West Pacific and North Indian Ocean Seafloor and Their Ocean-Continent Connection Zones: Evolution and Debates

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Abstract: The Indian Ocean and the West Pacific Ocean and their ocean-continent connection zones are the core area of "the Belt and Road". Scientific and in-depth recognition to the natural environment, disaster distribution, resources, energy potential of "the Belt and Road" development, is the cut-in point of the current Earth science community to serve urgent national needs. This paper mainly discusses the following key tectonic problems in the West Pacific and North Indian oceans and their ocean-continent connection zones (OCCZs): 1. modern marine geodynamic problems related to the two oceans. Based on the research and development needs to the two oceans and the ocean-continent transition zones, this item includes the following questions. (1) Plate origin, growth, death and evolution in the two oceans, for example, 1) The initial origin and process of the triangle Pacific Plate including causes and difference of the Galapagos and West Shatsky microplates; 2) spatial and temporal process, present status and trends of the plates within the Paleo- or Present-day Pacific Ocean to the evolution of the East Asian Continental Domain; 3) origin and evolution of the Indian Ocean and assembly and dispersal of supercontinents. (2) Latest research progress and problems of mid-oceanic ridges: 1) the ridge-hot spot interaction and ridge accretion, how to think about the relationship between vertical accretion behavior of thousands years or tens of thousands years and lateral spreading of millions years at 0 Ma mid-oceanic ridges; 2) the difference of formation mechanisms between the back-arc basin extension and the normal mid-oceanic ridge spreading; 3) the differentials between ultra-slow Indian Ocean and the rapid Pacific spreading, whether there are active and passive spreading, and a push force in the mid-oceanic ridge; 4) mid-oceanic ridge jumping and termination: causes of the intra-oceanic plate reorganization, termination, and spatial jumps; 5) interaction of mantle plume and mid-oceanic ridge. (3) On the intra-oceanic subduction and tectonics: 1) the origin of intra-oceanic arc and subduction, ridge subduction and slab window on continental margins, transform faults and transform-type continental margin; 2) causes of the large igneous provinces, oceanic plateaus and seamount chains. (4) The oceanic core complex and rheology of oceanic crust in the Indian Ocean. (5) Advances on the driving force within oceanic plates, including mantle convection, negative buoyancy, trench suction and mid-oceanic ridge push, is reviewed and discussed. 2. The ocean-continent connection zones near the two oceans, including: (1) Property of continental margin basement: the crusts of the Okinawa Trough, the Okhotsk Sea, and east of New Zealand are the continental crusts or oceanic crusts, and origin of micro-continent within the oceans; (2) the ocean-continent transition and coupling process, revealing from the comparison of the major events between the West Pacific Ocean seamount chains and the continental margins, mantle exhumation and the ocean-continent transition zones, causes of transform fault within back-arc basin, formation and subduction of transform-type continental margin; (3) strike-slip faulting between the West Pacific Ocean and the East Asian Continent and its temporal and spatial range and scale; (4) connection between deep and surface processes within the two ocean and their connection zones, namely the assembly among the

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Eurasian, Pacific and India-Australia plates and the related effect from the deep mantle, lithosphere, to crust and surface Earth system, and some related issues within the connection zones of the two oceans under the super-convergent background. 3. On the relationship, especially their present relations and evolutionary trends, between the Paleo- or Present-day Pacific plates and the Tethyan Belt, the Eurasian Plate or the plates within the Indian Ocean. At last, this paper makes a perspective of the related marine geology, ocean-continent connection zone and in-depth geology for the two oceans and one zone.

Key words: the Belt and Road, Indian Ocean, West Pacific Ocean, ocean-continent connection zone, seafloor, marine geodynamics

1 Introduction

The West Pacific Ocean and Indian Ocean as well as their ocean-continent connection zones (hereinafter referred to as “two oceans and one zone”) constitute the core area of the Belt and Road initiative and involves more than 60 countries covering the region of the Maritime Silk Road and the ocean-continent connection zones (OCCZ) geographically (Fig. 1). The purpose of the China-proposed Belt and Road initiative is to build the community of common destiny for all the countries along the Belt and Road, and promote the sustainable and stable development of human society. Thus, co-development of world’s multi-nation social integration via implementation of the Belt and Road initiative needs scientific support on the basis of international cooperation. China, as the country advocating the initiative, should seize every opportunity to launch a big international scientific project with participation of excellent scientists from all over the world on the key geoscientific issues of the Belt and Road region. On this background, it is definitely necessary and important that we carry out study on the two oceans and one zone in a timely manner.

Oceanic and continental lithospheres are two basic tectonic units having different composition and structure in the lithospheric section on the planetary Earth. They are of co-evolution partners operating in a fashion of interaction and mutual transition. To improve recognition of ocean and continent is fundamental for exploring the Earth. Besides a separated study on ocean and continent themselves, to focus on the transition and connection zones is coevally a direct way to study ocean and continent and their relationships. The study closely relies on a joint research on both, no knowledge about ocean means no recognition of continent, or vice versa. To develop the 4-D comprehensive study from oceanic crust (including seawater and related fluids) and continental crust on the Earth’s surface to deep oceanic mantle and continental mantle can reveal the essence of the ocean and continent and their relationships and further recognize the planetary Earth system as a whole. Among all the OCCZs on the Earth, those distributed in the region of the West Pacific Ocean and North Indian Ocean are extremely characteristic in terms of geoscience, and posses important strategic significance since they are located in or near our territorial water and homeland as well as they occupy the position of our pass way to deep ocean in the world.

In the history of mankind, the two oceans and one zone representing the core area of the Belt and Road have been an important region for human origin, breeding, migration, conflict, rise and fall of civilization. And today, the region is still a joint part of political, economic, military competition and development of the Human being -Earth relationship. As for geoscience, a series of global key issues are concentrated in the regional geology of the two oceans and one zone. For example, since the Mesozoic, the modern plate tectonics has been extremely active in the region where the amalgamation of three global-scale plates of the Eurasian, paleo- and modern Pacific Ocean and Australian occurred. The Laurasia Continent to the north and the Gondwana Continent to the south and the Tethyan belt in between have been experiencing prolonged supercontinental assembly and break-up processes through complicated subduction, collision and oceanic opening, closing and extinction as well as intensive interaction between the deep mantle, upper lithosphere, crust and surface Earth system, forming the widest tectonic domain, the most complex configuration of ocean-continent and ocean-ocean conjunction and transition, large-scale metallogenic zones (Hou and Zhang, 2015; Richards, 2015; Deng et al., 2017) and oil-gas enriched reservoirs (Gan et al., 2000; Qiu et al., 2009) on the Earth. The place also has the unique topographic relief on the Earth characterized by the third pole—the Himalaya Mountains and the so-called fourth pole—the Mariana Trench, deeply reflecting peculiar geodynamic background of the region. The surface Earth system of the complex OCCZs around the two oceans is an interface where the Earth’s atmosphere and hydrosphere strongly interact with each other, and the

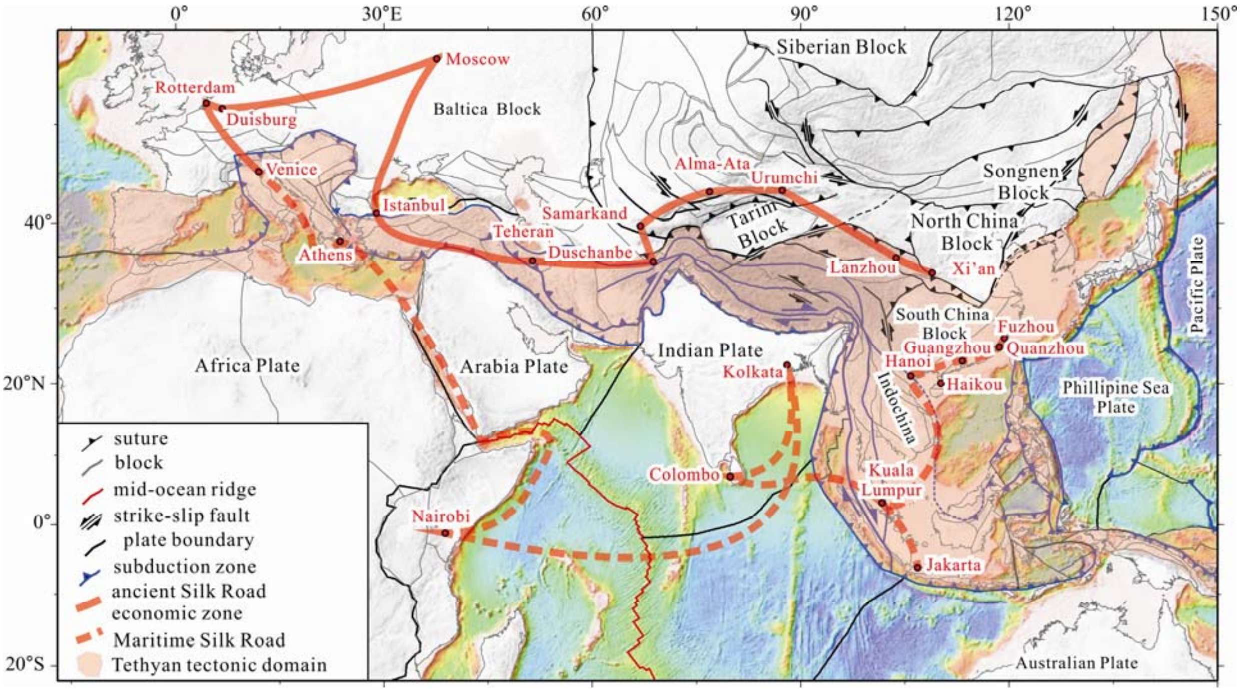

Fig. 1. Tectonic units along the Belt and Road.

critical zones where the effect of sedimentary source to sink and carbon cycling between the shallow and deep portions in crust and mantle occur, which create a striking biological diversity and on the other hand result in frequent and serious natural disasters. Interaction of oceanic/continental lithospheres induces earthquake, tsunami, volcanic eruption, sea-floor landslide and so on, while multi-scale ocean-continent interaction in the critical zones changes and/or worsens the Human Being-Earth environment, which attracted a lot of attention from human society and science community.

