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Microplate tectonics: A new tectonic paradigm

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Abstract
Earth is only one of planets in solar system to operate plate tectonics to be confirmed. Although traditional Plate Tectonic Theory had a successful achievement, it remains three conundrums. The first one is when, where and why plate tectonic regime started on the Earth. The second conundrum is difficultly to explain intraplate deformation. The third conundrum is plate driving forces. However, Microplate Tectonics Theory as a new tectonic paradigm does not need to resolve its own-making trouble set up by the Plate Tectonics Theory: only one unique origin and one driving mechanism of plate tectonics. Microplate Tectonics Theory includes six principles as follows:

- **Global geometry:** Rigid or deformable microplates can vertically develop not only in lithosphere but also within deep mantle, including continental, oceanic and mantle microplates in composition, and near 1000 continental and oceanic microplates on surface Earth and much more mantle microplates within the mantle.
- **Fundamental kinematics:** Microplates as rigid blocks not only move horizontally along the small girdles around the Euler poles or self-rotation axes, but also move down and up across the spheres. The velocity should be consistent within one microplate when its Euler pole is far away this microplate.
- **Deformation:** The inner microplate is either rigid or deformable, but deformation is mainly along the microplate margin. But continental and oceanic microplate is generally 400km×400 km or less, so the inner microplate can be deformable.
- **Evolution:** Microplate can grow and perish under many tectonic settings, having relatively independent evolutionary history relative to the surrounding (micro)plates and undergoing either Wilson or non-Wilson cycles without fixed periods.
- **Mobilism and transition:** Microplate could have been a large-scale plate in passive motion under either plate tectonic or non-plate tectonic regimes, without limit of plate margin, microplate can develop or terminate under any tectonic setting such as previous intraplate environment.
- **Kinetics:** Microplates have many regionally linked or dependent driving forces or mechanisms, but the ultimate driving force should be Relay-Taylor Instability.

Resümee
Die Erde ist der einzige Planet im Sonnensystem, auf dem die Plattentektonik bestätigt werden konnte. Obwohl die traditionelle plattentektonische Theorie erfolgreich war, bleiben drei Rätsel bestehen. Das erste ist, wann, wo und warum die Plattentektonik auf der Erde begann. Das zweite Rätsel besteht darin, dass es schwierig ist, die Deformation innerhalb einer Platte zu erklären. Das dritte Rätsel sind die Antriebskräfte der Platten. Die Theorie der Mikroplattentektonik als neues tektonisches Paradigma muss jedoch nicht die von der Theorie der Plattentektonik aufgeworfenen Probleme lösen: Es gibt nur einen einzigen Ursprung und einen Antriebsmechanismus der Plattentektonik. Die Theorie der Mikroplattentektonik umfasst die folgenden sechs Prinzipien:

- **Globale Geometrie:** Starre oder verformbare Mikroplatten können sich nicht nur in der Lithosphäre, sondern auch im tiefen Erdmantel vertikal entwickeln, einschließlich kontinentaler, ozeanischer und Mantel-Mikroplatten in der Zusammensetzung und nahezu 1000 kontinentaler und ozeanischer Mikroplatten an der Erdoberfläche und noch viel mehr Mantel-Mikroplatten im Erdmantel.
- **Grundlegende Kinematik:** Mikroplatten als starre Blöcke bewegen sich nicht nur horizontal entlang der kleinen Gürtel um die Euler-Pole oder Selbstrotationsachsen, sondern sie bewegen sich auch nach unten und oben über die Sphären. Die Geschwindigkeit sollte innerhalb einer Mikroplatte konstant sein, wenn ihr Euler-Pol weit von dieser Mikroplatte entfernt ist.
- **Verformung:** Eine innere Mikroplatte ist entweder starr oder verformbar, aber die Verformung erfolgt hauptsächlich entlang des Mikroplattenrandes. Eine kontinentale und ozeanische Mikroplatte ist jedoch im Allgemeinen 400 km x 400 km oder weniger groß, so dass die innere Mikroplatte verformbar sein kann.
- **Evolution:** Mikroplatten können unter vielen tektonischen Bedingungen wachsen und vergehen, wobei sie eine relativ unabhängige Entwicklungsgeschichte im Vergleich zu den sie umgebenden (Mikro-)Platten haben und entweder Wilson-Zyklen oder Nicht-Wilson-Zyklen ohne feste Perioden durchlaufen.
- **Mobilismus und Übergang:** Mikroplatten könnten aus einer großflächigen Platte in passiver Bewegung hervorgegangen sein, entweder unter plattentektonischen oder nicht-plattentektonischen Bedingungen, ohne Begrenzung des Plattenrandes. Mikroplatten können sich in jedem tektonischen Umfeld entwickeln oder vergehen, wie z. B. in der früheren Umgebung einer großflächigen Platte.
- **Kinetik:** Mikroplatten haben viele regional verknüpfte oder abhängige Antriebskräfte oder Mechanismen, aber die ultimative Antriebskraft dürfte die Relais-Taylor-Instabilität sein.

