Author’s response to the reviewer’s comments

We (as author) sincerely appreciate the reviewer for providing these comments on this manuscript. Below, we address all of these comments line by line. The reviewer’s comments are displayed in bold font, while the author’s response to them is displayed in nonbold font.

Reviewer’s report:

1. This is not a physically viable hypothesis.

We will echo this comment latter.

2. Because the density of the continents is larger than the density of water, it is the continents that would push the water, not the other way around.

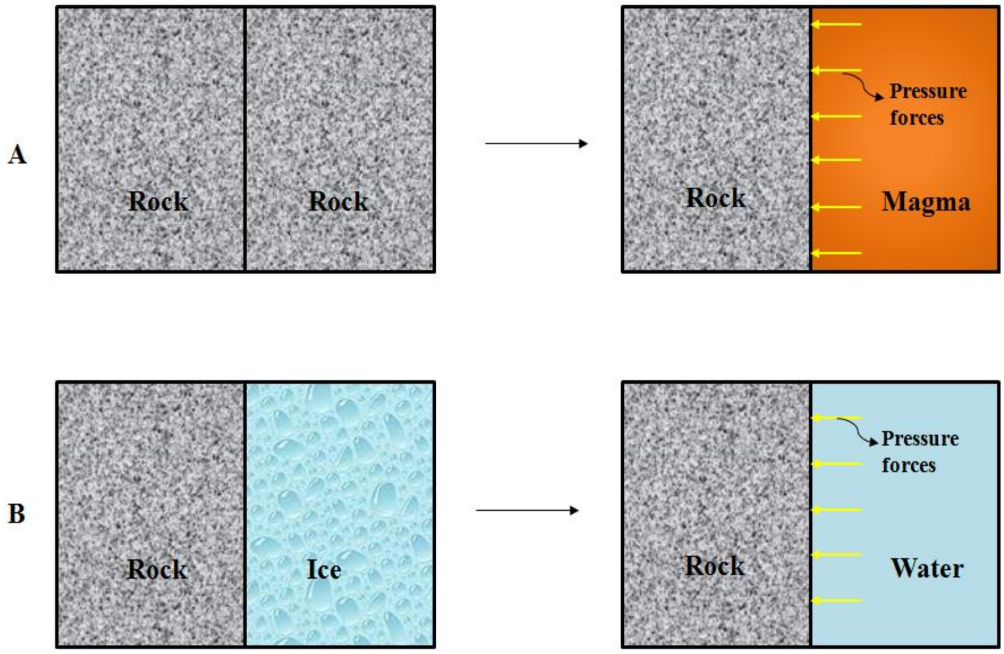
We thank the reviewer for providing this comment. Nevertheless, we acknowledge that the issue raised in this comment may require further attention.

First and foremost, fluid mechanics dictates that water pressure applied to the wall of a container generates a force that pushes the container's wall. This principle has been established for centuries. For further information on this topic, please refer to the book by Cengel and Cimbala (2014). Similarly, oceanic water pressure against the continent's wall produces a force that pushes the continent's wall. Liquid pressure differs from solid pressure in that the former arises from the weight and movement of liquid molecules, whereas the latter arises solely from the weight of solids. Additionally, the pressure at any given point within a liquid, such as water, is equal in all directions, unlike in a solid where the pressure is not uniform in all directions. Although continents are denser than oceans, their rocky materials are highly viscous and resistive, making it difficult for them to flow easily. Conversely, the low viscosity of ocean water allows water molecules to flow freely. This structural difference between the two materials explains why solid (rock) can maintain its shape, while liquid (water) conforms to the container holding it.

