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Geological understanding of plate tectonics: Basic concepts, illustrations, examples and new perspectives

Yaoling Niu[1,2]

With 16 figures

Abstract: In this paper, I have reviewed some basic concepts of the plate tectonics theory in a plain geological language with the aim of encouraging geologists to correctly understand this theory in its applications to geological problems. I emphasized the decisive role of subduction as the ultimate (dominant) driving force of all the plate tectonics phenomena. Hence, my discussion has focused on major issues such as the origin of subduction zones, slab rollback, trench retreat, trench suction and driving mechanism of plate motion (both oceanic and continental) by means of illustration with hypothetical and real examples. As much of the discussion is heavily based on my personal (original) perspectives, some of the concepts, interpretations and hypotheses may not be familiar to many and may not be readily found in the existing literature. Mantle plume hypothesis is not the focus of this paper and is thus only mentioned in passing.

Keywords: plate tectonics, driving mechanisms, subduction initiation, trench retreat, trench suction, back-arc basins, continental drift, western Pacific, eastern China, India-Asia convergence

"All truths are easy to understand once they are discovered; the point is to discover them."
Galileo Galilei (1564–1642)

1. Introduction

The advent of the plate tectonics theory over 45 years ago has revolutionized Earth Science thinking and provided a solid framework for understanding how the Earth works on local, regional and global scales. The theory is especially effective in explaining most of the geological processes taking place in the Phanerozoic. Nevertheless, it is common to hear and read misconceptions about this theory in its applications. Both knowns and unknowns are confused among the geological community without a clear understanding of these knowns and unknowns. For example, statements like "ultra-high pressure metamorphic rocks result from continental collision", "mantle convective current drives plate motion", "flat subduction explains magmatic anomalies" etc. are common in the recent literature. These examples reflect conceptual misunderstanding of the basic physics and principles behind the plate tectonics theory, and can thus mislead readers, particularly those younger minds and their scientific development. The purpose of this paper is to clarify some basic concepts of plate tectonics theory by means of illustration with examples using a plain geological language while also offering my personal perspectives on subduction initiation, trench retreat, trench suction and geodynamic consequences including testable hypotheses on the origin

Addresses of the author:
[1] Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China
[2] Department of Earth Sciences, Durham University, Durham DH1 3LE, UK; yaoling.niu@foxmail.com

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and evolution of backarc basins and mechanisms of continental drift. As a most illustrative example, I also discuss the most likely mechanism of lithosphere thinning beneath eastern China since the Mesozoic as a special consequence of plate tectonics of global significance.

2. Basic concepts of global tectonics

Geological processes are ultimately consequences of Earth's cooling with time. Plate tectonics theory, which explains geological phenomena along plate boundaries, effectively illustrates this concept. For example, the origin of oceanic plates at ocean ridges, the movement and growth of these plates, and their ultimate consumption back into the Earth's deep interior through subduction zones (Fig. 1) provide an efficient mechanism to cool the Earth's mantle, leading to large-scale mantle convection. Hence, the Pacific type oceanic plates (with subduction zones) are both expressions and actual driving force of mantle convection (e.g., Davies 1999). One of the primary assumptions of the plate tectonics theory is that the surface plates (Fig. 1) are rigid and do not deform internally, but they can move relative to one another along plate boundaries. Therefore, the plate tectonics theory can effectively explain all the Earth processes (e.g., magmatism, metamorphism, deformation and earthquakes) along plate boundaries, but cannot explain within-plate geological phenomena. The proposal of the mantle plume concept in the early days was simply the need to explain these within-plate phenomena such as the active Hawaiian volcanism and the Hawaiian-Emperor seamount chains within the vast Pacific plate. Initially, Wilson (1963) called the within-plate volcanoes like Hawaii as "hotspots" with a relatively fixed deep source, deeper than and thus unaffected by the moving Pacific plate. Morgan (1971) further proposed that the hotspots are surface expressions of deep-rooted thermal mantle plumes originated from the core-mantle boundary. Mantle plumes are considered as representing another mode of mantle convection (e.g., Davies & Richards 1992). In brief, the current view is

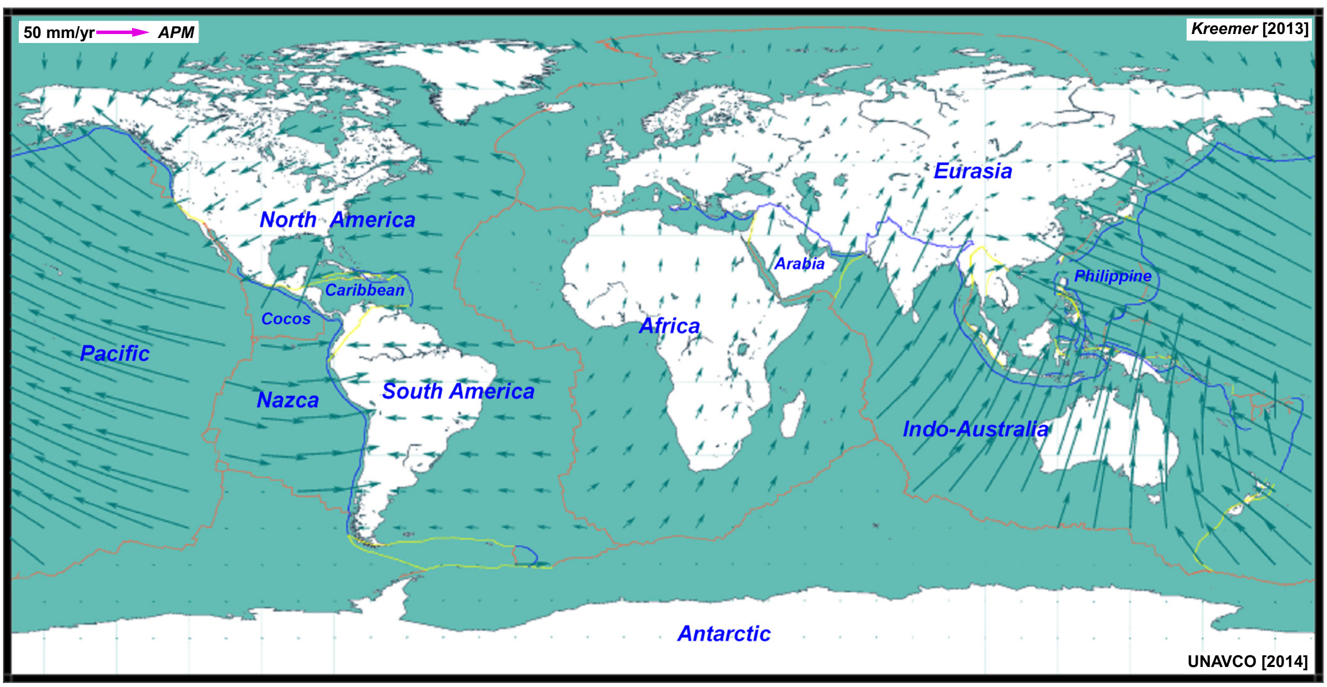

Fig. 1. World map contrasting oceans (ocean blue) and continents (white), also showing (1) the 12 "rigid" plates of varying size and nature as labeled (oceanic plates, continental plates and ocean+continent plates) (e.g., Forsyth & Uyeda 1975); (2) plate boundaries: divergent (brown; ocean ridges, back-arc spreading centers), convergent (blue; subduction zones indicated by trenches and continental collision zones), large transforms (yellow); and (3) the present-day plate motion vectors using the "sub-asthenosphere" reference frame (APM; from UNAVCO:http://jules.unavco.org/Voyager/GEM_GSRM). Note that both relative and "absolute" plate motion vectors depend on model references chosen. Also note (1) that the northern and western Pacific has well-developed back-arc basins, yet the eastern Pacific is characterized by active continental margins with oceanic lithosphere subducting beneath continents (except for the segment separated by the San Andreas transform in north America) without back-arc basins; and (2) that the Indo-Australian is a single giant ocean-continent plate in terms of the rigid plate concept.

that plate tectonics cools the mantle whereas mantle plumes cool the Earth's core. In other words, cooling of the mantle leads to plate tectonics while cooling of the core is responsible for mantle plumes. The plate tectonics theory and mantle plume concept thus complement each other to explain much of the whole picture of Earth processes and phenomena.

The above statements represent the mainstream view of global tectonics. The plate tectonics is well expressed by the plate motion and plate boundary zone processes, and has been repeatedly tested and proven to be a mature theory although the potentials of this theory remain to be further explored (see below). On the other hand, despite some persuasive arguments in favor of mantle plume derivation from deep mantle thermal boundary layers like the core-mantle boundary (e.g., Campbell & Griffiths 1990; Davies 1999, 2005) and its convenience to explain the origin of large igneous provinces (LIPs) since the late Paleozoic (e.g., Coffin & Eldholm 1994; Condie 2001; Courtillot et al. 1996), mantle plumes cannot yet be detected with confidence (e.g., Julian 2005). This difficulty, the confusing usage of "mantle plumes" and numerous alternative explanations for within-plate magmatism altogether have led to the great debate on whether mantle plumes exist or not (e.g., Niu 2005a). This great mantle plume debate (GPD) is currently rather heated (e.g., Davies 2005; Foulger 2005, 2010; Foulger et al. 2005; Campbell & Davies 2006), and is perhaps one of the greatest in the history of the solid Earth Science. Hence, the mantle plume concept is not yet a mature theory, but a hypothesis that remains to be tested. How to effectively test this hypothesis has been and will continue to be a challenge.

3. The origin of plate tectonics and driving force

When and how plate tectonics began on Earth has always been an intriguing question that remains unanswered (see Stern 2007). The fact that the plate tectonics only exists on planet Earth in the solar system suggests the possible connection with water (Niu et al. 2003), but the nature of such connection is unknown. Bercovici (1998) proposed that water may act as a lubricant, facilitating plate-like sheeted flow. I personally propose that bodies of water (e.g., oceans), not just water in other forms, are probably the primary cause of plate tectonics. This is because water has the highest heat capacity and oceans (whatever the proto-form maybe) must have acted as a uniform heat sink to cool the mantle, facilitating the development of "cold" and "dense" oceanic plates with the potential to subduct. In addition, water as an effective weakening agent can also facilitate subduction initiation (e.g., breaking prior plates), and as a lubricant can ease subduction (Niu et al. 2003). A continued effort is needed towards a genuine understanding of the origin of plate tectonics.

At present, one of our major interests concerns the driving force for plate motion in particular and plate tectonics in general. It is worth to note that over the ~50 year period of the early 20th century, sufficient evidence existed in support of the continental drift hypothesis (Wegener 1912), yet this hypothesis was unaccepted because of lacking driving mechanisms. Considering the radiogenic heat released by radioactive decays of Earth material deep in the mantle, Holmes (1931) was the first to propose the concept of [thermal] mantle convection as the driving force for continental drift. This mantle convection concept has been appearing in many geology textbooks since then, but hardly treated seriously. It is interesting to note that when the plate tectonics theory gained wide acceptance in the late 1960s, what may actually drive seafloor spreading and continental drift remained unknown.

In search of the driving force for plate motion, Forsyth & Uyeda (1975) recognized that the velocity of plate motion is independent of the size, circumference and ridge length of a plate (Fig. 2a–c), but shows a marked correlation with the trench portion of the circumference of a plate (Fig. 2d). This indicates for the first time that *Slab Pull* due to gravity into subduction zone is the primary driving force for plate motion. *Ridge push* is not negligible, but is one order of magnitude less than *Slab pull*. This is later confirmed by the results of the giant World Stress Map Project (Zoback et al. 1989; Zoback 1992). An important implication is that plate motions are driven by plates themselves without the need of an internal force such as "mantle convection" in a narrow sense. In a more logical and broad sense, the oceanic lithosphere (plates) formed at ocean ridges, its moving, accretion and ultimate subduction back into the mantle such as in the Pacific is both surface expression and actual driving force for mantle convection (see above). That is, the Pacific type oceanic lithosphere (plates) is an active and dynamic limb of the convecting mantle.

