Blue Earth

海と地球の情報誌

139

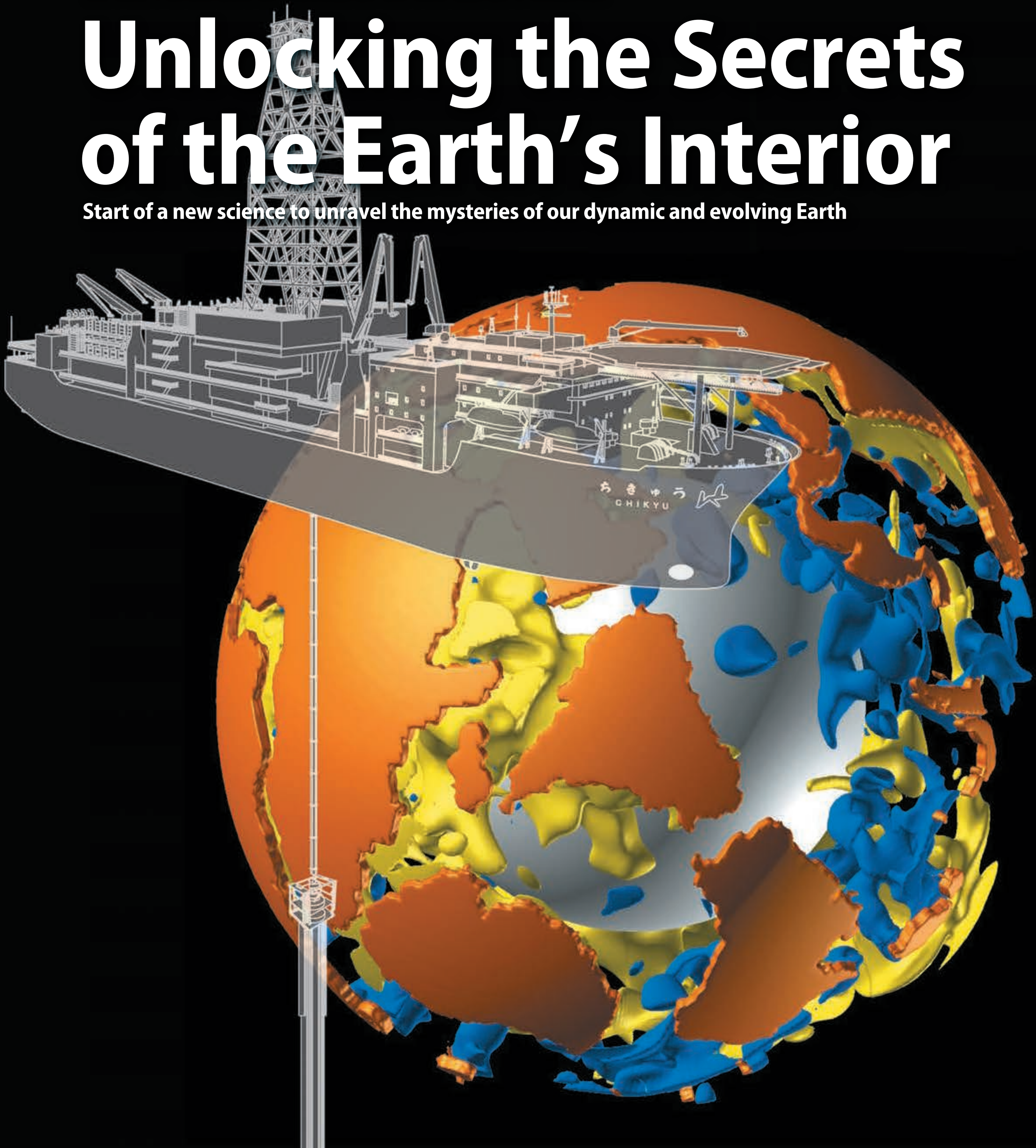
JAMSTEC

Japan Agency for Marine-Earth Science and Technology

Tenth Anniversary of the *Chikyu*
At the Forefront of Research on the Earth's Interior