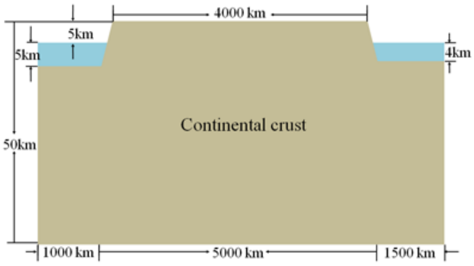
In general, discussing the topic of force involves two objects: the force exerting object and the object receiving the force. For a force to transfer from one object to another, the first object must move and change its position to apply force on the second object. Hence, without movement from continents, there can be no exertion of force on ocean water. Newton’s third law states that when an object is pushed, it pushes back with equal force. This implies that as ocean water pushes the continents, the continents push back on the ocean water in response. However, there exists a difference between the two types of force, whereby the former is active while the latter is passive.

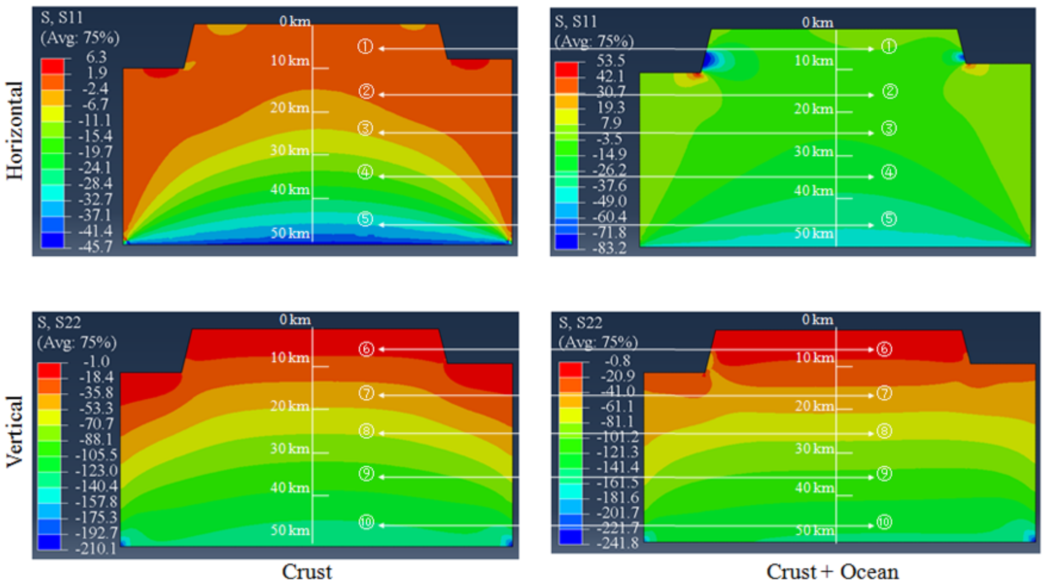
Second, we have engaged in private communication with Dr. John M. Cimbala regarding the question of whether ocean water is responsible for pushing the continents. We have received a response from him: “*Think about an empty tea cup sitting in a vacuum chamber with zero pressure. There is certainly internal pressure in the walls of the tea cup. However, those walls do not exert any kind of pressure or force on the surroundings (which is a vacuum). And the cup stays the same shape and holds its shape regardless of its surroundings. Now take the cup out of the vacuum chamber and into the air. Now air exerts a pressure on the cup walls. The cup walls* *exert and equal and opposite pressure on the air due to Newton's third law. Now fill the cup with water. The pressure inside the cup increases, and the cup expands ever so slightly, but it still maintains its shape. The cup exerts pressure on the water and vice-versa. But it is the water that causes this pressure, not the cup. Water is a liquid and cannot maintain its shape unless it is in some kind of container. That is where the pressure comes from.*"

Third, the conceptual model presented below explains why fluids have the ability to push solids. Initially, two rocks that are in contact with each other on the ground experience no horizontal force between them. However, if one of the rocks were to be melted into magma, based on the principles of fluid mechanics, the magma would exert a horizontal pressure force on the other rock, even though the density of the magma is slightly less than that of the rock. Similarly, if a rock and a piece of ice were to be placed in contact on the ground, there would be no horizontal force between them. However, if the ice were to melt into water, according to the principles of fluid mechanics, the resulting water would exert a horizontal pressure force on the rock, even though its density is less than that of the rock. The reason for these fluids to push denser solids is that the components of these fluids are highly capable of flowing. If there were no obstacle from the rock, these fluids would flow or collapse towards the ground.