The above is ascribed to the sinking of the "cold" and "dense" oceanic lithosphere (plates) in subduction zones. In addition, experimental studies and seismology reveal two major phase transitions in the mantle at depths of 410 km and 660 km (or called 410-D and 660-D seismic velocity discontinuities), between which is called mantle transition zone, and across which the density of new mineral assemblage becomes denser with depth (Fig. 3). Relative to the 410-D of the ambient mantle, the cold subducting slab changes to denser mineral assemblage earlier at a shallower depth, gaining excess negative buoyancy, enhancing the *Slab Pull*, and thus facilitating the plate motion.

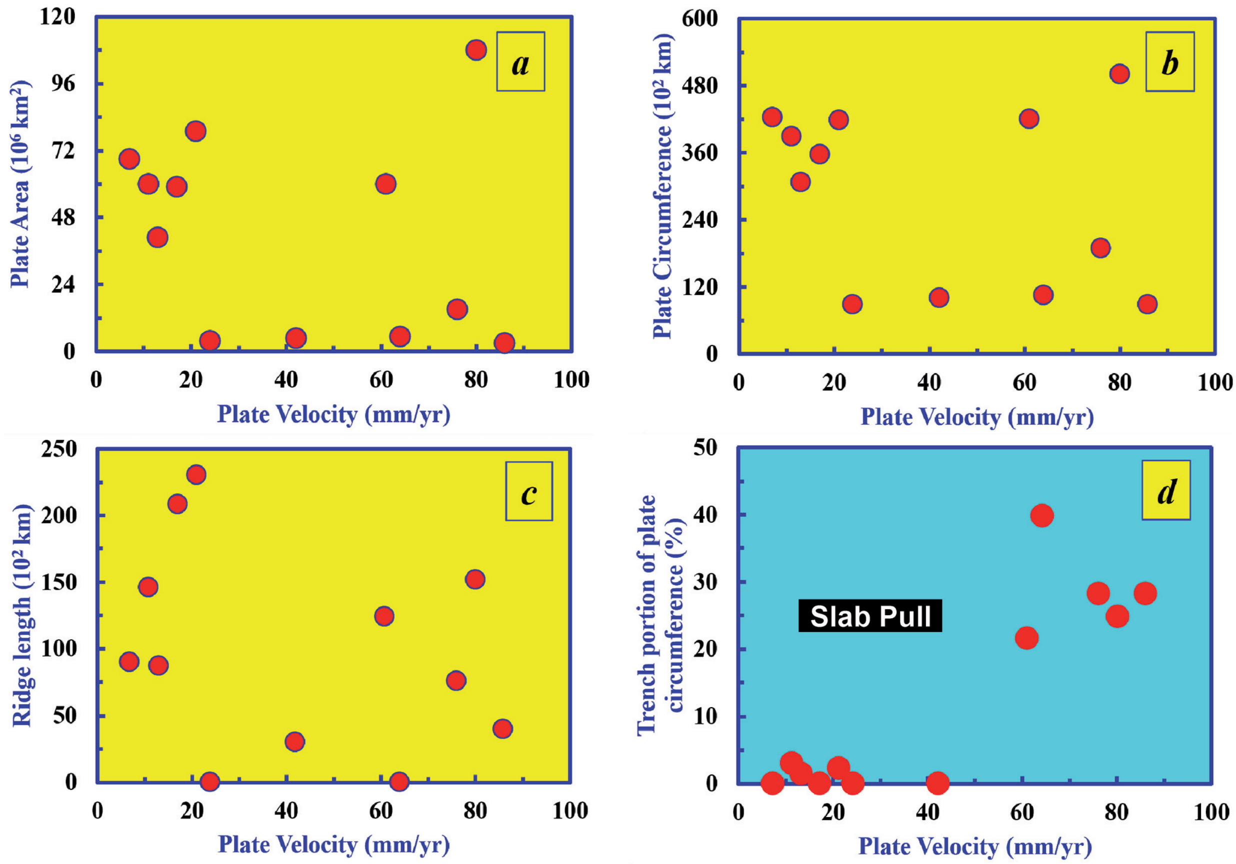

Fig. 2. In search of the driving force for plate motion, Forsyth and Uyeda (1975) recognized that the velocity of plate motion is independent of plate size (*a*), circumference (*b*) and ridge length (*c*), but is related to the trench portion of a plate circumference (*d*), suggesting that *Slab Pull* due to gravity is the primary force for plate motion. From left to right, the 12 data points are rigid plates of Eurasia (EU), North America (NA), South America (SA), Antarctica (AN), Africa (AF), Caribbean (CA), Arabia (AR), India-Australia (IA), Philippines (PH), Nazca (NZ), Pacific (PA) and Cocos (CO) as shown in Fig. 1.

Therefore, there would be no plate tectonics if there were no subduction zones (Niu et al. 2003). Ocean ridges are thus largely a passive feature (e.g., McKenzie & Bickle 1988; Davies & Richard 1992; Niu & O'Hara 2008). Hence, understanding the initiation of subduction zones is key to understanding plate tectonics. It should be noted however that such *Slab Pull* concept of plate driving force readily explains the Pacific type seafloor spreading connected to subduction zones but is *NOT* straightforward to explain the Atlantic type seafloor spreading and continental drift (see below).

4. The origin of subduction zones

Studies on subduction initiation have been many and continue to this day (e.g., McKenzie 1977; Karig 1982; Mueller & Phillips 1991; Toth & Gurnis 1998; Niu et al. 2003; Stern 2004; Gurnis et al. 2004; Stern et al. 2012; Shervais & Choi 2012; Marques et al. 2014). With all factors considered, the hypothesis of "subduction initiation as a consequence of lateral compositional buoyancy contrast within the lithosphere" (Niu et al. 2003) is physically straightforward, geologically consistent with observations, and is capable of making testable predictions. Figures 4 and 5 (modified from Niu et al. 2003) illustrate this concept using the compositional buoyancy contrast between an oceanic plateau lithosphere (OPL) and the normal oceanic lithosphere (NOL) as an example. The reason that $\rho_{OPL} < \rho_{NOL}$ is because the OPL may be produced as resulting from decompression melting of a "mantle plume" head – hot mantle with greater extent and volume of melting, producing thicker crust and thicker residual lithospheric root, both of which are less dense than the ambient lithosphere and the two together is less dense than the ambience as can be readily calculated (Niu &

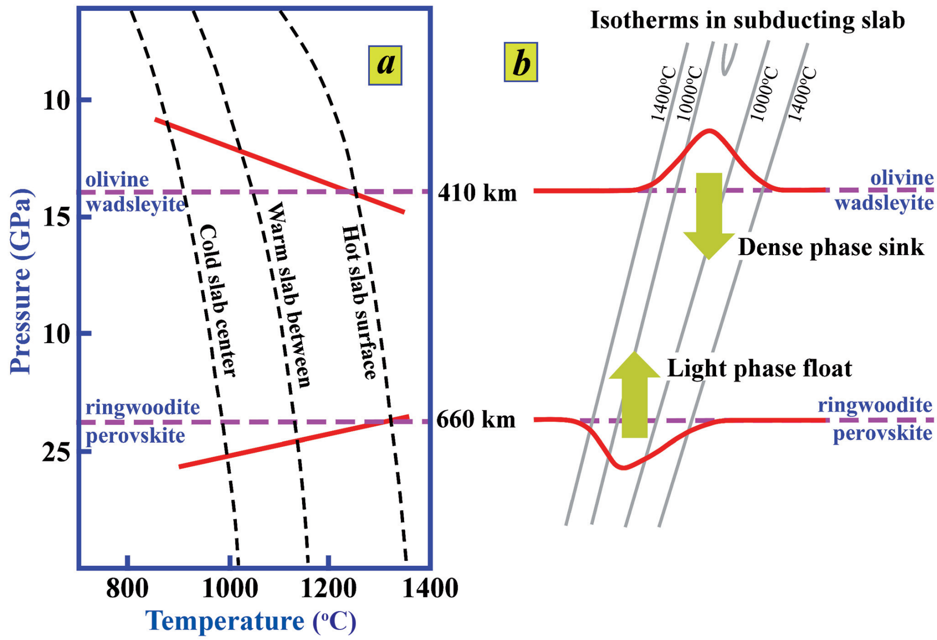

Fig. 3. a. Schematic phase diagram showing the two major phase transitions at depths of 410 km and 660 km, respectively, from low density phase (olivine < 410 km; ringwoodite < 660 km to high density phase (wadsleyite > 410 km; perovskite > 660 km). The positive Clapeyron slope of the 410 km phase transition makes the colder subducting slab change to denser phase at a shallower depth, whereas the negative Clapeyron slope of the 660 km phase transition makes the colder slab change to denser phase at a deeper depth (Ringwood 1991; Irifune & Ringwood 1993; Bina & Helffrich 1994; Agee 1998; Frost 1999). As a result, as shown in **b,** the density of the subducting slab at 410 km becomes denser than the ambient mantle, facilitating the slab to sink, promotes *Slab Pull*, and thus enhances the plate driving force. The cold subducting slab at 660 km, however, becomes less dense than the ambient mantle, inhibiting the slab to sink into the lower mantle.

Batiza 1991a, b) and as evidenced by the shallow depths of oceanic plateaus (see Niu et al. 2003). Figure 6a shows that the largest lateral compositional buoyancy contrast within the lithosphere is located at passive continental margins (i.e., $\rho_{CL\ (CC+CLM)} < \rho_{AS} < \rho_{OL}$) because the sub-continental lithosphere is compositionally more depleted and physically more buoyant than the oceanic lithospheric mantle and because continental crust is least dense among all lithologies of interest (Fig. 6).

It is conceptually important to note that it is physically unlikely to develop subduction within the normal oceanic lithosphere because of lacking significant compositional buoyancy contrast. In normal ocean basins, there is generally no location with large within-lithosphere thermal buoyancy contrast either that could favor subduction initiation. The Romanche transform in the equatorial Atlantic may be the only transform on Earth across which the ridge encounters old lithosphere of up to ~75 Ma. Here a large thermal buoyancy contrast may exist, but the lack of transform-perpendicular compression (i.e., equivalent to F_{RP} in Fig. 4) makes it unlikely to develop the required reverse faults (Fig. 4) for subduction initiation (Niu et al. 2003). Failed rifts/ridges, transforms and fracture zones have been proposed as possible sites of subduction initiation because these zones of weakness can be subsequently reactivated (e.g., Casey & Dewey 1984; Toth & Gurnis 1998; Gurnis et al. 2004), but again the lack of required compositional (and thermal) buoyancy contrast across these zones makes subduction initiation unlikely (Niu et al. 2003). This is because lithospheric materials on both sides of a ridge or transform should be broadly similar as they are produced by similar processes in similar environments. Hence, it is unlikely that compositional buoyancy contrast across these weak zones can develop throughout their evolution histories, thus no subduction initiation can take place within normal oceanic lithosphere.

