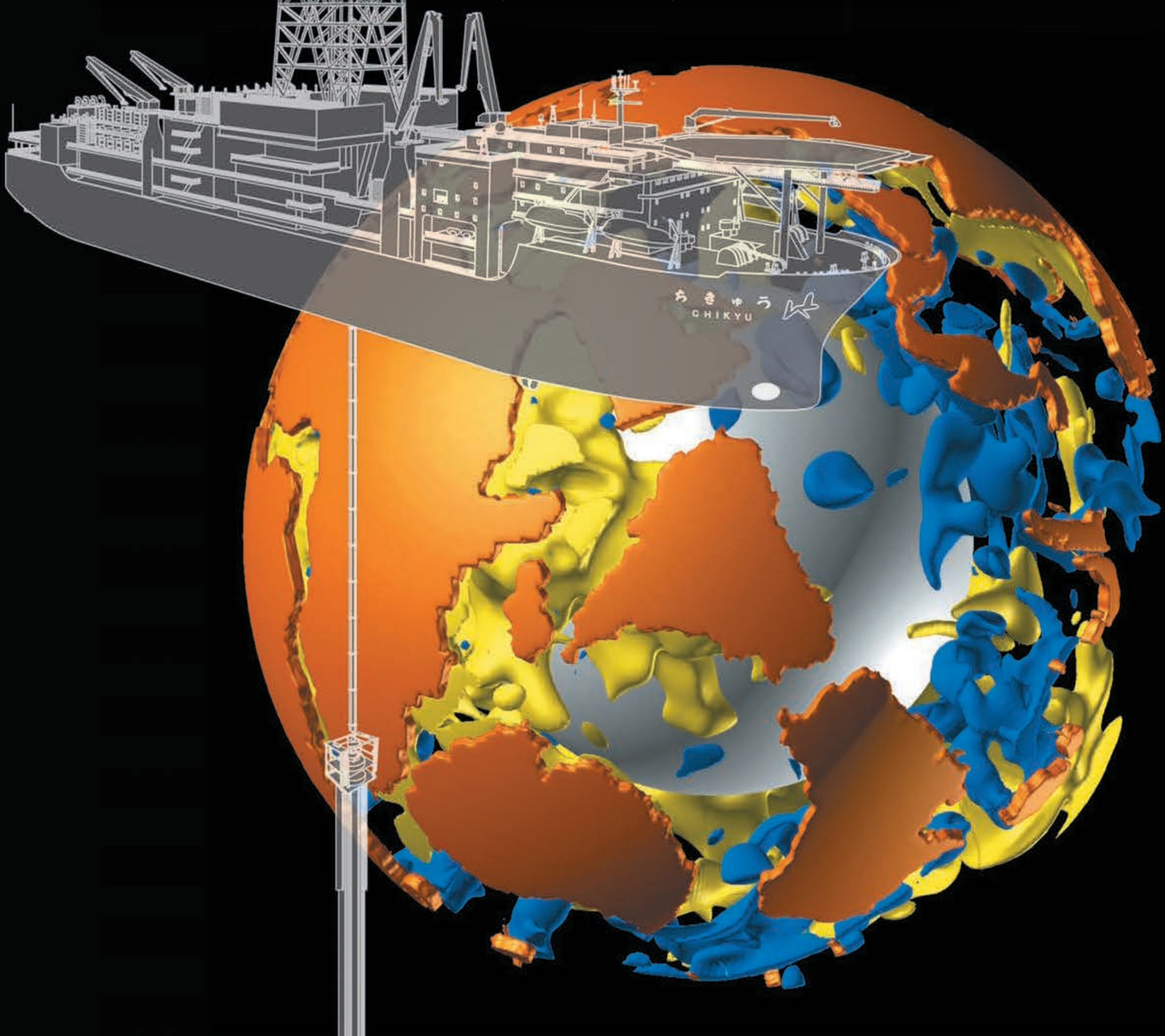
海と地球の情報誌
Blue Earth
139
Japan Agency for Marine-Earth Science and Technology

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



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Ten years have passed since completion of the deep sea drilling vessel *Chikyu*. As the flagship of the Integrated Ocean Drilling Program (IODP, renamed in 2013 as the International Ocean Discovery Program), an international collaborative effort in which Japan plays a leading role, the *Chikyu* carries out drilling expeditions around the world and is a driving force in the exploration of the as-yet-unknown interior of the Earth. Steady progress is being made in the development of technologies that will enable researchers to take on new challenges, such as drilling into the Earth's mantle, which is scheduled to take place in the near future.

To be certain, scientific drilling is not the only research method that yields insight into the Earth's interior. A variety of research methodologies are used in Earth Science, including experiments to reproduce the high-temperature, high-pressure conditions of the deep Earth that cannot be reached even by the *Chikyu*, simulations employing supercomputers, and imaging of the deep Earth using neutrinos. In this issue of Blue Earth commemorating the 10th Anniversary of the *Chikyu*, we introduce the most recent accomplishments and new developments in research on the Earth's interior, focusing on work by JAMSTEC.

Front cover: 3D plot of temperature distribution inside the mantle based on numerical simulation of mantle convection (related story on pp. 8 and 9)

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.

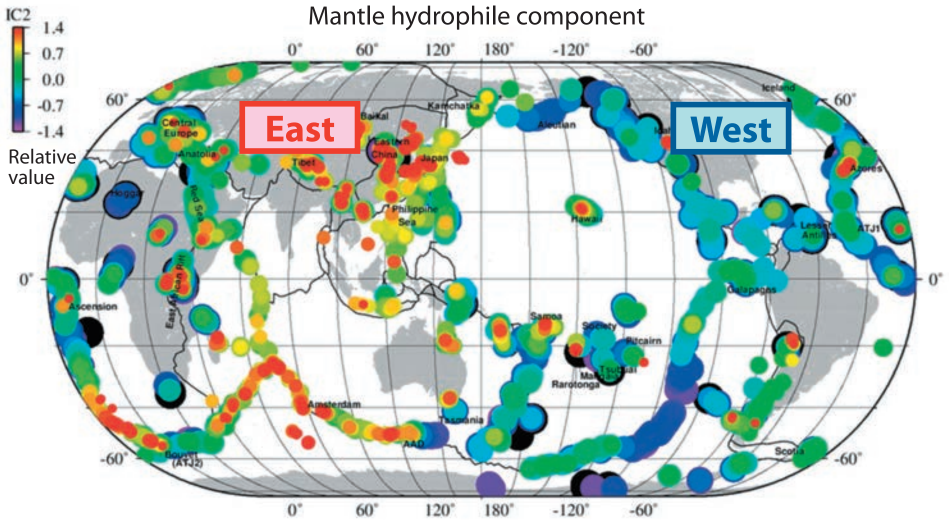
Using this method, Director Iwamori and his colleagues have discovered a surprising feature of the Earth's interior. After compiling data on the composition of volcanic rock from around the world and conducting detailed analysis of five isotopic ratios related to seven elements contained in volcanic 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.

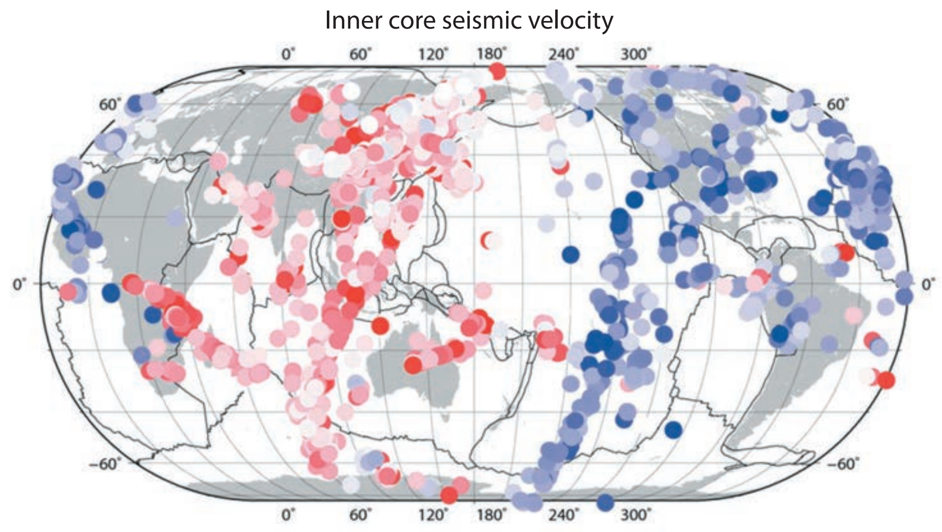
Seismic tomography had already revealed that the transmission of seismic waves through the inner core differs in the eastern and western hemispheres. However, this was the first time that results were obtained showing a corresponding hemispheric division in the mantle geochemistry. "Although the isotopic 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.

