Newsletter Plus Digest
Earthquake Research Institute, The University of Tokyo
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"Measuring absolute gravity outdoors in Antarctica"

Center for Geophysical Observation and Instrumentation: Prof. Akito Araya

Prof. Akito Araya of the Center for Geophysical Observation and Instrumentation participated as a summer member of the 63rd Japanese Antarctic Research Expedition. He brought with him a newly developed compact absolute gravimeter in order to conduct high-precision absolute gravity measurements in the cold outdoor environment of Antarctica, where such measurements have been difficult to date. We asked Prof. Araya about the current state of gravity measurements in Antarctica and the significance of such measurements.

Gravity is decreasing in Antarctica

On 10 November 2021, Prof. Akito Araya boarded the Antarctic research ship *Shirase* as a summer member of the 63rd Japanese Antarctic Research Expedition, which departed from Yokosuka Port. Although it was usually possible to board from the port of call in Fremantle, Australia, all the members boarded from Yokosuka as a precautionary measure against COVID-19. This was Prof. Araya's first visit to Antarctica. "My objective was to precisely measure gravity at Syowa Station and the surrounding rocky outcrops."

Gravity has been decreasing in Antarctica. During the coldest period of the last glacial period about 20,000 years ago, Antarctica was covered by a massive ice sheet. Gravity is decreasing because the ground, which had been sinking under the weight of the massive ice sheet, is now rising as the ice sheet melts after entering the interglacial period. As the ground rises, its distance to the center of gravity of the Earth increases, thereby decreasing the gravitational force.

"We hope to repeatedly measure gravity at various locations in Antarctica in order to accurately capture the changes in gravity caused by the increase and decrease of the ice sheet. Once this is known, then we will be able to estimate the structure and properties of the crust and mantle that are deformed by the increase and decrease of the ice sheet, as well as how the ice sheet melted since the last glacial period."

Successfully measuring gravity even at 0°C

However, Prof. Araya says, "It is not easy to measure gravity with high precision outdoors in Antarctica. First, the change in gravity as the ice sheet increase and decrease is so small that it must be measured to eight or nine decimal places."

Prof. Araya decided to bring a newly developed compact absolute gravimeter to Antarctica. He explained, "This is a modified version of the free-fall absolute gravimeter that was developed for volcanic observations."

Gravitational measurements are useful for understanding the state of volcanic activity. However, the volcanic environment is a harsh one. Prof. Araya developed a portable absolute gravimeter that is capable of high-precision observations even in harsh outdoor environments.

"Its greatest feature is that the dropping chamber and laser light source are separated. The dropping chamber is installed outdoors, the laser light source that must be maintained at room temperature is installed in a hut, and the gravity is measured by connecting the two with an optical fiber. Volcanoes and Antarctica are similar in that both lack facilities, such as power sources, and both are harsh environments. With this gravimeter, I believed that we can measure gravity with high precision, even in the cold outdoor environment of Antarctica. I decided to go to Antarctica to verify this."

On 17 December 2021, Prof. Araya arrived at Syowa Station in Antarctica and carried out observations at four locations.

The start of observations at Langhovde was delayed by two weeks. Gravity measurements have previously been taken here, because there was an observation hut that can be used for lodging. The first outdoor measurements were performed using TAG-1 (Fig. 1). Gravity measurements were conducted at night for two days in order to confirm whether the measurements could be conducted normally in the cold environment. Prof. Araya's face softened as he talked about the results. "Although the temperature dropped to 0–5°C, we were able to measure gravity continuously over a long period of time." Measured values on the first day were almost in agreement with the predicted values. Measured values on the second day varied more from the predicted values. This may have been due to the shaking of the tent caused by strong winds, so wind countermeasures remain an issue for the future.

Gravity, the unsung hero

Prof. Araya has also developed seismometers, interferometers, and strainmeters using state-of-the-art optical technology, which have produced high-performance observations. What attracted Prof. Araya to gravity, out of the various natural phenomena in the world? "Any change in mass will always cause a change in gravity. Along the way, the effects of gravity cannot be blocked, so strong constraints can be applied to the model. This makes it easy to perceive the phenomenon, and in that sense, I think that gravity is somewhat of an unsung hero. It is also interesting that we can see the remnants of the glacial period as far back as 20,000 years ago from changes in gravity."

