Earth's Interior Dynamics and Surface Responses (Postprint)

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Abstract

Earth science in the 21st century has entered a new developmental stage, transitioning from relatively isolated explorations across various domains to emphasizing nature' s impact on the human environment, with increasing attention devoted to the intrinsic linkages among different Earth components. Guided by Earth system science theory, and leveraging continuously advancing observational methods, experimental techniques, and big-data quantitative models to investigate the laws and mechanisms governing interactions between the internal and external spheres of the Earth system, thereby comprehending the Earth' s overall behavior and function, represents the future developmental trajectory of Earth science.

Full Text

Earth System Science in the 21st Century

In the 21st century, Earth science has entered a new developmental stage, shifting from relatively isolated explorations of individual fields to emphasizing nature' s impact on the human environment, with increasing attention paid to the intrinsic connections between Earth' s various components. Guided by Earth system science theory and utilizing continuously upgraded observational methods, experimental techniques, and big-data quantitative models, studying the patterns and mechanisms of interaction between Earth' s internal and external spheres to understand the planet' s overall behavior and function represents the future trend of Earth science.

1. Project Background and Significance

Earth is the only known planet in the solar system with a hydrosphere, atmosphere, and biological activity, a uniqueness that stems from its active interior. The solid Earth comprises three major layers from shallow to deep: the crust, mantle, and core. The transfer of material and energy between these layers controls lithospheric evolution, magmatic activity, and the transformation of surface systems. While providing humanity with essential resources for survival, these processes also bring geological hazards such as earthquakes, tsunamis, and volcanic eruptions. The primary bottleneck humanity faces in obtaining natural resources and mitigating disasters is the lack of profound understanding of Earth' s interior. Therefore, studying the state and operating mechanisms of Earth' s interior not only helps us comprehend the planet' s past but also enables us to predict its future.

The revolutionary breakthrough of 20th-century Earth science was the theory of plate tectonics, which successfully explained continental drift and aggregation. In the post-plate-tectonics era, the focus of solid Earth science has gradually shifted toward the intrinsic connections between Earth' s various spheres, leading to three major consensus points. First, Earth' s operational power originates from its interior. As a dynamic planet with multiple layers, the rocky mantle and iron-alloy core constitute the main body of Earth' s internal power system. The relative motion between Earth' s inner and outer cores generates the geomagnetic field, which provides crucial protection for the biosphere and hydrosphere, while mantle convection serves as the primary driving force for plate movement. Second, interactions between spheres maintain Earth' s internal vitality. Earth' s interior contains multiple discontinuities that divide it into various layers. Interactions between the core and mantle lead to the formation of mantle plumes, asthenosphere-lithosphere interactions determine plate thickness and movement rates, and plate subduction transports large amounts of surface material into Earth' s interior across these layers. This transport and exchange of energy and material between spheres is key to sustaining Earth' s internal vitality. Third, Earth' s internal operations control the evolution of surface systems. The surface system interacts with the internal core and mantle as well as external systems to form a unified, complex Earth system. Plate subduction delivers surface materials to the deep Earth, while mantle plumes transport material and energy from the core-mantle boundary to the surface, making them crucial links connecting Earth' s deep interior and surface.

Through multidisciplinary and multi-scale in-depth research on Earth' s internal state, sphere formation, and operating mechanisms, revealing how deep Earth processes influence surface systems represents a highly challenging frontier in contemporary Earth science research. However, no international multidisciplinary comprehensive program currently connects Earth' s interior and surface systems. China possesses rich geological phenomena, providing unique advantages for conducting this research, while the Chinese Academy of Sciences (CAS) holds obvious institutional advantages in academic accumulation, disciplinary configuration, and technical platforms. This positions CAS to seize the disciplinary high ground through multidisciplinary and integrated large-team research. The "Earth' s Internal Operating Mechanisms and Surface Response" Special Project (hereinafter referred to as the "Earth' s Interior" Special Project) plans to conduct research around three interconnected aspects: Earth' s internal state, operating processes, and effects [Figure 1: see original paper], aiming to reveal the constraints of deep Earth processes on surface systems and make original Chinese scientific contributions to alleviating environmental changes and ecological crises facing modern Earth.

2. Key Scientific Questions and Overall Layout

Focusing on three major research directions—Earth' s internal structure and material composition, interaction and material cycling between Earth' s internal spheres, and surface responses to deep Earth processes—the "Earth' s Interior" Special Project has established 13 interconnected research topics [Figure 2: see original paper]. Led by the Guangzhou Institute of Geochemistry, CAS, the project unites over 200 researchers from 6 CAS institutes, 2 universities, and 6 external research institutions [Figure 3: see original paper]. Through comprehensive and interdisciplinary research, the project aims to elucidate the operating mechanisms of Earth' s interior and establish a new theoretical framework coupling deep Earth processes with surface systems.