Unlocking the Secrets of the Earth's Interior

Start of a new science to unravel the mysteries of our dynamic and evolving Earth



Interview: Masaki Yoshida, Senior Scientist, Department of Deep Earth Structure and Dynamics Research

The Driving Force behind Continental Drift Revealed by Mantle Convection Simulations

JAMSTEC performs ocean drilling using the deep sea drilling vessel *Chikyu* and conducts seismic surveys using ocean bottom seismometers as well as other instruments to investigate the subsurface structure with the goal of elucidating the inner-mechanics of the Earth's interior. That said, to gain a detailed understanding of the behavior of the Earth's surface and long-term changes in the large-scale circulation of heat and materials in the mantle (mantle convection), it is important to reconstruct convective processes in the Earth's interior using supercomputer-based simulations in order to complement the geophysical observations obtained by ocean drilling and other methods. Furthermore, given that the mantle has played a major role throughout the Earth's 4.6 billion year history as the driving force behind movement of the Earth's surface and has substantially affected the structural evolution and dynamics of the Earth's interior, it can be said that correct understanding of the driving force behind plate tectonics and continental drift is the foundation of research on the Earth's interior.

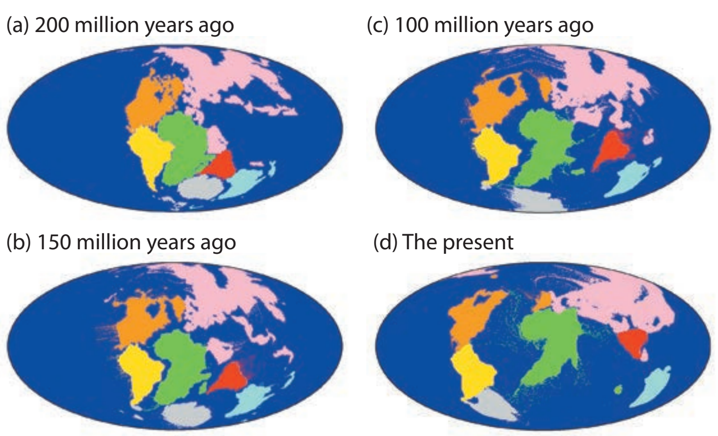
In this context, Masaki Yoshida, Senior Scientist in the Department of Deep Earth Structure and Dynamics Research, has been conducting numerical simulations of mantle convection to reproduce continental drift. Continental drift theory was proposed in 1912 by a German meteorologist, Alfred Wegener. The theory posits that the Earth's continents have repeatedly broken apart and merged from the time of Earth's formation up to the present and that, prior to arriving in their present positions, the continents formed massive land masses known as supercontinents. One such supercontinent is Pangea. Based on paleomagnetic observations and the distribution of fossils and current species, it has been scientifically demonstrated that Pangea formed 300 million years ago and started to break apart approximately 100 million years later and that the continents arrived in their current positions in the subsequent 200 million years. However, no clear cut explanation of the driving force behind continental drift has been put forth in the 100 years since the proposal of Wegener's theory. Yoshida and his colleagues have developed a model of the Earth's interior for simulating mantle convection and are attempting to reconstruct the breakup of Pangaea 200 million years ago up to the present using JAMSTEC's supercomputer.

"Up to now, it was not been possible to reproduce continental drift accurately and, thereby, to identify the driving force. This had to with various difficulties associated with running simulations up to this point, which made it necessary to represent continents as simple plates and did not allow simulations to take into account the actual shape and changes of the Earth's continents. In our current research, after overcoming various difficulties and repeatedly running simulations of mantle convection while changing physical parameters such as the viscosity of the mantle and plates, we have succeeded in reproducing the movement of continents from Pangea 200 million years ago to their present positions," explains Senior Scientist Yoshida.

