What Would Happen If Plate Tectonics Stopped Tomorrow?

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Abstract: As our only home in the universe so far, the Earth is currently more than 4.5 billion years old. The Earth is the only silicate planet we know which experiences plate tectonics. As a unique way to release heat energy, plate tectonics plays a critical role in moulding our Earth, almost everything of our planet is closely connected to it. However, as the Earth keeps cooling down from its birth, plate tectonics would disappear one day in the future, which would lead to the greatest cataclysm in the history. Without plate tectonics, the Earth would be withered and freezing planet of death, with a great possibility to suffer from another snowball Earth.

Keywords: Plate Tectonics; Subductions; Volcanism; Crustal Evolution; Mantle Differentiation; Environmental Changes

Introduction

Earthquakes, tsunamis and volcanisms, all of these geological activities are closely connected with global plate tectonic. Plate tectonic is the lateral motion of Earth's thermal boundary layer (lithosphere) over the asthenosphere and is mostly driven by the sinking of lithosphere within subduction zones. Plate tectonics could be used as an excellent example of a self-organizing driven by the negative buoyancy of the lithosphere and controlled by the elimination in the viscous lithosphere and asthenosphere[1]. Plate tectonics is a special way for a silicate planet to lose heat, it exists on the Earth only within the solar system, which contains five large silicate bodies in total (Mercury, Venus, Earth, Mars and Moon)[2]. Abe[3] suggested that all silicate planets probably had a magma ocean stage for a short time. After it is solidified, stagnant-lid would be the most common mode of planetary heat loss, together with inner heat loss by delamination and shallow intrusions of magma. Being created by decompression melting, the lithosphere of earlier and hotter Earth is different than the modern one, with thicker oceanic crust and thinner mantle lithosphere. Bédard[4] illustrated that such lithosphere would take much longer time to become negative buoyancy than today, therefore plate tectonics happened occasionally on early Earth, if at all. Plate tectonics turned to the modern style when the Earth is cooled down sufficiently after tens of millions of years that decompression melting beneath spreading ridges made thinner oceanic crust， allowing oceanic lithosphere to be negatively buoyancy[1].

This paper will firstly discuss on the initial of plate tectonics, including its principles, secondly show what does it include and why it is so important, and finally illustrate the destiny of the Earth without plate tectonics.

1. The initial of plate tectonics

1.1 What is plate tectonics? What makes the plates move?

To figure out the very beginning of plate tectonics, we need to know what exactly it is. According to Cox A.[5], plate tectonics describes how lithospheric sectors move and interact across Earth's nearly spherical surface. Absolute or relative reference frames are used to describe plate motions, with a rotation pole and angular velocity.

Plate motions ultimately result from the negative buoyancy of the lithosphere subducting from ridges towards trenches and sinking within subduction zones[6]. Lithosphere itself is buoyant when firstly being formed by spreading at a mid-ocean ridge. However, oceanic crust alone is less dense than asthenosphere, but the mantle part of the lithosphere is colder and therefore denser than asthenosphere, therefore, as oceanic lithosphere thickens by cooling of the upper mantle, bulk lithosphere density would increase progressively as it ages[7]. The result of this would be a buoyancy crossover, where oceanic lithosphere becomes denser than the underlying asthenosphere. The negative buoyancy of aging oceanic lithosphere provides the potential energy that powers plate tectonics. Buffett B.A. and Rowley D.B.[8] pointed out that sinking of the lithosphere in subduction zones controls plate motions in two different ways: by directly pulling on the plate (slab pull); and by the entrainment of surrounding mantle (slab suction). The sinking of lithosphere in subduction zones is resisted by dissipation forces within the lithosphere, plus viscous resistance of the asthenosphere (Figure 1).

In summary, modern plate tectonics is characterized by quite deep subductions. Tomographic images show that some subducting slabs can be traced down to 1100 – 1300km. There is also a strong agreement among geodynamicists that plate tectonics and subduction drive mantle convection[1].

