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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 and co-authors [4,6] advocate with quantitative illustrations that subduction initiation is a consequence of 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 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) beneath the compositionally buoyant continental plate (e.g., the South American plate), but is not so obvious to many for the Pacific plate subduction beneath western Pacific island arcs and backarc basin plates. The key element of the geologically testable hypothesis is:

> "*The present-day intra-oceanic arcs must have its basement of continental affinity (or basement of oceanic plateau affinity to a lesser extent). This is a fundamentally important hypothesis that can be tested through sampling the subarc basement rocks and studying them petrologically, geochemically and geochronologically.*" [4]

The smoking-gun evidence lies in the island arc basement of continental origin (or oceanic plateau origin to a lesser extent) because the hypothesis states that subduction initiation takes place along the compositional buoyancy contract within the lithosphere: (1) at the edges of oceanic plateau (buoyant relative to the adjacent normal seafloor lithosphere) in ocean basins and (2) at passive continental margins (significantly more buoyant than normal seafloor lithosphere) on a global scale [4,6]. In fact, this hypothesis has already been verified by the fact that the landmass of Japanese island arcs originated from the eastern margin of the Eurasian continent in the time period of ~ 27-16 Ma (?) in response to the opening of the Sea of Japan， which is again a passive response to the trench retreat of the Pacific plate subduction [4,12]. However, this "verification" could be considered as being coincidental and further rigorous testing is needed.

Where to go and what to do?

The western Pacific trench-arc-backarc-shelf systems developed and evolved since the Mesozoic offer opportunities for discovering solutions to many geological problems and puzzling observations [12,13], including testing the hypothesis in question here. We should choose geologically better studied trenches with less sediments to dredge rocks exposed on the overlying forearc trench slopes like those in the Izu-Bonin-Mariana trench [14] and Tonga-Kermadec trench [15] (Figs 2a-d). The Challenger Deep in the southern Mariana is the deepest point of the world trench system, ~ 11,000 mbsl (meters below sea level). All other trenches and trench localities are shallower, variably shallower than 10,000 mbsl. Some questions need clarification:

(1) About 5-10 km sub-vertical section exposed on the forearc trench slopes is rather shallow compared to the average continental crust thickness of ~ 35 km or oceanic plateau crustal thickness of ~ 20 km. Recent forearc magmatism can also complicate or camouflage the basement rocks underneath. In this case, *how can we expect to see continental basement rocks exposed on the forearc trench slopes*? The answer is straightforward as illustrated in Fig. 2e; it is the subducting slab dehydration that causes the overlying arc mantle lithosphere (recently modified continental or oceanic plateau lithosphere) to serpentinize. The serpentines, with their reduced density and enhanced plasticity/ductility, readily develop serpentine diapirs to carry up fragments of unserpentinized mantle lithospheric peridotite, lower and upper continental (or plateau) crustal lithologies to be sampled by means of dredging. The fact that highly depleted mantle harzburgites have been dredged from the Mariana and Tonga forearc slopes (see details in [6])

are simple manifestation. The lithologies expected to expose and sample by dredging include forearc volcanic rocks, magmatic cumulate, serpentinized and fresh mantle peridotites, lower continental crustal rocks such as amphibolite facies and granulite facies rocks. These rocks are *smoking-gun* evidence in support of the geologically testable hypothesis we aim to test.

(2) Dredging is the most efficient and effective method for sampling, using > 4000 tonnage research vessel with dynamic positioning system (DPS), built-in multi-beam facility and a 12 kHz Pinger. It is important to note that although it would be ideal to dredge rocks from the trench bottom upwards the slopes, it is not necessary for each dredge to start from the bottom because the objective is to dredge rocks exposed on the slopes. We emphasize sediment-absent or less-sedimented trenches to ensure sampling success. In this context, we should note a major scientific question in the community: *Why is the Mariana Trench so deep, in particular the ~ 11000 mbsl Challenger Deep*? I consider part of the answer lies in the fact that there is no terrigenous sediment input there. Otherwise, it would be ~ 3 km less deep, and trenches with depth of 7-9 km are common, and do not require complex answers to the question. That is, this is an interesting question, but whether this is a scientifically significant question or not needs research.

(3) On the basis of dredged samples and laboratory studies of these samples, selected targets should be identified for *in situ* sampling using submersibles for detailed investigations.

(4) If the subduction zone is verified to have been initiated at a passive continental margin associated with a thickened cratonic lithosphere, it is possible that we may discover ultra-high pressure metamorphic materials once formed and stabilized in the deep lithospheric mantle conditions as illustrated in Fig. 2f.

How to study these samples?

An integrated and comprehensive study by means of petrography, mineralogy, petrology, elemental geochemistry, Sr-Nd-Pb-Hf isotopic analysis and geochronology (zircon U-Pb, Ar-Ar, and Sm-Nd/Lu-Hf isochron methods) needs carrying out on the acquired samples to complete this hypothesis testing.

