What Drives Plate Motions?

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Abstract

Plate motion is an amazing feature on the Earth and is widely ascribed to several driving forces like ridge push, slab pull, and basal drag. However, an in-depth investigation shows these forces incomplete. Here we propose, the deep oceans are generating pressures everywhere, the application of these pressures over the walls of ocean basins, which consists of the sides of continents, may yield enormous horizontal forces (i.e., the ocean-generating forces), the net effect of these forces provides lateral push to the continents and may cause them to move horizontally, further, the moving continents drag the crusts that they connect to move, these totally give birth to plate motion. A roughly estimation shows that the ocean-generating forces may give South American, African, Indian, and Australian continents a movement of respectively 2.8, 4.2, 5.7, and 6.3 cm/yr, and give Pacific Plate a movement of 8.9 cm/yr.

1 Introduction

One of the most significantly achievements in the 20th century was the establishment of plate tectonics that developed from a previous 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. The first to consider the dynamics source of this 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 forces, these forces were latterly found to be too weak to work. Jeffreys (1929) estimated that the mean tidal friction slowing the Earth's rotation corresponds to a westward stress of the order of only 10^{-4} dyn/cm^2 over the Earth's surface, this stress is too small to maintain that drift. After these attempts failed, people turned 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 eventually fostered a series of driving forces like ridge push, slab pull, basal drag, slab suction, the geoid's deformation, and the Coriolis force (Holmes, 1931; Runcorn, 1962a, b; Turcotte and Oxburgh, 1972; Oxburgh and Turcotte, 1978; Spence, 1987; White & McKenzie, 1989; Conrad & Lithgow-Bertelloni, 2002). Of these driving forces, the geoid's deformation is almost symmetrical relative to the Earth's shape, the Coriolis force is also symmetrical relative to equator, the both can be easily excluded. Slab suction occurs when local mantle currents exert a downward pull on nearby plates in the subduction zone (McKenzie, 1969; Sleep & Toksoz, 1971; Elsasser, 1971; Richter, 1973), but its nature hasn't been well understood (Forsyth & Uyeda, 1975; Conrad & Lithgow-Bertelloni, 2002). Finally, ridge push, slab pull, and basal drag are thought be the mostly driving forces for plate motion. A strictly investigation, however, reveal there are large uncertainties for these forces.

Ridge push originates from the potential energy gradient from the raised oceanic lithosphere. Forsyth & Uyeda (1975) initially defined it as an edge force, from then on, it has been recognized as a force to drive plate (Hager and O'Connell, 1981; Spence, 1987; White & McKenzie, 1989; Turcotte and Schubert, 2002; Turcotte and Schubert, 2014). A key point to discount this force derives from a fact that all the plates are steadily moving over the Earth's surface. It is natural for us to infer, a plate in the movement would depart from another plate. The department would form a fracture between the two plates. The fracture then allows magma to erupt and form Mid-Oceanic Ridge (MOR). From this perspective, the MOR itself may be a result of plate motion. In fact, Wilson and Burke (1973) had pointed out that the ridges may have formed as a passive consequence of the plates moving apart. But now, the MOR itself are treated as a cause to yield force to further drive the plate. This goes to the notorious chicken-or-egg question, who is the first? In physical field, it is strictly required that a movement (i.e., result) must be separated from the force (i.e., cause) that sustains it.

Slab pull derives from a cold, dense sinking plate that uses its own weight to pull the remaining plate it attaches to (Forsyth & Uyeda, 1975; Conrad and Lithgow-Bertelloni, 2002; Turcotte and Schubert, 2014). This force is currently thought to be the greatest force acting on the plates. Unluckily, the chicken-or-egg question also occurs on it. As all the plates are moving over the Earth's surface, the oceanic plates are geographically somehow lower than the continental plates, these make the oceanic plates in the movements easily subducted into the continental plates to form downgoing slabs. From this viewpoint, the downgoing slabs themselves may be a result of plate motion. But nowadays, the downgoing slabs are treated as a cause to yield force to further drive the plate.

Basal drag relates to mantle dynamics and was thought to be caused by the viscous moving asthenosphere along the bottom of lithosphere (Holmes, 1931; Pekeris, 1935; Hales, 1936; Runcorn, 1962a, b; Turcotte and Oxburgh, 1972; Oxburgh and Turcotte, 1978; Tanimoto & Lay, 2000; Turcotte and Schubert, 2014; Bercovici, et al., 2015). A key point to discount this force is because mantle dynamics still remains controversial (Siler et al., 1988; Davies and Richards, 1992; Lay, 1994; Ogawa, 2008; Turcotte and Schubert, 2014). On the one hand, the cells proposed by mantle dynamics to undertake the asthenospheric motion require a strong fitting to plate size. Seismic tomography showed that rising mantle material beneath ridges only extends down 200 to 400 km (Foulger, et al., 2001). This depth gives an upper limitation on the scale of the proposed cells. Most of plates (South American, North American, Eurasian, and Pacific, for instance), however, hold a width of generally more than thousands of kilometers, such width has been far beyond the scale of the proposed cells. On the other hand, toroidal motion was proposed to undertake horizontal rotation, but 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; Tackley, 1998; Trompert and Hansen, 1998; Weinstein, 1998; Stein et al., 2004). Another point to discount basal drag comes from the force itself. Forsyth & Uyeda (1975) found no evidence to show a correlation between plate velocity and surface area and suggested basal drag cannot be a driving force. Some authors argued that the contribution of basal drag to plate motion depends on the flow pattern at the lithosphere mantle interface (Forsyth and Uyeda, 1975; Doglioni, 1990), but the nature of this interface and its flow pattern is presently unclear. So far, most of geophysicists believe basal friction to be resistive rather than driving (e.g., Richter, 1973; Richardson and Cox, 1984; Turcotte and Schubert, 2002; Turcotte and Schubert, 2014).

Regardless of these shortcomings mentioned above, the exploration of the driving force of plate motion has always been an intensive ongoing topic (Conrad and Lithgow-Bertelloni, 2004; Faccenna, et al., 2012; Eagles and Wibisono, 2013; Turcotte and Schubert, 2014; Bercovici, et al., 2015; Mallard, et al., 2016; Crameri, et al., 2018). Since 1970's, some authors had begun to evaluate the relative importance of these driving forces (Forsyth & Uyeda, 1975; Backus, et al., 1981; Bokelmann, 2002). These efforts give people a sense that all the forces related to plate motion had been known. The fact, however, is not so, a significant force has been completely ignored. In this work, we get back to the exterior of the Earth to seek for this force and very hopefully expand our understanding of plate motion.

2 An ocean-generating force driving mechanism for plate motion

2.1 Forces acting on continent

Liquid can exert pressure at the wall of a container that holds it. According to Figure 1, the pressure generated at the wall of a cubic container may be written as $P=\rho gy/2$, the application of this pressure over the wall yields a horizontal force, this force may be expressed as $F=PS=\rho gy^2x/2$, where S is the wall's area, ρ and g are respectively the liquid's density and gravitational acceleration, x and y are respectively the liquid's width and depth in the container. Get back to real world, ocean basins are naturally gigantic containers, their depths are often more than a few kilometers and especially vary from one place to another. All these determine that oceans can generate enormous pressures everywhere and the pressures generated are unequal between oceans, furthermore, the application of these pressures over the ocean basins' walls, which consist of the continents' sides, can yield horizontal forces for the continents. Geometrically, ocean pressure exerts always orthogonal to the continental slope, by which a normal force is formed. This normal force can be decomposed into a horizontal force and a vertical force. We here define the continental crust, which can be applied by ocean pressure, as continent in the following sections. Subsequently, we list the plausible forces acting on the continent as illustrated in Figure 1 and discuss the physical nature of these forces. The forces acting on continents can be classified into two categories: the forces acting at the parts of continent that connect to ocean, and those acting at both the bottom surface of continent and the parts of continent that connect to adjacent crusts. The forces acting at the parts of continent that connect to ocean originate from ocean pressures. They will be called horizontal forces and denoted F_L' at the right and F_R' at the left. The force acting at the bottom surface of continent arises from a viscous coupling between the continent and underlying asthenosphere. It will be called basal friction force and denoted f_{base}. As addressed by Forsyth & Uyeda (1975), if there is an active flow in the asthenosphere, such as thermal convection, f_{base} will act as a driving force (Runcorn, 1962a, b; Morgan, 1972; Turcotte & Oxburgh, 1972). If, on the other hand, the asthenosphere is passive with regard to the plate motion, f_{base} will be a resistive force. We here assume f_{base} to be a resistive force. The forces acting at the parts of continent that connect to adjacent crusts arise from a physical binding of the continent and adjacent crusts, given the continent moves towards right, they will be called push force from the crust at the right side, pull force from the crust at the left side, shearing force from the crust at the far side, and shearing force from the crust at the near side, and denoted f_{right}, f_{left}, f_{far}, and f_{near}, respectively. It is important to note that, if there were no fractures (i.e., the gaps along ocean ridges) within ocean basin, the horizontal forces generated may be balanced out by the basin itself. Forsyth & Uyeda (1975) showed that the world's extensional boundaries represented by the fractures may reach up to 50,000 km. These fractures of ocean basins allow the horizontal forces generated to interact with the basal friction. And then, a combination of all these forces for the continent may be written as

$$F = (F_L' - F_R') - (f_{base} + f_{right} + f_{left} + f_{far} + f_{near}) \quad (1)$$

where the first term (F_L'- F_R') denotes the net horizontal force, which provides a dynamic source for the continent, the second term (f_{base}+ f_{right} + f_{left} + f_{far}+ f_{near}) denotes the total resistive force, which attempts to hinder the continent's movement. We here mark (F_L'- F_R') with F_{ocean}, and mark (f_{base}+ f_{right} + f_{left} + f_{far}+ f_{near}) with $F_{resistive}$. F_L' and F_R' may be further written as F_L'=0.5ρgLh_L^2, F_R'=0.5ρgLh_R^2, and ρ, g, L, h_L, and h_R are respectively density of water, gravitational acceleration, ocean's width that fits to the continent's width, ocean's depth at the left, and ocean's depth at the right.