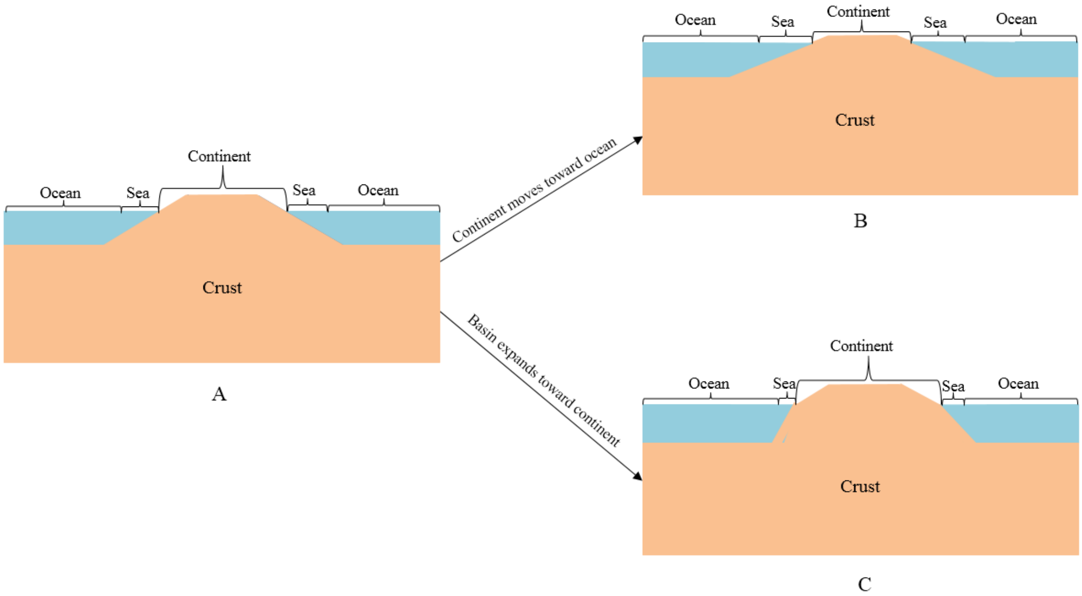


Fourth, we have developed a stress model for the rocks in the Earth's crust to demonstrate how ocean water exerts pressure on the continents. As depicted in the top figure below, our model involves a straight, ocean-loaded crust with a length of 7,500 km and a height of 50 km. We note that this model does not strictly adhere to size ratios, and the Earth's curvature has been ignored. The ocean depth ranges from 5.0 km on the left to 4.0 km on the right. The crust is composed of homogeneous and isotropic rocks, and finite element analysis software, such as Abaqus, is utilized to produce resultant stress. The model's bottom has a remote boundary condition, while no edge boundary conditions exist for the left and right ends. The lithosphere's upper part is represented by a 50 km depth of crust, that is mostly elastic so the ductile nature is neglected. Our inputs include the crust's pressure from its weight and ocean hydrostatic pressure, while our outputs comprise two datasets: one for the stress caused by the crust's pressure alone and the other for the stress caused by the combination of the crust's and ocean's pressures. A two-dimensional frame enables us to obtain horizontal stress (S11) and vertical stress (S22). Our results, depicted in the bottom image, show that ocean water has a significant impact on the crust's stress. The stress caused by ocean water is mainly compressive and penetrates the entire crust's thickness. Notably, we observed variations in stress concentrations in the continent's upper sections where, without water, the horizontal stress in the continent is slightly compressive (weak red). However, when the water is loaded, the horizontal stress in the continent becomes strongly compressive (green).

