What Drives Plate Motions?

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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 lower lithosphere to move, these totally form plate motion. Quantitatively estimation shows that the tide generating force give South American, African, Indian, and Australian continents a movement of respectively 2.8, 4.2, 5.6, and 6.3 cm/yr. A torque effect may independently rotate North American and Eurasian continents, and the 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. This also lead the theory of continental drift 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 ridge push and slab-pull 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 always 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 be responsible for plate motion. At first glance, these driving forces appear to be rather competent and comprehensive for plate motion. The fact, however, is not so. Behind them, it shows 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 left to be the greatest force to drive plate. However, most of plates (South American, North American, Eurasian, and Antarctic Plates, for instance) don’t hold the features of subducting into trenches. This indicates that there is no slab pull exerted to these plates. Ridge push is existed, but it cannot really work for these plates. Ridge push is only useful 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 usually represents 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 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 from the deep 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 now, the subducting plate and the MOR are used to yield slab-pull and the ridge push to further drive the plate. This goes to the chicken-or-egg question, who is the first? 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 torioidal 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; Cadek 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 the velocity of plate motion 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. It should be noted here, we must strictly differentiate these modelling works from physical reality. The models only show the plates may be moving under the conditions you ideally constrain, but the plates also may be moving under other conditions you 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 comparable to observation. We feel, to prove that plate motion is indeed related to the mantle density variations, you have to find directly observational evidence to support. Besides these shortcomings, other problems like changes in plate motion, plateness, 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 A tide driving 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 m may add a force of 29,404,900.0 N to the continent’s side, even if this volume of water itself owns a gravity of 9,800.0 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 force variation for the continent. We treat the upper part of continental crust, which can be applied by ocean pressure, as continent in the following sections. Refer to the bottom of Figure 1, we initially assume there were no tide within the ocean, the majority of the horizontal force generated due to the ocean at the left would be offset by the horizontal force generated due to another ocean at the right, the remaining horizontal force generated, which is due to the additional ocean depth at the left, would be offset by a horizontally push force from part of oceanic crust at the right. For the continent, the net force of these horizontal forces is zero, this remains the continent in a state of equilibrium (immovable). The presence of tide, however, breaks 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 the horizontal forces. According to the geometry of force, the horizontal forces generated at the left and at the right may be approximately written as $F_L'=0.5\rho gL(h_L+h_L')^2$ and $F_R'=0.5\rho gL(h_R+h_R')^2$, 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 the both sides. The tidal heights can be approximately expressed as $h_L'=A_L\sin\omega t$, and $h_R'=A_R\sin(\omega t+\varphi)$, A_L and A_R denote tidal amplitudes, ω, t, and φ are respectively angular frequency, time, and phase difference between the tides at the both sides. In consideration of the horizontally push force F_{P}, the net force of all these horizontal forces fits to a relationship $F=F_L'-F_R'-F_P$. As we stated above, $F=F_L'-F_R'-F_P=0$ when $h_L'=h_R'=0$, this results in $F_P=F_L'-F_R'=0.5\rho gL(h_L^2-h_R^2)$, and then, the net force may be further simplified as $F=F_L'-F_R'-F_P=0.5\rho gL(2h_Lh_L'-2h_Rh_R'+h_L'^2-h_R'^2)$. We define, if the net horizontal force is positive (i.e, $F>0$), it represents a forward force (F_{forward}) for the continent, whereas if it is negtive (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 simplified expression above actually represents a net varying force for the continent along the horizontal direction. Figure 3 demonstrates how the net horizontal force varies at different phase differences between the tides at the both sides during a day. A remarkable feature of this variation is that the range of the net horizontal force becomes minimal when the tides occur synchronously at the both sides (i.e, $\varphi=0^{\circ}$), namely, one side holds high (low) tide when another side holds high (low) tide, whereas becomes maximal when the tides oppositely occur (i.e, $\varphi=180^{\circ}$), namely, one side holds high (low) tide when another side holds low (high) tide. And then, we combine basal friction (f) and the net horizontal force (F) together to consider the continent's movement at the matter of tidal phase difference $\varphi=0^{\circ}$. It should be noted, the net horizontal force at the tidal phase difference $\varphi=0^{\circ}$ is minimal, if this force is strong enough to move the continent, naturally, the net horizontal force at the tidal phase difference $\varphi\neq0^{\circ}$ has ability to move the continent. We thus use the net horizontal force at the tidal phase difference $\varphi=0^{\circ}$, which acts as a threshold of lowest limitation, to evaluate the continent's movement. We here assume that basal friction is constant and its magnitude is slightly less than the maximum of either the forward force (F_{forward}) or the backward force (F_{backward}). At the stage of t_1, F_{forward} begins to increase as the tidal heights increase, but since $F_{\text{forward}}<f$, the continent remains immovable; At the stage of t_2, $F_{\text{forward}}>f$, the continent accelerates and moves rightwards, and its speed reaches a high level at the end of this period; At the stage of t_3, $F_{\text{forward}}<f$, the moving continent begins to decelerate still its speed becomes zero at the end of this period; At the stage of t_4, $F_{\text{forward}}<f$, the continent keeps immovable; At the stage of t_5, F_{backward} begins to increase, but since $F_{\text{backward}}<f$, the continent remains immovable; At the stage of t_6, $F_{\text{backward}}>f$, the continent accelerate and moves leftwards, and its speed reaches a high level at the end of this period; At the stage of t_7, $F_{\text{backward}}<f$, the moving continent begins to decelerate still its speed becomes zero at the end of this period; At the stage of t_8, $F_{\text{backward}}<f$, the continent keeps immovable. Simply, the continent discontinuously obtains a forward movement (D_1) from t_1 to t_4 and a backward movement (D_2) from t_5 to t_8. From a viewpoint of energy input, a larger force trends to push an object to move a longer distance. If we assume $h_L>h_R$ and $h_L'>h_R'$, there would be $F_{\text{forward}}>F_{\text{backward}}$, further, there would be $D_1-D_2>0$. This relationship reflects a net forward movement for the continent during a period of from t_1 to t_8. Similar movements take place in the following period. Expanding this day to the whole year, it indicates that the continent obtains a steadily forward moment during the year. Further, extending this case to the matter that the tides are extensively distributed around the globe and the resultant horizontally forces are around all the continents, we conclude that the resultant horizontally forces from the tides may be responsible for the movements of these continents. Figure 4 exhibits a globally distribution of the tides and the resultant horizontal forces.