Keywords/Schlüsselwörter
Microplate tectonics, plate tectonics, Earth system, tectonic paradigm
Mikroplattentektonik, Plattentektonik, Erdsystem, tektonisches Paradigma

Since Heliocentrism of Nicolaus Copernicus in 1543 to promote the revolution of astronomy, everybody knows the sun is the center of the solar system. The solar system has four terrestrial planets at the inside and four Jovian planets at the outside. Since 1968, many research results following the traditional Plate Tectonics Theory confirm that the Earth is only one of planets in solar system to operate plate tectonics.

1 The paradigm of traditional Plate Tectonics Theory

The traditional Plate Tectonics Theory divided the Earth into several vertical layers of lithosphere, asthenosphere, 410-660 km mantle transition zone, lower mantle, outer core and inner core from top to center. Rigid plate in Plate Tectonics Theory is constrained in lithosphere. It is the rocky outer part of the Earth. It is made up of the brittle crust and the top part of the upper mantle. The lithosphere is the coolest and the most rigid part of the Earth over the asthenosphere between 200-410 km at depth. The deeper mantle is the lower mantle down to core-mantle boundary at about 2850 km depth.

The rigid lithosphere can be broken into six or thirteen large-scale plates according to the traditional Plate Tectonics Theory. Plates can be subdivided into large plate, medium plate, small plate and microplate in size. Large-scale plates or megaplates can also be subdivided into many secondary-scale small plates or microplates. So, the population of microplates is naturally more than that of large-scale plates. However, researchers have been focusing on these large-scale plates for over 50 years since the birth of Plate Tectonics Theory.

55 years ago, plate tectonics revolution made a big shift away from geosyncline and platform to plates, and shifted an attention away from vertical tectonics to horizontal tectonics. It unified continental drifting, seafloor spreading, subduction, transform faulting and orogeny together. Although the traditional theory of Plate Tectonics has no popularly-accepted summary until now, here we try to summarize it from six aspects.

The first one is on global geometry. The Earth has a rigid outer layer, known as the lithosphere, which overlies a plastic and partially molten layer called the asthenosphere. The lithosphere is broken up into six or thirteen large-scale continental or oceanic plates with some secondary plates.

The second one is on kinematics. Plate motion on spheric surface can be described by a rotation axis which passes through the center of the Earth and intersects the surface at two points, called the Euler pole of plate rotation. Each plate has its own rotation axes in different time, respectively.

The third one is on deformation. Deformation generally takes place along some plate boundaries. Plate boundaries have three basic types, namely subduction zone, mid-ocean ridge and transform fault. So, based on traditional tectonics plate theory, intraplate should be rigid or undeformable.

The fourth one is on plate evolution. Oceanic plate is generated at mid-ocean ridges and consumed along subduction zones. The oceanic basin has a cycle accompanying with plate birth to death – called a Wilson cycle of about 200 Myr.

The fifth one is on mobilism. Traditional Plate Tectonics theory considers that continental drifting is passive, mid-oceanic seafloor spreading is active. Continent was relegated to plate passengers.

The last one is on geodynamics of plate moving. Final plate driving force is active mantle convection.

Plate motions are thought to be responsible for most of the earthquakes and volcanic eruptions. Slow plate motions also cause mountain building and plate collision. In addition, Plate motions also can cause continents or supercontinents to break up and oceans to develop, where plates pull apart or diverge – resulting in some significant geographic and geological changes. So, all the deformations mainly dominate the plate boundaries. However, we also can find some dispersive within-plate earthquakes in the Eurasia Plate, especially in the Tibet Plateau, this phenomenon is contradictory to the rigidity of large plates based on traditional Plate Tectonics Theory. So, the traditional Plate Tectonics Theory is not complete.