When asked where he would like to measure gravity next, he responded with, "The deep seafloor." "Making observations in locations that were previously impossible at a level of precision that was unheard of before will certainly reveal a new world. The gravimeters that we have today need to be much smaller in order to measure absolute gravity on the deep seafloor, so I am excited to take on this new challenge.

Figure 1. Absolute gravity measurements using TAG-1 at Langhovde

A dropping chamber is installed in the tent, a laser light source and recording device are installed in the observation hut. The dropping chamber and laser light source are connected by an optical fiber. It was confirmed that gravity measurements were possible even in a cold environment.

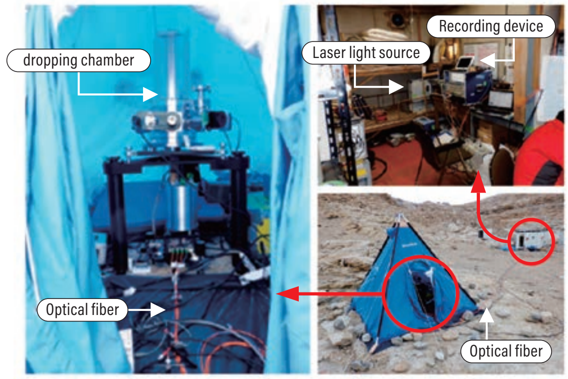


Figure 1

“Does the Earth’s surface drive whole Earth dynamics?”

Division of Earth and Planetary Materials Science : Prof. Hikaru Iwamori

The Earth is in dynamic motion, from plates on the surface to the mantle in the interior and the core. Does the Earth’s surface drive these dynamics, or does the interior? Prof. Hikaru Iwamori of the Division of Earth and Planetary Materials Science uses a variety of methods in order to explore the true structure and dynamics of the Earth.

Differences in mantle composition between the eastern and western hemispheres

The structure of the Earth’s interior can be studied by measuring the velocity of propagation of seismic waves. The detailed structure of Earth’s interior, such as the existence of subducting plates and upward flow of the mantle, has been revealed by using the properties of seismic waves, which propagate faster in colder and harder areas and slower in hotter and softer areas. However, seismic tomography cannot reveal the composition of the Earth’s interior.

Hence, materials need to be extracted from the Earth and their chemical compositions need to be examined in order to identify what elements and isotopes they contain. Because materials cannot be extracted directly from the mantle or core, lavas from erupting volcanoes are used. Lava is molten rock in the mantle rising in the form of magma, cooling, and solidifying on the surface. Therefore, examining the chemical composition of lava can reveal the composition of the mantle.

Professor Iwamori and his collaborators collected data of isotopic compositions for approximately 7000 samples of lava from around the world, including those that have been reported in previous studies and samples that Prof. Iwamori and his collaborators themselves have collected and analyzed. The isotopic compositions of lava were analyzed using Independent Component Analysis. Their results showed that isotopes derived from water-soluble hydrophilic components were abundant in the eastern hemisphere approximately bounded by the International Date Line, and scarce in the western hemisphere (Fig. 1, top).

Supercontinents affect the mantle and inner core

Why is there a difference in mantle composition between the eastern and western hemispheres? Measurements of isotopes from radioactive decay in lava have shown that such differences have been present for hundreds of millions to billions of years. “On Earth, there was a supercontinent called Pangaea 300 million years ago, and another, Rodinia, 700 million to 1 billion years ago. The supercontinents were broadly in the eastern hemisphere. We think that the existence of supercontinents may have caused the difference in mantle composition.”

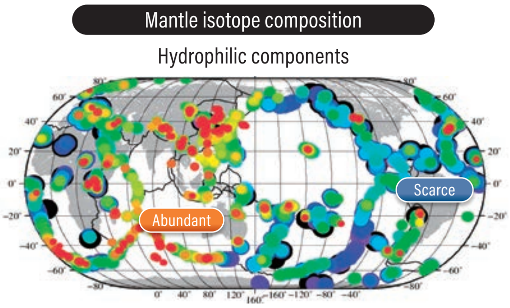
Oceanic plate subduction occurred around supercontinents (Fig. 2). Oceanic plates contain large quantities of water, causing hydrophilic components to be carried into the Earth’s interior as well. As a result, the mantle beneath the supercontinent in the eastern hemisphere is abundant in hydrophilic components. Meanwhile, the mantle in the western hemisphere was relatively scarce in hydrophilic components because there was less water transport associated with plate subduction, which was revealed by Independent Component Analysis for the first time.