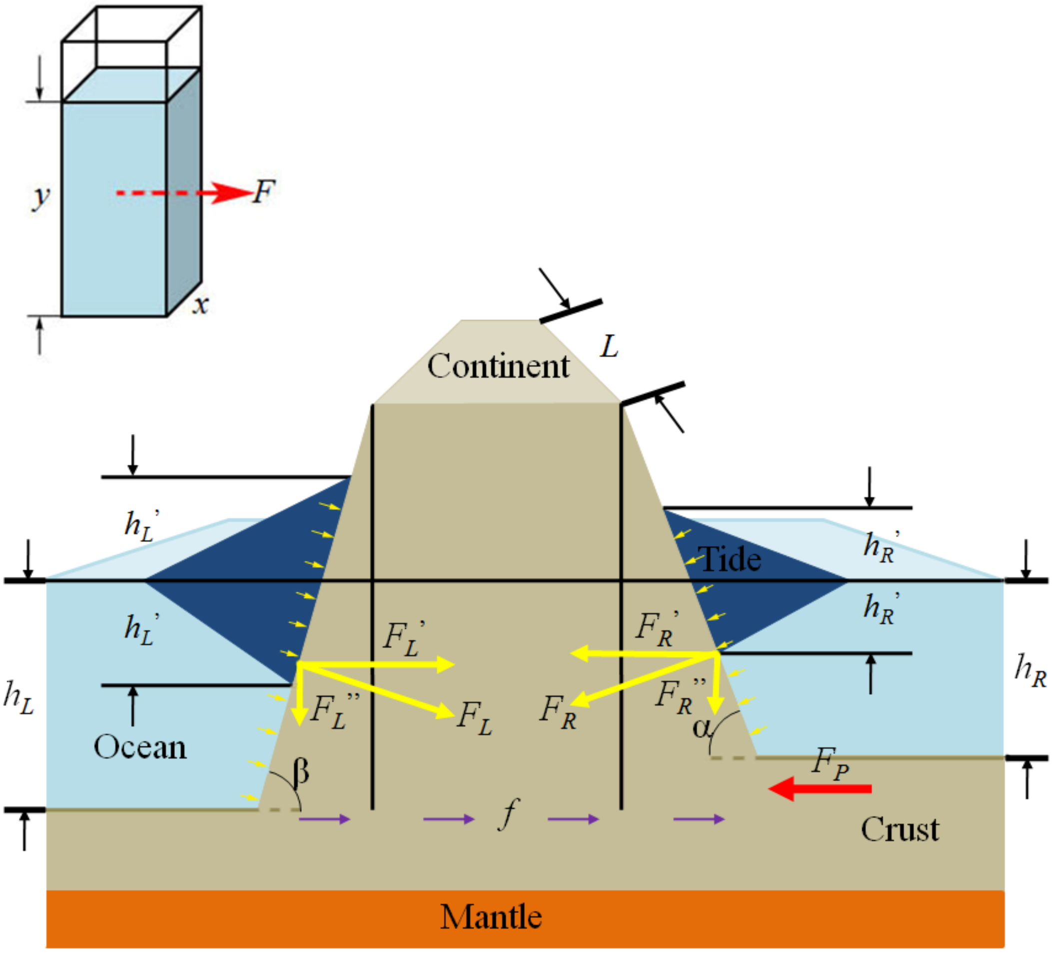


Fig. 1. Modelling the dynamics of the continental crust under the effect of ocean and tide. F_L(F_R) represents the normal force generated at the left (right) side of the continent, while F_L'(F_R') and F_L''(F_R'') denote respectively the horizontal and vertical forces decomposed from the normal force. F_P, f , and L are respectively the horizontally push force from the oceanic crust, the basal friction between the upper part of continental crust and its lower part, 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 the 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.

