What Drives Plate Motions?

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Abstract

Plate tectonics that principally describes earth's plate motion and terrestrial features was long thought to be a manifestation of mantle dynamics. However, an in-depth investigation finds the convection currents incompetent in explaining plate motion. Here we propose, the daily tide loadings around the margins of continents yield unequal pressures onto continental slopes, the net effect of these pressures is to push continents to horizontally move. The travelling continents, by means of basal friction, moderately entrain the continental crusts beneath them and adjoining oceanic crusts, creating weaker motions and terrestrial features for the latter. Quantitatively estimation shows that the pressures yielded due to tide loadings provide South American, African, Indian, and Australian continents respectively a motion of 33, 20, 64, and 71 mm/year. A torque effect likely contributes rotation to North American and Eurasian continents, while the combination of two lateral push forces respectively from North American Plate and from Australian Plate gives Pacific Plate unusual motion (nearly orthogonal to the Australian Plate's).

1 Introduction

One of the most significantly achievements in the 20^{th} 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 for 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 to these, 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 still remains poorly understood, regardless of unremitting efforts made by scientists during the past 100 years. The first to consider the origin 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 continental drift to the centrifugal and tidal forces, but these forces were latterly found to be too weak to work. This thus 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 feed the mantle convection theory in the following decades (Holmes, 1931; Pekeris, 1935; Hales, 1936; Runcorn, 1962a, b; Turcotte and Oxburgh, 1972; Oxburgh and Turcotte, 1978). The mantle convection theory invoked mantle convection as the engine of plate motions. Simply, it conceived a combination of the mantle currents, by providing basal drag along the more rigid overlying lithosphere, and subducting plates, by providing downward slab pull, to dominantly drive plate motions. Personally speaking, we feel the mantle currents theory rather plausible, although many consider it as standard when understanding earth's dynamics. Actually, the mantle convection theory is impracticable and being seriously trapped by much difficulty. First of all, the existence of mantle convection is still uncertain because some techniques based on 3D seismic tomography cannot recognize the large-scale convection currents; Second, the wheel-like convection cells proposed would require plates to sink at the subduction zones so as to compensate the loss of mantle material, which had early rose up to form new crusts at the spreading center. However, most of the plates (North American, Eurasian, and Antarctic Plates, for instance) don't hold the feature of subducting or being subducted anywhere. Third, the diversity of plate motions roasts the mantle currents seriously. Some plates (South American, African, and Indian-Australian) move approximately along straight path, while others (Eurasian and North American) run in a rotating way. In particular, Eurasian Plate rotates clockwise while North American Plate rotates counterclockwise, Antarctic Plate waddles slightly. Most strangely, both Indian-Australian and Pacific plates moves nearly orthogonal to each other. It is considerably difficult for us to imagine how the mantle currents exert at the bottom of lithosphere 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 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). Fourthly, the notion of the mantle currents explaining plate tectonics appears to be contradictive with our cognition of the earth's magnetic field. The highly chaotic plate motions require a large number of convection currents to exert at the bottom of lithosphere along different directions given these currents are the engine of plate motions. The presently accepted view believes that the Earth's magnetic field is generated by electric currents created by convection currents due to heat escaping from the core. However, the earth's magnetic field tends to allow these currents to be orderly arranged along some fixed pattern, for example, computer models suggest that they be organized by the Coriolis force into some rolls that are nearly parallel to the earth's magnetic field. Lastly, the mantle convection theory is unsuccessful in generating plate motions, although some works of mantle currents had modeled 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). In other words, the convection theory cannot tell people how much force is produced by convection currents. Without an quantification of force, you cannot track/expect the following plate motion. Besides these major shortcomings mentioned, other problems of the mantle convection theory (changes in plate motion, plateness, asymmetry of subduction, i.e.,) also cannot be neglected (Bercovici, et al., 2015). Notwithstanding, this work doesn't consider to repair the mantle convection theory, instead go back to the exterior of the earth to find a possible solution for plate motions. Of course, we also would moderately demonstrate how the mantle convection theory fights against with some of observations and why it is not in accordance with our understanding of the dispersal of supercontinent.

2 A tide loading driving for continental drift

Liquid can exert pressure on the side of a vessel that holds it. The total pressure a liquid exerts practically includes static and dynamic pressures, the former relates to liquid's motion, while the latter is exhibited by liquid equally in all directions. As shown in the left top of Figure 1, the static pressure a liquid exerts on the side of a cubic vessel can be approximately written as $F=\rho g y^2 x/2$, where ρ, g, x, and y denote density of liquid, gravitational acceleration, vessel width, and height of liquid, respectively. This expression indicates that the pressure accepted by the side is exponentially proportional to the height of liquid. Go back to real world, ocean (naturally a gigantic vessel of water) is so deep (usually more than thousands of meters) that any small-scale oscillation in depth may yield a remarkable pressure change onto continent's side. For example, a water loading of 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 pressure of 29,404,900.0 N to continent's side, although this volume of water itself owns only a gravity of 9,800.0 N. Most of coasts experience two cycles of high and low water per day, that's the tides we see in everyday life. At coast tidal range usually reaches a few meters, this means that tide loading/unloading is relatively slow and that the dynamic pressure yielded may be neglected. The static pressure a tide loading yields, by virtue of ocean depth, may be wholly transferred to the continent's side. Refer to the bottom of Figure 1, we first assumed that, if there were no tide loading at coast, the pressure yielded by the ocean at the left side would be offset by the pressure yielded by another ocean of same depth at the right side, the excessive pressure yielded at the left side due to excessive ocean depth would be offset by the resistance from oceanic crust at the right, the continent therefore remains immovable. The presence of tide loading, however, may break this equilibrium. Since ocean depth differs from one site to another, tidal range largely varies from one coast to another, the pressures yielded due to tide loadings thus cannot be equal everywhere around the sides of continent. Tide loading yields the pressure $F_1(F_2)$ that is vertical to the continent's slope and that may be written as

$$F_1=0.5\rho_{water} g L[h_1'(2h_1+h_1')]/\sin\alpha$$

$$F_2=0.5\rho_{water} g L[h_2'(2h_2+h_2')]/\sin\beta$$

where ρ_{water}, g, and L denote respectively density of water, gravitational acceleration, and width of ocean. h_1 and h_2 denotes ocean depth respectively at the right and at the left, h_1' and h_2' denote the height of tide at the two sides. α and β denote the inclination of continent's slope respectively at the right and at the left side.

Pressure $F_1(F_2)$ can be further decomposed into horizontal component $F_1'(F_2')$ and vertical component $F_1''(F_2'')$. According to the geometry of force, there would be $F_1'= F_1\sin\alpha$, $F_2'= F_2\sin\beta$, $F_1''= F_1\cos\alpha$, and $F_2''= F_2\cos\beta$. We here term the upper part of continental crust, which is exerted by the pressure due to tide loading, as continent in the following sections. For the continent, the combined force in the horizontal direction would be (F_1'-F_2'-f), where f denotes basal friction between the upper part of continental crust (i.e., continent) and its lower part. Once this kind of combined force is extended to the tide loadings around the coasts of all continents, it inevitably drives these continents to horizontally move. Figure 2 exhibits a globally distribution of tide loadings and the resultant pressures.

