Seeing inside the earth

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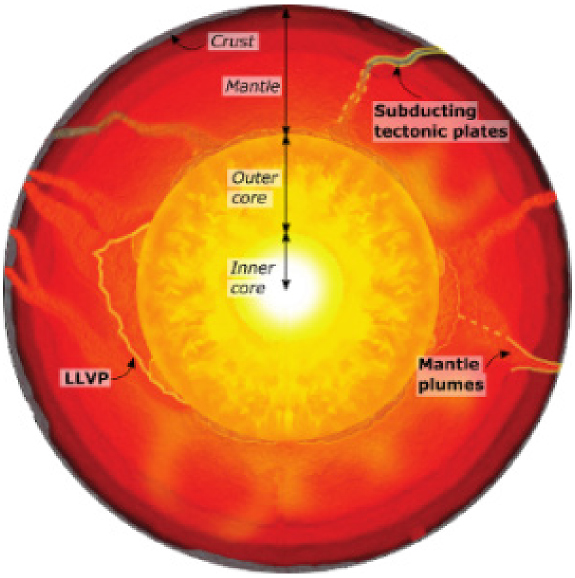
Have you ever wondered what's going on deep inside the Earth, 100's km beneath your feet? This article looks at how geoscientists see inside our planet, the new things they are learning from cutting-edge research and what implications the Earth's internal dynamics have for us at the surface.

Crust, mantle, outer core, inner core – the basic layered structure of the Earth is a familiar picture, Figure 1. But how do we actually know this is what the inside of the Earth looks like? And is it really that simple? Unfortunately, going there is not an option, the deepest hole ever drilled is only 12km deep (0.2% of Earth's radius)! Luckily, geoscientists have a secret weapon up their sleeves – seismic waves!

Seismic waves are vibrations which travel through the Earth, produced by explosions, waves in the sea, or even cars and the movement of people. For imaging the Earth, the strong waves generated by earthquakes are the most useful to geoscientists.

The major layers of the Earth were all discovered by observing seismic waves that bounce off them (reflect) (side note1). This is similar to how medical ultra-sound imaging works. However, the structure of the deep Earth is a lot more complicated and detailed than the simple layered structure we're used to thinking about. One way to see the details within the Earth's layers is to use a technique called seismic tomography, which allows us to make 3D pictures of the inside of the Earth.



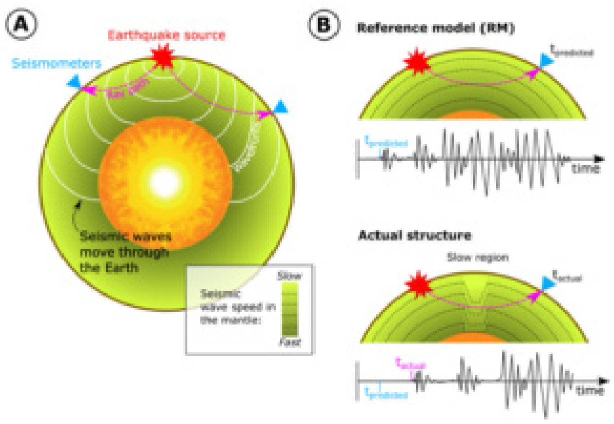
^ *Figure 1. Structure of the Earth*

STEM LEARNING

How does seismic tomography work?

Imagine an earthquake: the ground in the area shakes, and seismic waves are released in all directions into the Earth (figure 2A). They travel through the deep Earth, and eventually re-emerge at the surface, where they are recorded by sensitive instruments that measure the shaking of the ground (seismometers).

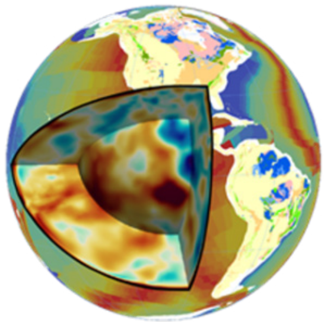
The time that the seismic waves arrive at each seismometer depends on the distance from the earthquake source to the seismometer, and the speed the wave travelled at. For each earthquake and seismometer combination, we can predict what time the wave should arrive, assuming we know how fast it travels through the Earth (using a simple, layered reference model, figure 2B)). We then compare the actual time it arrives to when we thought it would – if it arrived later than expected then we know it passed through slower material than we thought was there, and vice versa.



^ *Figure 2 – A) Seismic waves spreading through the Earth. B) Comparison of the arrival time predicted by a layered reference model for seismic waves speed in the Earth, and the actual arrival time where the ray path passes through a slow region. The wiggly lines are examples of seismograms (predicted and actual)*

Enormous amounts of these time-delay measurements (from thousands of earthquakes, each detected by many seismometers) are combined to make a 3D image of how the speed of seismic waves varies within the Earth in a seismic tomographic model (Figure 3) (side note2.) This technique is similar to a medial CT scan (computer tomography), where x-rays are taken from many different directions around the patient, and then combined to make a 3D image of inside the body.