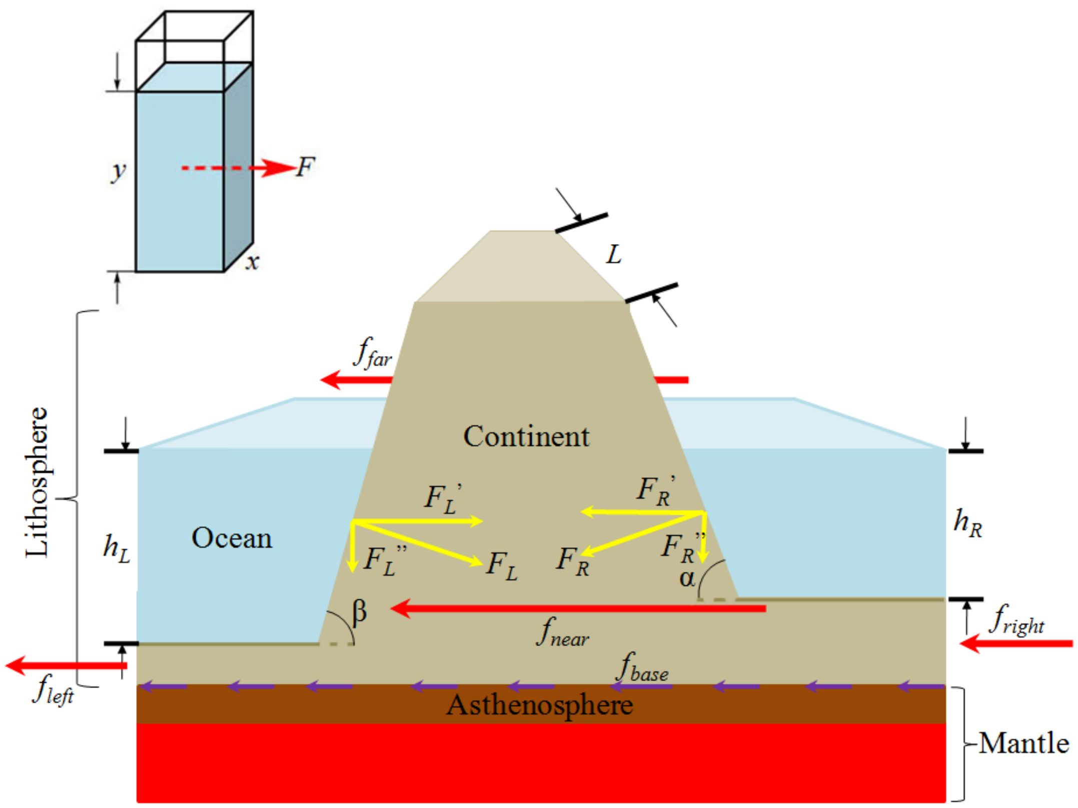

Fig. 1. Modelling the dynamics of continent. $F_L(F_R)$ represents the normal force generated due to ocean pressure at the left (right) side of the continent, while F_L'(F_R') and F_L''(F_R'') denote respectively the horizontal and vertical forces decomposed from that normal force. f_{base} denotes basal friction force exerted by the asthenosphere, while f_{right}, f_{left}, f_{far}, and f_{near} denote the push force from the crust at the right side, the pull force from the crust at the left side, the shearing force from the crust at the far side, and the shearing force from the crust at the near side of the continent. L denotes the width of the continent's side, h_L and h_R are respectively ocean's depth at the left and at the right. α and β denote the inclinations of the continent's slope at both sides. Note that ocean depth is highly exaggerated with respect to the lithospheric thickness.

2.2 Continent's movement

Equation (1) above provides three possibilities for the continent. If the net horizontal force is always less than or equal to the total resistive force, the combined force will be less than or equal to zero, the continent would remain motionless; If the net horizontal force is always greater than the total resistive force, the combined force will be greater than zero, the continent would get an accelerating movement. Practically, it is impossible for the continent to own such a movement; And if the net horizontal force is sometimes greater than the total resistive force but other times less than the total resistive force, the combined force will be discontinuous, the continent would get a discontinuous movement. We assume there exists a weak balance between the net horizontal force and the total resistive force, and this balance can be periodically broken by an unusual event. The existence of this weak balance would be discussed later. Most of oceans experience two cycles of high and low water per day, these movements of water are the tides we know in everyday life. The addition of tides to oceans makes oceans oscillate vertically, this leads the pressures in the oceans to periodically vary. Ocean pressure variations had been confirmed by bottom pressure measurements (Fig. 2). In particular, these variations exhibit different from one ocean to another during a month. For example, at the time of new Moon the range of bottom pressure variation at North Santo Domingo (Atlantic ocean) is almost within 100 millibars, while at South Dutch Harbor (Pacific ocean) the range may reach up to 260 millibars. The periodically varying pressures determine the net horizontal force generated to periodically vary, and thus provide possibility for the net horizontal force to be discontinuously greater and less than the total resistive force. And then, the continent's movement may be outlined with Figure 3: at the stage of t_1, the net horizontal force begins to increase, but since F_{ocean} - $F_{resistive}$ <0, the continent remains motionless; At the stage of t_2, F_{ocean} - $F_{resistive}$ >0, the continent is accelerated to move, and its speed reaches a highest level at the end of this period; At the stage of t_3, F_{ocean} - $F_{resistive}$ <0, the continent begins to decelerate until its speed becomes zero at the end of this period; At the stage of t_4, due to F_{ocean} - $F_{resistive}$ <0, the continent remains motionless; And at the stage of t_5 and t_6, the continent gets a movement that is similar to the movement at the stage of t_2 and t_3, but at the stage of t_7, the continent again remains motionless. Simply, the continent discontinuously obtains some forward movements at the stages of t_2, t_3, t_5, and t_6, and some stagnations at the stages of t_1, t_4, and t_7. These movements and stagnations totally provide a net forward movement for the continent during the day. Expanding this day to one year, the continent obtains a steadily forward movement during the year. Further, extending this year to a long timescale of millions of years and taking into account the fact that the oceans are extensively distributed around the globe, we conclude, the continents could have obtained steadily forward movements over millions of years. Figure 4 exhibits a globally distribution of the oceans and the resultant horizontal forces around the continents.

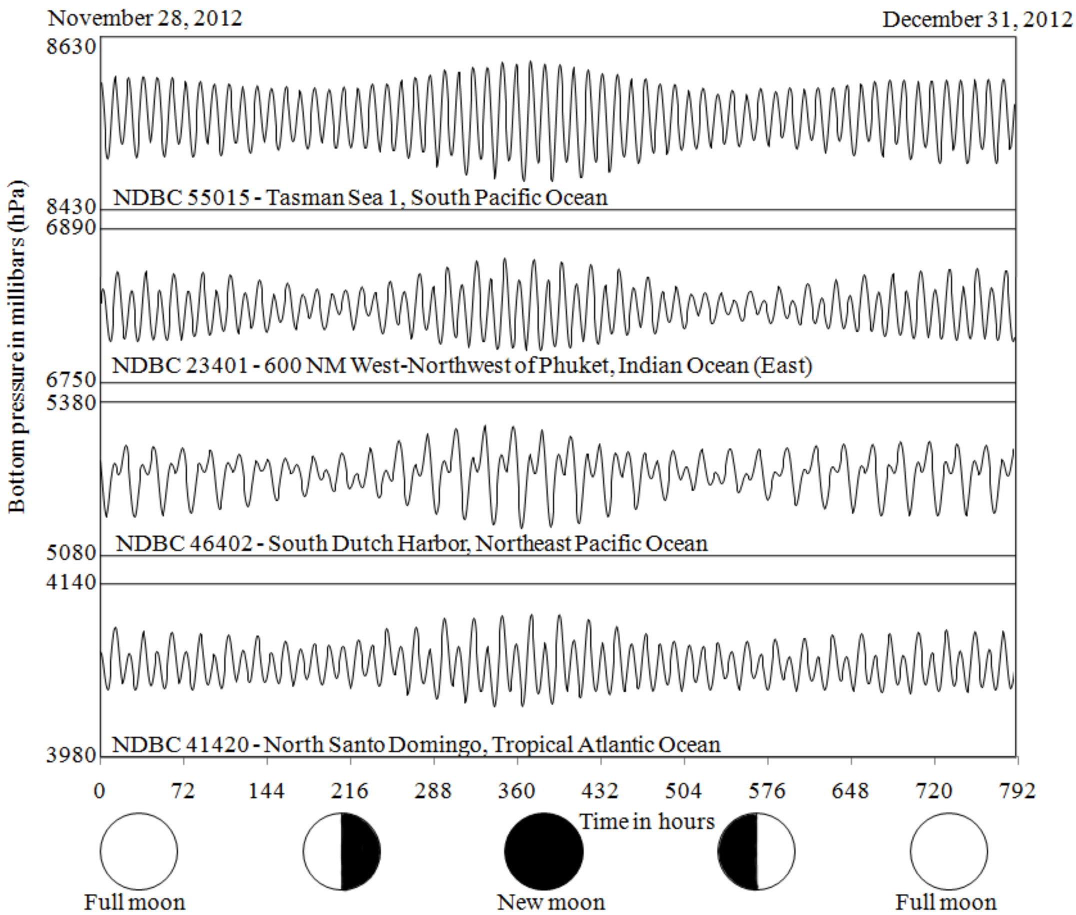

Fig. 2. Representatives of typical 1-month bottom pressure records during 2012. Bottom pressure record data are from PSMSL (Permanent Service for Mean Sea Level).

