Carbon Storage in Basalt

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The advantage of unsupervised learning is that one does not require training examples (usually human-curated), which can be time consuming to generate and may be subject to human bias or error. Instead, such algorithms find inherent structures or clusters in the data, which can be interpreted as meaningful (e.g., distinct behavioral states). A potential disadvantage is that although such learning algorithms do not have human bias, they necessarily contain bias in their underlying assumptions and parameters. Vogelstein *et al.* carefully validated their analysis post-hoc, finding several identifiable behaviors including turning, escaping, and backing up.

Interestingly, repeated stimulation of the same neurons on different trials did not always elicit the same behavior. For example, in single animals, the activation of a neuron produced "left-right-avoid" in some trials and "straight escape" behaviors in others. Similarly, an identified neuron-behavior relation did not always hold between animals. Specific neurons sometimes evoked turning whereas in other animals they evoked reversal of motion. In general, the relationships between neural activation and

behavior were best characterized as probabilistic rather than deterministic. Aside from noise, two generic features of nervous systems can explain this. One aspect is that the effect of an input, or activation of a neuron or circuit, is often state-dependent—in other words, what the rest of the circuit is doing can determine the effect of a repeated activity perturbation in a subset of neurons. The other feature is that all nervous systems—even those with genetically identifiable neurons—are unique to each individual due to phenotypic variability and environmental fluctuations.

One limitation of the approach taken by Vogelstein *et al.* is that strong, stereotyped stimulation of single neurons is not likely to mimic in vivo activity patterns, nor does it capture the coordinated activation of multiple neurons and the relative strengths and timings of their activation. As a consequence, the data in this study provide a fabulous starting point for understanding which neurons are likely to participate in the circuits for one or many behaviors. But truly understanding how these circuits work will require the marriage of these new approaches with a wiring diagram, or so-called "connectome" (7), as

well as characterizing relevant physiological properties of the neurons themselves. This will then allow the manipulation of multiple circuit elements to test specific ideas about how these circuits work.

Vogelstein *et al.* have thus achieved a technical, multidisciplinary tour de force that will provide a rich source of research questions. The next big challenge is developing coherent theory to make sense of the data. Machine learning and computational models are likely to be important in this endeavor, pointing to a growing and intriguing symbiosis between computational and experimental neuroscience, both for data analysis and theory development.

References
1. C. A. Wiersma, K. Ikeda, *Comp. Biochem. Physiol.* **12**, 509 (1964).
2. I. Kupfermann, K. R. Weiss, *Behav. Brain Sci.* **1**, 3 (1978).
3. E. Marder, R. L. Calabrese, *Physiol. Rev.* **76**, 687 (1996).
4. J. T. Vogelstein *et al.*, *Science* **344**, 386 (2014); 10.1126/science.1250298
5. B. D. Pfeiffer *et al.*, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 9715 (2008).
6. A. Fiala, A. Suska, O. M. Schlüter, *Curr. Biol.* **20**, R897 (2010).
7. C. I. Bargmann, E. Marder, *Nat. Methods* **10**, 483 (2013).

GEOCHEMISTRY

Carbon Storage in Basalt

Field projects are beginning to demonstrate the potential for carbon storage in basaltic rocks.

Sigurdur R. Gislason[1] and Eric H. Oelkers[2,3]

All the carbon in the atmosphere, living creatures, and dissolved in the oceans is derived from rocks and will eventually end up in rocks, the largest carbon reservoir on Earth. The carbon moves from one reservoir to another in what is called the carbon cycle (1). Humans have accelerated this cycle by mining and burning fossil fuel since the beginning of the industrial revolution, causing rising atmospheric carbon dioxide (CO_2) concentrations that are the main cause of global warming. One option for mitigating high levels of global warming is to capture CO_2 and safely store it for thousands of years or longer in subsurface rocks. By accelerating carbonate mineral formation in these rocks, it is possible to

rebalance the global carbon cycle, providing a long-term carbon storage solution. However, this approach is both technically challenging and economically expensive.

