# Reply to Zoback and Gorelick: Geologic carbon storage remains a safe strategy to significantly reduce $CO_2$ emissions

Zoback and Gorelick (1) highlight the importance of considering the potential for induced seismicity in geologic carbon storage (GCS) projects. We agree that site characterization is needed for safe $CO_2$ storage; that is, without inducing large earthquakes ($M > 4$) that might jeopardize the stability and sealing capacity of caprock and faults (2).

Zoback and Gorelick (1) argue that the subsurface is critically stressed and small pore pressure increases could induce large seisms. However, sedimentary formations, where $CO_2$ will be stored, are rarely critically stressed (see figure 1 and *Supporting Information* of ref. 2 for details and references) because they are softer than the crystalline basement and thus accumulate fewer stresses. Still, some sedimentary formations may be critically stressed, which is why proper site characterization remains crucial (3, 4).

We agree that (local) microseismicity will be induced in deep fluid injection projects, including GCS. However, microseismic events are not a concern (e.g., the 9,500 microseisms at In Salah have not caused $CO_2$ leakage) and may even be positive, if confined to the reservoir, because they may enhance permeability. The question is whether large seismic events could be induced. Although each site needs specific analysis, we showed that GCS can be done safely in many sedimentary basins around the world (2).

Zoback and Gorelick (1) argue that $CO_2$ dissolution will have a negligible effect on diminishing overpressure. Indeed, $CO_2$ dissolution may not be significant at sites with low vertical permeability (2), such as In Salah. However, such "low-permeability" reservoirs will tend to be avoided because of their low injectivity. In relatively permeable aquifers, $CO_2$ will dissolve into brine at relatively high rates (5), reducing overpressure.

The ultimate issue is the validity of the popular view—shared by Zoback and Gorelick (1)—that injecting large volumes of $CO_2$ requires large overpressures, not necessarily for saline aquifers (the issue is obvious for enhanced oil recovery cases, which we did not mention in our report 2). This view is supported by the overpressure growth with the logarithm of time induced by injection of high-viscosity and low-compressibility wastewater, making wastewater injection more prone to induce seismicity than GCS. Instead, $CO_2$ injection requires relatively constant overpressure, making it easy to control.

Overall, the large injected $CO_2$ volumes are compensated by three processes: (*i*) compression of the fluid and expansion of the rock (driven by overpressure); (*ii*) dissolution (i.e., the volume of $CO_2$ saturated water is much smaller than the sum of the volumes of the two phases); and most importantly, (*iii*) water leakage through the caprock, which we expect to be the most relevant in most sites (see refs. 2 and 6).

In summary, we agree with the conclusion that "the potential for triggered earthquakes represents one . . . potential mode of failure that must be considered" (1). However, we do not think it is the most critical one. Instead, permeabilities (horizontal, controlling overpressure; vertical, controlling dissolution; and of the caprock, controlling water leakage) may be the (economic) limiting factors. Therefore, $CO_2$ storage can be performed safely without inducing felt earthquakes, provided that proper site characterization and pressure management are carried out, thus remaining "a safe option to mitigate anthropogenic climate change" (2).

***Victor Vilarrasa***[a,b,1] ***and Jesus Carrera***[c]

[a]*Earth Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720;* [b]*Soil Mechanics Laboratory, School of Architecture, Civil and Environmental Engineering, Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland; and* [c]*Groundwater Hydrology Group (GHS UPC-CSIC), Institute of Environmental Assessment and Water Research, Spanish National Research Council, 08034 Barcelona, Spain*

1 Zoback MD, Gorelick SM (2015) To prevent earthquake triggering, pressure changes due to $CO_2$ injection need to be limited. *Proc Natl Acad Sci USA* 112:E4510.
2 Vilarrasa V, Carrera J (2015) Geologic carbon storage is unlikely to trigger large earthquakes and reactivate faults through which $CO_2$ could leak. *Proc Natl Acad Sci USA* 112(19):5938–5943.
3 Juanes R, Hager BH, Herzog HJ (2012) No geologic evidence that seismicity causes fault leakage that would render large-scale carbon capture and storage unsuccessful. *Proc Natl Acad Sci USA* 109(52):E3623–E3623, author reply E3624.
4 Vilarrasa V, Carrera J, Olivella S (2013) Hydromechanical characterization of $CO_2$ injection sites. *Int J Greenh Gas Control* 19:665–677.
5 Hidalgo JJ, Carrera J (2009) Effect of dispersion on the onset of convection during $CO_2$ sequestration. *J Fluid Mech* 640:441–452.
6 Birkholzer JT, Zhou Q (2009) Basin-scale hydrogeologic impacts of $CO_2$ storage: Capacity and regulatory implications. *Int J Greenh Gas Control* 3(6):745–756.

Author contributions: V.V. and J.C. wrote the paper.

The authors declare no conflict of interest.

[1]To whom correspondence should be addressed. Email: victor.vilarrasa@upc.edu.