In summary, the regional geology of the Maritime Silk Road and the composition, structure, evolution and dynamics from deep to shallow Earth in the two oceans and one zone bring forward a number of critical scientific questions such as the present-day recognition about the two oceans and one zone and unsolved core issues, the natural law regarding the interaction between the spheres across ocean and continent and its processes, constrain on the interaction of solid and liquid oceans and its essence, issues of the regional mineral and energy resources and environmental hazards in the two oceans and one zone, the driving force and its origin for oceanic plates and various effects, the general trend of regional development and sustainable development of human society and so on. Thus, to recognize the interrelations of atmosphere-hydrosphere, ocean-land and crust-mantle, especially their horizontal and/or vertical critical interfaces has become a key issue to learn about processes and dynamics of the Earth system which has been so far the weakest research field. Although a series of achievements have been made in the past, we are now facing more unsolved problems related to the regional and global geology, as the initiation of the Belt and Road strategy, further highlighting the importance and urgency for solving these problems. From the view of marine geology, especially of Marine geodynamics, this paper will focus on the following three scientific issues: 1) Geology of the two oceans; 2) Geology of the OCCZs and 3) Connection and transition, convergence and effects of two oceans and three plates from the deep mantle to the surface Earth system. The scientific issues will be discussed in the order of the West Pacific Ocean floor and the related OCCZs, the Indian Ocean floor and its northern OCCZs, and connection and transition of two oceans and three plates and their OCCZs.

2 Frontier Scientific Issues on the West Pacific Ocean Floor and Its Connection Zones

Tectonically, the connection zones of the West Pacific Ocean extend from the Eurasian, Pacific Ocean plates to the Australian Plate, and generally cover all the areas involved in the subduction zones caused by the Paleo- and modern Pacific plates (Fig. 2) and the ocean realm to the west of the Izu-Bonin-Mariana island chain, with their western limit along the Great Khingan-Taihangshan-Wulingshan gravity gradient zone in Mainland China, and the eastern boundary located along the Izu-Bonin-Mariana

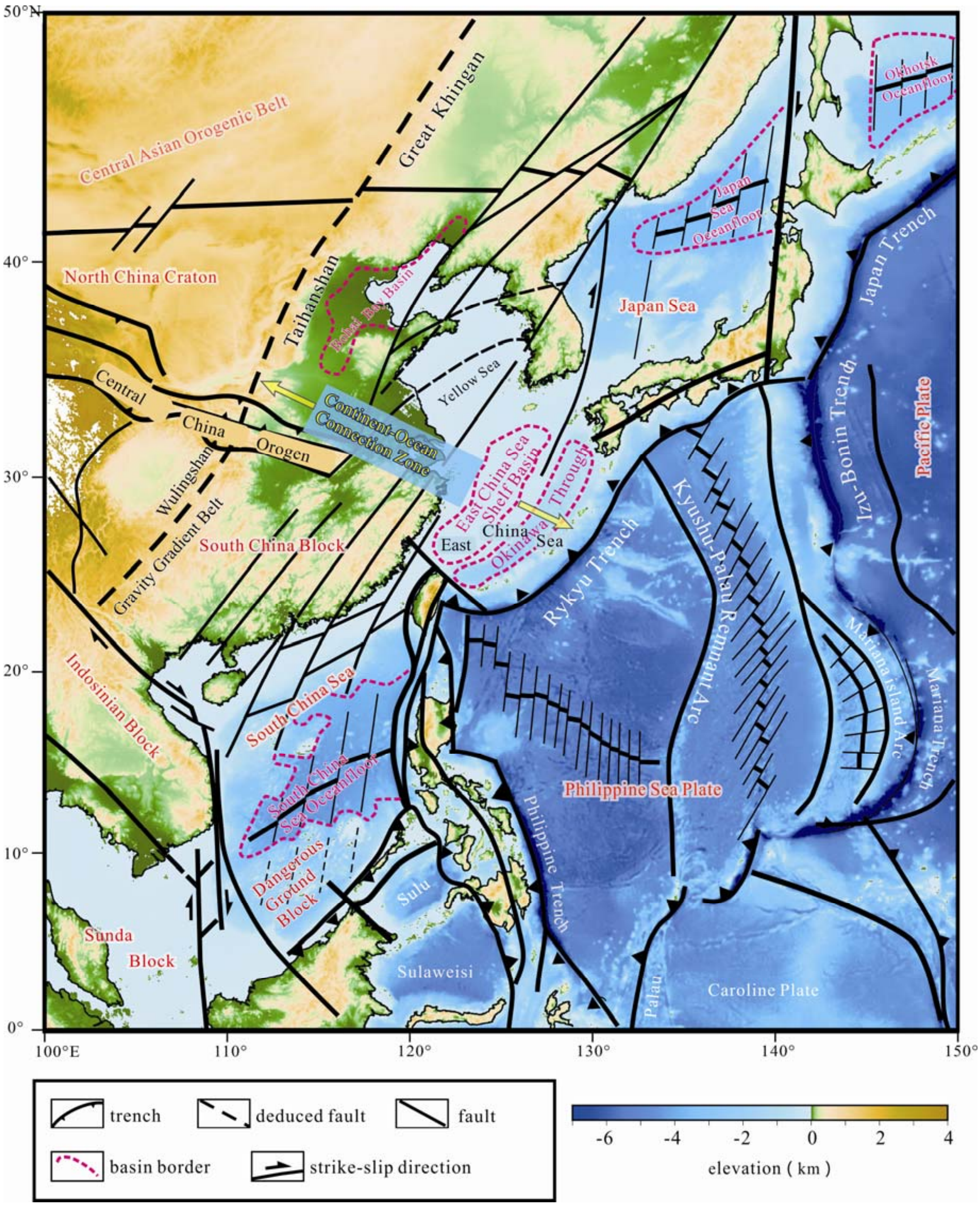

Fig. 2. Elevation and bathymetry of the West Pacific Continent-Ocean Connection Zone and Location of the Study Area (after Jiang et al., 2017).

Trench (Jiang et al., 2017). The ocean, trenches, island arcs and basins in the whole region are configured in a complex structural pattern, representing a peculiar tectonic domain. It is obvious that the West Pacific Ocean and its OCCZs possesses significant position for China in terms of national sovereignty, politics, military, economy, ecological environment and scientific research. Firstly, the region including the east and southeast China continent and islands occupies the important strategic location regarding homeland border security. Secondly, the region is the base for building up naval power and the access to go to the deep blue. Thirdly, the region has a large population and developed social economy, representing our economic lifeline; Fourthly, the region has many abundant natural resources and complicated ecological environment which should be protected and developed.

As mentioned above, the West Pacific Ocean and its OCCZs are similarly important for geosciences. It is the widest and complicated OCCZs between the Eurasian Plate and the Paleo-Pacific Plate. There are arc-trench systems in different type and size, oceanic basins and marginal sea basins in the region. It is characterized by the multiple island chains, huge sedimentary systems on the continental margin, highly-varied landform of the OCCZs, ecological settings under extreme condition, large volcanic plateau and the deepest trench on the Earth. The region has been experiencing some complicated subduction, collision events, strong magmatic and hyperthermal activities, crust-mantle interaction and geodynamic processes operating between the regions, the Tethyan belt and the Indian Ocean. The surface Earth system here is a typical interaction interface of the lithosphere, hydrosphere and atmosphere, forming a relatively independent scientific system containing information about the Paleo-Pacific Ocean. The region shows a great change in topographic relief and controls the temperature and salinity in water body of the ocean and atmosphere. In a word, the West Pacific Ocean and its OCCZs is an ideal natural laboratory and experimental base where the breakthrough of globe-class grand scientific challenges can be made (Li et al., 2012).