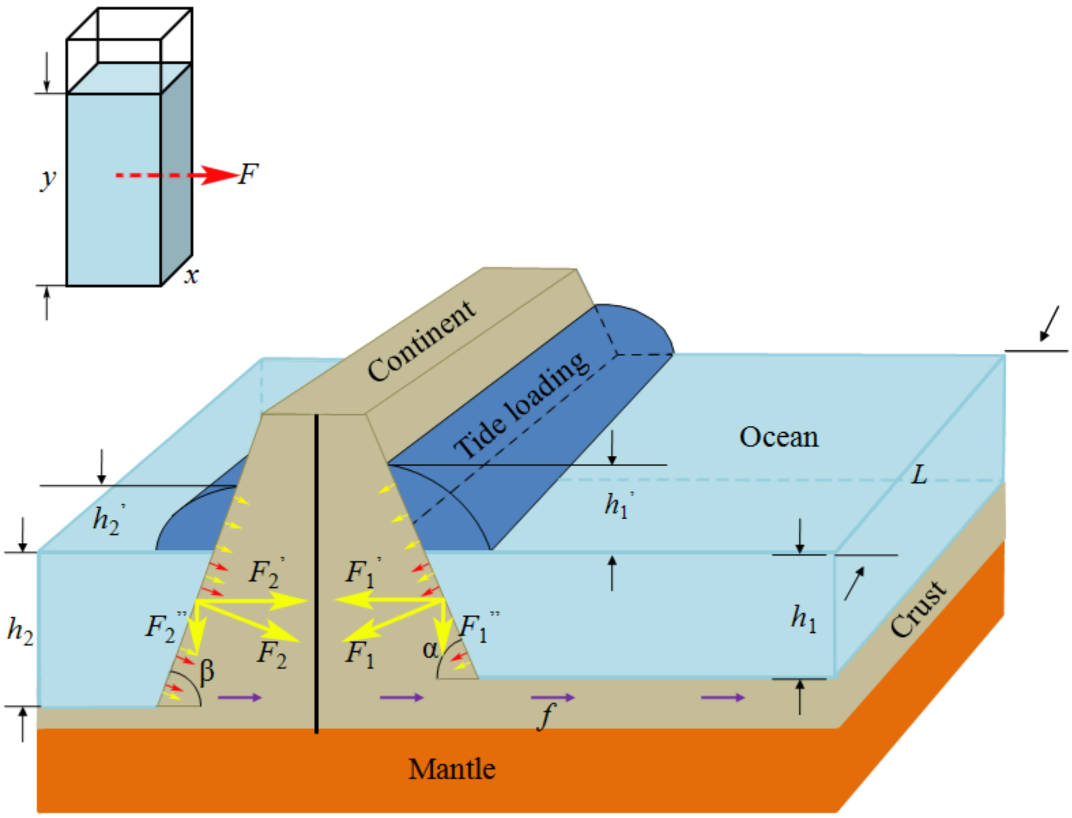

Fig. 1. Modelling the dynamics of continental crust under the effect of tide loading. F_1(F_2) , marked with thick yellow arrow, represents the total pressure exerted due to tide loading onto the continent's side, while F_1'(F_2') and F_1''(F_2'') denote respectively horizontal and vertical components decomposed from the total pressure. Red thin arrows denote the pressures yielded due to ocean itself, while yellow thin ones denote the pressures yielded due to tide loading, both of them are always vertical to the continental slope. f (purple) denotes basal friction between the upper part of continental crust and its lower part. L denotes width of ocean. h_1 and h_2 denotes ocean depth respectively at the right of continent and at the left, h_1' and h_2' denote the height of tide loading at the two sides. α and β denote the inclinations of continent's slope at the two sides. Note that the height of tide is seriously exaggerated relative to ocean depth.

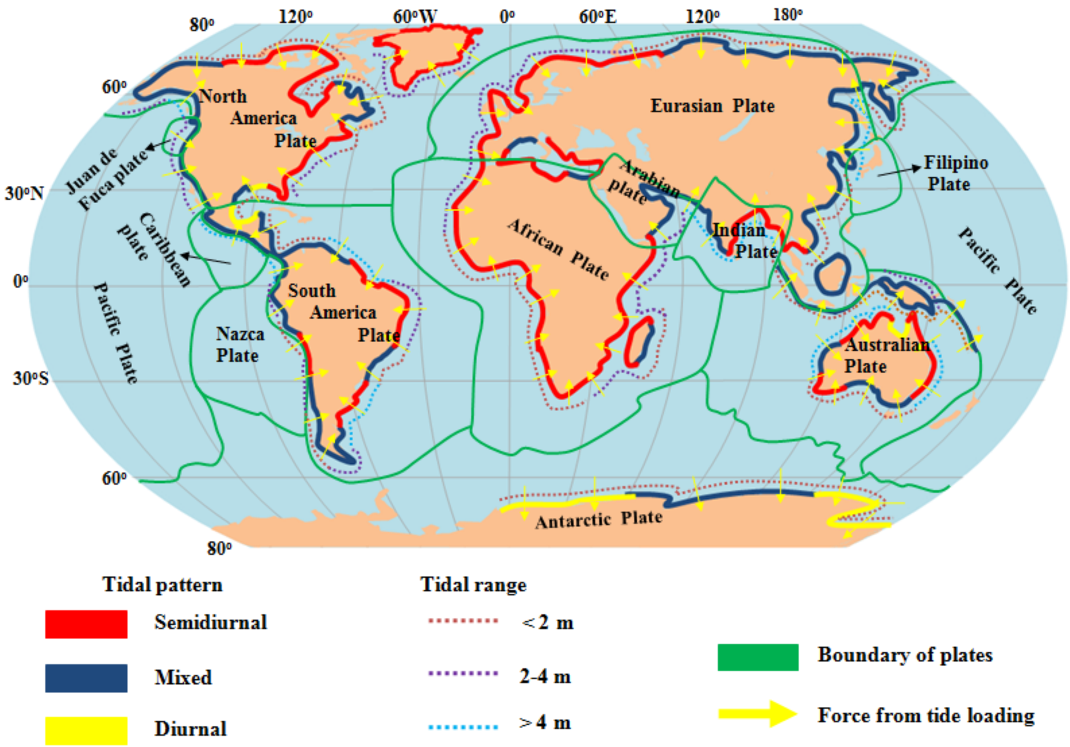

Fig. 2. A global view of the distribution of tidal pattern, tidal range, plate tectonics, and the resultant horizontally forces from tide loading. Tide data supporting is from U.S. NOAA, GLOSS database - University of Hawaii Sea Level Center (Caldwell et al. 2015), and Bureau National Operations Centre (BNOC) of Australia, and tide range also refer to the times atlas of the oceans, 1983, Van Nostrand Reinhold, NY.

