Chapter 3
Basic Scientific Issues Relating to Earth Habitability

3.1 Important Issues in Resources and Energy Security

3.1.1 Oil and Gas Resources

Oil and gas are strategically essential for China's national energy security and economic development. In 2019, the total global primary energy consumption was 14.05 billion tons of oil equivalent. Among them, the consumption of crude oil, natural gas, coal and non-fossil energy sources accounted for 33.1%, 24.2%, 27%, and 15% of the total, respectively (BP 2020). It is estimated that oil and natural gas will still provide about 50% of global primary energy in 2050, which means that fossil fuels will continue to dominate the primary energy consumption for the foreseeable future.

Current theoretical studies in oil and gas geology integrate the interactions between Earth's spheres with their effects on resources and the environment. Since the Yanshan Movement in Eastern China, a series of petroliferous basins have formed in Northeast Asia under the influence of the deep dynamic process of the continuous subduction of the Western Pacific Plate into the Eurasian Plate (Li et al. 2010; Zhu et al. 2015; Meng 2017). These eastern petroliferous basins have unique geographical advantages and great scientific research value which can offer scientists a natural laboratory for exploring deep-surface interactions, organic–inorganic interactions, and land-sea interactions, material circulation, energy migration, etc. Geologists from around the world have documented a large number of research results and innovative understandings about the geological impact of Western Pacific Plate subduction on Northeast Asia (Sun et al. 2008; Jin et al. 2007; Zhu and Xu 2019). However, the precise coupling mechanism between the subduction process of the western Pacific plate and the oil and gas resources in the eastern basins of China has not been established. Researchers should pay attention to the key mechanisms closely related to the study of petroleum geology, not only to the interactions between the Earth's

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spheres and organic–inorganic interactions, but also to the deep-Earth processes and thermal dynamics, marine processes and the terrestrial environment, Earth system processes, and the oil and gas generation and supply potential (Zhang et al. 2017; Liu et al. 2019a, b). Three issues are crucial to study of the coupling mechanisms linking subduction of the Western Pacific Plate with generation of oil and gas in eastern basins of China.

(1) Understanding the processes of sedimentation-diagenesis-transformation, the mechanisms of source-reservoir-cap development, and the laws governing distribution of petroliferous basins undergoing dynamic transformation by plate subduction. The formation of petroliferous basins in eastern China is controlled by plate tectonics, lithospheric structure, and the crust-mantle and lithosphere-asthenosphere interactions. A crucial frontier scientific issue in petroleum geology is to study the source-reservoir-cap development mechanisms, dynamic evolution, and distribution laws of the petroliferous basins and their correlations with plate movements and mantle convection.
(2) Determining the interactions of the Earth's spheres, the dynamics of material and energy transmission and conversion under high temperature and pressure conditions, and the mechanisms of oil and gas generation, migration, accumulation, and preservation. Oil/gas generation, migration, accumulation, and preservation is a thermal/dynamic process with circle interaction. Oil and gas are formed in particular tectonic environments—accumulation of material and energy of the Earth's lithosphere, hydrosphere, biosphere, and atmosphere under the physical, chemical, and biological actions during Earth's evolution.
(3) Organic–inorganic interactions have been ubiquitous throughout the Earth's evolution. A better understanding of the reservoir accumulation and preservation mechanisms and the distribution laws of various substances (including hydrocarbon fluids) in the deep Earth, such as solids, liquids, and gases, will help to reveal the dynamic mechanisms of deep fluid migration into basins, the controlling effect of deep geological structures on hydrogen-rich and hydrocarbon-rich deep fluids, the material and energy exchange pathways of deep fluids in basins, etc.

The research on the coupling mechanism between the subduction of the western Pacific plate and the oil and gas resources in the eastern basins of China can not only provide theoretical support for the increase of oil and gas reserves and production in the eastern basins of China, but also promote international cooperation in the study of active continental margin petroliferous basins around the world. The large-scale volcanic activity and source rock development are the focus in this research. High productivity of organic matter and favorable conditions for its preservation are fundamental to the formation of high-quality source rocks. Large-scale volcanic activity is a potential geological agent driving global climate change and biological extinctions, which greatly affect the enrichment and preservation of organic matter. Volcanic materials produced by terrestrial or submarine eruptions migrate into lakes, oceans and other water bodies. Inorganic elements and inorganic salts produced by hydrolysis promote the proliferation or extermination of organisms in water bodies, impacting the development of high-quality source rocks. Volcanic ash and sulfide-containing gases dissolve in water, creating a reducing aquatic environment. Ferruginization and sulfurization protect organic matter to a certain extent. Previous studies have focused on the impact of volcanism on single factors such as paleo-productivity and sedimentary environment. However, large-scale volcanic activity not only influences the Earth's atmosphere, hydrosphere, biosphere, and lithosphere, but also transports materials up from the deep mantle that alter the original ecosystem and biological community, thereby affecting organic-rich paleo-productivity and preservation conditions. The impact of volcanic activity on organic-rich source rocks should therefore be comprehensively analyzed from the perspectives of paleo-climate, paleo-sedimentary environment, hydrocarbon generating organisms, and early diagenetic evolution. A coupling mechanism of volcanic activity and organic-rich source rocks under the comprehensive action of multiple layers should be established. The core scientific issues mainly include: (1) the spatial relationships and geochemical responses between large-scale volcanic activity and organic-rich source rock accumulation; (2) the influence of volcanic activity on paleo-climate and paleo-sedimentary environment and its controlling effect on hydrocarbon generating biological assemblages of organic matter; (3) the coupling mechanism between large-scale volcanic activity and the development of the organic-rich source rocks.

