

on the circumpolar westerlies, rather than stratospheric ozone depletion.

Steig and colleagues⁹ find a more subtle change hidden in the oxygen isotopic composition of ice cores spanning West Antarctica. The oxygen isotope signature of ice is typically interpreted as a proxy for temperature. However, it also responds to wider circulation anomalies that have influenced the region, including changes in sea ice and wind-driven ocean changes. Steig *et al.* interpreted the isotope values in terms of these broader trends. They used an ice core from the West Antarctic Ice Sheet Divide that spanned 2,000 years, in conjunction with an array of shorter cores, to document unusually high oxygen isotope ratios in the 1990s. Comparable events occurred in just 1% of the time series studied. The trend in oxygen isotopes over the past 50 years at the divide is also unusual, with comparable trends present in just 2% of the records.

Building on previous work that identified tropical influences on West Antarctic climate, they link the isotopic anomalies to changes in atmospheric convection over the tropical Pacific Ocean, propagated to the high latitudes through atmospheric waves. An isotope-equipped climate model, fed with tropical Pacific sea surface temperatures, reproduces the prominent isotope anomaly in the 1990s

that is recorded in the West Antarctic ice cores. Interestingly, the authors note that the Pacific variability associated with this 1990s anomaly was not outside the natural range of variability observed over past centuries.

Although the tropical drivers of the West Antarctic isotopic anomalies may not be unprecedented, the very existence of a link adds to concerns about future change in the region. A strong influence of tropical processes on the climate of West Antarctica adds an extra source of uncertainty in estimates of the manifestation of greenhouse-gas-induced climate change. Steig and colleagues also suggest that the decadal-scale variability in the tropics has masked the local Antarctic response to anthropogenic forcing.

These studies remind us that we should not expect Antarctic climate change to be uniform in time or space. The climate response is mediated by multiple processes, each having varied seasonal and geographical expressions, linked by hemispheric and global scale connections, and subject to decadal-scale variability that can confound detection of the forced signal. Improvements in capturing these processes in models and testing with improved data, both observational and palaeoclimatic, are the keys to predicting the patterns and rates of change.

Individually, the ice core records presented by Abram *et al.*⁸ and Steig *et al.*⁹ add to the evidence that changes currently seen in Antarctica are unusual relative to the past 2,000 years. Taken together, alongside other indicators of change, the message is becoming clearer: Antarctica is very likely to be showing a response to the warming climate of the planet. □

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MINERALOGY

Garnet goes hungry

Sinking slabs of oceanic lithosphere often stagnate in Earth's mantle. Experiments show that common slab minerals transform to their high-pressure, high-density counterparts at very slow rates, thus keeping the slabs buoyant and impeding subduction.

Craig R. Bina

Students in the petrology lab learn quickly that the mineral garnet — an abundant component of the Earth's mantle — 'eats' everything. Indeed, this mineral's complex crystalline structure can accommodate a bewildering variety of cations. Writing in *Nature Geoscience*, van Mierlo *et al.*¹ use high-pressure and high-temperature experiments to show that garnet dines rather slowly, at least under conditions prevailing in subduction zones, with important implications for subduction dynamics and mantle chemistry.

Slabs of oceanic lithosphere contain abundant amounts of the minerals garnet

and pyroxene. As the slabs sink into the mantle, the pyroxene is thought to dissolve into the denser garnet, where it forms a component known as majorite². The rate at which such dissolution occurs, however, is controlled by how fast majorite can diffuse through the garnet structure. High pressures within the mantle should cause the remaining components of the subducting oceanic slab — dominated by the mineral olivine — to also undergo phase transitions, thus increasing the slab's density as it sinks deeper into the Earth. Yet in seismic images of Earth's interior, the slabs often seem to stall near the base of the mantle transition zone, which is a region

located between 410 and 660 km depth. This stalled subduction may be linked to these complex mineral transformations that occur within the slab.

Our understanding of how pyroxene in an oceanic slab dissolves into garnet is based on laboratory experiments. In an attempt to simulate these transformations, which occur over long geological timescales and at hundreds of kilometres depth in the mantle, the samples are usually ground into fine powders that are squeezed and heated. Yet, in real subduction zones, grain sizes within subducting slabs are large and the temperatures in the slab are low compared with the warm surrounding mantle.