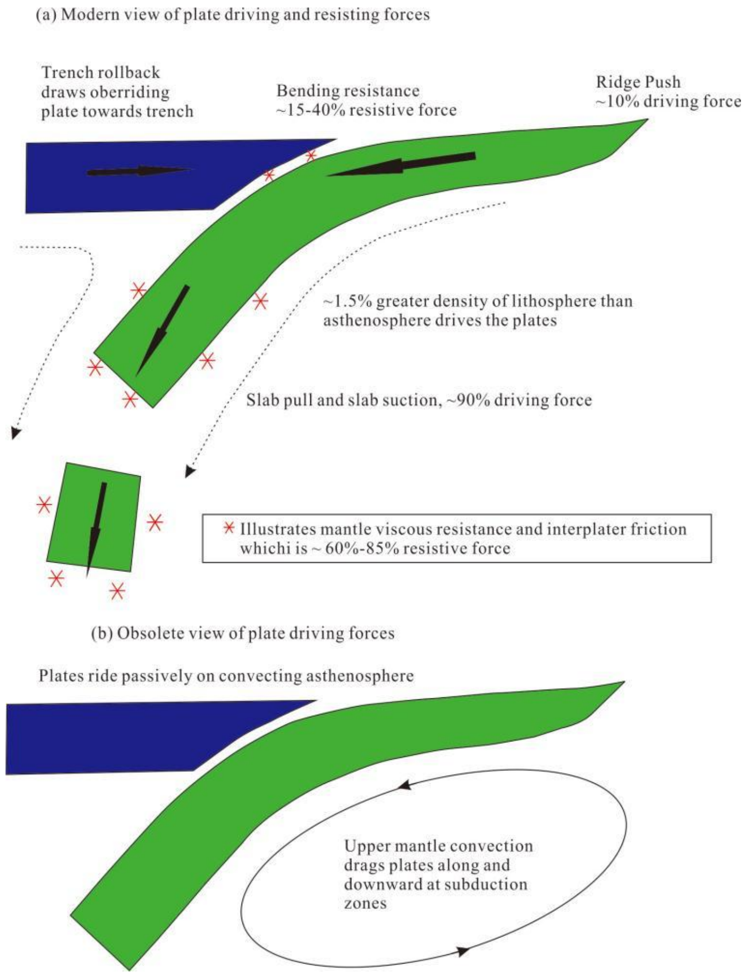

Figure 1 *Summary diagram of plate-driving forces. (a) Modern view of plate-driving forces; (b) obsolete view of plate-driving forces. Diagram modified after Stern R.J. (2007).*

1.2 Physical requirements for plate tectonics

Based on the current fact that the negative buoyancy of old oceanic lithosphere drives plate motions, we must understand how lithospheric density has changed as the Earth cooled down over the last 4.5 Ga if we want to understand when plate tectonics began. A significant fraction of the lithosphere became gravitationally unstable is necessary for plate tectonics to start. The instability of lithosphere is important but not sufficient, because lithosphere needs to be weak enough to be ruptured and bend, yet stronger enough to maintain coherence from spreading ridge into the subduction zones[9].

Stern R.J.[10] suggested that oceanic lithospheric density is mostly determined by its age. The thickness and the composition of oceanic crust are controlled by the mantle potential temperature (T_p), which determines how much melting accompanies a given amount of mantle upwelling. The T_p of the Archean earth was dramatically higher than modern mantle by perhaps 300-500^{o}C. Thicker oceanic crust would be generated by seafloor spreading and decompression mantle melting of the Archean Earth, which would result in more buoyant lithosphere[11]. Conductive cooling and thickening is a function of age, oceanic lithosphere should finally become unstable relative to asthenosphere, although for a hotter and younger Earth this may take even hundreds of millions of years comparing to about 20-40 million years today[12].

Mei S. and Kohlstedt D.L.[13] pointed out another significant consideration – water. The fact that most of active plate boundaries on the Earth are underwater may be the reason why we have plate tectonics while other silicate planets do not. They suggested that water could weaken rocks, lower their melting points and lowers the strength of the lithosphere as well as the viscosity of the mantle.