3.1.2 Mineral Resources

Generally, the formation of mineral deposits in shallow Earth is directly or indirectly related to crust-mantle structure, substances cycle, and energy transmission. Most endogenetic deposits in shallow and surface regions were originally formed in the deep Earth and subsequently reached the superficial position as a result of uplifting and denudation. High-conductivity and low-velocity blocks in the upper mantle correspond well to the concentrated deposits in the upper crust. Low-velocity blocks may have been produced by metasomatic re-enrichment in the lithospheric mantle. Therefore, the study of metallogenic mechanisms, especially study of core scientific issues such as the enrichment of minerals, must be closely integrated with systematic study of deep geological processes. However, the current research on metallogenic mechanisms mostly focuses on mineralization processes, and metallogenic fluid and mineral precipitation, while the controlling effects of deep geological processes on the migration and enrichment of ore-forming materials are still poorly understood. The precise relationship between the crust-mantle structure and large ore concentration areas has not been revealed. In view of this, in the future study of mineral resources, the following aspects should be focused on: (1) The geochemical behavior and metallogenic specificity of key metal elements; (2) The precise definition of the contribution of oceanic crust subduction and collision process to ore-forming sources and ore-forming properties; (3) The macro-controlling mechanism of crust-mantle structure and mantle metasomatism on large ore concentrations; (4)

The effect of the global deep-Earth activities and major events in specific geological periods on the large-scale supernormal metal enrichment.

The Central Asian metallogenic domain and the Tethyan and circum-Pacific metallogenic domain have both undergone complex dynamic processes such as the creation of multi-block collages, mutual superposition, and subduction/collision. The Central Asian metallogenic domain was formed by multiple rounds of convergence and aggregation of the ancient continental crust and new geological bodies. It is a gathering area of two types of geological bodies, including the closure of the Paleo-Asian Ocean and the new-born crust and ancient land blocks. It is a geological body gathering area formed through mountain bend structures, large-scale rotations, and multiple accretion. The accumulation areas dominated by island arcs include the large-scale arc-basin system in south Siberia and the Junggar, and the young crust in the east. Accumulation areas dominated by continental blocks include the areas around Balkash and Ili (Xiao et al. 2019). The Central Asian metallogenic domain was later superimposed and transformed by multi-continental collisions and the remote effects of the southern Tethyan metallogenic domain, forming a more complex pattern of plate accretion, collision, and transformation (Xue et al. 2020; Li et al. 2019). The period of frequent alternating collisions and disintegration of ancient continental crust and formation of new geological bodies which followed was the most intense phase of magmatic hydrothermal activity. Did this phase control large-scale mineralization at its peak? What was the control mechanism? Did magmatic hydrothermal activity in the geological body accumulation area dominated by newly-formed island arc determines the types and distribution laws of accretionary deposits? Did magmatic hydrothermal activity in the geological body accumulation area dominated by land masses control the type and distribution of deposits formed by collision and transformation (Xiao et al. 2019; Li et al. 2019)? These are the main scientific issues that urgently need to be studied in relation to the multi-phase oceanic basin subtraction and step-and-repeat processes related to the law of accretion, collision, and transformation of the mineralization in paleo-Asian tectonic domain.

3.1.3 Surface Water Resources

Since the mid-twentieth century, with rapid economic and social development and increasing population, water resources have become an increasingly prominent problem that has directly affected the social development and the human living environment. The World Water Development Report 2019 estimates that the global water consumption will increase by 20–30% from its present level by 2050 (UNESCO 2019). The average precipitation in China is about 648 mm, which is 20% lower than the global land average. The per capita water resources are about 2100 m^3, which is only 1/4 to 1/3 of the world average. In the context of global climate change, some areas have already suffered from frequent droughts, while others suffered from unprecedented flooding. The frequency of the extreme weather events, such as sudden heavy precipitation and typhoons is increasing, which has a significant impact on global water resource patterns (Future Earth Transition Team 2012; Stocker et al. 2014). In order to meet the national demand for a safe water supply against this background of climate change and human activity, two major scientific issues need to be addressed:

(1) Clarifying the laws governing the Earth's major climate patterns, predicting future changes in water resources, and revealing the evolution trends and active mechanisms of water systems under the influence of climate change and human activity. Major engineering decisions should be made based on a full understanding of likely future trends in water resources. Projects that are likely to have a serious impact on water resources should be subject to scientific regulation and control.
(2) Exploring the mechanisms of water resources supporting capacity, scientifically judging the changes in water resources capacity caused by major national strategies and global change, studying the scientific issues such as the improvement mechanism and threshold of water resources support capacity in response to environmental changes, and evaluating whether the existing water resources can support national strategies into the future.