In this context, it is noteworthy that subduction zones in the western Pacific have been considered as a category of subduction of oceanic lithosphere beneath another oceanic lithosphere (i.e., island arcs and back-arc basin oceanic lithosphere) as if the subduction began within the normal ocean basins. This perception is incorrect and at the time of subduction initiation the back-arc basin did not exist (see below). Therefore, the largest within-lithosphere compositional buoyancy contrast in ocean basins is located at the edges of oceanic plateaus (e.g., the On-

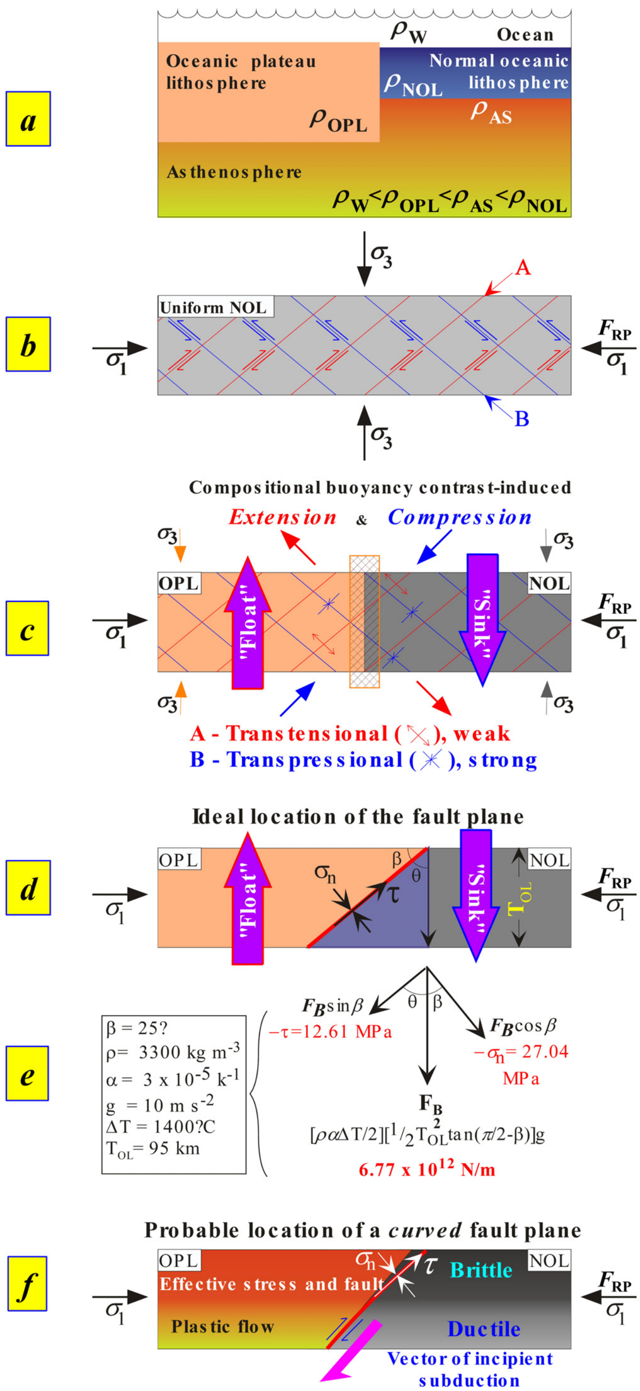

Fig. 4. a. The ocean-lithosphere-asthenosphere system illustrating "mean" density differences due to thermal or compositional differences, indicating the thick oceanic plateau lithosphere (OPL) to be less dense than the normal oceanic lithosphere (NOL). **b.** Two groups (A and B) of conjugate faults develop in the normal oceanic lithosphere as a result of ridge push (F_{RP}) or other lateral deviatoric compression. **c.** Compositional buoyancy contrast exists between the less dense oceanic plateau (OPL, which tends to "float") and dense normal oceanic lithosphere (NOL, which tends to "sink"). This buoyancy contrast makes Group A faults transtensional and Group B faults transpressional, thus leading to the development of a transtensional reverse fault along an A-fault plane at or near the lithological contact. **d.** Idealized geometry and location of the reverse fault plane for quantitative evaluation of the relevant forces and stresses associated with it. **e.** The physical consequences of the incipient sinking of the NOL are evaluated by considering the volume of the lithosphere of 1 m thickness defined by the triangular cross area beneath the fault plane. The parameters used are from Stein and Stein (1996). **f.** Schematic illustration showing that the reverse fault for subduction initiation may be developed on the NOL side owing to its weakness (vs. OPL, which is arguably stronger because of rapid within-plate emplacement) during its early history of development near ocean ridges where the lithosphere is highly faulted. This suggests that slivers of normal oceanic lithosphere as rare genuine ophiolites formed at ocean ridges could be incorporated in the fore-arc region during subduction initiation. Adapted from Niu et al. (2003).

tong Java Plateau in the Southwest Pacific, the Kerguelen Plateau in the Indian Ocean) as illustrated in Figure 4a. On a global scale, within a given lithosphere (or plate) the largest compositional buoyancy contrast is located at the passive continental margins (e.g., on both sides of the Atlantic and much of the Indian Ocean) as illustrated in Figure 6a (also see Fig. 1). Hence, passive continental margins (also edges of oceanic plateaus) are the ideal and necessary loci of future subduction zones (see Niu et al. 2003 for observational arguments). This model explains many aspects of the geological record as elegantly described by the Wilson cycle (Dewey & Bird 1970; Burke et al. 1976), and the fact that no ancient (> 200 Ma) ocean floor has survived from recycling (Niu et al. 2003). The Ryukyu subduction zone in the Northwest Pacific is the present-day example of subduction initiation at passive continental margins.

We can see from Figures 4d and e that at the onset of subduction initiation, the body force of the sinking plate (F_B) is important, and is inversely related to the dip angle (β) of the fault plane, i.e., $F_B \propto 1/\beta$. The smaller the β is, the greater the F_B will be, in favor of subduction initiation (i.e., towards left in Fig. 5a). This manifests that gravity is the ultimate force for subduction initiation and why $\beta < 90°$ in all subduction zones. As the subduction continues under gravity, the subducting slab tends to rotate vertically (i.e., β increases), sustaining subduction continuation (i.e., towards right in Fig. 5b), finally leading to *slab rollback* (see Fig. 7 and below).

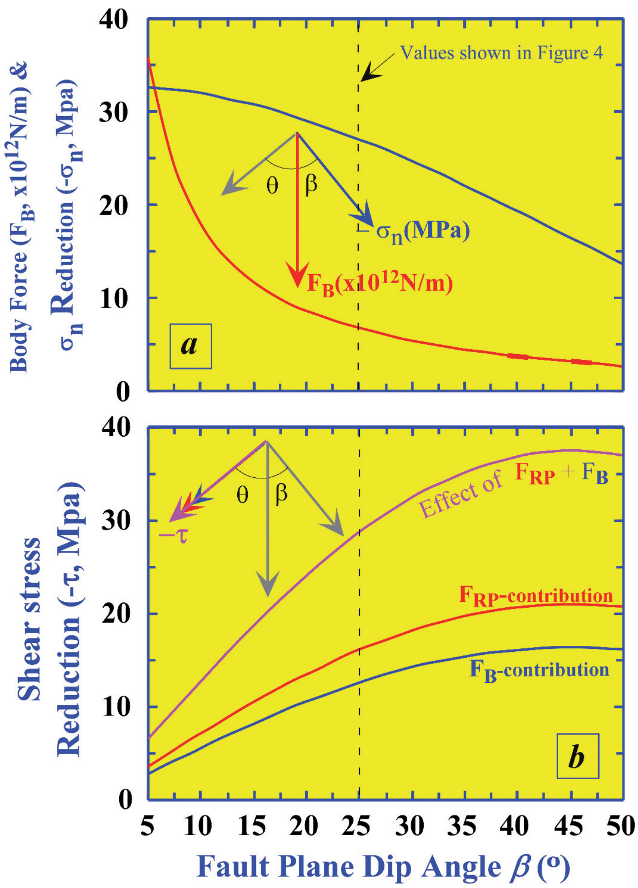

Fig. 5. Calculated forces and stresses as a function of the dip angle β of the fault plane across a plate of 95 km thick. **a.** Potential negative buoyancy forces (or body force; F_B) at all practical dip angles of 20-45° is similar to or significantly greater than ridge push forces (~4 x 10^{12} N/m), which by itself reduces normal stress by ~15 to 30 MPa, effectively "opening" the fault plane and creating resistance-free sliding. **b.** Both F_{RP} and F_B together reduce along-fault plane shear resistance by 25–37 MPa for realistic dip angles (20–45°). This shear-stress reduction is significantly greater than the shear strength of the oceanic lithosphere – only a few MPa (Kanamori & Anderson 1975; Wiens & Stein 1983) and is also greater than the assumed lithosphere shear strength of ~10–20 MPa (McKenzie 1977; Hynes 1982). It should be noted the shear-stress reduction would be > 50–70 MPa if only the upper elastic portion (~50 km) is considered, and would be still greater if the effect of water (weakening and lubrication effects) is included. Adapted from Niu et al. (2003).

5. Trench retreat and global geodynamic significance

5.1 Slab rollback

Figure 7 shows schematically that a young subducting slab has a shallow dip angle (e.g., β_{T1} at time T1), but the dip angle increases with time as the slab rotates (e.g., from time T1 to T2 and to T3) towards vertical under gravity. This is the very mechanism of the familiar concept of *slab rollback*. For conceptual clarity, I assume the overriding plate as being "fixed", but this is not the case in practice (see Fig. 8 below). To emphasize the concept, I assume the overriding plate to be continental plate/lithosphere.

5.2 Trench retreat and its geodynamic significance

Figure 8 illustrates the evolution of a subduction system from time T1 to T2 and to T3, during which the slab is rolling back as shown in Figure 7, but importantly the trench migrates seaward with time also because of the gravity as indicated by the dashed line. This is the concept of *trench retreat*. The importance of the trench retreat here is the induced *trench suction* force (Forsyth & Uyeda 1975) as illustrated by the inset in Figure 8, which sucks/drives the overriding continental plate/lithosphere to *passively follow* the retreating trench as indicated by the yellow arrows in Figure 8. I should emphasize that

- the passive migration of the overriding continental plate/lithosphere in response to trench retreat/suction is the very mechanism of *continental drift*, whose ultimate driving force is seafloor subduction;
- the principal lithospheric level (vs. within deep subduction zones) stress associated with active subduction is thus dominantly extensional, *not compressional*, although induced secondary compression can exist on small/local scales; and
- the overriding continental plate/lithosphere is under extension.

If the overriding plate is similar in nature to the South America Plate (i.e., the composite plate with both continental and oceanic portions "connected" by the passive continental margin), the eastward subduction of the Nazca Plate beneath the South America Plate will cause trench retreat to the west and the westward drift of the South America Plate (see Fig. 1). Because the weakest extensional stress is not within the South America Plate, but is concentrated at the southern mid-Atlantic Ridge (MAR), both the continental drift and seafloor spreading are thus different expressions of the same process. That is, the Nazca plate subduction-induced westward trench retreat/suction is followed passively by the westward migration

