

## Editorial

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In the last two editorials we have had very good exposure to MAGMA through invigorating interaction. In this issue another fascinating topic is selected for editorial. Length of the editorial has increased as it is an important topic containing various details.

### \*\*\*Plate Tectonics-revisited

Any study that involves a percentage of subjectivity needs to be re-evaluated using new data and new models that have taken into consideration the subjectivity based limitations. However, none can unequivocally state any of these refined models can provide ultimate answers to many questions posed earlier by the learned way back in 19<sup>th</sup> and 20<sup>th</sup> century. This enigmatic and intriguing reality allows earth science researchers to be active continuously both in the field, laboratory and before a computer, hoping to find apt solutions. As a part of subjective cutting edge research activity I have selected an interesting topic for this issue's main editorial-**Plate Tectonics**.

Our readers, young and senior, are informed about Plate Tectonics that gained worldwide significance nearly five decades back. However, a series of studies carried out in the recent past made me to bring out this editorial to excite the inquisitive researcher to go into details of various facets of the plate tectonics. I have collected some relevant information covering the basics and the recent studies and the same are detailed below.

The plate tectonics theory tries to explain the movement of the Earth's lithosphere. The Earth's surface is made up of a series of large plates that can travel up to 2 or 3 cm per year. Convection currents beneath the plates drive the plates in different directions; the source of the heat driving the convection currents is from the radioactive decay taking place within the Earth's core. The idea behind the plate tectonics theory originated from meteorologist Alfred Wegner's ideas of continental drift. He observed that the continents seemed to fit together like a jigsaw forming a super continent called Pangaea. Overall there are seven major plates: North America, South America, Eurasia, Africa, Indo-Australian, Pacific and Antarctica. Mantle convection, Earth rotation and gravity are all drivers of the movement. As these plates interact they form plate boundaries, which cause many different features to emerge.

### \*The Theory of Plate Tectonics

The basic theory of plate tectonics is that along seafloor spreading zones, the continents are separating from one another. As they spread apart, magma comes to the surface and becomes new continental crust. As the tectonic plates move away from spreading zones, they collide with one another. In some cases, the edges of two different plates will grind against each other in a horizontal fashion. These areas, called transform boundaries, experience many earthquakes. In other cases, the plates directly collide, forcing one plate upward while the other plate is forced back into the mantle. These collision areas, called convergent boundaries, create mountain ranges. An active convergent boundary is under the Himalayan Mountains, which are being created by the subduction of the Indian crust sliding under the Tibetan crust.

### Evidence for Plate Tectonic Theory:

**1. Sea Floor Magnetism:** Stripes of magnetic material in the seafloor provide strong evidence for tectonic theory. The stripes alternate between those with magnetic material orientated

toward magnetic north, and those oriented in the opposite direction. Seafloor spreading is the mechanism behind this phenomenon. As new magma forces its way up to the surface, magnetized minerals in the liquid rock orient along the Earth's magnetic field and then harden as the lava cools. As spreading continues, the material moves away from the spreading zone as if on a conveyor belt. The Earth's magnetic field flips every few hundred thousand years, and the stripes on the ocean floor show a record of those changes. By estimating when the flips occurred and pairing that with the distance the stripes have moved from the spreading zone, scientists can estimate how fast the continents are moving. This supports plate tectonic theory as it shows that there has to be plates for continents to move independently to each other.

**2. Fossil Evidence:** The continents have moved a great deal in the history of the planet, but they carry records of where they've been. Some of this evidence is the fossils of animals and plants. Palaeomagnetic evidence is a stronger piece of evidence. Magnetic strata within the fossil record show how the land masses were oriented at different times during Earth's history. By constructing detailed records of changes in land mass orientation, scientists can reconstruct paths of tectonic movement much further back in history than they can from the magnetic striping on the sea floor.

**3. Direct Measurement:** Modern technology gives us a range of ways to directly measure the movement of tectonic plates. These methods are based around the idea of measuring distance between two points on Earth by using some intermediary transmitter in space. Using these measurements, scientists can accurately estimate movement of the tectonic plates today.

### Evidence against Plate Tectonic Theory:

The evidence against is due to the mechanism of plate movement. This is because convection cell currents have not been proved conclusively to exist due to technological limitations. We have never been able to get deep enough into earth to prove the theory. The main fault in convection cell currents is the evidence collected, which suggests that these cells are impossible to occur. Their occurrence is only supported by theory. More questions have surfaced about the formation of plates and how energy is gained through convection to move truly slabs of rock. Finally convection cell currents do not have the force to form mountain ranges such as the Andes and Himalayas.

