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What the Earth's 'voice' tells us about its underground architecture

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To explore inside the Earth, scientists measure the speed of sound in underground rocks – or the 'voice' of our planet – created by plates' movements. Sometimes, they detect mysteriously fast sound waves. A new study reveals that these fast sound waves are produced by a unique underground architecture that drives a volcanic eruption, called a mantle plume.

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What's under our feet? Our planet has [layered internal structures] – the central inner and outer cores covered by mantle, crust, and the ground on which you are standing.

While these layers are mostly solid, the outer core is liquid since it's extremely hot (around 3000°C) and rocks constituting it are molten. The 3000 km thick mantle, that overlies the outer core, is much colder and thus forms a boundary with a huge gap in temperature. The intense heat mobilises mantle rocks and creates superheated pod-like structures above this boundary. Because they are hotter and thus less dense than the surrounding mantle theses viscous pods rise and evolve into mushroom-shaped 'mantle plumes'. This whole process is similar to the rising hot wax in a lava lamp.

Mantle plumes are important as an efficient way for the Earth to release heat from the outer core. An active mantle plume can even reach near the Earth's surface, where, because of loss of pressure, undergoes melting. When this happens, the plume collapses on (or near) the surface by massively pouring out magma via volcanic eruptions. In other words, mantle plumes serve as a channel that connects the interior and the exterior of our planet. Today, we can see such mantle plume activities at volcanic hotspots such as Hawaii and Iceland.

Understanding mantle plumes helps us figure out intra-plate volcanism and the movement of Earth's tectonic plates, as volcanos usually form at the boundaries of the plates. However, recent studies have shown that ancient plume heads tend to get broken up by movements of the Earth's plates and become dispersed, which challenges scientists to study such ancient, extinct plumes.

Earthquakes, or the 'voice' of the Earth, may allow us to solve this problem. To remotely explore the Earth's interior, scientists traditionally measure the speed of sound in buried rocks – the 'voice' of our planet – generated by plates' movements. Seismic sound waves called P-waves travel in the very top of the Earth's mantle, usually with a constant speed. However, there are also exceptionally fast P-waves near the Earth's surface (around 50 kilometres underground). These fast P-waves remain a mystery as they are not linked to any known mantle rocks. Solving this puzzle is exciting since geologists have noted that the fast P-waves appear to be associated to rocks that were once part of ancient mantle plumes.

We set out to uncover this fast P-wave mystery and its link to extinct mantle plumes. We analysed seismic data collected from the ocean area beneath the eastern North Island, New Zealand, which includes the Manihiki Plateau, the Hikurangi Plateau and the Ontong-Java Plateau. These three plateaus were likely once all together forming one ancient region (the original Ontong-Java plateau), where the largest volcanic outpouring in the Earth's history is thought to have happened.

A simulation using computer modelling allowed us to find that special flow conditions that produce fast P-waves can be created over the head of superplumes: exceptionally large mantle plumes where the mushroom-like head is more than 2000 kilometres across. In these conditions, like a pancake mix being poured into a pan, the mixture expands out in all directions after it hits the plate, which, in turn, creates a distinct 'flow fabric' over the superplume head. It's this fabric that permits P-waves to travel unusually fast in all horizontal directions. The simulation also showed that fast P-waves occur when grown superplumes start to collapse leading to a volcanic eruption. Collectively, our simulation revealed that fast P-waves could be generated by the 'flow fabric' over a once-existed superplume's head.

Beyond our analysis, Siberia is another interesting area to study as it is the only known additional location that produces fast P-waves. Importantly, this area is the location for the Earth's second largest volcanic outpouring, which occurred about 250 million years ago. The size of the outpouring here is similar to the ancient Ontong-Java plateau, supporting our finding that fast P-waves mark the presence of ancient superplumes.

In summary, we propose that the mysterious fast P-waves can be used as fingerprints of ancient superplumes that are now cooled and partially broken down. We also show that a distinct 'flow fabric' associated with a superplume causes these P-waves on the top of the superplume. Furthermore, our findings point out that mantle plumes were present in the earlier evolution of the Earth, with the testimony of P-wave-related rocks that were formed 100- 250 million years ago.