Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which CO₂ could leak

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Zoback and Gorelick ([2012] Proc Natl Acad Sci USA 109(26):10164–10168) have claimed that geologic carbon storage in deep saline formations is very likely to trigger large induced seismicity, which may damage the caprock and ruin the objective of keeping CO₂ stored deep underground. We argue that felt induced earthquakes due to geologic CO₂ storage are unlikely because (i) sedimentary formations, which are softer than the crystalline basement, are rarely critically stressed; (ii) the least stable situation occurs at the beginning of injection, which makes it easy to control; (iii) CO₂ dissolution into brine may help in reducing overpressure; and (iv) CO₂ will not flow across the caprock because of capillarity, but brine will, which will reduce overpressure further. The latter two mechanisms ensure that overpressures caused by CO₂ injection will dissipate in a moderate time after injection stops, hindering the occurrence of postinjection induced seismicity. Furthermore, even if microseismicity were induced, CO₂ leakage through fault reactivation would be unlikely because the high clay content of caprocks ensures a reduced permeability and increased entry pressure along the localized deformation zone. For these reasons, we contend that properly sited and managed geologic carbon storage in deep saline formations remains a safe option to mitigate anthropogenic climate change.

This is Not True That the Whole Upper Crust Is Critically Stressed

It is generally accepted that the crystalline basement is critically stressed at some depth intervals (14–16). However, CO₂ will be injected in shallow (1–3 km deep) sedimentary formations, which are much softer than the brittle and stiff crystalline basement. As such, stress criticality, i.e., mobilized frictional coefficients, μ, in the range of 0.6–1.0 (17), is not usually observed at shallow depths within sedimentary formations (16, 18–21). We have compiled effective stress data of sedimentary formations and they fall within values of mobilized frictional coefficients around 0.4, i.e., the actual deviatoric stress is lower than the critical one (Fig. 1). This value is moderately low compared with the frictional coefficients around 0.6–0.8 of the critically stressed crystalline basement. In particular, the mobilized friction coefficients of sedimentary rocks where CO₂ is being, has been or is planned to be injected is always lower than the critical value of 0.6. This means that there is a wide margin before CO₂ injection might induce failure conditions and therefore, trigger a seismic event.

To illustrate that sedimentary formations are unlikely to be critically stressed, we have built a simple model of the upper sedimentary formations are rarely critically stressed; (ii) the least stable conditions occur at the beginning of injection; (iii) CO₂ may dissolve at a significant rate, reducing overpressure; and (iv) brine will flow across the caprock, lowering overpressure in the reservoir. For these reasons we believe that geologic carbon storage in deep saline formations remains a safe option for mitigating climate change.

Significance

Geologic carbon storage remains a safe option to mitigate anthropogenic climate change. Properly sited and managed storage sites are unlikely to induce felt seismicity because (i) sedimentary formations, which are softer than the crystalline basement, are rarely critically stressed; (ii) the least stable situation occurs at the beginning of injection, which makes it easy to control; (iii) CO₂ will dissolve into brine at a significant rate, reducing overpressure; and (iv) CO₂ will not flow across the caprock because of capillarity, but brine will, which will reduce overpressure further. Furthermore, CO₂ leakage through fault reactivation is unlikely because the high clay content of caprocks ensures a reduced permeability and increased entry pressure along localized deformation zones.

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Sedimentary rocks result, the crystalline rock becomes critically stressed (crystalline rocks are critically stressed, sedimentary rocks are usually not). The mobilized frictional coefficients, \( \mu \), are marked with black circles. The lines corresponding to several mobilized frictional coefficients, \( \mu \), are included as a reference. Note that whereas crystalline rocks are critically stressed, sedimentary rocks are usually not.

Some support for this simple model results from the fact that it yields the maximum mobilized frictional coefficient at a depth between 5 and 6 km (Fig. 2). This means that shallow earthquakes are most likely to occur in the crystalline basement at this depth. Interestingly, this depth of maximum occurrence of earthquakes is consistent with observations of frequency-depth distribution of earthquakes in continental intraplate regions such as Haicheng, China; Thessaloniki, Greece; Hansel Valley, Utah; Pocatello Valley, Idaho; Wasatch, Utah; Coso geothermal field, California (23) and Galicia, Spain (24); and in the plate boundary of the San Andreas Fault, California (23, 25, 26).

