Author’s response to the Referee 1’s comments

We (the author) gratefully thank the Referee 1 for this review of our manuscript. Below, we have addressed each of these comments in turn, with the Referee 1’s comments presented in bold font and our reply in non-bold font.

Comment 1. This is a very ambitious paper that aims to reconsider and advocate against most of the papers that have discussed the equilibrium of plate tectonics. The goal is also to reconsider the effect of tides on plate motions (and on seismicity) and to propose a scenario for the initiation of plate tectonics.
Reply: These comments are accurate.

Comment 2. The author insists that "mantle convection had been given up by most of geophysicists" and "mantle convection cannot be realistic". I am not totally sure what he means by that, probably that convection cannot explain plate tectonic? (although various papers involving Schmalzl, Bercovici, Tackley, Coltice... provided mantle convection models with self generated plates). I hope he does not think that mantle convection does not exist.
Reply: These comments require the author to exercise caution. Upon reviewing section 4.6 of the manuscript and examining relevant research on mantle convection (e.g. Bercovici et al., 2015, Coltice et al., 2017), we believe that the statements "**mantle convection had been given up by most geophysicists**" and "**mantle convection cannot be realistic**" are problematic. As indicated in lines 59 to 65 of the manuscript, the geophysical community currently acknowledges the large-scale circulation of plate and mantle, while some improved models of mantle convection, as discussed in Coltice et al. (2017), are still being developed. Furthermore, we did not perform a statistical analysis to support the claim that most geophysicists reject mantle convection. Additionally, arguing the shortcomings of mantle convection is not particularly relevant to this work. Given the current state of affairs, we have decided to remove section 4.6 in the revised manuscript.

Comment 3. The paper is very long and, for me, very difficult to follow. The concepts are often unclear. The very large bibliography is always presented as confirming the author ideas even though I would say that they often oppose his ideas.
Reply: We apologize that the Referee 1 may have found this paper difficult to understand. We would like to address the feedback provided by Referee 1 regarding the clarity of certain concepts mentioned in the manuscript. If possible, providing more details on the specific lines or sections where the concepts are unclear would be helpful for us to make appropriate revisions.
Additionally, the comment that the bibliography may oppose our ideas is appreciated and we have carefully checked the literature cited in our manuscript, specifically in lines 50~65, lines 119~123, and lines 225~230. Although we may have missed some discrepancies, we have made revisions in the revised version of the manuscript to address these inconsistencies.

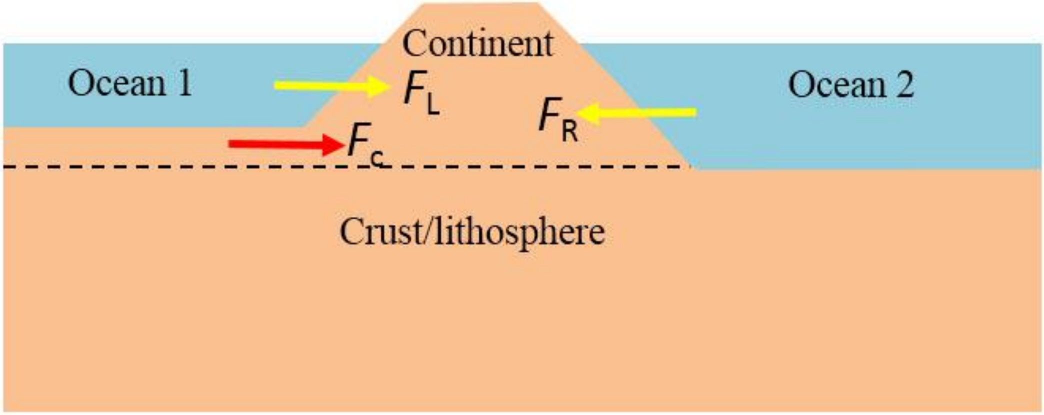
Comment 4. I was really unable to understand exactly the theory itself; the "plates" and the "forces" are not clearly defined. For exemple, the author says that the pressure on a continent, due to the ocean, is larger when the ocean is

deeper, and he seems to interpret this observation as "a deep ocean pushes the continent". However, it is obvious than the crust/lithosphere has to be thicker on the side of the shallow ocean and it is rather this side, where the shallow ocean is present, that pushes the continent (i.e; continents tend to extend over the oceans). When the objects on which forces are applied are not properly defined, it is difficult to write correct force balances.