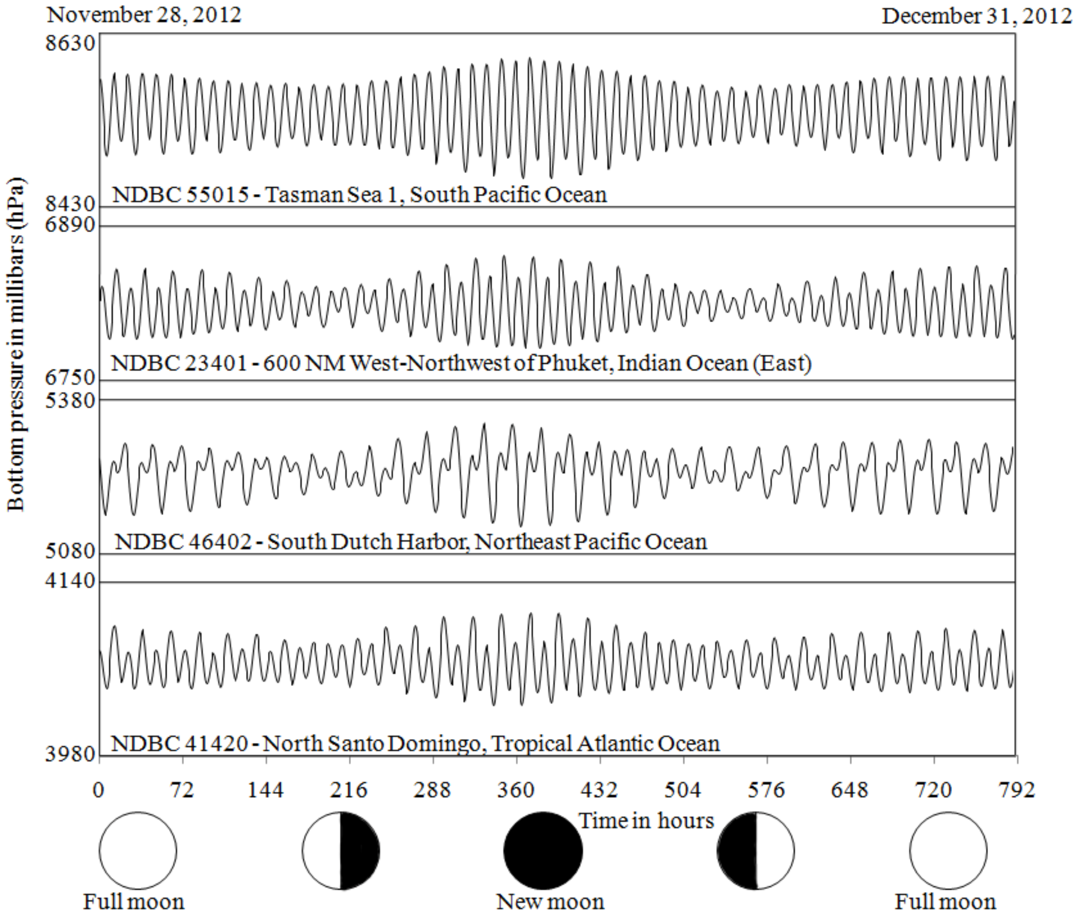


Fig. 2. Typical 1-month bottom pressure records from Pacific, Atlantic, and Indian oceans during 2012. Bottom pressure record data are from PSMSL (Permanent Service for Mean Sea Level).

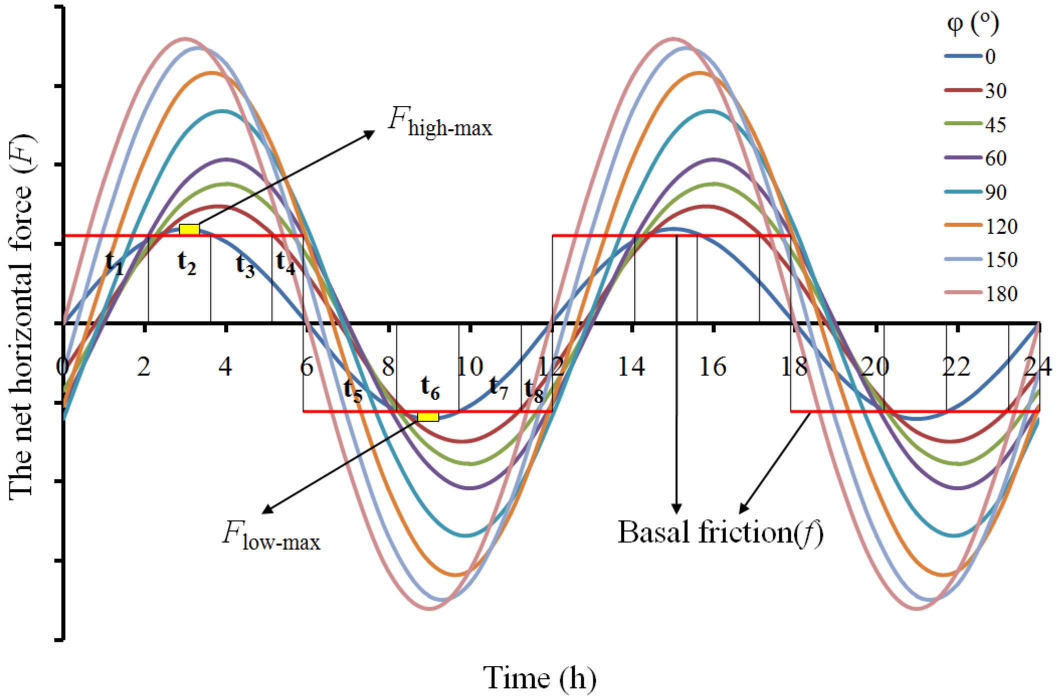


Fig. 3. Dynamic analysis for the continent's movement based on tide loading.