The daily two high (low) waters a coast experience correspond to two loadings (unloadings) of a tide, each loading (unloading) takes a time of almost 6 hours. For continent, tide loadings around its all coasts cannot be synchronous everywhere, but this wouldn't affect the pressures to be yielded and to work further. In addition, the rate of tide loading is not uniform, this leads the pressure generated to vary and results in a difficulty in determining the time that continent takes to accelerate during a day. Moreover, tidal range performs two cycles per month, which is associated with the positions of the earth, moon, and sun. This range becomes maximal at the times of full and new moon and minimum at the times of first quarter and last quarter. We here assumed the rate of tide loading to be uniform anywhere, all of the tide loadings to occur at identical time, and tidal range to be invariable during month. Apparently, tide looks like a vibration of water about a reference level. Based on Figure 3, we treat the lowest water level of a tide to be the reference level (zero) that yields no pressure onto the continent's side and the time of the lowest water level to be a starting point. From then on, the horizontal force (F) increases because tide begins to load, but the continent that bears this force will not move until the horizontal force is greater than resistance (f) at the time t_1. Once $F>f$, this yields acceleration (a) for the continent to move. With the advent of the highest water level of tide, the horizontal force reaches its maximal, which also responds to a maximum of acceleration. After this moment, tide begins to unload, the horizontal force gradually decreases, but the speed of the continent continues to increase until $F=f$ at the time t_2. Subsequently, the motion begins to decelerate due to $F<f$, and eventually terminates at the time t_3. As a tide loading with uniform rate yields an uniform changing pressure, there would be a matter of $t_2-t_1=t_3-t_2$. Once resistance (f) is given, the time that the continent takes to accelerate or decelerate during a day may be got.

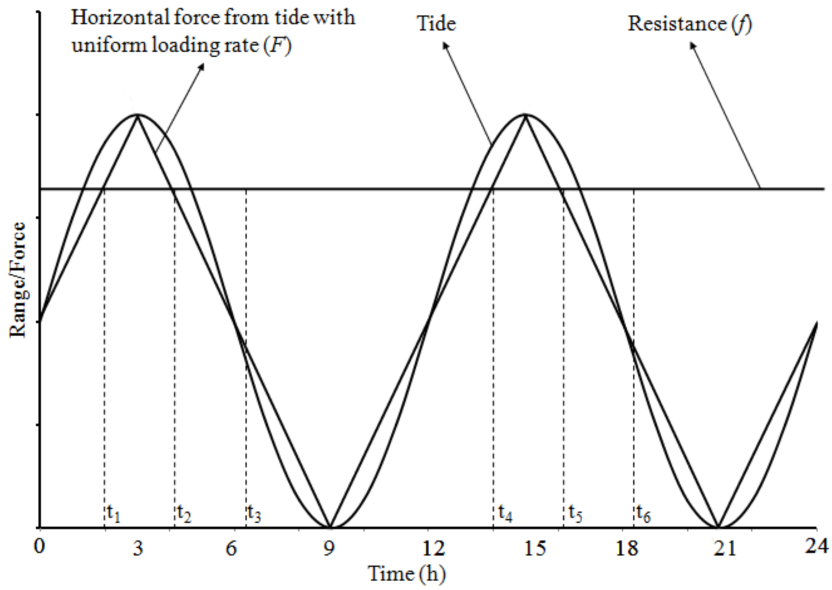

Fig. 3. Dynamic analysis for the continent's motion based on tide loading. Stage t_1~t_3 and t_4~t_6 denote the time that the continent takes to move during a day.

Practically, a continent, if not connected to another, must be circled by a train of coasts, this determines that the total horizontal force this continent accepts would be a combination of the horizontal forces yielded due to tide loadings around these coasts. The spherical earth bends continent, this makes the horizontal forces unable to fall onto identical plane. We here decompose each of the horizontal forces into latitudinal and longitudinal forces, assume continent to be more rigid and planar, and further assume all of the decomposed forces to ideally pass the continent's barycenter. This treatment is to give continent a straight motion. Finally, the total horizontal force a continent accepts is expressed into a combination of all of the decomposed forces in the latitudinal and longitudinal directions. And then, the displacement a continent accepts under the effect of the total horizontal force during a year may be written as

$$D=0.5a*\Delta t^2*2*365$$

Where $0.5a$, Δt, 2, and 365 denote respectively the average acceleration, the time that the continent takes to accelerate during a tide loading, the number of tide loading per day, and the number of day during a year. Single a denotes the acceleration that the continent holds at the time of the highest water level of tide, and may be expressed with Newton law as $a=(F-f)/M$, F and f are respectively the total horizontal force and resistance, (F-f) denotes the final force in the horizontal direction that the continent accepts, M denotes the continent's mass and can be expressed as $M=Sd\rho_{plate}$, S, d, and ρ_{plate} are respectively the continent's area, thickness, and density. Δt may be written as Δt=(1-*f*/*F*)*12, and 12 is the time length of a tide of loading and unloading.

With these theoretical ideas, we constrain the parameters involved in the expressions above to estimate the horizontal movement of a few continents (South American, African, Indian, and Australian). The selection of the controlling sites that determine the horizontal forces of these continents refers to Figure 4, the longitudes and latitudes of these sites are roughly resolved from Google Earth software. The given values for related parameters, the horizontal forces yielded due to tide loadings, and the resultant motions are respectively listed in Table 1 and 2. Overall, the expected motions (South American, African, Indian, and Australian, respectively 3.3, 2.0, 6.4, and 7.1 cm/yr) from tide loadings may be consistent with the observed motion of 5.0~10.0 cm/yr (Read and Watson 1975) on the assumptions that all of related parameters are reasonably considered.

