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Slab dynamics linked to transient weakening during mineral phase transitions

New experiments shed light on the complex interplay between rock deformation and metamorphism. Slab stagnation in Earth's mantle transition zone may be explained by transient weakening during the olivine–spinel phase transition.

This is a summary of:
Cross, A. J. et al. Direct observations of transient weakening during phase transformations in quartz and olivine. *Nat. Geosci.* https://doi.org/10.1038/s41561-025-01703-6 (2025).

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The problem

Researchers have long suspected that phase transitions – abrupt changes in crystal structure at high pressures and/or temperatures – can produce temporary weakening in crystalline materials[1], including rocks and minerals[2]. Such weakening is thought to heavily influence tectonic plate motions during subduction and continental collision. Until now, however, this behaviour has proven particularly difficult to isolate in the laboratory – relatively few rock deformation apparatuses are capable of reaching sufficiently high pressures to induce phase transitions in major rock-forming minerals, and even fewer permit direct, simultaneous observation of sample materials under such extreme conditions. Previous studies have therefore struggled to disentangle the effects of mineral phase changes on rock strength. In the absence of laboratory measurements, it cannot be confidently said whether phase changes affect the interior dynamics of Earth and other rocky planets.

The solution

To overcome these technical challenges, we performed high-pressure, high-temperature experiments in a hydraulic multi-anvil press at a synchrotron beamline facility[3]. Using powerful X-rays generated by electrons sped up to within a fraction of the speed of light, we were able to directly measure changes in stress, pressure, sample shape, sample size and crystal structure during phase transformations in quartz and olivine – major constituents of Earth's crust and mantle. In some experiments, we simply increased pressure to induce a phase change. However, in most experiments, we simultaneously deformed our samples to see how their strength would evolve during those same transformations.

Both quartz and olivine undergo temporary but dramatic weakening while changing to their high-pressure forms. Upon the emergence of the high-pressure phase, our samples suddenly began deforming up to one hundred times faster than before. By performing experiments at various temperatures and deformation rates, we found that weakening is most pronounced when the transformation is rapid, and deformation is slow. More specifically, the magnitude of weakening is directly proportional to a ratio between the transformation and deformation rates. By calculating the rates of olivine deformation and the olivine-to-spinel transformation in downgoing slabs of various temperatures, hydration states and stress states, we found that cold, wet slabs are most susceptible to transformation-induced weakening (Fig. 1). These predictions are consistent with geophysical observations, from seismic tomography, of downgoing slabs stagnating and becoming trapped in the mantle transition zone beneath the western Pacific Ocean.

Future directions

Our next step is to identify the specific processes that give rise to weakening during phase transitions. Preliminary observations suggest that transformational faulting[4] and grain-size reduction[5] are unlikely explanations in this instance (although they may well be complementary processes under different conditions).

A promising avenue for exploration is transformation plasticity – that is, the anomalous flow of materials due to elevated internal stresses and crystal defect densities during a phase change[2]. Although this behaviour has been studied extensively in metals and engineering materials, observations in rock-forming minerals remain sparse. To address this knowledge gap, we recently completed a suite of experiments where quartz specimens were extracted mid-way through their transformation to coesite, one of the high-pressure phases of SiO_2. Using electron microscopy, we are in the process of quantifying how internal stresses and defect (dislocation) densities evolve during the quartz-to-coesite phase transition. This information will help us build a more complete picture of the microphysical mechanisms responsible for transformation-induced weakening. From there, we can start to develop constitutive equations that describe the magnitude of weakening as a function of time, mineral phase proportions, elasticity, defect density, flow strength, pressure, temperature and other evolving variables during phase transitions.

Ultimately, we hope to work with geodynamic modellers to more fully explore the influence of phase transformations across various settings; for example, during mantle convection, mantle plume upwelling, continental collision, and even during meltwater percolation and refreezing in ice sheets.

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EXPERT OPINION

"Transformational plasticity describes the weakening produced by a phase transformation and has long been known in materials science. The idea that transformational plasticity also plays a part in geodynamics is widely accepted in the deep-Earth science community, but the phenomenon has remained unquantified. This study is therefore a tremendous step forwards to a proper quantitative assessment of how transformation plasticity might facilitate geodynamic processes in the deep Earth." **Julien Gasc, Ecole Normale Supérieure, Paris, France.**

FIGURE

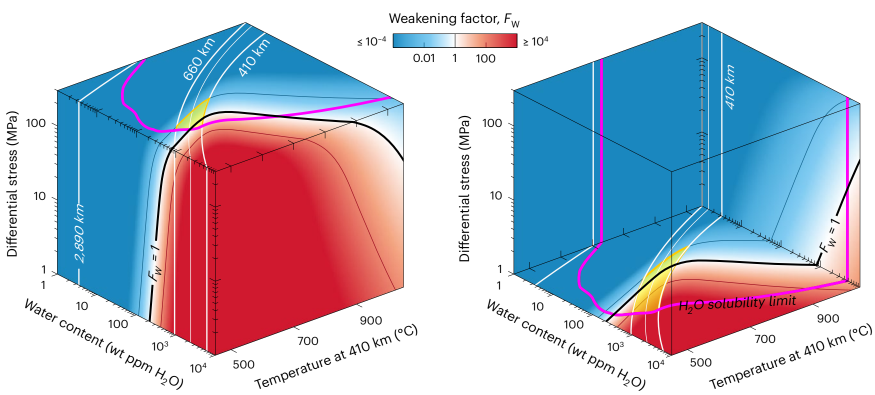

Fig. 1 | The weakening potential of downgoing slabs under various temperatures, water contents and stresses. At each set of conditions, we have calculated the rate of the olivine–spinel phase transformation, and the rate of plastic deformation in olivine. The magnitude of weakening, F_W, is predicted from the ratio of these two rates using a power-law equation. The yellow regions indicate the range of conditions where >1% weakening is predicted to coincide with the mantle transition zone, within the limit of water solubility in olivine. © 2025, Cross, A. J. et al.

BEHIND THE PAPER

This study has been a long time in the making. The first successful experiments were completed in late 2019, borne out of conversations between myself and David Goldsby, who had previously worked on transformation plasticity in ice. With Lars Hansen, we applied for funding from the National Science Foundation in early 2020, just as the COVID-19 pandemic was beginning. Although the proposal was selected for funding, we struggled to make progress owing to site-access restrictions at the Advanced Photon Source (APS) synchrotron. Those restrictions were lifted in early 2022, and then began a 12-month scramble to complete as many experiments as possible before another closure of the APS — this time due to a long-planned upgrade of the electron storage ring, lasting ~20 months. Thankfully, we were able to complete our experiments in the final few hours before the facility went offline. Now that the APS is back in operation, we plan to pick up where we left off: investigating the precise grain-scale mechanisms that give rise to macroscopic weakening. **A.C.**

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FROM THE EDITOR

"This work stood out to me because it sheds light on why subducted slabs in the deep Earth stagnate. Their findings open up the prospect of better informed geodynamic models, while highlighting the important role mineral phase transformations play in the Earth's interior." **Alison Hunt, Associate Editor, *Nature Geoscience*.**