Keeping the Earth's plates oiled

Earth’s surface is a very active place; its plates are forever jiggling around, rearranging themselves into new configurations. Continents collide and mountains arise, oceans slide beneath continents and volcanoes spew. As far as we know Earth’s restless surface is unique to the planets in our solar system. So what is it that keeps Earth’s plates oiled and on the move?

Scientists think that the secret lies beneath the crust, in the slippery asthenosphere. In order for the mantle to convect and the plates to slide they require a lubricated layer. On Mars this lubrication has long since dried up, but on Earth the plates can still glide around with ease.

Beneath continents the asthenosphere appears at around 150km depth, while under oceans it can be as shallow as 60km. Above the asthenosphere lies the lithosphere: a more rigid layer that includes the crust. By 220km depth the asthenosphere comes to an end and the mantle goes back to a less flexible state.

What makes the asthenosphere so slippery and why does it exist on Earth but not other planets? These are some of the key questions that have puzzled Earth scientists ever since plate tectonics was discovered, but only now are the answers starting to emerge. A combination of new experimental techniques and powerful computational theory is enabling scientists to work their way through the asthenosphere atom by atom.

Björn Winker, a mineralogist at the Johann Wolfgang Goethe University in Frankfurt, Germany, believes that the key to the asthenosphere is water. “We have to have water in the asthenosphere to get it plastically deforming,” he explains. This water is no longer in its liquid state, but is bound to oxygen in crystal structures to form hydroxyl (OH-) groups instead.

The question that really interests Winkler is ‘where does the water go’? Which minerals are clinging on to their hydrogen and enabling the Earth to perform its plate tectonic dance?

Unfortunately we can’t get samples from the asthenosphere – no-one has ever managed to drill a hole deep enough. But seismic wave patterns and magma spurting out of volcanoes give us clues as to which minerals make up the majority of the asthenosphere. Winkler finds samples of these candidate minerals on the Earth’s surface and, using specialist experimental equipment, subjects them to the pressures and temperatures estimated for the asthenosphere.

The diamond anvil cell is just one of the tools his group uses. A sample is placed between two diamonds and compressed, to reach pressures of 10GPa – one million times the pressure at the Earth’s surface. When these experiments are carried out at a synchrotron, which provides extremely bright x-ray radiation, he is able to use X-ray diffraction to analyse the way the sample behaves as the pressure is ratcheted up. “It is only possible to make these measurements at a synchrotron,” says Winkler. “Laboratory x-ray sources are far too weak for such experiments.” In other experiments infra-red radiation shines through the sample and makes the O-H bonds vibrate. By measuring how much of the infra-red radiation is absorbed by the sample Winkler can estimate how much water the sample contains and whether it manages to hold onto it as the pressure increases. However, spectroscopic measurements can’t reveal everything. “They can only give you a frequency. It is like trying to figure out a car’s problems from listening to the way it rattles,” says Keith Refson, a colleague of Winkler’s who is based at the CCLRC Rutherford Appleton Laboratory near Didcot in the UK.

Afterwards Winkler and Refson use powerful computer calculations to work out what the atoms are doing and where the water might be held within the structure. “With computer models we can calculate where the sample should rattle and match the theory with experiment,” says Refson.

Already Winkler and Refson have analysed a number of minerals in this way including ‘diaspore’ and ‘clinochlore’. “It was known previously that diaspore would not survive going into the asthenosphere, but we are able to use the knowledge we have gained and apply it to other minerals,” says Winkler. Meanwhile, clinochlore was found to be good at holding onto water, but showed some interesting changes in its structure at around 8GPa. “The nature of the hydrogen bonds start to change and the layers within the structure slide,” explains Refson.

These kind of results have been invaluable for Hans Keppler, a geologist at the University of Bayreuth in Germany. He has been trying to work out why the asthenosphere exists.

Previous theories have suggested that this ‘wet’ and slippery layer exists because minerals leave their water behind them when they melt and turn into magma. “This explains why the asthenosphere appears beneath oceans, but it doesn’t explain why we have an asthenosphere beneath the continents,” says Keppler. Lava continually bubbles up at mid-ocean ridges, but continental plates don’t have an equivalent spring of constant magma. It also fails to explain why there is a lower boundary to the asthenosphere.

Instead, Keppler has been investigating water solubility in the asthenosphere. Using a loaded piston cylinder apparatus he was able to heat and pressurise mixtures of aluminium-saturated enstatite (estimated to make up around 40 percent of the asthenosphere) and water to asthenosphere values. Similar experiments were also done with olivine (thought to make up around 60 percent of the asthenosphere).

What he found was that water solubility in olivine continuously increases with temperature and pressure, whereas in aluminium-saturated enstatite the solubility reaches a distinct minimum at asthenosphere temperatures and pressures. “It means that the mantle minerals cannot contain all the water and the excess water forms a hydrous silicate melt,” says Keppler, who presenting his findings at the 1st EuroMinScI Conference in La Colle-sur-Loup, France, in March this year. The presence of even small quantities of melt in a rock in known to drastically reduce its mechanical strength.

EuroMinScI is the European Collaborative Research (EUROCORES) Programme on “European Mineral Science Initiative” developed by the European Science Foundation (ESF).

The water solubility model explains why the asthenosphere has a lower boundary and why it exists under continental and oceanic plates. Once the aluminium-saturated enstatite passes through its minimum solubility it starts to absorb water again and deeper in the mantle (at higher pressures and temperatures) the mantle becomes dry once more – creating a lower boundary.

Meanwhile, temperatures increase more slowly underneath continents, meaning that the minimum water solubility zone for aluminium-saturated enstatite is not reached until a greater depth under continents, compared to oceanic plates. (see Fig 4 from the Science paper.)

For now the jury is still out on Keppler’s new model. “It is a very elegant, but simplified model,” says Winkler. “Essentially it is based on two minerals, which is definitely not the whole story. The question is, if we refine the theory and include a greater range of minerals will it change things much?”

Some scientists are quite hostile to Keppler’s water solubility model. “It puts a lot of people out of business,” says Keppler. Nonetheless, most people agree that the theory is consistent with what is known about the asthenosphere and that it can’t be discarded. “Only more experiments and calculations can reveal the truth,” says Winkler.

Source: European Science Foundation