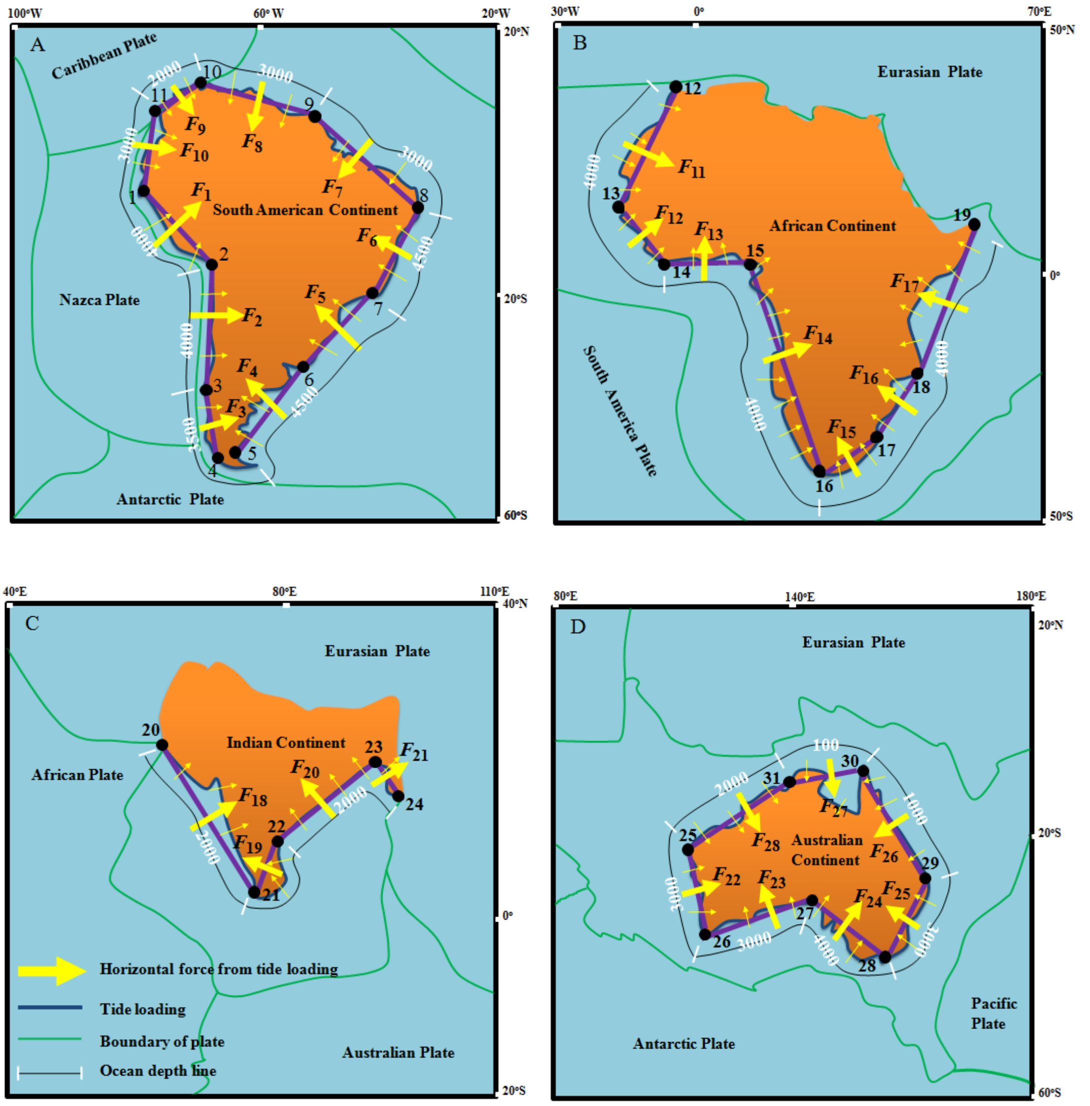

Fig. 4. Geographic treatment of the controlling sites for selected continents and the resultant horizontal forces exerted on them. *F* (yellow arrow) denotes the horizontal force, while purple

bar denotes the distance applied by the horizontal force. Dot with number denote controlling site. Note that the determination of ocean depth is artificially resolved from Google Earth software.

Table 1 Basic information for slected continents

Continent	Area (S)	Thickness (d)	Density (ρ)	Mass (M)	Site			Distance of from site to site (L)		Tide range (Δh)	Ocean depth (h)
	km^2	km	kg/m^3	kg	Num.	Longitude	Latitude	km		m	m
					1	80^{o}W	2.0^{o}S	1_2	2,087	3	4,000
					2	70^{o}W	18.0^{o}S	2_3	1,153	3	4,000
					3	73^{o}W	28.0^{o}S	3_4	2,780	3	3,500
					4	73^{o}W	53.0^{o}S	5_6	2,308	4	4,500
					5	68^{o}W	52.5^{o}S	6_7	1,730	4	4,500
South American	17,840,000	6	2,700	2.89E+20	6	54^{o}W	34.5^{o}S	7_8	1,952	3	4,500
					7	42^{o}W	23.0^{o}S	8_9	2,525	3	3,000
					8	34^{o}W	7.0^{o}S	9_10	2,157	3	3,000
					9	53^{o}W	5.5^{o}N	10_11	836	3	2,000
					10	72^{o}W	12.0^{o}N	11_1	1,033	3	3,000
					11	78^{o}W	7.0^{o}N				
					12	6^{o}W	35.5^{o}N				
					13	17^{o}W	14.7^{o}N	12_13	2,535	2	4,000
					14	7^{o}W	4.6^{o}N	13_14	1,531	2	4,000
African	30,370,000	6	2,700	4.92E+20	15	8^{o}E	4.4^{o}N	14_15	1,696	2	4,000
					16	22.2^{o}E	34.7^{o}S	15_16	4,577	2	4,000
					17	30.4^{o}E	30.7^{o}S	16_17	886	2	4,000
					18	40^{o}E	16^{o}S	17_18	1,904	2	4,000
					19	51^{o}E	11^{o}N	18_19	3,237	2	4,000
Indian	4,400,000	6	2,700	7.13E+19	20	66.8^{o}E	25^{o}N				

					21	77.5°E	8°N	20_21	2,205	4	2,000
					22	80°E	15.2°N	21_22	846	4	2,000
					23	91.5°E	22.7°N	22_23	1,468	4	2,000
					24	94.3°E	16°N	23_24	801	4	2,000
Australian	8,600,000	6	2,700	1.39E+20	25	114°E	23°S	25_31	2,162	4	2,000
					26	117.2°E	35°S	25_26	1,370	4	3,000
					27	131°E	31.5°S	26_27	1,340	2	3,000
					28	149.8°E	37.6°S	27_28	1,846	2	4,000
					29	153°E	25.4°S	28_29	1,390	4	3,000
					30	142.4°E	10.8°S	29_30	1,970	4	1,000
					31	131°E	12.2°S	30_31	1,252	4	100

Table 2 Horizontal forces and resultant motions for selected continents

Continent	Horizontal force (F) N						Friction coefficient (ζ)	Resistance (f)	Combined force (F-f)	Acceleration (a)	Time for acceleration during a tide loading (Δt)	Displacement (D)
			Latitudinal East (+)	Longitudinal North(+)	Total	Inclination to latitude (°)		N	N	$m \cdot s^{-2}$	hour	mm/year
South American	F_1	2.46E+14	+2.08E+14	+1.30E+14								
	F_2	1.36E+14	+1.30E+14	-3.90E+13								
	F_3	2.86E+14	+2.86E+14									
	F_4	4.07E+14	-3.17E+14	+2.56E+14								
	F_5	3.05E+14	-2.11E+14	+2.20E+14								
	F_6	2.58E+14	-2.34E+14	+1.10E+14								
	F_7	2.23E+14	-1.22E+14	-1.86E+14								
	F_8	1.90E+14	-6.31E+13	-1.80E+14								
	F_9	4.92E+13	+3.25E+13	-3.70E+13								
	F_{10}	9.11E+13	+8.83E+13	-2.26E+13								
			-2.03E+14	+2.52E+14	3.23E+14	128.89	0.9965	3.22E+14	1.13E+12	3.91E-09	0.042	32.65
African	F_{11}	1.99E+14	+1.76E+14	-9.22E+13								
	F_{12}	1.20E+14	+8.49E+13	+8.49E+13								
	F_{13}	1.33E+14	+8.85E+12	+1.33E+14								
	F_{14}	3.59E+14	+3.38E+14	+1.21E+14								
	F_{15}	6.95E+13	-3.05E+13	+6.25E+13								

	F_{16}	1.49E+14	-1.25E+14	+8.16E+13								
	F_{17}	2.54E+14	-2.35E+14	+9.58E+13								
			+2.17E+14	+4.86E+14	5.33E+14	65.96	0.997	5.31E+14	1.60E+12	3.25E-09	0.036	19.91
Indian	F_{18}	1.73E+14	+1.46E+14	+9.22E+13								
	F_{19}	6.64E+13	-6.27E+13	+2.18E+13								
	F_{20}	1.15E+14	-6.29E+13	+9.65E+13								
	F_{21}	6.28E+13	+5.80E+13	+2.42E+13								
			+7.88E+13	+2.35E+14	2.48E+14	71.44	0.997	2.47E+14	7.43E+11	1.04E-08	0.036	63.86
Australian	F_{22}	1.61E+14	+1.56E+14	+4.15E+13								
	F_{23}	7.88E+13	-1.94E+13	+7.64E+13								
	F_{24}	1.45E+14	+4.47E+13	+1.38E+14								
	F_{25}	1.64E+14	-1.58E+14	+4.15E+13								
	F_{26}	7.74E+13	-6.26E+13	-4.55E+13								
	F_{27}	5.01E+12	+6.10E+11	-4.97E+12								
	F_{28}	1.70E+14	+9.10E+13	-1.43E+14								
			+5.19E+13	+1.03E+14	1.16E+14	63.39	0.995	1.15E+14	5.79E+11	4.16E-09	0.06	70.91

Nevertheless, the assumptions above are moderate only for these small-sized continents. For those larger ones like Eurasian and North American, their curvatures cannot be ignored, the horizontal forces yielded due to tide loadings cannot pass their barycenters, a torque effect is necessarily generated to rotate them. Figure 5 apparently demonstrates how these continents move under the torque effect of the horizontal forces.

