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News & Views

Testing the geologically testable hypothesis on subduction initiation

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> "Resolution of the sixty-year debate over continental drift, culminating in the triumph of plate tectonics, changed the very fabric of Earth science. Plate tectonics can be considered alongside the theories of evolution in the life sciences and of quantum mechanics in physics in terms of its fundamental importance to our scientific understanding of the world." [1]

Indeed, the plate tectonics theory established in late 1960's has revolutionized Earth Science thinking and formed a solid framework for understanding how the Earth works on all scales. This theory has also correctly and explicitly explained to us that geological processes are ultimately consequences of Earth's cooling (i.e., heat loss) with time. This is manifested by the origin of oceanic plates at ocean ridges, the movement and thickening of these plates, and their ultimate consumption back into the Earth's deep interior through subduction zones, which provides an efficient mechanism to cool the Earth's mantle, leading to large-scale mantle convection [2–4]. That is, the immediate driving force for plate tectonics is the sinking of the cold and dense oceanic lithosphere, under gravity, into the deep mantle through subduction zones [5]. Given the understanding that the Pacific-type oceanic plates (sinking into subduction zones) are both expressions and actual driving limbs of mantle convection [2–4], Niu [4] illustrates that (1) seafloor spreading in ocean basins with passive margins (e.g., the Atlantic-type) and (2) continental drift are simply passive movement in response to trench retreat of active seafloor subduction in ocean basins like the Pacific with subduction zones. To be more specific and explicit, particular for those who have been influenced by incorrect statements in old textbooks, the driving force for plate tectonics is well known and well understood to be dominated by subducting slab pull (sinking): it directly drives (1) Pacific-type seafloor spreading, (2) major aspects of mantle convection, and indirectly drives (3) the Atlantic-type seafloor spreading and (4) continental drift. Forces such as ridge push are not negligible, but are one-order of magnitude less important; plus, ridges are known to be passive features produced because of subducting slab pull in the first place [2, 3].

Therefore, there would be no plate tectonics if there were no subduction zones [6]. Yet how a subduction zone begins remains speculative [4]. Studies on subduction initiation have been many and continue to this day by using modeling (both kinematic and dynamic), geological and petrological approaches [e.g., 4, 6–11], culminating with three consecutive IODP drilling expeditions (IODP 350, 351 and 352 in 2014) in the western Pacific to test the ideas of spontaneous and induced subduction initiation [10]. Niu et al. [4, 6] advocate with quantitative illustrations that subduction initiation is a consequence of lateral compositional buoyancy contrast within the lithosphere. All these studies attempt to explain how a subduction zone may initiate (not about when and how plate tectonics began in Earth's history). Thermal buoyancy contrast in the lithosphere is attractive [7], but no large scale linear thermal

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buoyancy contract exists on the Earth except the Romanche transform in the equatorial Atlantic across which the ridge encounters old lithosphere of ~75 Ma, where large thermal buoyancy contrast must exist, but there is no sign of subduction initiation [6]. Subduction initiation along prior zones of weakness such as earlier transforms, fracture zones and failed seafloor spreading centers has been a popular idea [9–11], but it is physically difficult to understand why and how one side of these features would prefer to sink while the other side would choose to rise under any deviatoric stresses [6]. The Macquarie Ridge, marking the boundary between the Australian and Pacific plates in the Southern Ocean, has been considered by some as the most convincing case of incipient initiation of a subduction zone, but again there is no sign of subduction initiation [6]. Subduction initiation along passive continental margin is geologically expected as manifested by the modern example of the Ryukyu Arc-subduction system developed on the Chinese continental shelf margin since <~15 Ma [4, 6], but failures in numerical modeling of subduction initiation along passive margins made some to have ruled out this possibility (see [6] for detailed discussion). The ideas of "induced" or "spontaneous" subduction initiation [10] are welcome summary of observations developed to explain the arc magmatism and ophiolite emplacement in the western Pacific.