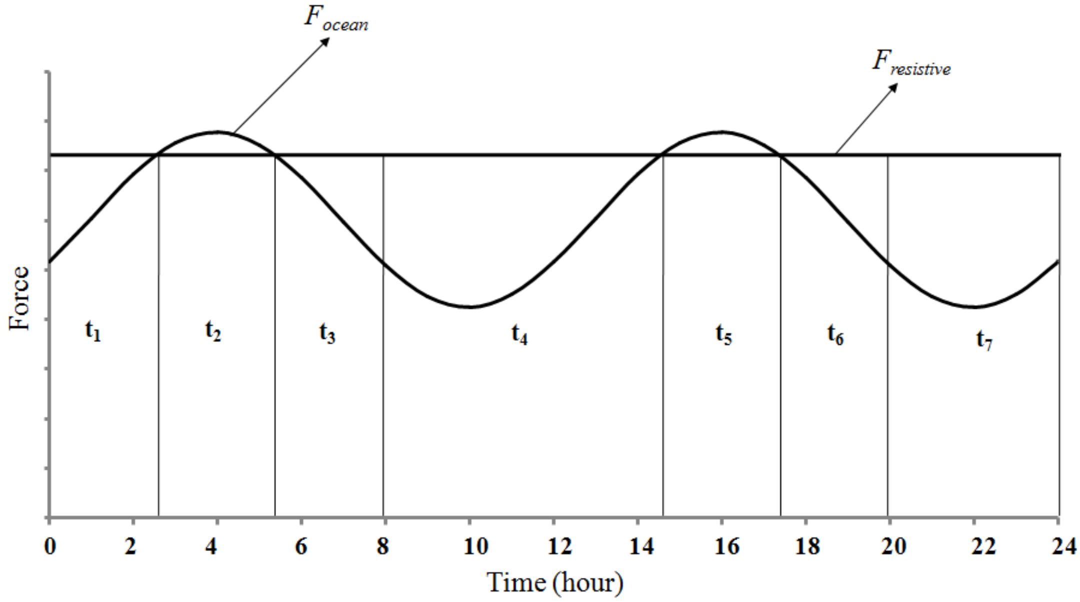

Fig. 3. Dynamic analysis for continent. F_{ocean} denote the net horizontal force generated for the continent, $F_{resistive}$ denotes the total resistive force undergone by the continent. Note that the oscillation of the net horizontal force is somehow exaggerated.

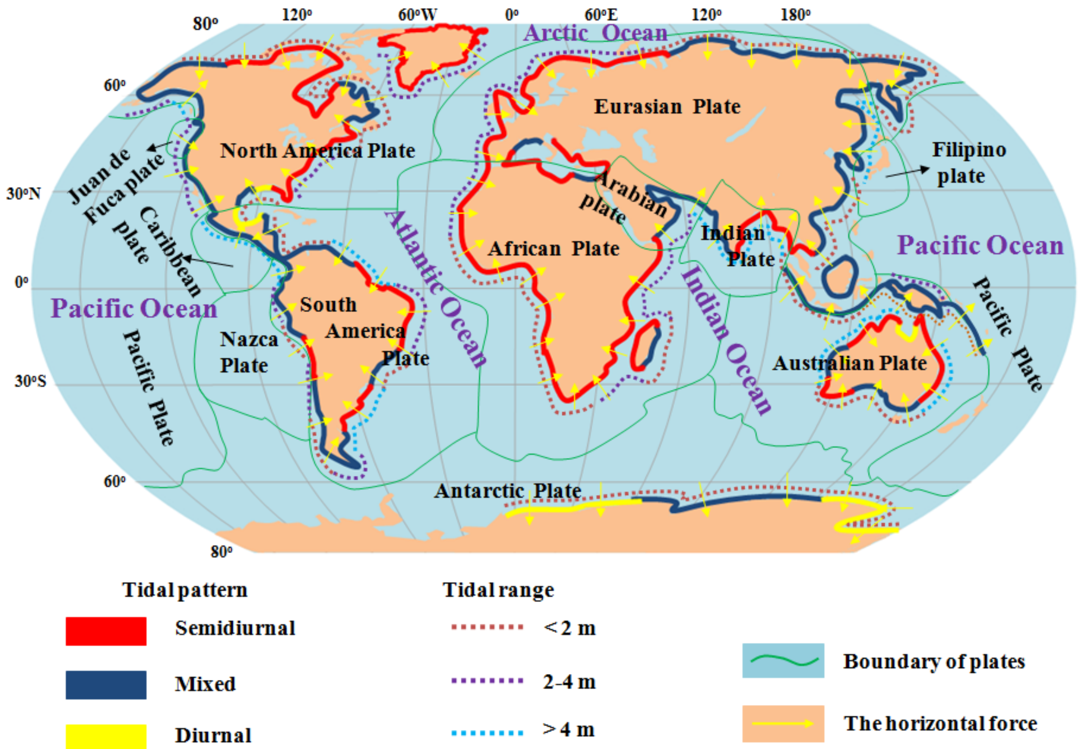

Fig. 4. A global view of the distribution of tidal pattern, tidal range, plate tectonics, and the horizontal forces generated for continents. Tide data supporting is from U.S. NOAA, GLOSS database - University of Hawaii Sea Level Center (Caldwell et al. 2015), and Bureau National

Operations Centre (BNOC) of Australia, and tide range also refer to the times atlas of the oceans, 1983, Van Nostrand Reinhold, NY.

A quantitative resolution of the continent's movement must consider more details. Most of continents are being surrounded by oceans, this indiates that the net horizontal force obtained by a continent would be a consequence of the combination of the horizontal forces generated at all the sides of this continent. The curved Earth's surface makes the horizontal forces generated unable to fall into a plane to interact with each other. Additionally, the tides surrounding a continent are not synchronous, their amplitudes perform two cycles per month, this rhythm is thought to be related to the positions of the Sun, Moon, and Earth. For example, the tides become maximal at the times of full and new Moon, and become minimum at the times of first quarter and last quarter. Furthermore, the tidal loading/unloading rate is not uniform. More features of the tides may refer to these works (Pugh 1987; Pugh and Woodworth 2014). To realize our deduction smoothly, the continent is considered to be more rigid and its surface is assumed to be flat, this allows Newton's mechanics to be applicable. We further assume the tides around a continent to be synchronous and their amplitudes to be constant during a month. The tidal loading/unloading rate is assumed to be linear, this enables us to easily infer that the time taken by the continent to accelerate is the same as the time taken to decelerate, namely, $t_2=t_3$. And then, according to the knowledge of Newton's 2nd law, and given there are two tides per day, the movement that a continent obtains during a year may be approximately written as

$$D = \mathbf{365} * \mathbf{2} * \frac{1}{2} * \frac{(F_{ocean-\max} - F_{resistive})}{M} * t^2 \qquad (2)$$

where $F_{ocean\text{-}\max}$ denotes the net horizontal force generated at the time of highest tide, $F_{resistive}$ denotes the total resistive force, M denotes the continent's mass and may be gotten through $M=Sd\rho_{\mathrm{continent}}$ (where S, d, and $\rho_{\mathrm{continent}}$ are respectively the continent’s area, thickness, and density), t is the time that the continent takes to accelerate during a tide. As the horizontal forces exerted to the continent are often along different directions, we need to combine these forces into a horizontal force. A strategy is to firstly decompose each of the horizontal forces into a latitudinal component and a longitudinal component, subsequently, by a simple addition, all the latitudinal and longitudinal components are separately combined into a latitudinal force and a longitudinal force, finally, the latitudinal force and the longitudinal force are further combined to form a horizontal force. The net horizontal force may be written as $F_{ocean-\max} = \left((\sum_{i=1}^{n} F_{i-ocean-latitudinal})^2 + (\sum_{i=1}^{n} F_{i-ocean-longitudinal})^2 \right)^{\frac{1}{2}}$, where $F_{i\text{-}ocean\text{-}latitudinal}$ and $F_{i\text{-}ocean\text{-}longitudinal}$ are respectively the latitudinal and longitudinal components that are decomposed from the horizontal force, these components can be further expressed as $F_{i-ocean-latitudinal} = F_{i-ocean} \sin\Omega_i$, $F_{i-ocean-longitudinal} = F_{i-ocean} \cos\Omega_i$. Ω_i denotes the inclination of the *i*th side to latitude (+), and may be gotten through geographic latitudes and longitudes of the two ends of this side. $F_{i\text{-}ocean}$ denotes the horizontal force generated at the *i*th side of the continent at the time of highest tide, and can be written as $F_{i-ocean} = \mathbf{0.5\rho g}L(h_{ocean} + h_{tide})^2$. ρ, g, L, h_{ocean}, and h_{tide} are respectively density of water, gravitational acceleration, the continent side's width, the ocean depth that connects to the continent side, and tidal height. Tidal height may be expressed as $h_{tide}=A\sin\omega t$, A is tidal amplitude, ω and t are respectively angular frequency and time.

