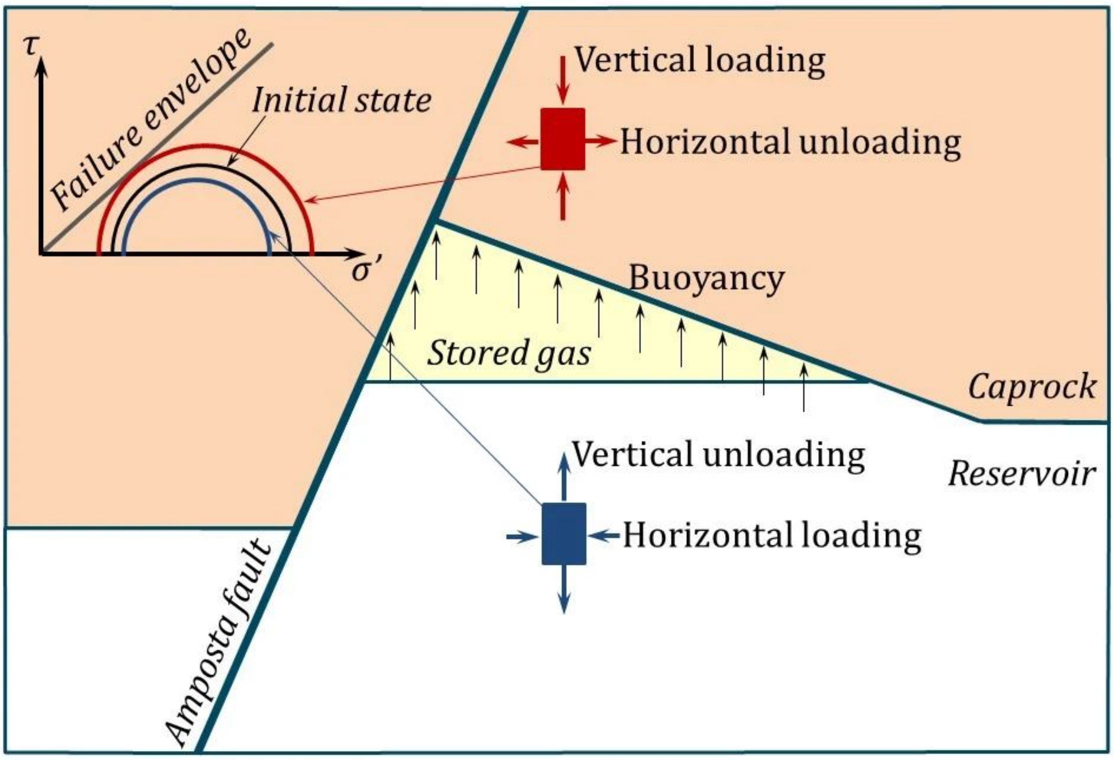
PRESSURE BUILDUP

Pore pressure is the classical triggering mechanism of induced seismicity and, sometimes, is considered as the unique one. Nonetheless, its role at Castor was minor since the largest earthquakes occurred once pore pressure had dissipated and at a deep fault that is hydraulically disconnected from the storage formation by low-permeable sedimentary rock layers. Pore pressure buildup most likely caused microseismic events during gas injection within and in the vicinity of the storage formation. It also contributed to destabilize the critically stressed Amposta fault, which bounds the storage formation.