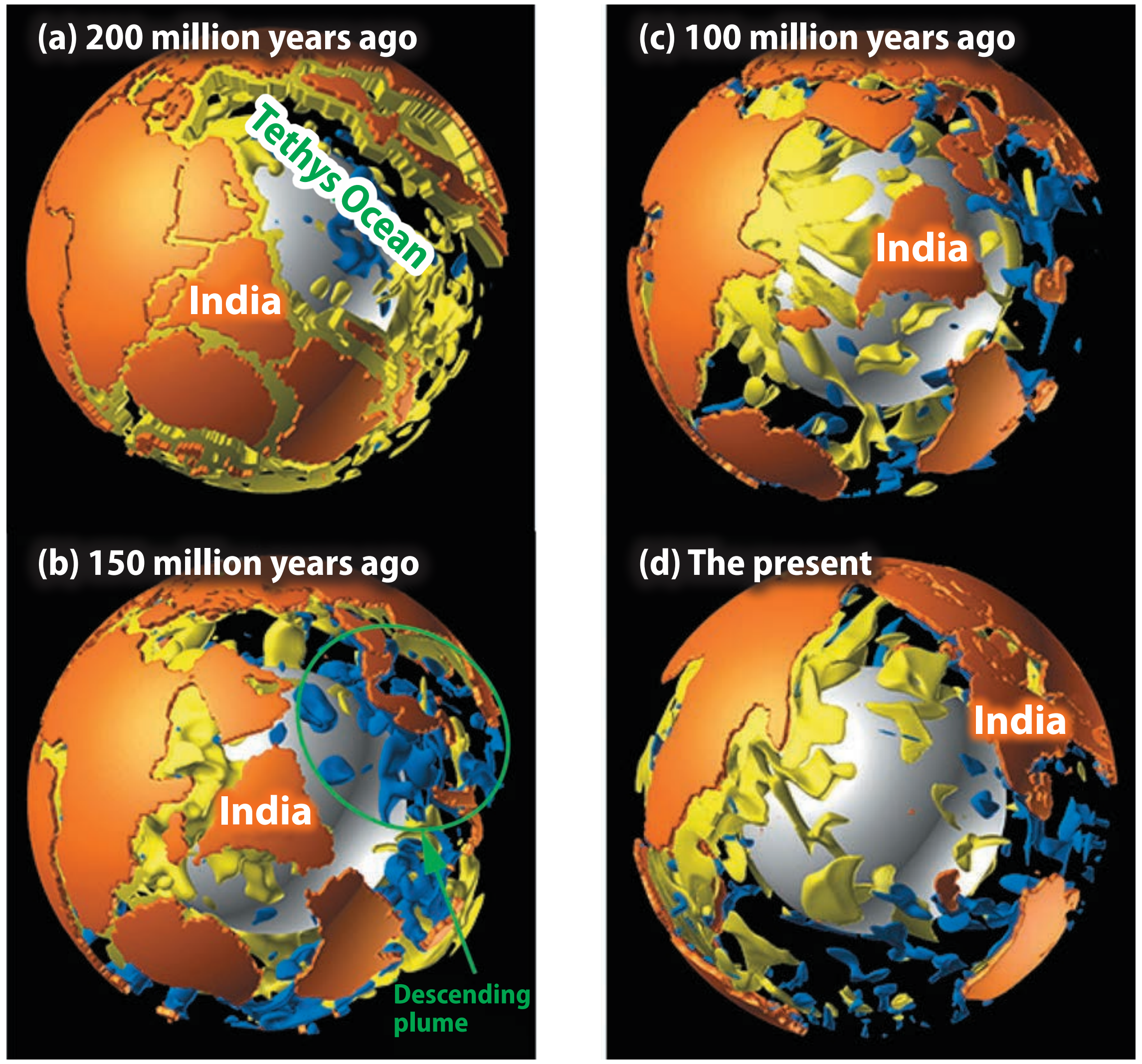
According to Senior Scientist Yoshida, the driving force responsible for the breakup of Pangea was not massive plumes rising up from the deep mantle, as had been believed in the 1980s, but, rather, the supercontinent's thermally-shielding effect (i.e., the blanket effect). With the supercontinent acting as a blanket, the mantle directly below the supercontinent increased in temperature. Cracks formed in the supercontinent to enable heat to be released at the surface. Furthermore, this heating of the mantle created a mantle flow that broke Pangea apart in horizontal directions.