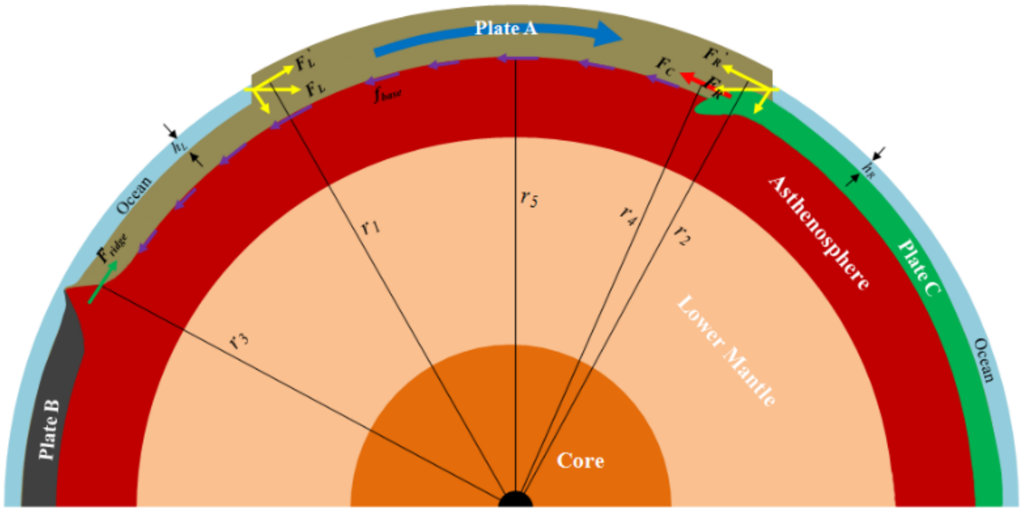
Reply: These comments raise two key issues: first, the Referee 1 believes that the crust beneath the shallow ocean is providing force to push the continent, rather than the deeper ocean; and second, the Referee 1 suggests that the author's definition of the plates and the forces acting upon them may be inadequate. We will address each concern individually below.

For (A):

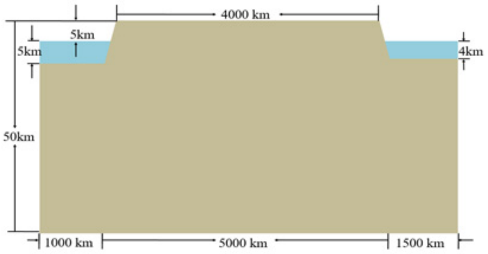
The Referee 1's view requires to carefully differentiate the crust's (continent's) deformation from plate motion. To make the issue become clear, we use a simple model below to illustrate the Referee 1's view. The Referee 1 believes that, as the crust beneath the shallow Ocean 1 is thicker than the crust beneath the deeper Ocean 2, and because the crust's density is greater than the density of water, the thicker crust beneath Ocean 1 provides a force (F_c, for example) on Continent; and since $F_L+F_c>F_R$, there results in a net force that pushes Continent to move toward Ocean 2. The Referee 1's implication is that the higher and denser Continent would extend towards Ocean 2 and Ocean 1(**i.e; continents tend to extend over the oceans)**.

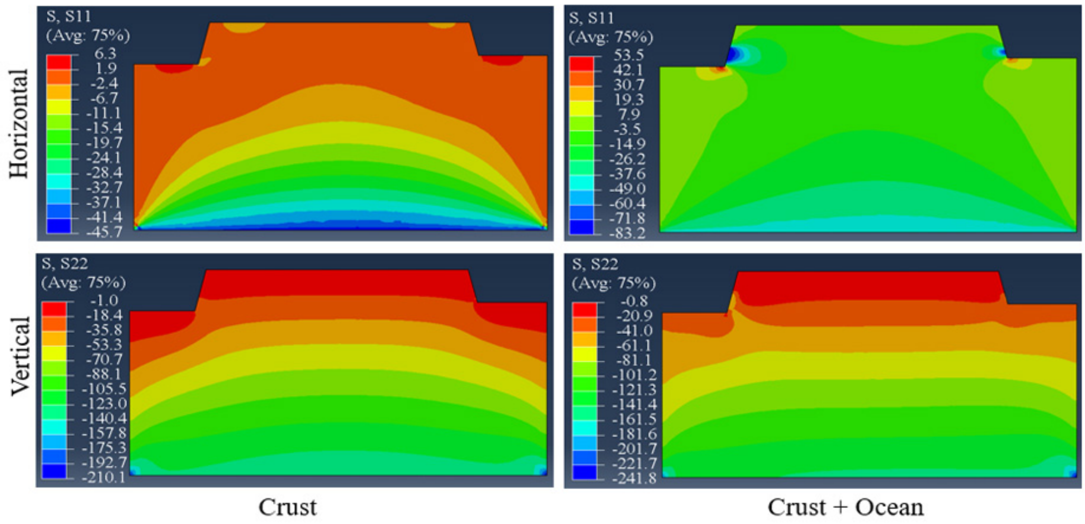


And now we list Figure 5 of the manuscript as below to express our view. We state in the manuscript that, the ocean provides one force ($F_L{}'$) on the left side of the continent and another force ($F_R{}'$) on the right side; the continent is fixed on the top of the continental plate (for example, Plate A), this attachment allows the two forces to be transferred to the plate. These two forces combine the ridge push force (F_{ridge}), the collisional force (F_c), and the basal friction (f_{base}) to determine Plate A's motion.