(Source: <http://education.seattlepi.com/list-describe-evidence-plate-tectonics-theory-5600.html>;  
<http://mrrudgegeography.weebly.com/plate-tectonic-theory.html>)

Researchers added to the above by stating that much of the theory based on continuing observations of the sea floor and continental margins. The initial determination was that, as the continents spread apart, new oceanic crust is formed at the mid-oceanic ridges. But what happens to it then? Somewhere it has to be consumed. If not, the earth would have to keep getting bigger to accommodate the additional crust (Originally proposed, but generally discounted). Earth would have had to start out real small if spreading rates historically approached today's rates. Harry Hess in the early 1960's Proposed that old oceanic crust is consumed at island arcs. Amidst plausible supporting evidences major opposition emerged questioning what causes the plates to move? This always been the weak point of the theory and the rallying cry of the non-believers.

Lots of possibilities have been proposed. Lunar drag; Centrifugal pull due to rotational velocity (these first two were Wegener's original proposal-Demonstrated to be too small); Gravitational sliding away from the topographic highs of the spreading centers; Expansion of the earth-Possible mechanism to start it off; Lithosphere cracks; New material rises to fill the void; Density differences between descending lithosphere; mantle drags plate behind; Pulls open at the ridges-Slab-pull, ridge-push; Mantle Convection. Currently popular theory-Most probably a combination of several of the above, as well as others not imagined yet.

(Source: [http://jersey.uoregon.edu/~mstrick/RogueCom/College/RCC\\_Lectures/ConDrift\\_PlateTec.html](http://jersey.uoregon.edu/~mstrick/RogueCom/College/RCC_Lectures/ConDrift_PlateTec.html))

As stated in the beginning when there is subjectivity in our proposals/theories scores of knowledgeable researchers make it a point to find apt solutions. Some of the recent studies are listed below to show where we stand with regard to Plate Tectonics.

#### **\*Plate tectonics on the early Earth: Limitations imposed by strength and buoyancy of subducted lithosphere**

The tectonic style and viability of modern plate tectonics in the early Earth is still debated. Field observations and theoretical arguments both in favour and against the uniformitarian view of plate tectonics back until the Archaean continue to accumulate. Authors of a study published in "Lithos" presented the first numerical modelling results that address for a hotter Earth the viability of subduction, one of the main requirements for plate tectonics. A hotter mantle has mainly two effects: 1) viscosity is lower, and 2) more melt is produced, which in a plate tectonic setting will lead to a thicker oceanic crust and harzburgite layer (**PS:** Harzburgite is an ultramafic, igneous rock, a variety of peridotite consisting mostly of the two minerals, olivine and low-calcium (Ca) pyroxene (enstatite). Harzburgite layers play significant role in the morphology of subducting plates and the behavior of oceanic crustal layers).

Although compositional buoyancy resulting from these thick crust and harzburgite might be a serious limitation for subduction initiation, modelling results show that eclogitization significantly relaxes this limitation for a developed, ongoing subduction process. Furthermore, the lower viscosity leads to more frequent slab break-off, and sometimes to crustal separation from the mantle lithosphere. Unlike earlier propositions, not compositional buoyancy considerations, but this lithospheric weakness could be the principle limitation to the viability of plate tectonics in a hotter Earth. These results suggest a new explanation for the absence of ultrahigh-pressure metamorphism (UHPM) and blue-schists in most of the Precambrian: early slabs were not too buoyant, but too weak to provide a mechanism for UHPM and exhumation.

(Source: Jeroen van Hunen and Arie P. van den Berg, *Lithos*, Volume 103, Issues 1-2, June 2008, 217-235)

#### **\*Tiny Mineral Grains Could Drive Plate Tectonics**

The idea of plate tectonics—that Earth's plates smash into each other to form mountains, slide underneath one another to form ocean trenches, and pull apart to form new oceans and continents—is well known. The underlying mechanism driving these processes, which scientists think may be vital to the evolution of life, remains unclear. No one knows for sure how plate tectonics even evolved.

At a global scale, individual plates can be easy to see—their borders are defined by where earthquakes occur. Global perspectives have also allowed scientists to precisely map

the movement of plates over millennia by tracking magnetic signatures on the bottoms of the oceans. In addition, vast networks of GPS receivers can also track minute movements of plates today.

To fully understand plate tectonics, we need to zoom in from the global scale into the microscale. However, investigating the factors that first triggered plate tectonics requires a different perspective, said David Bercovici, a geophysicist from Yale University.