3.2 Deep-Sea Resources, Energy Potential, and Marine Security

3.2.1 Deep-Sea Energy

For the deep-sea areas that are enriched in renewable and easily exploitable energy resources, the local effects of the output and transformation of these regional energy (such as offshore wind and tidal energy) from the ocean interior on marine dynamic processes need to be understood urgently. In addition, extensive use of the deep-sea energy has already impacted materials and energy movements in the oceans and has also caused changes in the marine environment—even marine disasters. How to make rational use of deep-sea energy is a vital scientific issue.

3.2.2 Deep-Sea Mineral Resources

Deep-sea minerals include polymetallic nodules, cobalt-rich crusts, polymetallic sulfides, and REE-rich sediments, which are characterized mostly by multiple metals in composition (Hein et al. 2013) and by nanoscale sizes of mineral particles (Hochella 2008). Therefore, the chemical compositions and material properties (Sun et al. 2003) of deep-sea minerals will be utilized. The essential scientific issues concerning deep-sea minerals to be addressed currently are inter alia identification of existing phases of associated valuable elements for comprehensive utilization, and

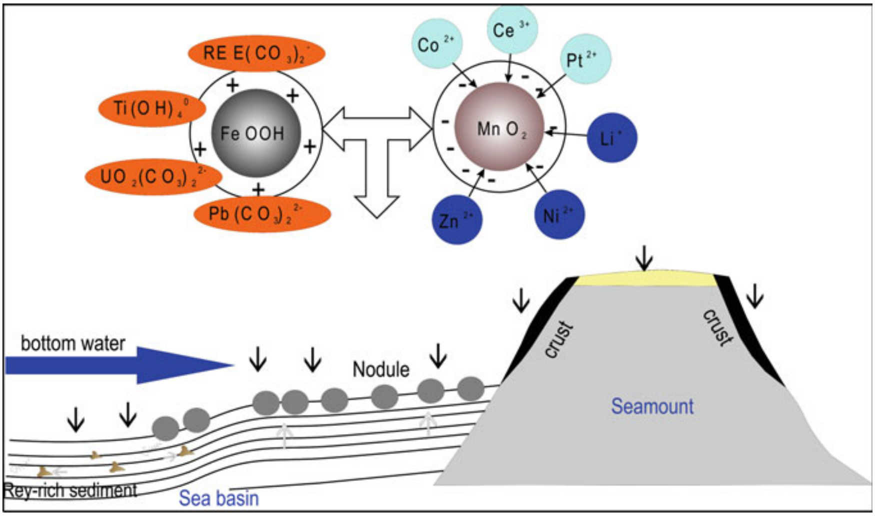

Fig. 3.1 Metallogenic model for deep-sea sedimentary deposits polymetallic nodules were formed in basins, and manganese crusts were formed on seamounts (modified from Hein et al. 2020).

clarification of material basic features. The critical scientific issues on exploration and mineralization research of polymetallic nodules, Co-rich crusts and REE-rich sediments include spatial controls on deep-sea mineral distribution, and anomalous concentration of deep-sea ore-forming elements. Essentially, those issues concern the controls of material and energy transportation in multiple spatial scales (in nanometers, centimeters, meters, and kilometers) (Fig. 3.1), namely, multiple spatial scale dynamics of deep-sea mineral sedimentation. To clarify those issues, we need to research controls from major geological and palaeoceanographical events, such as Antarctic Bottom Water, on the spatial and temporal distribution metal deposits, and controls from fluids features and ocean conditions on transportation-aggregation of metal elements in deep sea.

3.2.3 Deep-Sea Biological Resources

The deep sea harbors special microbes and large marine organisms such as fish, shrimp, crabs and shellfish, hosting many new, unknown functional genes and other active substances with specialized structures and functions (Daletos et al. 2018; Tortorella et al. 2018). In view of the abundant deep-sea biological resources, it is urgent to strengthen China's ability to excavate and utilize deep-sea biological resources (Fig. 3.2). However, the vital problem that is yet to be solved is how to obtain such resources efficiently. How to excavate microbial resources in the deep sea which are difficult to be cultured? How can we reveal the functions of the unknown