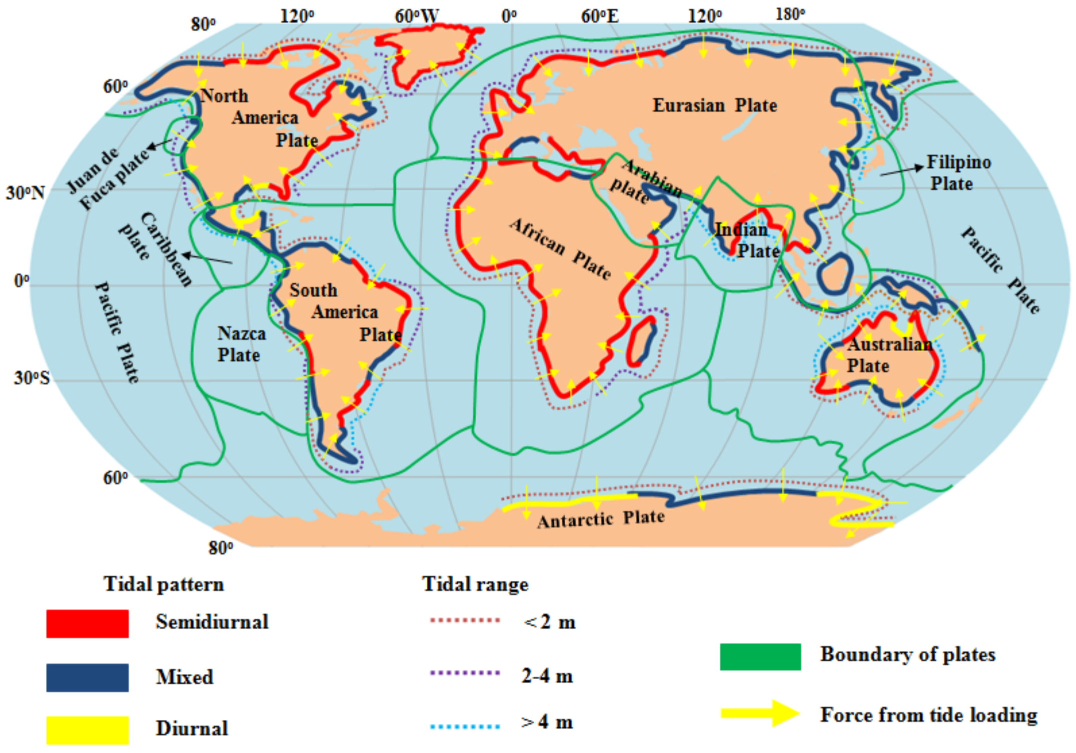


Fig. 4. A global view of the distribution of tidal pattern, tidal range, plate tectonics, and the resultant horizontally forces from tide loading. Tide data supporting is from U.S. NOAA, GLOSS database - University of Hawaii Sea Level Center (Caldwell et al. 2015), and Bureau National Operations Centre (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 mayn'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 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 run the following calculation, we assume the continent to be more rigid and planar, the tides in 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 that a continent obtains in a year may be approximately written as $D=365*2(D_1-D_2)$, where $D_1=0.5(F_{\text{high-max}}-f_r)t_{\text{high}}^2/M$, $D_2=0.5(F_{\text{low-max}}-f_r)t_{\text{low}}^2/M$, they respectively denote the movement that the continent obtains within a high tide and within a low tide. $F_{\text{high-max}}$ and $F_{\text{low-max}}$ denote the net horizontal force at the time of highest high tide and at the time of lowest low tide, respectively, $F_{\text{high-max}}=(F_{\text{sum-high-latitudinal}}^2+F_{\text{sum-high-longitudinal}}^2)^{0.5}$, $F_{\text{low-max}}=(F_{\text{sum-low-latitudinal}}^2+F_{\text{sum-low-longitudinal}}^2)^{0.5}$,

$F_{\text{sum-high-latitudinal}}$ ($F_{\text{sum-high-longitudinal}}$) and $F_{\text{sum-low-latitudinal}}$ ($F_{\text{sum-low-longitudinal}}$) respectively denote the sum of all the latitudinal (longitudinal) forces at the time of highest high tide and at the time of lowest low tide. The latitudinal and longitudinal forces can be written as $F_{\text{latitudinal}}=F_{\text{horizontal}}\cos\theta$, $F_{\text{longitudinal}}=F_{\text{horizontal}}\sin\theta$, where $F_{\text{horizontal}}=0.5\rho_{\text{water}}gL(2h_{\text{ocean}}h_{\text{tide}}+h_{\text{tide}}^2)$ and represents a horizontal force variation at a side of the continent from the reference level to the extreme (i.e, the highest high tide or lowest low tide). It should be especially noted that the direction of the horizontal force must be carefully considered when calculating the latitudinal and longitudinal forces. ρ_{water}, 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 positions of two sites that respectively locate at the ends of the side. M is the continent's mass and can be expressed as $M=S\mathrm{d}\rho_{\text{continent}}$, where S, d, and $\rho_{\text{continent}}$ are respectively the continent's area, thickness, and density. f_r denotes the resistive force that mainly includes basal friction and/(or) push force related to continent. t_{high} and t_{low} are the time that the continent takes to accelerate within a high tide and within a low tide, given there are two high tides and two low tides per day, they may be written as $t_{\text{high}}=2*\arccos(f_r/F_{\text{high-max}})/\omega$ and $t_{\text{low}}=2*\arccos(f_r/F_{\text{low-max}})/\omega$, where ω is angular frequency and roughly equal to 15° per hour. It also should be noted, $D_1=0.5(F_{\text{high-max}}-f_r)t_{\text{high}}^2/M$ is just a simplified expression of the movement within a high tide, and actually includes the movement at an accelerating stage and that at a decelerating stage. This matter is also suitable for $D_2=0.5(F_{\text{low-max}}-f_r)t_{\text{low}}^2/M$. The resistive force ($f_r$) is so far unknown, we have to constrain it in the calculation. It should be noted that, as the continent (i.e, the upper part of the continental crust) is more rigid, the application of the Newton mechanics to the continent's movement above is rational. Nevertheless, some continents like African and Indian continents connect not only to oceans but also to other continents. The argument we made above agrees a continent, which is fully surrounded by oceans, to obtain a forward movement within a high tide and a backward movement within a low tide. The reason for this kind of back and forth movement is there are pressure variation differences between the oceans around this continent. This means that, for the continent that connects to both oceans and other continents, the net horizontal force generated at the time of high tide is able to push it forward, whereas the net horizontal force generated at the time of low tide is unable to push it backward, given the other continents perform more rigid than elastic, this limits them to provide a reaction thrust. These totally guarantee that we only need to take the net horizontal forces generated at the time of high tides to deal the movement of this kind of continent.

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, which represent with liquid's motion, are weak in producing the dynamic pressure because of their relatively slow speeds. We here neglect the dynamic pressure completely when treating the continent's movement. In reality, continent (representing the upper part of continental crust that can be applied by ocean pressure) has the features that its side is not flat, and its base is also wider than its top, making 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 (also 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, compose the horizontal forces into a single net horizontal force for this continent. 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 may refer to Figure 5, the longitudes and latitudes of 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. Among of these selected continents, we calculate a forward movement within a high tide and a backward movement within a low tide for South American per day, only a forward movement for both African and Indian because they connect to other continents, and also a forward movement for Australian, this is because the ocean depth around this continent varies largely from south (4000 m depth) to north (100 m depth), this makes Australian continent highly like the matter of both African and Indian continents whose sides are connecting to other continents. Overall, the resultant movements of South American, African, Indian, and Australian, respectively 2.8, 4.2, 5.6, and 6.3 cm/yr are well consistent with the observed movement of generally 5.0~10.0 cm/yr (Read and Watson 1975) on the assumptions that all related parameters are ideally treated. The sole weakness of this estimation is an uncertainty of the resistive force (f_r), but we believe, the progress of measurement or experiment or both will improve the understanding of this physics.