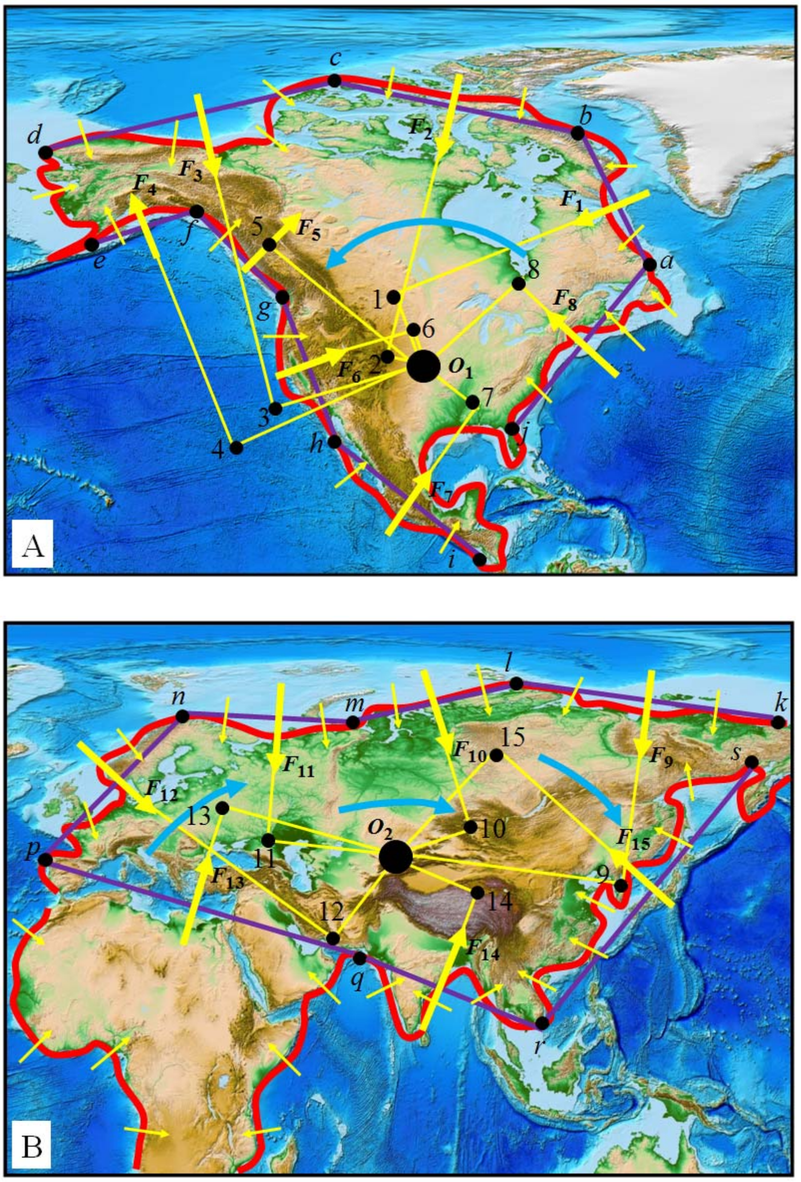

Fig. 5. Modelling the rotations of North American (A) and Eurasian (B) continents under the torque effect of the horizontal forces due to tide loadings. O_1 and O_2 denote possible positions of the barycenters of two continents. F_1, F_2, F_3, i,e., marking with yellow arrows, denote the horizontal forces yielded due to tide loadings (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 multiplying arm. Curved blue arrows represent the expected rotations around the barycenters. Note F_{13} actually represents push force

from moving African continent. The background map is produced from ETOPO1 Global Relief Model (Amante and Eakins, 2009).

3 A general understanding of plate tectonics

Plate tectonics is clearly a manifestation of unequal pressures yielded due to tide loadings around the margins of continents. This work indicates that a very little part of the pressures yielded, no more than 0.5% of the total, may be enough to generate the requisite surface motions. The remaining pressures, however, are used to entrain both the continental crust beneath continent and the adjoining oceanic crust and to shape the continental crust extensively. The overriding of the continent onto the more plastic oceanic crust may create a squeeze effect to the latter, forming terrestrial features like trench, earthquake, and volcano at the zones where they meet each other. Even so, not all overridings can generate trenches, the continent's thickness that determines weight possibly plays a critical role for that squeeze. This has got clue at the west of South American continent, from where the Peru-Chile Trench looks like echoing everywhere to the swelling landmass, different from this, the relatively flat landmass at the south end exhibits no trench. A periodically fracture of the oceanic crust may account for the formation of the Mid-Oceanic Ridge (MOR). As shown in Figure 6, the travelling continent drags by basal friction the adjoining oceanic crust, this generates strain for the oceanic crust. With the passage of time, the accumulated strain eventually rips the oceanic crust, allowing the magma from the deep to erupt dramatically. The erupted magma then cools by ocean to crystallize and form new crusts. The newly formed crusts in turn seal that fracture, terminating that eruption. The fracture relieves strain temporarily, but since the pressures continue to push the continent to move, strain is again generated and gradually accumulated, the following fracture and closeness occur again. The newly formed crusts naturally add height to the oceanic crust, forming the MOR. The fracture of the oceanic crust reflects a fact that the upper part of the oceanic crust has slightly moved, but essentially, this motion is too weak (shallow) to reach the oceanic crust's bottom. In addition, the travelling continent provides not only drag to the oceanic crust at the rear and but also push by basal friction to the oceanic crust in the front, the drags or pushes or both of different directions to identical oceanic crust may deform the crust to fracture, allowing magma to erupt to form the MOR. Finally, we treat these trenches and the MORs as marks to plot the earth's surface, this consists of a basic frame of plate tectonics.

