

## Carbon sequestration and natural analogs

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Anthropogenic emission of carbon into the atmosphere has caused an imbalance of the global carbon cycle (Broecker et al. 1979; Sundquist, 1993). Ancient geologically stored carbon has been released primarily as CO<sub>2</sub> during fossil fuel combustion, and is building up in the atmosphere because the sinks of carbon (soils, plants, oceans) cannot keep up with the pace of emission (Raynaud et al., 1993). As a result, the atmospheric carbon burden has been overloaded, and is changing the Earth's surface through changes in global temperature, atmospheric and oceanic circulation, weather patterns, storm severity, global vegetation profiles, and atmospheric, land, and ocean chemistry (McClintock et al. 2009; Nema et al., 2012; Walsh et al., 2012).

A proposed solution to this problem is to pump anthropogenic CO<sub>2</sub> back into deep geologic formations—basically, to return this ancient carbon back to where it originated (Furnival, 2006; Jones, 2006). One proposed solution is to collect the CO<sub>2</sub> at the stacks of coal-fired power plants and cement plants, purify the CO<sub>2</sub>, compress it to supercritical densities, then pump this CO<sub>2</sub> down deep wells into geologic formations (Engelburg and Blok, 1993; Notz et al., 2011). The U.S. Department of Energy has invested billions of dollars over the past 8 yr to determine if this type of approach could help stop the atmospheric CO<sub>2</sub> increase (Litynski et al., 2009). Specific research has focused on separation and purification technologies to isolate CO<sub>2</sub> from coal-fired power plants, engineering optimization strategies of how best to move this CO<sub>2</sub> to a geologic storage site, understanding the storage capacity of different geologic reservoir types, optimizing well designs, monitoring the fate and transportation of CO<sub>2</sub> in storage reservoirs, and assessing the risk of storage failure at many different scales within a geologic reservoir (Eiken et al., 2011; Jensen et al., 2011; Koornneef et al., 2012).

Natural analogs, geologic formations where CO<sub>2</sub> naturally occurs as either stored (e.g., trapped under a seal) or escaping (e.g., geyser) gas, are good research opportunities to understand how CO<sub>2</sub> behaves in natural settings, or how CO<sub>2</sub> might behave in an engineered storage site over time. Research topics such as equilibrium CO<sub>2</sub>-reservoir interactions, kinetic surface-chemistry changes, monitoring optimization, risk assessment, and groundwater impacts are examples of areas of research where natural analogs have been useful for carbon capture and storage (CCS) missions (Keating et al., 2010; Pearce et al., 2011).

One area of active research where natural analogs have been used is the tracking of CO<sub>2</sub>-rich brine water movement through varying geologic settings, and understanding how this acidic water impacts the local mineralogy and chemistry (Pauwels et al., 2007; Lu et al., 2011). The CO<sub>2</sub>-brine fluid has been shown to mobilize trace metals, change the major and minor ion chemistry, and change the isotopic composition of the solution and sediments that the fluid is moving through (Rempel et al., 2011). The chemical signatures of the CO<sub>2</sub>-brine fluid as it is sampled through a reservoir can give information about the source of this fluid (depth, origin), the impact of the fluid on the regional sediments (metal leaching), and the lifetime of the channel openings (timing of fracture cementation) (Lowenstern et al., 1999; Nightingale et al., 2009; Eke et al., 2011).

Wigley et al. (2012, p. 555 in this issue of *Geology*) use chemistry signatures to interpret the origin and impact of CO<sub>2</sub>-brine solutions in a natural CO<sub>2</sub> reservoir along the Green River anticline in Utah (United States). Their work highlights the chemical transformations that are occur-

ring in the hematite-rich sandstones within the Green River anticline as the CO<sub>2</sub>-rich brine moves through the sediments. The trace-metal leaching of the sediments is best observed at the reaction front. The stable isotope and elemental composition of the fluids and the mineralogical analysis of the sediments show that the Green River natural analog is distinct from other hydrocarbon-bleaching locations along the Colorado Plateau. Wigley et al. use their findings as an example of how chemical signatures of fluids and sediments can show the nature and origin of CO<sub>2</sub>-brine movement, and geologic impacts. The significance of Wigley et al.'s findings is that carbonate re-precipitation and formation was observed in red sandstone. This shows that hematite-rich sandstones could effectively be used as engineered CO<sub>2</sub> storage sites, because fracture systems could cement over time due to this carbonate formation.

Wigley et al.'s work is an excellent example of a current trend of research where natural analogs are more commonly being used as model systems to best understand how CCS reservoirs will behave over time. At the onset of CCS research efforts in the late 1990's and early 2000's, there was public concern about the stability of CO<sub>2</sub> sequestration, and how CO<sub>2</sub> may impact local resources and public health (Van Alphen et al., 2007; Miller et al., 2008; Stephens et al., 2009). During the mid to late 2000's, CO<sub>2</sub> storage pilot studies and larger demonstration studies showed safe permanent storage of CO<sub>2</sub> pumped into sequestration sites (Sohrabi et al., 2011; Whittaker et al., 2011). This, along with outreach efforts performed by the CCS community, allowed the public to become more at ease with CCS as a viable option to greenhouse-gas emission control (Daly et al., 2011). As a result, the study of natural analogs has come into favor as a model to explore CO<sub>2</sub> impacts to local geology, groundwater, infrastructure, and surface systems (Pearce, 2006). These natural analogue studies have provided decision makers with a model system of how best to decide upon risk assessment, monitoring, mitigation, and verification approaches for CCS sites.

In summary, the use of natural analogs for the understanding and assessment of CO<sub>2</sub> sequestration permanence is critical if engineered storage reservoirs will be accepted worldwide. The natural analogs provide an example of CO<sub>2</sub> storage over thousands of years. The interaction of the CO<sub>2</sub> with the natural environment (e.g., the storage reservoir, the groundwater) is typically in an equilibrium state, and monitoring the chemistry of the reservoir and intermediate liquid layers can provide insight into how engineered storage reservoirs will behave with time. The study presented by Wigley et al. shows such an example of a natural analog site, and how the site chemistry can be used to understand the origin of the CO<sub>2</sub>, the reservoir-CO<sub>2</sub>-brine interaction, and the reaction front behavior with time. This study provides a perfect example of how natural analogs can be used for CCS research on reservoir performance, monitoring optimization, risk assessment, and mitigation.

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