Indeed, when Prof. Iwamori first saw the Independent Component Analysis results, he was so surprised to see that there was such a clear separation between the eastern and western hemispheres that he thought it was the product of human error. He was even more surprised when he compared the results with the seismic wave velocity structure of the inner core that was obtained from a previous studies on seismic waves (Fig. 1, bottom).

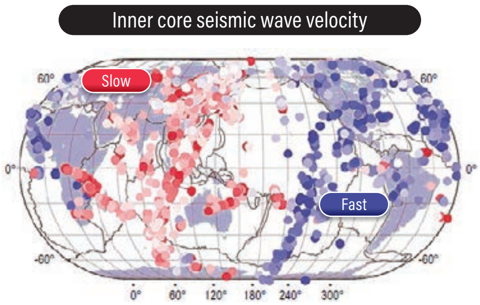
The core is beneath the mantle at the center of the Earth. The core is composed mainly of iron and nickel, with a liquid outer core and a solid inner core. It has previously been known from study on seismic waves that the seismic wave velocity and structure of the inner core differ greatly between the eastern and western hemispheres. “When we projected the seismic wave velocity distributions in the inner core onto a surface geographic map, we found that the distributions were very similar to the mantle composition of the respective eastern and western hemispheres. These results gave us the idea that the existence of supercontinents affected not only the mantle but also the inner core.” (Fig. 2)

Subduction of cold plates around supercontinents cooled the mantle beneath them. As the core transfers heat easily because of its metal composition, the outer core surface in contact with the mantle also cooled, which caused a downward flow that also cooled the inner core. As a result, the inner core of the eastern hemisphere, where a supercontinent was located, was relatively cool and had higher seismic wave velocities; whereas the inner core of the western hemisphere was relatively hot and had lower seismic wave velocities. This is "top-down hemispherical dynamics" theory proposed by Prof. Iwamori to explain the apparent differences in the eastern and western hemispheres.

Figure 1. East-west hemispherical structures in the mantle isotope compositions and inner core seismic wave velocities



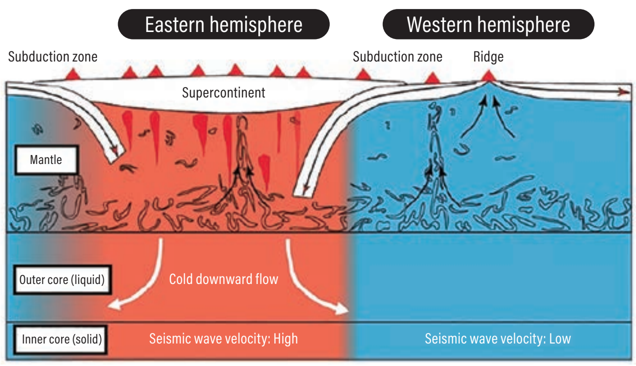
Statistical component distributions of hydrophilic component concentrations in the mantle. The eastern hemisphere has abundant hydrophilic components, whereas the western hemisphere has scarce hydrophilic components, with the area around the International Date Line as the boundary.



Relative seismic velocity of the inner core obtained by a previous study (after Waszek et al., 2011). Color coding represents relatively fast parts (dark blue) to slow parts (dark red).

Figure 2. Circulation model of the “Top-down hemispherical dynamics”

Plate subduction around a supercontinent supplied hydrophilic components to the mantle along with water. This resulted in a high concentration of hydrophilic components in the mantle of the eastern hemisphere, where the supercontinent was located. Additionally, the subduction of cold plates cooled the mantle beneath the supercontinent, which affected the outer and inner cores. As a result, the eastern hemisphere of the inner core has lower temperatures and higher seismic wave velocities.



“Developments in pioneering seafloor observations using optical fiber seismometers”

Center for Geophysical Observation and Instrumentation : Prof. Masanao Shinohara

With fewer seismic observation stations in marine areas than on land, constructing a marine-based high-density seismic observation network has been an urgent task. An innovative technology for creating such a network that has been attracting attention in recent years is Distributed Acoustic Sensing (DAS), which measures vibrations using an optical fiber itself. We asked Professor Masanao Shinohara of the Center for Geophysical Observation and Instrumentation, who conducts seismic observations with DAS technology using a seafloor optical fiber cable system off the coast of Sanriku for earthquake and tsunami observations, how this optical fiber seismometer will change seismic observations on the seafloor.