2 Three basic conundrums of traditional Plate Tectonics Theory

The first conundrum of the traditional Plate Tectonics Theory is difficultly to explain the intraplate deformation as mentioned before. Although the unified motion sense and speed for the rigid Indian Plate are measured by Global Positioning System, and its consistent velocity for rigid intraplate is well predicted by traditional Plate Tectonics Theory, but the mosaic Eurasian Plate is also one unified plate according to traditional plate tectonic division, many intraplate earthquakes developed within this large-scale plate. the GPS velocities are so different for each sub-blocks within the Eurasian Plate in the Tibet Plateau. However, if we subdivide this large-scale plate into some microplates, we can resolve the conundrum of intraplate deformation as marked by earthquakes, its nature is that the Tibet Plateau is not under complete cratonization, but under the orogeny of mosaic-like linked microplates. The traditional Plate Tectonics Theory also cannot explain a depression which the craton basin underwent, and something within plates.

The following conundrum of Plate Tectonics Theory is plate driving Force. Plate Tectonics Theory proposed that active mantle convection is the ultimate mechanism to drive plate motion. Lithospheric plates become passengers over the asthenosphere and move as the mantle flow. In fact, the initial proposal by Holmes in 1928 described that mantle convection is a mantle behavior under Moho. His mantle convection served for the fixism of Geosyncline-Platform Tectonics Theory. However, in the Plate Tectonics Theory, mantle convection is the asthenospheric behavior. Some problems of asthenospheric convection are small convection cell in scale and more slower convection speed than plate motion speed. If so, the plate should actively drive asthenospheric mantle convection. Even though mantle convection can drive plate motion, it is also difficult to explain intraplate earthquake and other kind of within-plate deformation.

The final one is when, where and why plate tectonic mechanism started on the Earth. Palin et al. (2020) showed some representative views on when plate tectonic regime initiated to operate on the Earth. Here we don't discuss more. It is difficult to interpret some deformation and continental origin of Early Precambrian or Archean tectonics.

In summary, although the traditional Plate Tectonics Theory had a successful achievement, it remains three conundrums mentioned above. But we have engaged in microplate tectonics research for over thirty years. we did not meet these conundrums. So, our simple philosophy is that microplate tectonics have not this kind of conundrums.

3 The paradigm of Microplate Tectonics Theory

What is Microplate? The term of microplate is not new term, it was proposed coeval to the birthday of the Plate Tectonics Theory, but it has no detailed definition until we made it in 2018 (Li SZ et al., 2018). Microplate requires four conditions. At first, it is a geological or tectonic unit with a length or width of about 300 to 1000 km and a size of about ten to the fifth to sixth power square kilometers in area. Secondly it is a relatively-unified and rigid block moving with the same motion sense and speed in the present GPS or plate reconstruction velocity fields, or with the progressively-decreased speed near the Euler pole. It has a relatively independent evolutionary history relative to the surrounding (micro)plates. Finally, microplates at different evolutionary stages of the Earth have many distinct geodynamic mechanisms such as subduction, collision, delamination, underplating, mantle plume rising, ridge propagation, block rotation, transformation, sagduction, impact, dripping, foundering and other tectonic processes. Based on this new conception of microplate, we can find that microplate tectonics theory does not need to resolve the own-making trouble as the plate tectonics theory that it requires us to look for only one unique origin of plate tectonics.

Compared to the traditional Plate Tectonics Theory, this paper simply introduces six principles of microplate tectonics as follows.

The first one is on global geometry: Rigid microplates can vertically develop not only in lithosphere but also within deep mantle, having three types continental, oceanic and mantle microplates in composition, and over thousand microplates on the surface Earth and many mantle microplates through the mantle revealed by tomography or tomotectonics. In some previously-published papers, you can find over 50 previously-published microplates developing around the present ocean floor. The microplate population is far more than six large-scale plates in number.

The second one is on fundamental kinematics: Microplates as rigid or deformable blocks not only move horizontally along the small girdles around the Euler poles or self-rotation axes on the surface Earth, but also move down and up across the solid and deep spheres.

The third one is on deformation: The inner microplate is either rigid or deformable, deformation is mainly along the microplate margin and deformation can propagate into the center of microplate. For example, according to the traditional Plate Tectonics Theory, the recent earthquakes between two large plates of the Eurasia and Arabia plates in Turkey or along the South Anatolia Fault is easy to be understood. But we are difficult to understand the earthquakes along the North Anatolia Fault. If we try to understand this question from the Microplate Tectonics Theory, the Anatolian Microplate should be isolated blocks between the Eurasia and Arabia plates, even though the North Anatolia Fault is now within the traditional Eurasia Plate.