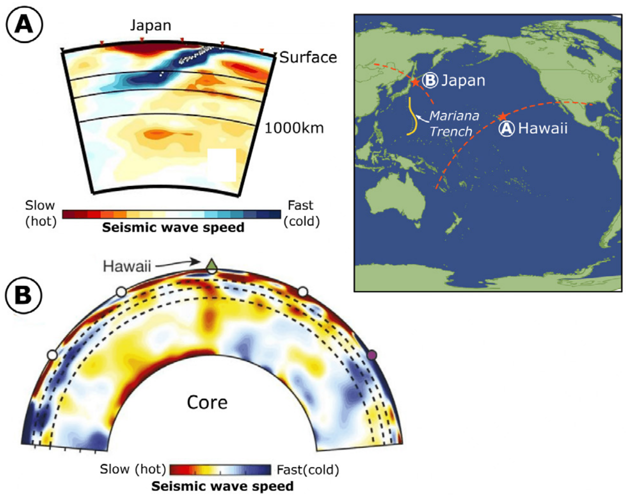
Understanding what these pictures of seismic wave speed mean for what is going on deep inside the Earth is quite difficult, because wave speed is affected by lots of things, but it's generally agreed that the most important factor is temperature. When solids are hot, their particles are further apart and move around faster, which means that it takes longer to pass a vibration between them. So we think the slow bits in our images probably show hot material, and fast bits show cold material.



< *Figure 3. A 3D tomographic model of the seismic wavespeed in the Earth. Red is slow, and blue is fast. Surface shows geology and oceanic plate age.* *[From Thorsten Becker (University of Texas)]*

What can we see inside the mantle?

One of the features we can see in tomographic images of the mantle are columns of hot material (mantle plumes, figure 4B), and sheets of cold material (subducting tectonic plates, figure 4A). The effect of temperature on density means that these warmer regions are rising up, and colder areas are sinking down into the solid mantle through the process of convection (side note 3). What's even cooler, is that it's possible to see the effects of mantle convection at Earth's surface!



^ *Figure 4- Tomographic 2D slices through the Earth. A) A mantle plume below Hawaii from French and Romanowicz (2015). B) A subducting tectonic plate below Japan from Fukao and Obayashi (2013)*

As hot mantle rises up in mantle plumes some of it melts because of the unusually high temperature, forming magma. This rises through the Earth's crust and erupts at the surface forming volcanoes like Hawaii. Because of the movement of Earth's tectonic plates over the stationary mantle plume below, a long line of volcanoes is produced over time.

Mariana trench, south of Japan, marks the deepest place in the worlds' oceans at 11,034m beneath the sea surface!

Where tectonic plates collide and one sinks down beneath the other into the mantle below, we see submarine trenches on the Earth's surface. The deepest of these is the Mariana trench, south of Japan, which marks the deepest place in the worlds' oceans (11,034 m beneath the sea surface!).

Submarine trenches host unique marine ecosystems, living at extremely high pressures with low nutrient input and no light. Inside the Earth the shallower parts of down-going tectonic plates (down to 600km depth) produce lots of earthquakes (you can see them as tiny white dots on figure 2B), including some of the biggest in the world, such as the magnitude 9 2011 Tohoku earthquake in Japan which caused a tsunami and nuclear power plant meltdown.

Where are we at today?

More seismometers and better computers are slowly allowing us to see smaller and smaller structures and add more detail to our picture of what the Earth looks like inside. This means we are still discovering new things we don't yet fully understand...

For example, tomographic images show two huge "mountains" of slow material at the bottom of the mantle, sitting on top of the outer core. These are called "large low velocity provinces" or LLVPs for short (Figure 1), and no one really knows quite what they are. Scientists argue about why they have slow seismic wave speeds; normally this would mean they are warmer than their surroundings, but then we would expect them to be buoyant and rise upwards. Instead they seem to be stable – sitting on top of the outer core for long time periods. Are they perhaps instead made of a different material to the rest of the mantle? It seems like LLVPs might be very important, changing how much heat can escape from the core (which could affect the Earth's magnetic field which is generated there), and maybe controlling the location of where hot plume upwellings that create volcanoes on the surface can form...

LLVPs are just one of the many mysterious structures we are still trying to understand. What we really need is more data, and more geoscientists to find new ways to work out what these structures are. There is still much more to learn about what our planet looks like inside and how it works!