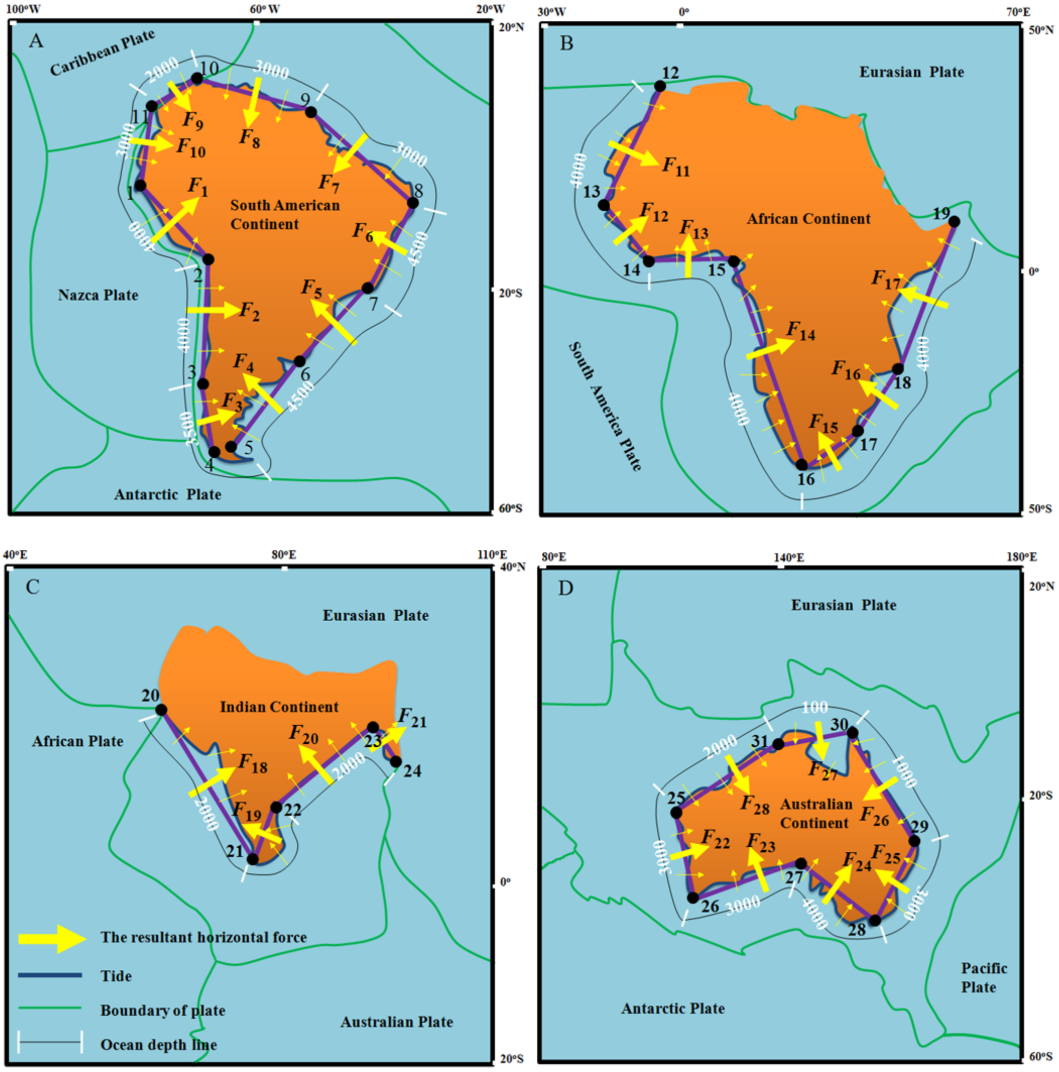


Fig. 5. Geographic treatment of the controlling sites for selected continents and the resultant horizontal forces exerted on them. *F* (yellow arrow) denotes the horizontal force, while purple bar denotes the distance applied by the horizontal force. The product of this distance and ocean depth is the 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 continents

Continent	area	thickness	density	mass	site			distance of site to site		tide amplitude	ocean depth
	S	d	$\rho_{continent}$	M				L		h_{tide}	h_{ocean}
	km^2	km	kg/m^3	kg	Num.	Longitude	Latitude	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

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

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

Table 2 The resultant forces for continents

Continent	the horizontal forces										the resistive force
	at the time of highest high tide					at the time of lowest low tide					
	F	horizontal	latitudinal , east (+)	longitudinal , north(+)	net	F	horizontal	latitudinal , east (+)	longitudinal , north(+)	net	
		$F_{\text{horizontal}}$	$F_{\text{Latitudinal}}$	$F_{\text{Longitudinal}}$	$F_{\text{net-high}}$		$F_{\text{horizontal}}$	$F_{\text{Latitudinal}}$	$F_{\text{Longitudinal}}$	$F_{\text{net-low}}$	f_{r}
	N (*10^{14})					N (*10^{14})					
South American	1	1.2274	1.0408	0.6505		1	1.2270	1.0405	0.6503		
	2	0.6783	0.6497	-0.1949		2	0.6781	0.6495	-0.1948		
	3	1.4306	1.4306	0.0000		3	1.4299	1.4299	0.0000		
	4	2.0364	-1.5859	1.2775		4	2.0355	-1.5852	1.2769		
	5	1.5264	-1.0561	1.1021		5	1.5258	-1.0557	1.1016		
	6	1.2912	-1.1692	0.5480		6	1.2908	-1.1688	0.5479		
	7	1.1139	-0.6122	-0.9306		7	1.1134	-0.6119	-0.9301		
	8	0.9513	-0.3153	-0.8975		8	0.9508	-0.3152	-0.8970		
	9	0.2460	0.1622	-0.1849		9	0.2458	0.1621	-0.1848		
	10	0.4556	0.4414	-0.1128		10	0.4553	0.4412	-0.1127		
			-1.0140	1.2574	1.61535			-1.0136	1.2571	1.61484	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	0.8471	0.4542	-0.7150		
	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	0.0243	0.0030	-0.0241		
			0.2594	0.5191	0.58030	0.57897

Note: all parameters refer to text and Figure 5.

Table 3 The resultant movements for continents

Continent	within a high tide		within a low tide		total per year	to latitudinal direction, East (+)
	time	displacement	time	displacement	displacement	
	t_{high}	D_1	t_{low}	D_2	$D=365*2(D_1-D_2)$	
	seconds	m	seconds	m	m	degrees
South American	695.77	3.77E-05	79.55	6.44E-09	0.02752	128.89
African	777.90	5.71E-05			0.04165	65.96
Indian	624.74	7.61E-05			0.05556	71.44
Australian	920.44	8.59E-05			0.06270	63.39

Note: all parameters refer to text and Figure 5.