Practically, the continent's side is not flat, and the continent's base is generally wider than its top, these make the continent look more like a circular truncated cone staying in the ocean. As the horizontal force generated relates to the ocean's width (i.e., the continent side's width), we need to horizontally project the continent into a polygonal column and cut the whole side of this column into a series of smaller rectangular sides connecting one to another, subsequently, to calculate the horizontal force generated at each of these rectangular sides, finally, we combine these horizontal forces to form a single horizontal force. With these theoretical ideas, we take the parameters involved to estimate the movements of a few continents (South

American, African, Indian, and Australian). The controlling sites used to determine the length of side refer to Figure 5, the longitudes and latitudes of these sites are gotten through Google Earth software. The parameters involved and the horizontal forces generated are separately listed in Table 1 and 2. Please note, the determination of the time taken by the continent to accelerate and the time taken to decelerate during a tide is rather complicated. Normally, if these parameters (h_{tide}, h_{ocean}, L, $F_{resistive}$, for instance) can be given, we may use Figure 3 to develop a non-linear relationship of these parameters and time to resolve the time. As we attempt to estimate the continent's movement, the non-linear relationship is currently not considered, instead, we select to value the time t, which is taken by the continent to accelerate during a tide. Finally, South American, African, Indian, and Australian continents obtain a movement of respectively 2.8, 4.2, 5.7, and 6.3 cm/yr, as shown in Table 3. These results are well consistent with the observed movement of generally 5.0~10.0 cm/yr (Read and Watson 1975).

Careful readers would discern that the total resistive force ($F_{resistive}$) we used in the calculation is technically valued. Undoubtedly, this treatment should deserve a discussion of necessity. As shown in Figure 1, the total resistive force includes four components: the basal friction force, the push force, the pull force, and the shearing forces. The push force, the pull force, and the shearing forces essentially originate from the basal frictions exerted by the asthenosphere onto the lithosphere. The basal friction is determined by a few factors, i.e., the asthenosphere's viscosity, the continent's area, the continent's speed, and the asthenosphere's thickness. The area and speed can be exactly measured, but the viscosity and thickness of the asthenosphere remain high uncertainty. 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 concluded 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. These totally determine that the total resistive force cannot be exactly known and need to be valued.

Careful readers would find that our understanding of the continent's movement begins on the assumption that there is a weak balance between the net horizontal force and the total resistive force. This balance should also deserve a discussion of possibility. The basal friction exerted by the asthenosphere along the continent's base can be expressed as $F_A=\mu Au/y$, where μ, A, u, and y are respectively the viscosity of the asthenosphere, the continent's area, the continent's speed, and the thickness of the asthenosphere. We here adapt $\mu= 3*10^{19}$ P and y=200 km to estimate the basal friction forces undergone by the four continents (South American, African, Indian, and Australian). The speeds of these continents are assumed to be 2.7, 4.2, 5.6, and 6.4 cm/yr, respectively, and the areas of these continents are listed in Table 1. The basal friction forces estimated are eventually listed in Table 2. It can be found that, for each of these four continents, the magnitude of the horizontal force generated is extremely close to the magnitude of basal friction force. We believe this closeness is not a coincidence, because these two forces are gotten through two different passages. Finally, we get to the point that there may be a weak balance between the net horizontal force and the total resistive force.

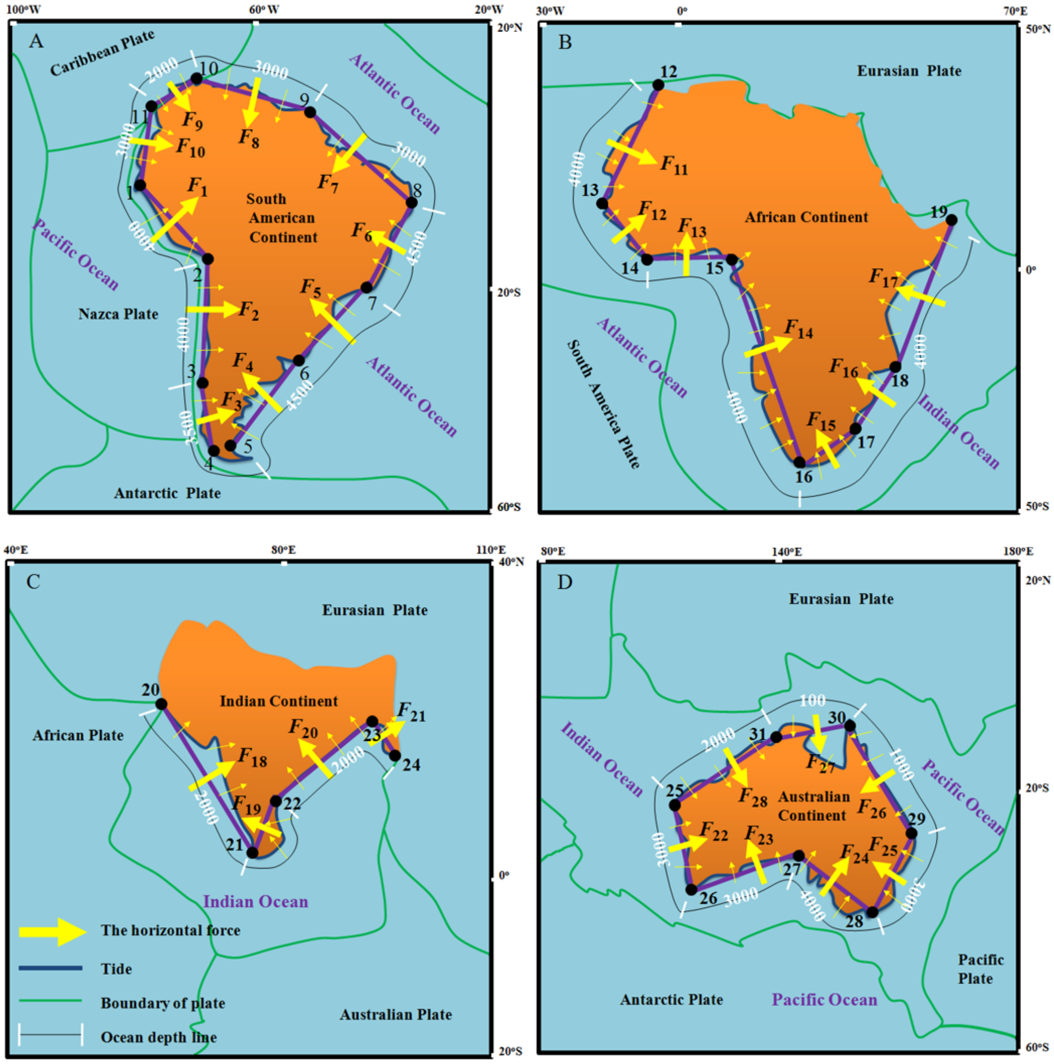

Fig. 5. Geographic treatment of the controlling sites for selected four continents and the horizontal forces generated for them. *F* (yellow arrow) denotes the horizontal force generated, while purple bar denotes the distance applied by the horizontal force. The product of this distance and ocean depth is the area applied by the horizontal force. Dot with number denotes 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			site to site: distance		site to site: inclination to latitude, east (+)		tidal height	Ocean depth
	S	d	ρ	M				L		i	Ω_i	h_{tide}	h_{ocean}
	km^2	km	kg/m^3	kg	No.	Longitude	Latitude	km			degree (°)	m	m
					1	80.0°W	2.0°S	1_2	2,087	1	122.01	1.5	4,000
					2	70.0°W	18.0°S	2_3	1,153	2	73.30	1.5	4,000
					3	73.0°W	28.0°S	3_4	2,780	3	90.00	1.5	3,500
					4	73.0°W	53.0°S	5_6	2,308	4	51.15	2.0	4,500
					5	68.0°W	52.5°S	6_7	1,730	5	43.78	2.0	4,500
South American	17,840,000	6	3,100	3.32E+20	6	54.0°W	34.5°S	7_8	1,952	6	64.89	1.5	4,500
					7	42.0°W	23.0°S	8_9	2,525	7	146.66	1.5	3,000
					8	34.0°W	7.0°S	9_10	2,157	8	160.64	1.5	3,000
					9	53.0°W	5.5°N	10_11	836	9	41.26	1.5	2,000
					10	72.0°W	12.0°N	11_1	1,033	10	75.66	1.5	3,000
					11	78.0°W	7.0°N						
					12	6.0°W	35.5°N						
					13	17.0°W	14.7°N	12_13	2,535	11	117.65	1.0	4,000
					14	7.0°W	4.6°N	13_14	1,531	12	45.00	1.0	4,000
					15	8.0°E	4.4°N	14_15	1,696	13	3.81	1.0	4,000
African	30,370,000	6	3,100	5.65E+20	16	22.2°E	34.7°S	15_16	4,577	14	109.75	1.0	4,000
					17	30.4°E	30.7°S	16_17	886	15	26.00	1.0	4,000
					18	40.0°E	16.0°S	17_18	1,904	16	56.85	1.0	4,000
					19	51.0°E	11.0°N	18_19	3,237	17	67.83	1.0	4,000
					20	66.8°E	25.0°N						
					21	77.5°E	8.0°N	20_21	2,205	18	122.19	2.0	3,000
Indian	4,400,000	6	3,100	8.18E+19	22	80.0°E	15.2°N	21_22	846	19	70.85	2.0	3,000
					23	91.5°E	22.7°N	22_23	1,468	20	33.11	2.0	3,000
					24	94.3°E	16.0°N	23_24	801	21	112.68	2.0	3,000

					25	114.0°E	23.0°S	25_31	2,162	28	32.43	2.0	2,000
					26	117.2°E	35.0°S	25_26	1,370	22	104.93	2.0	4,000
					27	131.0°E	31.5°S	26_27	1,340	23	14.23	1.0	5,000
Australian	8,600,000	6	3,100	1.60E+20	28	149.8°E	37.6°S	27_28	1,846	24	162.02	1.0	5,000
					29	153.0°E	25.4°S	28_29	1,390	25	75.30	2.0	3,000
					30	142.4°E	10.8°S	29_30	1,970	26	125.98	2.0	1,000
					31	131.0°E	12.2°S	30_31	1,252	27	7.00	2.0	100

Note: all geographic sites refer to Figure 5; tidal height is half of tidal range.