Based on previous study and current development, we discuss the critical questions as follows.

2.1 Origin, initiation and evolution of paleo- and present-day Pacific Plate

For the origin, commence and evolution of the Paleo- and present-day Pacific Plate, the outstanding questions are: How the original triangular or polygon intraoceanic microplate originated and started within the Paleo-Pacific Ocean floor, and became different plates in the Pacific Ocean, which affected the eastern margin of the Asian continent and eventually transformed into the unified ocean-continent connection.

The Pacific Ocean, a long-lived old ocean, has undergone a prolonged evolution and is now experiencing the change of mid-oceanic spreading and marginal subduction (shrinking). Some plates in the Pacific Ocean have been subducted, the others are still growing and evolving. The Pacific Plate is situated in the region to the west of the present-day Pacific mid-oceanic ridge, while the oceanic area to the west of the Bering Strait-Hawaii Islands-Society Island of the Polynesian Island Chain belongs to the West Pacific Plate whose the western part is separated from the Eurasian Plate with the OCCZs formed by subduction and accretionary processes. Additionally, the paired subduction zones and the corresponding island chains are developed within the plate, and the Philippine Sea and Caroline plates are sandwiched between the two chains in plan view. The southern part of the West Pacific Plate is in conjunction with the Indian-Australian Plate.

Previous studies on the formation of the original triangular Pacific Plate can be divided into two schools. One school suggested that the primary plate originated from the RRR type triple junction in the sea-floor (Engebretsonet al., 1985; Mueller et al., 2008). The other proposed that three mid-oceanic ridges did not meet in one point, instead they propagated to crosscut one another and generated a triangular block (Boschman and van Hinsbergen, 2016), and then grew outward around the block to the present-day scale. In other words, the Pacific Plate completely originated from the intraoceanic plate setting. However, the problem of these models is that new study found that the Pacific Plate is not composed entirely of oceanic crust, today its eastern boundary is marked by the mid-ocean ridge in the California Bay—the San Andreas continent-type transform fault—the Juan De Fuca Ridge, to the west of the boundary there is a small island arc-the Guerrarite Terrane. Moreover, its present southwestern limit is along the Alpine transform-type continental margin, and there are Campell Plateau and Chatham oceanic rise which are recently thought to be a submersed continental block in SW New Zealand and the adjacent area in the ocean interior. Although these need to be studied further, the conclusion of the Pacific Plate in the origin of pure intra-oceanic setting has been shaken. Since the continental block is near the eastern and southeastern margin of the plate, some people employed ridge jumping, subduction-captured continental block and supercontinental break-up-related continental block to explain its formation. However, the interpretation for the formation of the early triangular Pacific Plate is not convincing. So, for the origin of the triangular core especially the Galapagos triangular microplate in the east Pacific Rise, further study is definitely needed.

2.2 Over one thousand years and ten thousand years behavior, growth pattern and dynamics of mid-oceanic ridges

The magnetic lineations clearly exhibit lateral spreading and accretion processes of ocean floor during one million years period. Vine and Matthews' hypothesis reasonably explained the lateral spreading mechanism of oceanic crust (Vine and Matthews, 1963; Vine and Wilson, 1965). However, the oceanic crust growth of less-than-one-million-year-long time scale in the 0 Ma magnetic lineation does not seem to fit the mechanism, due to its vertical growth. Recent dating results interpret the lava flooding event at mid-oceanic ridge on an one-thousand-year-long time scale. Therefore, the question regarding the accretion mechanism of mid-oceanic ridge even oceanic crust is how the ridge accretion behavior at an one-thousand-year-long time scale is transformed to that at an one-million-year-long time scale. If we attempt to reveal one thousand-year accretion pattern during one million-year period, the complete drill core of oceanic crust must be required. This should be a real need for an ocean drilling plan to drill through the Moho although the Moho is exposed on sea-floor in some cases.

Taking fresh drill core samples from each million-year magnetic stripe of mid-ocean ridges for elaborate geochronological study can make up the time link missed in oceanic crust accretion investigation, also can find the link between the million-year-long processes and a one-thousand-year-long behavior for oceanic crust growth, promoting a further study on control factor in compositional change of the ridge rocks at different time scale. The following questions need to be addressed too: What processes in magma chamber at depth in mid-oceanic ridges determine the behavior at different time scale in shallow portion? How are magmas or magma chambers distributed and migrating along the different axial segments along a mid-ocean ridge? What is a reason at depth for a different mid-ocean ridge growth speed? How do these behaviors control the fluid distribution of hypothermal vents? How can a hydrophone be adopted to probe the temporal-spatial evolution of ridge behavior such as small earthquake, fault propagation, geofluid-magma migration?

2.3 Motion senses of the Pacific Plate and deformation processes of the OCCZs

Previous study indicates that the Mid-Late Mesozoic change of motion senses of the Pacific Plate is closely related to the destruction of the North China Craton (Zhu et al., 2012), and the Cenozoic different strikes of the seamount chains in the Pacific Ocean are identical to the various extensional processes of the intraplate basins in the continental margins (Huang et al., 2015). The correlations of the various oceanic plate motion senses to the principal stress directions in the basins of the OCCZs means that the OCCZs were under a strong coupling state, particularly the plates on both sides of the subduction zone kinematically couple with each other (Suo et al., 2014, 2015; Suo et al., 2017). But how to determine the processes to be coupling or decoupling through study on the subduction zones? How do the oceanic and continental plates on the both sides of the subduction zones couple? Is subduction the driving force for plate motion? At present, it is obviously difficult to answer these questions. Recent study found that the sequence of events occurring in the Pacific Plate is as follow: 135 Ma, 100 Ma, 85 Ma, 45 Ma and 21−13 Ma. A great amount of work on plate reconstruction, especially the work done by Mueller et al (2008) has revealed that the Pacific Plate did not directly affect the continental margin of east Esia 60 Ma ago. Liu et al (2017) suggest that the Pacific Plate was stagnant in the mantle transition zone of the eastern East Asia during subduction, which was completed during recent 30 Myr. The results are so different from traditional understanding by Earth science researchers that it needs to be carefully considered if the Mesozoic deformation of the OCCZs was directly related to the subduction of the Pacific Plate (Jin et al., 2009; Zhang et al., 2013; Zhang et al., 2017; Guo et al., 2017). So far some studies have thought that all the plates in the Paleo- and modern Pacific Ocean domain have successively taken turning in their evolutionary history, which have directly affected the OCCZs or continental margins. However, the studies also indicate that a fine reconstruction of the plate configuration of the Paleo- and modern Pacific Ocean plates and their temporal-spatial evolution is the key to deepen our understanding of ocean-continent dynamic processes and interactions.

2.4 How a transform fault turned into an intraoceanic arc

Niu et al (2005) recently argued that the precondition for subduction to initiate in an intraplate is of density difference like the cases presented between oceanic and continental crust on a passive continental margin. However, there is no density difference in some intra-oceanic or intraplate setting. Thus, the initial mechanism of subduction is still an unsolved problem by the model given by Niu et al (2005). The Mariana Trench is an intra-oceanic arc, Hilde et al (1977) brought up in an early time that the Mariana Trench was caus by edge convection along a near S-N trending transform fault or a fracture zone, which turned into a subduction zone, the mechanism could be that the old lithosphere in the western part of the Pacific Plate became thicker than that of the young Philippine Sea Plate, which led to edge convection at the contact transform fault or fracture zone between the two lithospheres of different thicknesses and resulted in a subduction of the old lithosphere. In the model, that subduction of the mid-oceanic ridge perpendicular to the East Asian continental margin could interpret the formation of the slab window on the continental margin. Nevertheless, the model of Hilde et al (1977) has no way to illustrate the the paleomagnetic data indicating a near 90 degree rotation of the Borneo Block. The plate reconstruction of Mueller et al (2008) and Seton et al (2012) also suggested that the Mariana Trench was generated from a transform fault or a fracture zone. Different from Hilde et al (1977), in their model the original strike of the Mariana Island Arc was in an east-west strike and then it rotated to the present-day north-south strike, which addresses the issue of the rotation of the Borneo Block. However, in the model, a mid-ocean ridge between the Izanagi Plate and the Pacific Plate was parallel to the continental margin and it started subducting underneath the East Asia at 60 Ma in the model. In the case, it is difficult for the model to explain the formation of adakite related to the subduction of mid-oceanic ridge on the continental margin of East China and Japan (Kinoshita, 2002; Zhang et al., 2001, 2008; Sun et al., 2007). Therefore, it is necessary to explore the unknowns including different mechanisms of the adakite, while the key is to reasonably reconstruct the framework of the intra-oceanic plates and reveal the genesis of the intra-oceanic island arcs.

