LETTER

To prevent earthquake triggering, pressure changes due to CO_2 injection need to be limited

Vilarrasa and Carrera (1) dissent from our view (2) that pore pressure increases resulting from large-scale CO_2 injection could potentially trigger earthquakes that would threaten long-term CO_2 storage. Since our article appeared, the National Academy of Sciences (3) has expressed an even greater concern about large-scale carbon capture and storage (CCS), that "the large net volumes of injected fluids, may have potential for inducing larger seismic events."

Vilarrasa and Carrera (1) are not addressing the key issues we raised when they equate enhanced oil recovery projects with large-scale CCS. Unlike enhanced oil recovery, during large-scale, long-term CCS, huge injection remains unbalanced by similarly huge withdrawal of fluid. In addition, it is obvious that there are locations where relatively small quantities of CO_2 can be safely injected or where cap rocks are clay rich, ductile, and not fault-prone. However, as we stated in our report (2) "... the issue is not whether CO_2 can be safely stored at a given site; the issue is whether the capacity exists for sufficient volumes of CO_2 to be stored geologically for it to have the desired beneficial effect on climate change."

We agree with Vilarrasa and Carrera's (1) concern that injection-induced pressure increases in sedimentary rocks can cause earthquakes in underlying crystalline rock. Small pressure changes from saltwater disposal near Azle, Texas were recently reported to have triggered seismicity in both sedimentary rocks and underlying crystalline basement.

The stress measurements in Vilarrasa and Carrera's figure 1 (1) (presented without explanation or reference), neglect numerous sites where stress measurements in sedimentary rocks indicate that well-oriented faults are in frictional equilibrium, prone to pressure-induced slip. In other words, in many cases the stress magnitudes in sedimentary rock are indistinguishable from those the authors present for crystalline rock, with which we agree that pressure-induced earthquake triggering is a potential problem.

Vilarrasa and Carrera (1) also misrepresent the significance of earthquake occurrences in sedimentary rocks at In Salah, where CO_2 was injected into sedimentary rock. Choosing their words very carefully, Vilarrasa and Carrera state (1), "Even at In Salah, Algeria, where a huge overpressure was induced, no felt seismic event has been induced..." The issue is not whether there were felt seismic events. There were over 9,500 earthquakes triggered by CO_2 injection at In Salah, all apparently in sedimentary rocks (4).

Finally, Vilarrasa and Carrera (1) mention that solubility trapping can diminish pressure build-up. However, solubility trapping can be insignificant [at In Salah "only 0.03–0.1% of the injected CO_2 dissolves into the brine" (1)]. Even when dissolution occurs, hundreds of years after injection, 75% of the remaining injected CO_2 will still be pressurizing the storage formation (5).

Proposed large-scale CCS projects must evaluate all potential modes of failure that might occur over periods of hundreds of years. In recent years, pressure-induced faulting in both sedimentary and underlying crystalline rock has been occurring at a number of sites of large-scale saltwater injection in the central and eastern United States and other areas (3). Thus, the potential for triggered earthquakes represents one critical potential mode of failure that must be considered.

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2 Zoback MD, Gorelick SM (2012) Earthquake triggering and large-scale geologic storage of carbon dioxide. *Proc Natl Acad Sci USA* 109(26):10164–10168.
3 National Research Council (2013) *Induced Seismicity Potential in Energy Technologies* (National Academies Press, Washington, DC), 300 pp.
4 Stork A, Verdon JP, Kendall J-M (2015) The microseismic response at the In Salah carbon capture and storage (CCS) site. *Int J Greenh Gas Control* 32:159–171.
5 Metz B, Davidson O, De Coninck HC, Loos M, Meyer LA (2005) *IPCC, 2005: IPCC (Intergovernmental Panel on Climate Change) Special Report on Carbon Dioxide Capture and Storage* (Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge Univ Press, New York).

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