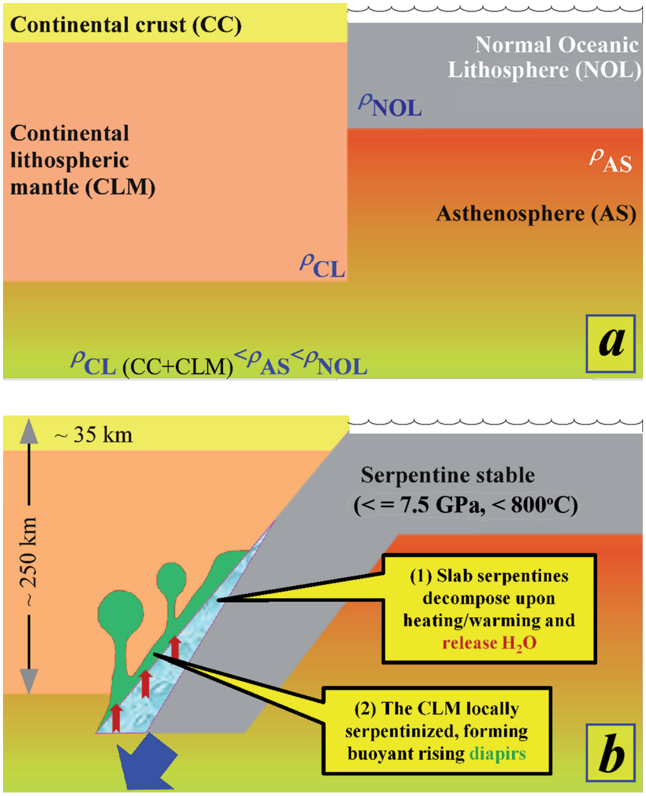

Fig. 6. a. A schematic illustration of density relationships of continental lithosphere (CL), normal oceanic lithosphere (NOL, without considering oceanic plateaus) and asthenosphere (AS). The relative mean densities are estimated to be ρ_{CL} (3.219 g/cc) < ρ_{AS} (3.297 g/cc) < ρ_{NOL} (3.306–3.324 g/cc) with the following assumptions: (1) a 250 km thick cratonic lithosphere with 35 km thick crust; (2) a 95 km thick oceanic lithosphere with 6 km thick crust; (2) room temperature mean density for continental crust ρ_{CC} = 2.800 g/cc, for continental lithospheric mantle ρ_{CLM} = 3.308 g/cc, for ocean crust ρ_{OC} = 3.000 g/cc (3.500 g/cc under eclogite facies during subduction), for oceanic lithospheric mantle ρ_{OLM} = 3.330, for asthenosphere ρ_{AS} = 3.330 g/cc; (3) mean temperature of 600 °C for both continental and oceanic lithosphere, 1200 °C for asthenosphere; (4) thermal expansion coefficient of 3×10^{-5}/K (see Niu et al. 2003). That is, under realistic conditions, ρ_{NOL}/ρ_{CL} = 1.027 to 1.033 (i.e., 2.7% to 3.3% denser), and ρ_{NOL}/ρ_{AS} = 1.003 to 1.008 (i.e., 0.3% to 0.7% denser), which are physically significant (see Niu and Batiza, 1991a,b). **b.** It is well known that the oceanic upper mantle lithosphere beneath the crust is highly serpentinized (Dick 1989; Niu & Hekinian 1997; Niu 2004). It is also known experimentally that serpentines can be stable up to 7.5 GPa at T ≤ 800 °C (Ulmer & Trommsdorff 1995; Williams & Hemley 2001; also see Fig. 14). Hence, it shows the possibility that serpentines of the subducting oceanic lithosphere beneath the thickened cratonic lithosphere can become unstable under heating/warming and thus decompose and lose the water into the overlaying continental lithospheric root, which can then cause serpentinization within it under the conditions of P ≤ 7.5 GPa and T ≤ 750 °C. The serpentines can form and rise as diapirs, carrying its ambient harzburgitic rock fragments and high pressure minerals like diamonds seen in some "supra-subduction ophiolites" including the Luobusha chromitite mine in southern Tibet (Bai et al. 1993; Robinson et al. 2004; Yang et al. 2007, 2014; Dobrzhinetskaya et al. 2009).

of the composite South America Plate: both the continental drift and Atlantic-type seafloor spreading being different expressions (continental vs. oceanic) of the same plate motion. In this sense and in concept, we can consider the Atlantic Ocean as a giant "back-arc basin" in its current state (see below) regardless of its origin (i.e., the cause or causes of the Atlantic opening in its histories).

If the overriding lithosphere is a weak composite plate with complex histories without a MAR-like zone of weakness such as the giant Eurasia Plate (Fig. 1), then the northwestward subduction of the Pacific Plate and the eastward retreat of the western Pacific subduction zones will result in the development of back-arc basins in the western Pacific (Fig. 1; also see below).

5.3. The development and growth of back-arc basins

With the continuation of seafloor subduction and trench retreat (Fig. 8; from Time T1 to T2 and T3), the overriding continental plate under extension will develop rifting and extensional basins on land, and some of these close to and behind the magmatic arc become "back-arc basins" with a spreading center (Fig. 9). The back-arc basin continues to grow with time from T1 to T2 and to T3. This indicates explicitly that the prior active continental margin (continental magmatic arc) becomes an "island arc". This leads to my hypothesis here that "*all the intra-oceanic island arcs must have split off continental margins (some off edges of oceanic plateaus)*". This hypothesis is testable by examining the material record of the island arc basement (Niu et al. 2003).

If the back-arc spreading cannot catch up with the trench retreat, the continental lithosphere along with the back-arc basin can migrate in response to the trench retreat/suction as indicated by the thick black arrow in Figure 9.

With continued trench retreat and open ocean basin shrinking (e.g., the Pacific at present), a back-arc basin can evolve to a large open ocean basin and the "island arc" or "island arc system" may become micro continents. All this is conceptually important in understanding the arc-continent evolution as well as the disintegration and amalgamation of supercontinents. For example, the for-

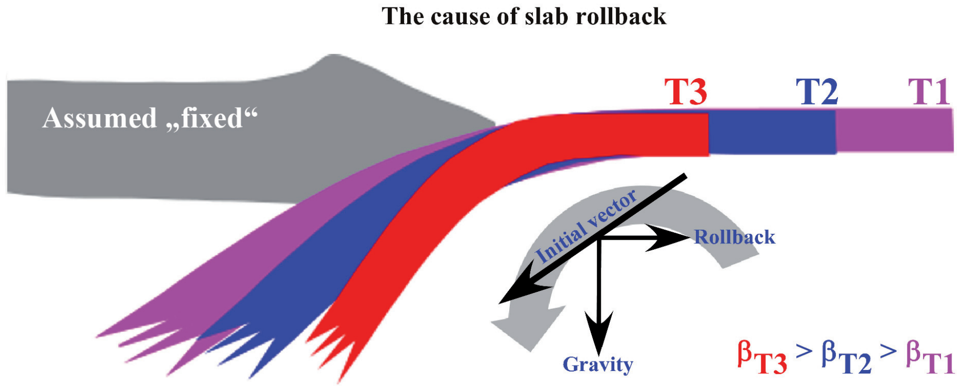

Fig. 7. Cartoon illustrating the cause of slab rollback. Figures 4e and 5a show that F_B is the principal force for subduction initiation and is inversely related to the dip angle (i.e., $F_B \propto -\beta$). That is, a smaller dip angle β (thus a larger triangular volume beneath the fault plane in Fig. 4d, and a greater F_B) favors subduction initiation. However, once subduction began, the slab tends to rotate vertically under gravity ($\beta_{T3} > \beta_{T2} > \beta_{T1}$). This is the concept of slab rollback. Note that the trench position is actually not fixed, but retreating under gravity (see Fig. 8).

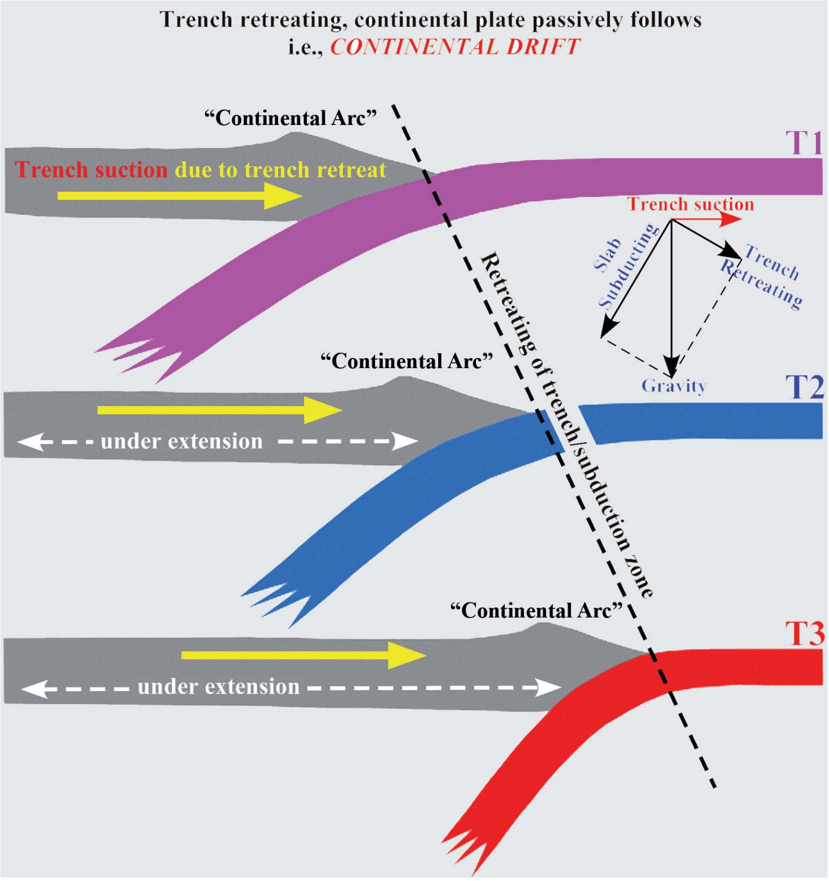

Fig. 8. Cartoon illustrating trench retreat and continental drift. Under gravity, slab will roll back (Fig. 7), and importantly, subduction zone will necessarily move seawards or retreat, which is often described as "trench retreating" because the trenches are surface expressions of subduction zones. The dashed line indicates the newer position of the trench/subduction zone with time: T1→ T2→ T3. Importantly, the overriding continental plate will passively follow the retreating trench, which may be termed as the result of *trench suction* (Forsyth & Uyeda 1975). That is, continental drift is a passive response to subduction. Also note that the drifting overriding continental plate is under extension.

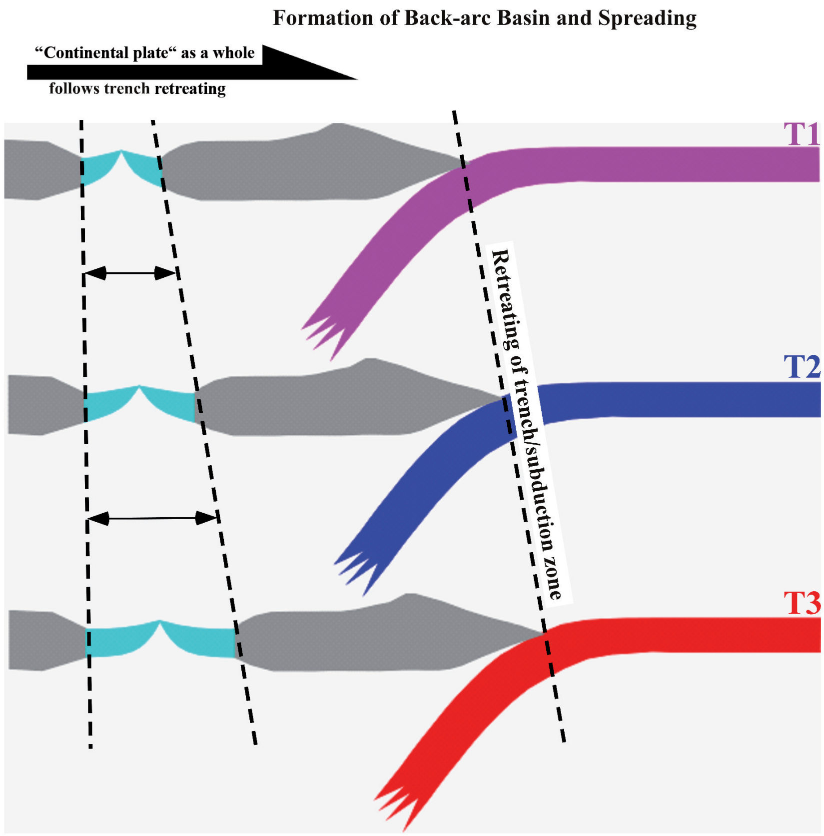

Fig. 9. Cartoon illustrating back-arc basin formation and growth. The drifting overriding continental plate that is under extension (Fig. 8) can develop within its interiors extensional basins on land and even back-arc basins with spreading centers. It is thus conceptually clear that the "Island Arc System" is simply split from the margin of the overriding continental plate. That is, the "Island arc system" must have its basement of continental origin. Also note that back-arc spreading centers can evolve to large open ocean basins and the "Island arc systems" can become micro continents.

mation history of the Greater Tibetan Plateau since the Paleozoic resulted from a sequential accretion of micro continents split off and drifted from Gondwana (Niu & O'Hara 2009; Niu et al. 2013; Zhu et al. 2013). In this context, it is necessary to consider correctly redefining Proto-, Paleo-, Meso- and Neo-Tethyan ocean basins in global tectonic reconstruction and in studying eastern Eurasian geological evolution.