Table2 The generated horizontal force and constrained parameters for selected four continents

Continent	i	the horizontal force [a]				the resistive force [b]	the friction [c]	the time taken to accelerate during a tide [d]
		horizontal	decomposed					
			latitudinal , east (+)	longitudinal , north(+)	$F_{ocean\text{-max}}$	$F_{resistive}$	f_{base}	t
		$F_{i\text{-}ocean}$	$F_{i\text{-}ocean\text{-}latitudinal}$	$F_{i\text{-}ocean\text{-}latitudinal}$				
		N(*10^{17})				N(*10^{17})		Second
South American	1	1.6375	1.3886	0.8679				
	2	0.9050	0.8668	-0.2600				
	3	1.6701	1.6701	0.0000				
	4	2.2925	-1.7853	1.4382				
	5	1.7184	-1.1890	1.2406				
	6	1.9378	-1.7546	0.8225				
	7	1.1148	-0.6127	-0.9313				
	8	0.9520	-0.3156	-0.8981				
	9	0.1642	0.1083	-0.1234				
	10	0.4559	0.4417	-0.1129				
			-1.1817	2.0434	2.3605	2.3604	2.2911	197.18
African	11	1.9883	1.7613	-0.9226				
	12	1.2006	0.8489	0.8489				
	13	1.3304	0.0885	1.3275				

	14	3.5900	3.3789	1.2129				
	15	0.6953	-0.3048	0.6249				
	16	1.4932	-1.2502	0.8164				
	17	2.5392	-2.3515	0.9580				
			2.1711	4.8662	5.3285	5.3283	6.0670	165.14
Indian	18	0.9737	0.8241	0.5187				
	19	0.3734	-0.3527	0.1225				
	20	0.6482	-0.3541	0.5430				
	21	0.3536	0.3263	0.1363				
			0.4435	1.3205	1.3930	1.3929	1.1720	144.59
Australian	22	1.0751	1.0388	0.2770				
	23	1.6417	-0.4036	1.5914				
	24	2.2627	0.6983	2.1523				
	25	0.6137	-0.5936	0.1557				
	26	0.0969	-0.0784	-0.0569				
	27	0.0006	0.0001	-0.0006				
	28	0.4246	0.2277	-0.3584				
			0.8892	3.7604	3.8641	3.8640	2.5771	175.62

Note: all horizontal forces generated refer to Figure 5;

a (the horizontal force) and *c* (the basal friction) are calculated, while *b* (the total resistive force) and *d* (the time taken to accelerate during a tide) are technically valued.

Table 3 The resultant movements for selected four continents

Continent	movement per year	to latitudinal direction, east (+)
	mm/yr	degree
South American	27.59	120.04
African	41.85	65.96
Indian	56.46	71.44
Australian	63.09	76.70

The treatment of the continent's movement above is relatively idealized. As most of the horizontal forces generated exert along different directions and cannot pass the barycenter of a continent, a torque effect may be yielded to rotate the continent. Figure 6 (A and B) conceptually demonstrates how these continents (Eurasian and North America, for instance) move under the torque effect yielded by the horizontal forces.

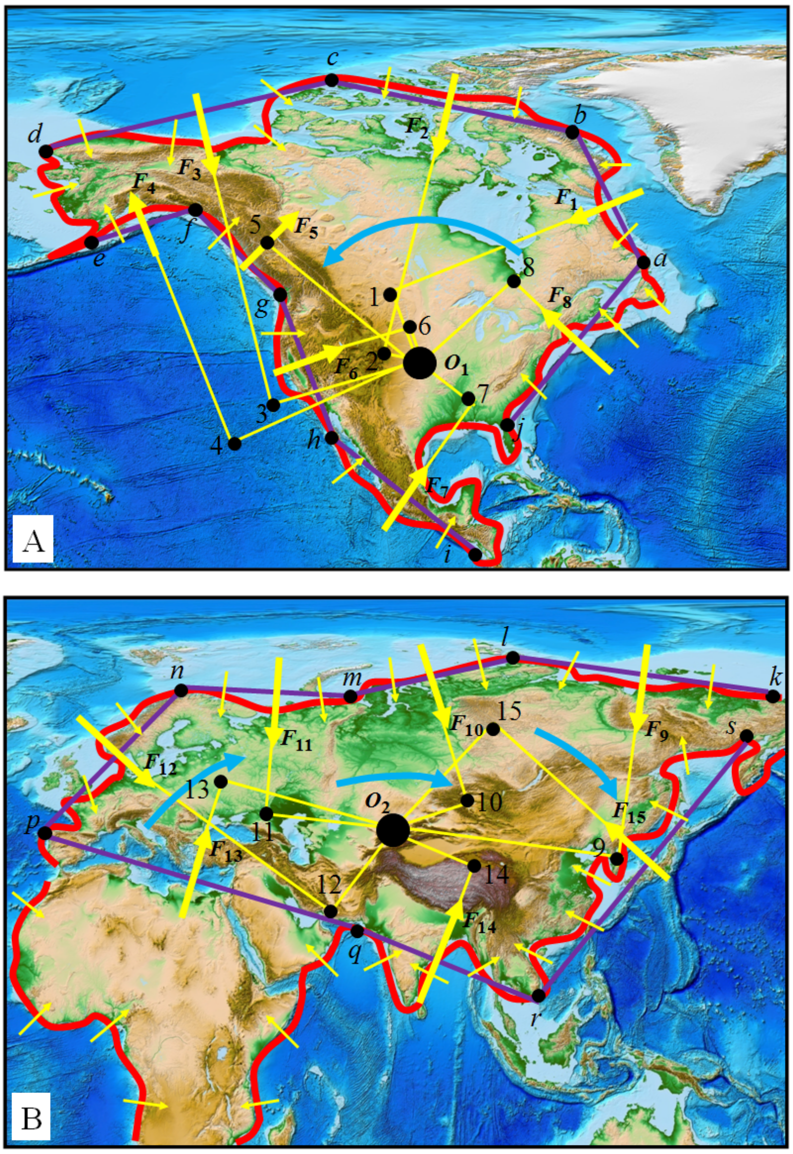

Fig. 6. Dynamics for the rotations of North American and Eurasian continents. O_1 and O_2 denote possible positions of the barycenters of two continents. F_1, F_2, F_3, i.e., marked with yellow arrows, denote the horizontal forces generated, *a*, *b*, *c*, i.e., denote the selected controlling sites, while *ab*, *bc*, *cd*, i.e., marked with purple bars, denote the length of continent's side, 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 a product of force and arm. Curved blue arrows represent expected rotations around these barycenters. Note F_{13} represents a lateral push force from the travelling African continent. The background map is gotten from ETOPO1 Global Relief Model (Amante and Eakins, 2009).

2.3 Plate motion

Plate motion may be a consequence of the horizontal force. Refer to Figure 1 and Table 2, a majority of the net horizontal force has been used to oppose the total resistive force, which is consisted of the basal friction exerted by the asthenosphere, the push force from the crust at the right side, the pull force from the crust at the left side, the shearing force from the crust at the far side, and the shearing force from the crust at the near side. If we use the principle of action and reaction to imagine, these forces may further drive the crusts that bear them to move, such an interactive process totally create plate motion over the globe.