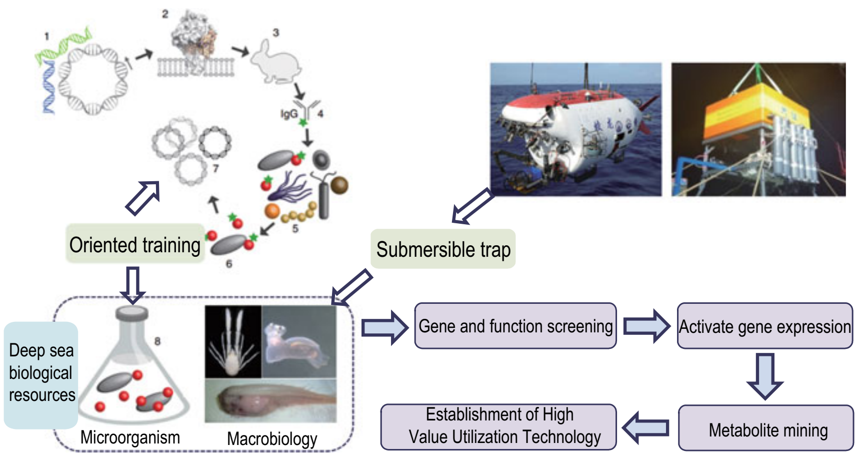

Fig. 3.2 Deep-sea biological resources acquisition and resource mining

genes in deep-sea organisms? How can we obtain active deep-sea substances that may be applied potentially in the fields of disease prevention and control, environmental protection, and in industry and agriculture, as well as establish high-valued utilization technologies for deep-sea biological resources?

3.2.4 Marine Security

The ocean is a complex nonlinear system that includes interactions among multi-scale dynamic processes such as large-scale circulation, meso (and sub-meso) scale eddies, small-scale internal waves, and micro-scale mixing. On one hand, the oceanic multi-scale dynamic processes have a direct impact on the underwater and surface navigations. On the other hand, through modulating the marine hydrological environment, the multi-scale dynamic processes can alter the acoustic, photoelectric, and magnetic fields, which further influence the underwater detection, communication, navigation, and target recognition in the ocean (Colosi and Worcester 2020). Therefore, it is an urgent scientific problem to reveal the oceanic multi-scale dynamic environment and its effects on various physical fields and through which to make their characteristics "transparent".

The extreme deep-sea environment has fostered the development of unique gene structures and physiological mechanisms in marine microorganisms. With the increasing of human activity in the oceans, some pathogenic microorganisms in the deep ocean would be released into the human environment, which could result in the emergence and spread of new and unknown microbial pathogens on land and in offshore areas, causing incalculable harm to human health, social stability, and ecological security. Explorations of deep-sea pathogenic microorganisms and strategies for deep-sea microbial infection prevention, control, and biosecurity are therefore important and frontier researches.

3.3 Deep-Space Resources and Deep-Space Economy

3.3.1 Exploration, Development, and Utilization of Space Resources

Space resources are defined as material or non-material resources from outer space, including location resources, environmental resources, and mineral resources, which can be developed and utilized by humans to deliver economic and other benefits. For the future sustainable development of society, scientists must come to understand the types, scale, distribution, and formation mechanisms of space resources. Non-material space resources must be effectively utilized, and material resources developed, so methods and technologies must be developed for their enrichment, mining, storage and transportation.

Research on space resources encompasses many basic fields. In order to effectively utilize space resources, and to develop our capability for space exploration, we will have to develop quantitative, high-resolution remote sensing and in-place detection technologies, expand the use of terrestrial, lunar, and planetary orbital space, and establish observation, communication, navigation, and positioning infrastructure across the solar system. We must establish and maintain base stations on the surface of the moon, the planets, and their satellites. To service these bases, we must develop in-situ 3D printing capabilities, establish water, hydrogen and oxygen caches, utilize local mineral resources, and introduce other related technologies. By utilizing in-situ resources, lunar or planetary bases will provide convenient and low-cost access to deep space. Technologies for advanced mineral mining, extraction, and purification, as well as safe storage and transportation, will be developed.

3.3.2 Utilization and Transmission Technology for Deep-Space Solar Energy

Use of the abundant solar energy in space, and other space resources, is critical for exploration of deep space, as well as for the promotion of sustainable development of society and the national economy here on Earth. In order to guarantee safe, green, sustainable energy as space activity increases, and to construct large-scale energy plants in space, the following key issues must be addressed: Solar power plants should be developed, based on thermal cycles, with working technologies such as radiation heat exchangers and cooling systems to make them suitable for operation on stratospheric platforms or in a lunar environment. Breakthroughs should be sought in high-efficiency solar cells and key materials preparation for space-based solar power stations. Structural design and control systems for high conversion efficiency solar cells, and preparation of photocatalytic materials for high efficiency hydrogen production using lasers should be explored and the general service performance of materials in a space environment evaluated. We must reach a better understanding of fluid and materials interactions and related system mechanics under the effects of high-intensity lasers, develop experimental methods for working with materials and structures under complex loads, develop multi-physical field-test technology, and explore the basic laws of the behavior of materials and structures under the action of high-intensity lasers. The basic data thus obtained will provide theoretical support for microwave radiation or laser energy transmission in near space.