There is indeed a lateral density difference between continent and ocean. However, the idea that this difference makes continent tend to extend over ocean may not be realistic. If continent were forced by the lateral density difference to extend over ocean, it would cause ocean basin to be filled with substances from the continent, leading to a rise in sea level and submerging the coast. Ultimately, this would result in the decrease of the continent’s area, which contradicts the concept of continental accretion that has been confirmed by the geophysical community for many years. For more information on continental accretion, please refer to a recent review article by Zhu et al. (2021) (https://doi.org/10.1029/2019RG000689). In addition, the crust’s (continent’s) deformation does not conflict with plate motion. As seen in the figure above, the external forces (F_{L}', F_{R}', F_{ridge}, F_{c}, and f_{base}) are responsible for controlling the motion of Plate A, but these forces also impact the crust (continent), leading to its deformation. Ultimately, the final deformation of the crust (continent) is determined by several factors, including the external forces, physical properties of the crust’s rock, and internal pressure resulting from its weight. To demonstrate, we utilized a model to show that when ocean water is loaded on the crust, the resulting stress permeates the entire crust (continent), causing the horizontal stress to change from tensile (red) to compressive (green). This provides evidence that ocean water is responsible for pushing/compressing the continent, rather than the other way around. The reason for why the denser continent does not extend/flow towards the ocean has been extensively discussed in our response to CC1's comments, as it may relate to differences in pressure properties between rock and water and differences in flexibility between the two.





In fact, the mechanism behind continental accretion (**i.e; continents tend to extend over the oceans**) remains elusive. As demonstrated in the above model, ocean water may play a role in the deformation of the crust/continent. This leads us to propose a possible explanation for continental accretion: ocean water compresses the continent, causing the elastic continent to deform in response to the pressure. As a result, the ocean basin would expand, causing water in the shallow sea to flow towards the ocean basin. This, in turn, would expose parts of the seafloor under the shallow sea and transform them into landmasses. This occurrence would ultimately lead to an increase in the continent's area. In light of this, we have decided to address this issue raised by the Referee 1 and CC1 by adding a section 4.6 to the manuscript (see below).

“4.6 Does the ocean force relate to the continent’s movement?

Some individuals believe that a lateral density difference results in dense continents extending over oceans. It is crucial to examine this notion, as it sheds light on how continents interact with oceans. If continents were compelled by a lateral density difference to extend over oceans, the ocean basin would be filled with substances from the continent, which would cause the sea level to rise and flood the shore, ultimately resulting in a decrease in the continent’s size. This contradicts the concept of continental accretion, which has been accepted by the geophysical community for many years. More information about continental accretion can be found in a recent study by Zhu et al. (2021). Additionally, continents must deform in response to any force, such as the ocean-generated force presented in this work.

A model has been developed to demonstrate the stress generated by ocean-generated forces. The model comprises the Earth’s crust, which is carrying the weight of the ocean. The Earth’s curvature is neglected, and the crust’s length and thickness are 7,500 km and 50 km, respectively. The depth of the ocean ranges from 5.0 km on the left to 4.0 km on the right. The crust is made up of rocks and is assumed to be homogeneous and isotropic. We have used finite element analysis software, namely Abaqus, to analyze the resultant stress. The bottom of the model is remotely constrained, while there are no edge boundary conditions on the left and right sides of the model. The elastic modulus, Poisson ratio, and rock density of the model are set to 100,000 MPa, 0.3, and 2,690 kg/m^3, respectively. The inputs consist of the pressure exerted on the crust by its own weight and the hydrostatic pressure of the ocean. The outputs comprise two data sets: one for stress caused solely by the pressure of the crust, and another for stress resulting from a combination of the crust's pressure and the ocean's pressure. The two-dimensional framework enables us to calculate both horizontal stress (S11) and vertical stress (S22). Figure 19 illustrates the model and the corresponding stress values. Notably, the addition of the ocean's pressure leads to stress that fully penetrates the crust (continent). This causes the previously horizontal tensile (red) stress in the continent to shift to compressive (green).