Force transition from one plate to another may be expressed with Pacific Plate's motion. As outlined in Figure 7, Australian Plate and North American Plate independently provide push force F_{PA} and F_{PN} to Pacific Plate, a composition of these two forces would be the force F_{P}, which provides a dynamics for Pacific Plate. A quantitative treatment on Pacific Plate's motion is relatively complicated. Pacific Plate is firstly considered to be more rigid and plat. These assumptions allow deformation to be negligible and related forces to interact at a plane. According to a relationship of movement and force, equation (2) can be simplified as $F \sim DM$, where F, M, and D are respectively the force that a continent obtains, the continent's mass, and the continent's movement. Applying this simplified equation to South American continent, it would be $F_S \sim D_S M_S$. Furthermore, we apply this equation to North American continent and make analogy with South American continent, there would be $F_N \sim F_S D_N M_N / D_S M_S$, where F_N and F_S denote the net horizontal force obtained respectively by North American continent and South American continent, D_N and D_S are the movements obtained respectively by these two continents, M_N and M_S denote the masses of these continents. Refer to the parameters listed in Table 1, 2, and 3, there would be F_S=2.3605*10^{17} N, D_S=2.7 cm per year, M_S=3.32*10^{20} kg. North American continent has an area of about 24,709,000 km^2, according to another expression M=Sd$\rho_{continent}$ (where S, d, and $\rho_{continent}$ are respectively the continent's area, thickness, and density), the continent's mass can be calculated as M_N=4.60*10^{20} kg. North American Plate rotates counterclockwise and moves at a speed of about 1.5~2.5 cm per year, we here adapt D_N=2.0 cm per year for the western portion of this plate to interact with Pacific Plate. And then, the net horizontal force calculated for North American continent should be F_N =~2.4227*10^{17} N. To drive North American Plate to move, the net horizontal force F_N needs to overcome the total resistive force, which is mainly consisted of the push force from Pacific Plate and the shearing force from South American Plate. As the push force and the shearing force derive from the basal friction exerted by the asthenosphere, and refer to the basal friction expression F_A=μAu/y, the push force provided by Pacific Plate can be written as F_{PN}= $F_N S_P/(S_P+S_N)$=1.0261*10^{17} N, where S_P and S_N are respectively the area of Pacific Plate and South American Plate. Refer to Table 2, the total resistive force for Australian plate is $F_{Au\text{-}resistive}$ =3.8640*10^{17} N, given 25% of this resistive force is expended to overcome the push force from Pacific Plate, and then, the push force is calculated as F_{PA}=9.6600*10^{16} N. Australian Plate moves dominantly in a northeast direction, the inclination of this direction to latitude (+) is about 76.7°, as listed in Table 3. Most of North American Plate moves roughly in a southwest direction away from the Mid-Atlantic Ridge, we here assume the push force from North American Plate to be arranged in a southwest direction, the inclination of this direction to latitude (+) is about 190°. Subsequently, the net horizontal force obtained by Pacific Plate can be expressed as $F_P=((F_{PN}^2+F_{PA}^2-2*F_{PN}*F_{PA}*\cos(\alpha-\beta))^{0.5}$, and $\cos\gamma=(F_P^2+F_{PN}^2-F_{PA}^2)/(2*F_P*F_{PN})$, where α=76.7°, β=10°. Finally, it is calculated as F_P=1.096315*10^{17} N, and γ=54.03°. Similarly, we assume that a majority of the net horizontal force obtained by Pacific Plate has been expended to overcome the total resistive force, which is mainly consisted of the friction exerted by the asthenosphere along Pacific Plate's base. Refer to Table 2, the ratio of the total resistive force and the net horizontal force for South

American continent may reach up to 0.99999907. This amplitude allows us to consider a ratio of 0.99999 for Pacific Plate, and then, the total resistive force for Pacific Plate would be $F_{Pa\text{-}resistive}$=1.096304*10^{17} N. The continental crust's thickness is given as 6.0 km, and refer to Table 1, the average of ocean depth is less than 4.0 km, these two allow us to accept a thickness of 2.0 km to be left for the continental crust to contact the oceanic crust. Pacific Plate's mass may be written as $M_{\text{Pacific}}=S\text{d}\rho_{\text{plate}}$ (where S, d, and ρ_{plate} are respectively the plate’s area, thickness, and density). If we consider the continent's density is the same as the plate's density, and adapt Pacific Plate's area to be 103,300,000.00 km^2, and then, there would be M_{Pacific}= 6.4046*10^{20} kg. Applied by equation (2) and given a time of 1194.45 seconds to accelerate, Pacific Plate finally obtains a movement of 89.44 mm per year, roughly along a northwest direction.

Nevertheless, if we look back to see North American Plate, it must had rotated much during a timescale of more than millions of years, this indicates that North American Plate could have oriented towards northeast in the past, if so, the push force F_{PN} may be not existed at that time, subsequently, Pacific Plate was most likely to be pushed by Australian Plate alone to move along a northeast direction. This suggests that an abrupt change in motion might had occurred for Pacific Plate at a time when North American Plate rotated to a central angle, from which a combination of the two lateral forces mentioned above becomes realized. Such a plate motion change has been supported by the Hawaiian–Emperor bend (Sharp and Clague, 2006; Wessel and Kroenke, 2008).

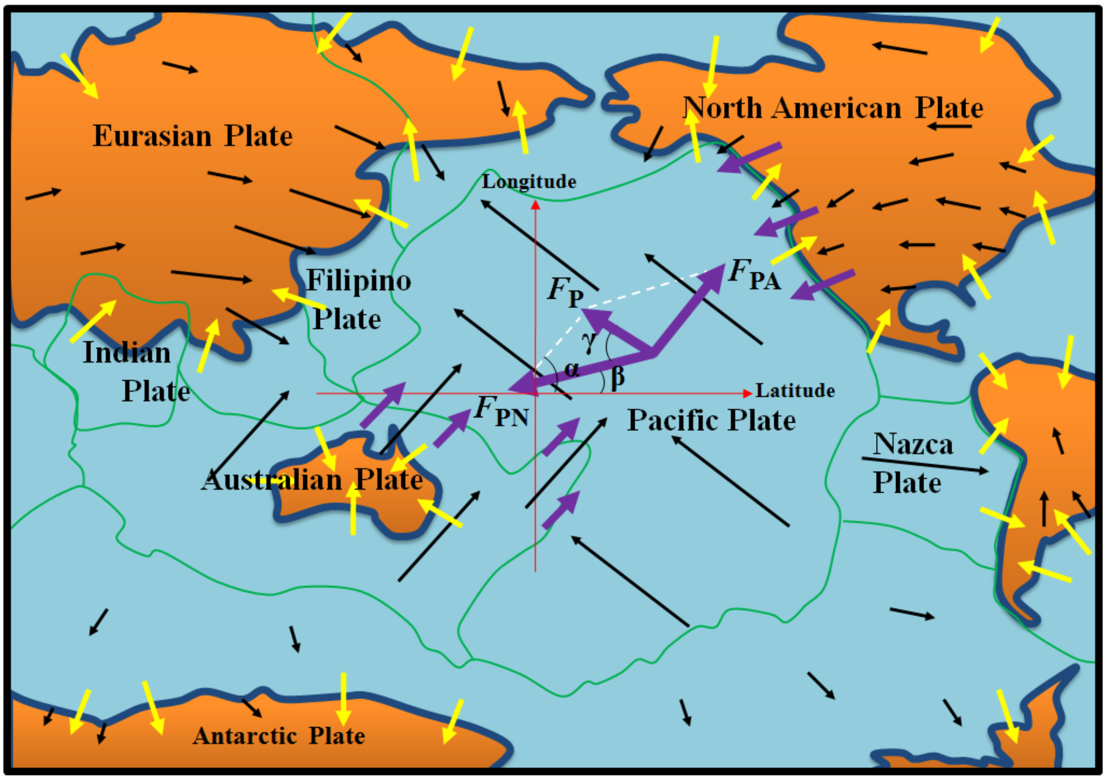

Fig. 7. Modelling the dynamics of Pacific Plate. Black, yellow, and purple arrows denote respectively plate motions, the horizontal forces generated due to oceans, and lateral push forces from related plates. Note that lateral push force $F_{PN}(F_{PA})$ is approximately parallel to the motion of North American (Australian) Plate.

3 Discussion

3.1 Comparison of the ocean-generating force and the existing driving forces

Figure 4 clearly exhibits that the horizontal forces exert always orthogonal to the continents' sides that consist of the walls of ocean basins, especially, the oceanic ridges trend to follow the shapes of the continents' sides. This final point is particularly correct for these continents like North American East, South American East, Africa, and India. As ridge push forces exert also orthogonal to the ridges, this results in a fitting of direction between the horizontal force and ridge push force. In other words, if we use a torque method to evaluate, these two forces are undistinguishable. Nonetheless, these two forces perform different in the position of force acting on plate. Figure 8 outlines a distribution of the horizontal force and existing driving forces around American Plate and African Plate. It can be found that the horizontal forces (F_h) exert at the upper part of a continental plate, whereas ridge push force (F_p) and other driving forces (trench suction F_{ts} and basal drag F_b) exerts at or below the middle and lower part of this plate. Tectonic stresses are caused by the forces that drive plate tectonics (Middleton and Wilcock, 1996), and may give feedback on the constrain of the forces acting on the plates. This provides a point to differentiate the horizontal force from these existing driving forces. As these existing driving forces exert generally at or below the middle and lower part of a continental plate, they would require the stresses generated to geometrically distribute around these regions of the plate. Contrary to this, the horizontal force would require the stresses generated to geometrically distribute around the upper part of the plate.

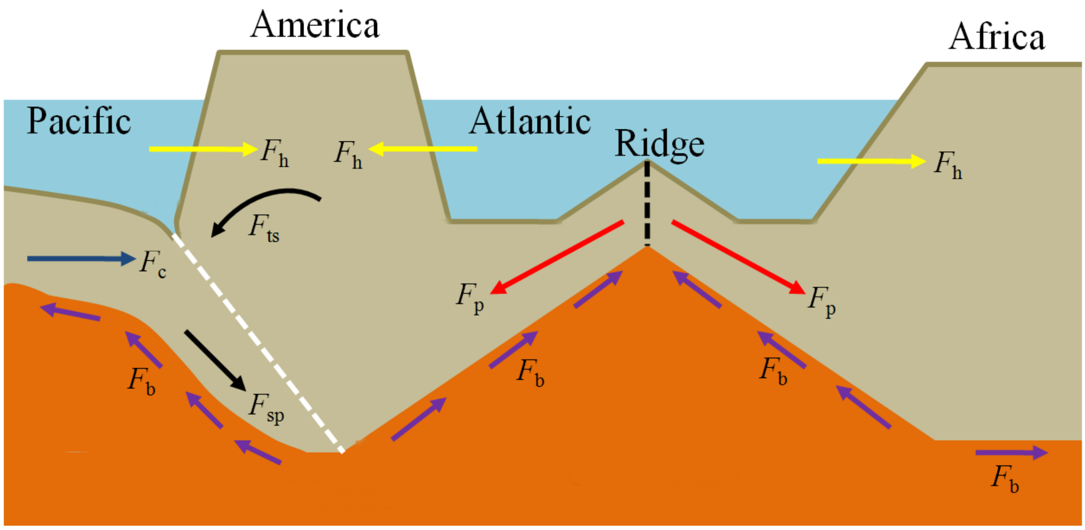

Fig. 8. A distributed comparison of the ocean-generating force and the existed driving forces. F_h, F_p, F_c, F_{ts}, F_{sp}, and F_b denote respectively the horizontal force, ridge push force, collisional resistance, trench suction, slab pull, and basal drag (if resistive).

