

What Drives Plate Motion?

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Abstract

Plate motion was widely thought to be a manifestation of mantle dynamics. However, an in-depth investigation shows this understanding incompetent. Here we propose, the daily tides yield varying pressures between oceans, the application of these pressures to the continent's sides forms enormously unequal horizontal forces, the net effect of these forces provides lateral push to the continent and may cause it to move horizontally, further, the moving continent by basal drag entrains its adjacent crust to move, these totally give birth to plate motion. A roughly estimation shows that the oceanic tide-generating force may independently give South American, African, Indian, and Australian continents a movement of respectively 2.8, 4.2, 5.6, and 6.3 cm/yr. Some torque effects may rotate North American and Eurasian continents, and a combination of two lateral pushes offers Pacific Plate unusual motion (nearly orthogonal to Australian plate's motion).

1 Introduction

One of the most significantly achievements in the 20th century was the establishment of the plate tectonics that developed from the earlier conception of continental drift. The continent drift theory hypothesized that the continents had slowly floated over the earth's surface in the distant past (Wegener, 1915 and 1924). The evidences supporting this surface motion include a shape fitting at the opposed sides of African and American continents, coal belt crossed from North American to Eurasian, identical direction of ice sheet of southern Africa and India, and speed measurement made by global positioning system (GPS). In addition, the discovery of paleomagnetic reversals in oceans, which reflects seafloor spreading, further consolidated the belief of earth's surface motion (Hess, 1962; Vine and Matthews, 1963). Nevertheless, the driving force behind this motion always remains poorly understood, regardless of unremitting efforts made by geophysicists in the past 100 years. The first to consider the dynamics source of this surface motion is the contraction theory, which proposed that a wrinkling process of earth's surface had forced the Himalayas to climb up. Wegener (1915) directly ascribed continent's drift to the centrifugal and tidal drag forces, but these forces were latterly found to be too weak to work. For instance, Jeffreys (1929) claimed that the mean tidal friction slowing the earth's rotation corresponds to a westward stress of the order of only 10^{-4} dyn/cm² over the earth's surface, this stress is too small to maintain the drift. This discrepancy also lead the continental drift theory to be rejected. After these attempts failed, people began to turn their eyes to the interior of the earth to seek for the answer, together with the rebirth of the continental drift theory in the form of 'plate tectonics', this cultivated a series of various driving forces like basal drag, slab suction, ridge push, slab-pull, tidal drag, the geoid's deformation, the Coriolis force, and the centrifugal force to account for plate motion (Holmes, 1931; Runcorn, 1962a, b; Turcotte and Oxburgh, 1972; Oxburgh and Turcotte, 1978; Spence, 1987; White & McKenzie, 1989; Conrad & Lithgow-Bertelloni, 2002). Among of these driving forces, both basal drag and slab suction relate to mantle dynamics and are thought to be the first level force. Mantle dynamics considers mantle convection currents as the dynamic

source of plate motion (Holmes, 1931; Pekeris, 1935; Hales, 1936; Runcorn, 1962a, b; Turcotte and Oxburgh, 1972; Oxburgh and Turcotte, 1978; Tanimoto & Lay, 2000; Bercovici, et al., 2015). Simply, it provided a basal drag that is exerted by mantle convective current along the more rigid overlying lithosphere and a slab suction that is generated by local mantle convection current exerting a downward pull on plate in subduction zone. Both of them relate to gravity and are thought to be the second level force. Ridge push represents a gravitational sliding of the increasingly cooling and thickening plate away from a spreading ridge (Spence, 1987; White & McKenzie, 1989), whereas slab-pull mainly proposes a cold, dense sinking plate uses its weight to pull other plate it attaches to (Conrad & Lithgow-Bertelloni, 2002). The remaining forces relate to the earth's rotation and are thought to be the systematic force. As the systematic force is almost symmetrical relative to the earth's shape, it may be easily excluded. Finally, these four forces, i.e., basal drag, slab suction, ridge push, and slab-pull, are left to act as the dominant forces to be responsible for plate motion. At first glance, these driving forces are rather abundant and might be competent for plate motion. The fact, however, is not so. Behind them, it shows highly chaotic and unclear. First of all, let's check the applicability of these driving forces. The asthenosphere is so weak (insufficiently rigid) that it cannot cause motion by basal friction along the base of the lithosphere, slab pull is therefore thought to be the greatest force to drive plate motion. However, most of plates (South American, North American, Eurasian, and Antarctic Plates, for instance) don't hold the features of subducting into trenches. This means that there is no slab pull available for these plates. Ridge push is existed, but it cannot work for these plates, this is because ridge push is only applicable to a plate whose one end stands at the spreading center whereas another end is sinking at the subduction zone, it is this slight tilt to provide a gravitational sliding to drive the plate. For these two plates like South American and North American, the continent loading at the west of the plate forms a tilt to fight against the tilt that is due to the ridge loading at the east, thus, the ridge push is useless. And then, without slab pull and the ridge push, and also due to the weakness of the asthenosphere, we cannot find any effective force to drive these plates. Second, let's check the dynamic sources of these driving forces. Both basal drag and slab suction are originated from the mantle dynamics that is usually represented with some wheel-like convection currents, however, some techniques based on 3D seismic tomography still cannot recognize these large-scale convection currents. Back to the issue of the ridge push and slab-pull, as plates are steadily moving over the earth's surface, this means a plate may ride over another plate in the front and at the same time depart from a third plate in the rear, the result is natural to form a subduction zone and a fracture zone at the both ends. The fracture zone, if severe enough to pierce the whole lithosphere, may allow the magma to erupt, eventually forming the mid-ocean ridge (MOR). From this viewpoint, the subducting plate and the MOR themselves may be a sequence of plate motion. But nowadays, the subducting plate and the MOR are treated as a tool to yield the slab-pull and the ridge push to further drive themselves. This goes to the chicken-or-egg question, who is the first? To some extent, the introduction of the slab-pull and the ridge push are no more than a game of edge ball. In physical field, it is strictly required that a movement (i.e., result) must be separated clearly from the force (i.e., cause) that supports it. Third, the diversity of plate motions greatly challenges these driving forces. Some plates (South American, African, and Indian-Australian, for instance) move approximately along straight path, while others (Eurasian and North American) run in a rotating way. Most strangely, both Indian-Australian and Pacific plates move nearly orthogonal to each other. It is considerably difficult to imagine how these driving forces work together to control these various surface motions. In the scenarios of the mantle convection theory, poloidal motion involves vertical upwellings and downwellings, while toroidal motion undertakes horizontal rotation (Bercovic, et al., 2015). The generation of toroidal motion requires variable viscosity, but unfortunately, numerous studies of basic 3-D convection with temperature-dependent viscosity had failed to yield the requisite toroidal flow (Bercovic, 1993, 1995b; Cadec et al., 1993; Christensen and Harder, 1991; Stein et al., 2004; Tackley, 1998; Trompert and Hansen, 1998; Weinstein, 1998). Last, these driving forces are unsuccessful in yielding plate motions, although some models had yielded plate-like behavior and mathematically got solution for plate motion velocity by means of a

non-Newtonian way, i.e., a balance relationship of buoyancy force and drag force (Bercovici, et al., 2015). Some authors may argue that the global 3-D convection models have shown how mantle density variations can drive convection currents and plates at the surface with all the correct observables, such as plate speed and plate direction. We believe we have obligation to remind readers, you must strictly differentiate these modelling works from physical reality. The models show the plates may be moving under the conditions they ideally constrain, but the plates also may be moving under other conditions they don't know. For example, as demonstrated in the following sections, we have successfully employed another method to realize plate motion (including speed and direction) that is completely comparable to observation. We feel, to prove that plate motion is indeed related to the mantle density variations, one has to find direct evidence to support. Besides these shortcomings, other problems like changes in plate motion, flatness, and asymmetry of subduction also remains unresolved within these driving forces (Bercovici, et al., 2015). Since 1970's, some had begun to discuss the relative importance of these driving forces (Forsyth & Uyeda, 1975; Backus, et al., 1981; Bokelmann, 2002). This discussion give people the sense that all the forces related to plate motion had been known well. The fact, however, is not so, another force has been entirely neglected by scientific community. In this work, we go back to the exterior of the earth to seek this force and consider a solution for plate motion.

2 An oceanic tide-generating force driving mechanism for plate motion

Liquid can exert pressure at the side of a vessel that holds it. Refer to the top of Figure 1, the pressure at the side of a cubic vessel may be approximately written as $P=\rho gy/2$, the application of this pressure to the side generates force for this side, which may be expressed as $F=PS=\rho gy^2x/2$, where S is the area of the side that is exerted by the pressure, ρ , g , x , and y are respectively density of liquid, gravitational acceleration, vessel width, and liquid depth. This formula indicates that the force generated at the side is closely related to two key factors like liquid's depth and the side's area that this liquid applies to. Go back to real world, ocean is a naturally gigantic vessel, and its depth is usually more than thousands of meters, these suggest that any small-scale oscillation of ocean depth may generate an enormous force variation for the continent's side. For example, an addition of a water with volume 1.0 m^3 ($1*1*1$, length, width, and height, respectively) onto an ocean of depth $3,000.0 \text{ m}$ may add a force of $29,404,900.0 \text{ N}$ to the continent's side, even if this volume of water itself owns a gravity of $9,800.0 \text{ N}$. Most of oceans experience two cycles of high and low water per day, and the amplitude of this oscillation often reaches a few meters, these are the tides we see in everyday life. Connected to the expression we made above, the daily tides generate varying pressure for ocean, and further, the application of this varying pressure to the continent's side generates an enormous varying force for the continent. We treat the continental crust, which has been applied by ocean pressure, as continent in the following sections. Refer to Figure 1, we firstly assume no tide within the ocean, the horizontal forces generated due to ocean pressure at the two sides of the continent are F_L' and F_R' , the friction exerted by the asthenosphere along the continent's base is F_A and is related to the asthenosphere's viscosity, the resistive force from adjacent crust is f_r , the composition of these four forces would be $F_A+f_r-(F_L'-F_R')$. There are three possibilities for the combination of the friction and the two horizontal forces, i.e., $F_A-(F_L'-F_R') > 0$, $F_A-(F_L'-F_R') = 0$, and $F_A-(F_L'-F_R') < 0$, the first two represent the friction is greater than or equal to the difference of the two horizontal forces, whereas the last represents the friction is less than the difference. We trend to accept $F_A-(F_L'-F_R') = 0$, that means, if there is no other external force to overcome the resistive force, the continent would remain in a state of equilibrium (immovable). In a later part we shall discuss why the horizontal force generated due to ocean pressure may balance the friction generated due to the asthenosphere. The presence of tide, however, may break this relationship. The addition of tide to ocean arises the ocean to oscillate around a reference level, the horizontal forces generated vary accordingly. Ocean pressure variations had been extensively found by means of bottom pressure measurements around the globe (Fig. 2) and