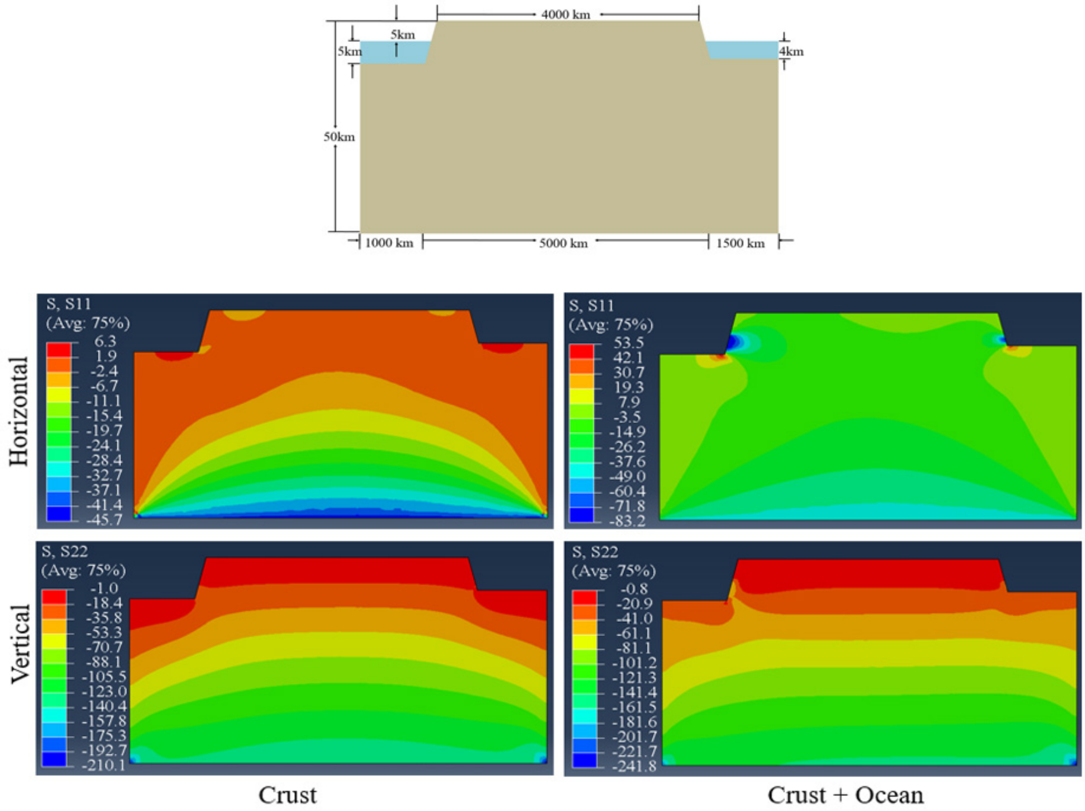


Figure 19. Modeling the stress produced by crust and ocean. Top, geometry of the model; bottom, the stress produced by the loads, where the stress's unit is MPa. The negative symbol "-" denotes compressional.

The modelling above leads us to consider a solution for the occurrence of continental accretion: As demonstrated in the above model, ocean water may play a role in the deformation of the crust/continent. This leads us to propose a possible explanation for continental accretion: ocean water compresses the continent, causing the elastic continent to deform in response to the pressure. As a result, the ocean basin would expand, causing water in the shallow sea to flow towards the ocean basin. This, in turn, would expose parts of the seafloor under the shallow sea and transform them into landmasses. This occurrence would ultimately lead to an increase in the continent's area. Figure 20 compares two paths of the continent's accretion: from A to B, continent extends towards ocean, then, the water's area increases whereas the continent's areas decreases; from A to C, basin expands towards continent, then, the water's area decreases whereas the continent's area increases.

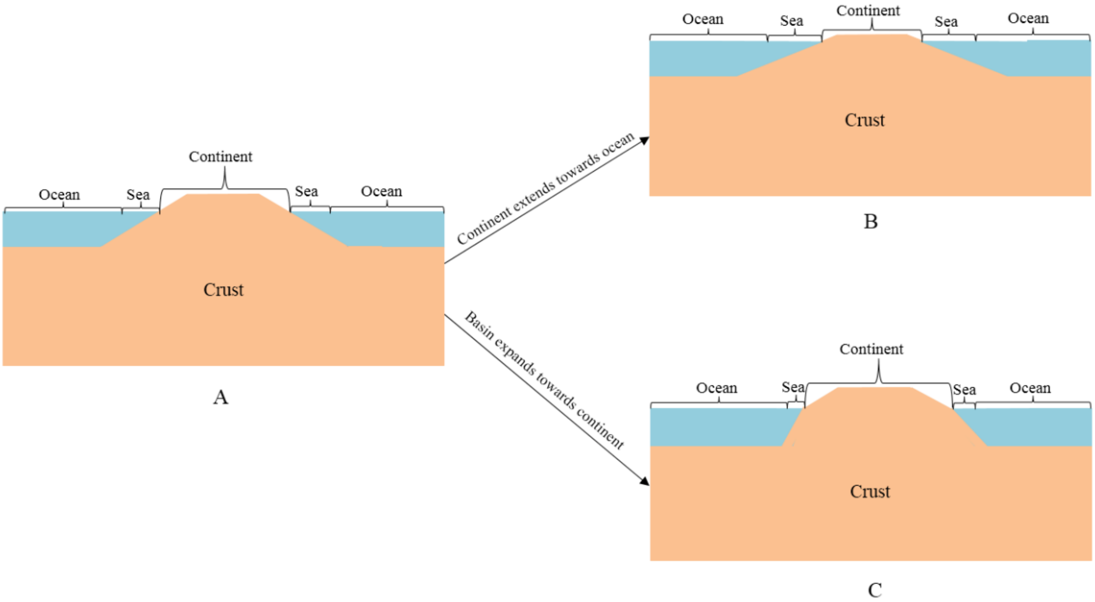


Figure 20. Comparing two paths of the continent's accretion.