2.5 Why mid-ocean ridge can jump and how microplate initiate

Until now, the complex processes within oceanic plate is not recognized by people. For instance, a new microplate, called ridge-jumping-related microplate by authors, was formed to the west of the Shatsky Rise due to ridge-jumping. The seamounts or oceanic plateaus can block the subduction zone during a subduction, which result in a microplate formed along the continental margin. The microplate can be called plateau-docking microplate; a new microplate can also occur in the place between the new-born ridge of a back-arc basin and the subduction zone after a back-arc basin is formed, like the Mariana Island. This sort of microplate is named back-arc-rifting microplate; When a ridge is subducting close to the continental margin, the zigzag ridge and arc-shaped trench could capture a ridge-subducting-related microplate; Conversely, when the mid-ocean ridges propagate toward each other and link to each other along the ridge strikes, overlapping spreading center occurs and gradually evolves to a new microplate called ridge-overlapping-related microplate. In a word, the formation of microplates is not simple, intra-oceanic setting and ridge propagation are complicated and varied, to clarify the forming processes and mechanism of microplates can improve the paleo-oceanic reconstruction and fill in the blank of intra-oceanic tectonic configuration.

2.6 Genesis and geochemical characteristics of back-arc basaltic magmas as well as origin of back-arc transform fault

The back-arc basin is referred to a deep-water basin with oceanic crust basement. But the thickness of oceanic crust in most of back-arc basins is clearly thicker than that of the normal oceanic crust. So, in this case, is the accretion mechanism for the basement of back-arc basins as the same as that of mid-ocean ridge? Why is the thickness of initial oceanic crust in back-arc basin different from that of the normal oceanic crust? Is the magma-forming mechanism in both back-arc and mid-oceanic ridge different from each other? To what degree is geochemistry of basaltic magmas imprinted by components from the rifted or drifted continental lithospheric mantle, subducted materials and asthenosphere under the continental lithosphere (its component is possibly not as the same as the asthenosphere under the mid-oceanic ridge)? Numerical modelling shows that some subduction zones can suddenly retreat at a large scale, which leads to initiation of new subduction zones within the ocean and in turn the new back-arc basins, and the magmas in these new back-arc basins are derived from the asthenosphere under the oceanic lithosphere, resulting in geochemical diversity of the magmas in the back-arc basins. As for the intra-oceanic arcs with different spreading speed, is their geochemistry the same (Taylor and Martinez, 2003)? Is there any correlation between the formation of transform faults in back-arc basin and the pre-existing strike-slip faults in the OCCZs? For example, is the transform fault in the Okinawa Trough in a NW-trending or NNE-trending strikes (Liu et al., 2016)? If in the NNE strike, what kind of linkage does it have to the large-scale strike-slip faults on the East Asian continental margin? To answer the mentioned-above questions, attention should be given to the ocean-continent interaction and the effect in the OCCZs and the complex trench arc-basin system.

2.7 Driving force of plate motion and subduction initiation

The subduction mechanism (origin, initiation, effect and dynamics) of the oceanic and intra-oceanic plates is still a puzzle. The similar issue in the West Pacific Ocean and its OCCZs are outstanding and waiting for solution.

When was the continental margin of the West Pacific Ocean transferred from the passive margin to the active margin (Suo et al., 2012; Li et al., 2013)? When and how did a series of subduction zones form? How many types for them? How did the intra-oceanic subduction initiate? How did a transform fault change to a subduction zone (Li et al., 2013) ? Here we highlight the issue that the subduction is passive or active when it initiates. In other words, we would like to know whether or not the subduction generates the driving forces for plate tectonics.

(1) Mid-oceanic ridge push: The oceanic asthenosphere is generally elevated in mid-oceanic ridge and downflowed in the subduction zone, making the boundary between the lithosphere and asthenosphere become a gentle slope and a wedge-shaped lithosphere cross-section be formed. When leaving the hot ridge, the lithosphere is descending to deep mantle due to cooling, which makes the asthenosphere material successively increase and attach to the bottom of the overlying cool lithosphere. As a result, the lithosphere is getting thicker and thicker. The thickened lithosphere causes the density difference for the whole plate and forms a dipping interface at the bottom of lithosphere. The high elevation of mid-ocean ridge having potential energy forces ridge to move to both sides in order to reach the lower energy state. As a result, the spreading plates produced on the divergent plate boundary can slide downward under gravity. This is referred to the mid-oceanic ridge push force. The major factor in the mentioned-above processes is the horizontal mass difference on the lithospheric plate and the dipping interface formed from the wedge-shaped lithosphere. Both make the plate sliding possible. The classical plate tectonics theory thinks that the gravity sliding (or mid-oceanic ridge push) is a major driving force for pushing plate to move. This kind of force is derived from the continuous upwelling mantle materials along the ridge axis, like a chock-knocked into the plates and push them to drift apart. The compressional stress state in the plate interior is in favour of ridge push model. The force acting at right angle to the mid-oceanic ridge has the strength equal to the loading of uplifted terrane and is not dependant on the spreading speed. However, the mid-oceanic ridge push force has the following questions: (1) Does the limited liquid or viscous upwelling magmas have capability to push a large-scale solid plate with the width of a few thousands of kilometers away? (2) Suppose that the ridge push force is right, what is a driving force for plates without mid-oceanic ridges developed, like the Philippine Sea and Caribbean plates? (3) Observation of mafic dykes in Iceland and other places indicates that the dykes freely intruded in extensional settings and have filling-in in nature. From this, it demonstrates that ridge push force cannot be the driving force to push plates to move laterally because the magmas did not force in, whereas dragging of gravity of oceanic plate itself played the role. In the case, intrusion of magmas into the ridge is a passive process, which is called ridge suction. (4) The investigation by bathymetry discovered that tensional fissures developed on the central valley margins of a ridge is wider than those in ridge axis. This is not easy to be interpreted by the ridge push force although the oceanic core complex was adopted to do so in 1990's; (5) Calculation indicates that the oceanic plate has enough potential energy to overcome the friction on the bottom and slide downward. However, some part of the oceanic plate moves in the direction differed from that of moving down; (6) Establishment of this model have to rely on the potential energy difference created by upwrap of mid-oceanic ridge or asthenosphere; (7) It is difficult to use the ridge push force alone to illustrate ridge jumping and subduction.

2) Gravity drag force of subducting plate: After having cooled in more than one hundred million years, a lithospheric plate moving from an accretion boundary to a subduction zone has become thickened and denser in its mass. When density of a subducting plate surpasses that of a surrounding mantle, the density difference generates a negative buoyancy. Therefore, it is clear that the older a plate is, the greater its density is, and in turn the larger its negative buoyancy is. In addition, the phase change accompanies with the subducting plate. For instance, gabbro is metamorphosed to be eclogite. Olivine phase mantle changes to spinel phase mantle. The processes make the plate density and negative buoaytncy become bigger. The negative buoyancy of a subducting plate is called the gravity drag force. The gravity drag force transmitted throughout the plate and makes it subduct, which becomes the primary power. This dynamic mechanism seems like a piece of cotton immersing in water, the wet part can drag the dry part into water. In particular, the Pacific Plate having a long-term subduction boundary has the highest moving speed, making the gravity drag force more attractive to people and thus the force is described as a subduction engine. However, the model cannot explain the following phenomena: (1) Motion of some plates without subduction zones (e.g., the Antarctica Plate and the African Plate) or obduction plates (e.g., the Eurasian Plate, American Plate and others) has nothing to do with the gravity drag force; (2) A reversal of the subduction polarity and the formation of new subduction zone; (3) Subduction of the spreading ridge; (4) Can dragging at one end have enough force and strength pull the rest of plate (as wide as a few thousands kilometers) moving as one thing? (5) Existence of the normal faulting outside trench shows elastic bending since the subducting slab experiences a resistance, demonstrating the gravity drag force is not a driving force; (6) Gravity drag force should generate tensional stress setting throughout the subducting plate. However, the stress state inside the plate in general is in a compressional state. The example is given by the Indian-Australian Plate in the Central Indian Ocean (McAdoo and Sandwell, 1985; Cloetingh and Wortel, 1986).

3) Trench suction force (slab pull force): Only the

Pacific Ocean has this sort of slab pull due to its shrinking, while the Atlantic Ocean has no slab pull force because it is experiencing spreading. The trench possesses slab pull force acting on the margin of the continental plate which can drag the American and Eurasian plates to the trenches around the ocean. Because of the Earth's unchanged radius, when the Atlantic Ocean is spreading, the Pacific Ocean is shrinking and also the trenches migrate oceanward or the trench jumps when ocean plateaus collides with the continental margin. For oceanic plate, the subduction of small seamounts or abyssal plateaus cannot obstruct the subduction of a large plate or change its original motion track. However, the trench suction force so far has not been clear, it maybe come from the gravity dragging or salb pull produced by phase change of the deep subducting slab.