5.4. The paleo-Pacific slab in the mantle transition-zone beneath eastern China: its origin and implication for continental drift

Karason & van der Hilst (2000) are the first to recognize many present-day subducting slabs that penetrate the seismic 660-D and enter the lower mantle (also see Li et al. 2008). However, the mantle tomographic sections across the southern Kurile island arc and Izu-Bonin island arc indicate that the paleo-Pacific slab did not pass through the 660-D, but lies horizontally in the mantle transition zone between 410-D and 660-D, extending far to the west beneath eastern China. This is confirmed by more recent studies (Fig. 10; Zhao & Ohtani 2009; Li et al. 2008). It is obvious in Figure 3 that relative to the normal mantle 660-D phase transition, the cold subducting slab shows delayed phase transformation until reaching a greater depth, thus resulting in local buoyancy and inhibiting slab penetration into the lower mantle. The penetration becomes possible only when its temperature approaches that of the ambience, which requires adequate time. This means that failure of slab penetration across the 660-D is physically "normal" and expected so long as there is any sort of preventing factor. Fast trench retreat is such a factor (see below).

Some would consider the transition-zone slab of the paleo-Pacific plate beneath eastern China (Fig. 10) resulted from westward *flat subduction*. This interpretation is simply *wrong* because there is no driving force for "flat

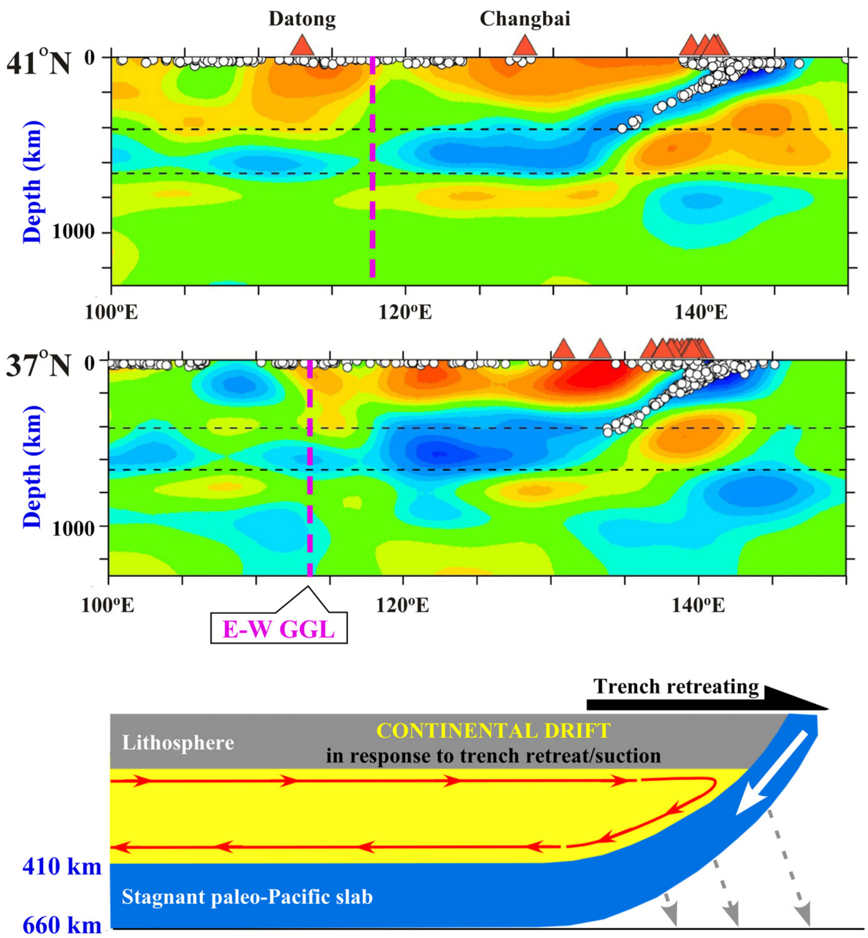

Fig. 10. Top, western Pacific-eastern China mantle seismic tomography across two sections at the latitude of 41°N and 37°N, showing the paleo-Pacific slab lying horizontally in the mantle transition zone between the 410 km and 660 km seismic discontinuities (after Zhao & Ohtani 2009). The pink dashed lines indicate the position of the East-West great gradient line (GGL) as shown in Figure 11, which is also termed North-South gravity lineament (NSGL; Xu 2007). Bottom, cartoon to emphasize that contrary to the popular interpretation, the transition-zone paleo-Pacific lab is NOT because of horizontal or flat subduction (no driving force, and thus unlikely) but simply because of passive stagnation as the result of trench/subduction retreating. The stagnant slab will not move, and can be used as a reference to evaluate the actual magnitude of continental drift of the eastern Eurasia plate towards east.

subduction", not possible and unlikely. In fact, its origin is a straightforward consequence of fast trench retreat of the western Pacific subduction zones as illustrated in the bottom panel of Figure 10. These slabs or slab fragments stay stagnant, do not move and cannot move without driving force. On the contrary, what can move and has actually been moving is the "continental drift" of the overriding Eurasia Plate, especially the eastward drift of continental China (Fig. 11) in response to trench retreat/suction of the western Pacific subduction zones, at least since the Cenozoic. Whether the subducting slab can or cannot penetrate the 660-D depends on the speed of trench retreat. Fast retreat does not allow adequate time for slab thermal equilibration with the ambience, and thus the buoyancy prevents the slab penetration as in the case of the western Pacific (Figs. 3, 11). If the retreat is slow, the subducting slab readily reaches thermal equilibrium and thus passes through the 660-D and enters the lower mantle as in most cases (see Li et al. 2008), including the seismically detected Farallon plate "subducting" beneath American plates throughout much of the whole mantle (van der Hilst et al. 1997). An important case is the Tonga-Kermadec trench retreat in the southwest Pacific, whose retreat speed increases from south to north over the last ~20 Myrs, leaving a transition-zone slab (horizontal) stagnation beneath Tonga in the north, but the slab passes straight

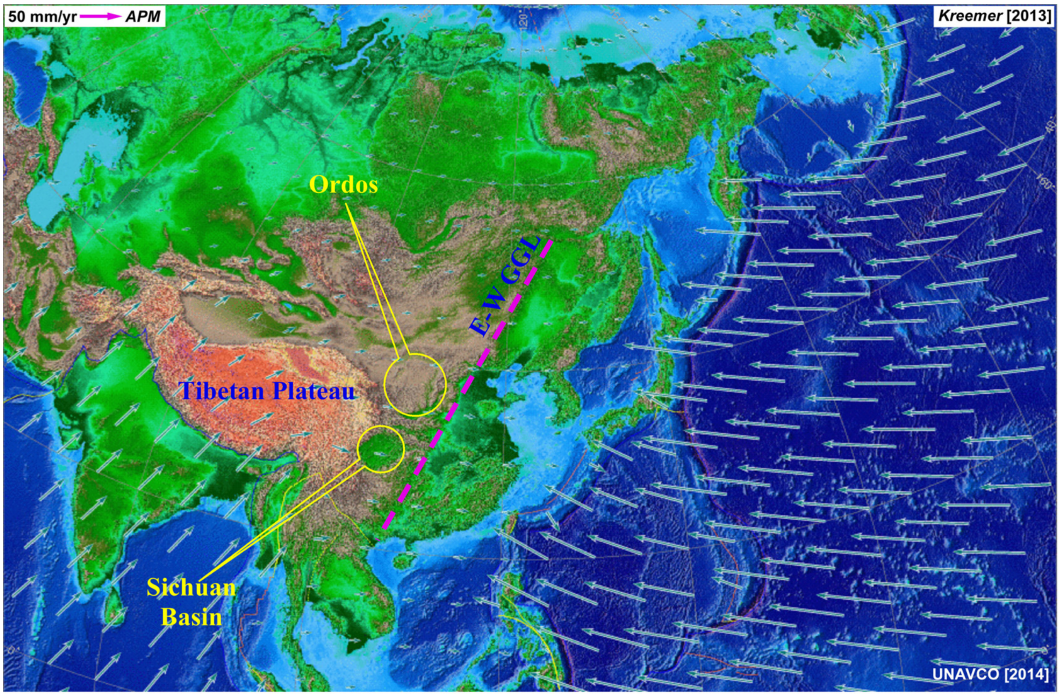

Fig. 11. Portion of the world topographic map emphasizing eastern Asia and western Pacific region with trenches and back-arc basins. Also shown are vectors of plate motion. The southeastward drift of the Chinese continent is the passive response to the trench retreat (see Figs. 8 and 9) of the western Pacific subduction zones. The origins and histories of northern and western Pacific back-arc basins are likely complex, but the mechanism can be readily explained by trench retreat and induced continental drift under internal extension. The pink dashed line is the great gradient line (GGL) marked by contrasting differences in elevation, gravity anomaly, crustal thickness and mantle seismic velocity from high plateaus in the west to hilly plains of eastern China, which is interpreted as the expression of variation in lithospheric thickness from ≥ 150 km thick beneath the plateaus in the west to ≤ 80 km thick beneath eastern China (Niu 2005b; also see Fig. 10). The Ordos Block and Sichuan Basin west of the GGL are considered the remnant cores of the NCC and Yangtze craton least affected by the lithospheric thinning. Generated from UNAVCO as in Figure 1 (http://jules.unavco.org/Voyager/GEM_GSRM).

through the 660-D and enters the lower mantle beneath Kermadec in the south (van der Hilst 1995).

It should be noted that the mantle transition-zone horizontal slab beneath eastern China is part of the same present-day western Pacific plate (connected; Fig. 10). The present-day western Pacific subduction began ~50 Ma and certainly < 60 Ma (Moberly 1972; Taylor 1993). If the E-W GGL (Figs. 10, 11) marks the western end of the transition-zone slab, then relative to the stagnant transition-zone slab, the Eurasia continent, especially much of the continental China, must have drifted eastwards for 2000–2500 km in the Cenozoic. This is an important novel understanding. Figure 11 shows that the present-day eastward drift speed of continental China is slow on the basis of "sub-asthenosphere" reference frame model (APM), but is actually as fast as 40-50 mm/yr with respect to the transition-zone stagnant slab.

5.5. Geodynamic significance of the mantle transition-zone slab beneath eastern China

The Paleozoic diamondiferous kimberlite volcanism in northern east China is consistent with the long-held view that there existed a North China Craton (NCC) that is one of the oldest in the world with a long history in excess of 3.8 Ga (Liu et al. 1992). However, many consider that the NCC is not a typical craton because of its widespread tectonomagmatic activities since the Mesozoic (Wong 1929; Chen 1960; Deng 1988; Menzies et al. 1993). It is widely accepted that these activities are associated with the removal of the lithospheric root or lithosphere thinning (e.g., Deng et al. 1998, 2004, 2007; Griffin et al. 1998; Fan et al. 2000; Xu 2001; Gao et al. 1998, 2002, 2004; Menzies et al. 2007; Zhu et al. 2012) by means of delamination (e.g., Deng et al. 1998, 2007; Gao et al. 2002, 2004; Liu et al. 2008), thermal and chemical erosion (Menzies et al. 1993; Deng et al. 1998; Griffin et al. 1998; Xu 2001; Zhang et al. 2012), and basal hydration weakening that physically converts the base of the mantle lithosphere into asthenosphere (Niu 2005b, 2006).

Here we explore the concept of "basal hydration weakening as a primary cause of the lithosphere thinning beneath eastern China (not just NCC)" proposed by Niu (2005b, 2006). It is my personal view that the lithosphere thinning of eastern China since the Mesozoic is a special consequence of plate tectonics because it is genetically associated with the paleo-Pacific plate and its subduction.