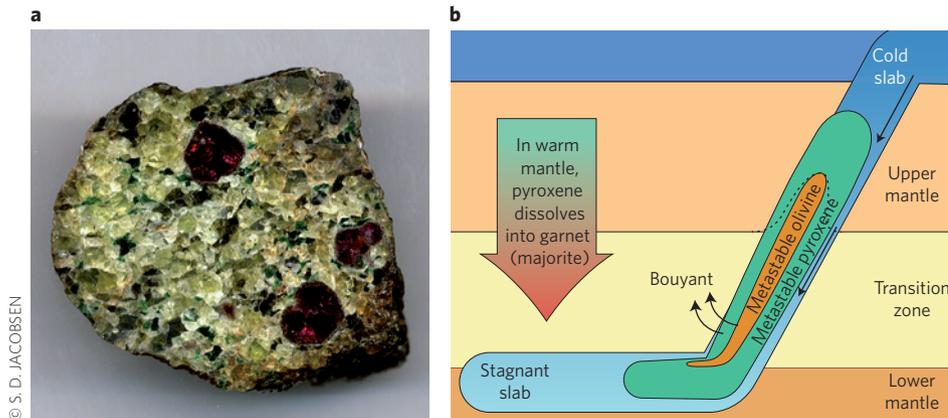


Figure 1 | Subduction of oceanic lithosphere in the mantle transition zone. **a**, Slabs of oceanic lithosphere contain a variety of minerals including olivine (pale green), pyroxene (dark green) and garnet (red). **b**, As the slab subducts into the mantle, it encounters higher temperatures and pressures that cause the minerals to undergo phase transformations. The common slab mineral pyroxene dissolves into garnet, forming the component majorite within the garnet. Similarly, the olivine transforms to denser phases. Van Mierlo and colleagues¹ use laboratory experiments to show that majorite is one of the slowest diffusing components of the mantle. Further dissolution of pyroxene is therefore inhibited and the pyroxene persists in a metastable, buoyant state that can potentially slow and deflect subduction.

A first step towards improved understanding of these transitions was to carry out experiments and modelling to explore reaction kinetics at the relatively low slab temperatures. The results suggested that, although olivine and pyroxene were expected to become unstable under the high-pressure conditions of Earth's mantle, they might instead remain in a metastable (and thus buoyant) state^{3–5}. Pyroxene was kinetically inhibited from dissolving into garnet⁶, but the relevant diffusion rates remained unknown.

Now van Mierlo *et al.*¹ have taken the next step. They use laboratory experiments to measure precisely (at the micrometre scale) the rate at which the majorite component — formed by the dissolution of pyroxene into garnet — diffuses through the garnet structure, over a range of high pressures and temperatures. The results are extrapolated to the conditions of the mantle transition zone, and they are striking. It turns out that garnet is a very slow eater. Even at high temperatures and pressures of 1,800 °C and 15 GPa — warmer than the corresponding depth in the mantle transition zone — the rate of majorite diffusion is extremely low, with a diffusion coefficient below $10^{-18} \text{ m}^2 \text{ s}^{-1}$. This rate of diffusion is comparable to the diffusion of magnesium in garnet at much lower temperatures and pressures, below 1,000 °C at 1 GPa (ref. 7). Majorite therefore seems to be one of the most slowly diffusing components in the mantle.

The slow diffusion of majorite has two important implications for mantle chemistry and geodynamics. First, majorite components formed in the mantle may persist over very long timescales. Van Mierlo and colleagues extrapolate the diffusion data to realistic grain sizes for oceanic slabs (on the order of millimetres) and show that majorite-bearing heterogeneities formed in the mantle transition zone would be homogenized at length-scales of, at most, tens of metres over timescales comparable to the age of the planet. Yet subducted slabs are typically thousands of metres thick, meaning that the majorite components will not fully homogenize and may remain as chemical anomalies in the transition zone for billions of years. This finding supports suggestions that the mantle transition zone may be a mechanical mixture of different components, rather than a homogenized unit⁸.

Second, there is the prospect of metastable pyroxene persisting to depths at which it should have been devoured by garnet. Entry of pyroxene into the garnet structure as majorite is controlled by the rate of majorite diffusion. Thus, the slow diffusion of majorite prevents pyroxene being dissolved into the garnet, and the garnet goes hungry. Pyroxene is less dense than garnet, and its persistence will impart positive buoyancy to the slab, thereby impeding subduction (Fig. 1). Similar buoyancy perturbations have been posited for other slab minerals, such as metastable olivine, at temperatures below about 700 °C

in the coldest core of the slab⁴. However, the new diffusion data imply that pyroxene can remain metastable and buoyant to temperatures as high as 1,400 °C, extending the potential for metastability over a much larger area of the slab and thereby amplifying the buoyancy effect.

The slow diffusion of majorite can therefore help explain the stagnation of subducting slabs in the mantle transition zone. The metastable pyroxene may remain undigested for some time, and the positive buoyancy would then generate slower slab descent rates and cause the wholesale flexure of the slab into a sub-horizontal stagnant posture in the transition zone. Such slab stagnation may persist until thermal assimilation warms the slab sufficiently to allow consumption or further reaction (perhaps to metastable akimotoite) of the buoyant metastable material.

The experiments illuminate the metastability of magnesium-rich pyroxene. However, complex natural pyroxenes may be more reactive than the magnesium-rich variety⁹. The behaviour of multi-component mineral assemblages with, for example, differing iron or hydrogen concentrations have yet to be fully investigated. Buoyancy relations are further complicated by the fact that, although metastable pyroxene may persist over a larger extent of the slab than metastable olivine, the latter is more buoyant than the former.

Van Mierlo *et al.*¹ demonstrate that garnet dines rather slowly, at least under conditions prevailing in subduction zones. Slow diffusion of majorite can inhibit the dissolution of pyroxene into garnet in subducting slabs, giving the slabs added buoyancy and causing them to stagnate in their descent through the mantle. Those investigating the chemistry, seismology and geodynamics of deep subduction will need to reflect on the dining habits of garnet. □

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