In summary, the scientific hypothesis advocated to test on subduction initiation is so far the *only known geologically testable hypothesis* to be tested effectively with lowest possible cost, many orders of magnitude cheaper than using IODP. Also, trench slope rock outcrops are “macroscopic” to sample by dredging whereas the “microscopic” drilling may not hit “right” rock samples for study because drilling has restricted penetration through recent arc/forearc magmatic rocks into the basement. Nevertheless, better planned IODP expeditions on ideal sites are expected to yield useful data if designed to test the hypothesis . Given the fact that the origin and initiation of subduction zones is the last frontier towards the total completion of the plate tectonics theory, I have expended efforts over the last years to persuade the Chinese National Natural Science Foundation (NSFC) for support of carrying out the hypothesis testing. A recent discussion with Professor Weicheng Cui in the Hadal Science and Technology Research Center of Shanghai Ocean University is encouraging, and we anticipate to conduct such collaborative research in the near future by using his newly built *R/V Zhang Jian* and his being-constructed submersible *Rainbow Fish* with 11000 mbsl diving capability designed to challenge the *Challenger Deep*. We welcome the international community to join this effort and in particular hope the NSFC will support such frontier research as a belated Chinese contribution towards the Earth Science Revolution developed about half-century ago.

It should be noted that in this paper, we do not wish to discuss when, where and how subduction began on the Earth, i.e., the beginning of the plate tectonics on our planet. This research is undergoing.

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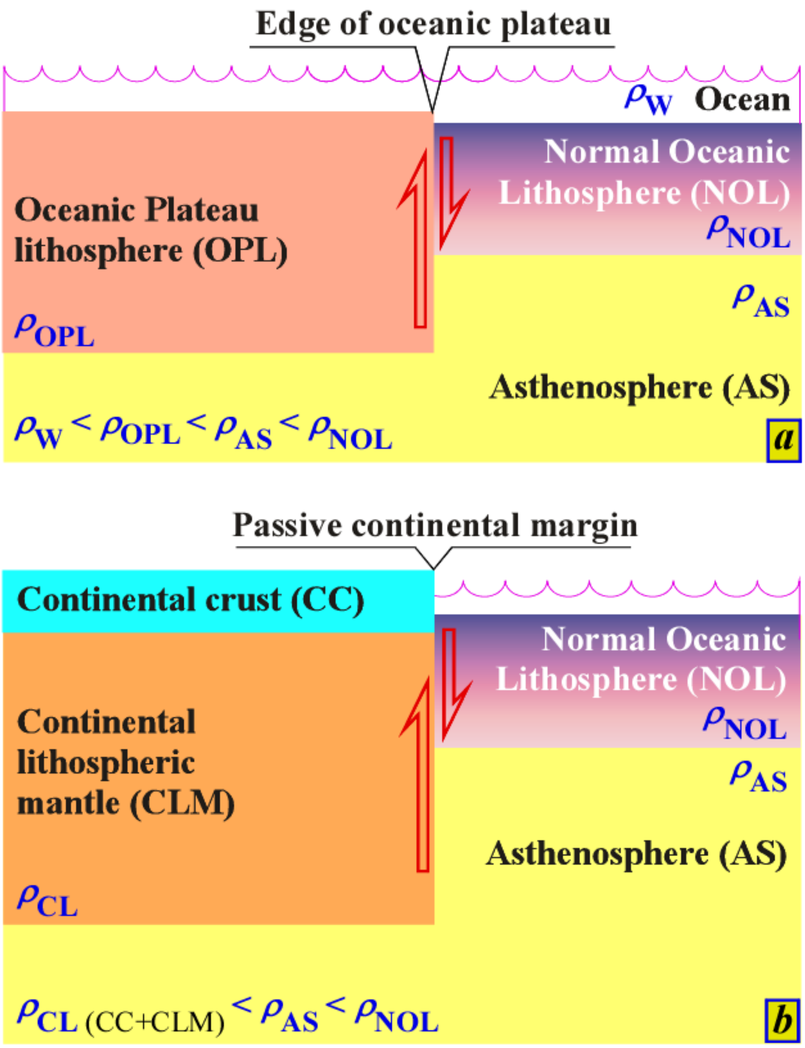

Fig. 1 a Illustration of buoyancy contrast (density difference) between an oceanic plateau lithosphere that is relatively buoyant (tend to float) and the normal seafloor lithosphere that is relatively dense (tend to sink) due to compositional differences (see [4,6]). **b** Illustration of buoyancy contrast at a passive continental margin between continent (where $\rho_{CC} << \rho_{CLM}$) 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.