3.3.3 Multi-scenario Economic Development in Space

'Space economy' refers to the technologies, products, services, and markets created by space-based and space-related activities, including economic benefits derived from the exploration, development, and utilization of space, such as space manufacturing, space agriculture, space resource utilization, space energy, space tourism, space culture industries, and space support and maintenance services. The space economy is a completely new form of business. Space resources are effectively limitless and have enormous potential for human exploitation. Space between the Earth and the moon is clearly the main field for exploration and is also the primary strategic space available for development of the aerospace industries of various countries in the future. The development of a space economy will be a new source and engine of economic growth, led by aerospace technology and driven by ingenuity and innovation. The development of diverse scenarios for a functioning space economy will promote government and social investment, drive innovation in traditional industries, promote the emergence and growth of new industries, stimulate economic growth, and be of enormous long-term benefit to human society.

3.3.4 Theories and Technologies for Human Intervention in the Trajectories of Dangerous Small Celestial Bodies

To make peaceful use of space and ensure the survival of human civilization, we must consider the harm that could be caused by the impact of small near-Earth objects on the planet's surface, not least the considerable quantities of space debris from mankind's own efforts in space over the past sixty years that are currently circling the Earth in orbits with varying degrees of stability. Theoretical research on human intervention in the trajectories of celestial objects requires focus on the following technical problems: ① development of detection methods for fast-moving 'dark'

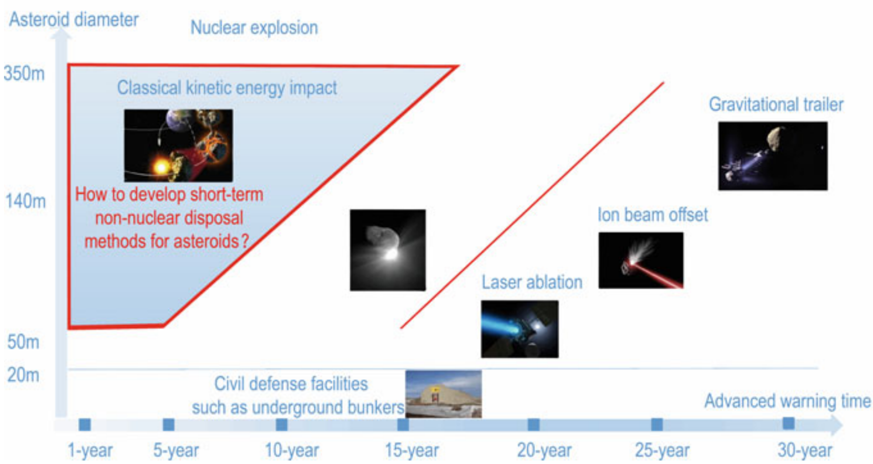

Fig. 3.3 Applicability of existing planetary defense methods

space targets, ② how to achieve large-scale, long-distance, non-contact, and efficient space debris removal, ③ how to scientifically and rationally plan the removal of space debris to obtain maximum benefit, and ④ how to utilize space waste and turn it into useful commodities (Fig. 3.3).

3.4 Mechanisms, Prediction, and Prevention of Natural Disasters

3.4.1 Earthquake Prevention and Mitigation of the Effects of Strong Continental Earthquakes

The formation and evolution of Earth habitability have been accompanied by many catastrophic events, including earthquakes. Most earthquakes occur in the upper and middle crust and can result in huge casualties and economic losses. A better understanding of the geophysical environments, stress states and dynamic processes in the focal depths of great earthquakes will lay a solid foundation for studies of earthquake preparation, rupture process and disaster mitigation.

The continental China has a highly complicated seismotectonic background. Great earthquakes occur frequently, mainly controlled by contractions among plate, intraplate mantle convection, and interaction between active tectonic blocks. Nevertheless, the complexity of seismotectonic structures and dynamics, the diversity of deformation and kinematics, and the randomness of temporal and spatial distribution of great continental earthquakes make it difficult to reach a full understanding of the factors resulting in earthquake occurrence. Two aspects of study are essential: mechanism of earthquake generation and effective earthquake early warning.

To study the mechanisms of great continental earthquakes, we need to bring modern science and technology to bear in monitoring the temporal and spatial evolution of tectonic stress in seismic zones. We need to fully comprehend the processes of energy accumulation and release in active fault zones and analyze the deep and shallow structures of fault zones and their relationships with deep ductile loading of faults and stress accumulation in seismogenic zones. Combining this with studies of fault friction and rheological experiments will reveal the generation processes of great earthquakes, the nucleation of earthquake ruptures, the characteristics of co-seismic slip and post-earthquake deformation. These studies will enhance a comprehensive understanding of the physical processes and temp-spatial evolution of earthquake occurrences.