The assumptions 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 yielded 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 previously speculated a dynamic pressure may explain the Pacific Plate's unusual motion, which is nearly orthogonal to Australian plate's. However, it now becomes clear that a combination of two lateral pushes respectively from North American Plate and from Australian Plate may be competent for this motion. 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 had 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 be 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 had 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 be a manifestation of the tide generating force. The estimation above indicates that only a very little part of the tide generating force (i.e, the horizontal force), no more than 0.06% of the total, is sufficient enough to yield the requisite continent's movement. The remaining force could be consumed in entraining the continental crust beneath the continent and the adjoining oceanic crust, and shaping the continental crust 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.

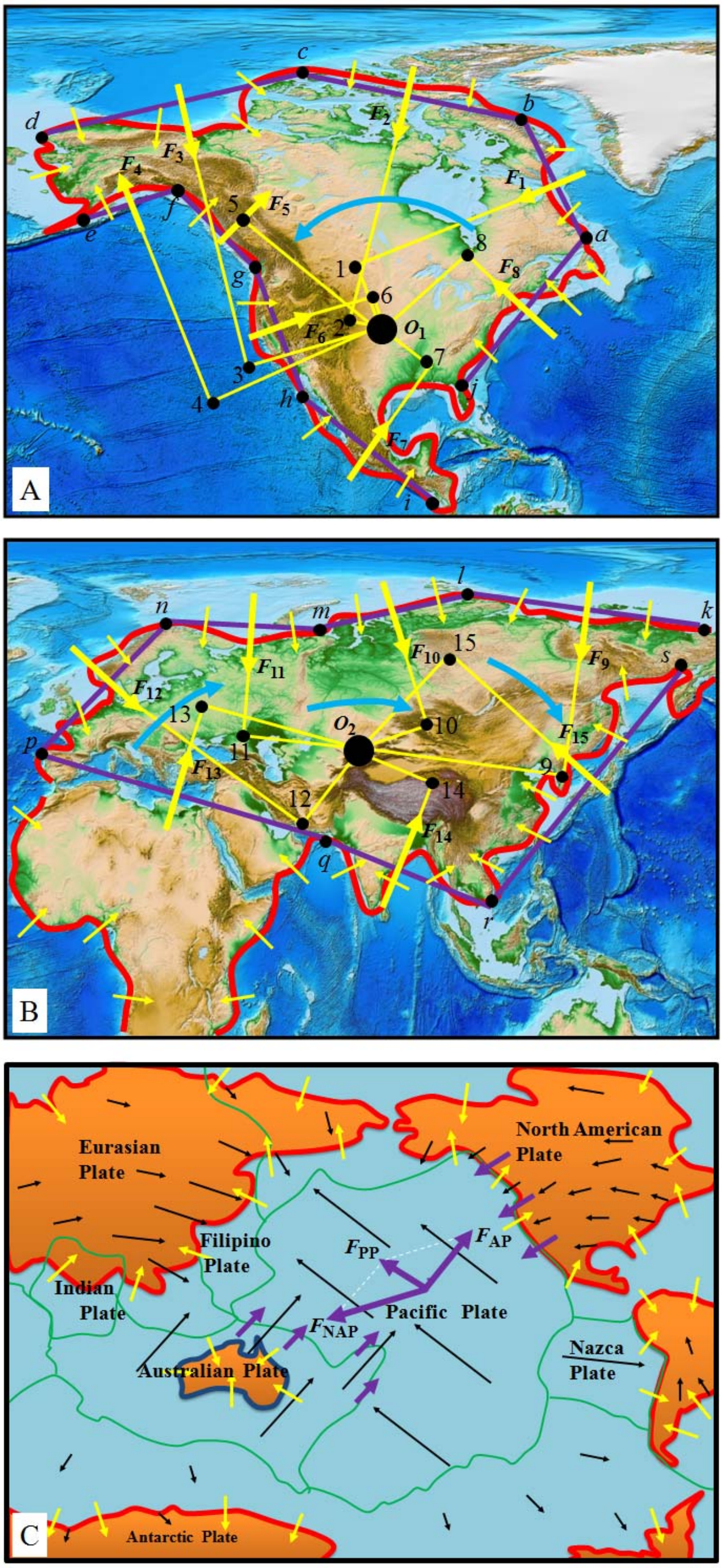


Fig. 6. Dynamics for the movements of North American, Eurasian, and Pacific plates. A and B, Modelling the rotations of North American and Eurasian plates under the torque effect of the horizontal forces due to the tides. O_1 and O_2 denote possible positions of the barycenters of two continents. F_1, 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 $O_1 1$, $O_1 2$, . . ., $O_2 9$, $O_2 10$, 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 $F_{\mathrm{NAP}}(F_{\mathrm{AP}})$ is approximately parallel to the motion of North American (Australian) Plate.

3 Discussion

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, day after day, month after month, and year after year, the accumulated movements must follow a timescale of more than millions of years. Some may argue that, by means of a comparison of the magnitude between the horizontal force generated due to tide and the ridge push (also slab pull), the horizontal force is insignificant. This comparison is completely 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 motion is related to both the force and the time that it accepts. In other words, if we give the object a smaller force but a longer time, the object still may move a long distance. The quantitative treatment on the continent's movement in this work shows no more than 0.06% of the horizontal force generated has been enough to yield the requisite movement. Therefore, the magnitude of force isn't the most important factor. 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, the ridge push and slab pull are only workable to a few plates (Nazca and Caribbean, for instance) who are either without continent loading or sinking at the trenches. For most of plates (African, Eurasian, North American, and South American, for instance), the selectable force for them has to give place to basal drag. Nevertheless, 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 horizontal force generated due to tide, which is globally distributed, may be applicable to all the plates. Last, an observationally confirmation should be considered as the second critical factor to judge the significance. So far, the ridge push, slab pull, and basal drag are all indirectly deducted and haven't yet been observationally recognized. In contrast, ocean bottom pressure measurement has provided direct evidence to support the horizontal force.

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.