Prof. Shinohara specializes in seismic observations in marine areas. “We focus on marine areas because most of the major earthquakes around Japan occur below the seafloor, and because we want to make detailed observations as close to the hypocenter as possible not only for conducting academic research on earthquakes, but also for obtaining useful information for disaster prevention, such as earthquake early warnings and tsunami warnings.”

There had been considerable progress in the development of seismic observation networks on the seafloor, such as the deployment of the Seafloor Observation Network for Earthquakes and Tsunamis along the Japan Trench (S-net) from the coast of Hokkaidō to the coast of the Bōsō Peninsula, and the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) from the coast of the Kii Peninsula to the coast of Cape Muroto. There has also been progress in the construction of the Nankai Trough Seafloor Observation Network for Earthquakes and Tsunamis (N-net) from the coast of Kōchi Prefecture to the Hyūga-Nada sea. However, Prof. Shinohara indicates that “compared to land, marine areas still have fewer seismic observation points.”

Detecting vibrations with optical fibers

How can we create high-density seismic observations in marine areas? Prof. Shinohara focused on a certain technology. “We aimed to utilize DAS, which is a technology that detects vibrations using optical fibers as sensors.”

“DAS has been used in security applications for over 10 years. For example, it can detect intruders by installing optical fibers on a fence.” Prof. Shinohara also knew that vibrations could be detected using an optical fiber itself. He reflects, “With seismic observations, it is necessary to capture not only whether a vibration has occurred, but also the high-fidelity recording of that vibration. I previously thought that incipient DAS could not be used for seismic observations since it did not seem to have this level of precision.”

His perceptions changed in 2017. “Pioneering researches on DAS were presented in the American Geophysical Union (AGU) meeting, where I learned that changes in the distance between scattering points is measured with high precision using a method called interferometry to analyze scattered light. I felt that this is an innovative technology that will enable high-density linear seismic observations in place of observations at the points that we have been conducting.”

“Using DAS, we can acquire data similar to those from seismometers installed at intervals of several meters across a 100-km distance. We can also acquire data at short time intervals of several hundred times per second. However, we needed to confirm whether the data could be used in earthquake research.”

Confirmation using a seafloor cable off the coast of Kamaishi

The first observations were conducted in February 2019. During observations on 15 February, there was an earthquake with a hypocenter depth of 50 km and magnitude (M) of 3.0. The distance from the epicenter to the observation system was about 50 km. Figure 1 shows the visualization of changes in strain obtained from the DAS data. The vertical axis shows the time, with values progressing from top to bottom, when the earthquake occurred at 6:10:50.61. The horizontal axis shows the distance from the land station up to 70 km away. Since the 70-km distance is measured at 5-m intervals, there are 14,000 points of data. Prof. Shinohara explains, “Warm colors indicate large changes in strain, or in other words, large vibrations. The data clearly recorded that the P wave arrived and caused vibrations, after which the S wave arrived and caused vibrations.”

Useful for crustal seismic structure exploration as well

In 2020, an active seismic survey was conducted using DAS and a sedimentary structure was obtained (Fig. 2). Moreover, crustal structures can be estimated using a seismic interferometry method, which uses ambient seismic noises caused by mainly ocean waves, known as microseisms, from two observation points. Prof. Shinohara’s group, led by graduate student Shun Fukushima, was the first in the world to succeed in the exploration of deep sedimentary layers by using DAS measurements of microseisms.