completely agrees to these arguments. Bottom pressure measurements also reflect the fact that ocean pressure variations not only closely relate to the daily tides but greatly differ from one ocean to another. For example, at the time of new Moon of the month, the range of bottom pressure variation at North Santo Domingo (Atlantic ocean) is almost within 100 millibars, while at South Dutch Harbor (Pacific ocean) this range may reach up to 260 millibars. Ocean pressure always exerts on the continental slope to form a normal force, this force can be decomposed into the horizontal force and a vertical force, the horizontal force is only related to ocean's depth and width, as demonstrated at the top of Figure 1. In the following sections, we focus on dealing the effect of these horizontal forces. According to the geometry of force, the horizontal forces generated due to ocean pressure adding tide at both sides may be approximately expressed as $F_L' = 0.5\rho g L (h_L + h_L')^2$ and $F_R' = 0.5\rho g L (h_R + h_R')^2$, where ρ , g , L , h_L , and h_R are respectively density of water, gravitational acceleration, ocean's width (also continent's width), ocean depth at the left, and ocean depth at the right; h_L' and h_R' are respectively the tidal heights at both sides. The tidal heights can be approximately expressed as $h_L' = A_L \sin \omega t$, and $h_R' = A_R \sin(\omega t + \phi)$, A_L and A_R denote tidal amplitudes, ω , t , and ϕ are respectively angular frequency, time, and phase difference between the tides at both sides. The variation of the horizontal force generated due to tide at both sides can be written as $\Delta F_L' = 0.5\rho g L (h_L'^2 + 2h_L h_L')$ and $\Delta F_R' = 0.5\rho g L (h_R'^2 + 2h_R h_R')$, respectively, the net horizontal force of these two variations may therefore be written as $F = \Delta F_L' - \Delta F_R' = 0.5\rho g L (2h_L h_L' - 2h_R h_R' + h_L'^2 - h_R'^2)$. We define, if this net horizontal force is positive (i.e, $F > 0$), it represents a forward force (F_{forward}) for the continent, whereas if this force is negative (i.e, $F < 0$), it represents a backward force (F_{backward}) for the continent. The net horizontal force provides a dynamic source for the continent. Since the tidal height varies with time, the expression above represents a net varying horizontal force for the continent. Figure 3 demonstrates how the net horizontal force varies at different phase differences between the tides at both sides during a day. A remarkable feature of this net varying horizontal force is that its amplitude becomes minimal when the tides occur synchronously at both sides (i.e, $\phi = 0^\circ$), namely, one side holds high (low) tide when another side holds high (low) tide, too, whereas becomes maximal when the tides oppositely occur (i.e, $\phi = 180^\circ$), namely, one side holds high (low) tide when another side holds low (high) tide. And then, we combine the net horizontal force (F) generated due to tide and the resistive force (f_r) together to deal with the continent's movement at the matter of tidal phase difference $\phi = 0^\circ$. It should be noted, the amplitude of the net horizontal force at the tidal phase difference $\phi = 0^\circ$ is minimal, if the net horizontal force under this condition is large enough to overcome the resistive force to cause the continent to move, naturally, the net horizontal force under other condition (the tidal phase difference $\phi \neq 0^\circ$) has ability to overcome the resistive force to cause the continent to move. We thus use the net horizontal force at the tidal phase difference $\phi = 0^\circ$, which acts as a threshold of lowest limitation, to determine the continent's movement. We further assume the resistive force (f_r) is constant and its magnitude is slightly less than the maximum of the net horizontal force. Refer to Figure 3, at the stage of t_1 , F_{forward} begins to increase as the tidal heights increase, but since $F_{\text{forward}} < f_r$, the continent remains immovable; At the stage of t_2 , $F_{\text{forward}} > f_r$, the continent accelerates and moves forward, and its speed reaches a high level at the end of this period; At the stage of t_3 , $F_{\text{forward}} < f_r$, the moving continent begins to decelerate until its speed becomes zero at the end of this period; At the stage of t_4 , $F_{\text{forward}} < f_r$, the continent keeps immovable; At the stage of t_5 , F_{backward} performs an oscillation similar to F_{forward} , but since its direction keeps same as that of the composition of the horizontal forces generated due to ocean pressure, the continent keeps immovable. Simply, the continent discontinuously obtains a forward movement from t_1 to t_4 and a stagnation at t_5 . This relationship reflects a net forward movement for the continent during a period of from t_1 to t_5 . Similar thing takes place in the following period. Expanding this day to the whole year, it indicates that the continent obtains a steadily forward movement during the year. Further, extending this case to the matter that the tides are extensively distributed around all the globe, we conclude that the resultant horizontally forces may be responsible for the movements of continents. Figure 4 exhibits a globally distribution of the tides and the resultant horizontal forces.

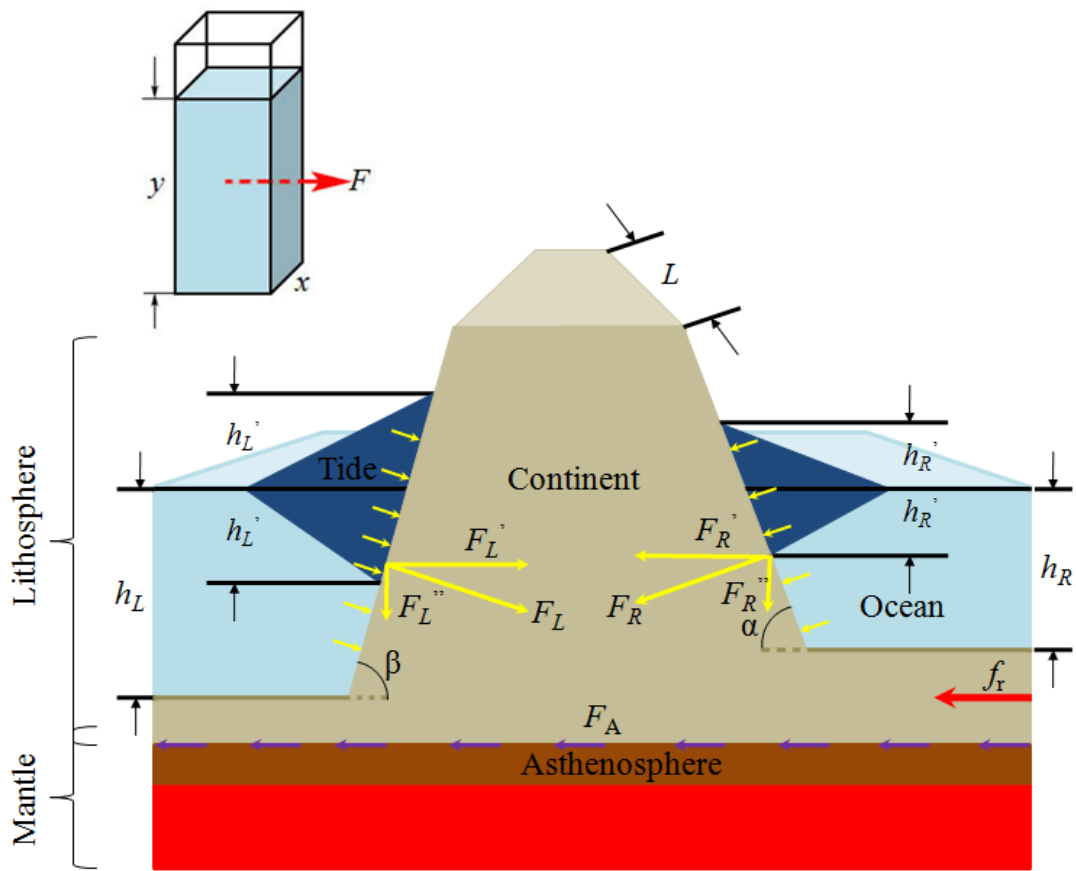


Fig. 1. Modelling the dynamics of the continent under the effect of ocean and tide. $F_L(F_R)$ represents the normal force generated at the left (right) side of the continent, while $F_L'(F_R')$ and $F_L''(F_R'')$ denote respectively the horizontal and vertical forces decomposed from the normal force. F_A , f_t , and L are respectively the friction from the asthenosphere, the resistive force from adjacent crust, and the width of continent's side. h_L and h_R are respectively ocean depth at the left and at the right, h_L' and h_R' are the tidal heights at both sides. α and β denote the inclinations of continent's slope at the both sides. Note that the tidal heights are seriously exaggerated relative to ocean depth.