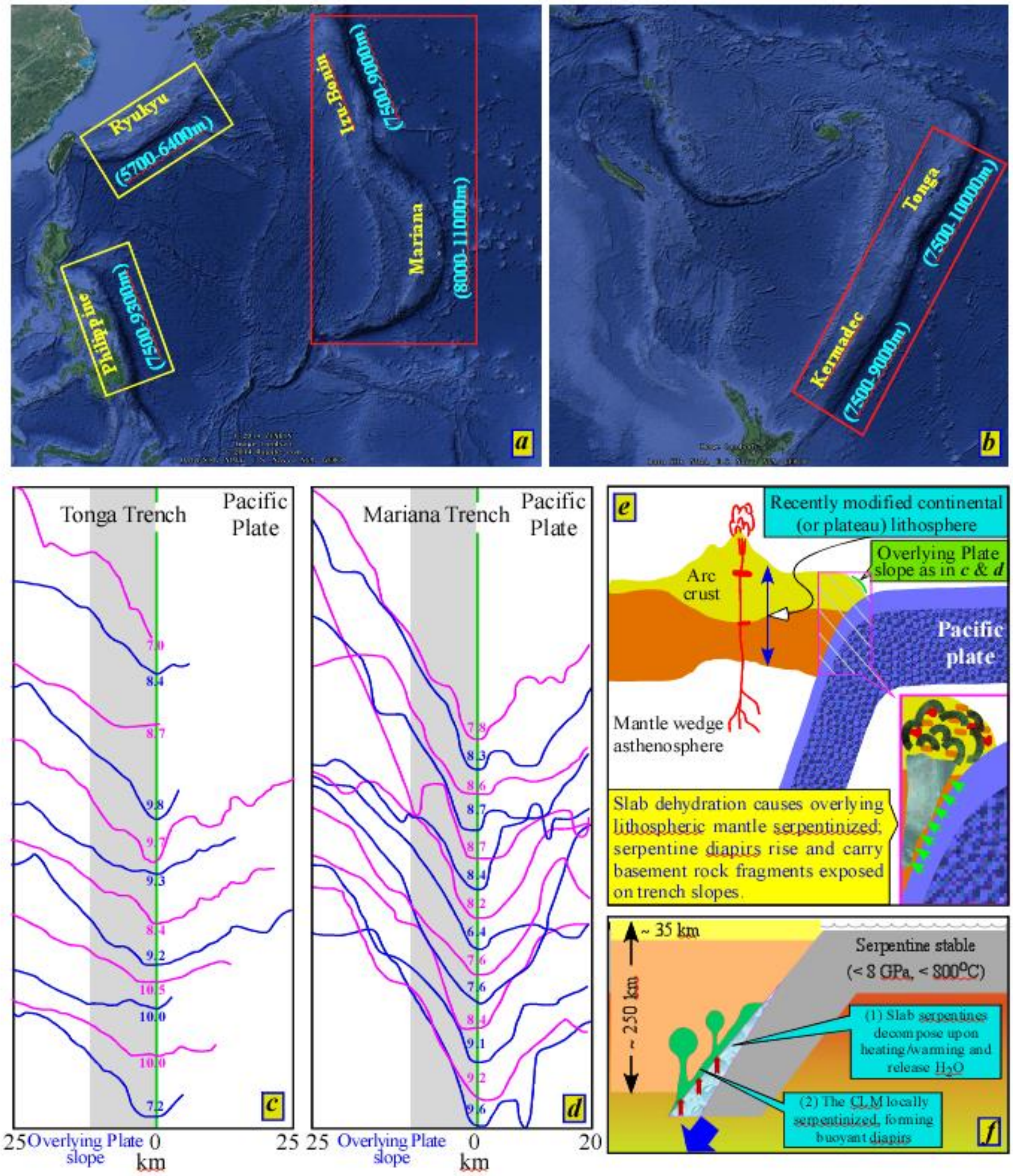

Fig. 2 a, b Portions of Google Map (2016) highlighting the geologically better studied Izu-Bonin-Mariana arc-trench system and the Tonga-Kermadec arc-trench systems with no or little sediments. The Philippine and Ryukyu arc-trench systems have more land-derived sediments in the trench floors, but whose slope sampling is still possible with additional geological and geophysical survey. **c, d** Representative Tonga [15] and Mariana [14] across trench depth profiles, respectively, with trench axial depths indicated in km below sea level. The gray band in **c** and **d** are sampling target slope intervals. **e** Illustration that subducting-seafloor dehydration can cause mantle lithosphere of the overlying continental (or oceanic plateau) plate to serpentinize with the serpentines developing diapirs to carry fragments of mantle peridotites and crustal lithologies to be exposed on the forearc trench slopes for sampling and study. **f** If the subduction zone is proved to have been initiated at a passive continental margin with thickened craton, it is possible that the serpentine diapirs can carry ultra-high pressure rocks and minerals formed and stabilized under the deep lithospheric mantle conditions, including diamonds (see [4] for discussion).