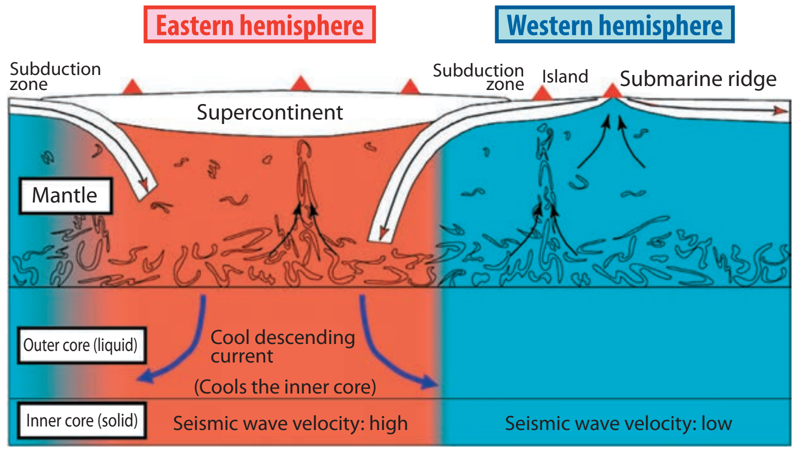
The east-west geochemical hemispheric structure of the mantle discovered by Iwamori and colleagues is only one aspect of the Earth's interior brought to light by using geochemical probes. Future research will undoubtedly reveal not-yet-imagined truths about the Earth's interior.





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 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.

Iwamori et al. (in preparation)

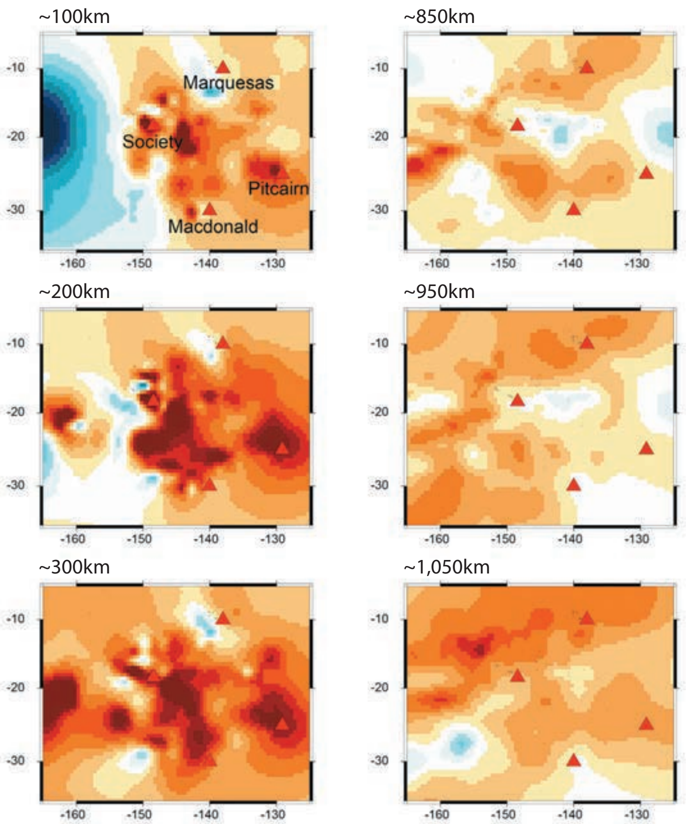
Exploring Deep Earth based on Seismic Wave and Electromagnetic Observations.

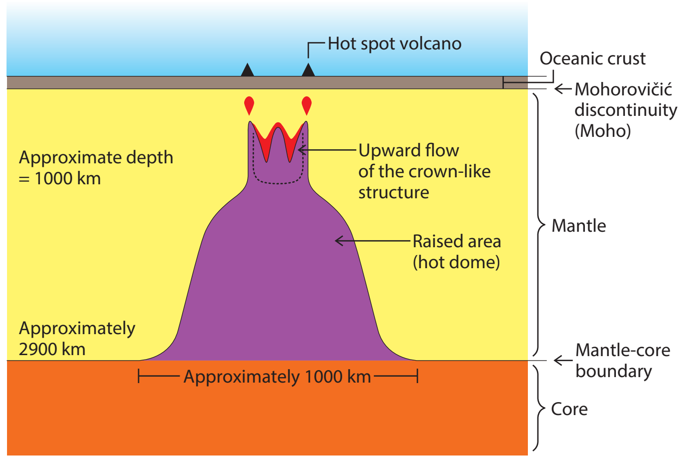
Seismic tomography is a method that is used widely to clarify the structure of the Earth's interior by studying the way seismic waves from earthquakes occurring around the world are transmitted. It has been used not only to clarify the large-scale internal structure of the Earth comprising the core, mantle, and crust, but has also enabled scientist to visualize in detail the birth of tectonic plates at ocean ridges and subduction of plates into the mantle. Given its high spatial resolution, seismic tomography has become an essential technology for studying the Earth's internal structure. In recent years, attention has been paid to a new technology: electromagnetic observation conducted on the ocean floor. Daisuke Suetsugu, Director of Department of Deep Earth Structure and Dynamics Research explains, "In electromagnetic observation, ocean bottom electro-magnetometers (OBEMs) consisting of magnetometers, potentiometers and other sensors are deployed on the ocean floor. The technology exploits the interaction (change in magnetic field) between geomagnetism and Earth currents to measure electrical conductivity—in other words, the ease (or difficulty) with which electricity travels through rock—to clarify the temperature as well as the type and condition of subterranean rock."

Earth currents are induced in a direction that cancels the geomagnetic field, which changes with solar activity. In electromagnetic observation, the electrical conductivity of subterranean rock is estimated by measuring the Earth current and geomagnetism. Director Suetsugu and colleagues are attempting to study the structure and dynamics of the deep earth by using electromagnetic observation in conjunction with seismic tomography. One target of such observations is the ocean in the vicinity of Tahiti in the South Pacific.

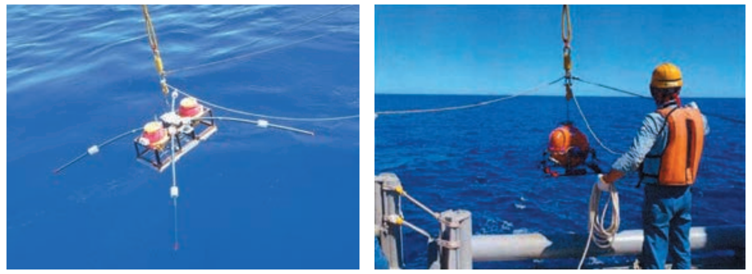
French Polynesia is made up of a large number of volcanic islands, including the well-known island of Tahiti. As in the case of the Hawaiian archipelago, these islands were formed by hot spot volcanoes from which magma generated deep in the mantle rose and was expelled. Although the area is currently inactive, it is believed that the region experienced vigorous volcanic activity 120 million years ago. Postulating that vestiges of this age should exist below the French Polynesian ocean floor, a collaborative research project to monitor seismic waves using ocean-bottom seismometers (OBS) was carried out between 2003 and 2005 in collaboration with French researchers: an unexpected subseafloor structure was discovered. Director Suetsugu recalls, "When we deployed OBSs in the area near French Polynesia and began monitoring seismic waves, we discovered that there was a massive structure at an approximate depth of 1000 km below the sea floor measuring 1000 km across; the seismic wave transmission velocity of this structure was low. Furthermore, there was an anomalous region with a diameter of 100 km or so rising from the top of this massive structure, which exhibited similarly low seismic wave transmission velocity.

Intrigued by this unknown structure, Director Suetsugu deployed OBSs and OBEMs in 2009 and 2010 in a narrower target area consisting of the ocean surrounding Tahiti and conducted seismic wave and electromagnetic observations. The images at the bottom of page 4 show the results of these observations. The figures show seismic wave transmission velocity from 100 to 1050 km below the seafloor. The red areas represent areas with low transmission velocities; the blue areas, high transmission velocities. Vertically stacking the images for each layer reveals the existence of a low-transmission-velocity, crown-like structure between 600 and 950 km below the seafloor that appears to connect volcanic islands (indicated by the red ▲ symbols) and above which lie hot spot volcanic islands. It can also be seen that the structure at this depth range clearly differs from that of the underlying structure at 1000 km below the seafloor.





Results of seismic wave monitoring of the ocean near Tahiti and neighboring volcanic islands using ocean bottom seismometers (OBS). A massive, high-temperature structure was found to exist at an approximate depth of 1000 km below the seafloor. In addition, a high-temperature, crown-like structure connecting volcanic islands (indicated by red ▲ symbols) was found to exist above the structure at a depth of 600 and 950 km below the seafloor. Above is a conceptual model of the hot dome and the crown-like structure based on the results of seismic observation.



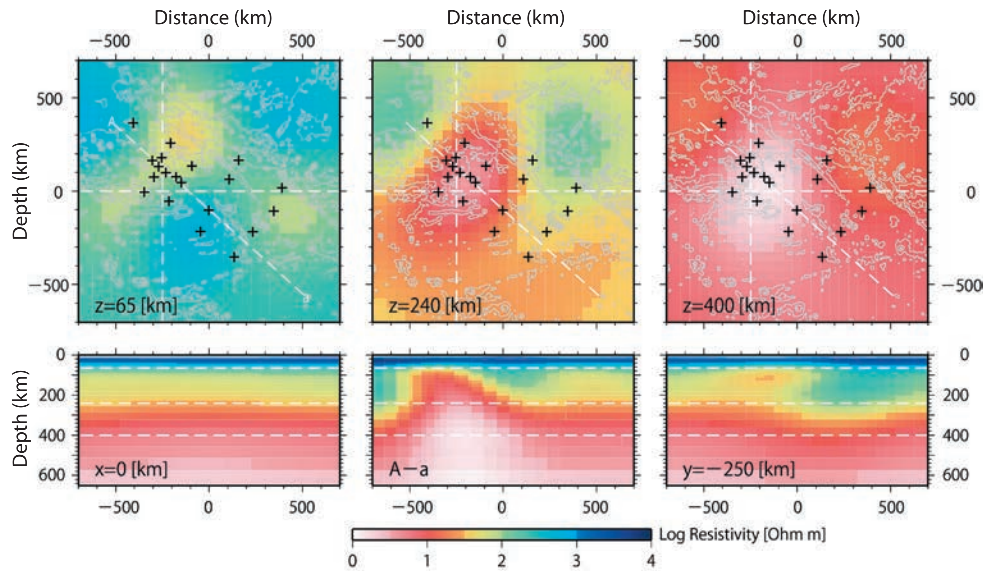
An ocean-bottom-electromagnetometer (OBEM, left) and ocean-bottom seismometer (OBS, right) being deployed to the ocean floor.