At present, early warning systems are useful in mitigating the destructive disasters of earthquakes, but they could be improved enormously. For the future, there are two key directions: first, improvement of existing early warning theories and methods, including the development of new earthquake early-warning algorithms using the three-dimensional accelerometers now commonplace in smart mobile phones in conjunction with big data and artificial intelligence technology; second, to explore earthquake early warning systems based on the electromagnetic waves associated with earthquakes, or the elastic, light-speed gravity waves generated by seismic dislocation, to enable more rapid detection than the current systems based on detection of seismic waves.

3.4.2 Observation, Mechanism and Possible Control of Artificially Induced Earthquakes

'Induced earthquakes' refer to seismic activity induced or triggered by human activity. Increasingly frequent and serious induced earthquakes are being generated by human exploitation of natural resources, particularly the construction of high dams and large-capacity reservoirs, the development and utilization of deep underground space, and large-scale shale oil and gas exploitation. Studies of induced earthquakes should focus on three areas: (1) continuous observation using dense surface and underground seismic arrays and optical fiber strain sensors, and developing big data processing technology based on artificial intelligence to achieve continuous detection and monitoring of micro, medium, and strong earthquakes; inversions of stress fields, fluid pressure fields, three-dimensional fine velocity structure, and tomography using the continuous observation data to improve on-site real-time detection and monitoring for signs of fault activation; (2) experimental researches on faults with different lithologies, diverse scales, and various levels of maturity to understand the spatio-temporal processes of fault activation and earthquake induction, especially the nucleation, expansion, and arresting mechanisms of seismic and aseismic fractures of faults with varying maturity under fluid action; (3) to transform existing well sites and wastewater reinjection sites where induced earthquakes have occurred into experimental sites to carry out advanced experimental researches on the controllability of induced earthquakes to reduce the earthquake magnitude.

3.4.3 Marine Hazard Forecast and Prediction

The ocean breeds the most extensive devastating meteorological and geological hazards on Earth in direct or indirect ways. Although humans have made prominent progress in forecasting and predicting marine hazards, understanding of their generation mechanisms still needs to be improved. For meteorological and climatic hazards, such as typhoons and extreme EI Niño, the key factors to improve their forecast and prediction capabilities are to clarify the impact of small-scale and mesoscale ocean dynamic processes on thermal structure of the upper ocean, to develop accurate parameterization for air-sea turbulent exchange, and to establish a high-resolution Earth system model associated with a multi-element coupled assimilation system. For geological hazards, such as earthquakes, landslides, and tsunamis, to better understand their controlling geological and geophysical generating conditions, it is necessary to conduct various underwater surveys (e.g., geologic and geophysical observations, ocean drilling) to identify fault structures, rock compositions, stress characteristics, temperature and pressure conditions and so on; Then the controlling factors of geological disasters can be revealed by combining observations with laboratory experiments and numerical simulations. The urgent problem to be solved is to establish a scientific early warning system to mitigate disasters. Based on theoretical research, identifying high-risk areas and deploying submarine observation networks can monitor submarine disasters in real time and obtain key physical parameters, which will significantly improve the early warning capability of the geological disasters.

3.5 Ecological Safety

3.5.1 Ecosystem Structures and Processes

An ecosystem is the set of interactions between a community of biological organisms and its physical environment. Ecosystem structure is the basic attribute of ecosystems, reflecting how various elements in the ecosystem interact with each other, and also determining ecosystem functions and the ecosystems' responses and adaptation strategies to the external environment. Ecological processes include the ecosystem material cycle and energy flow. The ecosystem material cycle is the process by which chemical elements circulate between the biological population and the inorganic environment. Energy flow is the process by which the stored solar energy of green plants is transferred unidirectionally along the food chain, decreasing gradually as it goes. The material cycle and energy flow account for the interactions and relationships between biotic and abiotic elements within ecosystems and among the biotic factors of organisms at various food chain levels, representing the most important functions of an ecosystem. It is pivotal to understand the responses and adaptation mechanisms of ecosystem structures and processes to global change. Quantitatively revealing how ecosystems respond and adapt to global change will provide the scientific basis for human adaptive intervention in ecosystems. In order to maintain Earth's habitability in the future, three issues need to be addressed: ① Identification of the mechanisms governing ecosystem structure and stability, ② determination of the material cycle and energy flow mechanisms of ecosystems, and ③ quantitative assessment of ecosystem responses to global change.

3.5.2 Soil Health

With the increasing global population, the demand for food is rising inexorably day by day. Soil health plays an important strategic role in global food security. However, high-intensity human activities are causing severe degradation in soil quality of cultivated land, poor soil health, and continuous decline in grain production capacity. The *Status of World's Soil Resources Report* suggests that soil worldwide faces issues including acidification, nutrient imbalances, salinization, pollution, erosion, hardening and compaction. The ecological services and functions of soil are declining, which seriously restricts its capacity to sustain food supply. To improve the fertility and soil quality of cultivated land and maintain healthy soil, we must address the following issues: ① Improving the soil fertility of cultivated land to support global food production with a safe margin to avoid shortages; ② Preventing, controlling, and repairing soil pollution on cultivated land to ensure food safety and proposing strategies for the safe and sustainable use of contaminated soil to ensure soil health and food quality; and ③ making use of the ecological services and functions of soil organisms in cultivated land to maintain sustainable soil health and food security, studying the multitrophic biological interactions, immunity and detoxification functions of soil organisms to maintain soil ecosystems to ensure soil health and long-term food security.