All the above can be regarded as scientific hypotheses. Hypotheses may not be opinionated as right or wrong, but can be objectively analyzed as being reasonable or not. The hypotheses that can be tested are deemed reasonable whether they are proven to be correct or not. A hypothesis rigorously tested to be valid becomes a theory. Kinematic modeling is useful in evaluating relevant hypotheses by exploring the possibilities. Dynamic modeling is considered better in evaluating the hypotheses by exploring time varying observables in the interaction between motions, forces and material properties. However, such modeling results cannot be used as evidence (for or against) because more than often many parameters used in modeling cannot be fully constrained. With all the hypotheses objectively considered, the following hypothesis is geologically testable with the highest probability and least cost to discover the smoking-gun evidence:

> *Initiation of subduction zones is a consequence of lateral compositional buoyancy contrast within the lithosphere*. [4, 6]

Simply put, the compositional buoyancy contrast within the lithosphere refers to density difference due to compositional difference related to prior different geological and petrogenetic histories [6]. Hence, the compositional buoyancy contrast within the lithosphere is the prerequisite for subduction initiation. This means that it is unlikely for subduction to initiate within the normal oceanic lithosphere (in normal ocean basins) because of lacking such compositional (or thermal) buoyancy contrast. The observation of "oceanic plate subduction beneath oceanic plate" such as in the western Pacific has been misguiding many to believe that the western Pacific subduction zones were initiated and developed within the normal oceanic lithosphere. This is incorrect and a compositional buoyancy contrast must have existed within the lithosphere before these subduction zones were initiated [6].

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 (Fig. 1). These localities are likely loci of future subduction zones [4, 6]. This is straightforward for the subduction of the dense oceanic plate (e.g., Nazca plate)

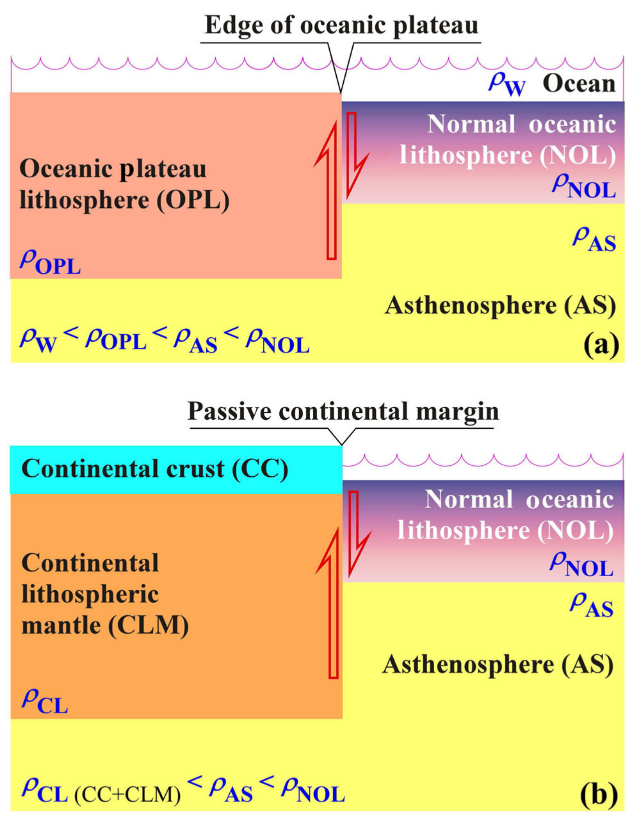

Fig. 1 **a** Illustration of buoyancy contrast (density difference) between an oceanic plateau lithosphere that is relatively buoyant (tend to float) and the normal seafloor lithosphere that is relatively dense (tend to sink) due to compositional differences (see [4, 6]). **b** Illustration of buoyancy contrast at a passive continental margin between continent (where $\rho_{CC} \ll \rho_{CLM}$) that is buoyant (tend to float) and the normal seafloor lithosphere that is dense (tend to sink) due to compositional differences. This oceanic plateau edge and passive continental margin represent the locations of compositional buoyancy contrast that marks the potential sites for subduction initiation. See [4, 6] for details