Below the seafloor near Tahiti and surrounding volcanic islands, even today, there is a massive structure that is warmer than the surrounding rock. "It might be a type of hot plume," speculates Director Suetsugu. The term "hot plume" refers to the upward flow of mantle material melted by the core, "which, up to this point was believed to erupt and form mushroom-shaped plumes. However, as far as we can tell based on what was observed in the sub-seafloor near Tahiti, it seems that the material that erupts is not only hotter than the surrounding rock but, also, has a different chemical composition than the normal mantle.

Consistent with the results of seismic tomography, the electromagnetic observations added in the second study also indicated the presence of a hot spot located above the crown-shaped structure that is hotter than the surrounding rock. "Although we were able to discern the same sub-seafloor structure indicated by seismic tomography using electromagnetic observation, whereas seismic tomography indicated that the hotspot temperature was approximately 200°C higher than that of the surrounding rock, electromagnetic observation indicated that the temperature difference was closer to 500°C. This discrepancy of 300°C cannot simply be explained by measurement error. We believe the material must contain some component that does not affect how seismic waves are transmitted but that does affect electrical conductivity, increasing electrical conductivity," explains Director Suetsugu. The electrical conductivity of a rock is known to increase if it contains crust material, water, or carbon compounds. At present, Director Suetsugu and colleagues are working to identify the source of the discrepancy in temperature estimates based on electromagnetic observation and seismic tomography by comparing the result to data from laboratory experiments.

In addition, Director Suetsugu's team is currently looking into the cause of the massive volcanic eruptions that occurred in the South Pacific during the period of vigorous volcanic activity some 120 million years ago and are conducting OBS- and OBEM-based observations on the Ontong Java Plateau (off the coast of New Guinea) that was formed during this active period. Given the speculation that this volcanic activity may have caused climate change at the time, it has attracted the attention of an international audience, and plans are being made to conduct drilling research expeditions in the area. Obtaining information about the structure of the crust and mantle underlying the plateau will be a major first step towards drilling.

"If we were able to directly get our hands on mantle material, we would have a sure way of knowing about the structure, state, and composition of the Earth's interior. At present, however, we are only able to get information about the mantle through seismic and electromagnetic observations. To obtain information that is as accurate as possible, it is important to not rely on a single method and to use combinations of different methods. We plan to continue elucidating the deep Earth using simulations as well as seismic and electromagnetic observations while comparing our results with the results of drilling studies," declares Director Suetsugu.



The results of electromagnetic observation in the ocean near Tahiti conducted jointly with a French research team. The color scale represents resistivity (reciprocal of electrical conductivity). Colors closer to red indicate higher electrical conductivity. The images show a hot spot (image centers) located above the structure indicated by seismic tomography. The + symbols indicate locations of observation points where ocean-bottom electromagnetometers were deployed.

Using Various Research Methods to Unravel the Mysteries of the Origins and Evolution of Early Life

There is a long history of research on the origins of life; although it is estimated that life emerged 3.8 to 4 billion years ago, we know very little with any certainty. Organic matter believed to be the artifacts of chemosynthetic biological communities made up primarily of methanogens (methane producing bacteria) have been found in 3.5-billion-year-old geological formations (western Australia, artifacts of hot water activity). These artifacts are considered to be the "world's oldest fossils (trace fossils)." In 2014, Manabu Nishizawa and colleagues in the Laboratory of Ocean–Earth Life Evolution Research conducted an experiment to culture methanogens from the Central Indian Ridge, which is believed to retain characteristics of the "hot water ecosystem" of the early Earth; they demonstrated that ancient microbial ecosystems supported by hyper-thermophilic methanogens may have already been fixing nitrogen, a process that is essential for protein synthesis, 3.5 billion years ago. While this discovery is important in terms of understanding the evolution of biological activity, countless mysteries remain regarding the emergence and evolution of the earliest forms of life.

Analyzing samples collected by ocean drilling in the research area aboard the *Chikyu*.

In this context, research based on a very different approach is being conducted to study early life: that is, research to look for life in space. There is growing evidence that liquid water once existed on the surface of Mars. In addition, a number of celestial bodies with hidden oceans lying underneath thick crusts of ice have been discovered, including Europa, one of Jupiter's moons. Of course, direct evidence of life on other planets has not yet been discovered. If, however, the existence on life on other planets were to be confirmed, that would contribute greatly to unraveling the mysteries regarding the emergence and evolution of life on Earth. In March of this year (2015), Takazo Shibuya and colleagues in the Laboratory of Ocean–Earth Life Evolution Research recently published the results of important research that addresses such questions by demonstrating the existence of an environment capable of supporting life on one of Saturn's moons, Enceladus.

Enceladus' interior hides an underground ocean with water that erupts into space as plumes (geysers) from cracks in the moon's surface near the South pole. As part of its mission to explore Saturn, the US's Cassini Probe passed through these plumes and used its on-board dust analyzer to identify various substances contained in the water including salts, organic matter, and carbon dioxide. Among these substances, Research Scientist Shibuya and colleagues focused on nano-silica particles that can be used as an indicator of ocean floor temperature. Using experimental methods, Shibuya and colleagues discovered that a hot water environment with temperatures in excess of 90°C exists at the bottom of Enceladus's underground ocean and that this thermal activity is occurring even today. With this discovery, it was confirmed that, in addition to liquid water and organic matter, Enceladus has the third component necessary for the emergence of life: energy. This is the first time that an environment capable of supporting life has been shown to exist anywhere outside of the earth.

Meanwhile, to unravel the processes by which life emerged and evolved on Earth, the Laboratory of Ocean–Earth Life Evolution Research has experimentally recreated the early Earth's high temperature/high pressure environment in which life is believed to have emerged and is studying the behavior of single-celled organisms in this environment. "Although it was previously thought that life emerged in the presence of abundant water, given that proteins are created through the polymerization of amino acids via dehydration, protein synthesis does not occur in environments with lots of water. It is now believed that life emerged in environments with relatively little water. As such, high temperature, high pressure subterranean environments are being studied as the potential birthplace of life. With this in mind, we are attempting to study biological activity in high temperature/high pressure environments," explains Research Scientist Haruka Ozawa and Director Mitsuhiro Toriumi. "We change the environment of microbial cells to study their reactions and changes in structure. Thinking about these responses in the context of the early Earth environment, we explore how the earliest organisms might have behaved and evolved. The reactions of cells are infinitely diverse. We hope to explore the evolution of early life by studying this diversity and employing methods borrowed from statistical mechanics."

While, on the one hand, Director Toriumi engages in experimental research such as that described above, on the other hand, he explains that he has "high hopes" for ocean drilling-based research on the sub-seafloor biosphere using the deep sea drilling vessel *Chikyu*. Director Toriumi explains, "if organisms retaining the characteristics of the earliest life forms are recovered from the subseafloor, we can conduct our studies while complementing our result with empirical observations." Director Toriumi hopes to continue pragmatically using a wide range of research methods ranging from ocean drilling to searching for life in space to unravel the mysteries of how life emerged and evolved on Earth.

Plumes (geysers) erupting from cracks near the south pole of Enceladus, observed by the US's Cassini Probe as part of it mission to explore Saturn.
Image source: NASA/JPL/Space Science Institute

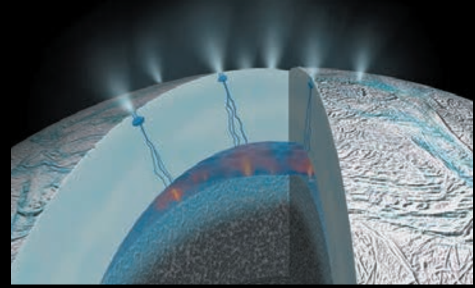


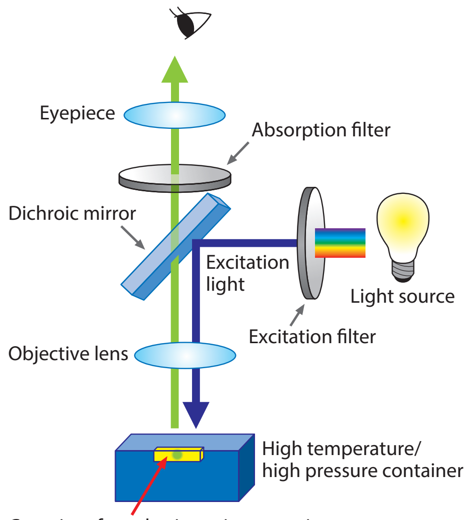
Image source: NASA/JPL

The search for extraterrestrial life

A model of the interior of one of Saturn's moons, Enceladus. Analysis of observations made by the US's Cassini Probe (see below) as part of its mission to explore Saturn revealed the existence of an underground ocean that is in contact with the moon's rock core and comprises a hot water environment suitable for habitation by living organisms.