3.5.3 Environmental Pollution Control

With the rapid industrialization and urbanization, we are now facing increasingly serious problems of environmental pollution. Although many nations have embarked on research programs to examine the ecological and social effects of environmental change and pollution, these initiatives have so far failed to solve the fundamental problem of ensuring sustainable human development. The following are urgent scientific questions for the future. First, we must enhance research on the transmission, migration, sedimentation, and distribution of environmental pollutants, and on regional environmental processes and risks at the global scale under climate changes. Meanwhile, we must analyze viruses' origins, transmission, and monitoring and their mechanisms based on environmental pollution processes. Second, we must strengthen research on the ecotoxic effects of pollutants and their transformation products and explore the impact of environmental pollution on ecosystems. We must conduct ecological risk assessments, develop early warning systems, and predict the ecological effects of future environmental changes. This will allow us to establish a complete theoretical system for environmental biology research and understand the changes and interaction mechanisms in the Earth's biosphere.

3.6 The Carbon Cycle and Carbon Neutrality

Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas. Carbon neutrality refers to the global or regional removal of anthropogenic CO_2 by energy conservation, emissions reduction, afforestation, and carbon capture, so as to reach net-zero carbon emissions. However, it should be noted that CO_2 is not the only anthropogenic greenhouse gas. The Paris Agreement of 2015 proposed a balance between greenhouse gas emissions caused by human activities and their removal in sufficient quantities to reach a net-zero emissions position in the second half of the twenty-first century. An IPCC Special Report on Global Warming in 2018 pointed out that the maximum 1.5 °C global temperature rise specified in the Paris Agreement will require global CO_2 emissions to reach a net-zero level around 2050, and that net-zero emissions of non-CO_2 greenhouse gases needs to be achieved before then (IPCC 2018).

The essence of carbon neutrality is the interaction of the Earth's climate system with the carbon cycle. The Earth's climate system is composed of the lithosphere, atmosphere, hydrosphere, cryosphere, and biosphere, which together regulate the Earth's temperature, precipitation, and air pressure. The principal factors controlling the change of the Earth's climate, such as land surface temperature, vary on different time scales. In a temporal scale of over a million years, the tectonic cycle is the main driving force, whereas on a scale of one hundred thousand years, the most important factor is the Milankovich cycle. Note that the response of the Earth's climate to changes in solar radiation intensity is complex and non-linear. Other factors influencing the Earth's climate include marine physical processes (such as sea surface temperature oscillations in tropical oceans) and the chemical composition of the atmosphere (such as the content of aerosols and greenhouse gases including CO_2), which play a significant role on relatively short time scales. The carbon cycle involves the migration and transformation of carbon and its compounds between and within the atmosphere, land, ocean, and other spheres. Its core encompasses cross-sphere and multi-scale carbon fluxes, processes, mechanisms, and interaction with the climate system. The injection of anthropogenic CO_2 into the atmosphere and its subsequent distribution across the ocean, land and atmosphere components of the Earth system have led to an unprecedented perturbation of the global carbon cycle that has been ongoing since the Industrial Revolution (Gruber et al. 2019). Since carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas, carbon neutrality generally refers to net-zero CO_2 emissions globally or regionally attained by balancing the emission of CO_2 with its removal through energy conservation, emissions reduction, afforestation, and carbon capture. However, CO_2 is not the only anthropogenic greenhouse gas. The Paris Agreement defined climate warming targets of 2 °C, 1.5 °C, and 1v, associated with end-of-century atmospheric CO_2 concentrations of ca. 450, 400, and 350 ppm, respectively. These scenarios approach carbon neutrality by about 2070, 2055, and 2040, respectively, and remain negative thereafter (Hansen et al. 2017). More than 130 countries have proposed commitments on the reduction of individual carbon neutrality-related emission. Adoption and implementation of the actions proposed by many countries will introduce another set of perturbations to the global carbon cycle on decadal time scales.

Research should focus on increasing the precision of carbon flux estimates and revealing the controlling processes and mechanisms to enable more accurate predictions of future climate changes. In order to achieve carbon neutrality in response to climate change, it is vital to examine how the global carbon cycle evolves under both natural conditions and human intervention, as well as the response and feedback of the Earth's climate system.

Emissions reduction (reducing CO_2 emission into the atmosphere) and increasing carbon sinks (enhancing the removal of atmospheric CO_2) are two essential pathways for realizing carbon neutrality. When compared to the extensive researches on the paths, measures, and policies related to CO_2 emissions reduction, the patterns, time scales, and future trends of carbon sinks in various spheres and their interactions with the climate system remain to be better constrained. In addition, increasing attention is paid to a variety of methods targeting the alleviation of climate change, or climate intervention, but its impact on the carbon cycle and ecosystem is not clear and therefore requires more research.