Furthermore, there are the other two kinds of forces: (1) Ridge suction force. Ridge may generate suction force and promote the mantle convection because it is subject to decompressional melting, which results in accumulation of the asthenosphere materials toward the ridge at low pressure. (2) Mantle plume suction force. Mantle plume (Maruyama, 1994) rises up from the deep mantle and generates suction force for mid-oceanic ridge, making the ridge gradually move close to the plume and experience ridge jumping. After a mantle plume obtains the identical position to the ridge, a large volume of heat is released and the action on the ridge becomes weak. The mid-oceanic ridge influenced by other forces decouples with the plume and migrates away from the plume, and then the plume likely forms the resistance to the plate movement again.

Lately, according to comprehensive analysis from the Tethyan belt and the Mesozoic East Asian continent including older lithosphere and preserved continent and gravity images of the Earth satellite, some researchers have emphasized the subduction engine induced by the relative movement occurring in the solid outer crust (lithosphere) of the Earth. Combining with the relevant heterogeneity and transfer of mass and density at depth of the Earth, they are also considered if the "black hole" exists in the deep Earth and generates continuous superconvergence. The "black hole" is a challenging astronomical theory which is still in debating. The theory was put forward by American physicist John Wheeler in 1967 and then it was pushed forward by British astrophysicist Hawking who brought up the "Hawking radiation". As our study object, the Earth is a planet, we have to cite some new astronomy outcomes including new theory and new viewpoints in the study on its origin and dynamics in order to deepen our understanding of the core issues of Earth science.

2.8 Sea-floor attribute: Okhotsk Sea basement is continental crust within ocean?

Ocean drilling indicates that the sea-floor can have continental crust which is dispersed on the slow and medium speed passive margin or far away from margin, and even remains as a relict in the deep water of ocean. These have been taken as an evidence against the plate tectonics. However, the idea about the ocean-continent transition zones can explain the above phenomena well, which thought the continental crust represents an extremely thinned, isolated continental relict apart from the main continent along the detachment interface. Even though crustal property of some sea-floor is worth of consideration. For example, the crustal thickness of the Okhotsk Ocean is approximately 20 km which is traditionally thought to be the transitional crust. However, there is only oceanic and continental crust on the Earth, whether the "transitional crust" exists or not is still a concept in debate. Yang (2013) suggests that the Okhotsk Ocean resulted from an abyssal plateau accretion (oceanic crust) docking or blocking along the subduction zone. Usually, the abyssal plateau is composed of oceanic crust in a thickness of 20 km. But, that the basement of the Okhotsk Ocean is the oceanic crust or thinned continental crust is not conclusive due to lacking of drilling data. Additionally, a huge continental block on the sea-floor has been reported offshore of New Zealand. Because no drilling data confirms it, its origin is also in puzzle. It is necessary to strengthen the study on the growth process of continental crust at the continental margin and continental growth in early time of the Earth.

2.9 West Pacific Ocean/Indian Ocean, the OCCZs and effects of mineralization, accumulation and geohazards

From the view of social, economical and scientific development, the mineralization, oil-gas accumulation and geohazards are significant issues in the Belt and Road initiative. Although quite a few achievements have been obtained in study on the OCCZs, generally, further research and exploration work need to be done on regional mineralization, oil-gas accumulation, environment and geohazards.

(1) We are basically weak in actual control of the deep-ocean realm of the West Pacific Ocean. The critical issue now is how we can break through the Izu-Bonin-Mariana Island Chain and strengthen the marine scientific investigation while considering the navy strategy. The purpose for this is to protect the sovereign of territorial sea and maritime and gain more data and resources in open sea. The country needs to think and plan the goal, approaches and key issues of scientific investigation in the West Pacific Ocean.

(2) Researchers from home and abroad have done a lot of work on the OCCZs of the West Pacific Ocean. In the present situation, we have to focus on the core issues including temporal and spatial division of the mineralization and geohazards in the region and recognize the property, characteristics and natural laws of the ore deposits and geohazards in the region and especially determine segmentation and zonation of oil, gas, hydrates and metallization in the OCCZs.

(3) Study on the surface Earth system of the OCCZs of the West Pacific Ocean has made great progress. However, we do need wide cooperation research on the surface Earth system and mineralization-accumulation-geohazards for extracting the key scientific issues in a way of big science and multi- and inter-disciplines.

(4) At present, the state needs to implement comprehensive assessment on the ocean-continent relationship, characteristics and mineralization and oil-gas accumulation systems between the Indian Ocean and East African continent. Taking the opportunity of building the China “Dream” ocean drilling vessel, the state can promote the large-scale scientific and technological international cooperation of China-African Union and China-ASEAN for construction of the Maritime Silk Road.

(5) To enhance comprehensive study on the regional mineralization background and ore-forming potential of the hypothermal sulfide ore deposit in the Indian Ocean ridges and Co-rich and Mn-rich nodules in the Pacific Ocean. Make effort to develop the advanced exploration and sea-floor-based mining equipments, promote talents having morality and skills to manage overseas tasks in order to safeguard the national rights and interests.

(6) It is a must to investigate the different OCCZs around the Indian Ocean and carry out the regional survey of marine geology, ore deposit mineralization and oil-gas accumulation. And recognize the various local and regional geological characteristics, natural laws and mineralization potential of the continental margin around the Indian Ocean.

(7) To analyze and evaluate the resource potential at depth of the OCCZs and the remained petroliferous basins for strategic substituting region of resources. To explore the link between the oil-gas accumulation system at depth and gas hydrate mineralization system at deep water continental slope, to study the geohazard effect from decomposition of gas hydrates and grasp the know-how of protecting and monitoring the problems.

2.10 Carbon, water, elements and biogenic elements cycle and global change

The sedimentary record of over a hundred million years on the vast sea-floor corresponds to the historic archive of global change. Establishment of the surface Earth system theory is strongly dependant on recognition of deep-time climate change. Thus, we have to refine the global climate record of various time and space through the acquirement of more drilling core samples, modelling dynamics of the Earth system constraining the paleo-ocean, paleoclimate and paleo-circulation. By doing this, to improve human cognitive capability of predicting long periodical trend of the Earth system, standardize human behavior and build the habitable planet. Abyssal sediments containing biogenic elements are transported to trench where they undergo subduction, in which dehydration, desulfurization and decarbonization occur. The processes control the carbon cycle and storage at depth but also determine carbon cycle and preservation in the surface Earth system via volcanic eruption and chemical deposits in sedimentary basins. The Earth surface system and deep Earth system belong to the complicated and dynamic Earth system, they are closely correlative. Deep carbon cycle and human activity stand for a unified and varied materials-elements system of the Earth system. The Earth material and element cycle contains a number of cycle, exchanging and kinematic systems such as the seawater-lithosphere interface element cycle, crust-mantle-scale element cycle and ocean-continent lithosphere-scale element cycle. The cycles can lead to a series of different type rock- and ore-forming processes. These are hot spots concerned by marine science and also important topics for oil-gas and solid minerals exploration on sea-floor of deep-water region.

Beside the aforesaid scientific issues, the following specific questions in the West Pacific Ocean are concerned:

(1) How is the Tethyan domain transferred to the tectonics of the West Pacific Ocean (Wang et al., 2015)?

(2) Is the Mesozoic continental margin of the OCCZs in the West Pacific Ocean the Andes an type or South China-type or intra-continental and continental margin combined?

(3) The characteristic continental margin in the West Pacific Ocean and the accumulation mechanism of oil, gas and gas hydrates?

(4) What is a background at depth and agent in the shallow portion for geological hazards at sea-floor? For example, is dissociation of gas hydrates caused by sea-level change or triggered by endogenic factors? Does gas hydrate dissociation induce landslide on sea-floor or vice versa?

3 Frontier Issues of the North Indian Ocean Floor and the OCCZs

The OCCZs in the North Indian Ocean cover the northwest, northeast Indian ocean floor and the Neo-Tethyan Tectonic Domain (Fig. 3). The Indian Ocean is characterized by unique geology with some important issues such as the ultra-slow spreading ridge, the Ninetyeast Ridge and the Chagos-Laccadive Ridge in parallel, the initial subduction or thrust system, the mantle plume-ridge interaction, the oceanic core complex, the transform continental margin, the oblique convergence and the associated world third polar-the Tibet Plateau and its strike-slip type or pull-apart back-arc basin. These all need to be explored and recognized.