Most subsurface carbon storage projects to date have injected CO_2 into large sedimentary basins. Perhaps the best known of these projects is that at Sleipner, west of Norway, where about 1 million metric tons of CO_2 have been injected annually since 1996 and stored more than 700 m below the ocean floor in the Utsira sandstone. However, the transformation of CO_2 to carbonate minerals in such systems, referred to as mineral trapping, takes tens of thousands of years, if it occurs at all (see the figure, panel A) (2). This limitation results from both the low reactivity of silicate minerals in sedimentary rocks and a lack of the calcium, magnesium, and iron required to make carbonate minerals.
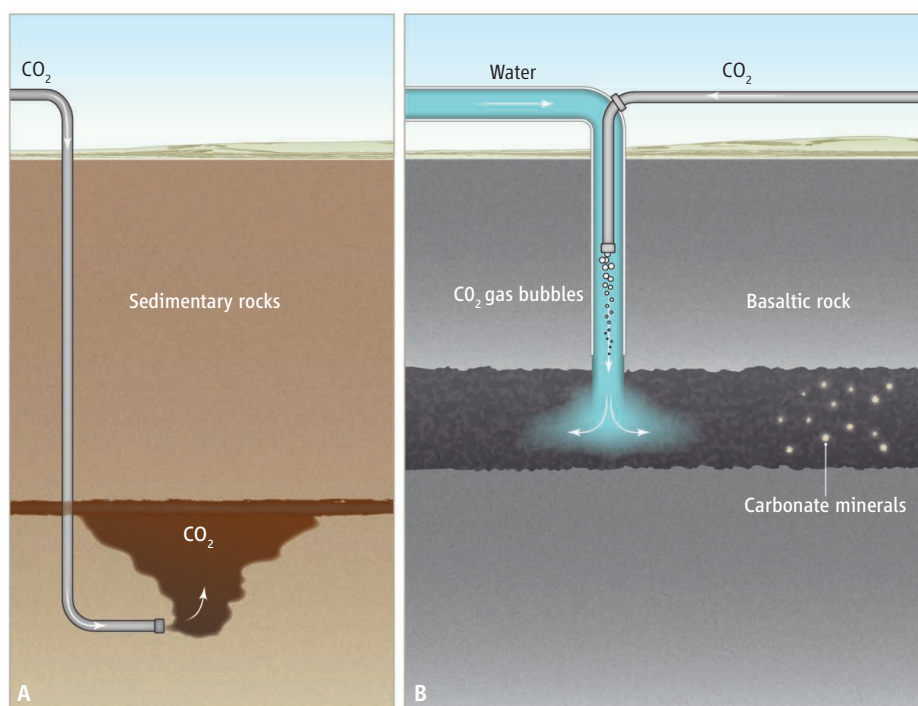
An alternative, designed to overcome these limitations, is the injection of CO_2 into

reactive basaltic rocks. This approach has several advantages. Basalt contains about 25% by weight of calcium, magnesium, and iron oxides (3). Basaltic rocks are also far more reactive in water than are sedimentary silicate rocks, and the metals contained in basalts are therefore readily available to combine with injected CO_2 to form carbonate minerals (3–5). And basaltic rocks are abundant on Earth's surface; ~10% of the continents and much of the ocean floor is composed of basalt (4, 6). Basalt carbonation could therefore become an important carbon storage solution. However, one challenge to storing carbon in both sedimentary and basaltic rocks is the buoyancy of CO_2, which could cause it to rise toward Earth's surface through pores and fractures, eventually escaping back to the atmosphere.

Two ongoing field injection projects are assessing the feasibility of carbon storage in basalts: the CarbFix project in southwest Iceland (4, 7), where carbon injection started

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Carbon storage in sedimentary basins and basaltic rocks. (**A**) Carbon storage in sedimentary basins proceeds via the injection of pure CO_2 into porous sedimentary rocks. Ideally this CO_2 is trapped below an impermeable cap rock. Eventually some of this CO_2 becomes stuck in small pores, limiting its mobility (structural and residual trapping) (*15*). Over time, CO_2 dissolves in the formation water (solubility trapping). Some of this dissolved CO_2 reacts to form stable carbonate minerals (mineral trapping). As one progresses from structural to mineral trapping, the CO_2 becomes more immobile and thus the storage more secure, though this process can take thousands of years or more (*15*). (**B**) In the CarbFix method, CO_2 is dissolved into water during its injection into porous basaltic rocks. No cap rock is required because the dissolved CO_2 is not buoyant and does not migrate back to the surface. Solubility trapping occurs immediately, and the bulk of the carbon is trapped in minerals within 1 year (*10*, *11*).

in January 2012, and the Big Sky Carbon Sequestration Partnership (BSCP) in the northwest United States near Wallula, Washington, where injection started in July 2013 (*8*, *9*). A major difference between these two projects is the method through which the CO_2 is injected. In the BSCP project, pure CO_2 is injected as a separate buoyant phase into a porous basaltic layer at more than 800-m depth; it is anticipated that the presence of an impermeable layer will keep the CO_2 from escaping back to the surface. In the CarbFix project, CO_2 is released as small bubbles at 350-m depth into down-flowing water within the injection well. The CO_2 bubbles dissolve in the water before it enters the rock. Once dissolved in water, CO_2 is no longer buoyant, and the CO_2-charged water accelerates metal release from basalt and formation of solid carbonate minerals. Once stored as a mineral, the CO_2 is immobilized for geological time scales. More than 80% of CO_2 injected into the CarbFix injection site was carbonated within a year at 20° to 50°C and 500- to 800-m depth [(*10, 11*); see the figure, panel B]. This result suggests that the

CarbFix method can change the time scale of mineral carbon trapping considerably.