The fourth one is on evolution: Microplates can grow and perish under many tectonic settings, having relatively independent evolutionary history and undergoing either Wilson or non-Wilson cycles without the fixed period.

The fifth one is on mobilism and transition: Microplates could have been a large-scale plate in passive motion under either plate or non-plate regimes, without a limit of plate margin, microplate can develop or terminate under any tectonic settings such as previous intraplate environment of one megaplate without complete cratonization, for example, the Tibet Plateau has many microplates until now.

The sixth and final one is on kinetics: Microplates have many regionally-linked or dependent driving forces or mechanisms such as plume rising, delamination, foundering, dripping, subduction, accretion, rifting and others, but the ultimate driving force should be Relay-Taylor Instability of top-down paradigm rather than bottom-up paradigm in the traditional Plate tectonics Theory.

Figure 1 shows more than 100 identified active microplates around the modern Earth.

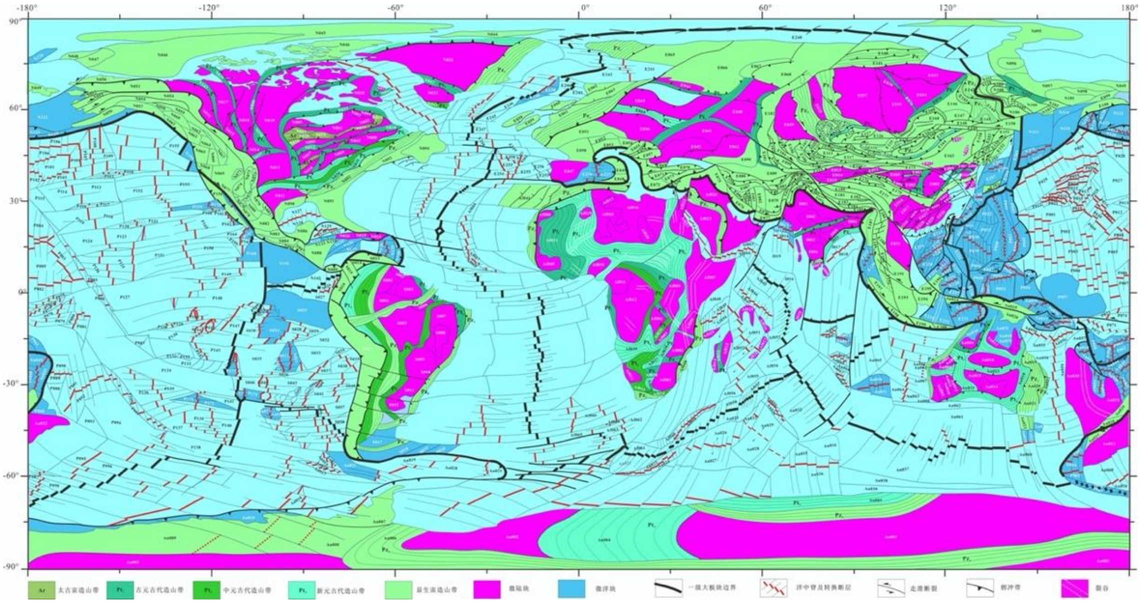

Fig. 1: Initial OUC2022 version of global microplate division (see Li et al. 2022).

In addition, over 800 fossil microplates are used in the GPlates software. And over 10000 stagnant mantle microplates through the mantle have been revealed by tomographic imaging. So, you can find microplates across many solid spheres rather than only in lithosphere as mentioned in the traditional plate tectonics theory.

4 The differences between Plate and Microplate Tectonics Theories

Traditionally the Earth lithosphere was divided into 6 to 13 megaplates. Now we divide the Earth lithosphere into over 861 continental and oceanic microplates (see Li et al. 2022). The division evidence is from crustal thickness, free air anomaly, Bouger anomaly, magnetic anomaly and earthquakes. Microplate behaviors is so different from megaplate behaviors as mentioned before.

The first difference between microplates and megaplates is in plate boundary. There are only three basic types of megaplate boundaries: subduction zone, mid-ocean ridge and transform fault. However, microplate boundaries have over 20 types. One large-scale plate can be generally subdivided into or interacted with many microplates with different types of microplate boundaries along different segments.