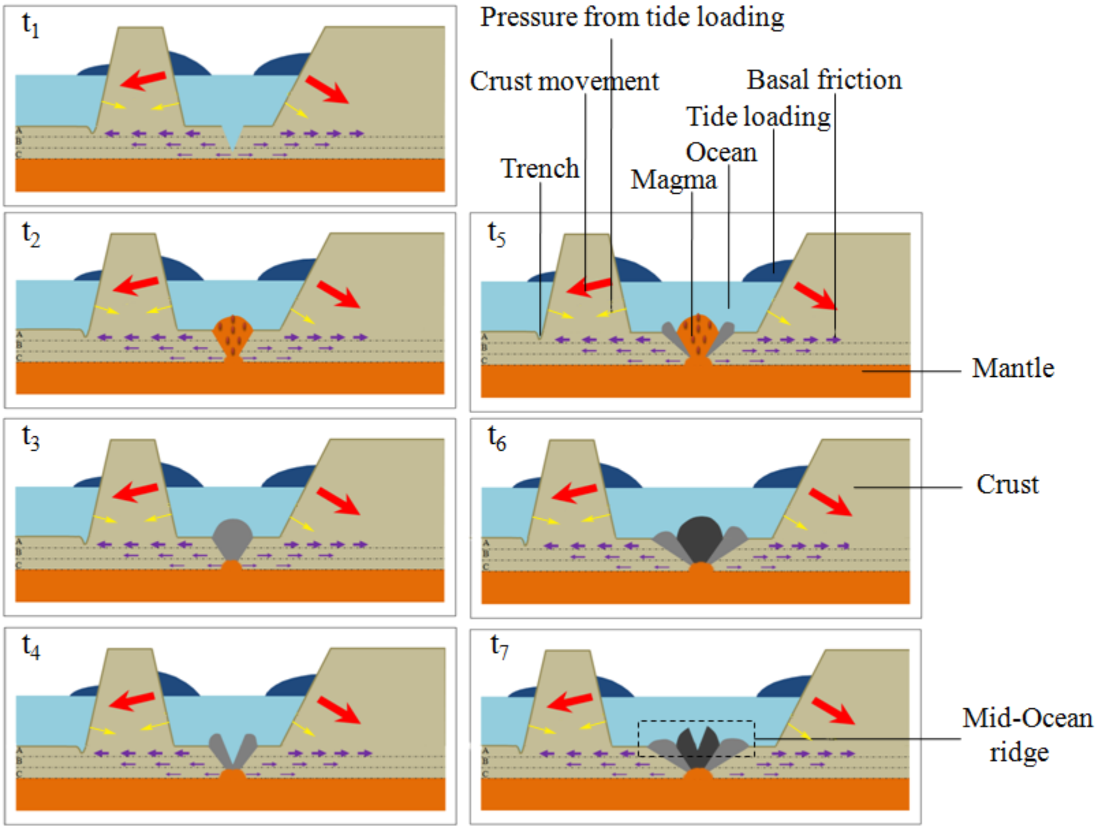

Fig. 6 Modelling the formation of MOR under the pressures yielded due to tide loadings. From t_1, t_2, …, to t_7, it exhibits a sequence of evolution. The lower part of lithosphere is apparently divided into three layers A, B, and C, so as to depict motions of different amplitude due to the drag exerted. Note that thin yellow arrow denotes the total pressure yielded due to tide loading.

The pressures yielded push continent's every side inwards, this kind of lateral compressions automatically deform continent to create folded mountains and rifts. Of course, the collision of two continents also may form high mountains. For example, as shown in Figure 7, the pressures yielded push Indian continent to impinge into Eurasian continent, because the pressures are vertical to the continental slope, this provides a bulldozer effect to uplift materials in the front, forming the Himalayas. It should be kept in mind 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 35 (6) km (Turcotte & Schubert 2002), the overlay of these two plates would get 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) appears to be too low to satisfy with the requisite height. In contrast, if we consider the Himalayas as a result of the collision of two continents, it could be more 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 sea depth to accept the pressures yielded due to tide loadings. 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 only need to add a continent of 4,000 m thickness, which is equal to the sea depth that accepts the pressures, onto

Tibetan Plateau, the requisite height may approximately be got. By the way, the Himalayas provides a good reference for us 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 consideration is the relatively deeper Ionian and Tyrrhenian seas contribute more pressures to the sides of Italian island, this provides the island a dominantly lateral push along northwest.

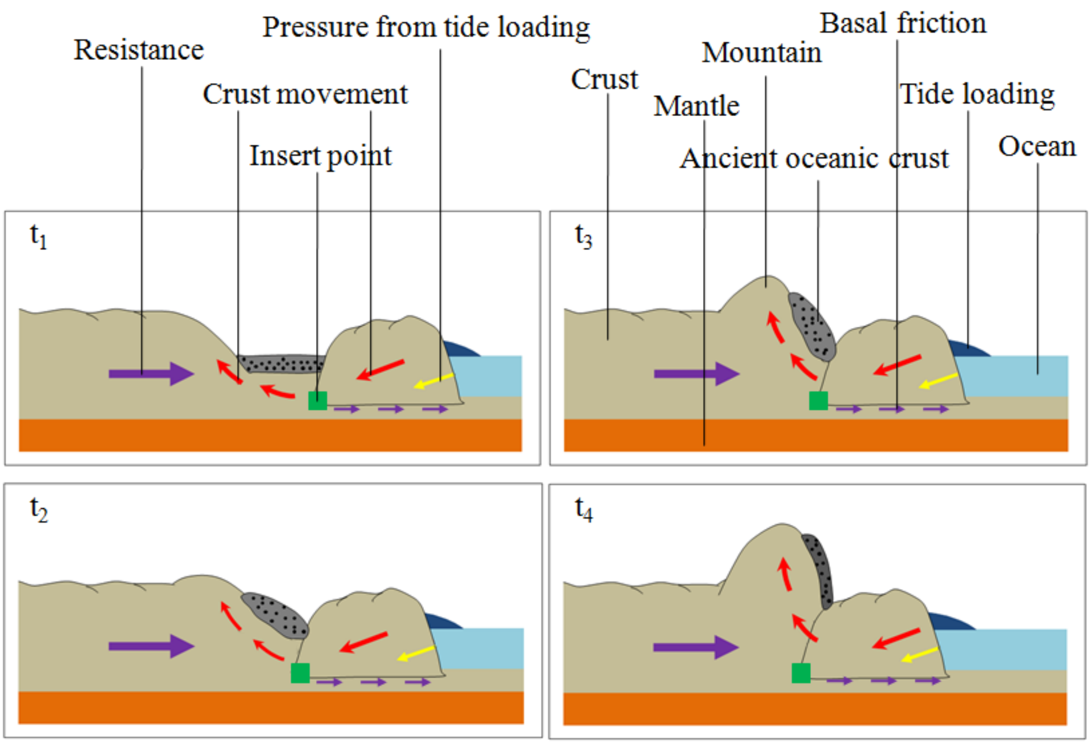

Fig. 7. Modelling the formation of the Himalayas under the collision of Indian continent and Eurasian continent. From t_1, t_2, …, to t_4, it shows a sequence of formation at different time.

4 Discussion

Our previous understanding presented a dynamic pressure yielded due to the water movement in the oscillating ocean basin to account for the Pacific Plate's motion (nearly orthogonal to Australian plate's). However, it now becomes clear that a combination of two lateral push forces respectively from North American Plate and from Australian Plate may be competent for this unique motion. As shown in Figure 8, 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 meant that the present-day North American could be reversed to northeast in the past, if so, the push force F_{NAP} might be not 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 immediately becomes possible. Such plate motion change actually has been witnessed by the Hawaiian–Emperor bend (Sharp and Clague, 2006; Wessel and Kroenke, 2008).