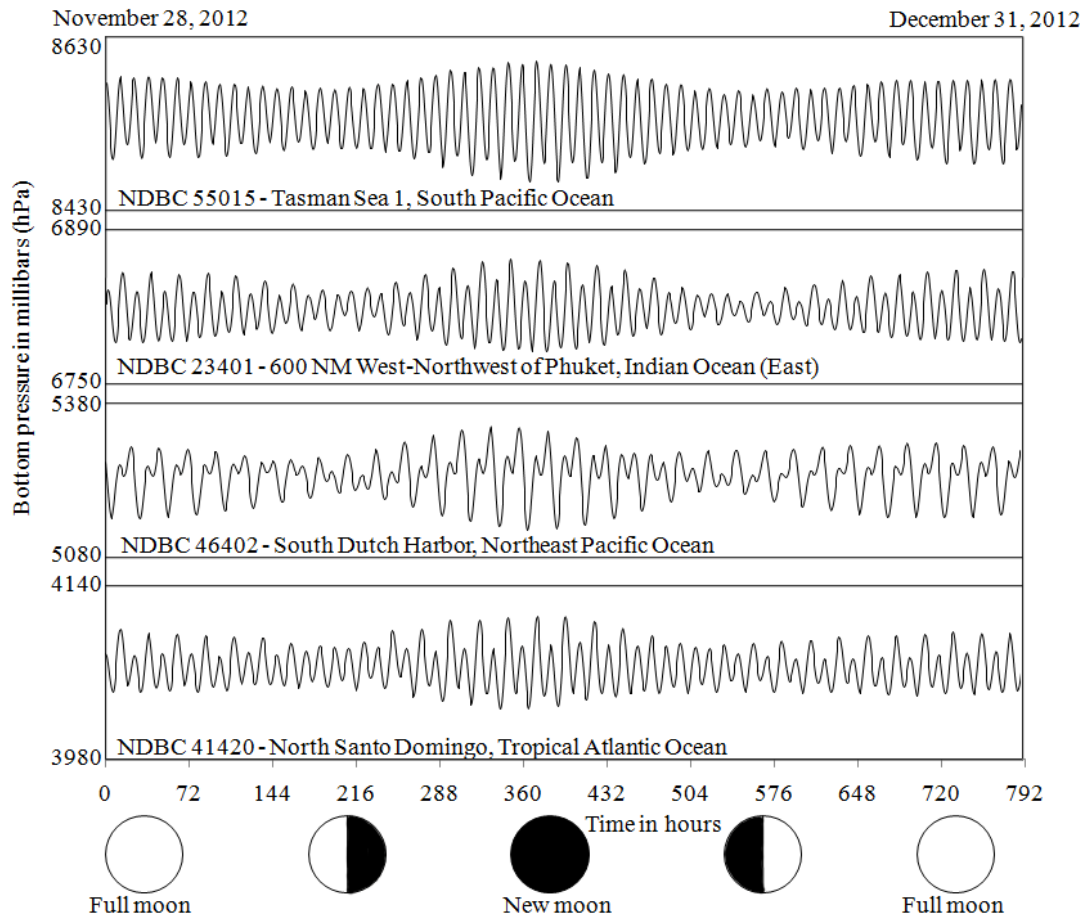


Fig. 2. Typical 1-month bottom pressure records from Pacific, Atlantic, and Indian oceans during 2012. Bottom pressure record data are from PSMSL (Permanent Service for Mean Sea Level).

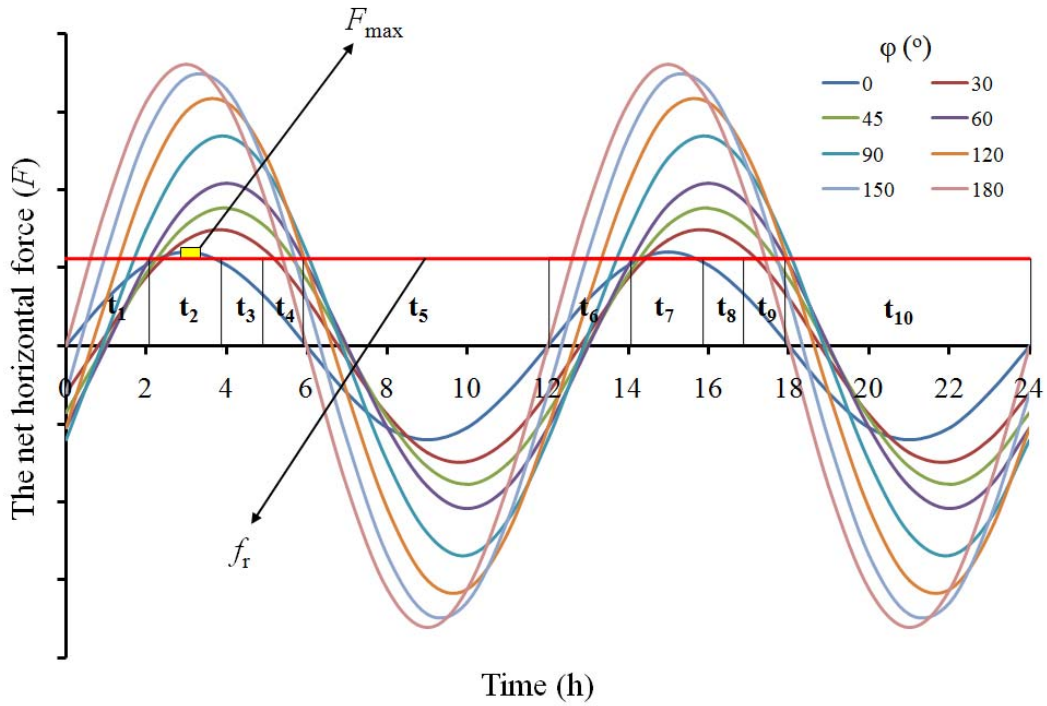


Fig. 3. Dynamic analysis for the continent movement based on tide loading and unloading.

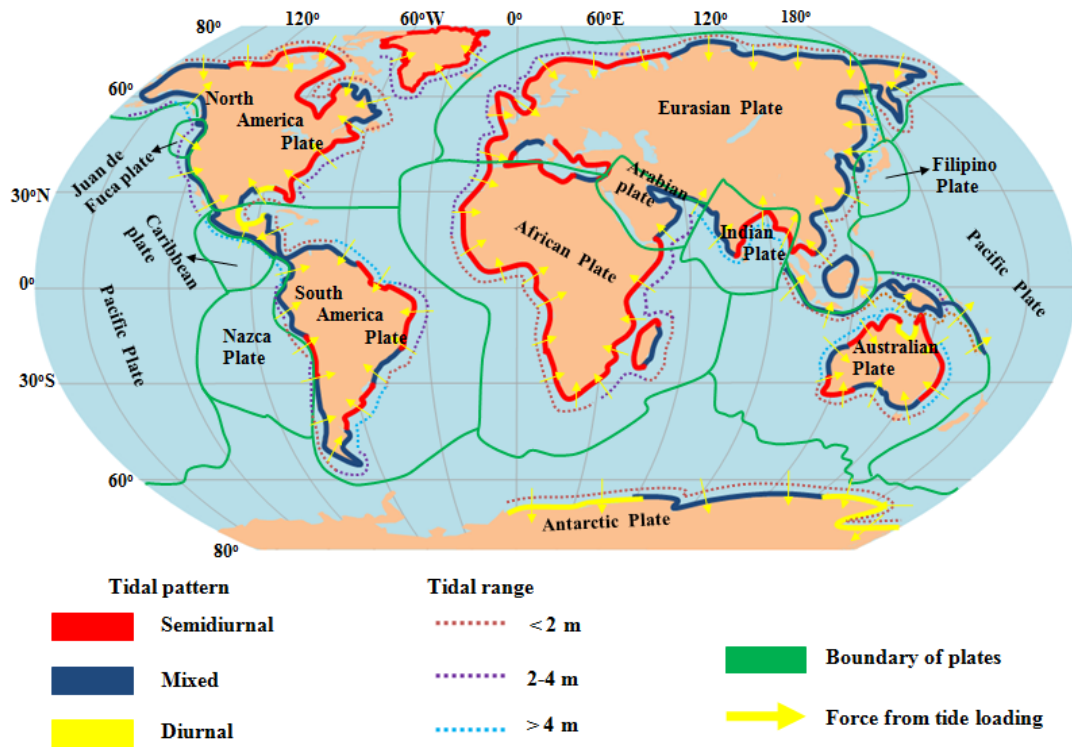


Fig. 4. A global view of the distribution of tidal pattern, tidal range, plate tectonics, and the resultant horizontally forces from tide loading. Tide data supporting is from U.S. NOAA, GLOSS database - University of Hawaii Sea Level Center (Caldwell et al. 2015), and Bureau National Operations Centre (BNOC) of Australia, and tide range also refer to the times atlas of the oceans, 1983, Van Nostrand Reinhold, NY.