References

Fukao, Y. and Obayashi, M., 2013. Subducted slabs stagnant above, penetrating through, and trapped below the 660 km discontinuity. Journal of Geophysical Research: Solid Earth, 118(11), pp.5920-5938. agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2013JB010466

French, S.W. and Romanowicz, B., 2015. Broad plumes rooted at the base of the Earth's mantle beneath major hotspots. Nature, 525(7567), pp.95-99. www.nature.com/articles/nature14876

Side notes

SIDE NOTE 1

Inge Lehmann: In 1936, Danish seismologist Inge Lehmann noticed an unusual seismic wave arrival peak on an earthquake seismogram. Looking at other records, she noticed the same peak again and again. However, it only existed on seismograms where the earthquake and seismometer were at certain distances apart from one another. She called this new type of seismic wave arrival PKiKP waves, or P' for short. Through careful analysis, she realised that these peaks were due to the arrival of waves bouncing off something solid within the centre of the core – this is how she discovered the Earth's solid inner core! Inge published her findings in a scientific paper which has the shortest title of any paper ever written – it's just called: 'P'!

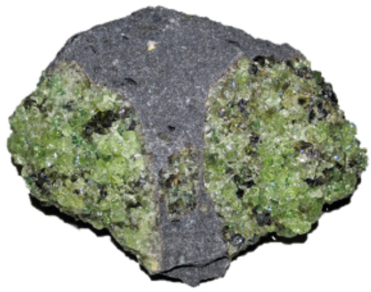
Figure - Photo of Inge Lehmann (1932), beside a cross-section of the Earth showing the new layer of the Earth she discovered – the inner core. Photo courtesy of The Royal Library, National Library of Denmark and University of Copenhagen University Library, under a Creative Commons License.

SIDE NOTE 2

Earth Science skills: Making these images requires the help of a whole range of different Earth scientists. Many geoscientists work writing computer code to produce models of the Earth from enormous data sets. Others work in labs putting rocks under enormous pressures and temperatures, performing experiments to find out what controls the speed seismic waves can travel through a material. Theoretical geoscientists use maths to calculate physical relationships between temperature and wave speed. While some travel to remote locations to install new seismometers to record Earthquakes.

SIDE NOTE 3

Mantle, solid or liquid?: The mantle is solid rock – not liquid magma. Even though it's very hot inside the Earth, the high pressure from all the rock above stops the mantle from melting. Kimberlite pipe volcanoes pull up bits of the deep mantle with them that show us that the mantle is made of a green crystalline rock called peridotite. However, tomographic models show that the mantle is moving, flowing and convecting, like a liquid. But how can the mantle flow if it is a solid? Many solids can flow over long timescales by creep, the accumulation of tiny motions to produce overall flow. An excellent example is silly putty. At the high temperatures of the mantle, over millions of years, tiny motions of crystals sliding against each other add together to produce large overall motion and flow. This means flow in the mantle is extremely slow, with movements of only a few cm per year.



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Glossary

Reference model – The approximate variation of how seismic wave speed changes with depth in the Earth which is used to predict the arrival times of waves. These arrival times are then compared to the actual arrival times in order to identify places where waves travel faster or slower than we'd expect.

Seismic waves – Vibrations (sound) which pass through the solid Earth, typically produced by earthquakes.

Seismometer – A sensitive instrument which measures the shaking of the Earth's surface caused by seismic waves.

Seismogram – The record of ground shaking with time produced by a seismometer.

Tomography – The creation of 3D images and 2D slices of the inside of a 3D object by measuring rays passing through it; for example, medical tomography of the body using x-rays or seismic tomography of the Earth using seismic waves.

Tectonic plates – Rigid plates that make up the Earth's crust, that move around the Earth's surface relative to one another, causing continents to move away from/towards one another.

Mantle plume – An area of hotter than usual mantle which rises upwards, and causes melting of the mantle beneath the base of the crust, resulting in volcanoes. Famous examples are beneath Hawaii and Iceland. This upwards movement of hot mantle is part of the convection of the mantle.

Subduction – The downwards movement of cold tectonic plates of the Earth's crust and upper mantle into the warmer mantle below. The movement of the cold mantle and crust downwards is part of the convection of the mantle.

Find out more

For more information about the research going on at the University of Cambridge, visit: deepearth.esc.cam.ac.uk

About the authors

Hero (pronouns: they / them)

I started my degree thinking that I was going to be a chemist, before realising how much I liked rocks! I'm primarily interested in the metamorphic minerals that make up the Earth's crust, and what they can tell us about geological processes. In my free time I like to sing, do science outreach, and go on the swings in the park.

Jenny (pronouns: she / her)

I am a research scientist specialising in deep Earth seismology. I am fascinated by how much earthquakes can teach us about our planet – and how much there is that we still don't understand. I work as an Assistant Professor at Durham University, where I teach students all about geophysics and how it can be used to understand the Earth.