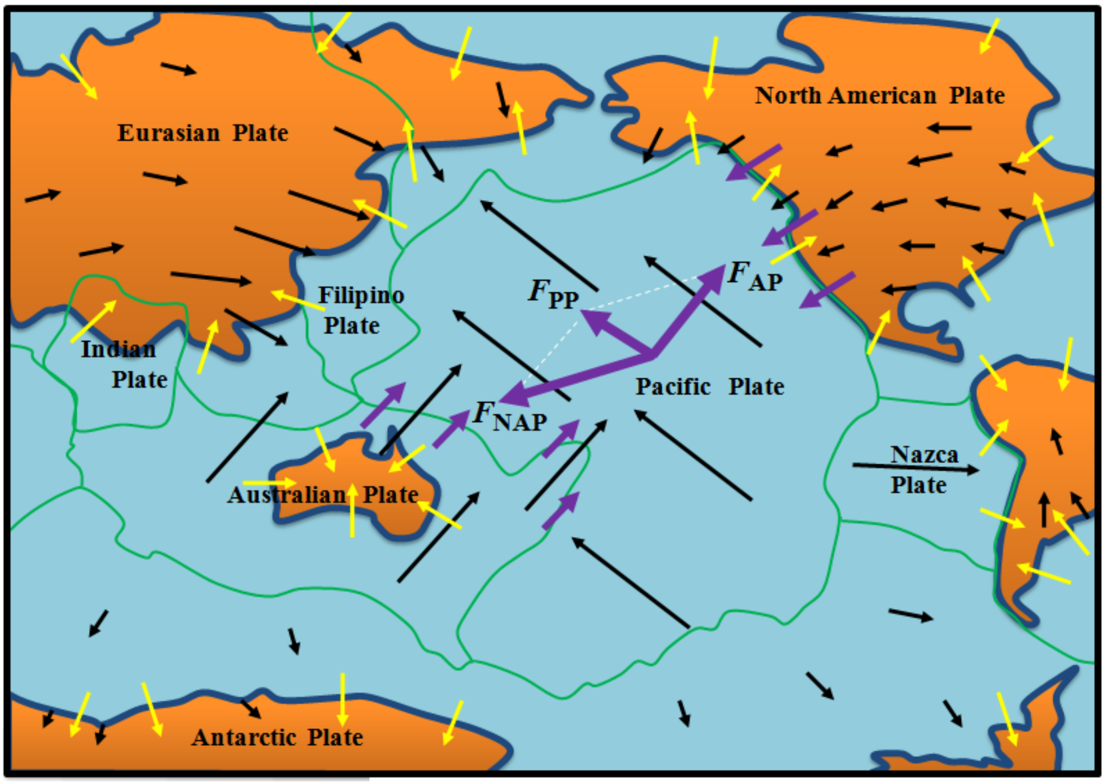

Fig. 8. Modelling Pacific Plate's motion based on a combination of two lateral push forces from Australian and North American Plates. Black, yellow, and purple arrows denote respectively plate motions, pressures yielded due to tide loadings, and push force (resultant combined force), while blue around the margins of continents denote tide loadings. Note lateral push force F_{NAP}(F_{AP}) is approximately parallel to the motion of North American(Australian) Plate.

The proposed periodically fracture and closeness of the oceanic crust, reflecting alternate heat release from the earth's interior, may couple with the past 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). The existence of continental fragments and crustal remnants in the oceanic basins had been extensively proven through marine geology, geophysics survey, and seafloor drilling, these fragments and remnants generally consist of either large ridges or plateaus (Ren et al., 2015). The most famous among them include Jan Mayen Ridge, Rockall Pleteau, Rio Grande Rise, Falkland Plateau, and Seychelles Plateau. The formation of oceanic plateaus was thought to experience three stages: firstly rising of mantle plumes through asthenosphere, subsequently flattening along lithosphere's base, and finally decompressed melting (Saunders et al., 1992). However, once the origin of the mantle plumes, which is the mantle convection theory, is pendent in this work, it is necessary to consider alternative solution for the formation of these fragments and remnants. As we may infer from Figure 1, besides the pressures yielded by tide loadings, the ocean itself also yields pressures, it is the sum of these two pressures to press the continent's slope to gradually sink. After continent has submerged into ocean, a formation of plateau is natural. Possibly, the ancient and isolated small-sized landmasses due to the influences of the pressures had sunk into oceans to create these ridges and plateaus.

The biggest bottleneck for the mantle convection theory lies in that it seriously conflicts with our understanding of the dispersal of supercontinent, which was thought to form pieces of presently smaller continents. As the basal friction that the mantle currents exert is always at the bottom of the continental crust, if it is the drag of this basal friction to split supercontinent into pieces, the continental crust that holds this supercontinent must had fractured thoroughly from bottom to top. The eruption of volcano reflects a fact that a crust's fracture that pierces mantle would lead magma to rise up to earth surface, after cooling, the remnants of magma would in turn weld/occupy the fracture. Go to the matter of the separation of American continent and African continent, if it were made by the mantle currents splitting supercontinent, the remnants of ejected magma also would weld/occupy the fracture, this disallows water to enter and to form the Atlantic. The MOR reflects another fact that, once the crust's fracture pierces mantle, the high pressure of ocean water still cannot prevent magma erupting from the deep. In fact, there are strong evidences to show that the continental crust's fracture is rather shallow and never pierces mantle. African Great Rift Valley and Iceland's Rift Valley are such examples. Contrary to this, if we use the pressures yielded due to tide loadings to split the continental crust, the result is necessarily a fracture of the upper part of the continental crust, this not only avoids the eruption of magma from the deep but also provides room for water to enter and to form ocean. The pressures yielded due to tide loadings here provide line for us to dynamically track the dispersal of supercontinent. Since tides are launched from east to west as the earth spins on its axis, and a coast's blocking can form larger tide, this allows larger tides to be loaded mainly at the east and west sides of the continents, while the weaker ones to be loaded mainly at the south and north sides. As is well 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 tides, we demonstrate how the supercontinent splits into pieces of smaller continents. As shown in Figure 9, at the time of Upper carboniferous the opening at the east of the landmass at first facilitates larger tide to load, the resultant pressures push the adjoining landmass to move away from each other. This in turns expands the opening further. The weaker pressures at the south of the landmass give little resistance to that expansion. With the passage of time, the landmass was slowly broken and displayed the shape at the time of Eocene. This, again, facilitates more water to enter, more tides to load, and also more pressures to be generated to push the landmass. We believe, it is this positive feedback to possibly control the first stage of the landmass's dispersal. The landmass was finally broken up until the advent of the older quaternary, the primitive shapes of separated smaller continents were formally established. After that time tide loadings continued to go proceed, and the continents also continued to move away from each other until present.

