events. However, in the less extreme settings, incision rates of 8–18 mm yr$^{-1}$ would need to be maintained over 10,000 years to erode the several hundred metres of relief observed in some gorges.

Notably, Montgomery and Korup argue that if postglacial fluvial incision was powerful enough to form gorges, glacial erosion would need to be just as effective to eradicate the gorges formed during the previous interglacial period. Repeated incision and glacial eradication of this magnitude over several glacial–interglacial periods would result in the erosion of more than 10 km of upper crust during the past one million years. Such a large removal of crust is in conflict with the much lower rates of exhumation measured for the region$^{10}$.

If the gorges were indeed preserved throughout successive glaciations, they would need to be protected from glacial erosion. Most gorges were at one time filled with extensive deposits of sediment$^{24}$, which could have helped to preserve those cut into weak types of rocks. The presence of sediment remnants within them points to periods during which river sediments were building up in already carved gorges, and then were removed as rivers eroded down again, which, incidentally, would require even higher rates of erosion in the gorges than the estimates Montgomery and Korup dismiss. But the suggestion that gorges are preserved and carved throughout successive glacial–interglacial cycles relies on the assumption that gorge topography must have been similar throughout all interglacial periods. This argument is based on the uniformity of processes, rates and conditions during successive glacial periods. But gorge topography might be unique to the most recent postglacial periods.

Glacial periods have become increasingly more severe and prolonged since about 700,000 years ago. Perhaps previous periods with less ice cover, meltwater and glacial sediments resulted in minor or insignificant gorge incision, and only the more recent and largest glaciations led to an environment that strongly enhanced incision when the ice retreated. In this situation, the total erosion from all the Quaternary glacial–interglacial periods would not be as excessive as 10 km, and therefore need not exceed the rate of long-term exhumation set by thermochronometric constraints. The model of long-term gorge formation is not, however, meant to be a universal model for all inner gorges worldwide. Even the inner Alpine gorges have a range of morphologic expression and relief, and no single process could be evoked for their formation. Regardless, Montgomery and Korup$^{4}$ present a compelling argument for the persistence of gorges during numerous glaciations in the Alps, with the exciting corollary that fluvial incision must outpace glacial erosion of the valley floors across several glacial periods.

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References

Oceanography

Carbon cycle at depth

The existence of a microbial community in the ocean crust has long been hypothesized. Isotopic evidence indicates that a deep biosphere of microbes both scrubs oceanic fluids of organic matter and produces new, yet old, organic carbon in situ.

Katrina J. Edwards

I n the 1980s hit song Once in a Lifetime, David Byrne sings about water flowing underground: “water dissolving and water removing. There is water at the bottom of the ocean...there is water under the water.” It turns out that Byrne got it about right. In recent decades we have learnt that the Earth’s largest aquifer system resides below the ocean in the pore spaces of basalt, the volcanic rock that makes up most of the ocean crust. Amazingly, the volume equivalent of the world’s ocean basins circulates through this aquifer about once every 70,000 years$^1$. This subseaﬂoor aquifer is thought to host diverse communities of bacteria and archaea. However, difficulty in sampling the deep ocean, let alone the underlying crust, has precluded characterization of this potentially extensive biosphere. Furthermore, in some heavily sedimented
regions of the ocean crust, gas hydrates serve as a habitat for methane-consuming microbes. Two papers in Nature Geoscience propose that microbes living in these two highly different ocean crust environments serve as a source of ancient dissolved organic carbon to the deep ocean.

Analyses of basalt cores from beneath the seafloor were used to reveal the presence of peculiar textural features — channels and pits — that were hypothesized to be produced during microbial alteration of the rock. Molecular studies suggest that diverse bacteria and archaea reside in basaltic mid-ocean-ridge flanks. And thermodynamic and bioenergetic calculations, based on the energy released during water–rock reactions, suggest that basaltic-ridge flanks could support the growth of lithoautotrophs — microbes that obtain energy through the oxidation of inorganic compounds. However, it has proved difficult to verify the proposed microbial processes taking place in the oceanic crust, and to assess their magnitude and implications, because of the difficulties associated with sampling active hydrothermal rock for scientific analysis. Recently drilled bore-holes in the ocean crust could help to resolve the uncertainty, by providing rare and unprecedented access to the rocky crustal realm.

McCarthy and colleagues provide support for the existence of a subsurface biosphere in the oceanic crust, using measurements of the stable carbon isotope composition of dissolved organic carbon in fluids venting from a bore-hole at a ridge-flank hydrothermal system off the Juan de Fuca spreading centre in the Pacific Northwest. They show that the stable isotopic composition of dissolved organic carbon in vent fluids is depleted relative to sea water, and falls within the range known for carbon dioxide fixing chemosynthetic microbes — microorganisms that obtain energy from the oxidation of both organic and inorganic compounds. Radiocarbon isotope measurements were also made to determine the age of the dissolved organic carbon. Values matched those of ancient dissolved inorganic carbon — 11,800–14,400 years before present — implying that chemosynthetic microbes synthesize dissolved organic carbon from aging fluids that travel through the crustal aquifer.