In addition, the simulations were able to recreate the rapid northward migration of the Indian subcontinent, which was a part of Gondwana (southern half of Pangea), across the Tethys Ocean and its collision with Laurasia (northern half of Pangea). The driving force behind this migration was a massive descending plume that developed in the northern part of the Tethys Ocean just after Pangea broke into two. This descending plume formed naturally as a result of a mantle current created by massive ascending plumes in hot regions of the mantle directly underneath Pangea and in the lower part of Gondwana. The Indian subcontinent was carried northward by this mantle current until it collided with Laurasia, creating the Himalayan-Tibetan Plateau of today. Senior scientist Yoshida continues, "Regarding the driving force of continental drift, the conventional hypothesis in the 1970s was that 'slab pull force' resulting from the subduction of the oceanic plates was the dominant force and that 'mantle drag force' caused by mantle convection pulling on the bottoms of oceanic and continental plates was a much smaller force. However, we believe that our current simulations of mantle convection demonstrate that mantle drag is also a major driving force behind continental drift."

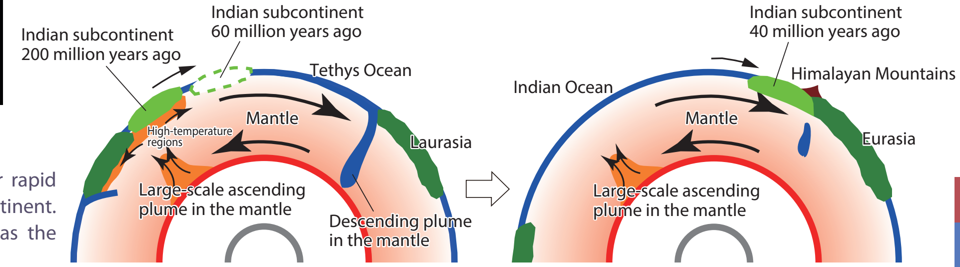
If the only results of simulation research by Senior Scientist Yoshida and colleagues was the discovery of the 'blanket effect' as the driving force behind the breakup of the supercontinent, which had been a mystery for an entire century since continental drift theory was first proposed by Wegener, and the demonstration that mantle drag force is also a major driving force for continental drift, these, in and of themselves, would be major accomplishments. However, it should be possible to take the mantle convection simulations a step further to enable researchers to predict the future positions of the continents. The continents, which are separated today, are predicted to eventually merge again to form another supercontinent. The question is which ocean, the Pacific or the Atlantic, will be closed when the supercontinent forms. There are currently two competing scenarios: one involves the formation of supercontinent 'Amasia' through the closing of the Pacific Ocean, while the other involves formation of supercontinent 'Pangea Ultima' through the closing of the Atlantic Ocean. With regard to such future predictions, Senior Scientist Yoshida explains, "We have already begun running simulations. According to simulations based on current plate movements, there is a greater likelihood that the Pacific Ocean will close." Senior Scientist Yoshida's simulation research gives us a glimpse into the future.



The change over time in distribution of continents over the Earth's surface based on simulations. The simulations faithfully recreate the continental drift reconstructed based on previously-obtained paleomagnetic and geological data and clearly show the breakup of Pangea and expansion of the Atlantic Ocean 200 million years ago as well as the northward migration of the Indian subcontinent (red), which was a part of Gondwana comprising the southern half of Pangea, across the Tethys Ocean and its collision with Laurasia comprising the northern half of Pangea.



