We discovered a new way mountains are formed—from 'mantle waves' inside the Earth

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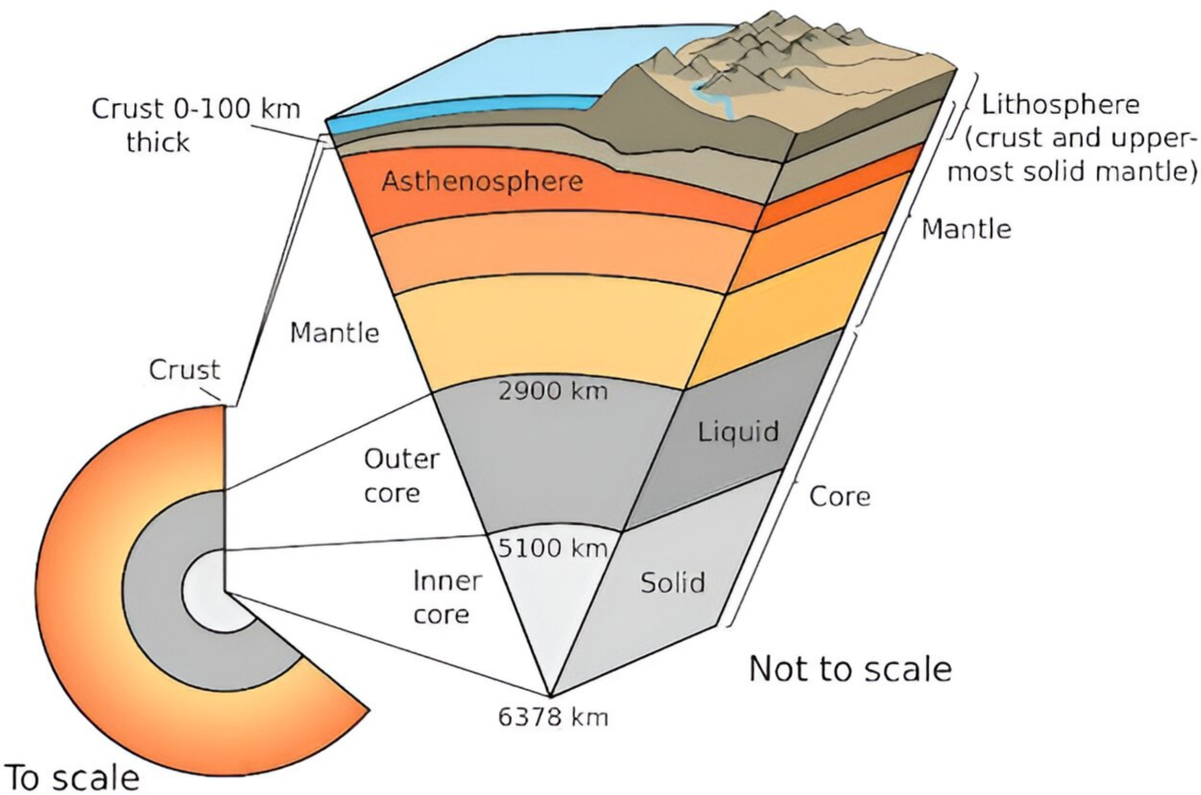

Cross section through Earth showing the mantle. Credit: USGS

In 2005, I was navigating winding roads through the Drakensberg

Mountains, in Lesotho, Southern Africa. Towering cliff-like features known as escarpments interrupt the landscape, rising up by a kilometer or more. Taken aback by the dramatic scenery, I was struck by a question: how on Earth did it form?

The outer shell of our planet is fractured into seven or eight major sections, or tectonic plates, on which the continents sit. We expect to see the continents rise up at the active boundaries of these plates, where volcanism and earthquakes are often concentrated.

But why—and how—do these dramatic features form far away from these boundaries? Our new theory, published in *Nature* after nearly two decades of thinking and forensic work, explains how uplift like that seen in Drakensberg can occur in supposedly stable parts of continents.