5.5.1. The concept of basal hydration weakening – the very cause of the lithosphere thinning

Figure 12 illustrates the concept of basal hydration weakening by converting the lower portion of the prior lithosphere into asthenosphere in terms of physical properties. Figure 13 further demonstrates that under the upper mantle conditions, addition of very small amount of water, say ~100 ppm, can effectively lower the viscosity by 2–3 orders of magnitude (from > 10^{21} Pa s to ~10^{19} Pa s), thus changing the physical property from "lithospheric" to "asthenospheric", thereby accomplishing the thinning of the lithosphere. The water (more likely hydrous melt) comes from the paleo-Pacific slab lying horizontally in the mantle transition zone beneath eastern China (Fig. 10). This slab is predicted to be a water-rich reservoir because subduction-zone dehydration is incomplete (Niu 2004, 2005b). Studies of subduction-zone metamorphic rocks of ocean crust (also terrigenous sediments) protoliths indicate that subduction-zone dehydration is necessarily incomplete (Xiao et al. 2012, 2013, 2014). Importantly, water transported deep into the mantle through serpentinized peridotites within subducting/subducted slabs is likely even more significant (Niu 2005b) because serpentines contain up to 13 wt % H_2O, and is stable up to 7.5 GPa (Ulmer and Trommsdorff, 1995) before transformed to dense hydrous magnesium silicate phases (DHMS: A, B, D-F-G and G) at greater pressures (see Fig. 14 and the caption).

5.5.2. The concept of basal hydration weakening – An alternative perspective

Figure 15 shows that in a global context, the upper mantle depth range of 100–150 km beneath eastern China is characterized by the property of seismic low velocity, resembling the seismic low velocity zone (LVZ) beneath young oceanic lithosphere. We can thus state that the process leading to the lithosphere thinning beneath eastern China is the process of LVZ formation. That is, formation of the LVZ in the upper mantle beneath eastern China converted basal portion of the prior lithosphere into the LVZ. The question is why the LVZ could have formed here? The answer is straightforward: introduction of water and the water comes from dehydration (hydrous melt) of the paleo-Pacific slab lying horizontally in the mantle transi-

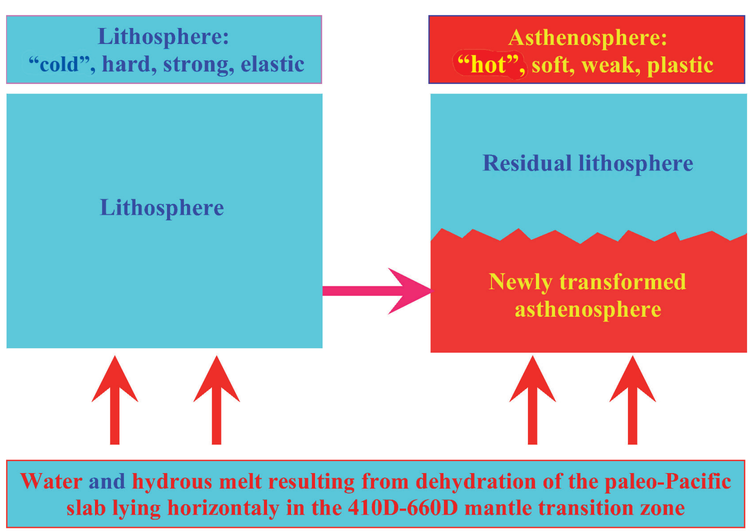

Fig. 12. Illustration of the concept of basal hydration-weakening as an effective mechanism to have caused the lithosphere thinning beneath eastern China (Niu 2005b, 2006). The basic physical difference between the lithosphere and asthenosphere lies in the physical properties as indicated. Water and hydrous melt derived from dehydration of the paleo-Pacific slab in the transition zone (Fig. 10) will convert the basal portion of the lithosphere into asthenosphere, accomplishing the lithosphere thinning.

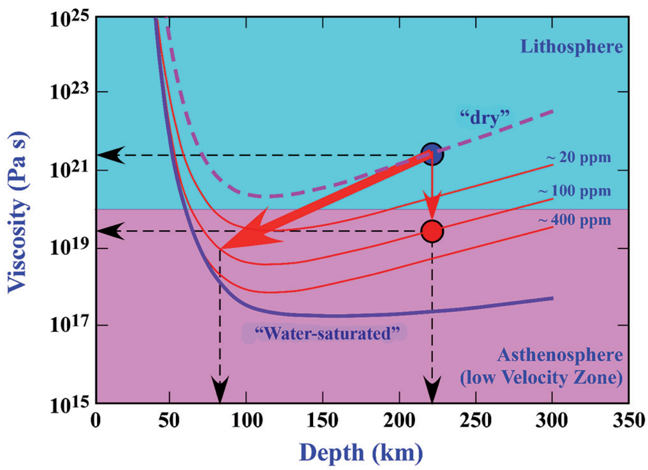

Fig. 13. Experimental data showing the effect of water content on the upper mantle peridotite viscosity (after Karato 2003). The upper light blue portion lies in the "rigid" range of lithospheric viscosity (> 10^{20} Pa s), and the lower purple portion lies in the "plastic" range of asthenospheric viscosity (< 10^{20} Pa s). The seismic low velocity zone (LVZ) has the viscosity of ≤ 10^{19} Pa s (Hirth & Kohlstedt 1996; Karato 2003). Assuming the North China Craton in eastern China was ~220 km thick (e.g., Xu 2001) and relatively dry with a viscosity of ~3 × 10^{21} Pa s (e.g., the blue solid circle) prior to the thinning, addition of small amount of water (e.g., 100 ppm, dissolved in the nominally anhydrous minerals like olivine) will reduce the bulk viscosity of the mantle lithosphere by two orders of magnitude, ~3 x 10^{19} Pa s (red solid circle), giving it the asthenosphere/LVZ property, i.e., the "rigid" basal portion of the mantle lithosphere has been thinned with the upper ~80 km left at present. In fact, the paleo-Pacific slab in the mantle transition beneath eastern China can provide more than needed water (Niu 2005b, 2006).

tion zone (Fig. 10; Niu 2005b, 2006). Because subduction-zone dehydration is incomplete, the transition zone paleo-Pacific slab will experience isobaric heating with time to change from water rich phases to water poor phases (Fig. 14), releasing water (Niu 2005b).

In brief, the transition zone paleo-Pacific slab beneath eastern China is the source of water for the formation of the LVZ. This makes the concept explicitly clear that "basal hydration (physically H_2O-CO_2- rich silicate melt) weakens the base of the prior lithosphere, converts it to the LVZ in terms of physical properties with low viscosity and reduced bulk modulus and shear modulus. This concept explains all the observations in simple clarity and is far superior to other models (e.g., delamination and thermal/chemical erosion without physically plausible mechanism) proposed to explain the lithosphere thinning beneath eastern China in general and beneath the NCC in particular (Niu 2005b, 2006).

5.5.3. Caveat and new revelation

The hypothesis of basal hydration weakening is conceptually clear, logically sound and physically plausible in explaining, in simple clarity, the lithosphere thinning beneath eastern China as a special consequence of plate tectonics. However, there is a caveat. The present-day western Pacific subduction began 50–60 Ma (Moberly 1972; Taylor 1993), but the lithosphere thinning beneath eastern China took place largely in the Mesozoic (e.g. Zhu et al. 2012) and was probably completed before ~110 Ma (Liu et al. 2008; Yang & Li 2008; Meng et al. 2014). Therefore, the transition-zone slab beneath eastern China seen seismically today is of Cenozoic subduction and is not the cause of the major lithosphere thinning event in the Mesozoic. However, the present-day mantle transition-zone slab provides the needed water, maintaining the already formed LVZ and thus the already thinned lithosphere state.

Because the lithosphere-asthenosphere boundary (LAB) is a petrological boundary (Green et al. 2010; Niu et al. 2011; Niu & Green 2014), i.e., representing the pargasite (amphibole) dehydration solidus:

Pargasite-bearing peridotite [lithosphere] ⇔ peridotite + melt [asthenosphere]

Hence, the stability of the lithosphere is the stability of the pargasite amphibole, i.e., P ≤ 3GPa, T ≤ 1100°C. The presence of mantle transition-zone slab with water implies that the LVZ will not disappear, and the eastern China lithosphere will not thicken. With the presence of water, the lithosphere cannot be thicker than P = 3GPa in terms of pressure equivalence. Given the low density of the crust, the depth equivalent to 3GPa is ~100 km. The observation that the lithosphere thickness beneath eastern China is not uniform and is in many places < 80 km (Chen et al. 2009) indicates that the rate of thinning is greater than the rate of thickening (due to conductive cooling). That is, the lithosphere remains at the state of "net thinning". This is an important revelation.

5.5.4. A Mesozoic Pacific slab may exist in the mantle transition-zone beneath eastern China

The current consensus is that the major lithosphere thinning beneath eastern China took place in the Mesozoic (e.g., Zhu et al. 2012). The geochemical difference of NCC basalts erupted before 110 Ma (e.g., with a Nb-Ta depleted "crustal" or "arc" signature) and after 110 Ma (e.g., with an enriched "OIB" signature) (Liu et al. 2008; Yang & Li 2008) suggests that the NCC lithosphere thinning must have been largely completed by ~110 Ma (Meng et al. 2014), probably related to dehydration proc-