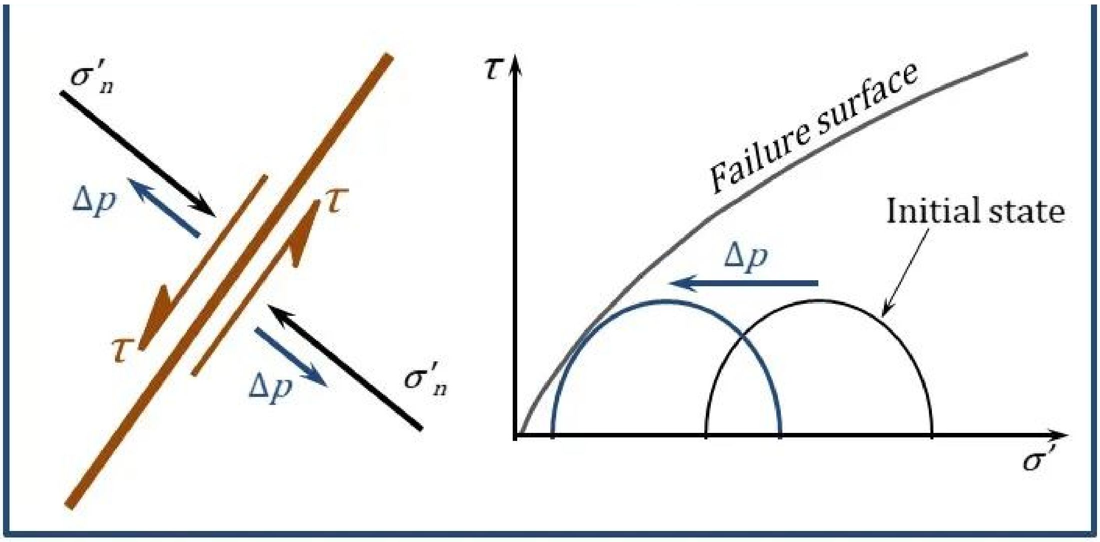
The mechanisms that caused the induced seismicity at the Castor Underground Gas Storage (UGS)



