Zoback and Gorelick PNAS 2012
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This article by Zoback and Gorelick (PNAS 2012, doi: 10.1073/pnas.1202473109) presents a well argued and fundamental challenge to be proposition that geological storage of CO_2 by deep injection of fluid can be an important technology against climate change.

The two authors are experienced and well respected senior professors at Stanford University, USA. The challenge certainly deserves to be heard, considered, and rebutted if possible by CCS proponents.

The argument falls into three categories:

1) The Earth's crust is critically stressed, so that earthquakes can be induced, or brought forward in time, by additional fluid pressure injection to temporarily tip the subsurface stress state beyond metastable equilibrium.

Comment: this is undoubtedly true, and has been demonstrated worldwide in many situations. It is very difficult to predict the size of induced earthquakes, and especially their timing. Seismic monitoring equipment can be placed at the surface to listen for minute responses of tiny earth tremors, which grow in intensity, and become more closely spaced in time, before larger earthquakes. However, if this is chosen, such equipment will need to be deployed not just above the physical location of CO_2 injected, but also across many tens of kilometres radius of the pressure plume spreading in the subsurface away from the injection site, and lasting for about 50 years.

2) Radius of influence is very large and unmanageable

Comment: The radius of physical CO_2 is small for each site 5 to 20km. The radius of pressure increase, potentially driving earthquakes is much larger, perhaps 50 or even 100km. So earthquakes coinciding with the physical CO_2 are possible but not probable. The pressure radius could be managed by producing formation water, or oil, to create space for CO_2. In the short term, oil production is the most likely balancing mechanism, especially in the USA. Water balancing would require large volumes of water to be cleaned and disposed at the surface. Alternatively, injection offshore is viable for CO_2 storage, and any consequent earthquakes will not be felt by onshore residents. Monitoring can detect any CO_2 leakage. Dissolution of CO_2 into formation water will progressively reduce any possibility of leakage, so that after about 50 years the pressure pulse has declined and earthquake risk has decreased to pre-existing levels.

3) If earthquakes are induced, these will form open fracture pathways by which the injected CO_2 will leak to the earth's surface, negating the purpose of storage.

Comment: an important question here is, when will new earthquakes occur, and how much CO_2 will leak? The implication in Zoback is that any fracture will enable leakage of all injected CO_2. This is extremely unlikely to occur, for three reasons:

i) the new fault needs to intersect the physical seal above separate fluid CO_2, Thus the new faulting has to occur within the radius of physical CO_2 trapping. This is only very few kilometres or tens of kilometres. This should be solvable by high quality site selection, based on prior knowledge, measurements made remotely from surface, and direct measurements of stress in subsurface boreholes. It may also be possible to engineer around the problem by drilling boreholes in advance of large earthquakes.

ii) even if some fluid CO_2 leaks through a fracture, this will be a localized leak, easily identifiable from the earthquake epicenter, and so can be remediated – for example by drilling and cementing, as with oil-well blowouts. The possible rate of leakage upwards along faults is known from natural examples in Colorado or Italy. These rates are typically 10 tonnes CO_2 per day – so leaving ample time of many years for detection and remediation.

iii) More than 60% of CO_2 injected is not recoverable, because of residual saturation effects. These are where tiny bubbles of liquid CO_2 are retained within individual microscopic pores, across many tens of kilometres. These small individual bubbles are not mobile. This is like a damp sponge, some mobile water can be squeezed out of the pores, but a lot remains within and around tiny pores, and cannot be moved. In addition, injected CO_2 gradually dissolves in the subsurface, to form salty sparkling carbonated water. This takes decades to hundreds of years, and dissolved CO_2 is immobile, so CO_2 retension increases with time after injection.

So in summary
1) There is risk of inducing earthquakes by CO_2 injection. This can be reduced and managed by drilling technologies, but is unlikely to be eliminated from any CCS project .

2) New open flow faults or fractures could form, some of these could enable leakage of CO_2. But these faults are very unlikely to be at the storage structure crest where CO_2 would leak.

3) Very little CO_2 can leak out, due to residual saturation effects – like a damp sponge. Dissolution of CO_2 into subsurface water means that CO_2 will not leak. Pressure dissipation, by leakage into surrounding rocks, will reduce the driver for earthquakes to background levels within about 50 years

4) An easy place to start CO_2 injection is in depleted oil or gas fields, where the pressure is below the natural level due to hydrocarbon extraction. These can be developed into saline formation storage sites as learning progresses, and consequently enable progressive learning to reduce adverse consequences.