3D plot of temperatures of the mantle interior at different time points based on simulations. The blue and yellow isosurfaces indicate regions with temperatures that are 250°C lower and 100°C higher, respectively, than the average mantle temperature. The orange regions of the surface layer indicate the locations of continents.



Conceptual model of the mechanism for rapid northward migration of the Indian subcontinent. It is believed that mantle convection was the driving force behind this migration.

Interview: Hikaru Iwamori, Director/Principal Scientist, Department of Solid Earth Geochemistry

The East-West Hemispheric Structure of Mantle Composition Revealed by Geochemical Probe

The Earth's interior can broadly be divided into three distinct layers differing in chemical composition and structure: the crust covering the Earth's surface, the mantle extending to an approximate depth of 2900 km below the crust, and the core extending to the Earth's center. Pressure and temperature increase with depth, reaching an estimated 3.6 million atmospheres and 5000°C near the Earth's center. Of these three layers, the mantle accounts for 70% of the Earth's total mass. In addition, it accounts for more than 50% of the total heat generated by the Earth and also has an extremely high heat capacity. Accordingly, the mantle has a considerable influence on the circulation of heat between the Earth's core and the Earth's surface; the mantle is, therefore, the most important subsystem for understanding Earth dynamics. This is the main reason researchers are hoping to drill into the mantle and collect mantle material using the deep sea drilling vessel *Chikyu*.

One widely used method for assessing the Earth's internal structure, including the mantle, is seismic tomography, whereby the Earth's internal structure is assessed based on how seismic waves are transmitted. Seismic tomography exploits the fact that seismic waves are transmitted more quickly through hard and low-temperature/high-pressure materials and the fact that reflection waves are generated when seismic waves undergo sudden changes in speed, to develop high-resolution images of the Earth's internal structure. However, we only have a limited ability to study the composition and age of the material that comprises the mantle. As such, there is much interest in geochemical methods (geochemical probes) for assessing the composition of magma originating from the mantle and for studying the rocks and minerals from the deep Earth contained in magma. "If we were to make an analogy to medical technology, seismic tomography is the same as a CT scan. Although we are able to see structures in the Earth's interior that correspond to bones and internal organs in the human body, we cannot study their composition." The geochemical probe, on the other hand, is like a blood test. Just as we extract blood from the body to study it, we can analyze the elements, isotopes, minerals, and so on contained in magma ejected from volcanoes—in other words, the Earth's blood—to obtain valuable information about the Earth's interior," explains Hikaru Iwamori, Director of Department of Solid Earth Geochemistry who carries out geochemical probe research. Geochemical probes can also be used to date material. For example, by studying radioactive isotopes of strontium, neodymium, lead, and other elements with long half-lives contained in volcanic rock, which represents solidified magma originating in the mantle, it is possible to make inferences about mantle convection occurring on the timescale of several hundred million years.

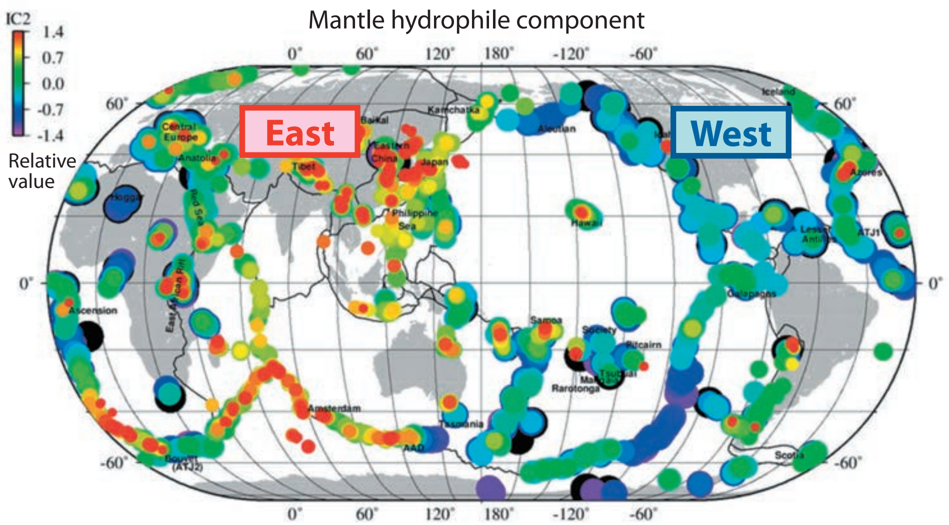
Using this method, Director Iwamori and his colleagues have discovered a surprising feature of the Earth's interior. After compiling data on the composition of volcanic rock from around the world and conducting detailed analysis of five isotopic ratios related to seven elements contained in volcanic rock (strontium, neodymium, lead, and rubidium, etc.), they discovered that the chemical composition of the mantle generally falls into one of two patterns, one found in the eastern hemisphere and the other found in the western hemisphere. As can be seen in the top panel of the figure on page 2 titled "Mantle Enrichment of Aqueous Elements" the chemical composition of volcanic rock clearly differs between the eastern and western hemispheres on either side of the boundaries near the International Date Line and the continents of Europe and Africa.

