

observational data, Miralles and colleagues³ suggest that, at least at northern mid-latitudes, temperatures exceeding 40 °C are only possible if dry soils, heat inflow from warmer regions and the accumulation of heat over several days occur in concert. This implies that heatwaves that start with a rapid 10–15 °C temperature rise — reaching more than 40 °C within a day, as observed in places such as Melbourne, Australia — are not expected in the areas where the mega-heatwaves occurred. Such sudden temperature jumps result primarily from advection of hot air rather than a local build-up of heat over several days.

The improved understanding of heatwaves enables us to scrutinize weather and climate models used for predicting heatwaves and estimating human contributions to their frequency as the climate warms. If the world warms, for example, by 2 °C, we would not expect every day to be 2 °C warmer. Climate models project that for some regions temperature increases on the hottest days may be substantially higher than the mean warming^{2,9} (Fig. 1), depending on which model is employed. The amplified warming of hot days partly results from feedback mechanisms, such as those highlighted by Miralles and colleagues³. However, models are known to have limitations in representing some of the key heatwave-generating processes, including the frequency and persistence of atmospheric blocking, variability of soil moisture and soil moisture feedbacks with precipitation¹⁰. Thus, it is

important to understand whether heatwaves in models occur for the same reasons they occur in nature. Ultimately, our confidence in the prediction of future climate does not come from more models or faster computers to run them, but from understanding the relevant processes and reliably representing them in models.

Anthropogenic warming has more than doubled the risk of mega-heatwaves such as those of 2003 and 2010^{11,12}. If the variability in weather is like rolling a die, anthropogenic influence has loaded the die and increased the odds for rolling a six, a mega-heatwave. But should we expect future events that are more intense than those possible in today's climate — the equivalent of rolling a seven or even an eight on the weather die? There is a limit to the scorching heat during mega-heatwaves: we do not expect temperatures to reach 70 °C or more, even in a bone-dry desert under clear skies. There are physical constraints on maximum temperatures at the Earth's surface, simply based on the length of the day and the season. The observational record is too short — and will remain so for a long time — to tell us what is possible. The only way to identify the bounds on extreme temperatures, and understand how they are affected by climate change, is to employ physical models that incorporate what we know from observations, and that reliably describe all relevant physical processes.

Miralles *et al.*³ reveal that the progressive build-up of heat in the atmospheric boundary

layer helped hot weather in Europe in 2003 and Russia in 2010 escalate into mega-heatwaves. We have been surprised again and again by the extreme heatwave, rainfall and windstorm events that nature has thrown at us. There is much we do not yet understand about present-day weather and climate, let alone how they will change in the future. Thus, dissecting the underlying processes is crucial so that we will be better prepared for when the next surprise record-breaking event hits. □

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A piece of the deep carbon puzzle

Carbon loss from subducting slabs is thought to be insufficient to balance carbon dioxide emissions at arc volcanoes. Analyses of ancient subducted rocks in Greece suggest that fluid dissolution of slab carbonate can help solve this carbon-cycle conundrum.

Craig E. Manning

The carbon cycle in Earth's near-surface reservoirs — the atmosphere, oceans, biosphere and sedimentary rocks — has received widespread attention^{1,2}. Yet there is another carbon cycle that operates on the planetary scale: carbon is buried in the mantle where one tectonic plate slides under another, and it returns to the surface from the deep Earth, mainly through volcanism³. The mass of carbon involved in the familiar, shallow cycle merely reflects the balance between the two principal transfers of this deep carbon cycle. In essence, the carbon that is so essential to life and modern society is available to us

only with the permission of the deep Earth⁴. The deep carbon budget is poorly constrained, however, largely because the mechanisms for transferring carbon from subducting slabs to arc volcanoes are unclear. Ague and Nicolescu⁵ now suggest in *Nature Geoscience* that significant amounts of carbonate minerals are dissolved from subducting slabs by infiltrating fluids, aiding the transfer of carbon back to Earth's surface.

Carbon-bearing minerals in sediments and oceanic lithosphere are carried into the Earth by subduction^{6–8}. Conversely, magmas erupted at volcanoes above subduction zones

contain carbon, which is mainly degassed to the atmosphere as carbon dioxide during crystallization or eruption of the magma⁹. The mantle beneath arcs contains only small amounts of carbon¹⁰, so much of the carbon that is emitted by these volcanoes must come from the subducting slab. The transfer of carbon during subduction therefore lies at the heart of any attempt to constrain Earth's deep carbon cycle (Fig. 1), and the quantity of carbon retained in the slab and carried into the deep mantle, compared to that released from the slab and returned to the surface, is under debate^{9,11–13}. The ultimate solution