A quantitative treatment of the continent's movement must include more details. Practically, a continent, if not connected to another, is being surrounded by oceans, this means that the net horizontal force obtained by this continent would be a combination of the horizontal forces generated at its all sides. The spherical earth bends the continent inevitably, this makes the horizontal forces unable to fall onto an identical plane. In addition, the tides in the oceans are not synchronous everywhere, and their amplitudes perform two cycles per month, which is related to the positions of the sun, moon, and earth, and become maximal at the times of full and new moon and minimum at the times of first quarter and last quarter. Another thing we shouldn't ignore is the loading/unloading rate of a tide is not uniform, this leads the horizontal force generated to vary at a changing rate and results in a difficulty in determining the time that the continent takes to accelerate and decelerate during a tide. More features of the tides may refer to these works (Pugh 1987; Pugh and Woodworth 2014). In order to facilitate the following calculation, we assume the continent to be more rigid and planar, the tides within the oceans to be synchronous anywhere, the tidal amplitudes to be constant, and the tide loading/unloading rate to be uniform. Each of the horizontal forces generated at the sides of a continent is firstly decomposed into latitudinal and longitudinal forces, and then, the net horizontal force is expressed with a recombination of these latitudinal and longitudinal forces. According to the knowledge of Newton's 2nd law ($F=Ma$, $D=0.5at^2$, where F , M , a , and t are respectively the force that an object accepts, the object's mass, the resultant acceleration, and the time that the object takes to move) and refer to Figure 3, the movement a continent obtains within a year may be approximately written as $D=365*2*0.5(F_{\max}-f_r)t^2/M$, where F_{\max} denotes the net horizontal force generated at the time of the highest high tide, and $F_{\max}=(F_{\text{sum-latitude}}^2+F_{\text{sum-longitude}}^2)^{0.5}$, $F_{\text{sum-latitude}}$ and $F_{\text{sum-longitude}}$ are respectively the sum of all the latitudinal and longitudinal forces decomposed. Each of these latitudinal and longitudinal forces can be further got through $F_{\text{latitudinal}}=\Delta F\cos\theta$ and $F_{\text{longitudinal}}=\Delta F\sin\theta$, where $\Delta F=0.5\rho gL(2h_{\text{ocean}}h_{\text{tide}}+h_{\text{tide}}^2)$, representing the variation of the horizontal force generated at the time of the highest high tide. It should be noted that the direction of the horizontal force must be carefully considered when decomposing it into the latitudinal and longitudinal forces. ρ , g , L , h_{ocean} , and h_{tide} are respectively density of water, gravitational acceleration, the continent side's width, ocean depth, and tidal height. θ is the inclination of the horizontal force to latitude and may be got through the geographic latitudes and longitudes of two sites that respectively locate at the ends of a side. M is the continent's mass and can be got through $M=Sd\rho_{\text{continent}}$, where S , d , and $\rho_{\text{continent}}$ are respectively the continent's area, thickness, and density. The resistive force (f_r) is presently unknown, we have to constrain it in the calculation. t is the time that the continent takes to accelerate within a high tide, given there are two high tides and two low tides for a continent per day, it may be written as $t=2*\arccos(f_r/F_{\max})/\omega$, where ω is angular frequency and roughly equal to 15° per hour. It also should be noted, $0.5(F_{\max}-f_r)t^2/M$ is only a combined expression of the movement within a high tide, it actually includes the movement at an accelerating stage and that at a decelerating stage. As the continent is assumed to be more rigid, the application of the Newton mechanics to the continent above is rational. The total pressure a liquid exerts includes static and dynamic pressures, the former relates to liquid's motion, while the latter is exhibited by liquid equally in all directions. In the oceans there are many kinds of currents such as Antarctic circumpolar current, deep ocean current, western boundary currents, and so on. The ebb and flow of a tide also may be treated as current. All these currents representing liquid's motion are relatively weak in producing the dynamic pressure because of their slow speeds, we here neglect the dynamic pressure completely when treating the continent's movement. In reality, continent (representing the whole continental crust) has the features that its side is not flat and its base is also wider than its top, these make it more like a circular truncated cone. The expression of the horizontal force we made above indicates that this force is only related to the ocean's width (i.e., the continent side's width), ocean depth, and tidal height, rather than to the continent's slope. This suggests that we may firstly project a continent along horizontal direction into a polygonal column and cut its side into a series of rectangular sides connecting one to another, and then, calculate the horizontal force generated at each of these rectangular sides, last, combine the horizontal forces generated into a single net horizontal force. With

these theoretical ideas, we constrain the parameters involved to estimate the movement of a few continents (South American, African, Indian, and Australian). The selection of the controlling sites that determine the horizontal forces of these continents refers to Figure 5, the longitudes and latitudes of these related sites are resolved through Google Earth software. The given values for related parameters, the horizontal forces generated, and the resultant movements are respectively listed in table 1, 2, and 3. Overall, the resultant movements of South American, African, Indian, and Australian continents are respectively 2.8, 4.2, 5.6, and 6.3 cm/yr, which are well consistent with the observed movement of generally 5.0~10.0 cm/yr (Read and Watson 1975) on the assumptions that all parameters are ideally constrained. The weakness of this calculation is the resistive force (f_r) isn't strictly considered, but we believe, the progress of measurement or experiment or both will improve the understanding of this physics. The precondition for the calculation above is the friction exerted by the asthenosphere onto the continent has been offset by the horizontal forces generated due to ocean pressure. The offsetting is estimated along such a line. The friction exerted by the asthenosphere may be got through a theoretical expression $F_A = \mu Au/y$, where μ , A , u , and y are respectively the viscosity of the asthenosphere, the area of the continent, the speed of the continent, and the thickness of the asthenosphere. Both the viscosity and thickness of the asthenosphere vary largely according to different authors. Cathless (1971) concluded the viscosity no less than 10^{20} P, Jordan (1974) treated the thickness as 300 km. Fjeldskaar (1994) suggested that the asthenosphere has a thickness of less than 150 km and a viscosity of less than 7.0×10^{20} P. Some works using glacial isostatic adjustment and geoid studies showed the asthenospheric viscosity ranges from 10^{19} to 10^{21} P (Hager and Richards, 1989; King, 1995; Mitrovica, 1996). James et al. (2009) used model to show that the asthenospheric viscosity is varied from 3×10^{19} P for a thin (140 km) asthenosphere to 4×10^{20} P for a thick (380 km) asthenosphere. We here adapt $\mu = 3 \times 10^{19}$ P and $y = 140$ km to estimate the friction exerted by the asthenosphere for the selected four continents. The speed of these continents (South American, African, Indian, and Australian) is valued as 2.7, 4.2, 5.6, and 6.3 cm/yr, respectively. These values are presently accepted by geophysical community. The horizontal force generated due to ocean pressure at each side of a continent may be got through $F' = 0.5 \rho g L h^2$, where ρ , g , L , and h are respectively density of water, gravitational acceleration, ocean's width (also the continent side's width), and ocean depth. The continent's area, the width of each side, and the ocean depth that corresponds to the length of a side refer to Table 1. Table 4 shows the estimated results of both the horizontal forces and the friction. Evidently, for each of the selected four continents the composition of the horizontal forces generated due to ocean pressure is extremely close to the friction generated due to the asthenosphere. We believe this approach is not coincidence, because the two kinds of forces, as seen above, are calculated through two different passages. The discrepancy between the two kinds of forces may arise from that our constrain on related parameters cannot be strictly exact relative to the real physics. We should remind reader that, if ocean basin has no fracture (i.e., the gap at the ocean ridge), the horizontal forces generated due to ocean pressure at all the sides of the basin would be balanced by the basin itself and wouldn't interact with external force. The existence of the gaps at the ocean ridges allows the horizontal forces generated to fight against the friction, and it is this offsetting of the two to provide condition for the oceanic tide-generating force to drive the continent. Finally, we come to the conclusion that the estimate above agrees with the precondition.



Fig. 5. Geographic treatment of the controlling sites for selected continents and the resultant horizontal forces exerted on them. F (yellow arrow) denotes the horizontal force, while purple bar denotes the distance applied by the horizontal force. The product of this distance and ocean depth is the area applied by the horizontal force. Dot with number denote controlling site. Ocean depth is artificially resolved from Google Earth software.

Table 1 Basic information for selected four continents

Continent	area	thickness	density	mass	site			distance of site to site		tide amplitude	ocean depth
	S	d	$\rho_{\text{continent}}$	M	No.	Longitude	Latitude	L	h_{tide}	h_{ocean}	
	km ²	km	kg/m ³	kg				km	m	m	
South American	17,840,000	6	3,100	3.32E+20	1	80.0°W	2.0°S	1_2	2,087	1.5	4,000
					2	70.0°W	18.0°S	2_3	1,153	1.5	4,000
					3	73.0°W	28.0°S	3_4	2,780	1.5	3,500
					4	73.0°W	53.0°S	5_6	2,308	2	4,500
					5	68.0°W	52.5°S	6_7	1,730	2	4,500
					6	54.0°W	34.5°S	7_8	1,952	1.5	4,500
					7	42.0°W	23.0°S	8_9	2,525	1.5	3,000
					8	34.0°W	7.0°S	9_10	2,157	1.5	3,000
					9	53.0°W	5.5°N	10_11	836	1.5	2,000
					10	72.0°W	12.0°N	11_1	1,033	1.5	3,000
					11	78.0°W	7.0°N				
African	30,370,000	6	3,100	5.65E+20	12	6.0°W	35.5°N				
					13	17.0°W	14.7°N	12_13	2,535	1	4,000
					14	7.0°W	4.6°N	13_14	1,531	1	4,000
					15	8.0°E	4.4°N	14_15	1,696	1	4,000
					16	22.2°E	34.7°S	15_16	4,577	1	4,000
					17	30.4°E	30.7°S	16_17	886	1	4,000
					18	40.0°E	16.0°S	17_18	1,904	1	4,000
					19	51.0°E	11.0°N	18_19	3,237	1	4,000
Indian	4,400,000	6	3,100	8.18E+19	20	66.8°E	25.0°N				
					21	77.5°E	8.0°N	20_21	2,205	2	2,000
					22	80.0°E	15.2°N	21_22	846	2	2,000
					23	91.5°E	22.7°N	22_23	1,468	2	2,000
24	94.3°E	16.0°N	23_24	801	2	2,000					

					25	114.0°E	23.0°S	25_31	2,162	2	2,000
					26	117.2°E	35.0°S	25_26	1,370	2	3,000
					27	131.0°E	31.5°S	26_27	1,340	1	3,000
Australian	8,600,000	6	3,100	1.60E+20	28	149.8°E	37.6°S	27_28	1,846	1	4,000
					29	153.0°E	25.4°S	28_29	1,390	2	3,000
					30	142.4°E	10.8°S	29_30	1,970	2	1,000
					31	131.0°E	12.2°S	30_31	1,252	2	100

Note: all parameter refer to the text and Figure 5; tide amplitude is half of tidal range.