Measurements of tectonic stress had discovered remarkable features on the global patterns of tectonic stress (Zoback et al., 1989; Zoback, 1992): 1) The interior portions of plates (also called midplate or intraplate) are dominated by compression in which the maximum principal stress is horizontal; 2) In most places a uniform stress field exists throughout the upper brittle crust; 3) A strong correlation between S_{Hmax} (maximum horizontal stress) orientations and azimuths of absolute plate velocity exists in the interior portions of some plates. Additionally, detailed analysis of stress measurement data show that S_{Hmax} orientations are often rotated into a plane approximately parallel to the local trend of the continental slope.

It is very striking to see, these observed patterns of tectonic stress prefer a force that is closely related to the upper part of a continental plate. For most plates like North American and South American, their interiors are mainly covered with continents. The measurements of tectonic stress were made mainly in the continents (Zoback et al.,1989). According to Zoback (1992), these measurements employed four methods: earthquake focal mechanisms, well bore breakouts, in situ stress measurements (hydraulic fracturing and overcoring), and young geologic data including fault slip and volcanic alignments. Of these, the most reliable are well bore breakouts and in situ stress measurements. They are actually operated in a depth of less than 5.0 km. Such shallower region of a continental plate is almost dominated by continent. The correlation between S_{Hmax} orientations and the continental slope is also a indicator of a continent-related force. Undoubtedly, the best candidate for this force is the ocean-generating force rather than any of existing driving forces.

3.2 Formation of Mid-ocean ridge

The travelling continent drags the oceanic crust it connects in the rear, this would yield strain for the latter. We believe, a periodically fracture of the oceanic crust might have been responsible for the formation of MOR. As conceptually outlined in Figure 9, the continent continues to move, the accumulated strain eventually rip the oceanic crust, this allows magma to erupt. The raised magma after cooling crystallizes and creates new crusts. The newly formed crusts may help seal the fracture and terminate that eruption. The fracture temporarily relieves the accumulated strain, but since the continent continues to move, the strain is again accumulated, the subsequent fracture and closeness occur again. The newly formed crusts add height to the previous oceanic crust, forming the MOR. The representative of this type of MOR may be the Middle-Atlantic Ridge. Of course, not all the MORs are made through this way. For example, the travelling continent would also shear the oceanic crusts respectively at the far and near sides, these shearings may cause these crusts to fracture and form the MORs.

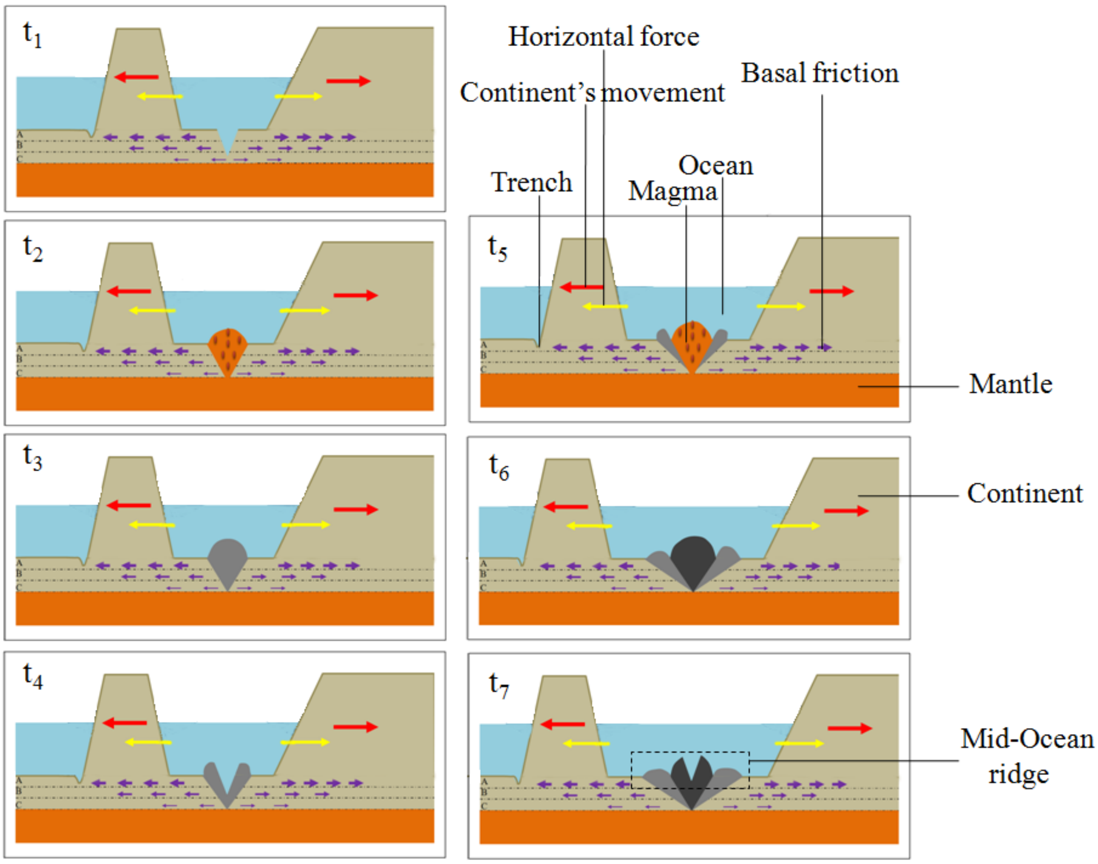

Fig. 9. Modelling the formation of MOR under the ocean-generating forces. From t_1, t_2, …, to t_7, it exhibits a sequence of forming MOR. The lower lithosphere is apparently divided into three layers A, B, and C, so as to depict different motions due to the drag exerted by basal friction.

3.3 Building of mountains

The travelling continent, if meet another continent in the front, would create high mountain. For example, refer to Figure 10, the horizontal force generated pushes Indian continent to impinge into Eurasian continent, as this force is almost vertical to the continental slope, a bulldozer effect is provided to uplift the materials in the front, forming the Himalayas. It is important to note that, the Himalayas was long thought to be a result of the collision of Indian Plate and Eurasian Plate. This understanding, however, is not exactly correct. The two plates have same rock density, the collision between them would result in an addition of height. The thickness of the continental (oceanic) crust is about 35 (6) km (Turcotte & Schubert 2002), an overlay of these two plates would form a thickness of at least 70 km, in spite of the folded situation generated for plate itself. Unfortunately, the present-day Himalayas (Mount Everest, 8,848 m) is still too low to reach the requisite height. Instead, if we ascribe the Himalayas to be a result of the collision of two continents, it seems to be practicable. Both the Arabian Sea and Bay of Bengal hold a depth of about 4,000 m, it is this depth to yield the ocean-generating force. Indian continent holds a height of no more 500 m, Tibetan Plateau holds a height of about 4,000~5,000 m, if we add a continent of thickness 4,000 m, which is the same as the sea depth that yields the horizontal force, onto Tibetan Plateau, the requisite height may be obtained. Actually, the Himalayas may provide reference for us to believe that the Alps could have derived from a collision of Italian island and its adjacent Europe. A major reason is the relatively deeper Ionian and Tyrrhenian seas can provide a dominantly lateral push (i.e., the horizontal force) to Italian island. Of course, not all the mountains are made through this way. For instance, most of continents are circled by oceans, the horizontal forces generated would compress all the sides of a continent inwards, these actions deform the continent to create folded mountains.

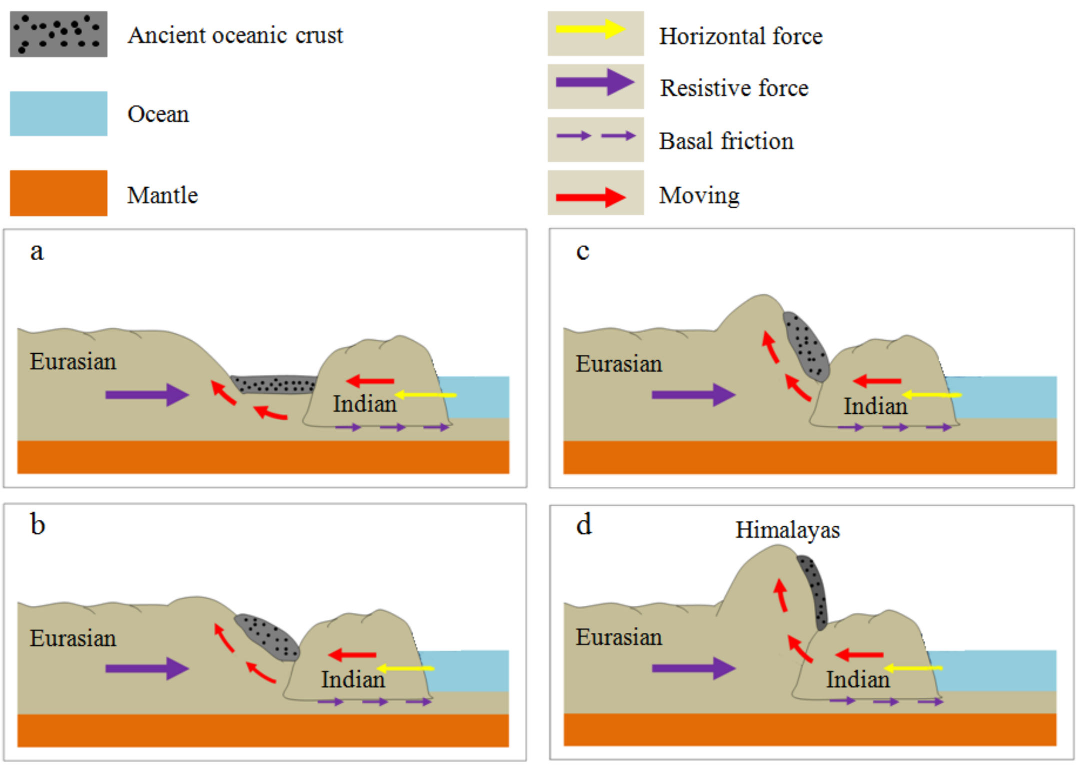

Fig. 10. Modelling the formation of the Himalayas under the collision of Indian continent and Eurasian continent. From a, b, …, to d, it shows a sequence of forming the mountain.