1.3 Five stages of Earth's evolution

Based upon numbers of previous works, the crustal and tectonics evolution of the Earth could be described in five various stages. The first stage, as Kamber et al.[14] and Kamber[15] suggested, included the initial accretion of the Earth, core and mantle differentiation and the development of the magma ocean. At this stage, the earth should have an undifferentiated mafic crust. They suggested that the magma ocean may exist for 5-10 Ma, with continuing volcanism and deformation would have gradually thickened the original mafic crust. The second stage was marked by elevated mantle temperatures compared to today that resulted in lithosphere weakened due to the replacement of melts[16]. Moore and Webb[17] suggested that this restrained subduction, hence plate tectonics, and magmatism were driven by upwellings within the mantle that percolated the lithosphere. They also suggested that these might have been associated with mantle plumes at depth. Besides, destruction and recycling of the early crust also occurred in the second stage. According to Johnson et al.[18] and Marchi et al.[19], this happened through a combination of delamination and meteorite impact. The stabilization of Archean cratons and the change in crustal growth rate ca. 3.0 Ga were highlighted in stage 3. Sizova et al.[16] suggested that the Earth had cooled efficiently for subduction to take place from ca. 3.0 Ga to ca. 1.7 Ga. There was thicker and more evolved continental crust, plate tectonics resulted in collisional orogenies and more developed supercontinent cycles. Erosion to the oceans was also increased because of the thickening and subaerial exposure of continental crust, resulting in an increase in Sr isotope ratios in seawater[20]. Referred to Holland[21], the forth stage was from 1.7 to 0.75 Ga as the "boring billion" and more recently as Earth's middle age. The overlying continental lithosphere was strong enough to be thickened and to support the emplacement of large plutons into the crust, yet the underlying mantle was still warm enough to result in widespread melting of lower thickened crust and the generation of anorthositic magmas[22]. The final stage is featured by a strongly episodic distribution of ages linked to the supercontinent cycles of Gondwana (Figure 2) and Pangea and the development of "cold" subductions. Oxygen levels in both the atmosphere and deep oceans were increased, phosphate and evaporate deposits became widespread, which provided the major support for metazoan evolution[23].