For (B):
The Referee 1 has raised concerns about the inadequate definition of plates and forces in the manuscript. However, this point can be tested. In section 3.1 (see lines 219-290), we firstly define the ocean-generated force that acts on a sample continent, and then, the direction of this force and its magnitude are specified for real continents (see Figure 4 and Table 1). In section 3.2 (see lines 303-304), we state "The continents are fixed on the top of the lithosphere, and the lithospheric plates connect to each other, this relationship allows the ocean-generated force to be laterally transferred to the lithospheric plates." So, the ocean-generated force is defined for the lithospheric plate. From lines 306 to lines 317, we list possible forces that act on a continental plate and further discuss the physical nature of these forces. This pattern follows Forsyth and Uyeda (1975). In Figure 5 of the manuscript, we use a model to exhibit plate distribution and the defined forces acting on the plates. For example, Plate A is treated as a continental plate, the forces acting on it include the ocean-generated force F_L' and F_R', the ridge push force F_{ridge}, the collisional force F_c, and the basal friction f_{base}. From line 326 to line 349, we discuss the torques resulting from the forces we have defined. Moving onto lines 351 to 485, we use Figure 6 of the manuscript to plot these forces onto a spherical frame, examine the torque balances that these forces create, and then use these balances to resolve the movements of the six plates. However, please note that in both lines 360-361 and lines 409-417, additional forces (such as collisional and shearing forces) were added to the defined forces. Unfortunately, we could not exhibit these forces in Figure 5, as the frame is only two-dimensional. We have also defined a few collisional forces for the Pacific Plate, while neglecting slab pull. We have provided reasons for this on lines 414-416.
Even so, we're still afraid that our definition of the ocean-generated force isn't too clear. To improve this, we add a figure (as below) in the revised manuscript. Of

course, if the definition of the plates and forces we have used is not acceptable to the Referee 1, we would appreciate some feedback, including references or examples so that we can make proper adjustments.