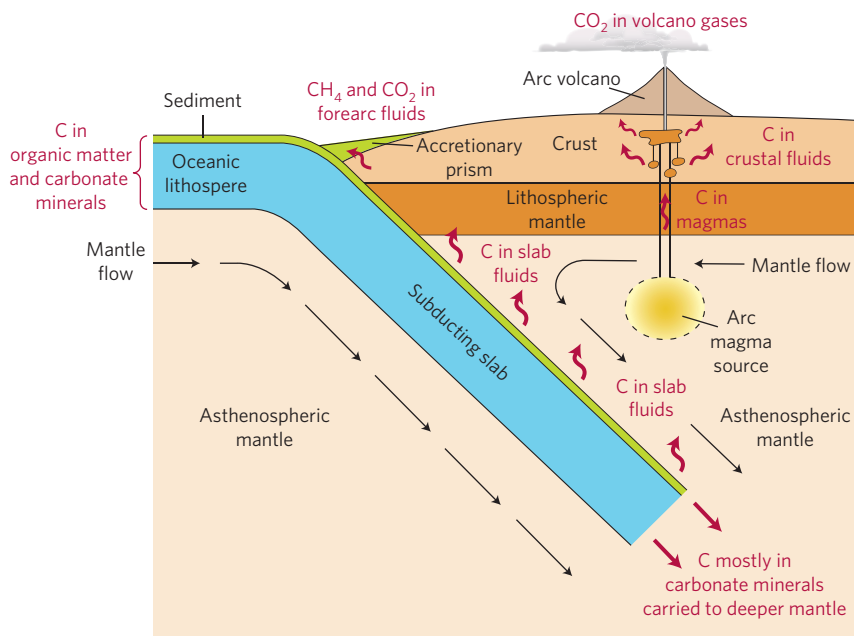


Figure 1 | The deep carbon cycle. Carbon stored in sediments and oceanic lithosphere is transferred into the deeper Earth by subduction. During subduction, high temperatures and pressures drive chemical reactions that release some carbon from the subducting slab, transferring it to buoyant fluids and eventually back to Earth's surface for release at arc volcanoes. However, current thermodynamic models of the chemical evolution of subducting slabs assume that only volatile components are transferred to the fluids, and they fail to explain the amount of carbon dioxide emitted by volcanism. Ague and Nicolescu⁵ analyse the composition of ancient subduction-zone rocks exhumed in Greece and show that in addition to devolatilization, subduction-zone fluids can cause large-scale dissolution of carbonate minerals, helping to balance the deep carbon cycle. C, carbon; CO₂, carbon dioxide; CH₄, methane.

to the problem requires identification of the chemical mechanisms that allow carbon to be removed from subducted lithosphere and to enter the magma that feeds volcanic eruptions.

When lithosphere is subducted, it is heated and pressurized. Volatile elements within the slab are lost from the rock and transferred to a fluid phase. These mobile, buoyant fluids readily escape upwards into the mantle wedge. The water in the fluid lowers the melting point of the rocks, eventually triggering melting of the mantle and eruptions at arc volcanoes. However, thermodynamic models of this devolatilization process assume that only water and carbon dioxide are removed from the slab^{14,15}. If so, relatively little carbon can be stripped from the slab beneath the arc — not enough to account for the significant amounts of carbon found in arc magmas. Dissolution may play a role, and it is known that minerals dissolve in subduction-zone fluids to a much greater degree than in shallower settings¹⁶. However, there has been little evidence from real subduction zones that a dissolution process could close the carbon imbalance.

To fill this gap, Ague and Nicolescu⁵ studied the composition of marbles, that is, metamorphosed rocks comprised mostly of the calcium carbonate minerals calcite or aragonite, that were exhumed from a roughly

50-million-year-old subduction zone in Greece. They identified layers in the marbles that appeared systematically altered by fluids, and showed that the marbles had been infiltrated by fluids derived from elsewhere in the slab, as demonstrated by isotopic analyses. On comparison with unaltered marbles, Ague and Nicolescu found that between 60 to 90% of carbon dioxide had been stripped from the altered marbles — much greater volumes than could have been removed by simple devolatilization processes alone. Most importantly, calcium had been removed from the altered marbles in amounts equal to the carbon dioxide. This is a smoking gun for the dissolution of calcium carbonate minerals, such as calcite and aragonite, because they possess equal molar concentrations of calcium and carbon. The results therefore imply that large volumes of calcium carbonate minerals were dissolved by the infiltrating fluids, providing a novel and potentially voluminous pathway for slab de-carbonation.

The precise cause of such large-scale dissolution of calcium carbonate minerals during subduction remains unclear. Calcium carbonate, for example, should dissolve more readily in pure water at high pressures and temperatures^{17,18}, but is still quite resistant to dissolution. Variations in the acidity, oxygen

fugacity and salinity of the subduction-zone fluids may conspire to dramatically raise the solubility of carbonate minerals^{19,20}, but this possibility needs further investigation. It is also not clear that the dissolution and transport of carbon occurred at a depth sufficient to directly supply the arc-magma source — additional dissolution and transport steps may be necessary.

The finding of significant calcium carbonate dissolution in the subducting slab may also have a bearing on ideas about carbon subduction and recycling through time. Current thinking regarding the amounts of carbon returned to Earth's surface through volcanism is based on measurements at today's active volcanoes. But the data from Greece were obtained from a 50-million-year-old subduction system. It is possible that carbonate subduction was more voluminous then, compared with today. It would be interesting to make quantitative use of the geologic record to inform our investigation of the deep carbon cycle — for today and in the past.

Ague and Nicolescu⁵ demonstrate that dissolution of carbonate minerals provides an important pathway for the transfer of carbon from subducting slabs back to arc volcanoes and eventually to the atmosphere. This finding will spark new studies on the chemical cycling of material in subduction zones — not just of carbon, but of all important elements. □

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