LETTER

Reply to Juanes et al.: Evidence that earthquake triggering could render long-term carbon storage unsuccessful in many regions

Juanes et al. (1) offer three specific arguments in response to our finding that "because even small to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories… large-scale [carbon capture and storage (CCS)] is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions" (2). We believe all three of their arguments are incorrect.

First, Juanes et al. (1) contend that, because most earthquakes in the Earth's crust occur at depths several kilometers greater than that proposed for CO_2 repositories, their occurrence is not an indication of the likelihood of faulting in response to injection-related pressure increases. The opposite is true. In just the past 2 y, moderate-sized earthquakes in Texas, Oklahoma, Arkansas, Colorado, and Ohio have been related to injection of relatively modest volumes of wastewater (2, 3) in similar geologic formations at similar 2- to 4-km depths as proposed for CO_2 repositories. The critical state of brittle formations throughout the crust is why one of the three major findings of the recent National Research Council report on induced seismicity potential in energy technologies was that "CCS, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events" (3). Triggered seismicity has been detected at several sites where small volumes of CO_2 have been injected into sedimentary rock at 2 to 4 km depth, including the In Salah field in Algeria. Seismicity triggered by fluid injection in brittle sedimentary rock at relatively shallow depths is a geophysical fact (3).

Second, Juanes et al. (1) argue that the existence of hydrocarbon reservoirs is prima facie evidence that buoyant fluids can be safely stored in the subsurface. However, pore pressure and stress evolve together in a hydrocarbon reservoir over long periods of time. When pore pressure increases too rapidly, it is relieved through faulting or hydraulic fracturing as a natural geologic process (4, 5). There are well-documented oil seeps along faults observed at the sea floor in the Gulf of Mexico (5) and the Santa Barbara channel in California (6). Recent press reports describe gas leaks along faults in the North Sea*, and operations in Bohai Bay, China, where fluid injection induced a fault slip event that caused oil to leak to the sea floor[†].

Finally, Juanes et al. (1) argue that site selection is the key to successful geologic storage of CO_2. As we originally noted (2), storage of CO_2 in limited volumes should be possible in geologic formations that are (*i*) porous, permeable, and laterally extensive to avoid significant pressure changes; and (*ii*) weakly cemented to avoid brittle formations that could release elastic energy through triggered earthquakes or aseismic fault slip events.

In summary, we agree that ideal geologic formations can be found for safe storage of limited volumes of CO_2 at depth. The purpose of our Perspective article (2) is to express reasons for concern about the widely held belief that CCS will be able to function at the extraordinary scale necessary for it to have a major impact on mitigating greenhouse gas emissions. There is ample evidence to suggest that triggered fault slip could render large-scale CO_2 storage unsuccessful.

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1. 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:E3623.
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 (2012) *Induced Seismicity Potential in Energy Technologies* (National Academy Press, Washington, DC).
4. Finkbeiner T, Zoback MD, Stump B, Flemings PB (2001) Stress, pore pressure and dynamically-constrained hydrocarbon column heights in the South Eugene Island 330 Field, Gulf of Mexico. *AAPG Bull* 85:1007–1031.
5. Seldon B, Flemings PB (2005) Reservoir pressure and seafloor venting: Predicting trap integrity in a Gulf of Mexico deepwater turbidite minibasin. *AAPG Bull* 89(2):193–209.
6. Lorenson TD, et al. (2009) *Natural Offshore Seepage and Related Tarball Accumulation on the California Coastline; Santa Barbara Channel and the Southern Santa Maria Basin; Source Identification and Inventory. US Geological Survey Open-File Report 2009-1225 and MMS Report 2009-030* (US Geological Survey, Reston, VA).

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*www.eco2-project.eu/newsarticles/items/north-sea-fracture-discovered.html.

[†]www.conocophillips.com.cn/EN/Response/Pages/default.aspx.

 www.pnas.org/cgi/doi/10.1073/pnas.1217264109