At many plate boundaries, scientists find a metamorphic rock made of deformed, very fine grained minerals called mylonite. The origin of mylonite is still unknown. The grains within mylonite are much smaller than the rocks in the plates around them, which makes mylonite relatively weak. Because of this relative weakness, mylonite seems to support or permit very, very rapid, focused deformation. Bercovici and colleagues suggest that the small-grained mylonite fuels a feedback mechanism that creates the weak spots on Earth that we know as active plate boundaries. As you deform [mylonite], somehow the grains in rocks become so small that it softens the rock up, and softened rock supports rapid deformation to allow you to have these plate boundaries. Small-grained mylonite fuels a feedback mechanism that creates the weak spots on Earth that we know as active plate boundaries. Scientists remain in the dark about exactly how mylonite forms at a granular level. However, decades of collaborative research gave Bercovici's team an idea.

In most rocks, minerals grow grain by grain, gobbling up the grains next to them—much like how the bubbles in foam get bigger by "eating" neighbouring bubbles. When a growing mineral grain swells up against a different type of mineral, its growth is blocked by the boundary between the two minerals in a process called "pinning." This process forces the grains into smaller and smaller sizes by further damaging the grain-to-grain interface.

As the grains get smaller and smaller, the resulting mylonite gets weaker and weaker. "By damaging the [grain] interface, we can drive the grains to smaller sizes and therefore get the self-softening feedback mechanism," Bercovici said.

#### **Origins of Plate Boundaries**

The last piece of the puzzle required a peek back in time—via exhaustive research on samples of 4.4-billion-year-old zircon. Zircon forms when granites crystallize from magma heated by the hot fluids that sweat off subduction zones.

The age of the zircon falls as much as 1 billion years before scientists think plate tectonics became a global phenomenon. This presents a puzzle—how did a mineral known to form from subduction processes crystallize before subduction became mainstream? Bercovici speculates that primitive subduction zones might have formed on Earth's surface early in its history, when cool, heavy mantle rock near the surface began to drip down deeper into the mantle, pulling overlying crust down with it.

Bercovici applied his theoretical model of mylonite formation to simulations that mimicked the formation of subduction zones. He found that where primitive subduction formed, a mylonitic-type weak zone formed. When the drip-like subduction ceased and started again elsewhere, it left behind a weak zone that would persist without healing for many millions of years.

Although the research may be the first to show how initial damage in surface plates can propagate through tectonic cycles,

it needs to be tested using more realistic rock mechanics, said Jun Korenaga, professor of geophysics at Yale University. Although Bercovici's work gives clues about how plates on Earth started to move, it does not solve the plate tectonic mystery completely. For example, what happens when two continents collide? In the future, Bercovici hopes to include the effects of continent-to-continent interaction in his models of mylonite-induced tectonics.

(Source: Wendel, J. (2015), Tiny mineral grains could drive plate tectonics, *Eos*, 96, doi:10.1029/2015EO024967.)

Another interesting article was published recently, keeping the dialogue interesting.

### **\*Heat from earth's core could be underlying force in plate tectonics**

For decades, scientists have theorized that the movement of Earth's tectonic plates is driven largely by negative buoyancy created as they cool. New research, however, shows plate dynamics are driven significantly by the additional force of heat drawn from the Earth's core. The new findings also challenge the theory that underwater mountain ranges known as mid-ocean ridges are passive boundaries between moving plates. The findings show the East Pacific Rise, the Earth's dominant mid-ocean ridge, is dynamic as heat is transferred. David B. Rowley, professor of geophysical sciences at the University of Chicago, and fellow researchers came to the conclusions by combining observations of the East Pacific Rise with insights from modeling of the mantle flow there.

"We see strong support for significant deep mantle contributions of heat-to-plate dynamics in the Pacific hemisphere," said Rowley, lead author of the paper. "Heat from the base of the flow of heat in the mantle and to the resultant plate tectonics." The researchers estimate up to approximately 50 percent of plate dynamics are driven by heat from the Earth's core and as much as 20 terawatts of heat flow between the core and the mantle. Unlike most other mid-ocean ridges, the East Pacific Rise as a whole has not moved east-west for 50 to 80 million years, even as parts of it have been spreading asymmetrically. These dynamics cannot be explained solely by the subduction -- a process whereby one plate moves under another or sinks. Researchers in the new findings attribute the phenomena to buoyancy created by heat arising from deep in the Earth's interior. "The East Pacific Rise is stable because the flow arising from the deep mantle has captured it," Rowley said. "This stability is directly linked to and controlled by mantle upwelling," or the release of heat from Earth's core through the mantle to the surface. The Mid-Atlantic Ridge, particularly in the South Atlantic, also may have direct coupling with deep mantle flow, he added.