Table 2 The horizontal forces from tides and the resistive force for selected four continents

Continent	ΔF	the horizontal force			composition	the resistive force
		horizontal	latitudinal , east (+)	longitudinal , north(+)		
		$F_{\text{horizontal}}$	$F_{\text{latitudinal}}$	$F_{\text{longitudinal}}$		
N (*10 ¹⁴)						
South American	1	1.2274	1.0408	0.6505		
	2	0.6783	0.6497	-0.1949		
	3	1.4306	1.4306	0.0000		
	4	2.0364	-1.5859	1.2775		
	5	1.5264	-1.0561	1.1021		
	6	1.2912	-1.1692	0.5480		
	7	1.1139	-0.6122	-0.9306		
	8	0.9513	-0.3153	-0.8975		
	9	0.2460	0.1622	-0.1849		
	10	0.4556	0.4414	-0.1128		
			-1.0140	1.2574	1.61535	1.61483
African	11	0.9935	0.8801	-0.4610		
	12	0.5999	0.4242	0.4242		
	13	0.6648	0.0442	0.6633		
	14	1.7939	1.6884	0.6061		
	15	0.3474	-0.1523	0.3123		
	16	0.7461	-0.6247	0.4080		
	17	1.2688	-1.1750	0.4787		
		0.0000	1.0849	2.4316	2.66260	2.66220
Indian	18	0.8640	0.7312	0.4602		
	19	0.3313	-0.3130	0.1087		
	20	0.5751	-0.3142	0.4818		
	21	0.3137	0.2895	0.1210		
		0.0000	0.3935	1.1716	1.23592	1.23684
Australian	22	0.0243	0.0030	-0.0241		
	22	0.8052	0.7780	0.2075		
	22	0.3938	-0.0968	0.3817		
	22	0.7237	0.2234	0.6884		
	22	0.8169	-0.7902	0.2073		
	22	0.3858	-0.3122	-0.2266		
	22	0.8471	0.4542	-0.7150		
			0.2594	0.5191	0.58030	0.57897

Note: all related forces refer to Figure 5.

Table 3 The resultant movements for selected four continents

Continent	movements per year	
	mm/yr	to latitudinal direction, east (+) degree
South American	27.52	128.89
African	41.65	65.96
Indian	55.56	71.44
Australian	62.70	63.39

Note: all the movement refer to Figure 5.

Table 4 The horizontal forces from ocean pressure and friction from the asthenosphere for selected four continents

Continent	F'	the horizontal forces			composition	the friction F_A
		horizontal	latitudinal , east (+)	longitudinal , north(+)		
		$F_{horizontal}$	$F_{latitudinal}$	$F_{longitudinal}$		
$N(*10^{17})$						
South American	1	1.6362	1.3875	0.8672		
	2	0.9043	0.8661	-0.2598		
	3	1.6686	1.6686	0.0000		
	4	2.2905	-1.7837	1.4369		
	5	1.7169	-1.1879	1.2395		
	6	1.9365	-1.7535	0.8219		
	7	1.1136	-0.6121	-0.9304		
	8	0.9510	-0.3153	-0.8973		
	9	0.1639	0.1081	-0.1232		
	10	0.4555	0.4413	-0.1128		
			-1.1807	2.0421	2.3589	3.2730
African	11	1.9873	1.7604	-0.9221		
	12	1.2000	0.8485	0.8485		
	13	1.3298	0.0885	1.3268		
	14	3.5882	3.3772	1.2123		
	15	0.6949	-0.3047	0.6246		
	16	1.4924	-1.2496	0.8160		
	17	2.5379	-2.3503	0.9575		
			2.1700	4.8637	5.3259	8.6672
Indian	18	0.8644	0.7315	0.4604		
	19	0.3315	-0.3131	0.1087		
	20	0.5754	-0.3143	0.4820		
	21	0.3139	0.2896	0.1210		
			0.0000	0.3937	1.1722	1.2365
Australian	22	1.2083	1.1675	0.3113		
	23	1.1816	-0.2905	1.1453		
	24	2.8951	0.8935	2.7538		
	25	1.2258	-1.1857	0.3110		
	26	0.1931	-0.1562	-0.1134		
	27	0.0012	0.0001	-0.0012		
	28	0.8475	0.4544	-0.7153		
			0.8832	3.6915	3.7956	3.6815

The treatments above are only reliable for these small-sized continents. For those larger ones like Eurasian and North American continents, their curvatures cannot be ignored, the horizontal forces generated due to the tides cannot pass their barycenters, a torque effect can be generated to rotate these continents. Figure 6(A and B) conceptually demonstrates how these continents move under the torque effect of the horizontal forces. We at a time speculated a dynamic pressure may explain the Pacific Plate's unusual motion, which is nearly orthogonal to Australian plate's. However, it presently becomes clear that a combination of two lateral pushes respectively from North American Plate and from Australian Plate may be competent. As shown in Figure 6(C), the northeasterly travelling

Australian Plate and the counterclockwise rotating North American Plate respectively provide push force F_{AP} and F_{NAP} to Pacific Plate, the net effect of a combination of these two forces could be force F_{PP} , which drives Pacific Plate to move along northwest. Please note, so long as we consider plate, as more rigid, the transition of lateral force from one plate to another is feasible. Of course, from a viewpoint of evolution, North American Plate must have rotated much during a timescale of more than millions of years, this means that the present-day North American could be reversed to northeast in the past, if so, the push force F_{NAP} might not have existed at that time, Pacific Plate was most likely pushed by Australian Plate alone to move along northeast. This further meant that, abrupt change in motion might have occurred for Pacific Plate at a moment when North American Plate rotated to a critical angle, from which the combination of two lateral forces becomes possible. Such plate motion change actually has been witnessed by the Hawaiian–Emperor bend (Sharp and Clague, 2006; Wessel and Kroenke, 2008).

Plate motion may therefore be a manifestation of the oceanic tide-generating force (i.e., the horizontal force). The estimation above indicates that only a very little part of the oceanic tide-generating force, no more than 0.06% of the total, is used to yield the requisite continent's movement. The remaining force could be consumed in entraining the adjoining oceanic crust, and shaping the continent itself. As a result, a great number of various terrestrial features like MOR, transform fault, volcano, earthquake, and high mountain are created for the earth.

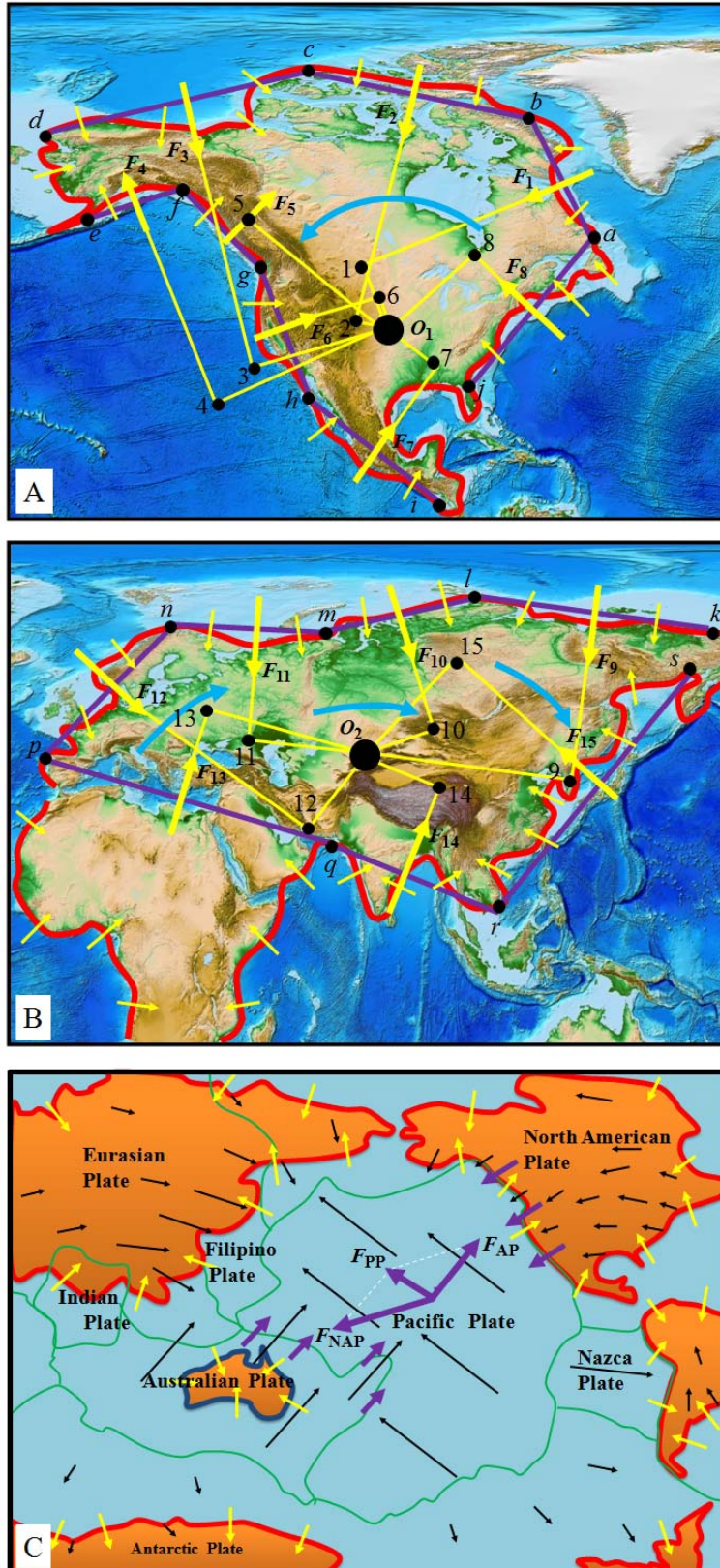


Fig. 6. Dynamics for the movements of North American, Eurasian, and Pacific plates. A and B, Modelling the rotations of North American and Eurasian plates under the torque effect of the horizontal forces due to the tides. O_1 and O_2 denote possible positions of the barycenters of two continents. F_1, F_2, F_3 , i.e., marking with yellow arrows, denote the horizontal forces yielded due to the tides (red), a, b, c , i.e., denote the selected controlling sites, while ab, bc, cd , i.e., marking with

purple bars, denote the distances that generate these horizontal forces, while O_{11} , O_{12} , . . . , O_{29} , O_{210} , i.e., denote the arms applied by the horizontal forces. Torque effect is expressed with the product of force and arm. Curved blue arrows represent the expected rotations around the barycenters. Note F_{13} actually represents lateral push force from moving African continent. The background map is produced from ETOPO1 Global Relief Model (Amante and Eakins, 2009). C, Modelling the motion of Pacific Plate based on a combination of two lateral forces respectively from Australian and North American Plates. Black, yellow, and purple arrows denote respectively plate motions, the resultant forces from the tides, and lateral push forces between related plates. Note lateral push force $F_{NAP}(F_{AP})$ is approximately parallel to the motion of North American (Australian) Plate.