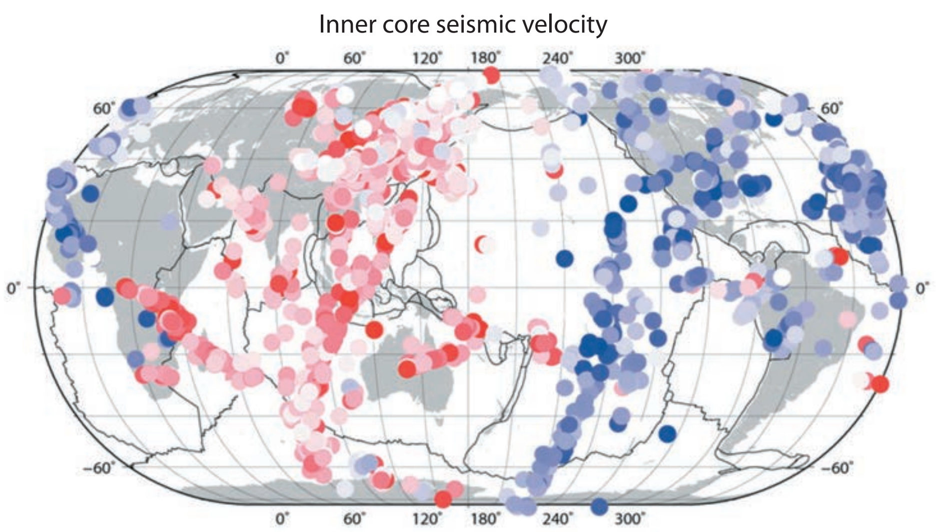
Seismic tomography had already revealed that the transmission of seismic waves through the inner core differs in the eastern and western hemispheres. However, this was the first time that results were obtained showing a corresponding hemispheric division in the mantle geochemistry. "Although the isotopic ratios of elements contained in rock do not, in and of themselves, show a division of geochemical characteristics in the eastern and western hemispheres, analyzing this data using a statistical method known as independent component analysis reveals that the mantle composition differs in the eastern and western hemispheres. It is further possible to trace the development of this east-west structure back several hundred million to a billion years by using isotopic ratios. We hypothesize that the east-west geochemical hemispheric structure we see today is the result of events involving a supercontinent that existed in the eastern hemisphere and the associated subduction zones," explains Director Iwamori.

It is believed that supercontinents known as Rodinia and Pangea existed on earth 700 million to 1 billion years ago and 300 million years ago, respectively, and that subduction zones were concentrated around these supercontinents. Given that water is readily supplied to the mantle by subduction zones, it is believed that the mantle material underneath these supercontinents must have been enriched in water. Furthermore, because this water is enriched with hydrophile elements such as rubidium and lead, the mantle material must have been enriched in these elements. At the same time, the eastern hemisphere of the mantle cooled, resulting in the development of the east-west hemispheric structure of the core. In contrast, the mantle material in oceanic regions with no subduction zones had lower water content and, as a consequence, had relatively lower proportions of elements such as rubidium and lead.