The emergence and evolution of life

Experimental research



The reactions of microbial cells to environmental changes are investigated using a fluorescence microscope system that enables observation of microbes cultured at high temperatures and high pressures.

Ocean drilling-based investigation of the subseafloor biosphere

Deep Hot Biosphere project to study the subseafloor biosphere in the Iheya hydrothermal field in the mid-Okinawa Trough using the *Chikyu* (IODP Expedition 331)

Approaches taken by the Laboratory of Ocean–Earth Life Evolution Research

The Driving Force behind Continental Drift Revealed by Mantle Convection Simulations

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

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.

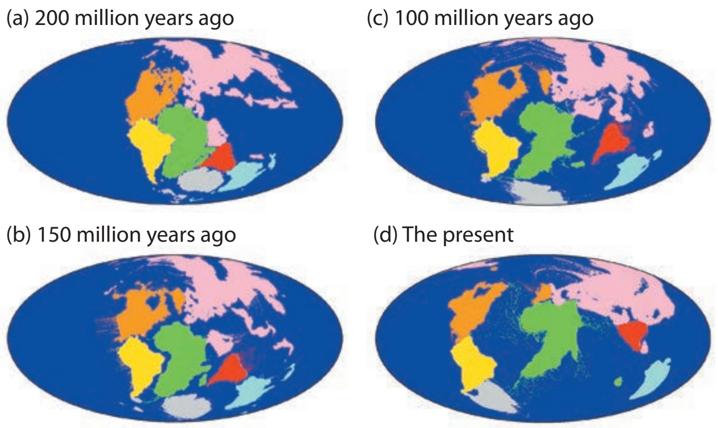
In this context, Masaki Yoshida, Senior Scientist in the Department of Deep Earth Structure and Dynamics Research, has been conducting numerical simulations of mantle convection to reproduce continental drift. Continental drift theory was proposed in 1912 by a German meteorologist, Alfred Wegener. The 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.

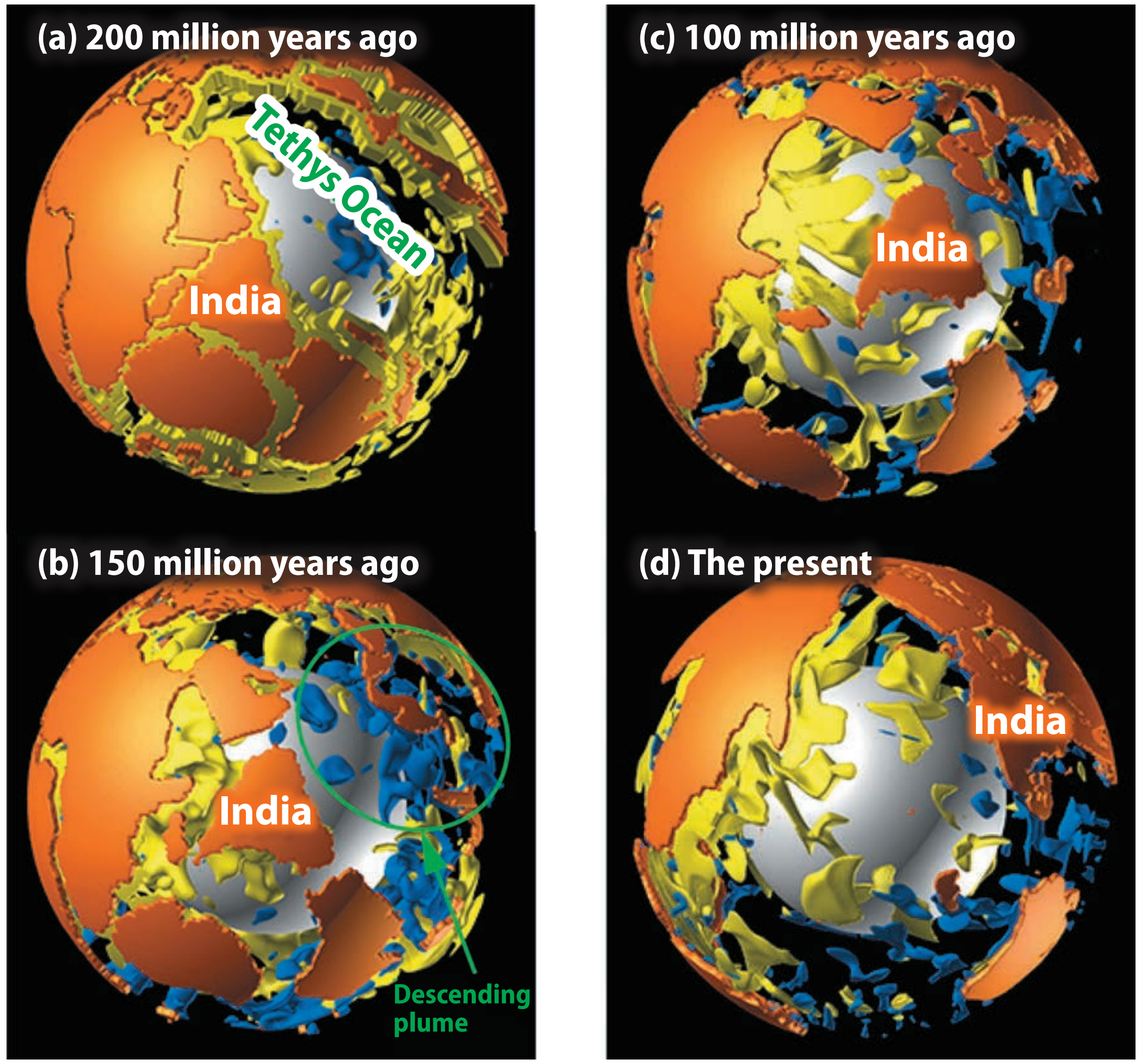
According to Senior Scientist Yoshida, the driving force responsible for the breakup of Pangea was not massive plumes rising up from the deep mantle, as had been believed in the 1980s, but, rather, the supercontinent's thermally-shielding effect (i.e., the blanket effect). With the supercontinent acting 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."

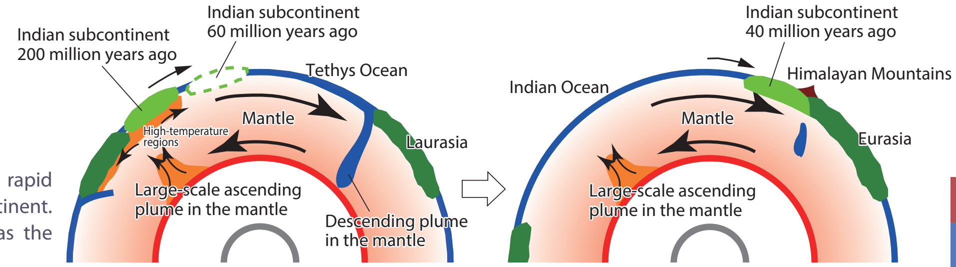
If the only results of simulation research by Senior Scientist Yoshida and colleagues was the discovery of the 'blanket effect' as the driving force behind the breakup of the supercontinent, which had been a mystery for an entire century since continental drift theory was first proposed by Wegener, and 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: Kei Hirose, Visiting Senior Researcher, Laboratory of Ocean-Earth Life Evolution Research and Director of Tokyo Institute of Technology Earth-Life Science Institute

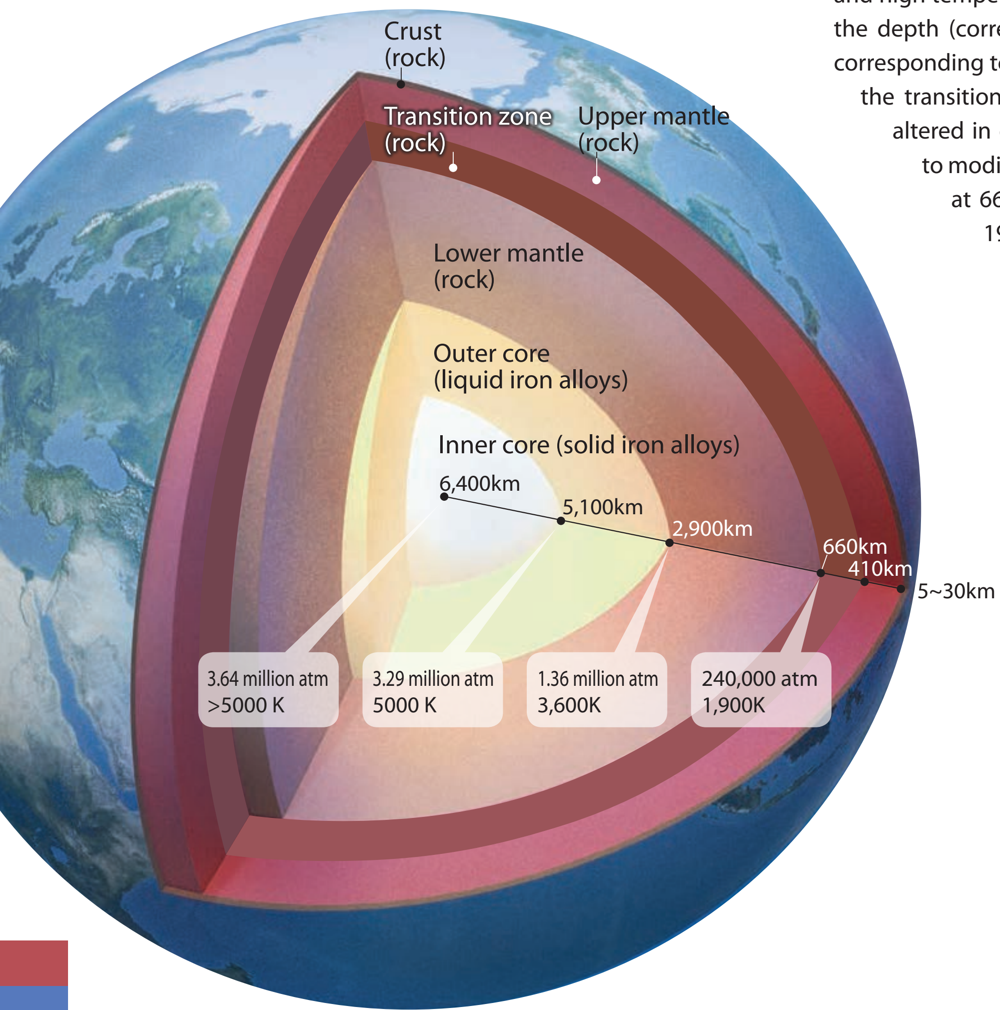
Revealing Conditions in the Earth's Depths by Creating an Ultra-Pressure, High-Temperature Environment in the Lab