The CarbFix method requires substantial water; only 5% of the injected mass is CO_2. Porous basalts near the continental margins have huge storage capacities adjacent to nearly unlimited supplies of seawater. On the continents, the water present in the target storage formation can be pumped up and used to dissolve CO_2 during the injection. Although the pumping of water from the subsurface may increase costs, water pumping is also necessary during the later stages of pure CO_2 injection into sedimentary basins, when a large portion of the pore space has been filled with CO_2.

A major challenge to all carbon capture and storage projects is the cost. The estimated cost of storing and transporting a ton of CO_2 at maximum reservoir exploitation at the CarbFix site via dissolved water injection is about $17 (*12*); this cost is about twice that of geologic storage via direct CO_2 injection at the BSCP site and in typical sedimentary basins (*9, 12, 13*), but offers enhanced security because CO_2 dissolved in

water is not buoyant. However, the cost of carbon capture and storage is dominated by capture and gas separation, which costs $55 to $112/ton CO_2 (*13*). In contrast, the current price for a ton of CO_2 emission at the European Union Emission Trading Scheme, the world's largest carbon market, is about $7/ton CO_2. Until either market forces or taxes result in a higher price on carbon emission, there is no financial incentive for carbon capture and storage using any of these technologies.

Carbon storage via basaltic rock carbonation is still in its infancy, but if it can be scaled up, it may provide a more secure alternative to the injection of pure CO_2 into sedimentary basins. Natural analogs have shown that up to 70 kg of CO_2 can be stored in a cubic meter of basaltic rock (*14*). This means that the storage potential of all the ocean ridges is an order of magnitude larger than the estimated CO_2 emissions stemming from burning all fossil fuel resources on Earth. How much of this storage potential will be of practical use in the future may depend more on political will and economic realities than on scientific efforts.

References and Notes
1. D. Archer, *J. Geophys. Res.* **110**, C09S05 (2005).
2. S. M. V. Gilfillan *et al.*, *Nature* **458**, 614 (2009).
3. T. Schaef, B. P. McGrail, A. T. Owen, *Int. J. Greenh. Gas Control* **4**, 249 (2010).
4. S. R. Gislason *et al.*, *Int. J. Greenh. Gas Control* **4**, 537 (2010).
5. R. J. Rosenbauer, B. Thomas, J. L. Bischoff, J. Palandri, *Geochim. Cosmochim. Acta* **89**, 116 (2012).
6. D. S. Goldberg, T. Takahashi, A. L. Slagle, *Proc. Natl. Acad. Sci. U.S.A.* **105**, 9920 (2008).
7. E. S. Aradóttir, E. Sonnenthal, G. Bjornsson, H. Jonsson, *Int. J. Greenh. Gas Control* **9**, 24 (2012).
8. B. P. McGrail, F. A. Spane, E. C. Sullivan, D. H. Bacon, G. Hund, *Energy Procedia* **4**, 5653 (2011).
9. B. P. McGrail *et al.*, *Int. J. Greenh. Gas Control* **9**, 91 (2012).
10. S. R. Gislason *et al.*, *Min. Mag. (Lond.)* **77**, 1178 (2013).
11. J. M. Matter *et al.*, American Geophysical Union Fall Meeting, abstract V41A-2753 (2013).
12. E. Ragnheidardottir, H. Sigurdardottir, H. Kristjansdottir, W. Harvey, *Int. J. Greenh. Gas Control* **5**, 1065 (2011).
13. Global CCS Institute, Economic Assessment of Carbon Capture and Storage Technologies: 2011 Update; see www.globalccsinstitute.com/publications/economic-assessment-carbon-capture-and-storage-technologies-2011-update (2011).
14. F. Wiese, Th. Fridriksson, H. Ármannsson, *Tech. Rep., ÍSOR-2008/003*, Iceland Geosurvey, www.os.is/gogn/Skyrslur/ISOR-2008/ISOR-2008-003.pdf (2008).
15. S. Benson *et al.*, in *IPCC Special Report on Carbon Dioxide Capture and Storage,* B. Metz, O. Davidson, H. Coninck, M. Loos, L. Meyer, Eds. (Cambridge Univ. Press, New York, 2005), pp. 195–276.