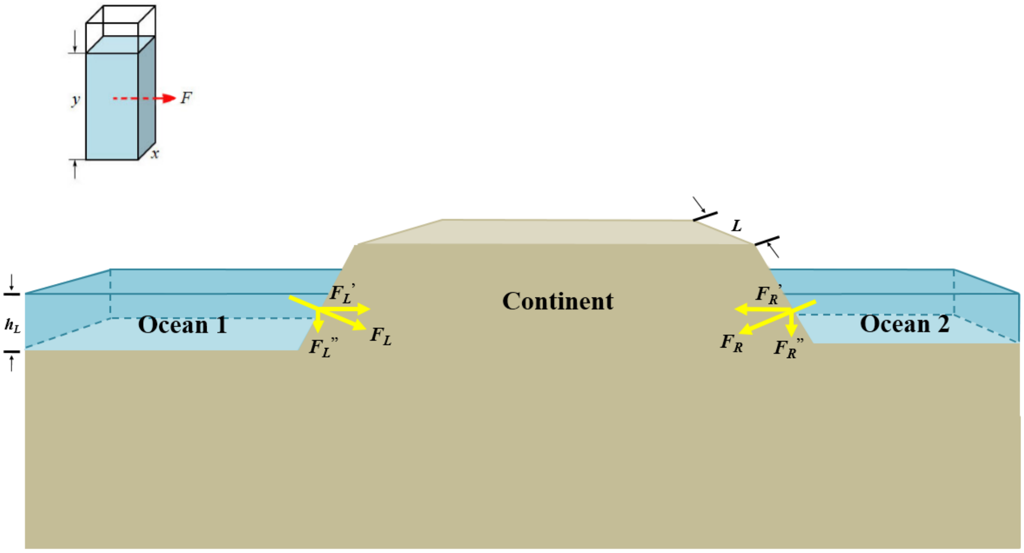
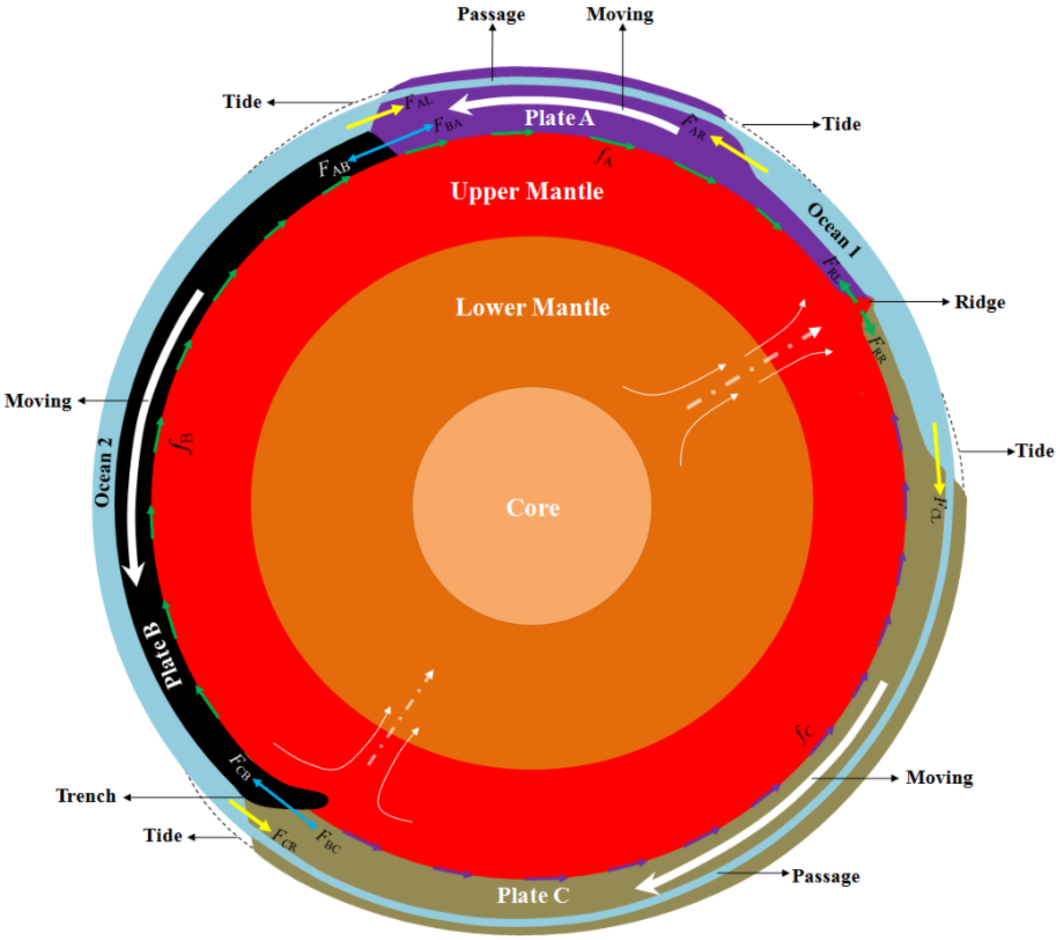


Figure 4. Modeling the ocean-generated forces acting on the continent. F_L(F_R) represents the ocean-generated force on the left (right) side of the continent, while F_L'(F_R') and F_L''(F_R'') denote the horizontal and vertical forces decomposed from the ocean-generated force, respectively. L denotes the width of the continent's side; h_L and h_R are the ocean's depth on the left and right, respectively. Note that the Earth's curvature is neglected.

Comment 5. I had also difficulties with the numerical applications. To take an exemple, around lines 700. Yongfeng Yang computes an "ocean force" F_AR= 0.245e12 N/m for a d=5 km ocean. I would compute this force as 1/2 rho g d^2=0.1225e12 N/m. I may be wrong but it seems that a factor 1/2 is missing. The same factor seems to be also missing in F_AL (the opposite force of a shallow ocean of 3km), and of course on the resulting force F_AR-F_AL (Yongfeng Yang uses 0.1568e12 N/m when it should be 0.0784e12 N/m).
Reply: These comments are correct. We did, in fact, overlook the factor of 1/2. As a result, we have made improvements to the numerical analysis in the revised version of the manuscript.

Comment 6. But already 5 km is an unrealistically large depth: the average depth of oceans is only 3.7 km and people looking for a potential 'dynamic topography, do not seem to see any difference in ocean bathymetries larger than say 1 km (and this is already a very generous value, by isostasy a h=2 km difference of bathymetry implies under the shallow ocean a crustal root of r=h (rho_crust-rho_water)/(rho_mantle-rho_crust)=9 km, so a crust thicker by 9+2=11 km under the shallow ocean). Therefore the ocean force between an ocean of depth d1=3200 m and an ocean of depth d2=4200 m, is only 0.036e12 N/m, 4-5 times smaller than the value chosen by the author.
Reply: These comments suggest that we may have overestimated the strength of ocean forces by focusing solely on deeper ocean sections. Connecting to the previous comments (**To take an exemple, around lines 700. Yongfeng Yang computes an**

"ocean force" F_AR= 0.245e12 N/m for a d=5 km ocean.), we will argue that the magnitude of this force is not crucial for section 4.1. As illustrated by Figure 12 in the manuscript (see the figure below), our model estimates ocean depths of 5 km and 3 km to the right and left of the continent respectively, but readers may consider depths of 4 km and 3 km on the right and left instead. This variation in estimation serves to demonstrate that force balance can be achieved with related forces. Further details can be found in our response below.