The Indian Ocean is significant for China's development since the North Indian Ocean takes a major position in the Belt and Road initiative: (1) National needs in society, politics, economy, military. i). The North Indian Ocean and its OCCZs used to be the Maritime Silk Road in ancient time and now is the pass way for China going to the world. The region is also a major thoroughfare or passageway to South Asia, East Africa and Europe for trade and cooperation; ii). A vital maritime transportation line for energy resources from South Asia, Africa and Europe; iii). It is important in China's development strategy. There are Gwadar Port, Ganda Port, Malacca Strait, China-Pakistan Economic Corridor, China-Myanmar Oil Pipeline and the ports under construction in Malaysia and other cooperation projects. (2) Enriched in

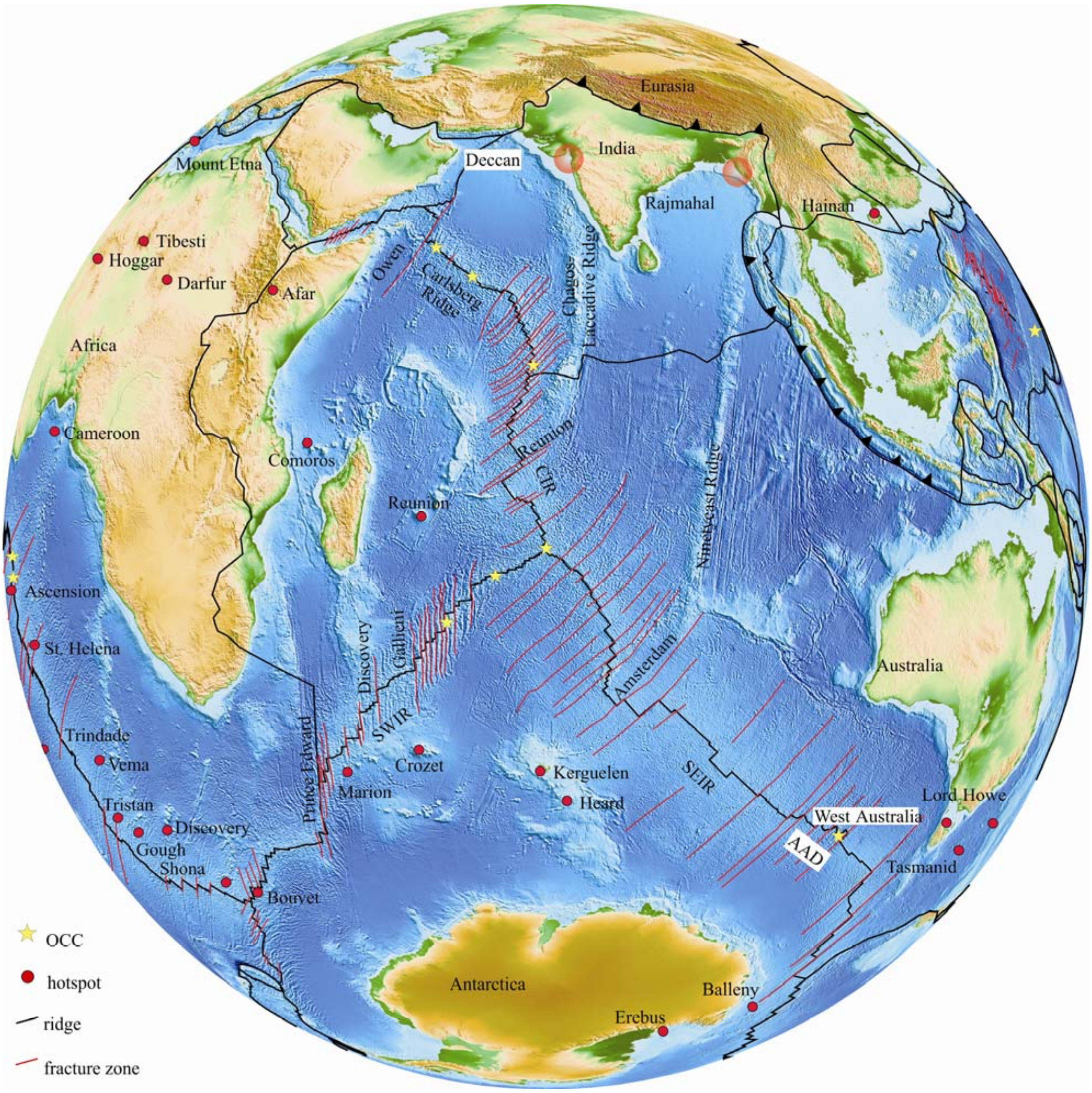

Fig. 3. Major tectonic units of the Indian Ocean.

information and theory of modern Earth science frontier. The Indian Ocean has its peculiar features different from those of the Pacific Ocean. They are the newly-born intra-oceanic subduction system, the seamount chain (the hotspot track), the Tibet Plateau-related archives-the Bengal Submarine Fan on sea-floor and the pull-apart Andaman Sea back-arc basin.

3.1 Initial opening and evolution of the Indian Ocean and break-up mechanism of supercontinent

When and how the Indian Ocean opened up and what temporal and spatial evolution relationships the ocean has with assembly and break-up of the Supercontinent Gondwana have been fundamental scientific questions. Study has indicated that the Indian Ocean interior records the complete breaking up processes of the Supercontinent Gondwana which can be used to trace the Indian Ocean evolution. Interestingly, the records can also be used to study the mechanism of how a supercontinent to break up (Replumaz et al., 2014; Gibbons et al., 2015; Zahirovic et al., 2015, 2016). Particularly, after the East and West Gondwana continents separated from each other, a number of microplates rifted and drifted away from the northern margin of the Gondwana continent and migrated a long distance northward, and eventually assembled with the Eurasian Plate, causing closure of the Tethyan Ocean. In the case, it is for certain that the driving mechanism is the deep processes globally. However, how can we examine the mechanism? As discussed previously, besides the Sunda and Markran subduction zones, there is no other subduction zone around the Indian Ocean. In addition, the Atlantic Ocean surroundings do not have any subduction zone. The question is that for the ocean without subduction zone, how the plates on both sides of the ridge could move? Especially, for the African Plate around which has no subduction zone at all, its movement has no way to explain until now. Therefore, it appears that the ridge push force is left as the unique driving force. If the driver is not a shallow one, whether or not the driver can only come from mantle convection or mantle plume at depth? If so, mantle convection becomes an active convection. However, Davies (2011) argued that the cold boundary layer (lithospheric plate) could be the active driver of a plate. Because if mantle convection is active, it is difficult for the ridge to migrate and then ridge jumping would be hard to interpret. These tangled questions have made the geodynamics in a puzzled situation and whatever they have to be clarified.

3.2 Oceanic core complexes in the Indian Ocean and rheology of oceanic lithosphere

Another feature in the Indian Ocean is development of the oceanic core complexes (OCC) characterized by twins symmetry on the both sides of a ridge and single asymmetry on the one-side inside corner of a ridge. An essential question is regarding that the oceanic crust or lithosphere are completely rigid or rheological in nature, which is related to the actual behavior of an oceanic plate and the principle of classical plate tectonics (Van Orman et al., 1995; Bull and Scrutton, 1990). Generally, oceanic plate is rigid relative to continental plate. However, under certain circumstances, the former can exhibit a rheological behavior and is not an absolutely undeformed rigid body. The oceanic core complex represents an expression of ridge spreading controlled by tectonic rheology. Some remarked locations of oceanic core complexes indicate that the oceanic core complex is clearly developed in the flunk of a ridge, telling that the activity of low-angle detachment faults led to athenospheric upwelling and exhumation of mantle peridotites. The mantle “cold spot” is a mantle down-welling region, how mantle is exhumed due to the development of the oceanic core complexes? What is a rheological relationship of the single asymmetric oceanic core complex and oceanic lithosphere? What is the rheological relationship of the twins symmetric oceanic core complex and oceanic lithosphere? What is the mechanism of oceanic core complex under different spreading speeds? are pudding structures formed by gabbro emplacement into peridotite or serpentinite widely developed? Is the oceanic lithosphere or mantle composed of peridotite? What factors control the development of the symmetric or asymmetric oceanic core complex? What is major control of the formation of slow spreading ridge with thicker oceanic crust? How does the oceanic core complex control mineralization?

3.3 Initiation of intraoceanic subduction zone in the northeast Indian Ocean and active/passive subduction

Does the northeast Indian ocean floor (the Central Indian Ocean) develop a new subduction zone or subduction system? The seismic reflection profiles at basement scale reveals that the ocean floor was thrust and offset, which is the unique visible thrust fault in global oceanic realm (Royer and Sandwell, 1989; Delescluse et al., 2008), while the crust-scale seismic reflection profiles show that the Moho was also offset (Chamot-Rooke et al., 1993). From these phenomena, it can be inferred that the fault may not only be a thrust zone but also a subduction zone. At present, there is no evidence to offset oceanic lithosphere and thus more work is needed. Some people linked the thrust belt to an uplifting of the Tibet Plateau (Bull and Scrutton, 1992; Replumaz et al., 2014; Gibbons et al., 2015; Zahirovic et al., 2015, 2016), and others attributed the Sumatra magnitude 9 earthquake to the thrust zone (Yue et al., 2012; Meng et al., 2012). It is foreseeable that the northeast Indian Ocean would be the development area of an intraoceanic subduction zone, and recently, quite a few papers paying attention to the region published in Nature, Science and Geology is evident? If the intra-oceanic subduction in the West Pacific Ocean is caused by density contrast due to different cooling extent, the subduction initiation on the basis of the near E-W-trending thrust fault within the same plate and perpendicular to the transform fault or fracture zone (the Ninetyeast Ridge) should not be caused by the density contrast. If so, what is a cause for the newly-formed subduction system? Furthermore, if the occurrence of the subduction is passive, what is the trigger? According to the trend of the would-be subduction zone in parallel to the Himalayan Orogen, it is likely that the collision of the Indian to Eurasian plates reached the shrinking limit or the Tibet Plateau uplifts to maximum, which triggered the initial subduction in the Indian Ocean down south and absorbs the push force generated by the spreading ridge. Now, the timing for the subduction initiation is at 7 Ma (Bull and Scrutton, 1992). If we accepted the inference, two questions are coming up: (1) the ridge spreading generates the driving force of plate movement; (2) It needs to drill through the overlying strata on the subduction zone and make a judgement whether the timing of thrusting is in coincidence with the rise of the Tibet Plateau.