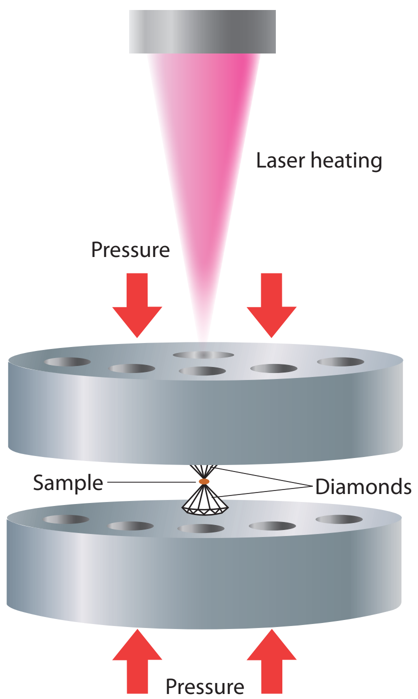
The deep sea drilling vessel *Chikyu* has pushed the envelope of drilling technology with the goal of drilling to the mantle. Beyond the mantle, deeper than even *Chikyu* could ever reach, lies the Earth's core. The core is divided into the (liquid) outer core, from 2900 to 5100 km below the surface, and the (solid) inner core, from 5100 to 6400 km. The heart of the inner core, at the center of the Earth, is understood to be an ultra-high-pressure, ultra-high-temperature environment, at 3.64 million atmospheres and 5000 K (kelvin, the unit of absolute temperature, equal to Celsius values plus 273).

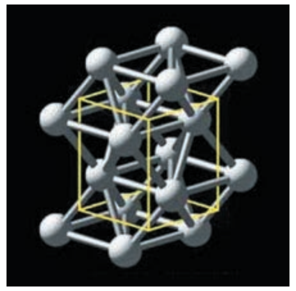
Because the core cannot be reached by drilling, a different approach is required to find out what materials the core is made of and what conditions are like in the core. Structural surveys of the Earth's interior have been carried out using seismic waves, but the information that can be obtained from seismic waves is limited. Therefore, a research group at the Laboratory of Ocean-Earth Life Evolution Research led by visiting senior researcher Kei Hirose (Director of the Earth-Life Science Institute at Tokyo Institute of Technology) have been conducting experiments to reproduce ultra-high-pressure, high-temperature environments and artificially create materials and structures that could be present in the depths of the Earth.

They used a laser-heated diamond anvil cell for these experiments. This apparatus squeezes a sample between two diamonds and, while pressure is applied to the sample from above and below, a laser is fired to heat the sample. High-pressure, high-temperature experiments to investigate changes in the principal minerals of the mantle have been conducted around the world since the 1950s. One of the principal minerals of the mantle is peridotite (Mg_2SiO_4). When peridotite is put under high pressure and high temperature, the structure changes in accordance with the depth (corresponding to the pressure). In an environment corresponding to 410 km depth, which is the boundary between the transition zone and the upper mantle, peridotite is not altered in chemical composition but its structure changes to modified spinel phases. Beyond the change to spinels, at 660 km depth in the lower mantle (240,000 atm, 1900 K), peridotite is replaced with perovskite ($MgSiO_3$) and periclase (MgO). In 2004, Hirose and his colleagues were the first in the world to demonstrate that perovskites change in structure to post-perovskites at 2600 km depth (1.25 million atm, 2500 K). It is generally thought that thermal convection takes place in the mantle. The phase transition between perovskites and post-perovskites that Hirose and his colleagues discovered is closely related to rising convection flows in the lowermost part of the mantle.

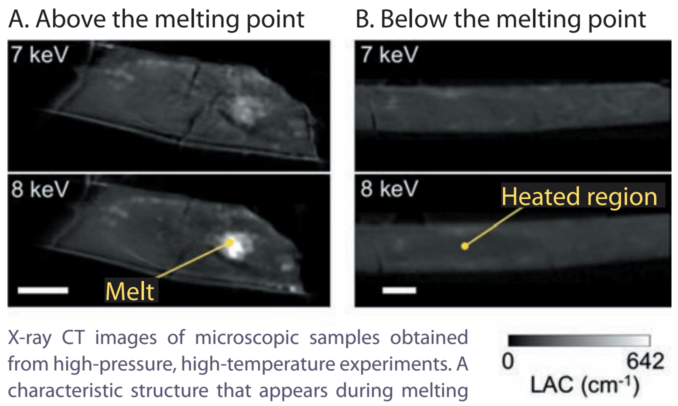
Internal structure of the Earth







The experiments showed that iron at the center of the Earth has the hexagonal close-packed structure illustrated here.



X-ray CT images of microscopic samples obtained from high-pressure, high-temperature experiments. A characteristic structure that appears during melting can be observed. The bright patch in the left images shows a melt produced by local melting of the mantle material. The pairs of images were captured with X-rays at two energy levels: 7 and 8 keV (kiloelectron volts). The strong contrast between the images is because the local melt is rich in iron oxide. Whether a sample has melted (left) or not melted (right) can be judged from the presence or absence of a region rich in iron oxide. In this way, accurate melting points for the whole mantle were found. The scale markers (white bars) are 5 μm long.

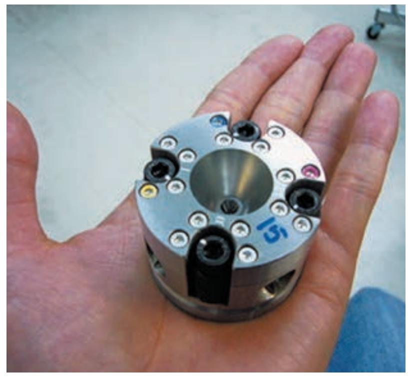
Then, in 2010, they were the first in the world to successfully create an ultra-high-pressure, high-temperature environment of 3.64 million atm, 5500 K, corresponding to the center of the Earth. They found that iron, the principal component of the core, has its densest crystal structure there, a hexagonal close-packed structure.

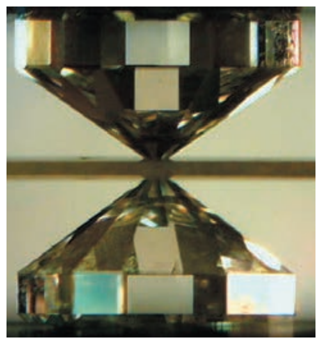
By putting mantle material in ultra-high-pressure, high-temperature environments, they were also able to find melting points in the mantle. To find the melting point of mantle material, they put the material in an ultra-high-pressure, high-temperature environment and accurately determined the temperature at which it started to melt. After the mantle material was melted in the diamond anvil cell, they used high-resolution microtomography imaging to identify characteristic structures that appeared during the melting. For this imaging, they used high-intensity X-rays at the "Spring-8" large synchrotron radiation facility in Hyogo Prefecture. X-ray computerized tomography (CT) is well known for its use in medical equipment but recently has also been applied to materials research. CT using high-intensity synchrotron X-rays, as in this experiment, makes possible non-destructive observations of the structures of samples down to resolutions from hundreds of nanometers to several micrometers.

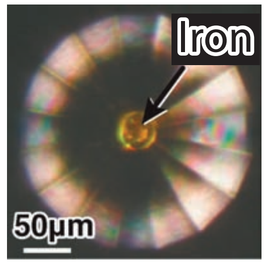
With this experiment, the research group managed to confirm that melts were formed and identified accurate melting points for the whole of the mantle, finding that the temperature at which the mantle material just outside the core melts is about 3600 K, some 600 K lower than the previous estimate. Given that the bottom of the mantle is solid, the temperature near the core must therefore be less than 3600 K; moreover, for the outer core to be liquid at this temperature, there must be other substances that lower the melting point in the core material. Hydrogen is very effective in lowering melting points and this result indicates that the core contains large amounts of hydrogen. The hydrogen content of the outer core must be about 0.6% by weight, which is about 25% in terms of numbers of atoms.

Hirose says: "These huge amounts of hydrogen are very likely the remnants of water that was trapped in iron in the magma that covered the surface when the Earth was formed (the magma ocean). If converted to water, the hydrogen that we now estimate to be present in the core would be about 1.6% of the total mass of the Earth (and about 80 times all the water in the oceans), which demonstrates that the young Earth had large amounts of water."