2.1. Earth' s Internal Structure and Material Composition

The early magma ocean event fundamentally established Earth's basic structure and influenced nearly all aspects of its operation. However, due to intense later modifications, geological records from early Earth are extremely scarce, making related research highly challenging. The Special Project plans to employ multidisciplinary approaches, including modern isotope and trace element geochemistry, Earth accretion dynamics, and computational geophysical dynamics, to determine the extent and formation mechanisms of the magma ocean.

Existing research generally considers Earth' s liquid outer core to be highly homogeneous, while the inner core exhibits significant complexity. Recent geophysical observation networks such as USArray, the China Himalaya Array, and the Global Superconducting Gravimeter Network have provided unprecedented high-quality waveform data, offering new opportunities for core structure research. The project will systematically study the properties and origins of major internal discontinuities, including the mid-lithosphere discontinuity (MLD), mantle transition zone (MTZ), core-mantle boundary (CMB), and inner-outer core interface. It will explore how mantle structure and material composition change at these discontinuities and their relationships with deep processes such as plate subduction, mantle plume upwelling, lithospheric evolution, and magma generation. Furthermore, the composition, element content, and occurrence states of major mantle minerals determine mantle dynamic properties and evolution. Through high-pressure experimental and computational simulation approaches, the project will reveal mineral high-pressure phase transitions and related effects in the deep Earth to probe internal structure and composition.

2.2. Interaction and Material Cycling Between Earth' s Internal Spheres

How plate subduction initiates, the geochemical behavior of elements during subduction, and the controlling factors and impacts of subduction modes constitute fundamental and long-standing questions in solid Earth science. The Special Project will quantitatively study subduction factories and the dynamic processes and effects of subduction mode transitions through the International Ocean Discovery Program (IODP). For decades, researchers have treated mantle plumes and plate tectonics as independent systems, lacking understanding of their important interactions. This project will systematically study the nature and dynamic processes of interactions between mantle plumes and oceanic lithosphere, subducting plates, and continental lithosphere to establish a theoretical framework and identification criteria for mantle plume-plate interactions. The migration and effects of volatiles serve as crucial clues for exploring Earth' s internal operating mechanisms. The project will organize research teams to focus on the distribution and migration patterns of volatile species such as N, S, Cl, and H_2O in Earth's interior, revealing their cycling fluxes in geological processes including plate subduction and mantle plume upwelling, and quantifying their impacts on mantle properties and internal operating mechanisms.

2.3. Surface System Response to Earth' s Internal Processes

The project will conduct multidisciplinary comprehensive studies on the third type of gravity gradient zone located within plate interiors—the North-South Gravity Gradient Zone in eastern China—to elucidate systematic variations in topography, magmatic activity, and crustal and mantle structure and composition across this zone, revealing the dynamic mechanisms by which deep processes constrain the lithospheric system. Geological processes that penetrate Earth' s internal layers, such as plate subduction and mantle plume activity, generate enormous resource effects. However, the mechanisms producing these resource effects remain poorly understood through multi-scale comprehensive research, and key controlling factors for mineralization and systematic metallogenic theoretical frameworks have not been established. To address these issues, the project will systematically study constraints of deep Earth processes on mineralization to provide basis for expanding exploration targets for relevant deposit types.

Major geological events and biological evolution events in Earth' s surface system throughout geological history are temporally highly correlated with intense crustal movements and large-scale magmatic activity. However, whether causal links exist between these simultaneous internal processes and major surface ecosystem evolution events, and what drives them, remain open questions. The project will address this through three research thrusts: (1) Neoproterozoic-Paleozoic transition lithospheric activity and its relationship with Snowball Earth events and multicellular biological explosion; (2) Paleozoic-Mesozoic transition large-scale volcanic eruptions and major biological-environmental events;

and (3) North China Craton destruction and the evolution of the Jehol-Yanliao biota.

3. Expected Outcomes and Contributions

The project aims to achieve breakthrough results in Earth' s internal state, operating mechanisms, and surface responses, constructing a theoretical framework for sphere interactions and deep process constraints on surface systems that will elevate China' s research in this field to a world-leading position. It will publish over 100 Nature Index papers, achieving a transformation from quantitative expansion to qualitative leap in research output and from single-discipline to multidisciplinary integration, thereby propelling Chinese geosciences from following frontiers to pioneering them. The project will cultivate a cohort of internationally competitive research talent, advancing China' s research level in this field into the top tier of international solid Earth science.

Note: Figure translations are in progress. See original paper for figures.