The evidence that sedimentary rocks are not critically stressed (Figs. 1 and 2) appears to contradict the large magnitude earthquakes induced by wastewater injection in sedimentary formations in 2011 at Oklahoma, Ohio and Arkansas. These earthquakes have been used as an argument against geologic carbon storage (1). However, the earthquakes were induced in the critically stressed crystalline basement and not in the sedimentary formations where wastewater was injected. Wastewater was injected into the basal aquifer, which led to the pressurization of faults in the crystalline basement (27–29). In the case of the earthquakes of Guy and Greenbrier, Arkansas, wastewater was injected into the Ozark aquifer (3 km deep), which is placed right above the crystalline basement. Wastewater leaked into a deeper fault, inducing four earthquakes of magnitude \( M > 3.9 \), with a maximum magnitude of 4.7, at around 6 km deep (30). This finding highlights (i) the need for proper characterization and (ii) the importance of a seal below the storage formation, to isolate the critically stressed crystalline basement from \( \mathrm{CO}_2 \) injection in sedimentary formations.

It has been conjectured that if an induced earthquake similar to those triggered by wastewater injection in 2011 occurred in a \( \mathrm{CO}_2 \) storage site, fault reactivation would lead to \( \mathrm{CO}_2 \) leakage (1). We contend that close analysis of fault zone architecture reveals that \( \mathrm{CO}_2 \) will not easily penetrate into the portions of the fault contained within shale rocks (31). Fault permeability, which is highly variable in reservoir-caprock sequences (32, 33), decreases several orders of magnitude for increasing clay content, leading to a much lower permeability in the caprocks than in the reservoirs (34, 35). Rocks with low clay content, like reservoirs, tend to fracture, increasing the width of the damaged zone and usually increasing permeability in response to shear (34). However, clay-rich rocks, like caprocks, tend to concentrate shearing in the fault core, which reduces the grain size by friction, thus reducing fault permeability (34). Therefore, shear slip will usually increase fault permeability in the reservoir, but decrease it in the caprock, increasing the permeability contrast in the vertical direction (31, 36). Indeed, numerical simulations show that \( \mathrm{CO}_2 \) leakage is negligible when accounting for this heterogeneity in permeability in the vertical direction within faults undergoing shear displacement (37). Even assuming constant permeability in the vertical direction within the fault, no correlation has been found between shear slip and \( \mathrm{CO}_2 \) leakage (38). Furthermore, capillary entry pressure increases with both clay content and reduced pore size, which is what ultimately hinders \( \mathrm{CO}_2 \) penetration into the fault (39).

**Overpressure Evolution**

The evolution of overpressure induced by \( \mathrm{CO}_2 \) injection is significantly different from that of water (or wastewater) injection. Water injection at a constant mass flow rate through a vertical well into an extensive (infinite) confined formation induces an overpressure that increases linearly with the logarithm of time (40). Therefore, overpressure will become large for very long injection times. This was the case at Paradox Valley, Colorado, where overpressure increased more than 16 MPa over a decade of injecting a constant volume of saline water (29). On the other hand, the low viscosity of \( \mathrm{CO}_2 \) implies that overpressure caused by \( \mathrm{CO}_2 \) injection peaks at the beginning of injection and drops

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**Fig. 1.** Maximum versus minimum effective stress measured in wellbores at depth in both crystalline (black squares) and sedimentary rocks (hollow circles). Sedimentary rocks where \( \mathrm{CO}_2 \) is being, has been or is planned to be injected are marked with black circles. The lines corresponding to several mobilized friction coefficients, \( \mu \), are included as a reference. Note that whereas crystalline rocks are critically stressed, sedimentary rocks are usually not.