3 Discussion

Tidal drag proposed as a driving mechanism for plate motion had been long debated. Wegener (1924) attributed the westward drift of the American blocks to tidal drag, but Jeffreys (1929) argued that the westward stress related to tidal drag is too small to be competent for the displacement. A rapid growth of tidal drag driving mechanism arises from the confirmation of a net rotation or westward drift of the lithosphere relative to the mantle (Rittmann, 1942; Le Pichon, 1968; Bostrom, 1971; Moore, 1973), which is supported by independent observations such as plate motion within the hot spot reference frame (Ricard et al., 1991; O'Connell et al., 1991; Gordon, 1995; Gripp and Gordon, 2002), plate motion relative to Antarctica (Le Pichon, 1968; Knopoff and Leeds, 1972), and supported by geological asymmetries (Doglioni, 1993). Another supporting to it comes from energy budget. For instance, many works calculated that tidal drag is energetically feasible for plate motion. According to Rochester (1973) and Jordan (1974), the total energy released due to tidal friction exceeds 5×10^{19} ergs/s, excluding the dissipation in both shallow seas and solid earth (Miller, 1966; Munk, 1968), a remaining energy of about 3×10^{19} ergs/s might be available for driving plate motion, this amount exceeds by 2 orders of magnitude the lower bound set by seismic energy release (Gutenberg, 1956). Some authors (Egbert and Ray, 2000; Ray, 2001; Riguzzi et al., 2010) latterly reevaluated the energy budget to show that the total energy released by tidal friction may reach up to 1.2×10^{20} J/yr, subtracting the dissipation in the mantle, oceans, and shallow seas, a residual energy of about 0.4×10^{20} J/yr is larger than the one required to maintain the net rotation, estimated at about 1.27×10^{19} J/yr. Nevertheless, a satisfaction in energy supply cannot shield tidal drag driving mechanism. Jordan (1974) and Jeffreys (1975) attacked the theoretical basis of tidal drag driving mechanism by claiming that the viscosity both related to tidal drag and necessary to allow decoupling between lithosphere and mantle ($\sim 10^{11}$ Pas) is far less than the present-day asthenosphere viscosity, estimated at between 10^{17} and 10^{20} Pas (Anderson, 1989; Pollitz et al., 1998; Fjeldskaar, 1994; Giunchi et al., 1997; Piersanti, 1999). Ranalli (2000) showed that any non-zero torque due to difference in angular velocity between the mantle shell and lithosphere shell would be extremely transient, and cannot be a factor in the origin of the westward drift of the lithosphere. In spite of these arguments, tidal drag driving mechanism continues to grow up. Scoppola et al. (2006) proposed the westward rotation of the lithosphere as the consequence of a combined effect of tidal torque acting on the lithosphere, downwelling of the denser material toward the deeper interior of the earth, and thin layers of very low viscosity hydrate channels occurring in the asthenosphere. Some recently works shows that, by assuming an ultra-low viscosity layer in the upper asthenosphere, the horizontal component of the tidal oscillation and torque have ability to move the lithosphere (Riguzzi et al., 2010; Doglioni and Panza, 2015).

Following the growth line of tidal drag driving mechanism and connecting to the oceanic tide-generating force driving mechanism presented in this work, we may pick up a few points to share that, first of all, the established tidal drag driving mechanism is proposed to primarily explain the westward drift of the lithosphere relative to the mantle, this means it is different from the oceanic tide-generating force driving mechanism. The latter is proposed to primarily explain the present-day various plate motions and related terrestrial activities; Secondly, tidal

drag driving mechanism has no objection to the established plate driving forces such slab-pull, ridge push, basal drag, and slab suction, and thus, tidal drag may be thought to be supplementary to these dominant forces. Contrary to this, the oceanic tide-generating force driving mechanism treats the oceanic tide-generating force as the dominant plate driving force; Lastly, geophysical community are encountering a big confusion: on the one hand, energy budget agrees tidal friction is feasible for the westward drift of the lithosphere, but on the another hand, torque calculation shows tidal friction incompetent. In fact, Jordan's work (1974) had set up a landmark for many of the geophysicists to overtly reject the tidal drag driving mechanism. The oceanic tide-generating force driving mechanism here provides solution for this puzzle: 1) plate motion is not directly powered by the energy released due to tidal friction, instead, the tidal dissipation in the oceans, which is represented with ocean tide, has transferred some of its energy, by means of ocean pressure oscillation, to the continents, causing plate motion. According to Egbert and Ray (2000), the total oceanic and shallow seas dissipation is about 0.75×10^{20} J/yr. A contribution from this dissipation to the continents might be sufficient for driving plate motion; and 2) Jordan's deduction itself is wrong, although both energy budget and torque calculation are mathematically correct. We believe, any reader who carefully grasps section 2 of this work must have known how Jordan had been wrong. Jordan doesn't know the basal drag exerted by the asthenosphere to the lithosphere had been offset by the horizontal force generated due to ocean pressure. Even so, it is presently uncertain whether the oceanic tide-generating force may be responsible for the westward drift of the lithosphere or not, this must be left to determine until a globally oceanic tide-generating force is evaluated.

Some suspect whether a hourly tide has ability to drive the continent to form a steadily movement. As shown in table 3, the resultant movements for South American and Indian continents are very subtle, no more than 0.075 and 0.152 mm per day, but we can imagine that, day after day, month after month, and year after year, the accumulated movements must follow a timescale of more than millions of years. Some authors may argue that, by means of a comparison of the magnitude between the oceanic tide-generating force presented in this work and the ridge push (also slab pull), the oceanic tide-generating force is insignificant. This comparison is inadequate. On the one hand, one mayn't use the magnitude of the ridge push (also slab pull) as a rule or standard to determine whether other force is significant or not. As we demonstrated in the section 2, the Newton's 2nd law ($F=Ma$, $D=0.5at^2$, where F , M , a , and t are respectively the force that an object accepts, the object's mass, the resultant acceleration, and the time that the object takes to move) shows an object's displacement is related to both the force magnitude and the time that it accepts. In other words, if we give the object a smaller force but a relatively longer time, the object still may move a long distance. The quantitative treatment on the continent's movement shows no more than 0.06% of the oceanic tide-generating force has been enough to yield the requisite movement. Therefore, the magnitude of force isn't the most important. On the other hand, the applicability of force should be considered as the first critical factor to judge the significance. As we demonstrated in the section 1, both the ridge push and slab pull are only workable for a few plates (Nazca and Caribbean, for instance) that are either without continent loading or sinking at the trench. For most of plates (African, Eurasian, North American, and South American, for instance), the available force for them has to give place to basal drag. But unfortunately, the effectiveness of basal drag is presently still in a state of debate, because the asthenosphere is insufficiently rigid to directly yield motion by friction along the base of the lithosphere. In contrast, the oceanic tide-generating force, which is globally distributed, may be available for all the plates.

The travelling continent by means of basal friction drags the lower continental crust beneath it, the lower continental crust further pulls its adjoining oceanic crust, this generates strain for the latter. A periodically fracture of the oceanic crust might have been responsible for the formation of Mid-Oceanic Ridge (MOR). For instance, as shown in Figure 7, with the passage of time, the accumulated strain eventually rips the oceanic crust, allowing the magma from the deep to erupt. The erupted magma then cools by ocean to crystallize and form new crusts.

The newly formed crusts in turn seal the fracture, terminating that eruption. The fracture relieves strain temporarily, but since the horizontal force continues to push the continent to move, strain is again accumulated, the following fracture and closeness occur again. The newly formed crusts automatically add height to the oceanic crust, forming the MOR. In addition, the travelling continent provides not only drag to the oceanic crust at the rear and but also push to the oceanic crust in the front, the drags or pushes or both of different directions to identical oceanic crust also may cause the crust to fracture, allowing magma to erupt to form the MOR.

