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The Risk of Induced Seismicity: Is Cap-Rock Integrity on Shaky Ground?

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A recent *Perspective* article in *PNAS*, as well as related testimony before the US Congress, has questioned the feasibility of large-scale geologic carbon dioxide sequestration (GCS) in North America. The first issue raised by Zoback and Gorelick [1] in the *Perspective* article with respect to the feasibility of GCS is that injection of large amounts of CO_2 into deep geologic formations will cause earthquakes (induced seismicity). The second issue is the assertion that these earthquakes will compromise the sealing capacity of cap rock, leading to the possibility of CO_2 leakage from the storage reservoir and back into the atmosphere.

In this editorial, I will briefly review these issues from my own perspective and suggest research directions that I believe should be pursued to address them.

First, regarding induced seismicity, it is well known that increasing pore pressure in geologic formations leads to induced seismicity. This effect can be understood through the Mohr-Coulomb theory, which adequately explains observations made over the last 50 years at a variety of liquid injection sites, oil and gas reservoirs, and even lakes created by dams. Earthquakes are measured on a logarithmic scale by very sensitive instruments (seismometers), and it is observed that the vast majority of induced seismicity consists of very small earthquakes that cannot be felt at the ground surface. Nevertheless, some induced earthquakes of magnitude 2.0 or higher will likely occur as a result of future large-scale GCS in the absence of mitigation or pressure management, and be felt at the ground surface. Experience with induced seismicity suggests that any earthquakes felt at the ground surface. Experience with induced seismicity suggests that any earthquakes felt at the ground surface, regardless of whether or not they cause damage, are serious concerns. But this concern is not primarily over leakage, but rather over public acceptance, owing to the discomfort, nuisance, and fear that accompany any felt earthquakes. A recent National Academy of Sciences report[2] provides a comprehensive overview of energy-technology-related induced seismicity.

Regarding the issue raised by Zoback and Gorelick[1] that induced seismicity will lead to compromise of cap rock integrity and potential leakage of CO_2, the authors rely on the study of Chen *et al.*[3] to motivate concern that small earthquakes can lead to compromise of cap rock integrity in GCS systems. However, using the Chen *et al.*[3] study, which was for *granitic* rock, to make assertions about the permeability of faults and fractures in *sedimentary* rock is questionable. In fact, as Zoback and Gorelick[1] describe, large-scale GCS sites are proposed for sedimentary basins where the cap rock is typically shale or mudstone rather than crystalline granite. Once fracturing and displacement occur along a rough fault or fracture in granite, the void space created by asperities tends to provide permeability to the fracture or fault. Given the crystalline texture of granitic rock, fractures in granite tend to provide essentially all the permeability there is in the rock. In contrast to crystalline rock, shales and mudstones are more plastic and ductile, and contain clay minerals that tend to deform and potentially fill in void space. Thus, when a fault in shale is reactivated, the smooth fracture or fault planes may not create much, if any, enhanced permeability, and what permeability that is created may not last long before fine-grained clay particles (e.g. fault gouge) fill in void space, and/or the openings close up. This latter aspect is one reason that the natural gas industry injects proppants into hydraulic fractures in shale: because the fractures would otherwise quickly close up following hydraulic fracturing. Furthermore, oil and gas reservoirs are often found in formations that are heavily faulted, and yet leakage is apparently negligible in these fault-trap reservoirs, as evidenced by the existence of hydrocarbons. In addition, the portions of faults potentially reactivated by injection of CO_2 may be much smaller than the thickness of the cap rock, meaning that even if permeability were enhanced in such faults, it would not necessarily lead to leakage through the entire thickness of the cap rock. Moreover, prospective geologic carbon sequestration sites often have multiple seals, so that if one is compromised, others will ensure storage integrity.

In short, induced seismicity is an issue for GCS that must be taken very seriously because of public concern about felt earthquakes. As for concerns about cap rock integrity related to induced seismicity, there is not sufficient evidence to conclude that induced seismicity and related reactivation of faults in shale or mudstone will compromise cap-rock integrity. There is clearly need for more work to expand the knowledge base beyond the Chen *et al.*[3] study, which is not directly applicable to GCS sites.

To address the main issues discussed by Zoback and Gorelick[1] in the context of the feasibility of GCS, research should be directed at

- Characterizing faulting and stress state at prospective GCS sites to understand the risk (likelihood and consequences) of induced seismicity.
- Developing approaches to maximize storage efficiency and manage pressure to mitigate induced seismicity risk in hydrologic systems subject to large-scale injection processes.
- Understanding fault and fracture permeability in shale and other sedimentary rock.

While we, as researchers in the GCS community, all have our own understanding and opinions on these issues, based on a wide variety of experience and published research, the points brought up by Zoback and Gorelick[1] are too important to debate on the basis of opinions or speculation in the venues of Perspectives or Editorials. Instead, these important issues deserve additional research in the areas mentioned and those suggested in the 2012 NAS report[2], as well as detailed, site-specific investigations, that will result in defensible peer-reviewed journal articles. We at GHGS&T encourage manuscript submissions covering these and other issues to bring additional light to the critical concerns facing GCS and the broader CCS endeavor.

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