The next goal is to use the possibilities of reproducing the ultra-high-pressure, high-temperature environments of the Earth's interior and handling liquid material to reproduce the liquid outer core and study its characteristics. Further progress in the research work of Hirose and his colleagues may show us the real conditions of the Earth's depths, a world of extremes that is hard for humans to access.







The structure of a laser-heated diamond anvil cell (see the diagram on page 10). The diameter of the apparatus (left) is about 5 cm. A microscopic sample (with a size at the micron scale) is placed between diamond tips in the center of the apparatus (below left), pressure is applied by turning the screws of the apparatus, and a laser is shone on the sample to heat it. Because these samples are small, high-intensity X-rays are used for analysis in the Spring-8 large synchrotron radiation facility. These X-rays are strong and highly dense, making possible analysis under high-pressure, high-temperature conditions.

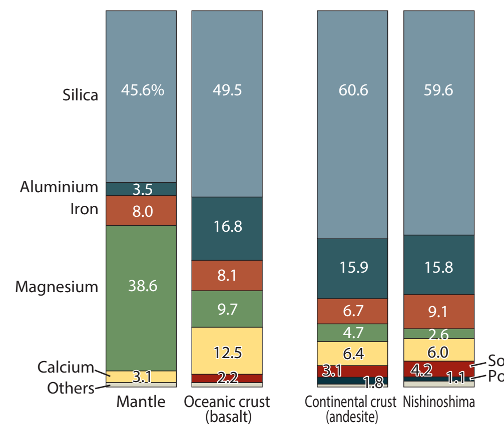
Ocean Drilling Shows How Continents are Born from the Sea

Earth is the only planet in the solar system with continents and oceans on its surface. What is more, the crust has different compositions beneath the continents and the oceans. The principal component of continental crust is andesite, containing about 60% silica (SiO_2), while oceanic crust is made of basalt, containing only about 50% silica. None of the other earth-like planets in the solar system (Mercury, Venus and Mars) has continents. Why only the earth has continents formed of andesite is a big question.

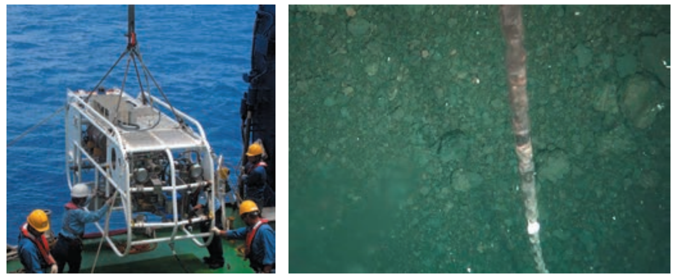
Group leader (GL) Tamura of the Mantle and Continental Crust Drilling Research Group at the Research and Development Center for Ocean Drilling Science and his group have been working on the Tairiku ("continent") Project to discover why only the earth has continents. (This is an extension and expansion of the previous Project IBM.) GL Tamura explains: "Beside uncovering the origin of the continents, a major subject of our research now is Nishinoshima, an island in the Ogasawara arc where vigorous volcanic activity has been continuous since 2013. Although Nishinoshima is being created by the eruption of a submarine volcano, the rocks being ejected from this volcano are andesite, the rock that forms continental crust."

Not just at Nishinoshima, most rocks found in the sea area around the Ogasawara islands are andesite; there is continental crust rock even here, far out to sea from the continents. In contrast, rocks found around the Izu islands are mainly basalt, the constituent of oceanic crust. So, what is causing this difference between the Ogasawara and Izu Arc? To answer this question, GL Tamura and his group have been working on an ocean drilling project using the deep sea drilling vessel *Chikyu* in the sea areas around the Ogasawara and Izu islands. In addition, in June 2015 they took the research vessel *Natsushima* to a location 4.5 km from the still erupting Nishinoshima and used the deep ocean floor survey system *Deep Tow* to collect rocks from the seafloor at water depths of 200 to 2000 m. They are now working on detailed analysis of the rocks. GL Tamura says that the rocks collected in the sea around Nishinoshima are very likely to be andesite that is close to primary magma. "Primary magma is the magma that is initially produced when the upper mantle melts. The composition does change before the magma is ejected at the surface but magma that has just been formed and is unchanged is referred to as primary magma. Previously, it was thought that all primary magma is basalt produced from peridotite. The proportions of silica contained in the mantle and in basalt are similar; so, it is believable that primary magma from the molten mantle would be basalt. However, experiments have shown that if water content is high and the mantle melts in a low-pressure environment, the primary magma is andesite instead. Therefore, if the rocks collected in the seas around Nishinoshima are nearly all andesite, the previous understanding that all primary magma is basalt will have to be discarded and this may be an important clue for understanding the mechanism by which continents are formed."

Nishinoshima from the southwest. The side to the south of the central scoria cone (the right side of the photograph) is growing higher due to continuing flows of lava. As the lava reaches the sea, it vaporizes seawater, sending up steam.



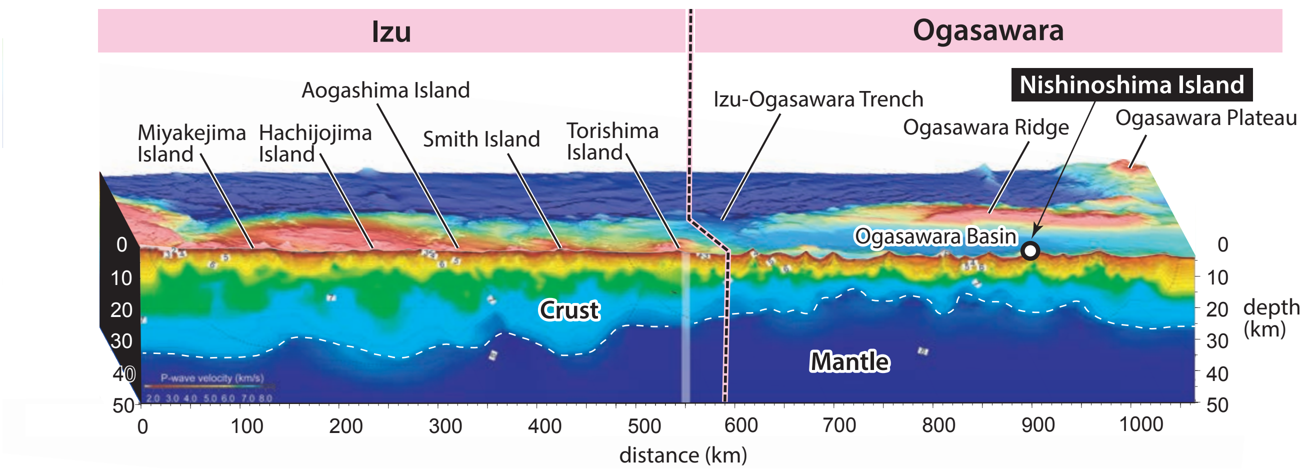
Comparison of rocks from the mantle, oceanic crust, continental crust and Nishinoshima (elements are represented by amounts of their oxides). Analysis results of 1973–74 ejecta from Nishinoshima are similar to continental crust: homogenous andesite with a silica content of around 60%.



The deep ocean floor survey system *Deep Tow*. While seafloor images from a high-resolution camera are viewed on the mothership, rocks pinpointed by a dredging collector towed behind the ship are collected (photos by Alex Nichol). The photograph on the right shows the seafloor, photographed by *Deep Tow* during the current Nishinoshima survey.

Part of the background to GL Tamura's thinking is the results of a crust structure survey around the Izu and Ogasawara islands. In the crust structure diagram from Izu to Ogasawara at the bottom of this page, the parts shown in green represent continental crust made of andesite (the middle crust). If the thickness of the crust from the yellow parts to the pale blue parts is examined, it is apparent that the crust is thin under the Ogasawara sea area (including Nishinoshima) but the crust is thick under the Izu sea area. Therefore, it would seem that the mantle melts at lower pressure and andesitic magma is produced under Ogasawara where the crust is thinner. As the crust steadily thickens toward Izu, the pressure of the depth at which the mantle melts rises and the magma is basalt, which is what the Izu islands are made of. GL Tamura explains: "Because the crust under the Izu islands is thick, when the mantle melts there, the pressure is high and the magma produced must be mainly basalt. Andesite is not produced from the primary magma into which the mantle melts and the continental crust (the middle crust) under the Izu islands is not likely to get any thicker. Whether this hypothesis is correct will have to be ascertained from the relationship between the rocks collected at Nishinoshima and the primary magma produced in the mantle below."

Because, as mentioned above, it has previously been thought that andesite is produced from primary magma, another hypothesis that has been proposed is that the crust is initially produced from basalt directly from the mantle and later some of the crust changes in composition to produce andesitic continental crust. It is hoped that the results of analysis of the rocks from Nishinoshima will show which hypothesis is correct. However, even if the rocks collected around Nishinoshima are andesite, the truth will not be certain as long as the true character of the continental crust below Nishinoshima is unknown. Therefore, in the Tairiku Project, GL Tamura is drilling around Izu and Nishinoshima using the American drilling vessel *JOIDES Resolution*; however, continental crust has not been reached in the three drillings conducted so far. It is hoped that core samples of continental crust will be obtained by ocean drilling by *Chikyu* in the near future. The mystery of the origin of the continents should become clearer soon.