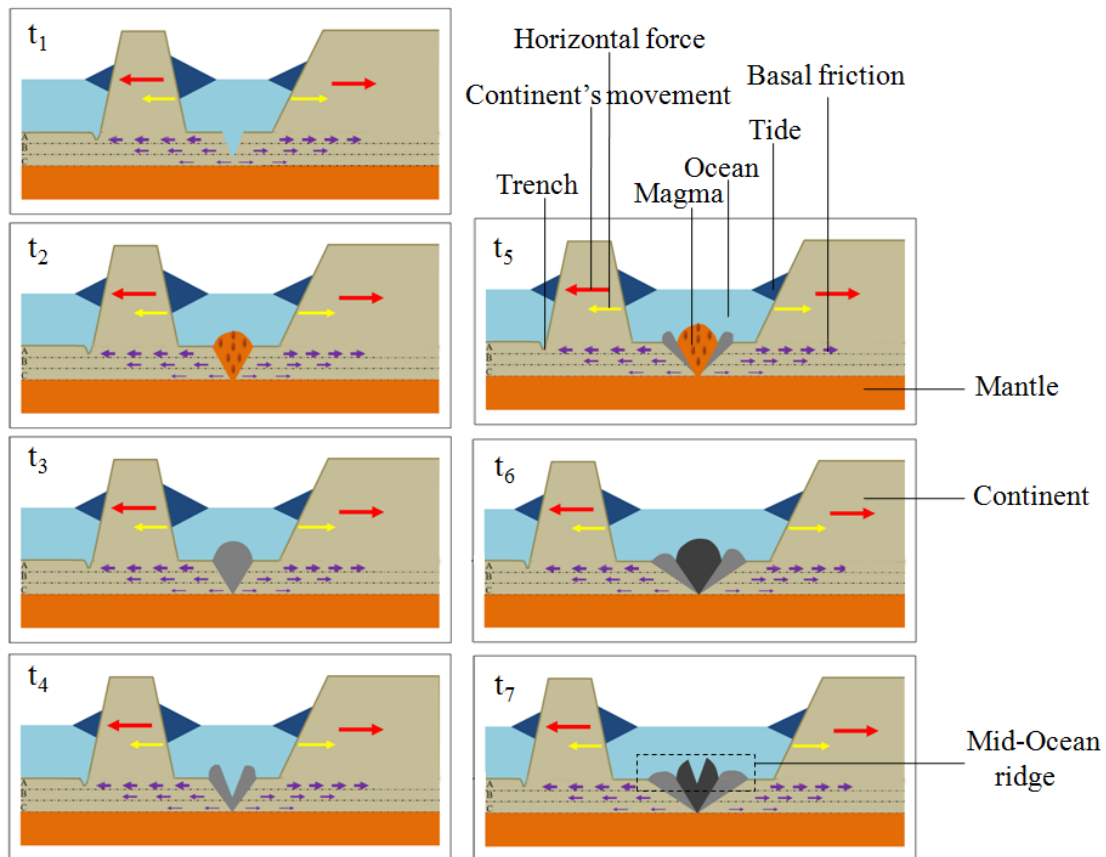


Fig. 7. Modelling the formation of MOR under the tide generating forces. From t_1 , t_2 , ..., to t_7 , it exhibits a sequence of the oceanic crust's evolution. The lower part of lithosphere is apparently divided into three layers A, B, and C, so as to depict different motions due to the drag exerted by basal friction.

The overriding of the continent onto the oceanic crust may create a squeeze effect to the latter, creating terrestrial features/activities like trench, earthquake, and volcano at the zones where they meet each other. As the horizontal forces generated push continent's every side inwards, these compressions may cause continent to form folded mountains and rifts. Refer to Figure 8, the horizontal force (i.e., the oceanic tide-generating force) pushes Indian continent to impinge into Eurasian continent, as the force is vertical to the continental slope, this provides a bulldozer effect to uplift the materials in the front, forming the Himalayas. It should be noted that, the Himalayas was long thought to be a result of the collision of Indian Plate and Eurasian Plate. This understanding, actually, is not exactly correct. These two plates have the same rock density, the collision between them would form an addition of height. The thickness of the continental (oceanic) crust is about 35 (6) km (Turcotte & Schubert 2002), the overlay of these two plates would give a thickness of at least 80 km, except for the folded situation generated by plate itself and the early formed oceanic crust in the middle of the two

ancient separated plates. However, the present-day Himalayas (Mount Everest, 8,848m) is too low to reach the requisite height. In contrast, if we treat the Himalayas as a result of the collision of the two continents who are thinner and represent the upper part of the continental crust, it could be rational. Both the Arabian Sea and Bay of Bengal have a depth of about 4,000 m, it is the continent's side of this depth to accept the horizontal force generated. Indian continent holds a height of generally no more 500 m, while Tibetan Plateau holds a height of about 4,000~5,000 m, we need to add a continent of 4,000 m depth, which is equal to the sea depth that accepts the horizontal force, onto Tibetan Plateau, the requisite height may approximately be got. Actually, the Himalayas provides a good reference to understand the formation of the Alps. The Alps could arise from a collision of the travelling Italian island and other part of Europe. A major reason for this treatment is the relatively deeper Ionian and Tyrrhenian seas provide more horizontal force to the side of Italian island, this gives the island a dominantly lateral push along northwest direction.

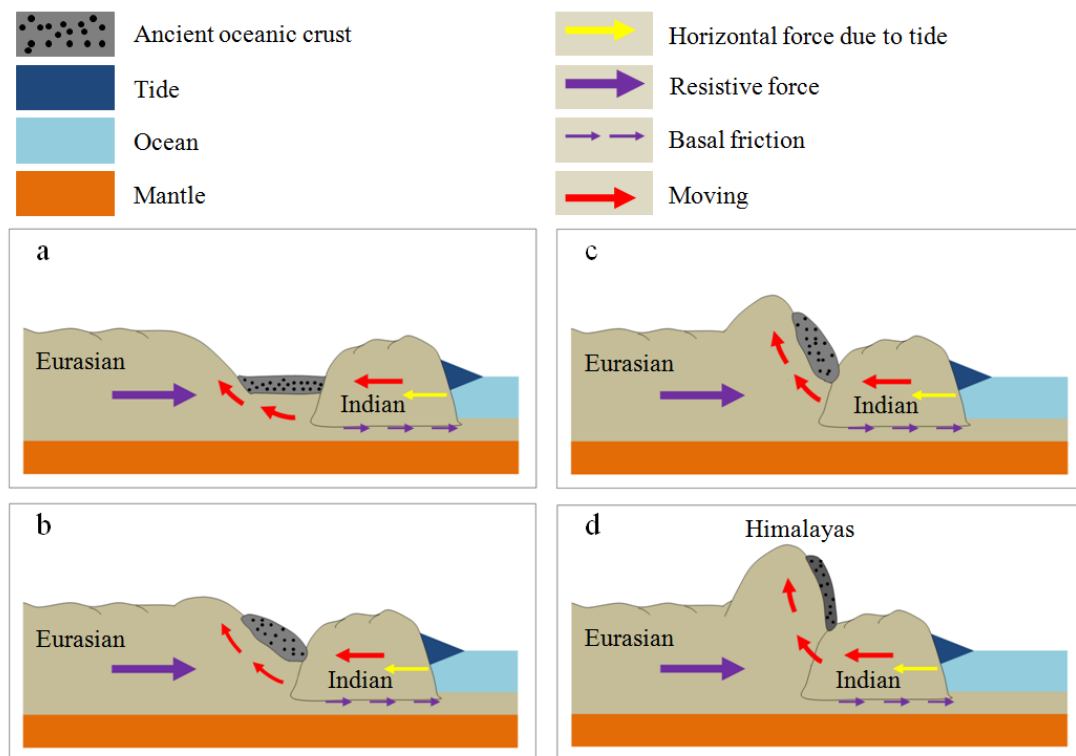


Fig. 8. Modelling the formation of the Himalayas under the collision of Indian continent and Eurasian continent. From a, b, ..., to d, it shows a time sequence of the formation.

One of the most unusual features around the MOR is the transform faults which cut the ridge into a train of smaller sections, but the formation of this structure remains in a state of debate among scientific community (Gerya, 2012). The currently accepted view believes that the oceanic transform faults originated from plate fragmentation that is related to pre-existing structures (Wilson, 1965; Oldenburg and Brune, 1972; Cochran and Martinez, 1988; McClay and Khalil, 1998; Choi et al., 2008). Gerya (2010) recently theorized the transform fault of Mid-Atlantic Ridge, and concluded (Gerya, 2012) that the asymmetric crustal growth at mid-oceanic ridge can create some transform faults, while others can form earlier during the onset of oceanic spreading. A distinguishable feature of the transform fault is there are many long and nearly-parallel structures that generally across the ridge to exert the cutting, this suggests that the ridge's formation is possibly later than that of these structures. We here consider a solution for the transform faults at the Mid-Atlantic Ridge. As exhibited in Figure 9, the early Atlantic is relatively narrow, the horizontal forces continue to push the

landmasses, forcing them to depart from each other, the travelling landmass further drags the continental crust beneath it and the adjoining oceanic crust, the oceanic crust is eventually split by the accumulated strain into smaller nearly-parallel segments. The narrowness of the oceanic crust at the time facilitates a nearly longitudinal fracture to occur. With the passage of time, the oceanic crust is largely expanded due to the opposed movements of the landmasses at the two sides, this fosters the latitudinal fracture to grow up. For each of these segments, the leading drag to it is exerted along nearly opposed directions, the accumulated strain has to fracture it in the middle. Finally, a ridge is formed for a segment, a connection of the ridges of all these segments consist of the transform faults of the Mid-Atlantic Ridge.