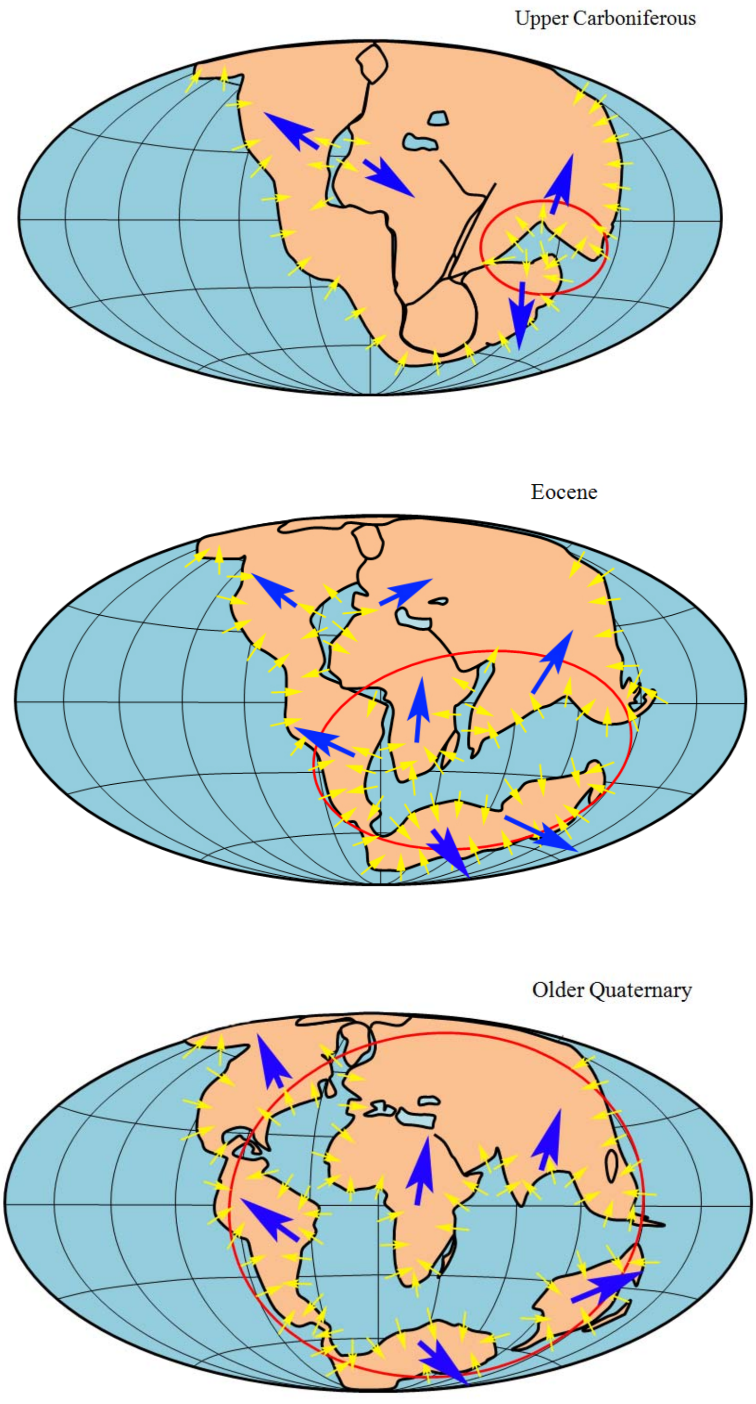

Fig. 9. Modeling the dispersal of supercontinent based on lateral pressures yielded due to tide loadings. Yellow and blue arrows denote respectively the pressures yielded due to tide loadings and the resultant landmasses' motions. Red circles represent an expansion of tide loading within the landmass. The background map is yielded referring to Wegener's work (1924).

One of the most unusual features around the MOR is the transform faults which cut the ridge into a train of smaller sections. Although the transform fault is a preferred subject among scientific communities, its origin still remains in a state of debate (Gerya, 2012). The widely 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 summarized (2012) that asymmetric crustal growth at mid-oceanic ridge can create some transform faults, while others can form earlier during the onset of oceanic spreading. A distinguished feature we shouldn't neglect is some long and nearly-parallel structures run across the ridge to exert the cutting, this suggests that the ridge forms possibly later than these structures. We therefore consider a solution for the formation of the transform faults at the Mid-Atlantic Ridge. As exhibited in Figure 10, the early Atlantic is relatively narrow in the dispersal of supercontinent, the pressures yielded due to tide loadings continue to push the landmasses, this makes these landmasses to depart from each other, the travelling landmasses by basal friction further drag the crust beneath it and the adjoining oceanic crust since the continental and oceanic crusts are physically connected, the oceanic crust is split by the accumulated strain into smaller nearly-parallel segments. The narrowness of the oceanic crust at the time benefits a nearly longitudinal fracture to occur. With the passage of time, the oceanic crust is highly 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, as we demonstrated in Figure 6, a ridge is formed for a segment, a connection between the ridges of all these segments consist of the transform faults of the Mid-Atlantic Ridge.

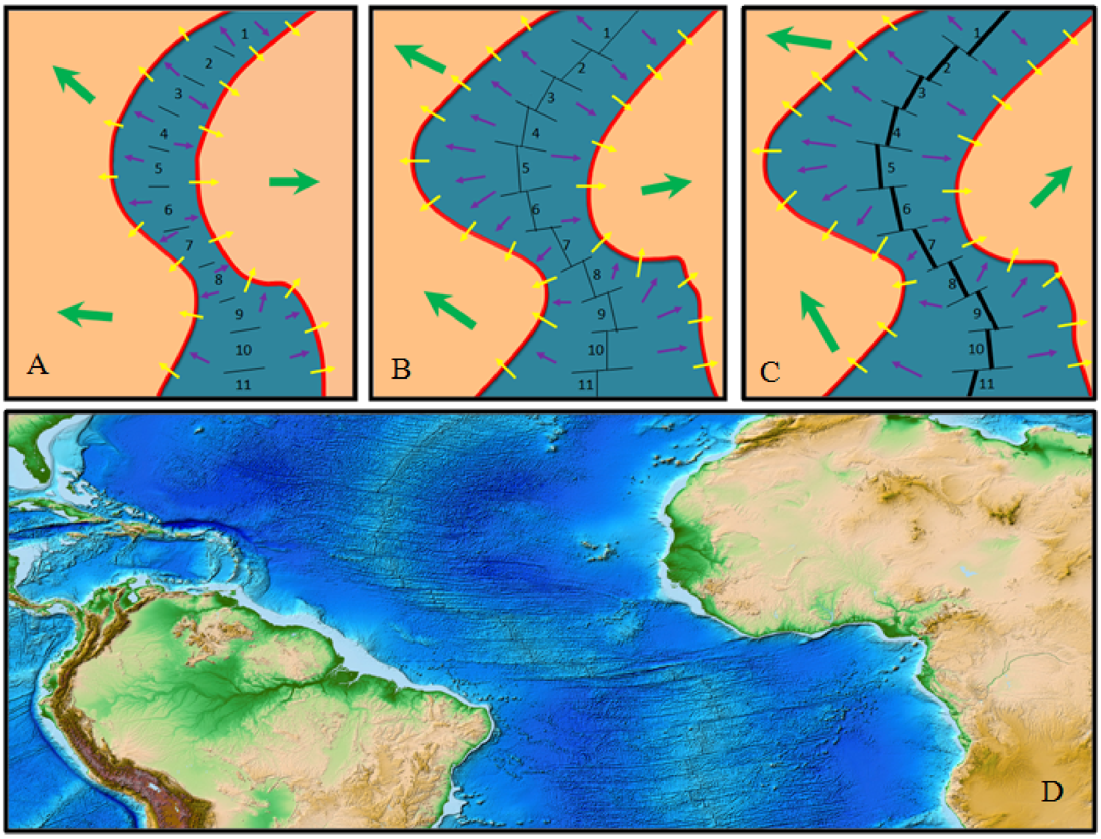

Fig. 10. Modelling the formation of MOR and transform faults based on the pressures yielded due to tide loadings. A, B, and C exhibit a sequence of how transform faults evolve with the growth of the MOR. Yellow, green, and purple arrows denote respectively the pressures yielded due to tide loadings (marked 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).

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 works, this work proposes the pressures yielded due to tide loadings as driving engine of plate tectonics, it is natural to think of, no water on the Venus, no generation of pressures by tide loadings, of course, no formation of plate tectonics.

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