The continents we now recognize were once united as single, great "supercontinents." One such example was Gondwana, which existed hundreds of millions of years ago and started to break up during the age of the dinosaurs. We believe that when these supercontinents break apart, it triggers a kind of stirring process under the continents, which we now call a "mantle wave." This motion deep in the Earth ripples slowly across the partially molten underbelly of the landmass, disturbing its deep roots.

The mantle is the 2,900km-thick layer of Earth that lies beneath the outer crust that we live on. To study what happens when continents break apart, we built sophisticated dynamic models to mimic the properties of the Earth's crust and mantle, and how they are physically strained when forces are applied.

When continents separate, the hot rock in the mantle below rushes up to fill the gap. This hot rock rubs against the cold continent, cools, becomes denser, and sinks, much like a lava lamp.

What had previously gone unnoticed was that this motion not only perturbs the region near what's called the rift zone (where the Earth's crust is pulled apart), but also the nearby roots of the continents. This, in turn, triggers a chain of instabilities, driven by heat and density differences, that propagate inland beneath the continent. This process doesn't unfold overnight—it takes many tens of millions of years for this "wave" to travel into the deep interior of the continents.

This theory could have profound implications for other aspects of our planet. For example, if these mantle waves strip some 30 to 40 kilometers of rocks from the roots of continents, as we propose they should, it will have a cascade of major impacts at the surface. Losing this rocky "ballast" makes the continent more buoyant, causing it to rise like a hot air balloon after shedding its sandbags.

This uplift at Earth's surface, occurring directly above the mantle wave, should cause increased erosion by rivers. This happens because uplift raises previously buried rocks, steepens slopes, making them more unstable, and allows rivers to carve deep valleys. We calculated that the erosion should amount to one or two kilometers or even more in some cases.

The innermost parts of the continents are considered some of the toughest and most stable parts of the planet, so removing a few kilometers from these regions is no mean feat.

But near the edges of these stable continental regions, called cratons, we get kilometer-high escarpments, just like the one in Lesotho. These giant escarpments encircle these regions, extending for thousands of kilometers. They are testament to a fundamental disruption of the landscape at roughly the same time that the supercontinent Gondwana broke apart—starting around 180 million years ago.

Mystery plateaus

Inland from these great escarpments, we find plateaus, such as the Central Plateau of South Africa, which rise over a kilometer above sea level. The origins of these plateaus have long been enigmatic and have typically not been linked with the escarpments.

Some scientists have previously invoked a phenomenon known as mantle plumes—colossal upwellings of hot, buoyant material from deep within the Earth—as a possible explanation for the plateaus.

Such plumes could potentially push up and dynamically support the Earth's crust. However, there is no evidence of such an inner continental plume feature in geological records from surrounding continents or oceans during the relevant time period. Could our mantle wave offer a fresh explanation?

To test our predictions, we turned to thermochronology—a science that helps us understand how rocks, now at or near the surface, have cooled over time. Certain minerals, like apatite, are sensitive to both temperature and time. Much like a flight recorder, these minerals capture a "cooling history," providing snapshots of how the temperature of a given rock has changed.

Here, we used multiple existing measurements scattered across Southern Africa. This analysis confirmed our model's predictions: several kilometers of erosion occurred across the region at broadly the times suggested by our models. Even more remarkably, the erosion moved across Southern Africa in a pattern closely mimicking the mantle wave in our simulations.

To probe this linkage further, we applied a different kind of simulation called landscape evolution modeling, which examines how water interacts with the landscape and how, as the landscape is sculpted by rivers, the Earth's surface effectively bounces or "flexes" in response.

When we included the mantle wave in our computer model, it showed how it could, in theory, form a high elevation plateau. Our results explain how vertical movements of continents can occur far from active tectonic plate boundaries, where most uplift is generally known to occur.

The massive erosion that occurs during these mantle wave events can give rise to intense chemical weathering of rocks, which removes carbon dioxide from the atmosphere, promoting global cooling. These uplifts can also physically separate flora and fauna, leading to speciation and shaping evolution. We've come a long way in understanding the processes that lead mountain ranges to form away from the edges of continents. And it still amazes me that all this started with an awe-inspiring view of Lesotho's landscape.

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