Some researchers pointed out that the consequences of this research are very important for all scientists working on the dynamics of the Earth, including plate tectonics, seismic activity and volcanism.

### ***The forces at work***

Convection, or the flow of mantle material transporting heat, drives plate tectonics. As envisioned in the current research, heating at the base of the mantle reduces the density of the material, giving it buoyancy and causing it to rise through the mantle and couple with the overlying plates adjacent to the East Pacific Rise. The deep mantle-derived buoyancy, together with plate cooling at the surface, creates negative buoyancy that together explain the observations along the East Pacific Rise and surrounding Pacific subduction zones. A debate about

the origin of the driving forces of plate tectonics dates back to the early 1970s. Scientists have asked: Does the buoyancy that drives plates primarily derive from plate cooling at the surface, analogous with cooling and overturning of lakes in the winter? Or, is there also a source of positive buoyancy arising from heat at the base of the mantle associated with heat extracted from the core and, if so, how much does it contribute to plate motions? The latter theory is analogous to cooking oatmeal: Heat at the bottom causes the oatmeal to rise, and heat loss along the top surface cools the oatmeal, causing it to sink. Until now, most assessments have favored the first scenario, with little or no contribution from buoyancy arising from heat at the base. The new findings suggest that the second scenario is required to account for the observations, and that there is an approximately equal contribution from both sources of the buoyancy driving the plates, at least in the Pacific basin.

Based on models of mantle convection, the mantle may be removing as much as half of Earth's total convective heat budget from the core," Rowley said. Much work has been performed over the past four decades to represent mantle convection by computer simulation. Now the models will have to be revised to account for mantle upwelling, according to the researchers.

The research could have broader implications for understanding the formation of the Earth. It has important consequences for the thermal budget of the Earth and the so-called 'secular cooling' of the core. If heat coming from the core is more important than we thought, this implies that the total heat originally stored in the core is much larger than we thought.

Also, the magnetic field of the Earth is generated by flow in the liquid core, so the findings of Rowley and co-authors are likely to have implications for our understanding of the existence, character and amplitude of the Earth's magnetic field and its evolution through geological time. (Citation: David B. Rowley, et al. Kinematics and dynamics of the East Pacific Rise linked to a stable, deep-mantle upwelling. *Science Advances*, 2016; 2 (12): e1601107 DOI: 10.1126/sciadv.1601107).

### **Increase in the Mantle Temperature**

It is stated in the previous sub-section that the mantle may be removing as much as half of Earth's total convective heat budget from the core. However, if the mantle temperature is higher than normally believed the picture may change. The mantle - the mostly solid, rocky part of Earth's interior - is about 60 degrees Celsius hotter than previously thought, a new study has found. The findings led by Woods Hole Oceanographic Institution (WHOI) in the US could change how scientists think about many issues in Earth science including how ocean basins form. A 60-degree increase may not sound like a lot compared to a molten mantle temperature of more than 1,400 degrees Celsius, researchers said.

However, the result is significant as a hotter mantle would be more fluid, helping to explain the movement of rigid tectonic plates.

Since it is not possible to measure the mantle's temperature directly, geologists have to estimate it through laboratory experiments that simulate the high pressures and temperatures inside the Earth. Water is a critical component of the equation: the more water (or hydrogen) in rock, the lower the temperature at which it will melt.

The peridotite rock that makes up the upper mantle is known to contain a small amount of water. To figure out how the water content of mantle rock affects its melting point, a researcher (Emily Sarafian), conducted a series of lab experiments.

Following standard experimental methodology, she created a synthetic mantle sample. She used a known, standardised mineral composition and dried it out in an oven to remove as much water as possible. She modified her starting sample by adding spheres of a mineral called olivine, which occurs naturally in the mantle. The spheres were large enough for her to analyse their water content using secondary ion mass spectrometry (SIMS). From there, she was able to calculate the water content of her entire starting sample. To her surprise, she found it contained approximately the same amount of water known to be in the mantle.

Based on her results, she concluded that mantle melting had to be starting at a shallower depth under the seafloor than previously expected. To verify her results, she made use of magnetotellurics - a technique that analyses the electrical conductivity of the crust and mantle under the seafloor. Reconciling the temperatures and pressures she measured in her experiments the melting depth from an earlier study. It led her to a startling conclusion: The oceanic upper mantle must be 60 degrees Celsius hotter than current estimates. (Source: INDIA TODAY NEWS, 5th March, 2017).