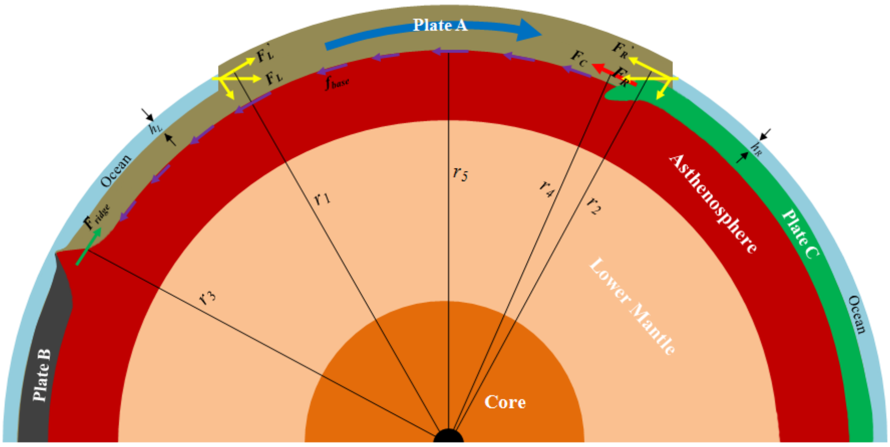




Fifth, some people believe that any lateral "density difference" would cause denser substances to flow towards lighter ones, supporting the idea that the denser continents would move towards ocean water. However, it is impossible for the positions of continents and oceans to remain motionless when they are put together. This means that either continents move towards ocean water or ocean water moves towards the continents. To further investigate this matter, consider figure (B) below: compared to figure (A), if continents were to move towards ocean water, the ocean basin would be filled with substances from the continent, causing the sea level to rise and submerge the coast, ultimately resulting in a decrease in the continent's area. However, this is contradictory to the concept of continental accretion, which has been confirmed by the geophysical community for many years. For more information on the continental accretion, please refer to the research by Zhu et al. (2021). Instead, consider figure (C) below: compared to figure (A), if ocean water were to compress the Earth's crust, the elasticity of the crust's rock would cause it to deform in response to the ocean water pressure. Consequently, the ocean basin would expand and the water in the shallow sea would flow towards it, causing parts of the seafloor to be exposed and become landmasses. As a result, the continent's area would increase, which aligns with the concept of continental accretion.



Sixth, the issue raised by the reviewer may be related to the difference between the internal pressure and external force acting on an object. The motion of any object is determined by its external forces, such as the force applied by two people on opposite sides of a rock on the ground. If the combined force is greater than the friction force, the rock moves; if not, the rock remains motionless. However, the object's internal pressure is not relevant to its motion. When there is an external force, there is deformation (stress) as a response. In this study (see Figure 5 of the manuscript), Plate A moves relative to Plate B, Plate C, Ocean, and Asthenosphere, so we only need to consider the forces exerted by these bodies to determine Plate A's motion. The reviewer may be referring to the continent's creep and its density comparison with ocean water, but this study focuses solely on plate motion, assuming the plate is rigid. The creep does not counteract plate motion, just as the deformation caused by the two people pushing the rock is distinct from the rock's motion relative to the ground.



Finally, we can offer a more practical perspective on this issue. When a reservoir is constructed and filled with water, the water pressure forces begins to compress the dam and walls of the reservoir. Initially, the deformation may be negligible, but over time it can accumulate. This is why protective-stability measurements are crucial when building a reservoir. Similarly, when the ocean water pressure force compresses the Earth's crust (including the walls of the continents), the deformation in the crust will become significant after billions of years of accumulation.

3. Even if the authors do a first order calculation of the ocean-generated force per unit area (F = drho*g*z^2, drho = 2800-1000 kg/m^3, g = 9.81 m/s^2 and z = 5000 m), the force is 4e11 N/m (directed from the continent to the water), which is an order of magnitude less than the ridge push force (~2.5e12 N/m) and 2 orders of magnitude less than the slab pull force (~30e12 N/m). So, this is not a first order contribution to the plate force balance.