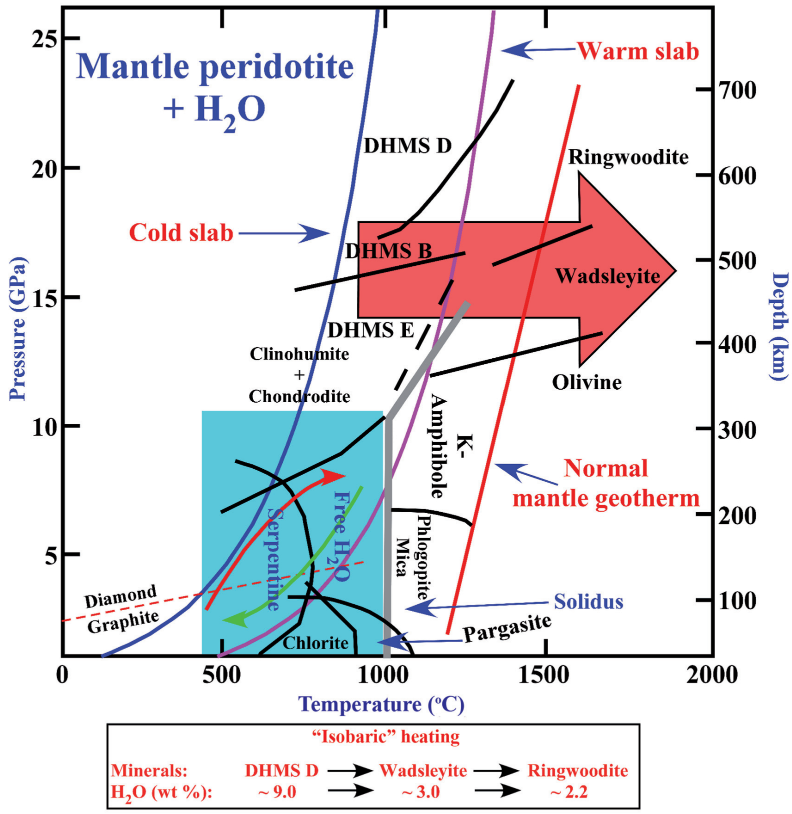

Fig. 14. Phase diagram of mantle peridotite to show mineral phases and their stability in the subducting/subducted oceanic lithospheric mantle under upper mantle conditions (after Williams & Hemley 2001). Prior to subduction, the oceanic lithospheric mantle has experienced considerable serpentinization, including near-ridge shallow (< 20km) hydrothermal metamorphism (Dick 1989; Niu & Hekinian 1997; Niu 1997, 2004) and serpentinization at depths (~50 km) caused by seawater penetration through extensional faults at trench outer-rise (Ranero et al. 2003; Dobson et al. 2002; Kerrick 2002), and thus contain abundant water (up to 13wt% in serpentine phases). Considering the thermal structure of the subducting slab, subduction-dehydration is necessarily incomplete (Niu 2004, 2005b). Antigorite serpentines is experimentally shown to be stable under P ≤ 7.5 GPa and T ≤ 800°C (Ulmer & Trommsdorff 1995) in the subducting slab, and can transform under higher pressures into dense hydrous magnesium silicate phases (DHMS: A, B, D-F-G and G) stable over a greater pressure range (~5 to 50 GPa; Frost 1999; Williams & Hemley 2001) with abundant water (~3 to 20 wt.%) that can be transported to the deep mantle (Kuroda & Irifune 1998). As indicated by the thick pink arrow and explanation in the bottom panel, the transition zone slab will undergo isobaric heating with time and release water (most likely in the form of hydrous melt) by changing into progressively water-poor mineral phases. The water (hydrous melt) so released will rise and percolate through the upper mantle to facilitate the formation and maintenance of the LVZ (see Fig. 15 below), which is in fact the process of lithosphere thinning and related magmatism.
The light blue region is highlighted to show the stability and significance of antigorite serpentine to explain the processes illustrated in Figure 6b. The brown arrowed line indicates the path of subducting slab with serpentines that becomes unstable when crossing the phase boundary to form "olivine + clinoenstatite" plus free water. The water so released will rise (the light green arrowed line) and percolate through the overriding cratonic lithosphere root, causing serpentinization. The serpentines formed in the overriding cratonic lithosphere may rise as diapirs as indicated in Figure 6b. It is possible and likely that such serpentine diapirs can carry up high pressure mineral phases (e.g., diamond) as observed in some "ophiolites" (e.g., Yang et al. 2007, 2014). Note the graphite-diamond phase boundary at the lower left corner of the diagram.

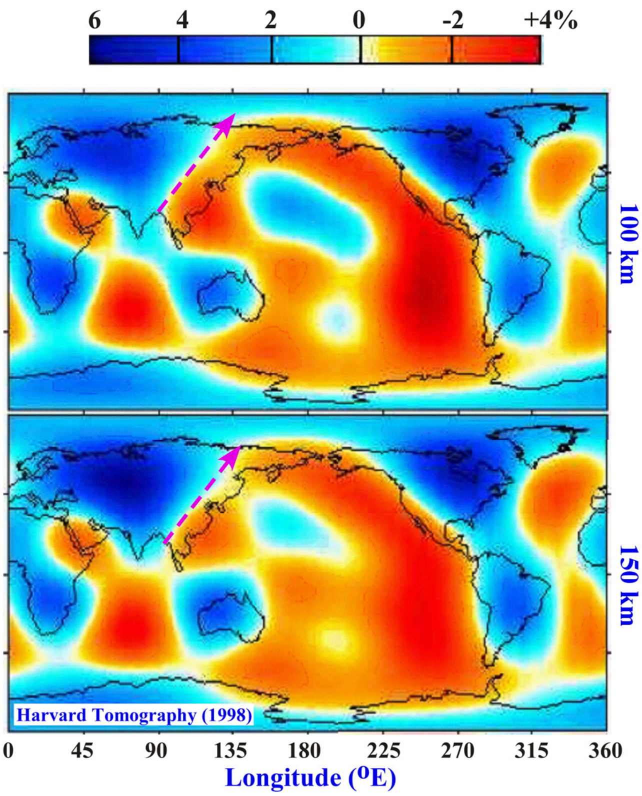

Fig. 15. The global mantle seismic tomography at depths of 100 km and 150 km (Ekström & Dziewonski 1998) to show that the seismic velocity anomalies beneath eastern China coincides with the NNE-SSW Great Gradient Line (blue lines with arrows; see Figs. 10 and 11). The key information is that the upper mantle seismic structure beneath the entire eastern China resembles that of younger oceanic upper mantle with a seismic low velocity zone (LVZ) beneath the lithosphere (Niu 2005b, 2011).

esses of a mantle transition-zone slab in the Mesozoic (Niu 2005b; Windley et al. 2010). Zhai et al. (2007) and Windley et al. (2010) gave an excellent account of the tectonic framework of the NCC in the Mesozoic, all illustrating the significance of the northwestward subduction of the paleo-Pacific plate beneath continental China. In fact, the widespread Mesozoic Yanshannian granitoids in eastern China (from Northeast China to North China and to Southeast China) are indirect but convincing evidence for the presence of paleo-Pacific plate subduction beneath continental China (e.g., Wan 2010; Zhou et al. 2006). That is, the Mesozoic eastern China was characterized by an active continental margin, similar to the Andean-type margin with a continental magmatic "arc" (Zhou & Li 2000; Li et al. 2012).

Zhang (2010), however, questioned the "Andean-type margin" hypothesis for eastern China because the distribution of the Mesozoic granitoids in eastern China is not confined in a narrow zone as would be expected, but rather spreads diffusively and widely in a zone in excess of 1000 km across (areal vs. linear distribution). This argument is useful here because eastern China was indeed an active continental margin, but not a typical Andean-type. I personally consider that the diffusely and areally-distributed Mesozoic granitoids reflect areally-distributed sources ultimately determined by the "areal distribution" of the subducted paleo-Pacific slab in the mantle transition zone. In other words, the areal (vs. narrow zone) distribution of the Mesozoic granitoids in eastern China resulted from crustal melting caused by under-plating of mantle-derived basaltic melts that provide needed heat, whereas the basaltic melts were most likely derived from transition-zone slab dehydration induced mantle melting (lithospheric and asthenospheric). Hence, the areal distribution of the Mesozoic granitoids in eastern China without a perfectly-defined NW-to-SE age descending (Zhou et al. 2006; Li et al. 2007), in fact, favors the "basal hydration weakening" hypothesis.

Windley et al. (2010) agreed with Niu (2005b) that basal hydration weakening is the most likely cause of the lithosphere thinning beneath the NCC and that the water came from transition-zone slabs of seafloor subduction. However, these authors emphasized that the mantle-transition zone beneath the NCC should have slabs with abundant water of multiple subduction zones, namely, southward subduction of the paleo-Asian Ocean seafloor before the collision of the Siberia/Mongolian block with the NCC, northward subduction of the paleo-Tethyan Ocean seafloor before the collision of the South China block with the NCC as well as the northwestward subduction of the paleo-Pacific seafloor. This analysis is useful for tectonic evolution. However, the basic condition for slab dehydration is its stagnation in the transition zone as a result of trench retreat (Fig. 10). In the Mesozoic, the western Pacific subduction zones would retreat, leaving subducted slab behind in the mantle transition zone, releasing water (Fig. 14), contributing to the formation of the LVZ and lithosphere thinning beneath eastern China (Figs. 12–15). Without trench retreat, there would be no slab stagnation in the transition zone, no water release, no basal hydration weakening and no lithosphere thinning. This is because subducting/subducted slabs entering the lower mantle will experience phase change to mineral assemblage dominated by perovskite (Fig. 3), which behaves like sponge and acts like "water reservoir" (e.g., Litasov et al. 2003), and thus will not release water.

The paleo-Asian Ocean was closing and closed upon Mongolia-NCC collision without trench retreating; the paleo-Tethyan ocean was also closing and closed upon South China-NCC collision without trench retreating (Windley et al. 2010). In fact, the paleo-Asian Ocean floor slabs had not stagnated in the mantle transition zone, but entered the lower mantle (van der Voo et al. 1999). We can predict that the paleo-Tethyan slabs must have entered the lower mantle without trench retreat. Hence, only the paleo-Pacific subduction zones experienced seaward migration (retreat) without ocean closing and continental collision; I hypothesize that the Mesozoic lithosphere thinning beneath eastern China must have a genetic connection only with the paleo-Pacific subduction.

6. Efficacies of the plate tectonics theory and its further development

The major assumption built in the theory of plate tectonics is that the plates are rigid and there are 12 such rigid plates (Fig. 1) that do not deform internally, but can move relative to each other through the three types of boundary (e.g., divergent, convergent and transforms). Studies over the last 40 years reveal that this assumption may not hold true for some plates, especially for continental plates where significant deformation takes place within the earlier defined rigid plates. These tectonically/structurally/seismically active localities within the "rigid" plates have been termed diffuse plate boundary or diffuse plate boundary zones (e.g., Gordon 1998) as color-coded in Figure 16, in which many more plates are now identified because of the "diffuse plate boundaries" (vs. the 12 "rigid" plates in Fig. 1). There have thus been statements in the literature such as "plate tectonics theory cannot explain continental tectonics". In fact, the rigid plate assumption is a good approximation in explaining most of the global geological phenomena and processes, and the plate tectonics theory needs further exploration and development.

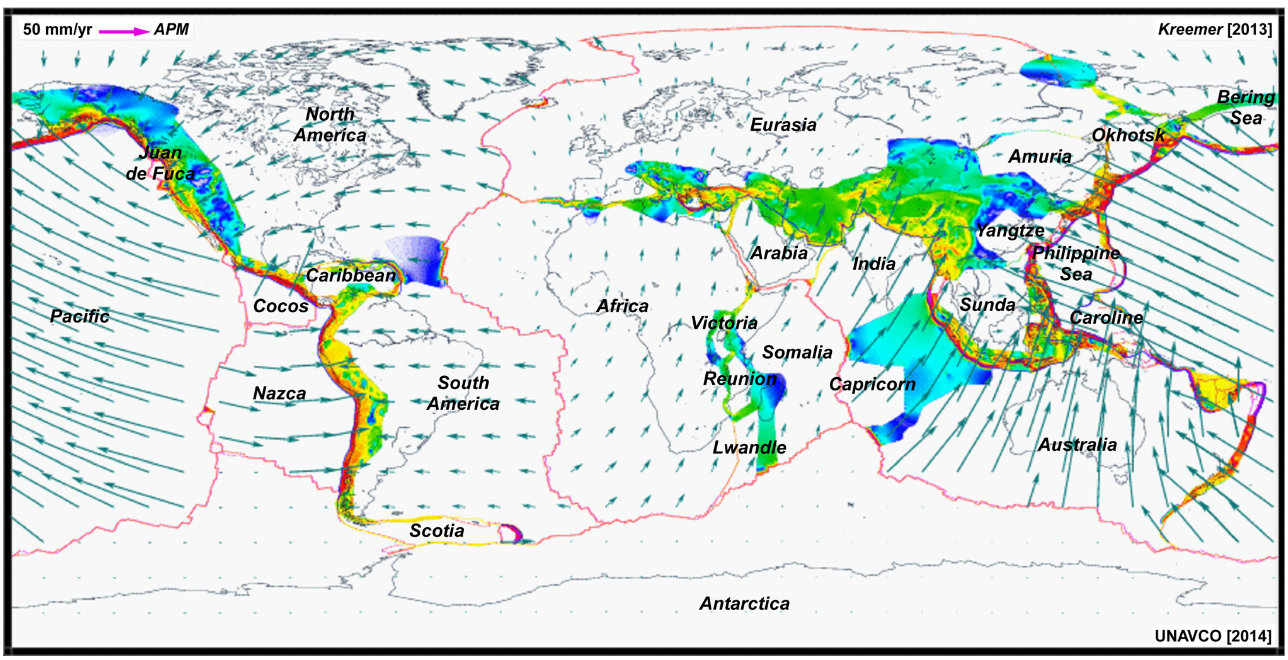

Fig. 16. Global plate tectonics map showing that many plates are not so "rigid" as originally defined (see Fig. 1), but exhibit active deformation of varying nature and degree as indicated by the color-coded locations along convergent margins and in regions within plate interiors. The active deformation has been recognized by means of GPS observations, seismic activities, and active tectonics as well as the need to better fit the global plate motion model (e.g., DeMets et al. 1990; Royer & Gordon 1997; Gordon 1998). These locations and regions are thus better termed as "diffuse plate boundaries" or "diffuse plate boundary zones" (Gordon 1998). As a result, some of the large "rigid" plates become multiple smaller plates. For example, the single large Indo-Australian plate is now considered as made of Indian plate, Australian plate and Capricorn plate because of the recognition of the large "diffuse plate boundary zone" connecting the Java subducting system. Also note the recognition of the Sunda plate, Yangtze plate, Amuria plate and Okhotsk plate as well as the giant diffuse plate boundary zones over much of the continental China all the way to the west along the Himalaya-Alpine Cenozoic orogenic zones from within the original Eurasia plate (Fig. 1). As in Figure1, also shown are standard plate boundaries and the present-day plate motion vectors using the "sub-asthenosphere" reference frame (APM; from UNAVCO: http://jules.unavco.org/Voyager/GEM_GSRM).