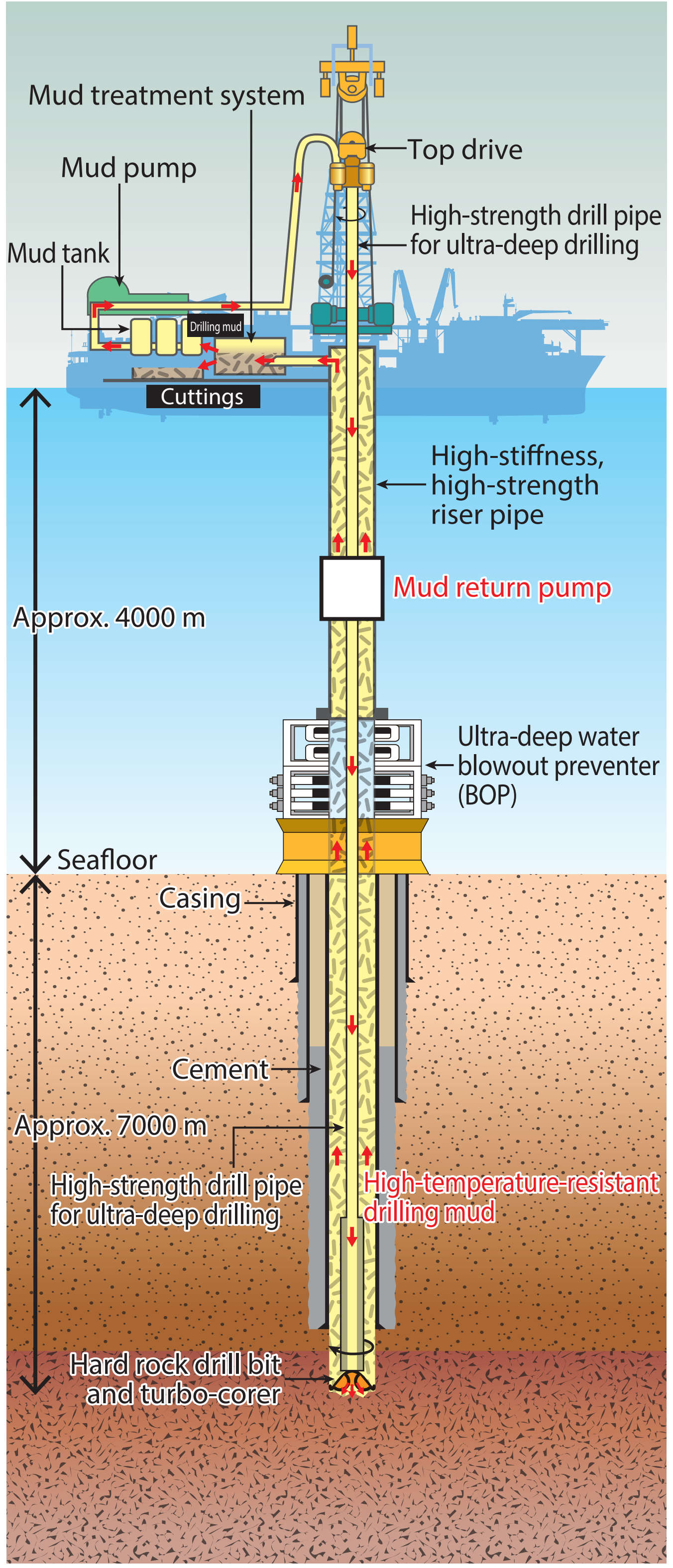


The crust structure under Izu and Ogasawara. In the Izu arc, Miyakejima, Hachijojima, Aogashima, Torishima and the other islands are volcanoes that eject basaltic lava and the crust below is 30–35 km thick. Meanwhile, Nishinoshima ejects andesitic lava and the thickness of the crust below the Ogasawara arc is only 15–20 km. Nishinoshima is known throughout the world as an island that is close to the mantle, an island where the crust is thin. It is not yet known why volcanic islands in oceanic island arcs that are close to the mantle eject andesitic magma as in continental crust and why the northern Izu islands where the crust is thick eject basaltic magma.

Interview: Eigo Miyazaki, group leader, Technology Group II, Technology Department, Center for Deep Earth Exploration

Developing Deep Drilling Technology to Reach the Mantle

Drilling to the mantle (not to scale)



Since we started planning the deep sea drilling vessel *Chikyu*, one of our main objectives has been to reach the mantle, but there remain technical challenges that must be overcome to achieve this. In a drilling survey of the Pacific off the Tohoku coast in 2012 (JFAST), the *Chikyu* successfully drilled to 850m below the seafloor at an ocean depth of 6900m (a total drill pipe length of 7750 m), setting a world record for the deepest scientific drilling. Now, to drill further toward the mantle in sea areas that have been suggested as candidates, technology is needed to extend drilling to about 7000 m below the seafloor under ocean depths of about 4000 m. To reach the mantle, which has never yet been achieved, the drilling capabilities of *Chikyu* must be improved even further. Group leader (GL) Eigo Miyazaki of the Second Technology Group in the Technology Department of the Center for Deep Earth Exploration (CDEX) explains: "In the JFAST drilling, a drill pipe about 7000 m long and weighing about 350 tons was being suspended from *Chikyu* to the seafloor, and the drill bit was being turned to conduct drilling a further 850 m below the seafloor. If we are to drill down to the mantle, the drill pipe will have to be about 1.5 times this length. Even if *Chikyu* can handle this, we anticipate that the pipe itself will stretch under its own weight and be damaged. As the pipe is lengthened, we must lighten the pipe to reduce its total weight or increase the pipe's strength."

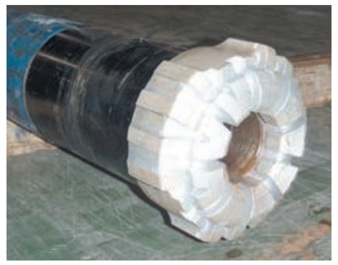
The group is investigating how to reduce the total weight by such measures as progressively reducing the outer diameter of the drill pipe down the string and replacing parts of the drill pipe with a material lighter than steel. Because a riser must be employed by *Chikyu* for drilling 7000 m below the seafloor, a riser pipe must be suspended down to the seafloor. The riser pipe is made of steel and has buoyancy modules fastened around it. The current riser pipe is too heavy; so, the group is working to replace parts of the riser pipe with carbon fiber-reinforced plastic (CFRP) and develop a CFRP riser pipe. This will mean that the riser pipe can be much lighter but has some potential problems, as GL Miyazaki explains: "How much the ship moves up and down during drilling depends on the weather. When the ship moves up and down, CFRP might be stretched and compressed; there is concern that it might be damaged. We are looking into using pitch-based CFRP, which is more resistant to stretching. Even so, it would be difficult to make the riser connectors CFRP. Therefore, because the connectors will be made of steel, we are having to consider how to improve the strength of connections where CFRP members and steel members are joined together."

Drilling to 7000 m below the seafloor to reach the mantle means drilling through hard rocks at high temperatures. To drill through the deeper parts of the crust, the drill bit must also be improved. If the drill bit wears out, it will have to be pulled up to the ship and replaced. From a depth of 10,000 m below the ocean surface, just pulling up the drill bit would take a whole day, and lowering the drill bit back to the deepest point of drilling after replacement would take a further day. Therefore, it is vital to develop a drill bit with higher strength and greater durability.

Modern drill bits are made by polycrystalline diamond. While they are hard, they tend to be brittle and prone to chipping. GL Miyazaki's group aims to improve durability with a material that, as well as being hard, is strongly bonded together and resistant to chipping. GL Miyazaki adds: "We must collect core samples, because that is the research purpose of the drilling. However, the rocks we are drilling are hard and fragile and tend to break up. In previous drillings, there have been times when the core barrels that hold the samples were only partially filled with rock. So that we can reliably collect core samples, we are working to develop a coring system that uses the operation of a turbine motor to cut out the rock." The idea is that this turbine motor is driven by the drilling mud pumped down from the ship to turn a cutting shoe at the tip at high speed. Hence, cores may be collected more reliably. The group is also considering a turbo-corer that drills by using a turbine motor to turn a drill bit.

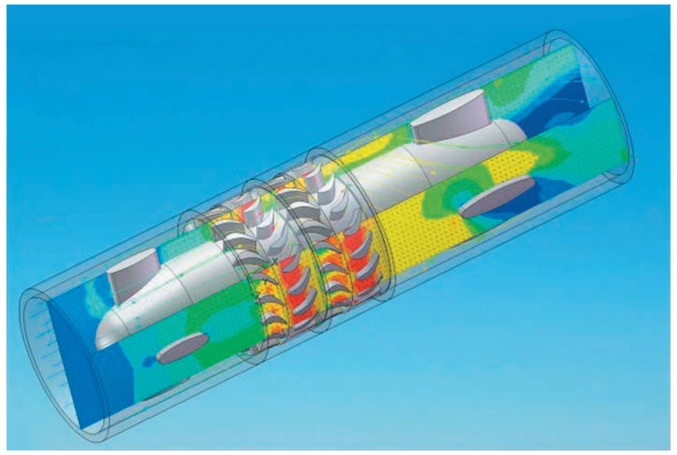
Because the drilling mud is exposed to temperatures close to 300°C as the drilling approaches the mantle, there is a danger that components of the drilling mud will degrade and coagulate. The drilling mud that *Chikyu* currently uses can withstand a maximum temperature of around 170°C. Therefore, the group is reviewing the components and trying to raise heat resistance. The same challenge of withstanding high temperatures also applies to electronic components such as those in the measurement-while-coring system.