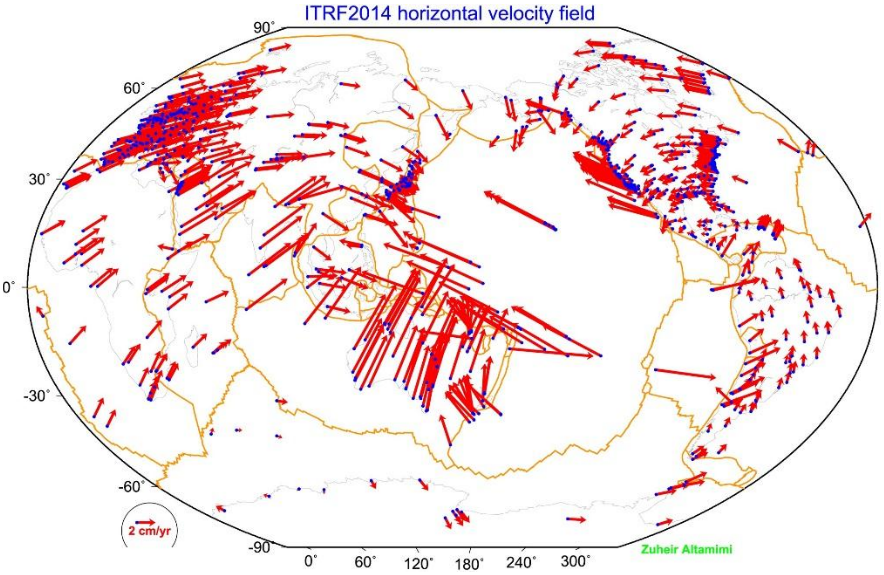
Comment 7. It is already difficult for me to understand how a force of 0.1568e12 N/m could play a significant role against a ridge push of 4e12 N/m (using the author numbers, i.e. against a force 27 times larger), but it seems that the ratio is in fact larger than a factor 100.

Reply: Based on our previous response, it appears that the Referee 1 is arguing that an ocean force of 0.1568e12 N/m is insufficient to counterbalance a ridge push force of 4e12 N/m. However, we do not use the ocean force to counteract the ridge push force. This can be seen in several parts of the manuscript such as lines 13~14, lines 314~317, lines 326~332, lines 356~358, lines 351~385, line 497~524, and lines 694~721. In our approach, the ridge push force is always treated as a plate driving force while the ocean force and ridge push force are combined to balance the collisional, shearing, and basal friction forces. This balancing act results in force balance and plate movement resolution. Let’s go back to the manuscript to see the thinking line of the paper. In Section 2.2, we model the existing forces (ridge push,

collisional, and basal friction) and find that they are not sufficient to account for observed stress, implying the need for additional force. In Sections 3.1 and 3.2, we introduce the ocean-generated force and use this force in tandem with the ridge push force to balance the collisional, shearing, and basal friction forces. In Section 3.3, we use modeling to demonstrate that even with a ridge push force of 4e12 N/m, the combination of the ocean-generated force, ridge push force, collisional force, and shearing force is still insufficient to account for observed stress. However, reducing the ridge push force to below the ocean-generated force can reach the observed stress (refer to lines 618-631). In Section 4.1 (refer to lines 694-721), we show that force balances can be achieved with these combined forces. It is important for the Referee 1 to note that the ridge push force is approximately symmetric around the ridge crest, as shown in the figure above. The ridge push force F_{RL} pushes Plate A at its right side, at the same time, F_{RR} pushes Plate C, Plate C pushes Plate B, and Plate B also pushes Plate A at its left side, consequently, F_{RL} is properly balanced out by F_{RR}. Therefore, regardless of whether the ridge push force is valued at 4e12 N/m or below, the force balance can still be achieved. Moreover, we have mentioned readers in the manuscript (see lines 717~721), " …, even if the ridge push force F_{RL} (F_{RR}) is given a smaller amplitude (~ 10^{10} N m^{-1}, for example), so long as the collisional force F_{BA} (F_{AB}, F_{CB}, and F_{BC}) is properly valued, these force balances can always be created. Nevertheless, as demonstrated in section 3.3, a ridge push force of 4.0×10^{12} N m^{-1} would result in a horizontal stress that is mostly concentrated on the lower part of the lithosphere, which is not in accordance with observation. Hence, we prefer to accept the ridge push force to be smaller than ocean-generated force."
This comment, "**the ratio is actually greater than 100 times,**" is accurate but lacks significant value. The Referee 1's comments are related to some of CC1's comments which have already been addressed by the author. Therefore, it is unnecessary to further emphasize this matter.