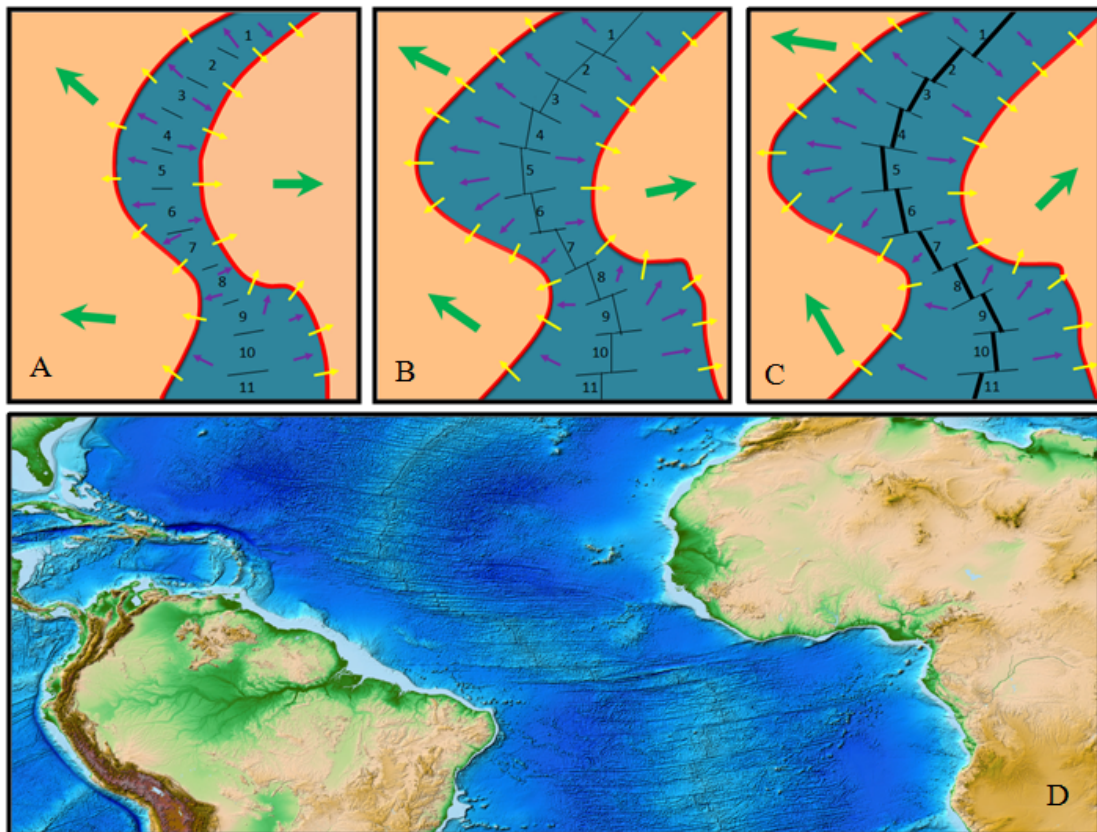


Fig. 9. Modelling the formation of MOR and transform faults based on the oceanic tide-generating forces. A, B, and C exhibit a sequence of how transform faults evolve with the growth of the MOR. Yellow, green, and purple arrows denote respectively the oceanic tide-generating forces, the resultant motions of the continents, and the drag exerted by the travelling continents to the oceanic crust. The thin black lines represent nearly- parallel structures. Number 1, 2, . . . , and 11 represent the fragments of the oceanic crust due to the fracturing, which consist of the section of transform faults. D compares the transform faults over the Mid-Atlantic Ridge. The background map is produced from ETOPO1 Global Relief Model (Amante and Eakins, 2009).

The biggest bottleneck of the mantle dynamics lies at that it seriously fights against our understanding of the dispersal of supercontinent, which had been thought to form presently smaller continents. Since the basal drag exerted by the mantle convection currents is always along the base of the lithosphere, if it were this internal force to split the supercontinent, the lithosphere should have been fractured from bottom to top. The volcano's eruption indicates a fact that a thoroughly lithosphere's fracture would lead magma to rise up to earth surface, after cooling, the magma's remnants would in turn occupy the room of the fracture. Similarly, if the separation of American and African continents were done due to the basal drag splitting the lithosphere, the fracture also must be thoroughly, the remnants of the ejected magma would inevitably occupy the room of the fracture, this disallows a large body of water to enter

and form the Atlantic ocean. In addition, the MOR reflects another fact that, so long as the lithosphere's fracture reaches mantle, the ocean water cannot prevent magma from erupting. These arguments trend to support that the dispersal of supercontinent is a consequence of the fracture of the lithosphere's upper part. In fact, there are other evidence to show that the lithosphere's fracture is indeed shallower. African Great Rift Valley and Iceland's Rift Valley are such cases. Different from the way that the mantle dynamics works along the base of the lithosphere, the oceanic tide-generating force works along the top of the lithosphere, the result is necessarily a fracture of the lithosphere's upper part. A shallower fracture not only avoids the magma's eruption but also keeps room for water to enter and form ocean. The oceanic tide-generating force driving mechanism provides line for us to dynamically track the dispersal of supercontinent. Since the tides are launched from east to west as the earth spins on its axis, in particular, a coast's blocking can also form larger tide, these allow larger tides to occur mainly at the east and west sides of the continents, whereas the smaller tides to occur mainly at the south and north sides. It's already known that the largest tide occurs often at the concave of some coasts such as Bay of Fundy (here tidal range may reach up to 16 meters). The concave actually acts as a funnel to amplify tide. With these basic ideas of the tides, we here demonstrate how the supercontinent splits into the pieces of presently smaller continents. Refer to Figure 10, at the time of upper carboniferous the opening at the east of the landmass at first facilitates a larger tide to occur, the oceanic tide-generating force pushes the adjoining landmass to move away from each other. This in turn expands the opening further. The weaker oceanic tide-generating force at the south of the landmass gives little resistance to that expansion. With the passage of time, the landmass was gradually broken and displayed the shape at the time of Eocene. This, again, facilitates more water to enter, more tides to occur, and also more oceanic tide-generating force to be generated. We speculate, it is this positive feedback to control the landmass's initial dispersal. The landmass was finally broken up until the advent of the older quaternary, a relatively primitive layout of the separated smaller continents was formally established. After that time, the tides continued to work, and the continents also continued to move away from each other until present.

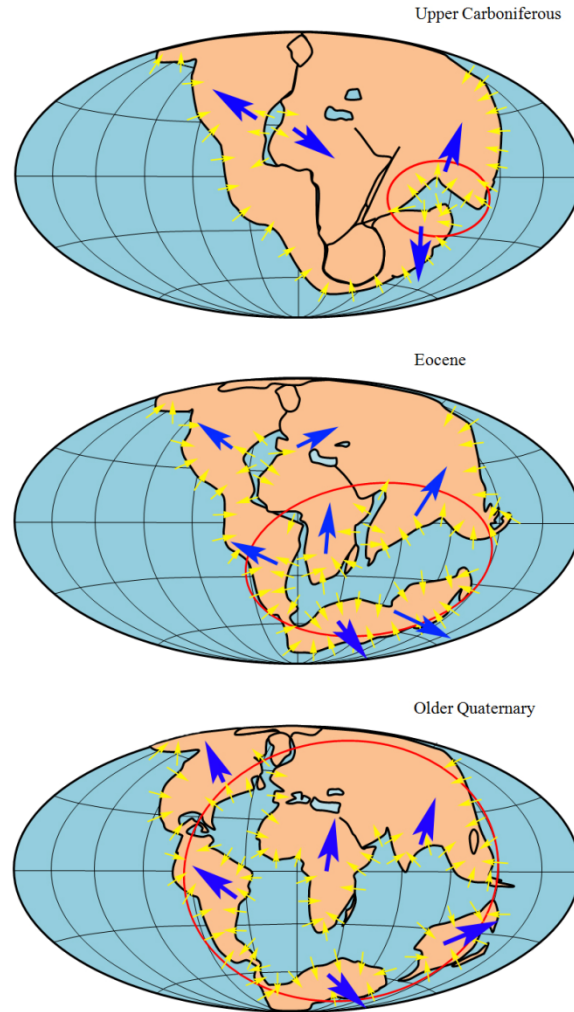


Fig. 10. Modeling the dispersal of supercontinent based on the oceanic tide-generating forces. Yellow and blue arrows denote respectively the oceanic tide-generating forces and the resultant movements. Red circles represent an expansion of the tides among the landmasses. The background map is yielded referring to Wegener's work (1924).

Another bottleneck of the mantle dynamics lies at that it evidently conflicts with the knowledge of fluid mechanics. In general, a wheel-like heat convection in a system depends a condition that the system's bottom is heated locally other than wholly. Otherwise, all the heated fluids would uniformly rise up to the top of the system, this doesn't allow to form density gradient along horizontal direction, without density gradient, it mayn't form horizontal movement of fluids. Simply, a local or uneven heating exerted at the system's bottom is needed to yield the wheel-like convection. Go back to the mantle dynamics, it ascribes the energy source of plate motion to radiogenic heating and the earth's core cooling (Bercovic, et al., 2015). Radiogenic heating arises from a release of heat energy from the radioactive decay of radiogenic nuclides. However, there is much uncertainty for the distribution of radiogenic nuclides in the mantle. Even if we assumed the distribution of nuclides to be uneven at the first stage when the earth was created, an unremitting mantle convection during a timescale of billions of years still would trend to mix them into uniform at the end. A spherically distributed heat generated due to core cooling heats the mantle wholly along its bottom. These totally determine the wheel-like mantle convection impracticable. In addition, it should be noted that, the convection (air, water, etc.) in a system often relies on an energy supply of third party. The mantle convection currents are entirely self-sustained, especially when their energy source are related to the radiogenic heating. Different from the mantle dynamics, the

energy source of the tide is related to a third party (the moon and sun). Finally, we get to the point that the oceanic tide-generating dynamics is more competent for plate motion than the mantle dynamics.

Many people feel extraordinarily perplexed why the earth has plate tectonics but her twin Venus does not. A large number of works, which generally treat mantle convection as driving engine of plate tectonics, asserted that water provides right conditions (maintaining a cool surface, for instance) for the earth's plate tectonics, while the loss of water on the Venus prohibits plate formation (Hilairiet et al., 2007; Korenaga, 2007; Lenardic and Kaula, 1994; Tozer, 1985; Hirth and Kohlstedt, 1996; Lenardic et al., 2008; Landuyt and Bercovici, 2009; Driscoll and Bercovici, 2013). Different from these understandings, this work proposes the oceanic tide-generating force (i.e, the horizontal force) as the driving engine of plate tectonics, it is natural to think, no water on the Venus, no generation of the oceanic tide-generating force, of course, no formation of plate tectonics on that planet.

To the end, it may be safe to say, whether the hypothesized mantle convection currents are found or not in the future, the oceanic tide-generating force driving mechanism we presented in this work may help extend our understanding of earth's dynamics. Under the effect of the oceanic tide-generating force driving mechanism, a dynamic tracking of the continent's movement and a more exactly prediction of earthquake become possible. Also, the continent's movement driven by the oceanic tide-generating force also may couple with the climate cycles supported by record from ice core and marine sediment (Petit, J. R. et al., 1999; Imbrie, J. et al., 1993; Bassinot, F. C. et al., 1994).

Acknowledgments We express honest thanks to Jeroen van Hunen, Thorsten Becker, Carlo Doglioni, and anonymous reviewers for their suggestive comments.

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