3.4 Behavior of ultra-slow spreading ridges in one thousand-year and ten thousand-year time scale and their accretion pattern

The Indian Ocean has another feature: the slow and ultra-slow spreading ridges. In the case, magma supply should be low and in turn the push force generated by upwelling magmas from the ridge is not effective. There is no subduction zone developed in the surrounding of the Indian Ocean and thus no strong drag or slab pull force. Therefore, what caused fast northward movement of the Indian Plate? And how about the differentiated movement between the Indian and Australian plates? What controls the tectonism-magmatism-mineralization processes in the slow and ultra-slow spreading ridges? what is genesis for different type oceanic core complex? What is a controlling factor for mineralization, wet spot? What has been a behavior of the ultra-slow ridges at over one thousand-year and ten thousand-year time scale and its accretion pattern? The occurrence of the oceanic core complex looks like that the slow and ultra-slow spreading ridges are pulled passively apart and thus the ridge push force is impossibly a major source of plate driving force. Besides ridges, what kind of effect do the processes off ridge axis have on the oceanic lithospheric evolution such as oceanic ridge extinction and jump, subducting slab docking and seamount growth? Is there a correlation between ridge spreading rate and heterogeneity of oceanic crust? Are there other effects (temperature, components) from mantle on the oceanic lithospheric evolution?

3.5 Extinction mechanism of mid-ocean ridges? How ridges divide mantle plume?

The collision of the Indian and Eurasian plates might have forced a ridge to jump or have death and even to form microplate, which can record the timing of collisional event of the Indian and Eurasian plates. Much older (80–60 Ma) ridge jumping or termination possibly record the break-up event of the East Gondwana continent (Li et al., 2015a, b). Another issue needs to be addressed is a correlation of ridge-jumping mechanism and widely-developed mantle plumes or slow-spreading ridges.

3.6 Large Igneous Provinces, seamount chain and the differentiated movement of the Indian and Australian plates

There are two south-north-trending seamount chains in the Indian Ocean: the Ninetyeast Ridge and the Chagos-Laccadive Ridge (Fig. 3), their northern ends up in the Deccan and Lajmahal basalts, respectively. These two ridges record the northward migration track of the Indian Plate and differentiated speed in both edges of the moving plates, which can be used to examine the collisional model of the Indian Plate (Gibbons et al., 2015). The Ninetyeast Ridge may extend to the Chinese south-north-striking Longmenshan-Helanshan Tectonic Zone (Zhang et al., 2017) and even to the Lake Baikal, Russia. What geodynamic background does this phenomenon reflect? When did the south-north-trending tectonic zone possesses the geodynamic coherence? What force made the Indian and Australian plates move in different speed along the Ninetyeast Ridge, which has affected the regional framework of continent-ocean and landform between today's Asia and India-Australia, showing deformed and complicated pattern of the Tibet Plateau, the trench-arc-basin system in Southeast Asia, the marginal seas and small oceanic basins? What processes can the Ninetyeast Ridge (Sager et al., 2013) represent for the Neo-Tethyan belt? The strike of the Ninetyeast Ridge is different from spreading direction of the present-day Indian Ocean ridge and the direction change occurred at 40–38 Ma, accompanied by the separation of the Borken and Kerguelen hotspots. Did the spreading direction change of the mid-oceanic ridge result in the separation of the two spots or the other way around? What is a link between the change and uplifting or orogeny of the Tibet Plateau?

3.7 Oblique subduction and opening mechanism of back-arc basin and small oceanic basin

There is the Sunda subduction zone in the northeast Indian Ocean. Different from those in the Pacific Ocean, the Sunda subduction zone is characterized by oblique subduction. Attention was not paid to the earthquake induced by the oblique subduction until the Sumatra earthquake which killed 240,000 people in 2004. With the development of oblique subduction and extrusion of some continental microblocks away from the Tibet Plateau, the back-arc basin of the Andaman Sea was formed by strike-slipping and pull-apart processes. With oblique subducting, the subduction zone can be bent to form orocline (Honza and Fujioka, 2004). However, the rotation tectonics of the Banda Sea and origin of the Banda Arc need to be analyzed from the view of regional tectonics and kinematics, it may be related to the indentation and a northward motion of the Australian Plate. Thus, the strong and multi-type interaction is going on in the northeast Indian Ocean

3.8 Extinction mechanism of ocean-continent transition zone and transform-type continental margin

Some progresses in recent study on the ocean-continent transition zones of the West Pacific Ocean has been made, but it is still weak. This has hampered our understanding of the break-up processes and mechanism of the Gondwana continent. Most plates in the Indian Ocean belong to co-ocean-continent lithosphere unlike the Pacific Plate dominated by the oceanic lithosphere, and their ocean-continent relationship (ocean-continent transition zone) is chiefly expressed by passive continental margin such as the Indian continental surroundings of the Indian Plate and the ocean-continent passive margin of the Australian Plate. Along the two mid-oceanic ridges on the eastern and western margins, the south Indian Ocean neighbors with the Antarctica Plate. Via the Ninetyeast Ridge, the central Indian Ocean neighbors with the Australian Plate whose OCCZs are all composed of the passive continental margins. The northern and eastern boundaries are characterized by the outward subduction zones, its north is the connection zones comprising the ocean-continent subduction, its east is the ocean-ocean subduction and transform fault forming the boundary between the Indian Ocean and the southeast Pacific Ocean. However, the ocean-continent relationship of the West Indian Ocean and the East African Plate remains controversy, there are two viewpoints: the passive ocean-continent connection zone and the ocean-continent transform zone. The latter now is in favor and it thinks that the Indian Ocean connects with East Africa by its characteristic transform continental margin. Further to the north along the margin, it is the Owen fracture zone, whose contribution to the formation of the Red Sea-Aden Bay small oceanic basin is not clear. So far, study of the transform continental margin has been the weakest in the three continental margin types. Its extinction processes are unknown either. However, research on this type of margin is definitely meaningful to understand the plate collage by horizontal movement in the Earth's history.

3.9 AAD and mantle cold spot-downwellings

AAD is a divergent boundary of the Australian and Antarctica plates. Its location is just sandwiched in between the two low-velocity mantle regions and thus it is thought to be a global downwelling region. Tomographic images show that the high velocity bodies are in the deep mantle in the region which are inferred to be the old subducted oceanic slabs which reflect a coupling effect of both deep and shallow levels. The effect made the region be featured by shallow water, high gravity and thin ocean crust. The following issues are not clear: these stagnant slabs are intraoceanic or ocean-continent subduction, subduction timing, age structure of the subducted slabs and the relationship with the extinction of the Neo-Tethyan Ocean. The oceanic core complex could also be developed in the region. Therefore, in the region of the mantle cold spot, what is mechanism for the oceanic core complex to form without heating source? Synthetic study indicates that the region is enriched by information of the peculiar crust-mantle relationships, which is also related to the Pacific Plate accretion in the cold spot of the mid-oceanic ridges.

3.10 Interaction between mid-ocean ridge and hot spot

Because the magma chamber of the ultra-slow spreading mid-oceanic ridge is less developed, the heat source and mechanism for the formation of the hydrohermal vents in the ultra-slow spreading mid-oceanic ridge is likely different from those for the vents formed in the East Pacific Rise. So, questions are: what is difference for the hydrohermal sulfide mineralization in the fast and ultra-slow mid-oceanic spreading ridge? Whether or not the formation of the hydrohermal vents must have extra heat supplied from outside mid-oceanic ridge, is the extra heat correlative with unusual heat from mantle plumes or hot spots? Twenty four hydrohermal vents found in the southwest Indian Ocean, of them five vents have heat from hot spots, the rest (nineteen vents) are developed at the tectonic background of slow and ultra-slow mid-ocean spreading ridges. And the hydrohermal fluids mostly occurred in the areas with normal or thin oceanic crust, while no hydrohermal vent is found in the hot spot-affected, thickened-crustal segments of the mid-oceanic ridge in the southwest Indian Ocean (35°−47°E and 0−10° E) . Is this lacking of hydrohermal fluid migration channels or some other reasons?