Adding spice to the debate another study surfaced to motivate Indian researchers.

#### **\*India was by no means as isolated as Plate Tectonists thought**

India harbours many unique species of flora and fauna that only occur in this form on the subcontinent. The prerequisite for such a unique development of species is that no exchange takes place with other regions. For a long time, scientists assumed that India was isolated in this way due to continental drift. The supercontinent Gondwana, which included South America, Africa, Antarctica, Australia, Madagascar and India, broke up over the course of geological history. What is now India also began moving towards the north east around 130 million years ago. It was common belief among researchers that, before it collided with the Eurasian plate, India was largely isolated for at least 30 million years during its migration. However, according to current findings by paleontologists at the University of Bonn, the Indian subcontinent may not have been as isolated on its journey as we have thought. "Certain midges that occurred in India at this time display great similarity to examples of a similar age from Europe and Asia," says lead author. These findings are a strong indicator that an exchange did occur between the supposedly isolated India, Europe and Asia.

#### **Mining for amber in the Indian coal seams**

A scientist from the University of Bonn mined for amber in seams of coal near the Indian city of Surat. Small midges, among other things, were encased in tree resin 54 million years ago and preserved as fossils. The paleontologist investigated a total of 38 biting midges encased in amber and compared them with examples of a similar age from Europe and China. Scientists from the University of Gdansk (Poland) and Lucknow (India) were also involved in this. It has been possible to assign a total of 34 of these insect fossils to those that are already known. There was significant conformity with biting midges in amber from the Baltic and Fushun in north-east China.

#### **Chains of islands presumably created a link to India**

Scientists assume that a chain of islands that existed at that time between India, Europe and Asia could have helped the biting midges to spread. As if from stepping stone to stepping

stone, the insects could have gradually moved forward along the islands.

(Source: Stebner et al. 2017, Jes Rust. Biting Midges from Cambay Amber Indicate that the Eocene Fauna of the Indian Subcontinent Was Not Isolated. *PLOS ONE*, 12 (1): e0169144 DOI: 10.1371/journal.pone.0169144)

From the basic studies carried out five decades back and many interesting more recent studies (some are given above) it is clear that researchers have to adapt to a changed perception, namely, look at micro level to understand the basic mechanism underlying Plate Tectonics. In other words try to see a grain of rock as the main component and formation of mylonite as the vital source in initiating and sustaining Plate Tectonics. We find it difficult to invoke in real time the role of forces associated with the slabs of rocks and mammoth crustal segments to understand the basic mechanism responsible for the plates to move, slide and subduct. The strongest part of the lithosphere that has to be softened, which is thus, the plate tectonic bottle-neck (as proposed by Bercovici) is the cold ductile region, below where failure and frictional sliding become ineffective. This is at about 50-100km in depth and ranging mostly around temperatures of 1000K. It turns out that rocks in deformation zones exhumed from these depths and temperatures exhibit very localized deformation and at the same time unusual grain-size reduction. In summary Bercovici would say that the main features of **plate tectonicness**, are (1) one-sided subduction of tectonic plates that involves entraining surface material (and from this the other unique feature of continental crust pops out), (2) focussed but passive divergent zones or spreading centers, and (3) significant strike-slip motion. If we want to recognize plate tectonics in all its glory on another planet or identify how, when and why it started on Earth, we need to find these features. But, then it also helps to understand why we have these features at all. This debate goes on and on, until theory is supported by in situ experiments; a reality in an unspecified time scale. As micro and macro structures tell us the striking similarity, a section of a leaf and a sea of cosmic world (full of galaxies, dark matter and innumerable number of unknown features) let us enjoy the beauty of William Blake's quote about a grain of sand: "**To see a world in a grain of sand and heaven in a wild flower Hold infinity in the palms of your hand and eternity in an hour.**"--William Blake.

#### **\*In this issue & status of JIGU**

In this issue apart from editorial and news at a glance we have 7 research publications. I place on record our thanks to authors for communicating good articles for publication in JIGU. I am indebted to learned scientists for sparing their valuable time in reviewing the manuscripts, following ethical norms. Couple of editorial board members extended their unequivocal support and help in editing the manuscripts and providing useful inputs for authors (especially students and young researchers) to enhance quality of the manuscripts. I am trying to meet various norms with my limited capabilities. Since I wish to be relatively stress free I seek the help of one and all to share more responsibility in managing the journal, by voluntarily monitoring day to day activities of JIGU, especially when I am not in a position to visit JIGU office.

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