3.4 Creation of transform faults

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 these structures remains poorly understood (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. A distinguishable feature for the faults is there are many long and nearly-parallel structures that usually cross the ridge to exert the cutting, this suggests that the formation of the ridge is most possibly later than that of these structures. We here consider a solution for the transform faults of the Mid-Atlantic Ridge. As exhibited in Figure 11, the early Atlantic was relatively narrow, the horizontal forces generated continued to push the two continents to move away, the travelling continents in turn dragged the oceanic crusts they connect to, the increasingly accumulated strains eventually split the oceanic crust into smaller nearly-parallel segments. This way of nearly-parallel fracture benefits from the horizontal forces. As these horizontal forces always exert orthogonal to the continents' sides, subsequently, a large number of radial strains are yielded to across the oceanic crust. For each of these nearly-parallel segments, the leading drag to it is along nearly opposed direction, it is mostly possible for the accumulated strain to split the segment in the middle. The fracture, as demonstrated in Figure 9, may yield a ridge. Finally, a segment yields a ridge, a connection of the ridges of all the segments apparently creates the transform faults of the Mid-Atlantic Ridge.

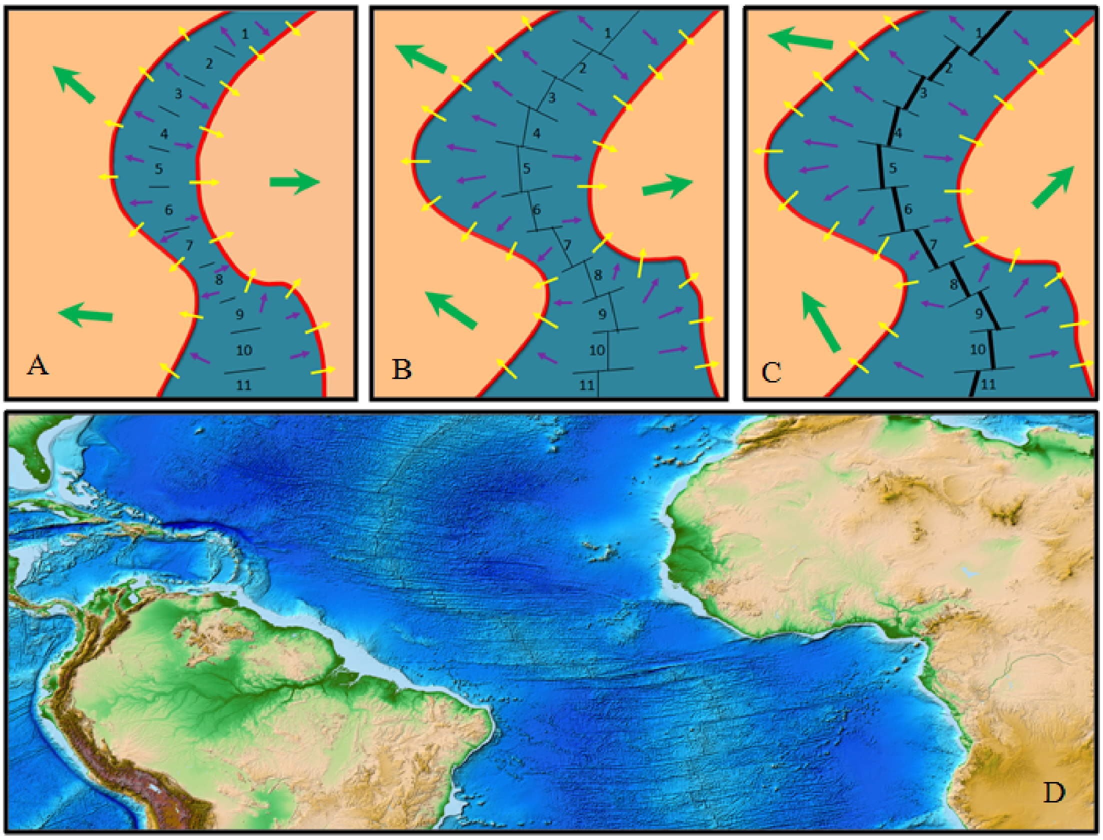

Fig. 11. Modelling the formation of MOR and transform faults. A, B, and C demonstrate a sequence of how transform faults develop with the growth of the MOR. Yellow, green, and purple arrows denote respectively the horizontal forces generated, the resultant movements, and the drags exerted by the travelling continents onto the oceanic crust. The thin black lines represent nearly-parallel structures. Number 1, 2, . . ., and 11 represent the fragments of the oceanic crust, which consist of the sections of transform faults. D shows observed transform faults over the Mid-Atlantic Ridge. The background map is produced from ETOPO1 Global Relief Model (Amante and Eakins, 2009).

3.5 Dispersal of supercontinent

The ocean-generating force driving mechanism provides line for us to conceptually track the dispersal of supercontinent. Refer to Figure 12, at the time of upper carboniferous the opening at the east of landmass allowed a large body of water to enter, the horizontal force generated pushed the landmass at the two sides of the opening to move away. This separation helped to expand the opening further. With the passage of time, the landmass was gradually separated and displayed the shape at the time of Eocene. This, again, allowed more water to enter, and also more horizontal force to be generated. We speculate, such a positive feedback may have controlled the landmass's initial dispersal. The landmass was nearly broken into pieces at the time of the older quaternary, a relatively primitive layout of separated smaller continents was formally established. After that, the horizontal force continued to push these continents to move away from each other until present.

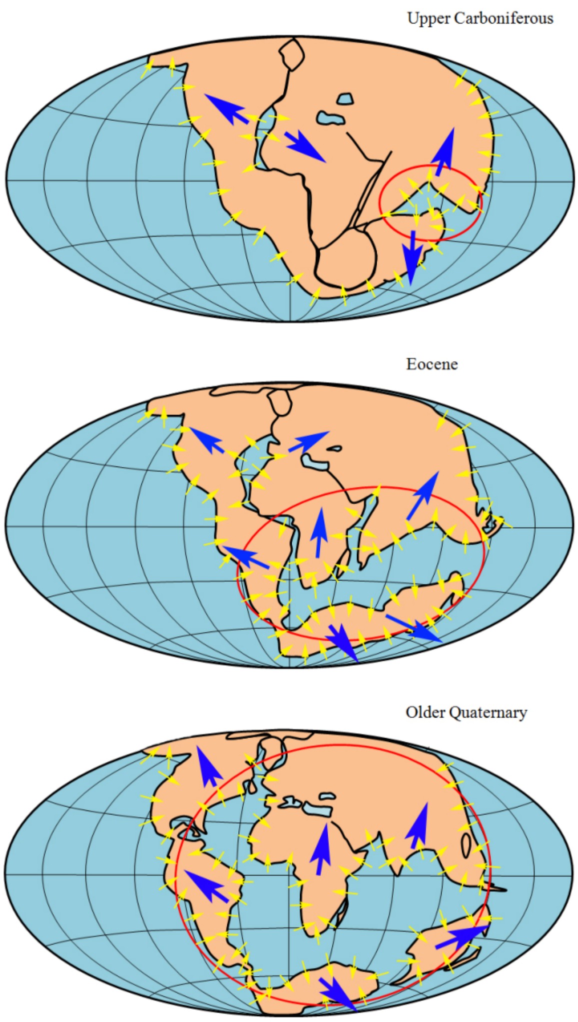

Fig. 12. Modelling the dispersal of supercontinent. Yellow and blue arrows denote respectively the horizontal forces generated due to oceans and the resultant movements. Red circles represent an expansion of the ocean among the landmasses. The background map is yielded referring to Wegener's work (1924).

3.6 Significance of ocean

Water is undoubtedly of great importance for understanding terrestrial phenomena. About 71% the Earth's surface is covered with oceans. It is true, facing such a gigantic body of water, we cannot refuse to consider a coupling of the ocean-generating force and plate motion. Many people feel extraordinarily perplexed why the Earth has plate tectonics but her twin Venus does not. A large number of works showed 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). This work extends these understandings, no water on the Venus, no the ocean-generating force, naturally, no formation of plate tectonics on the planet.

Acknowledgments We express honest thanks to Maureen D. Long, Jeroen van Hunen, and Thorsten Becker for their suggestive comments.

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