**Fig. 2.** Mobilized frictional coefficient as a function of depth after 6 Myr of applying a strain rate typical of plate tectonics (\( 10^{-17} \) s\(^{-1}\)) in the upper crust considering that the stress field is initially isotropic (see inlet for a sketch of the model). Note that whereas the crystalline basement becomes critically stressed, the sedimentary rocks remain far from being critically stressed.
slightly afterward (41–48) (see inlet Fig. 3). This difference makes CO₂ injection particularly interesting because the most critical state occurs at the beginning of injection (41, 49) (Fig. 3). This initial critical situation is illustrated by what happened at Weyburn, Canada, where around 200 microseismic events were induced at the beginning of CO₂ injection, but no more events were measured afterward (50). In fact, initial microseismicity may be reduced by progressively increasing the CO₂ injection rate to avoid the peak in overpressure at the beginning of injection.

Storage formations need not be extensive or fully confined, as assumed in the above discussion. Overpressure induced by CO₂ injection may increase over time if the pressure perturbation cone reaches a flow barrier, such as a low-permeability fault. In such case, or in a compartmentalized reservoir (51), the reservoir storage capacity could be limited by the maximum sustainable injection pressure, defined so as to avoid induced seismicity (52). Fluid pressure must be monitored to identify the presence of flow barriers and to adopt mitigation measures to avoid an excessive overpressure that could lead to induced seismicity and make the operation uneconomical. Nevertheless, the reservoir will never be totally closed and overpressure will dissipate with time, helping to maintain fault stability and hinder postinjection induced earthquakes.

Overpressure will extend tens to hundreds of km for the time scales of CO₂ storage projects, i.e., 30–50 y (53). At these spatial scales, the effective caprock permeability can be two orders of magnitude higher than that of the core scale due to the existence of discontinuities (54). Thus, caprock permeability can become relatively high, i.e., up to 10⁻¹⁶ m² (55). Because the caprock seals brine by permeability, but it seals CO₂ by capillarity, brine, but not CO₂, can flow through the caprock (56). Fig. 4 shows that overpressure can be significantly lowered for relatively permeable caprocks, which would reduce the risk of inducing seismic events through fault reactivation due to the lower overpressure. Furthermore, the lateral extent of the pressure perturbation cone will also be significantly reduced (Fig. 4), which increases the reservoir storage capacity (57) and reduces the number of fractures and faults that will undergo stability changes. Indeed, a steady state could be reached in which the flow rate of brine flowing through the caprock equals the injected flow rate. Using leaky aquifers theory (58), and the geological setting of Fig. 4, the steady state would be reached after some 200 y of injection if the permeability of the seals is 10⁻¹⁶ m², but only after 21 y if the permeability of the seals equals 10⁻¹⁷ m². Thus, this steady state may take place at some CO₂ injection sites before the injection finishes.

**CO₂ Dissolution**

CO₂ dissolution reduces the total fluid volume filling the pores, thus reducing overpressure (59) and the risk of induced seismicity. The high solubility of CO₂ makes dissolution one of the main trapping mechanisms in the long term. For instance, it has been observed in carbonate-dominated reservoirs containing naturally occurring CO₂ that up to 90% of this CO₂ can dissolve at the millennial timescale (the remaining 10% would be trapped in precipitated minerals) (60).

CO₂ dissolution also operates over relatively short timescales and provides a significant storage capacity (61, 62). CO₂-rich brine is denser than the native brine, which causes the brine immediately beneath the CO₂ plume to be denser than the brine below. This situation is hydrodynamically unstable and leads to the formation of CO₂-rich gravity fingers that sink to the bottom of the formation and bring fresh brine upwards, forming convective cells that enhance CO₂ dissolution rate (63–67).