4 Connection and Dynamic Evolution among West Pacific, Eurasian, Indian Ocean Plates

The Pacific Ocean and the Pacific Plate are related but different concepts. The former is of geographic concept, while the latter is geological. The Pacific Plate is limited by the San Andreas Fault-the Juan De Fuca Ridge in the Pacific Ocean to the east and its northwestern boundary is set by the subduction zone between the Eurasian and Indian-Australian plates. The Pacific Ocean is a long-lived ocean on the Earth and it has had a number of plates in the history. The present-day Pacific Plate is an evolved oceanic plate occupying the major area of the ocean, there are the Cocos and Nazca plates between the southeast Pacific Ocean and the south American Plate. The West Pacific Ocean is referred to the western part of the Pacific Ocean, corresponding to the portion of the Pacific Plate to the west of the Hawaiian Islands-Emperor Seamounts-Polynesian Islands limit.

The West Pacific Ocean and the plate, the East Eurasian Plate, the Indian Ocean and Indian-Australian Plate constitute a vast tectonic domain through ocean-continent and ocean-ocean convergence, amalgamation and conjunction. In other words, the ocean-continent interaction, transition and transform between the two oceans and three plates have drawn a colorful picture. Based on new development, we present three questions below:

(1) From the above discussion, it can be seen that the current situation of the Pacific Plate, the Eurasian Plate and its continent, the Indian-Australian Plate and the Australian continent and their ocean-continent and ocean-ocean connection zones reflects the result of long-term evolution and complicated geological processes. But, for all these, we do not know much about and thus it needs further study.

(2) The present-day conjunction and transition zones of the West Pacific Ocean, Eurasian continent and Indian Ocean, from north Aleutian Islands-Kamchatka Peninsula-Kuril Islands-Japanese-Mariana Trench-Okinawa Trough-Ryukyu Arc system with the Philippine Sea Plate-Carolina Islands-Tonga Island Arc all the way to the Puysegei Trench to the south of New Zealand formed the global-scale lithospheric connection zone on the Earth which can be divided into the northern and southern segments. The northern part assembles with the Eurasian Plate via the ocean-continent subduction, forming the paired island-arc zones with the medium- and small-sized plates sandwiched in between. The southern part sutured with the Indian Ocean through the ocean-ocean subduction and transformation. The conjunction and transition zones represent the prominent global tectonic zone in the upper ocean-continent lithospheres with various tectono-morphological units composed of the arc-trench-basin systems, ocean-ocean subduction zones and strike-slip transform island arc chains, The zones also control the supracrustal structure, interaction and evolution of different spheres of the surface Earth system, and especially record the Meso-Cenozoic interaction of the deep ocean-continent and mantle, reflecting that influence of the Earth deep dynamic system to the shallow system and their feedback to dynamic evolution trend. Thus, to study the subduction and transform relationship of the West Pacific Ocean, the Eurasian and Indian-Australian continents and the deep-surface Earth dynamics feedback is a frontier issue of Earth Science.

(3) Besides the Eurasian and Indian plates, the paleo- and present-day Pacific plates have interacted with the closed Paleo-Tethyan Ocean. During the Meso-Cenozoic, the Neo-Tethyan Ocean (Wu et al., 2016), from Alps to Himalaya has experienced the continent-continent collisional orogeny, resulting in the closure of the Neo-Tethyan Ocean and rising of the Tibet Plateau where the highest mountains and deepest trench on the Earth are co-existed. However, to the east of the Naga Node in the Tibet Plateau, from Myanmar-Malaysia- Thailand-Indonesia to the Banda Sea connecting with the West Pacific Ocean, there still is a remained arc-trench-basin system which has not completed its continent-continent collision. The arc-trench-basin system is involved in the modern subduction of the Indian Plate on the southern margin of the Sumatra Island, becoming the northern margin of the Indian-Australian Plate and a subduction boundary towards the Eurasian and the relict southeast Asian arc-trench-basin system. Additionally, it is important to emphasize that the Indian-Australian Plate is subdivided into two along the Ninetyeast Ridge. The fast moving Indian Plate caused the formation of the Himalayan Orogen and the Tibet Plateau, resulting in the crustal 2000 km shortening, whereas the slow-moving Australian Plate has not touched the Eurasian continent yet, making the southeast Asian arc-trench-basin system remained at the eastern end of the Alps-Himalayan Mountain system. Why could this happen and lead the occurrence of the south-north-trending Helan-Chuandian tectono-earthquake zone corresponding to the northern extension of the Ninetyeast Ridge? The zone divides the China Continent into the east and west portions which exhibit distinct tectonics and surface landscapes. How did the east Paleo-Tethyan Tectonic Domain connect with the

Paleo-Pacific Plate or other plate(s) in the ancient Pacific Ocean? How does the Neo-Tethyan Ocean and the Indian Ocean connect with the Pacific Plate in the region where the three plates (the Eurasian, Indian-Australian and Pacific plates) met ? What are the deep dynamic processes? What is their new dynamic trend from depth to surface? What is the relationship to development of human society?

There are a lot interesting scientific questions which need to pursue, of them the fine plate reconstruction is supreme.

5 Prospects

With the deep oceans, vast space, abundant resources and special social, political, economic and military positions, the two oceans and one zone have become the important strategic region attracting worldwide attention (Qin, 2011). Furthermore, having the broad and profound unsolved scientific problems and the massive amount of information contained, the two oceans and one zone are attracting and summoning scientists to throw themselves toward the deep blue ocean. At present, to build the strong marine nation has become the state will and strategic goal, the two oceans and one zone have no doubt been a great arena and fertile land for Marine Science including solid Earth Science (Ocean floor Science) and traditional Marine Science to develop. Currently, the China 13th Five-Year innovation plan has launched "Science and Technology Innovation 2030", aiming at strengthening Hi-Tech deployment and research for deep ocean, deep Earth, deep space, deep blue (representing Hi-Tech)realms. A great number of research institutions are reorganizing their working force and introducing talents from home and abroad in order to forge the platform and march to deep ocean. The deep ocean research is commencing its full arrangement in the deep diving, deep drilling, deep networking, deep mining, deep time, deep trees, deep petroleum-gas-gas hydrate programs. This is the unusual opportunity for Chinese scientific community and thus we have to value the chance.

China's Marine Science, particularly the deep ocean and ocean floor science has been backward for a long time. Comparing with the international advanced research level, we have to realize that our Marine Science, especially for deep ocean, and probing-monitoring techniques remain a large gap. In the information era, high-speed development of science and technology and intensive competition on the oceans inevitably push Marine Science including solid Earth science and deep ocean research to go forward. We have to strategically think and foresee the new progress and situation of the future Marine Science. To become a strong marine country, we need advanced Marine Science and cutting-edge probing techniques and change the decentralized management of Marine Science research. We have to focus on the core scientific issues and make major breakthrough, and implement scientifically in accordance with grand state needs and strategic goals. Cultivating talents is a big issue too, we have to make great effort to cultivate a group of young and high-leveled people who can collaboratively work together and climb the scientific summit, solve the key problems and lead the countries to an international scientific frontier.

Although our Marine Science are weak to some degree, a series of achievements have been gained in various areas and some of them have entered the international research front, which has created excellent conditions for further development. In recent years, under the guidance of the "From a large marine country to a strong marine country" strategy, the high-speed advance has been achieved in the Marine Science fields. From the entire development, China has had high-level technical storage and conditions. For example, the manned deep-sea submersible "Jiaolong", the sea-floor observatory network and 5000-ton scientific surveying ships have been built up. The platform construction of the China ocean drilling vessel has made a breakthrough. The deep Earth program has achieved great progress in over 10 thousand meters deep drilling project and highly-precise tomographic technique. For the deep blue program, dynamic simulation and numerical modeling will be implementing in the class-E supercomputer clusters soon. The completion of a batch of critical equipments has paved a road for China's ocean floor science development. By the ocean-continent combination, the prospect and leading research can be carried out around deep Earth dynamics in deep ocean, deep time environment in deep ocean, deep Earth resources in deep ocean, ocean-continent system evolution and human settlement assessment and so on. For the consideration of building strong marine nation and implementing the Belt and Road strategy, research on the two oceans and one zone can play a decisive role for the national strategy and marine science breakthrough. The research can focus on the core scientific issues of modern solid Earth science frontiers in the two oceans and one zone, such as plate dynamics, continental dynamics and marine geodynamics, ocean-continent transition and subduction dynamics, the crust and mantle hot-cold fluid system, the life and ecological system under extreme conditions, mineral and energy resources, environment and geohazards of offshore to deep ocean, coupling and decoupling relations of surface Earth system and deep Earth system (including deep ocean hyperthermal fluid system and oceanic temperature-salinity fluid system). As long as Earth scientists carry out assiduous researches, we believe that new discoveries, viewpoints and theories can be achieved. To meet national needs, lead marine and Earth sciences, deepen the Plate Tectonics Theory, create the Earth system and planet-Earth dynamics theory, and to make China—a strong marine nation in the world, let's play a magnificent symphony of two oceans and one zone.

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