Figure 1. Seismic records observed on the cable off the coast of Kamaishi

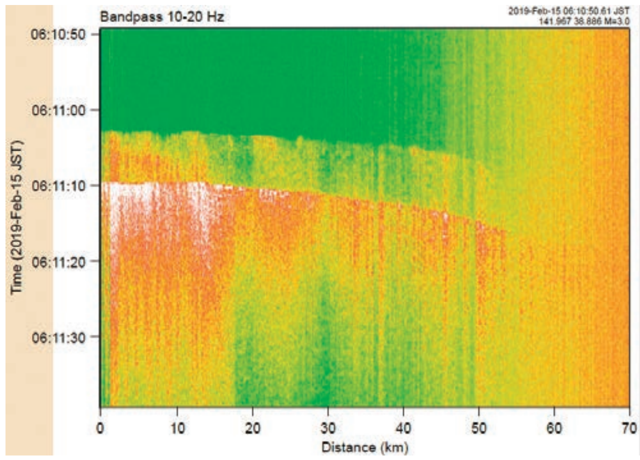
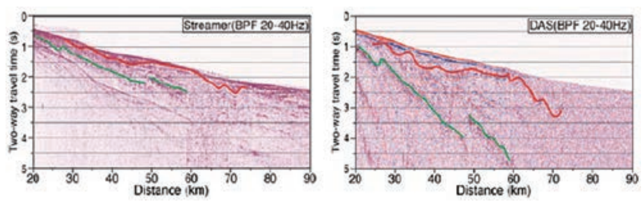


Figure 2. Seismic structure survey using controlled seismic sources

The left side shows the seismic structure based on data from a streamer cable towed by a ship. The right side is based on DAS data using the seafloor optical fiber cable system off the coast of Sanriku. A higher resolution is obtained because DAS is highly sensitive to S waves and S waves have slow seismic velocities.



"Visiting Programs for researchers at Earthquake Research Institute"

We offer unique opportunities for researchers worldwide to stay for collaborative research, from a few weeks to one year at the Earthquake Research Institute, the University of Tokyo. On Jan 20th 2023, Masa Kinoshita, head of the international office had a talk with Prof. Ruben Boroschek, visiting professor at ERI for six months from August 2022. He talked to us about his experiences at ERI.

Prof. Ruben Boroschek, Professor, University of Chile (right)
Interviewer: Masa Kinoshita, Head of the International Office, ERI

Q. Why did you choose ERI?

I have been working on structural health monitoring and early damage detection of civil infrastructure. The group of Dr. Kusunoki in ERI is working on this topic for many years.
It is a large research group of almost 20 people. They have a lot of publications, practical examples, and a lot of data. I thought it would be a good opportunity to be able to join in this group and understand what and how they are doing. I also wanted to introduce computer vision, which I have been working on, as a tool for structural health monitoring.

Q. What is your impression of the research environment here?

The Kusunoki lab offers a very rich research environment. There are a lot of interactions, conversations, and discussions in the group. However, outside of the group, they tend to work independently. Sometimes communication between groups seems difficult, particularly for non-Japanese speaking foreigners. Some interactions are made all in Japanese. However, technology helps in such a case.
Other than doing research, I had opportunities to teach master's and Ph.D. students here in the Kusunoki lab. I was asked to teach computer vision and special techniques on a health monitoring system. I have also had a chance to visit other universities in Japan and shared ideas with other professors.

Q: Advice for successful joint research at ERI?

It is a great opportunity. Scientifically speaking, Japan has a lot of resources. A lot of information can be shared. However, not always you can get the information if you do not have a good relationship with the researcher/research group you will work with.
We need an agreement on how to work together, if the research is conducted in a closed group or not, if the information can be shared, and how to work with other groups, etc. You may think it is common sense, but it is better to put it on the table. It has to be really clear what you will need from ERI, and from the research group in ERI.

Q: Coming to ERI to do research, what does it mean to you?

The time I was able to locate to get new knowledge and to formalize the knowledge was precious. I plan to develop a course to teach on this topic in Chile. It was great for me to have time to think without all the administrative work and teaching at my university. Personally, it has been very important and for my institution, it will benefit from my research and from the courses that I will be teaching.

The longer version of this interview is available on our website:

Long-term visiting program

Position for visiting professors or post-docs

- Term: 4 - 12 months between April 1, 2024 and March 31, 2025
- Application Deadline: August 2023

Long-term visiting program

https://www.eri.u-tokyo.ac.jp/en/international/for-researchers/long-term-visiting-program/

Short-term visiting program

Position for short-term visiting researchers

- Term: Up to 3 months
- between April 1, 2024 and March 31, 2025
- Application deadline: Fall 2023

Short-term visiting program

https://www.eri.u-tokyo.ac.jp/en/international/for-researchers/short-term-visiting-program/

Prof. Ruben Boroschek, teaching students of the lab, ERI

Prof. Ruben Boroschek, at the Yasuda Auditorium, The University of Tokyo

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