6.1. Within-plate plate tectonic processes

As elaborated above, the "within-plate" lithosphere thinning and associated magmatism in eastern China since the Mesozoic are special consequences of plate tectonics. The basal hydration weakening hypothesis (Niu 2005b, 2006) states that the immediate cause is dehydration of the transition-zone paleo-Pacific slab, and this slab is of plate tectonics origin. Furthermore, the ultimate control is the paleo-Pacific subduction, trench retreat and trench suction. The lithosphere thinning in western USA and South America, for example, also results from plate tectonics (Niu 2006).

Much of the continental China is color-coded as diffuse plate boundary zones (Fig. 16), but again the deformation and magmatism there result from plate tectonics. For example, formation of the Greater Tibetan Plateau (equivalent to processes of supercontinent amalgamation; see Niu et al. 2013) has been accomplished through sequences of micro-continent collision since the early Paleozoic, i.e., sequences of Gondwana disintegration, micro-continent drift across the varying "Tethyan oceans" and continental collision against the Eurasian Plate (Niu et al. 2013; Song et al. 2013; Zhu et al. 2013). Initiation/evolution of subduction zones is an indispensable element/process of all these events. The recent/current deformation and magmatism on and around the Greater Tibetan Plateau are largely a response to the continued India-Asia convergence of plate tectonics origin, but the complex boundary conditions (e.g., prior sutures and varying terrenes) make it difficult to resolve details using this theory (e.g., Yin & Harrison 2000; Zhao et al. 2009). This is where the "rigid plate" assumption fails, but the theory does not because it needs further development; recognition of diffuse plate boundary zones is an important improvement.

6.2. Driving force for the India-Asia convergence

The India-Asia continental collision took place some ~65–50 Ma (e.g., Mo et al. 2008), but the convergence continues to the present. Because upon collision, the subduction is expected to stop and slab pull as the driving force must disappear. This observation and reasoning have made many to believe that subduction is not the major driving force for plate tectonics and other forces such as ridge push and those yet unidentified forces may be at work to explain why the India-Asia convergence continues ~65–50 Myrs after the collision.

I consider that the continued India-Asia convergence is a consequence of active subduction of different parts of the same giant "rigid" Indo-Australia plate (Fig. 1). The active subduction of the same "rigid" plate at the Sumatra-Indonesia trench drags the India-Asia convergence; the latter actually acts as resistance rather than active driving force. This means that the Indo-Australian plate may not be rigid, but is under torque deformation and will break up at some stage. Once this plate breaks up, the India-Asia convergence will stop and the Himalayan orogenesis will give rise to gravitational collapse dominated by erosion. Indeed, it has already been recognized that there exists diffuse deformation/seismicity within the Indo-Australian plate as shown in Figure 16 (vs. Fig. 1), and this "rigid" Indo-Australia plate may actually be made of three plates (i.e., India, Capricorn and Australia) separated by the diffuse plate boundary zones.

6.3. Emplacement of diamondiferous ophiolites

Ophiolites were originally thought to represent normal oceanic lithosphere generated at ocean ridges (Anonymous 1972), but their emplacement onto land by obduction against gravity raises difficulties (Niu et al. 2003). Subsequent studies have showed that most "ophiolites" have typical arc magma geochemical signatures (e.g., Bloomer et al. 1995; Shervais 2001; Pearce & Robinson 2010; Whattam & Stern 2011). Niu et al. (2003) suggested that the suprasubduction zone "ophiolites" may represent magmatic assemblages developed at edges of oceanic plateaus during early stages of subduction initiation, but they can equally readily develop at early stage of subduction initiation at passive continental margins. In either case, both oceanic plateau lithosphere and continental mantle lithosphere can be as thick as ~250 km or more with deep portions well within the stability field of diamond (> 140 km; see Fig. 14). Figures 6b and 14 show that serpentines can be stable up to 7.5 GPa at $T \leq 800°C$. Serpentines in the subducting oceanic lithosphere may become unstable and decompose with heating with increasing depth. The water released can rise to the overriding mantle lithosphere (continental or oceanic plateau lithosphere) to cause serpentinization. The new serpentines formed at depth of the overriding mantle lithosphere may rise as diapirs, collecting/carrying ultrahigh pressure phases like diamond as part of the suprasubduction ophiolite assemblage. These scenarios can readily explain the diamondiferous ophiolites as reported in the recent literature (Bai et al. 1993; Robinson et al. 2004; Yang et al. 2007, 2014; Dobrzhinetskaya et al. 2009). This hypothesis suggests that the harzburgite-serpentinized harzburgite assembly with diamondiferous chromites may not be part of a genuine ophiolite. The hypothesis also suggests that if subduction initiation is indeed associated with compositional contrast in the lithosphere (i.e., edges of oceanic plateaus and passive continental margins), diamondiferous ophiolite may be common. This is a viable hypothesis to be tested.

7. Summary

(1) Compositional buoyancy contrast within the lithosphere is the decisive (primary) factor for subduction initiation. It is unlikely for subduction to initiate in normal oceanic lithosphere because of lacking such compositional (nor thermal) buoyancy contrast. In ocean basins, large compositional buoyancy contrast exists at edges of oceanic plateaus. Globally, the largest compositional buoyancy contrast exists along passive continental margins like those in the Atlantic and much of the Indian Ocean. These localities are likely loci of future subduction zones (Figs. 1, 4, 6).

(2) Although the primary driving force for subduction initiation is the gravity, a low angle fault plane favors the foot plane to sink (i.e., $F_B \propto 1/\beta$) and subduction initiation (Figs. 4, 5). Under gravity and with the continued subduction, the subducting slab tends to rotate vertically with β increase. This is the concept of *Slab Rollback* (Fig. 7).

(3) For a given subducting slab, β may be locally small (e.g., the shallow part of the Nazaca plate subducting beneath South America), but large scale flat subduction (i.e., β≈0) is impossible because no force drives flat subduction. The transition-zone paleo-Pacific slab beneath eastern China (Fig. 10) is not indication of flat subduction, but was passively left behind as the result of western Pacific subduction retreat (seaward migration) under gravity (the bottom panel of Fig. 10).

(4) In the western Pacific, the eastward trench retreat/suction drives the *continental drift* of the giant Eurasian plate, especially the continental China (Figs. 1, 8). In the eastern Pacific, the westward trench retreat/suction drives both *continental drift* and *seafloor spreading* of the South American "continental + oceanic" plate (Fig. 1). These examples illustrate that plate motion (both seafloor spreading and continental drift both) is ultimately driven by subduction. Simply put, the Pacific-type seafloor spreading is the immediate result of seafloor subduction. Seafloor subduction plays an active role in driving much of the global plate motions and mantle convection. The Atlantic-type seafloor spreading and continental drift are passive response to seafloor subduction (e.g., in the Pacific).

(5) The drifting overriding continental plate in response to trench retreat/suction is under extension (Fig. 8). If the rate of trench retreat is fast (e.g., the western Pacific; Fig. 1) and the overriding continental plate is relatively less rigid (e.g., the giant Eurasian plate with multiple blocks jointed by numerous sutures and orogenic belts), within-continent rifts and extensional basins will develop, and back-arc basin spreading centers like those in the western Pacific will form (Figs. 1, 9, 11). If the rate of trench retreat is relatively slow (e.g., the eastern Pacific; Fig. 1) and the overriding continental plate is relatively rigid (e.g., the composite "continental + oceanic" South American plate), the extensional stress will be focused at the weakest mid-Atlantic ridge (MAR). From a kinematic perspective, the Atlantic may be functioned as a giant back-arc basin (in its present physical state).

8. Hypotheses to be tested and questions remain

(1) The present-day intra-oceanic arcs must have its basement of continental affinity (and to a lesser extent basement of oceanic plateau) (Fig. 9). This is a fundamentally important hypothesis that can be tested through sampling the arc basement rocks and studying them petrologically, geochemically and geochronologically.

(2) Back-arc basins (if seafloor spreading is not ceased like the Sea of Japan and South China Sea spreading) can evolve to large open ocean basins and the "Island arc systems" can become micro continents. This concept can be used to explain the origin and evolution of the familiar yet unclearly defined proto-, paleo-, Meso- and Neo-Tethyan systems, and especially the formation and evolution of the Greater Tibetan Plateau. In other words, subduction initiation along a passive continental margin together with the origin and evolution of back-arc basins and micro continents ("island arcs") reflect processes of continental breakup. Conversely, collisions of these micro continents elsewhere leads to the amalgamation of super continents (e.g., the history of the "Greater Tibetan Plateau") (Niu & O'Hara 2009; Niu et al. 2013).

(3) Niu (2005b) emphasized that the lithosphere thinning was not restricted to the NCC, but occurred throughout entire eastern China as reflected in the global tomography (Fig. 15), in which the LVZ is areally continuous in eastern China. The process of the LVZ formation is the very process of the eastern China lithosphere thinning mostly in the Mesozoic (Figs. 12–14), whereas the progressive dehydration of the present-day transition-zone paleo-Pacific slab maintains the LVZ (Fig. 10). A key question is whether the E-W GGL (Figs. 10, 11) marks the western-most reach of the present-day Cenozoic slab in the mantle transition zone. Is there any evidence for the presence of the Mesozoic slab in the mantle transition zone beneath continental China? Is the high velocity layer west of the E-W GGL (Fig. 10) remnant of the Mesozoic slab? Is the present-day active volcanism in the Datong area (Figs. 10, 11) related to dehydration of such residual Mesozoic slab?

(4) If the major lithosphere thinning was largely completed before ~110 Ma, then 110 Ma must represent an important geological event. Is there any geological and geophysical record of this event? Furthermore, where is

the suture of the Mesozoic Pacific subduction? I predict that this must be on the Chinese continental shelf west of the Okinawa trough. All these require careful geological work on land and well-designed and planned marine geology and geophysics investigations.

(5) The NNE-SSW steep elevation gradient line is coincident with the North-South gravity lineament (NSGL), and thus the latter NSGL has been widely used. But this is better termed East-West Great Gradient Line (E-W GGL) because this is effectively descriptive of the coincidence of a number of observations (Niu 2005b): sharp altitude, gravity anomaly, crustal thickness, heat flow, and mantle seismic velocity changes from high plateaus in the west to hilly plains of eastern China, which is an effective expression of variation in lithospheric thickness from probably > 150–200 km thick beneath the plateaus in the west to < 80 km thick beneath eastern China. A key question is why the crust is thicker in the west than in the east (Gao et al. 1998). Is this crustal thickness difference inherited or thinned? If thinned, when and how? This is an important question that has been overlooked and needs attention.

(6) The Ordos of the NCC and the Sichuan Basin of the Yangtze Craton west of the E-W GGL (Fig. 11) are considered to have undergone least lithosphere thinning. Because the transition-zone slab is stagnantly (relatively) fixed and it is the overriding Eurasian Plate that is drifting towards east (Fig. 10, 11), these two cratonic cores may have not yet entered or just about to enter the realm of transition-zone slab dehydration (e.g., the LVZ) for effective "basal hydration weakening" and lithosphere thinning. If this inference is correct, then these two cratonic roots may have just begun to undergo thinning and there may thus be basal seismic anomalies, especially beneath the Ordos.

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