Grain size of rocks in Earth's mantle affects tectonics

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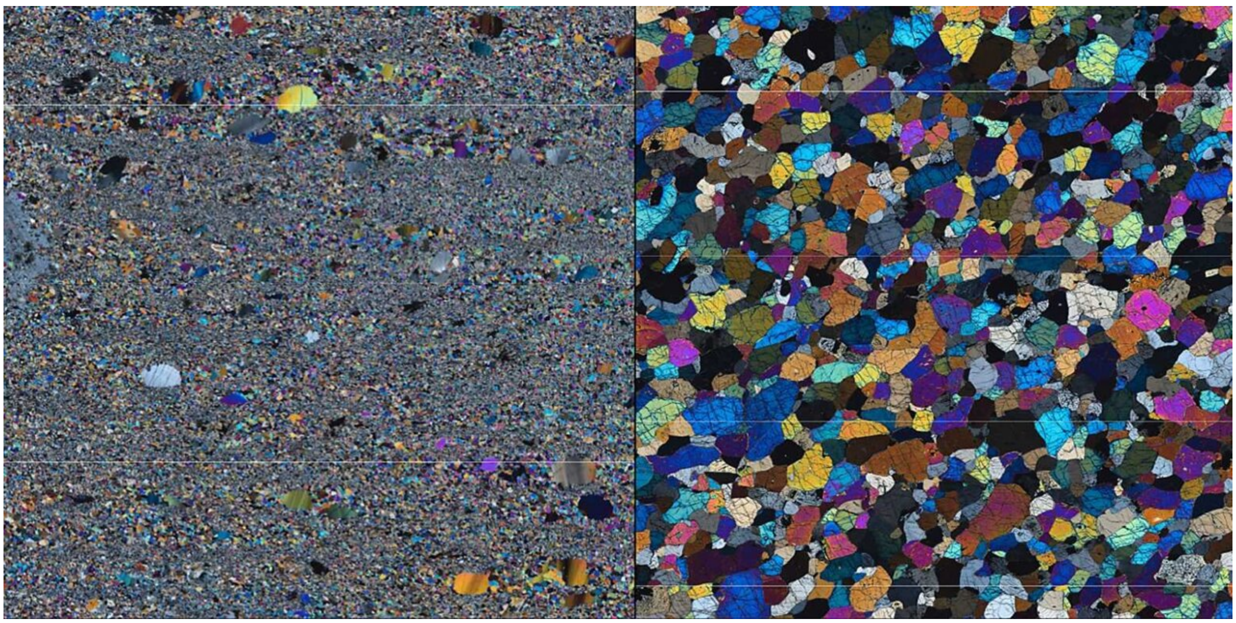


Depending on how coarse-grained the rocks in the upper mantle are, they deform quite differently under stress. The picture shows two microscopic thin sections of mantle rocks. Credit: Jonas Ruh / ETH Zurich

The planet is shaped by forces deep within its interior. These push the plates of the Earth's crust against each other, causing mountains and volcanoes to form along the collision zones. But when reconstructing what exactly is happening inside the Earth, we are limited to indirect observation; for example, by conducting pressure experiments on rocks from the Earth's mantle or by analyzing seismic waves triggered by earthquakes.

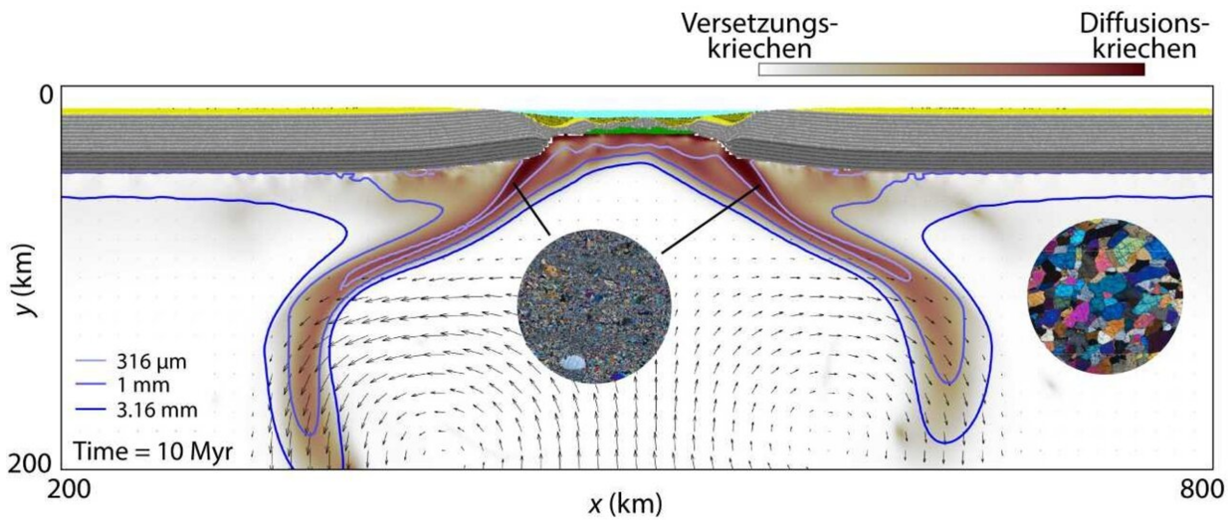
Yet all these observations provide only snapshots. If we want to understand the dynamics of what has happened over several millions of years, we need computer models that can simulate geological processes in fast motion. By feeding the above-mentioned observational data and physical formulae into these models, researchers can show how the Earth's surface and interior change over time.