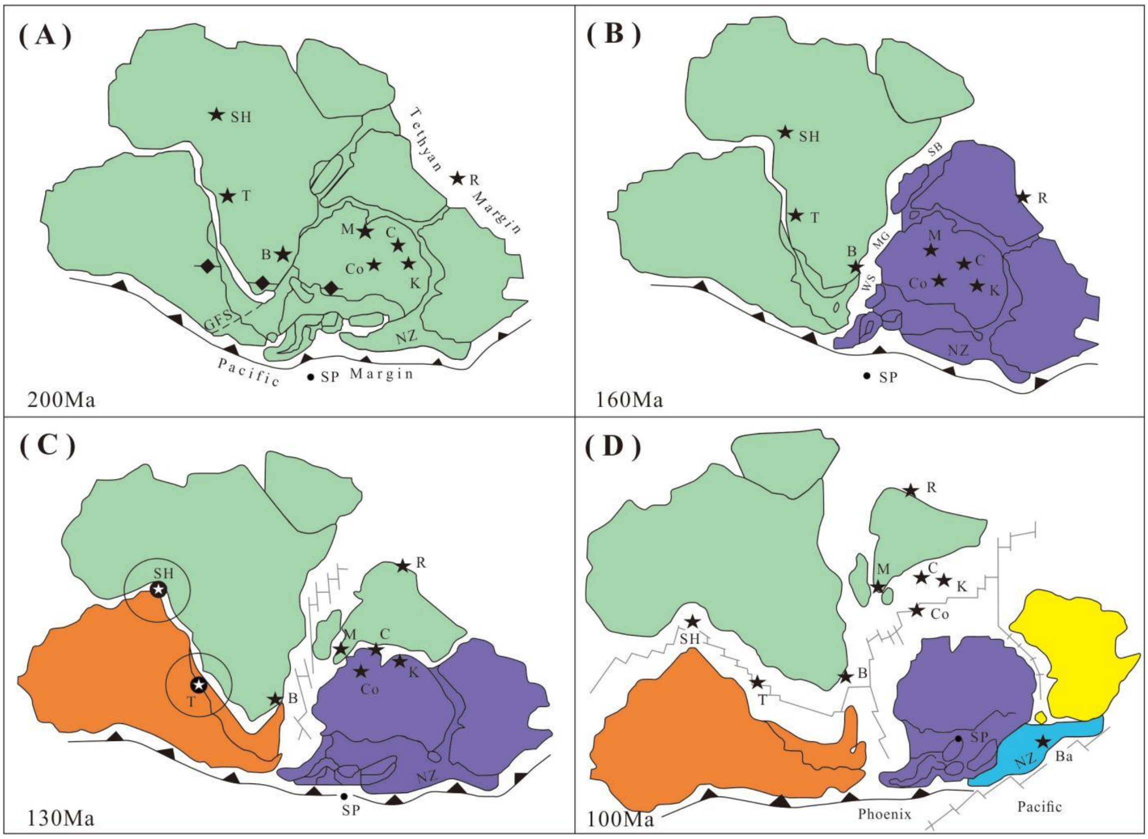

Figure 2 *Gondwana reconstructions during the last 200 Ma. Shown also are subduction zones (barbed lines), major hotspots (stars), and inferred sizes of plume heads (circles). Ocean ridges are diagrammatic. Modified after Condie K.C. (2016)[24].Abbreviations: Ba, Balleny; B, Bouvet; C, Crozet; Co, Conrad; K, Kerguelen; M, Marion; R, Reunion; SH, St Helena; T, Tristan, GFS, Gastre Fault System; MB, Mozambique Basin; NZ, New Zealand; SB, Somali Basin; SP, South Pole; WS, proto-Weddell Sea.*

2. The future world

2.1 An end to volcanism

If plate tectonics stops, so does the sea floor spreading, which will stop numbers of volcanic eruptions that occur on the Earth. Mountains and mountain chains would cease to rise[25]. According to Rino S.[26], their height would finally be eroded away. Eventually, mountains in the world would be reduced to sea level. The problem now is how long would it take. Based on Hawkesworth and Kepm[27], this problem is much more complicated than simply calculate the number of years required for the mountains to disappear by measuring average erosion rates. Because of the principle of isostacy, mountains and continents are a bit like icebergs: when the top is cut off, the bottom would rise up relative to sea level, leading to the rise of the entire mountain. Ultimately, however, even the isostatic effect would be overcome by the extent of erosion[28].

What would the sea level be without plate tectonics? All of the sediments produced by the simultaneous erosion of the mountain and continent on the Earth would have to go to the ocean, and the eroded contents would be carried into the ocean through river and wind transport, which would eventually displace seawater and lead to global sea level rise[29]. Finally, the entire Earth might be covered by a global ocean, although it would be much shallower than today.

2.2 Change on habitable environment

Carbon dioxide would be removed from our atmosphere, leading to the freeze of the Earth. With the continents where nearly all terrestrial creatures live being eroded away, the Earth would witness a mass extinction which would be more catastrophic than any in the past[30]. All land life would die off under water. Paradoxically, the increase of ocean area would probably also be accompanied by mass extinctions in the sea. On the other hand, ocean life depends on nutrients, while most nutrients come from the continent through rivers and streams into the ocean. Therefore, with the mass loss of land, the total amount of nutrients would eventually lessen and there would be fewer marine creatures.

The range of temperature that Earth has is resulted from numbers of results, including the effect of atmosphere. If the Earth did not have its appreciable atmosphere, including gases such as water vapour and carbon dioxide, its temperature would be similar to the Moon (-18^{o}C). However, the Earth has an average temperature of 15^{o}C thanks to greenhouse gases. Therefore, we could deduce that if plate tectonics stops, there would be much less carbon dioxide released from ocean ridges, which would cause global temperature to drop dramatically[31]. The lack of atmosphere could also increase the possibility of comet impacts and the harm of UV light, where the former could cause greater extinctions or even destroy the Earth itself.

3. Conclusion

Plate tectonics is one of the presences of planetary cooling, and so far it is shown on the Earth only. At the beginning of the Earth's history, there was deduced a magma ocean stage, which did not last long, followed by a stagnant-lid stage. The Earth kept cooling down, and plates were developing meantime. When the Earth was efficiently cooled in the Neoproterozoic, modern plate tectonics was finally formed, and that should be treated as the start of plate tectonics today. The Earth would eventually lose all its heat someday in the future, and that would be the end of the entire plate tectonics – all process would be stopped. Most things we know today would be greatly affected: mountains would be eroded, sea level will rise dramatically, which would lead to serious loss of continents; CO_2 emission at mid ocean ridge would be dramatically decreased, which could be one of the reasons of global temperature drop. The Earth might suffer another snowball earth due to the huge drop of average temperature, and this would certainly cause the most serious mass extinction the Earth have witnessed so far. In short, if all plate tectonics ends, the Earth will become similar to the Moon, or even worse.

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