Thank the reviewer for these comments. Below we have addressed each of the comments raised. The calculation "**Even if you do a first-order calculation of the force per unit area (F = drho*g*z^2, drho = 2800-1000 kg/m^3, g = 9.81 m/s^2, and z = 5000 m)**" may be inaccurate. One cannot use a density difference between solid and fluid to calculate the force between the two. As demonstrated in the manuscript, we agree that the ocean-generated force holds a magnitude of ~4e11N/m. We have addressed the comment "**the ocean-generated force is directed from the continent to the water**" in the author's response above. We also agree with the comment that the ocean-generated force is an order of magnitude less than the ridge push force (**~2.5e12 N/m**) and two orders of magnitude less than the slab pull force (**~30e12 N/m**). However, we argue that the comment "**So, this is not a first-order contribution to the plate force balance**" deserves further discussion.

First, we have demonstrated the issue of the plate force balance in section 4.1 of the manuscript (see lines 688~726).

Second, it is true that slab pull has a magnitude of approximately 10^{13} N/m. However, out of the 8 major plates (African, Antarctic, Eurasian, Indo-Australian, North American, Pacific, and South American), only the Pacific plate is attached to the slab. It is important to understand that the motion of a plate is controlled by its own force balance. Just because the magnitude of slab pull is the largest, it does not necessarily mean that this force has contributed to the motion of the African, Antarctic, Eurasian, Indo-Australian, North American, and South American plates. On the other hand, ridge push has a magnitude of around 10^{12} N/m. This force is believed to combine collisional, shearing, and basal friction forces to form force balance, which controls the motion of the continental plate. In contrast, ocean-generated force has a magnitude of around 10^{11} N/m. As demonstrated in section 3 of the manuscript, we have arranged this force to combine with ridge push, collisional, shearing, and basal friction forces to form force balance, which controls the motion of both continental and oceanic plates. This indicates that the magnitude of the plate driving force is not the most important factor. Therefore, the force balance generated by driving forces of different magnitudes can explain an identical plate motion. This peculiarity arises from the force balance itself. For any plate, the force balance equation can be expressed as $F_{\text{net-driving}}-F_{\text{basal}}=0$, where $F_{\text{basal}} = \mu Au/y$. In this equation, $F_{\text{net-driving}}$ represents the net driving force that includes the plate driving force, collisional force, and shearing forces. Meanwhile, F_{basal} denotes the basal friction force that the asthenosphere exerts on the plate. The variables μ, A, u, and y stand for the asthenosphere viscosity, plate area, plate speed, and thickness of the asthenosphere, respectively. Thus, u can be calculated as $yF_{\text{net-driving}}/\mu A$. It is essential to note that the force balance equation is used to replicate the observed speed of the plate motion. Although A and y are well established, the viscosity of the asthenosphere (μ) remains uncertain. According to the experiments and theoretical models of various authors presented in lines 447-466 of the original manuscript, μ can span a broad range from 10^{15} to 10^{20} Pas. In practice, if the plate driving force (e.g., slab pull or ridge push) is significant, a high viscosity value can be chosen to balance the equation. On the other hand, if the plate driving force (e.g., ocean-generated force) is small, a low viscosity value can be applied. Either choice is valid.

Last, the reviewer is arguing that the current plate driving forces (slab pull and ridge push) are still effective. However, the author believes that the reviewer should not disregard the long-standing controversy regarding these two forces, as detailed in section 2 of the manuscript. The weaknesses of these forces are numerous, and the advantage (i.e. their large magnitudes) can be greatly undermined. Furthermore, slabs are deeply buried under trenches and ridges are situated on the ocean floor - the topography, density, temperature, and rheology of these bodies have not been well established. This lack of knowledge means that our understanding of these two forces is still in the theoretical and modeling stages. On the other hand, we have a more substantial understanding of ocean-generated forces. Ocean topography has been well-measured, the density and temperature of ocean water are well-known, fluid mechanics has been well-established, and ocean bottom pressure is widely measured.

Consequently, our response to the reviewer’s comments above supports that the hypothesis presented in this study is physically viable.

At the end of this response, we look forward to hearing from you regarding our manuscript. We would be glad to respond to any further questions and comments that you may have.