There's a flaw here, though: every model is based on simplifications and is thus prone to error. Factors that may not seem particularly important at first glance can also turn out to play a key role, as a new study published in *Nature Geoscience* by the Structural Geology and Tectonics group at the ETH Department of Earth Sciences demonstrates. With their new simulations, the researchers are able to show that one crucial factor has not been adequately considered in previous models, even though it is known to have a potential effect: the grain size of the mantle rocks. The latest simulations now show how great the effect of grain size actually is.

Dislocation or diffusion?

Grain size is relevant because it affects how the rocks deform in the upper mantle. If the grain size is in the range of a few millimeters, the minerals in the rocks deform mainly through the shifting of the minerals' crystal lattice along planes. This leads to what is known as dislocation creep, considered the most important mechanism of rock deformation in the Earth's mantle.

If, on the other hand, the grain size is smaller, another mechanism becomes more important: diffusion creep. The rocks then deform, not by dislocations in the crystal lattice of the minerals, but by individual atomic vacancies in the crystal lattice migrating through the crystal structure. Depending on which deformation mechanism prevails, the strength of the rocks changes accordingly.



The simulation shows how the grain size of the mantle rocks develops when continents break apart along a so-called rift zone. Credit: Jonas Ruh / ETH Zurich

Many unanswered questions

"Fine-grained rocks are formed mainly in shear zones and are much weaker than the undeformed coarse-grained rocks," explains Jonas Ruh, senior assistant in the group and lead author of the study. "But until now, we haven't been able to realistically represent these differences in a dynamic model." Some of the previous models considered only dislocation creep, which is an oversimplification. Other models use constant grain sizes for the upper mantle rocks, which also does not do this factor justice.

Ruh considered recent studies from other groups as well as laboratory experiments from his own research group for his new model. "Specifically, we incorporated a new growth model for the main mineral, olivine," he explains. "And, based on new research, we now also know that there is significantly less mechanical energy going into grain size reduction than previously thought." If these new findings are taken into account, the processes in the Earth's mantle can be modeled much more realistically.

Contradiction resolves itself

Ruh was able to show that grain size reduction, the activation of diffusion creep, and the consequent weakening of the uppermost mantle significantly lowers the boundary forces needed to initiate rifting, and facilitates continental breakup.

However, the new study was prompted by a different, seemingly paradoxical feature of plate tectonics: the uppermost region of the Earth's mantle must be relatively solid, as this is the only explanation for why tectonic plates that are pushed under another plate do not plunge into the depths at a steeper angle.

But if this mantle region is as strong as the geometry of downgoing plates requires, the rocks in the uppermost mantle should be brittle in view of the major stresses that dominate there. It follows that there would have to be earthquakes in this area of the Earth's mantle that would release the stress in fits and starts. However, observations of such quakes have been extremely rare to date.

The new model now resolves the paradox: "The fine-grained, ductile shear zones relieve the high stresses to the point where earthquakes can no longer occur," Ruh explains. "At the same time, the uppermost part of Earth's mantle remains strong enough to be consistent with observed flexure geometries of descending slabs in collision zones."

More information: J. B. Ruh et al, Grain-size-evolution controls on lithospheric weakening during continental rifting, *Nature Geoscience* (2022). DOI: 10.1038/s41561-022-00964-9

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