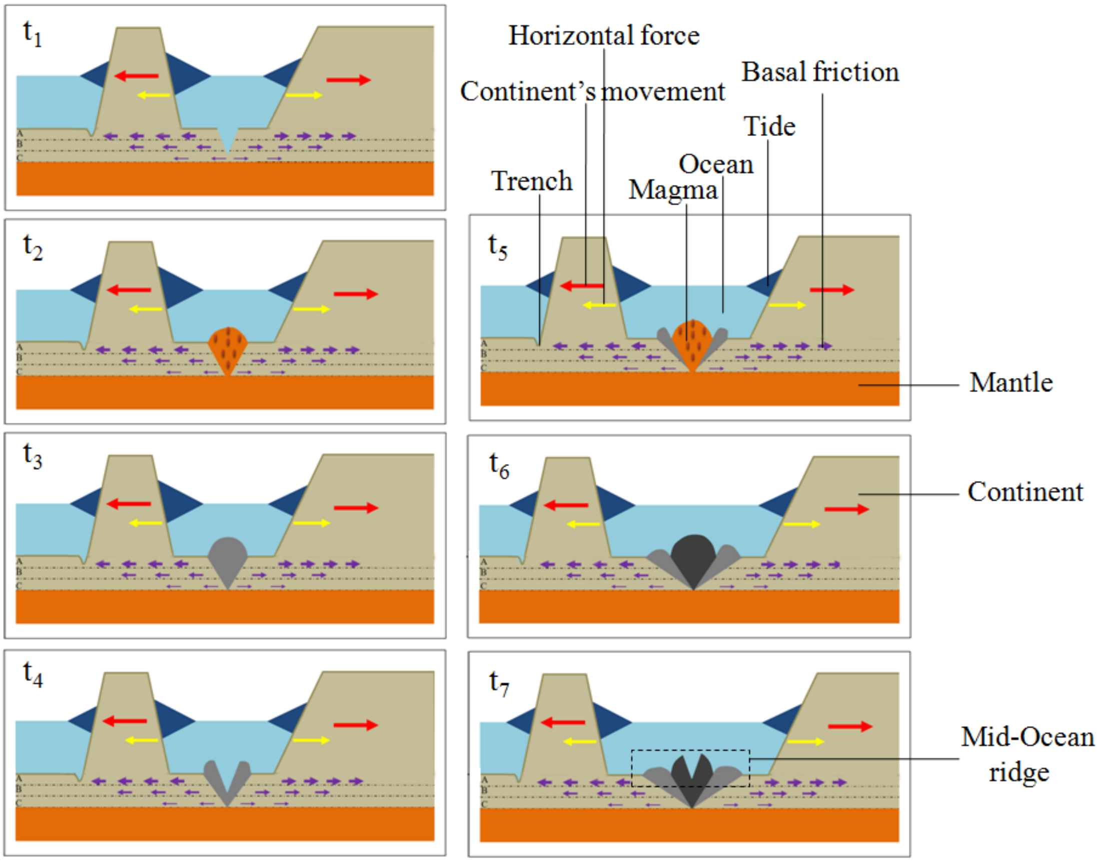


Fig. 7. Modelling the formation of MOR under the tide generating forces. From t_1, t_2, …, to t_7, it exhibits a sequence of the oceanic crust's evolution. The lower part of lithosphere is apparently divided into three layers A, B, and C, so as to depict different motions due to the drag exerted by basal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

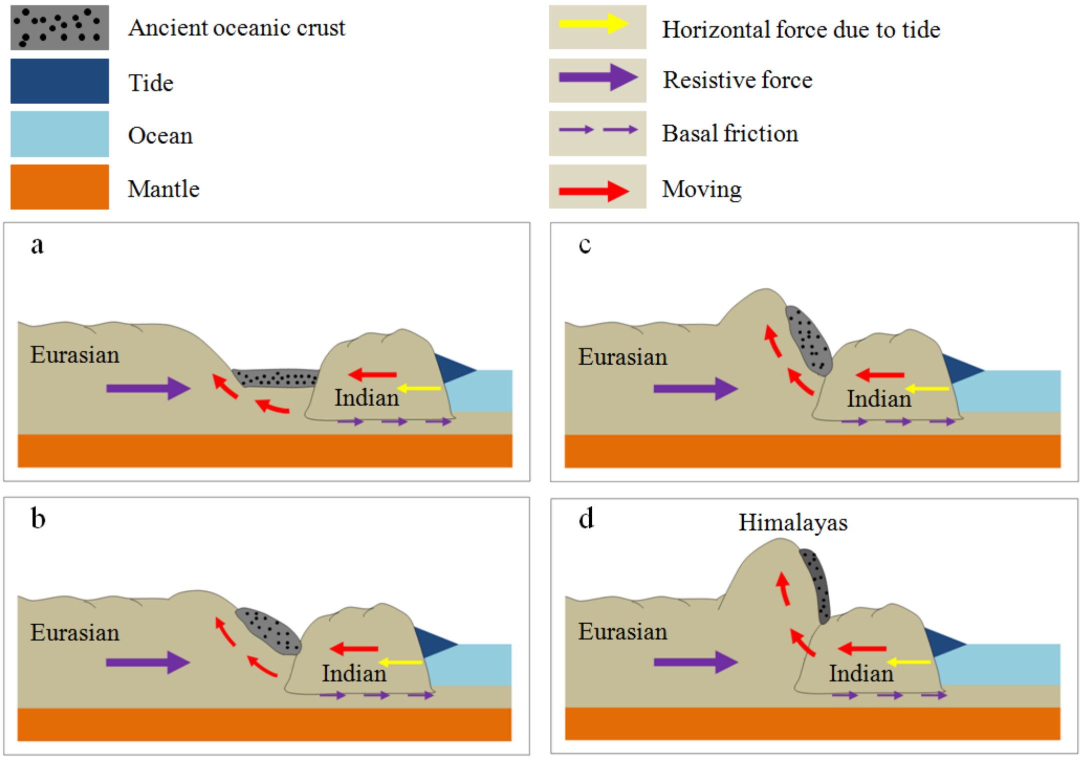


Fig. 8. Modelling the formation of the Himalayas under the collision of Indian continent and Eurasian continent. From a, b, …, to d, it shows a time sequence of the formation.

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 at., 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.