Except for divergent, convergent and transform plate boundaries, microplate boundaries also include: detachment fault, strike-slip fault, fracture zone, lithosphere-penetrated fault, pseudo-fault, oceanic convergent belt, overlapping spreading ridge, continental rift belt, continental collisional belt, mantle rheological discontinuity, non-transform offset and others. It means that all large-scale faults can be microplate boundaries. All of them can be either active or fossil. For example, around the Galapagos Microplate are oceanic spreading ridge, oceanic transform fault and oceanic collisional belt (see Bird 2003).

The second difference between microplates and megaplates is in compositions. The megaplate lithosphere with complex material properties has not a unified rheological behavior. Therefore, the typical "intraplate" deformation within large-scale plate lithosphere actually develops along microplate margin. However, the microplate composition is relatively unified, microplates have three composition-based categories: continental microplate dominated by continental crust, oceanic microplate dominated by oceanic crust, mantle microplate dominated by continental or oceanic mantle lithosphere.

The third difference is temporal-spatial relations among microplates away from megaplate margin. Spatial relation between microplate and megaplate can be vertically imbricated, superposed or overriding in the Microplate Tectonics Theory, but Two large plates are generally horizontal or parallel in lithospheric level according to the traditional Plate Tectonics Theory. Mantle microplates away from the subducting parent slab can be vertically and contactless coupled with lithospheric megaplate such as cratons, but large plates are usually limited in lithosphere in the traditional theory of plate tectonics.

The fourth difference is in evolution. Microplates not only develop under the plate tectonic context, but also occur in deep-past non-plate or pre-plate tectonic context. The dynamic mechanism of microplate changes with the thermal evolution through time of the Earth, it does not have a unified dynamic mechanism forever. Even if microplates are driven by mantle convection in early Earth, there are great differences in convection patterns at different stages, and the driving objects have also changed dramatically. Microplate tectonics can be applied not only to the present intracontinental and intraoceanic, but also to the early Precambrian and even to stagnant lid tectonics, and even to the initial formation stage of the shield or craton, which runs through the entire Earth history. To develop the theory of plate tectonics, our ultimate goal is to establish a unified planetary tectonics theory including pre-plate tectonics, early plate tectonics and modern plate tectonics.

The fifth difference is in kinematics. Megaplate can only move horizontally without any rotation around its own rotation rather than the Euler pole. Mantle convection velocity is generally lower one order than plate velocity. So, mantle convection should be possibly passive, not actively to drive large plate. Plate motion sense can be changed immediately as a change of forcing direction at the plate margin, so the curved hotspot track is not derived from the bending of one straight motion track responding to the anticlockwise Pacific plate self-rotation. Microplates have diverse motions such as self-rotation under toroidal mantle flow, and horizontal sliding, rising and dropping across different spheres under poloidal mantle convection.

The present-day active microplates are mainly formed along the margins of large-, middle- and small-scale plates. Under plate tectonic regime, most of continental or oceanic microplates are passive in kinematics, but many large-scale plates are active driven by subduction or phase transition.

Besides horizontal motion, there are also vertical motion and rotation for microplates. However, many large-scale plates are difficult to rotate by themselves as mentioned before.

Especially although some fossil microplates have become internal or marginal parts of supercratons, stable continental or oceanic megaplates in the lithosphere, or LLSVPs in the mantle, these fossil microplates can be re-activated during the other factors. If so, large plates are long-lived and can be tessellated again.

The sixth difference is on diverse growth models of microplates to megaplate. The growth of continental megaplates is generally dominated by lateral subduction, accretion and collision and amalgamation with other small continental slivers or microplates similar to that of the North American Craton. The growth of oceanic megaplates is dominated by lateral spreading, ridge accretion and jumping. Both continental and oceanic megaplates can have vertical accretion due to magma underplating or large igneous province. In addition to the mentioned-above ways, there are many other growth ways for microplates.

The final difference is in origin. Oceanic megaplates must be generated by mid-ocean ridges, continental megaplates must be generated along subduction zones. However, the formation sites of microplates are diverse, they can appear in any tectonic settings including intraplate and lower mantle. Until now we listed 10 mechanisms to form microplates as shown in this table. They are detachment-derived, rifting/spreading-derived, transform-derived, ridge propagation-derived, ridge jumping-derived, subduction-derived, accretion-derived, collision-derived, delamination-derived and so on (see Li et al. 2018). Of course, it is not limited in this list, such as impact-derived.