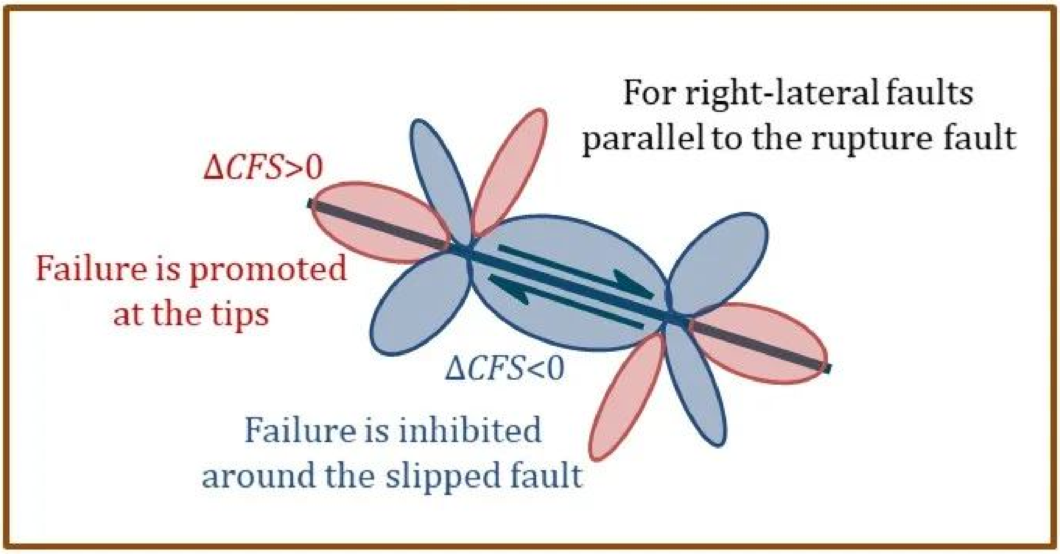
Buoyancy



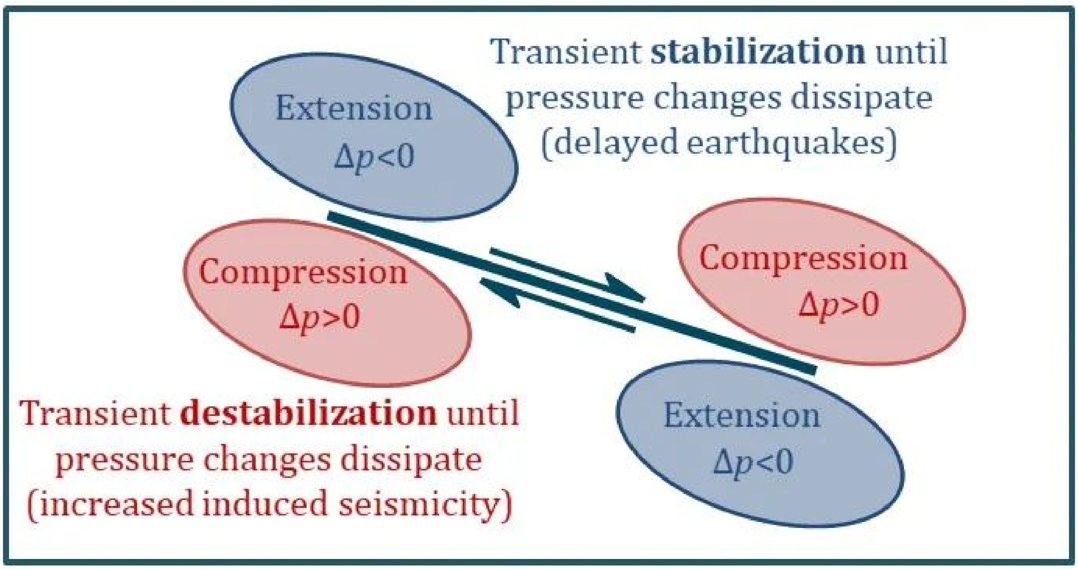
Pressure buildup



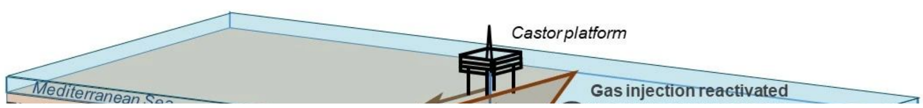
Shear slip stress transfer

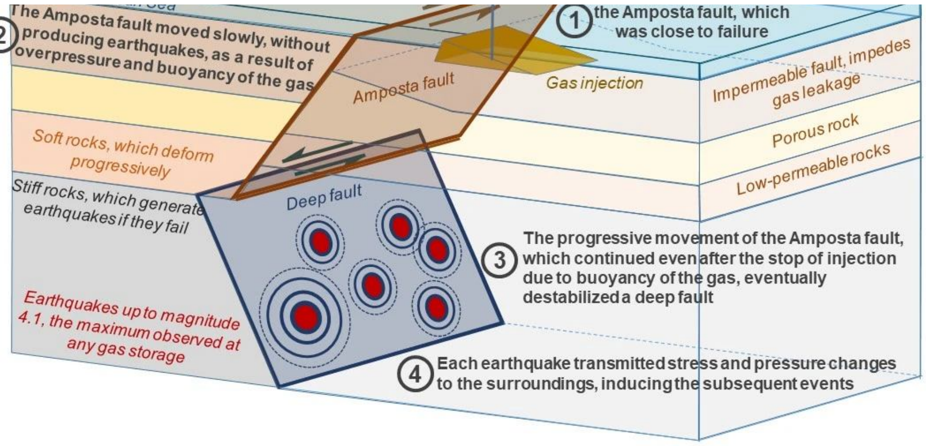


Slip-driven pressure changes



The mechanisms that caused the induced seismicity at the underground gas storage of Castor




The Amposta fault moved slowly, without producing earthquakes, as a result of overpressure and buoyancy of the gas
2
1
the Amposta fault, which was close to failure
Amposta fault
Gas injection
Impermeable fault, impedes gas leakage
Porous rock
Low-permeable rocks
Soft rocks, which deform progressively
Stiff rocks, which generate earthquakes if they fail
Deep fault
3
The progressive movement of the Amposta fault, which continued even after the stop of injection due to buoyancy of the gas, eventually destabilized a deep fault
Earthquakes up to magnitude 4.1, the maximum observed at any gas storage
4
Each earthquake transmitted stress and pressure changes to the surroundings, inducing the subsequent events

CONCLUSIONS

We found that the onset of seismicity was induced by gas injection, which reactivated the critically stressed Amposta fault through pore pressure buildup and buoyancy. The Amposta fault, a mature fault bounding the storage formation, crept, accumulating aseismic slip. Destabilization of the fault continued even after the stop of injection because of the permanent effect of buoyancy caused by the low density of the injected gas. The progressive accumulation of slip perturbed the stress around the rupture area of the Amposta fault and eventually reactivated a critically stressed unmapped fault located in the crystalline basement. Once this deep fault was reactivated, the sequence of earthquakes was induced by shear slip stress transfer, with transient slip-driven pore pressure changes likely controlling the delay between earthquakes. We contend that an analysis of fault stability prior to gas injection would have identified the high risk of inducing seismicity at Castor.

Reference: Vilarrasa, V., De Simone, S., Carrera, J. and Villaseñor, A., 2021. Unravelling the causes of the seismicity induced by underground gas storage at Castor, Spain. *Geophysical Research Letters*, 48, e2020GL092038 (https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020GL092038)

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AUTHOR INFORMATION

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ABSTRACT

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