CO₂ dissolution is likely to occur quickly for high vertical permeability (k > 10⁻¹⁴ m²), which will lower overpressure significantly. Indeed, Elenius et al. (68) calculated that up to 50% of the injected CO₂ at Sleipner (k = 2 · 10⁻¹² m²), Norway, becomes rapidly dissolved when the formation brine has no dissolved CO₂. Furthermore, they estimated that between 7 and 26% of the total 15 Mt of CO₂ injected in the period 1996–2011 is already dissolved. These results are in agreement with our calculations (SI Text), which predict a dissolution rate at Sleipner of 12% of the injected CO₂. Still, these calculations may underestimate the actual rate at which CO₂ dissolves because they neglect the effect of dispersion, which significantly accelerates the onset of gravitational fingering (64). Furthermore, mass transfer is enhanced by convection in inclined aquifers, which are common in sedimentary basins (69). However, dissolution becomes negligible for low vertical permeability. For instance, at In Salah (k = 10⁻¹⁴ m²), Algeria, only 0.03–0.1% of the injected CO₂ dissolves into the brine (68). Therefore, only when vertical permeability is high, CO₂ dissolution will contribute to significantly reduce overpressure with time, progressively leading to a mechanically more stable situation.
Discussion and Conclusions

We have given evidence that sedimentary formations are not, in general, critically stressed (recall Figs. 1 and 2). Furthermore, overpressure will be relatively small when injecting CO₂ because (i) it peaks at the beginning of injection and afterward drops slightly (recall Fig. 3); (ii) CO₂ dissolution may occur quickly and at a significant rate, if the vertical permeability of the reservoir is high, contributing to reduce overpressure; and (iii) because brine, but not CO₂ because of capillarity, can flow through the caprock, overpressure will be lowered significantly and a steady state may be reached at some time thereof the injection period (recall Fig. 4). The combined effect of a noncritically stressed storage formation and a small overpressure make geologic storage a safe strategy to reduce emissions of greenhouse gasses to the atmosphere.

This conclusion is not meant as an unqualified approval of any site for storage. Every site requires a proper suitability study. To this end, numerous best practices manuals are available (see ref. 70 for a review). The key issue is site characterization (71), which includes proper structural geology understanding and a good hydrogeomechanical testing (72). Characterization may lead to dismissal of some reservoirs. Still, the point is that suitable sedimentary basins to store huge volumes of CO₂ are abundant around the world (62, 73, 74).

Experience with CO₂ storage is still limited, so few generalizations can be made. Instead, some lessons can be learnt from geothermal operations, despite the fact that these tend to concentrate in regions of anomalous thermal gradients, which are geothermal operations, with shear displacements of up to 6 cm (86, 87). These numerical studies highlight the importance of overpressure management for avoiding felt induced seismicity.

Even if a seism of sufficient magnitude occurs, CO₂ may not necessarily leak because fault permeability is reduced and entry pressure increased in faults across rocks containing clay (37). Moreover, a self-healing mechanism that prevents CO₂ leakage has been observed in argillaceous limestones (88). We conjecture that these mechanisms, together with increased buoyancy, may explain why CO₂ natural analogs often leak at shallow depths (less than 700 m, where CO₂ is gaseous), but deep natural CO₂ deposits rarely do (89).

Coupled thermo-mechanical effects also deserve attention. CO₂ will generally reach the storage formation at a temperature lower than that of the rock (90). In fact, injecting liquid (cold) CO₂ and maintaining liquid conditions along the wellbore is energetically advantageous (and therefore, it is likely to become a common practice) because it significantly reduces compression costs (91). Cold injection will cause a cold region around the injection well, which will induce thermal stress reduction. This stress reduction may lead to fracture instabilities within the reservoir (92), where induced microseismicity may be beneficial as it enhances injectivity. However, cold CO₂ injection improves caprock stability in normal faulting stress regimes because the caprock tightens as a result of stress redistribution, even in the presence of stiff caprocks (93). Thus, injection of cold CO₂ should further improve stability in tectonically stable regions.

Zoback and Gorelick (1) concluded that large-scale geologic carbon storage will be extremely expensive and risky. Economic issues fall beyond our expertise and the scope of this review (but it seems evident that economic feasibility will depend on the prize of CO₂ emissions). However, we have provided abundant evidence to state that large-scale CO₂ storage is not risky and, thus, will be a safe option to mitigate anthropogenic climate change.

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