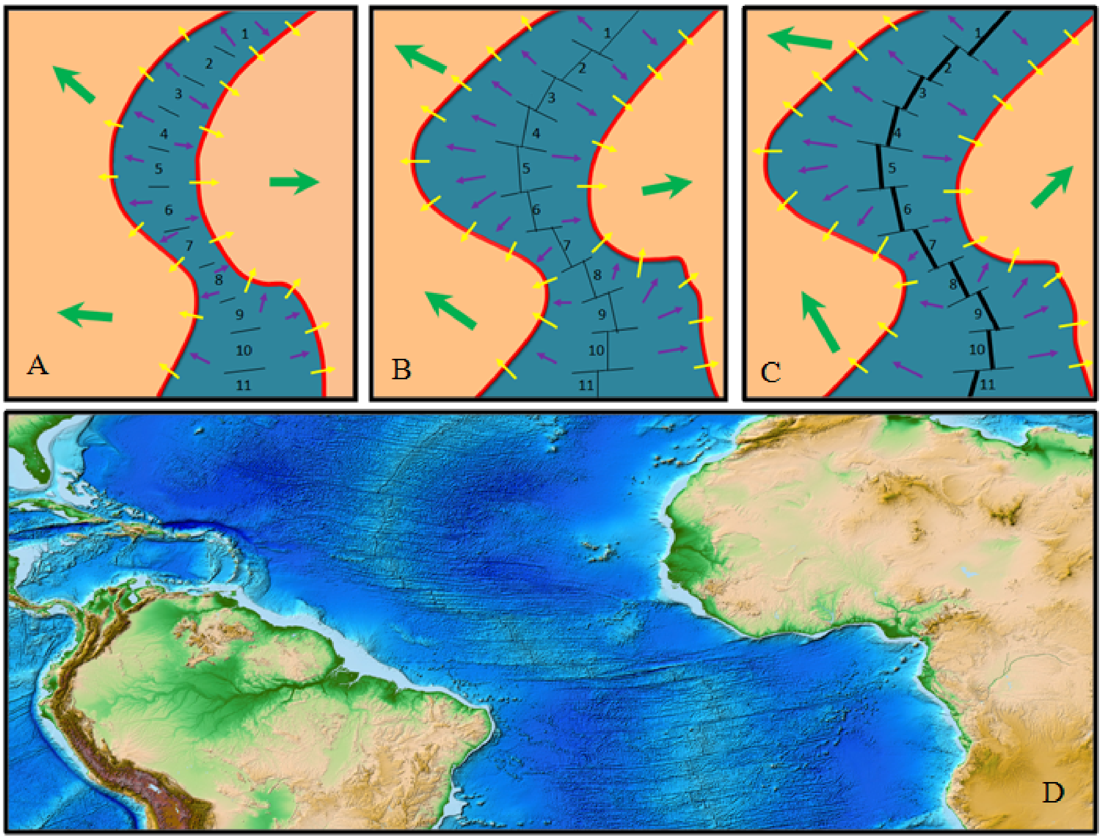
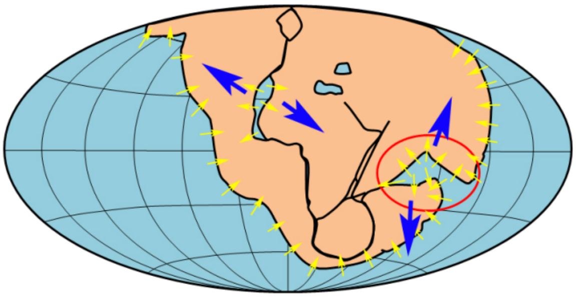


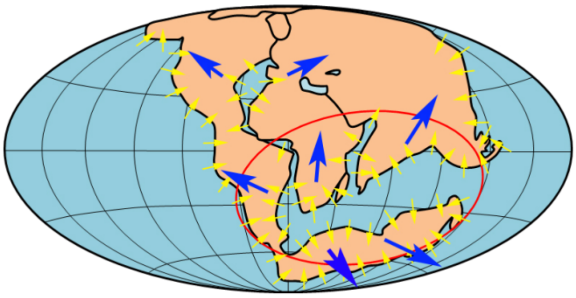
Fig. 9. Modelling the formation of MOR and transform faults based on the horizontal forces generated due to the tides. A, B, and C exhibit a sequence of how transform faults evolve with the growth of the MOR. Yellow, green, and purple arrows denote respectively the horizontal forces generated due to the tides (marked with red around the margins of continents), 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 that the mantle convection currents exert is always along the base of the lithosphere, if it were this internal force to split the supercontinent, the lithosphere must had 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 shallow. 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 horizontal force generated due to tide works along the top of the lithosphere, the result is necessarily a fracture of the lithosphere's upper part. This shallower fracture not only avoids the magma's eruption but also keeps room for water to enter and form the ocean. The horizontal force generated due to tide here provide lines 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 resultant horizontal force pushes the adjoining landmass to move away from each other. This in turn expands the opening further. The weaker horizontal 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 horizontal 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.

Upper Carboniferous



Eocene



Older Quaternary

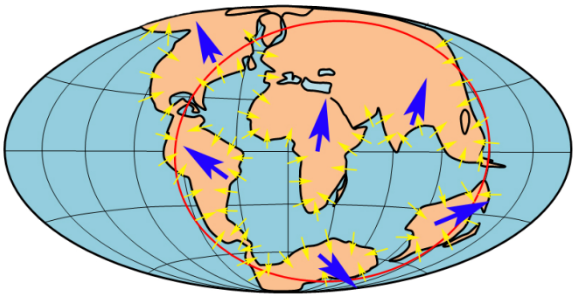


Fig. 10. Modeling the dispersal of supercontinent based on the horizontal forces generated due to the tides. Yellow and blue arrows denote respectively the horizontal forces generated due to the tides and the resultant movements. Red circles represent an expansion of the tides among the landmass. The 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 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 (Hilairet 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 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 tidal 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 tide generating force we presented in this work may help extend our understanding of earth's dynamics. Under the effect of this tide generating force, a dynamic tracking of the continent's movement and a more exactly prediction of earthquake become possible. Also, the continent's movement driven by this 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).

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