Although the investigation of marine geology and geophysics gave birth to the theory of plate tectonics, but the theory has always faced the problem of "plate origin" for more than 50 years. Actually, this problem is essentially how continental microplate originated within the early ocean and how to reconstruct ocean-continent configurations in the deep-time Earth system. Answering this problem will help us to improve the theory of plate tectonics. So, in the past 30 years we focused on the micro-continental assembly and the reconstruction of the ocean-continent configuration in the deep-ocean basin since 2.5 Ga, a new mechanism of rift-closure orogeny within one continent has been proposed from the perspective of plate tectonics, which has been constrained to originate between 2.5 Ga and 2.2 Ga. We also dynamically reconstructed the global continental microplates and paleo-ocean configuration since 1.8 Ga, revealing the three ways of rift-closed, collisional and accretionary microcontinental assembly into megaplates although it is not an origin of the first continent.

In addition, based on the formation of the continental microplates in the Tethys Ocean, a variety of dispersal mechanisms for continental microplates to break up from one megaplate and enter the ocean are proposed, and the deep-shallow processes of the multiple-stage breakup of supercontinent to continental microplates under the global tectonic framework between 1 Ga and 200 Ma are dynamically reconstructed. In fact, the driving force of microplate migration has many mechanisms rather than only mantle convection.

Based on tectonic reconstruction of the assembly and dispersal processes of some continental microplates in the present-day western Pacific Ocean, it is revealed that the Cenozoic Nansha, Palawan and other continental microplates are also split from the surrounding continental megaplates. The "trinity" of these results reveals the uniqueness of the assembly and dispersal behavior of the deep-time continental microplates relative to the "megaplate", and also provides a new model for solving the problem of continental microplates in the present-day ocean basin. That means that microplates have many kinds regimes for their origins.

Of course, we can replace to think about the first microplate on the Earth being derived from the first continental microplate to the first oceanic microplate. If so, the problem of plate origin in the traditional theory of plate tectonics is easy to explain. The original mechanism of the first oceanic microplate has many possibilities rather than only one mechanism.

Then, how to understand the conundrum on intraplate deformation in the traditional theory of plate tectonics. The ocean-continent transition zone is a complex zone in which the deep and shallow oceanic and continental lithospheres have intensive interaction. Not only the diversity of basin genesis of its surface system is difficult to be explained by the subduction process of a single oceanic megaplate, but also how far oceanic plate subduction can affect the hinterland of the continent? What is the effect? This is the "intraplate deformation" problem faced by traditional Plate Tectonics Theory. However, when we subdivide one megaplate into many oceanic or continental microplates, the far-field forcing rather than slow mantle convection can trigger the reactivation of pre-existing faults within the present megaplate as new microplate boundaries.

Therefore, we believe that the Microplate Tectonics Theory can answer three previous conundrums remained in traditional Plate Tectonics Theory. Based on microplate tectonics theory and its technical system of numerical modeling for deep-time Earth System, the mechanisms of deep-shallow coupling, ocean-continent coupling, flow-solid coupling and long-term and short-term coupling of the global and regional deep-time Earth system can be analyzed for precise resource exploration, AI sensing and digital prediction combined in the meta-Earth. We also can use Carbon Tectonics (see Li et al. 2022). Three-dimension microplate reconstruction of our recent results (see Liu et al. 2023), combined with deep-time mantle dynamics and paleogeographic reconstruction, will help the future study of the Earth system involving atmosphere, hydrosphere, biosphere and geospheres.

Microplates are attracted many scholars since the earliest start of 21th centry (see Bird 2003; Stampfli et al. 2013; Harrison 2016; Mallard et al. 2016; Torsvik/Cocks 2017; Vérard 2021; Hasterok et al. 2022). But they were named so many terms such as micro-continental plate, microcontinent, continental fragment, continental sliver, terrane or superterrane, collage, massif, platelet, subplate, cratonic nuclei, shield, H-block for continental microplate; and oceanic plateau, arc terrane, accretionary wedge or complex for oceanic microplate(see Wells/Heller 1988); and subducted slab, subducting slab, delaminated body, stagnant slab, drip, ocean-continent transition zone, ocean core complex, exhumed mantle, mantle patch and mantle blob(see Anderson 2007） for mantle microplate. Thus, we recommend here seriously the microplates as three-fold division of continental, oceanic and mantle microplates.

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