These supercontinents eventually arrived at the present arrangement of continents, yet a vestige of this supply of water to the mantle by subduction zones near the former supercontinents manifests itself in the East-West geochemical hemispheres of the mantle, revealed by geochemical analyses of rock samples collected from around the world.

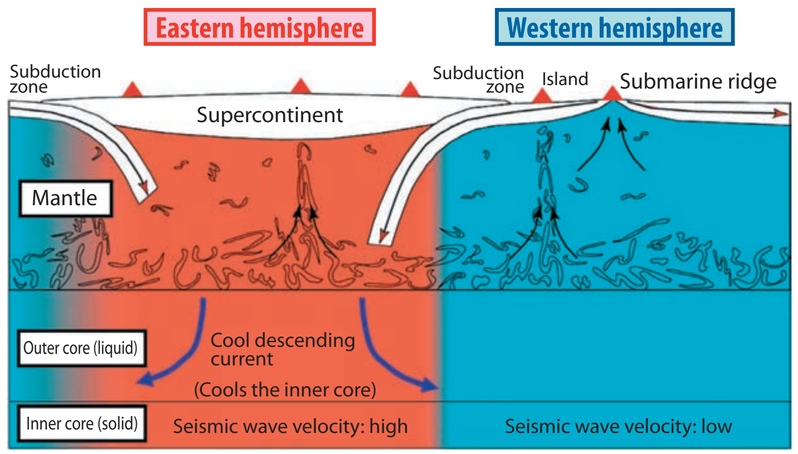
The east-west geochemical hemispheric structure of the mantle discovered by Iwamori and colleagues is only one aspect of the Earth's interior brought to light by using geochemical probes. Future research will undoubtedly reveal not-yet-imagined truths about the Earth's interior.





Iwamori & Nakamura (2015) Gondwana Res.

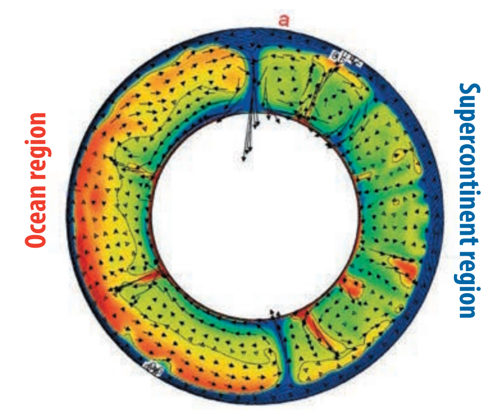
Concentration of hydrophile component in the mantle (upper panel: isotopic composition of the mantle) and seismic-wave velocity of the inner core (lower panel: red circles indicate higher seismic wave velocity and blue circles indicate lower seismic wave velocity). Not only is there a clear divide in the isotopic composition of the mantle between the eastern and western hemispheres, but a similar structure exists in the seismic wave velocity of the inner core. These results suggest that the subduction zones concentrated near the former of supercontinents affected not only mantle composition but, at the same time, had the effect of cooling the mantle and inner core.



Iwamori & Nakamura (2015)

Conceptual model of the Earth's interior showing the origins of the east-west hemispheric structure at the time of the supercontinents. Hydrophile components were supplied to the mantle along with water in subduction zones, which were concentrated in the vicinity of the supercontinent. It is further speculated that focused subduction cooled the region below the supercontinent including the core.

Temperature at the time of supercontinent formation



Numerical simulation of the temperature distribution in the Earth's interior at the time of supercontinent formation. The region below the supercontinent is cooled by the subduction zones concentrated near the supercontinent. Temperature below the supercontinent is lower than that below the ocean region.

Yoshida (2013) Geophys. Res. Lett.