The outcome of this R&D of drilling technology will be that we can reach depths that no one has reached before. Application of the developed technologies not just to scientific drilling but also to commercial drilling, such as developing offshore oil fields and gas fields, is being considered. Accordingly, GL Miyazaki's group is working to develop standards for certifying the safety and capabilities of the technologies it is developing. If consistent standards can be created and widely adopted for these technologies, they may be useful as intellectual property that can be applied to commercial drilling.



Above: Polycrystalline diamond compact core bit and center bit for deep drilling (8-1/2"). Right: Impregnated diamond core bit for deep drilling of very hard rock (in development).

Left: A contemporary steel riser pipe. Above: CFRP riser pipe with carbon fibers (in development).



Above: Mud driven turbine motor to be incorporated in the coring system. Below: Rotors and stators of turbine motor.

Interview: Shin'ichi Kuramoto, Deputy Director General, Center for Deep Earth Exploration

New Vistas for Earth Science Opened up by the *Chikyu*

Within the Earth, there is a whole world full of mysteries that are unknown to humanity. Through seismic measurements, model experiments and simulation studies using supercomputers, the reality is being revealed little by little. However, as Shin'ichi Kuramoto, Deputy Director General of the Center for Deep Earth Exploration (CDEX) explains: "In the end, we cannot find the truth unless we actually drill down and look for ourselves. One example is from D/V *Chikyu*'s IODP expedition 316, drilling into the Nankai Trough seismogenic zone. Fault cores obtained by drilling into accretionary wedge near the tip at the plate boundary revealed new facts. Previously, it was thought that adhesion between the plates is weak in the shallow region near the axis of the trough that has just started to subduct, with the continental plate being pulled down hardly at all, and that this is not a location where earthquakes and tsunamis would originate. However, the core samples that we collected included a fault with the appearance of a distinct fault surface. Analysis of the thermal history of the fault shows that the fault surface had at some time been at a high temperature (around 400°C). This kind of fault, which was not expected, showed that frictional heating effects associated with rapid slipping had occurred, which is to say that this is very likely to have been the slipping of an earthquake/tsunami fault. The JFAST, *Chikyu*'s IODP expedition 343, drilling study showed that something similar also occurred in the 2011 Tohoku Earthquake."

As for the Earth's interior, there are still many things that we cannot understand without actually drilling down to look. For example, from structural surveys of the boundary between the mantle and oceanic crust using seismic waves, it is well known that the Mohorovičić discontinuity (the Moho) exists. However, the true nature of the Moho is not well understood, such as whether there is a distinct boundary in materials or physical characteristics at the Moho.

About the mantle beneath the Moho, Kuramoto says: "It would not be an exaggeration to say that we know almost nothing. While it is clear that peridotite is present in the upper mantle, it is unclear how much of water and elements such as carbon are contained in the rocks of whole mantle. It is well known that rocks originating in the mantle are exposed on the surface in places such as Oman in the Middle East and the Hidaka Mountains in Japan. However, the lighter elements tend to be lost in environments that are greatly different from the high temperature and high pressure deep underground. There is no reason to think that these surface rocks can teach us much about the composition of rocks in the mantle."

It is for such reasons that it is important to actually drill to the mantle using the *Chikyu* to bring back material. However, as described on pages 14 and 15, new technological advances are necessary for us to reach the mantle. Currently, taking account of our scientific objectives and actual technological capabilities, three areas are leading candidates for the mantle drilling project: off Hawaii, off the west coast of Mexico, and off Costa Rica. These candidates were agreed on at the "Chikyu+10 International workshop" (2013) by researchers attending from around the world.

The main keys to selecting a candidate area are the ocean depth and the depth of the mantle below the seafloor. However there is another important condition: the subterranean temperature. Kuramoto explains, "It will not be sufficient just to drill into the Moho. We must also both collect core samples and conduct detailed measurements. Therefore, we cannot simply drill into rocks at high temperatures that would cause our core collecting equipment and sensors to fail."

At a mid-ocean ridge, the oceanic crust has just been formed and is hot, but further away from the ridge the oceanic crust is cooler. It would therefore seem more effective to drill in areas that are far from mid-ocean ridges, but the oceanic crust is thicker and the ocean depth is greater further from a ridge. So, the issue is finding drilling areas where the crust has cooled significantly but is not thick. Kuramoto's assessment is, "There will have to be discussions based on site survey data but personally, from the current information, I think that Hawaii is the most promising of the three candidates."

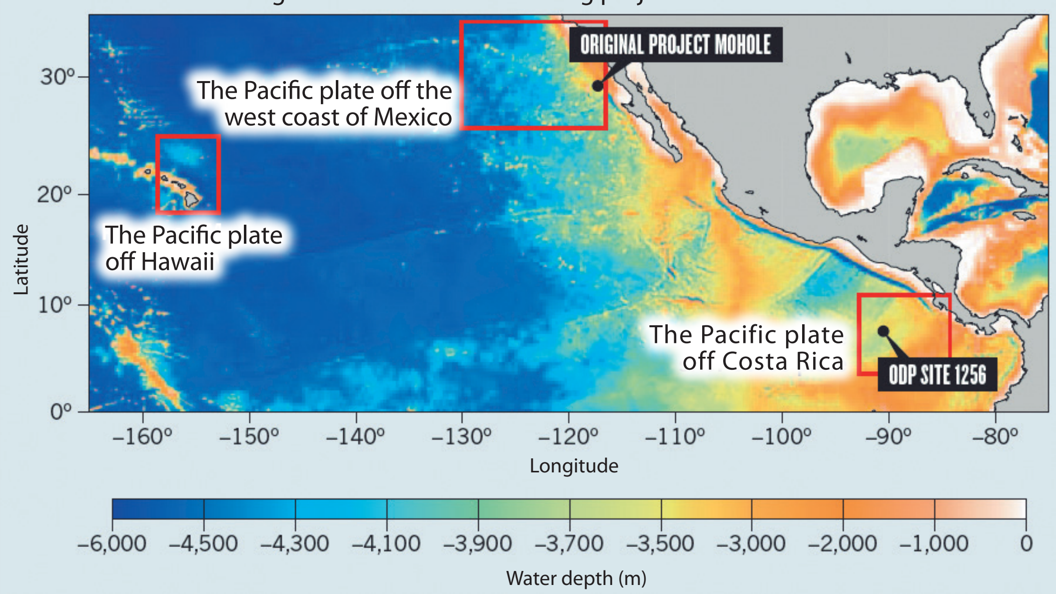
However, even Hawaii has problems. Because the Hawaii chain is positioned over a hotspot, findings are likely to be affected by magma coming up from the mantle. Whether the mantle under the Hawaii area can be considered typical will probably be determined from the results of an upcoming site survey.

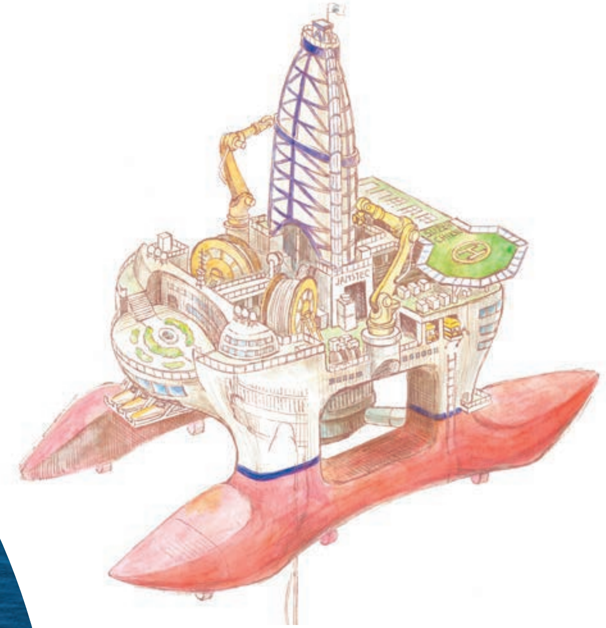
In any case, the mantle drilling will be carried out in a area selected on the basis of subsequent advances in drilling technology and conditions such as subterranean temperature. The question is when the drilling will actually be done. Kuramoto says: "That is a hard question to answer. I want to say that it will definitely be within the next 10 years. Ten years from now, we will have to be thinking seriously about the next generation of *Chikyu*.

The *Chikyu* has now been in service for 10 years. Because she is well maintained, she should be able to carry on for 30 or 40 years. However, given the progress of drilling technology and navigation technology, at some point it will no longer make sense to keep using previous generations of technology. We have already started thinking about a 'Super *Chikyu*' to carry on the work of the *Chikyu*."

The realization of the 'Super *Chikyu*' will be worked out in the future but the first requirement, after the present *Chikyu*, is that it must be able to reach the mantle quickly. Beyond that, the technology and knowhow required to drill even deeper will probably be realized by the next generation of drilling science and technology in the transition from *Chikyu* to 'Super *Chikyu*'. Kuramoto speaks with passion: "The Earth's depths hold information that is vital for us to obtain fundamental knowledge for research into the formation of planet Earth and the origins of life. The importance of drilling science in obtaining this information is great even now. Ocean drilling is definitely going to continue on. This is the important mission with which the *Chikyu* has been entrusted."

Candidate drilling areas for the mantle drilling project





An impression of the next-generation scientific drilling vessel Super *Chikyu*, whose purpose will be to bring back mantle samples from depths below the seafloor. This drilling vessel will incorporate technologies that are currently being developed with the aim of drilling to greater depths beneath deeper sea areas. With new technologies and greatly enhanced capabilities, she will be able to reliably continue effective drilling operations even under harsh sea and weather conditions.

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