The findings suggest that dissolved organic carbon that flows from ocean basins into the crust is effectively scrubbed from sea water during its voyage. The implications of these findings could be quite staggering — suggesting that the subseafloor biosphere is sufficiently large to support significant in situ primary production and the export of old dissolved organic carbon to the deep ocean. This could have ramifications for the global carbon cycle and the composition and source of dissolved organic matter in the ocean.

Whether chemosynthetic activity in ridge flanks have typically focused on open, oxic, low-temperature environments, and have shown that bacteria might contribute to the weathering of rock in these settings. McCarthy and colleagues extend the presence of chemosynthetic production to the more unusual conditions in Juan de Fuca ridge.

Old carbon in the deep ocean is also in the spotlight in a very different deep-sea habitat — gas-bearing methane hydrate seeps off Vancouver Island. They found that dissolved organic carbon in the deep sea was considerably aged compared with most mid-ocean ridges.

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Old carbon in the deep ocean is also in the spotlight in a very different deep-sea habitat — gas-bearing methane hydrate seeps, about 100 km northeast of the Juan de Fuca ridge flank. Pohlman and colleagues suggest that aged methane-derived carbon may contribute to the dissolved organic carbon pool in the deep ocean. They embarked on a stable- and radiocarbon-isotope study of dissolved organic carbon in the bottom water overlaying methane hydrate seeps off Vancouver Island. They found that dissolved organic carbon in the deep sea was considerably aged compared with background dissolved organic carbon in the sea water, and depleted in 13C. The authors attribute the source of this unique isotopic signal to biological degradation of local fossil methane. Mass balance calculations support the suggestion that the global flux of methane-derived dissolved organic matter to the deep ocean may be significant. However, some caution is advised, as the size of gas hydrate reservoirs and their susceptibility to biodegradation is unknown.

The findings presented in these two papers shed new light on the ocean
carbon cycle, and the sources and sinks of the elusive dissolved organic matter pool in the deep ocean. Both call into question the canonical view of dissolved organic matter production in the world’s oceans, which asserts that most dissolved organic matter is sourced from photosynthetic fixation of modern carbon in the upper water column. Clearly, further studies are needed to understand the production and flux of chemosynthetically derived dissolved organic carbon in ridge flanks, and methane-derived dissolved organic carbon from seeps, to explain how biogeochemical cycles of carbon in the deep ocean are coupled.

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References

VOLCANOLOGY

Carbon below the sea floor

Magma from the mantle meets the ocean at seafloor spreading centres. At young rifts, basalt sills may heat overlying sediments and induce natural carbon release; basalt flows elsewhere may offer secure reservoirs for sequestration of anthropogenic carbon.

David Goldberg

Where tectonic plates drift apart, magma moves upwards from the lithosphere towards the overlying ocean. At typical spreading plate boundaries, the resulting volcanic outpourings can be observed as pillow lavas and as sheet flows onto the sea floor. In the absence of significant amounts of sediments on the sea floor, these formations allow sea water to circulate through, which can cool them for extended periods of time. These volcanic outpourings generally occur within only about five kilometres of the location of spreading. However, in young and narrow ocean basins, thick loads of sediment rain down from nearby land sources. There, the volcanic zone is often heavily blanketed and magma outflows tend to be injected into the sedimentary layers in the form of sills below the sea floor. Writing in *Nature Geoscience*, Lizarralde and colleagues describe their investigation of one young spreading system, the Guaymas basin in the Gulf of California, where they have found shallow magmatism distributed over a much wider area than expected.

Sills derived from intrusive volcanism in sedimentary basins have been linked to huge natural methane fluxes in the past. Examples include sill emplacement at the Karoo basin, South Africa, 183 million years ago and at the Norwegian margin 55 million years ago, which may have generated substantial shifts in global climate. Because thick sediments in these basins limit cooling by sea water through hydrothermal circulation, the hot sills raise the temperature of the overlying organic-rich sediments and thermally alter them. As a result, these volcanic intrusions produce as much as ten times more carbon dioxide and methane gas than the equivalent volume of volcanic rocks outpouring onto unsedimented sea floor. The buoyancy of these hydrocarbon gases forces them upwards through the overlying sediments and into the ocean, increasing temperatures and stimulating biological

Figure 1 Basalt flow dated to about 200 million years ago, in the Central Atlantic Magmatic Province located in Virginia, USA. Lizarralde and colleagues show that basalt intrusions in young, sedimented seafloor spreading centres vent carbon to the ocean. Ancient basalt flows may have contributed initially to the global carbon budget, but may in the future provide an advantageous carbon-sequestration option. Photo courtesy of Paul E. Olsen, Columbia University.