In the context of carbon neutrality, the following research is seen to be essential.

3.6.1 Cross-Sphere and Multi-scale Processes and Mechanisms of the Carbon Cycle and Their Relationships with the Climate System

The core of the carbon cycle is multi-scale carbon fluxes, processes and mechanisms, which involves the migration and transformation of different forms of carbon within and between spheres including the atmosphere, land and ocean. Changes in the temporal and spatial patterns of carbon fluxes determine the degree and scope of contemporary climate change. There have been increasing observations of global and regional carbon fluxes and the general pattern of the CO_2 source and sink in each sphere. Whereas there is still a lack of supporting data and mechanistic understanding of the evolution of carbon spatiotemporal patterns under the combined stress of climate change and human activity, it is therefore necessary to accurately simulate and predict the cross-sphere and multi-scale processes of carbon evolution, which provides a solid theoretical basis for the path towards carbon neutrality.

3.6.2 Budgets, Reservoir Capacity, Uncertainty, and Evolution Trends of Carbon in Terrestrial, Oceanic, and Land-Sea Coupled Systems

About 46% of anthropogenic CO_2 remain in the atmosphere. The other 54% rapidly enters the oceanic (23%) and terrestrial (31%) ecosystems by sea-air and land-air exchanges, respectively. The core issue in carbon cycle research is therefore to accurately understand the budgets, reservoir capacities, and dynamics of carbon in terrestrial and marine ecosystems. Terrestrial ecosystems work as an efficient carbon sink, absorbing 3.4 Gt C yr^{-1} from the atmosphere (2010—2019), of which carbon storage in vegetation and soil is 2241 Pg C. With increasing anthropogenic CO_2 emissions, the CO_2 absorbed by terrestrial ecosystems has increased at a rate of 0.39 Gt per decade (1960–2019). Carbon fixation operates in a number of ways in terrestrial ecosystems, including photosynthesis by vegetation and organic matter secreted by plants roots into the soil, and the preservation of dead and decomposed plants in the soil. Due to the influence exerted by climate change and human activity, there is still great uncertainty regarding the capacity of terrestrial ecosystem in sequestering anthropogenic CO2 on both regional and global scales. The stability and sustainability of the carbon reservoirs also need to be better constrained. Future research foci are: ① the capacity of carbon in different forms and the uncertainty, stability, and sustainability of the carbon sink in typical terrestrial and marine ecosystems ② the spatiotemporal distribution patterns and evolution of carbon reservoir under the combined influence of natural processes and human activities; ③ the roles terrestrial and marine carbon sinks play in different carbon neutralization pathways.

3.6.3 Impact of Carbon Neutrality on the Coupling System Between Carbon Cycling and Climate

Achieving carbon neutrality will involve multi-spheric interactions between the ocean, land and atmosphere and human beings. How humans affect the Earth is crucial to the sustainable development of nature, society, and the economy. Studying the impact of carbon neutrality on the coupling between carbon cycles and climate is a new field in geoscience.

3.6.4 Scientific and Technological Basis for Negative Emissions Technology

Negative emissions technology (i.e., increasing carbon sinks) is vital for achieving carbon neutrality. At present, increasing carbon sinks on land by for example afforestation is an internationally recognized approach. Oceanic carbon sinks (such as those enhanced by marine fertilization) have great potential towards creating negative emissions, but relevant research is scarce. On the basis of accurately monitoring natural and anthropogenic carbon sources and sinks, it is necessary to reinforce basic research on negative emissions technologies including geoengineering, so as to build a conceptual framework for an optimal path towards carbon neutrality.

In order to monitor carbon sources and sinks, a new monitoring, verification, and support (MVS) system is needed. The horizontal transport flux of carbon within a sphere (e. g., land-river) and across interfaces (e. g., river-estuary-coastal ocean-open ocean) needs to be better quantified to reduce its impact on vertical carbon flux assessments. Based on high-quality field data of carbon sources and sinks, the Earth system model can be optimized to predict possible future scenarios and uncertainties in the context of carbon neutrality.

Basic research is critical for implementing any geoengineering project targeting the enhancement of carbon sinks based on natural ecosystems. To achieve carbon neutrality, we first need to construct high resolution data products of regional carbon budgets and develop models and theories to accurately evaluate the sink potential of land, coastal zones, and marine ecosystems. A comprehensive feasibility assessment system should be established for negative emissions technologies, and innovative theories and technologies should be explored. Finally, we need to integrate basic research with applied technology to develop carbon neutral solutions and plan climate change countermeasures based on natural ecosystems. In this way we will strive to protect the biodiversity of our environment and generate synergistic benefits for mankind and for nature as a whole.

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