Comment 8. I note that the slab traction is generally estimated about 10 times larger than the ridge push (the author mentions a slab traction of about 3.3e13 N/m which is the right amount). Quoting Bercovici et al, (AGU monograph, 2000) "As demonstrated by Forsyth and Uyeda [1975], the correlation between the connectivity of a plate to a slab (i.e., the percent of its perimeter taken by subduction zones) and the plate's velocity argues rather conclusively for the dominance of slab pull as a plate driving force".
Reply: These comments merit further discussion.
On the other hand, slab pull (traction) is widely accepted as the greatest. 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 slab that produces the pull force. Please be aware, these 7 plates (African, Antarctic, Eurasian, Indo-Australian, North American, and South American) don't attach to any slab. So, slab pull is only suitable for the oceanic plate like the Pacific Plate. Just because "**the correlation between the connectivity of a plate to a slab (i.e., the percent of its perimeter taken by subduction zones) and the plate's velocity**" is strong, it does not necessarily mean that the slab has contributed to plate motion. For example, we will argue that, as readers have seen in the manuscript (see lines 41~415, Table 2(D), Figure 7(f), lines 548~551, Table 4(B), Figure 9(c)), we have successfully produced a movement for the Pacific Plate by means of a combination of three collisional forces. In short, without the contribution of slab pull, the Pacific Plate's movement can still be reached. Perhaps, the strong correlation between the **connectivity and the plate's**

velocity is just a coincidence. See the figure below (Figure 13(B) of the manuscript is a copy of this feature), the Eurasian Plate rotates clockwise, the North American Plate rotates counterclockwise, the Indian-Australian Plates move northeast, and the Pacific Plate moves northwest, this situation allows the former three plates to circle the Pacific Plate. As a result, the Pacific Plate’s margin is forced to subduct, forming very long **subduction zones** in the boundaries between the Pacific Plate and these three plates. From this point, the slab itself may be a consequence of plate motion.
These comments require further discussion. While slab pull (traction) is widely accepted as the greatest force driving plate motion, it only applies to the Pacific Plate. Out of the 8 major plates (African, Antarctic, Eurasian, Indo-Australian, North American, Pacific, and South American), the Pacific Plate is the only one attached to a slab that produces the pull force. It is important to note that a strong correlation between the connectivity of a plate to a slab (i.e., the percent of its perimeter taken by subduction zones) and the plate’s velocity does not necessarily indicate that the slab has contributed to plate motion. As shown in the manuscript (see lines 41~415, Table 2(D), Figure 7(f), lines 548~551, Table 4(B), Figure 9(c)), a combination of three collisional forces has successfully produced movement for the Pacific Plate without the contribution of slab pull. In fact, perhaps the strong correlation between connectivity and plate velocity is merely a coincidence. The figure below (Figure 13(B) of the manuscript is a copy of this feature) shows that the Eurasian Plate rotates clockwise, the North American Plate rotates counterclockwise, the Indian-Australian Plates move northeast, and the Pacific Plate moves northwest, resulting in the former three plates circling the Pacific Plate. As a result, the margin of the Pacific Plate is forced to subduct, forming very long subduction zones at the boundaries between the Pacific Plate and these three plates. This suggests that the slab itself may be a consequence of plate motion.



On the flip side, the Referee 1 has utilized the work of Bercovici et al. (AGU monograph, 2000) to insinuate that slab pull still holds significance. However, this is not entirely accurate. The Referee 1 ought to recognize the longstanding controversy surrounding this force that’s delineated in section 2.1 of the manuscript. There are numerous loopholes in this force, which can significantly undermine its advantages (e.g., magnitude of 3.3e13 N/m). That being said, our model does leave room for slab pull, as evidenced by lines 414-416 in the manuscript “Taking into consideration the long argument of slab pull that is listed in section 2.1, we presently neglect slab pull. And if this force can be confirmed in the future, it can be added into this model.”

Comment 9. Yongfeng Yang does not believe in ridge push although, the same halfspace cooling model is used to estimate ridge push and slab pull.
Reply: As the Referee 1 has read our response above, this is not true that **Yongfeng Yang does not believe in ridge push although**. This comment “**the same halfspace cooling model is used to estimate ridge push and slab pull**” is right but not relevant to this research. If the Referee 1 has any specific concerns about this issue, please elaborate on them so that we can incorporate your feedback in the revised version.

Comment 10. I do not think the paper is clear, convincing and rigorous enough to be accepted for publication.
Reply: Along with this response, we have made revisions to the manuscript. Other modifications include changes to the literature, figure sequence, and references.
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.