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.

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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. 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 majorite. 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.
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. Pyroxene was kinetically inhibited from dissolving into garnet, 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 — warmer than 1,800 °C and 15 GPa — garnet consumes at a rate that is extremely low, with a diffusion coefficient below 10⁻¹⁸ m² 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 unit.

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). The buoyancy of the slab is sufficient to allow consumption or further reaction (perhaps to metastable akimotoite) of the pyroxene-bearing material.

The experiments illuminate the potential for metastability 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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References