Overview of the Special Issue
“The Hadean World (Part I): The Birth of a Habitable Trinity Planet”

Shigenori MARUYAMA* **, Ken KUROKAWA*** and Yukio ISOZAKI****

The Hadean geologic eon occupied the first 600 million years after the birth of the Earth. No records of Hadean Earth remain on the present Earth, so we have no clues for understanding Hadean rocks and geologic layers. That is why this age is named Hadean, meaning the darkest unknown age in the Earth’s history. However, in spite of the lack of evidence, scientists have tried to unravel Hadean Earth through research applying planetary formation theory and meteoritics.

The discovery of a tiny sample of the mineral zircon dated 4.37 Ga within a terrestrial rock (Wilde et al., 2001) accelerated research on Hadean Earth. Hadean zircons contain small minerals or fluid inclusions that can indicate the characteristics of the host magma; therefore, an isotopic chemical analysis of such zircons is used to reveal the Hadean surface environment. In addition, lunar rock samples obtained through US Apollo missions have also been analyzed to restore Hadean Earth. For example, zircons in 10-m thick regolith layers on the Moon have been analyzed for age and frequency distribution (Borg et al., 2015). Analyses of zircons that remained in small quantities on the surface of the Earth and the moon have progressed with the recent development of analytical equipment. As a result, recent research on carbon isotopes indicates a creeping prebiotic chemical evolution toward the birth of the first life in the Hadean (Bell et al., 2015). Now, the Hadean is no longer the darkest unknown world. New research from new perspectives are ongoing to unravel the origins of life.

In this special issue composed of three volumes, we focus on the Hadean to introduce not only the Hadean surface environment, which has been restored through recent research, but also current discussions on the Hadean world including the planetary formation theory of the solar system. The first volume comprises nine review papers focusing on conditions needed to create a habitable planet from the Earth’s core to its atmosphere. If we successfully pick up conditions for creating a habitable planet, it can be developed into an important verifiable model of a habitable planet, which would be a key model for discussing the origins of life.

So far, over 6,000 exoplanets have been found, and more than 200,000 exoplanets will be investigated within the coming two years using the Transiting Exoplanet Survey Satellite (TESS) launched in April 2018. So far, planetary scientists have studied the individuality of the solar system; however, further research including observations of exoplanets will expand the research from individuality to generality, in order to understand the vast universe.

Ebisuzaki (2018) introduces a new model incorporating new factors such as chemistry and magneto-rotational instability with a tra-
ditional N body simulation that has long been discussed in planetary formation theory. Inside a protoplanetary disk, material is circulated from the high-temperature region near the Sun (>10,000°C) to the extremely low-temperature region at 100 AU (astronomical unit). Through material circulation, chemical zonation is formed to produce planets mainly at two sites. One site is around 20 AU (about -100°C) where ice evaporates, and the other site is around 2 AU (about 1,000°C) where Na and K evaporates to form rocky planets.

Dohm and Maruyama (2018) introduces the new concept of the Habitable Trinity. Habitable Trinity means the co-existence of atmosphere, ocean, and landmass under a driving force (the Sun) to maintain material circulation. The presence of a Habitable Trinity environment promotes a prebiotic chemical evolution from which life emerges, and it is the most basic condition for a habitable planet. Therefore, the concept of a Habitable Trinity is useful and effective as a new index for exploring habitable exoplanets.

Zhao et al. (2018) introduce a method for elucidating the formation process of early Earth using the inner structure of the Moon. Hadean rocks and layers do not remain on the present Earth, except for detrital zircons of less than 1 mm across. Therefore, it is difficult to elucidate the Hadean surface environment. However, the lunar surface preserves “Hadean” records, because the Moon is small (1/80 of Earth's mass) and cooled quickly. Lunar mantle activity is thought to have terminated by 3.0 Ga. Using moonquake data obtained from Apollo missions, Zhao et al. (2012) provide a tomographic image of the lunar interior to show the coincidence between radiogenic isotopic elements and heat sources, and discuss the possibility of the presence of fluid within the Moon. It had been already been elucidated that the Moon was formed without volatiles based on the petrology of lunar rocks obtained from Apollo missions; however, recent research has revealed that lunar peridotite in basaltic rocks contains water as a fluid inclusion (Saal et al., 2008). Besides, observations of volcanic gas emissions with volatile components suggest the presence of volatiles in the Moon (Wetzel et al., 2015). The next research target to identify the origins of lunar volatile is to verify the ABEL model described later.

Ichikawa and Tsuchiya (2018) focus on the outer core of the Earth, which has been debated for more than 50 years, and the inclusion of light elements comprising 10% of it. However, it is still not known what kinds of light element are present or the ratios of those elements. Their paper introduces the research history of these light elements in the outer core.

Maruyama et al. (2018) introduce a newly proposed model of the Earth’s formation process (named ABEL model). Recently, the accretion of terrestrial volatiles was thought to occur through the Late Veneer on the basis of the dating of rock samples from Apollo missions. However, Maruyama et al. (2018) explain a newly proposed ABEL model, which differs from previous models. According to the ABEL model, 99.98% of the Earth’s mass is formed of an enstatite chondrite-like material, which does not contain any water components, followed by the accretion of carbonaceous chondrite between 4.37 Ga to 4.20 Ga. The trigger for delivering carbonaceous chondrite onto the Earth is gravitational scattering caused by big gas giants (Jupiter, Saturn, and the currently missing Black Sheep planet). They emphasize that the two-step formation of the Earth is the only way to make a habitable planet.

Komiya et al. (2018) introduce results that demonstrate the operation of plate tectonics at 4.0 Ga, based on the discovery of granite and the oldest accretionary complex.

Sawada et al. (2018) assume the growth history of the continental crust based on the age-frequency distribution of detrital zircon. Their method is grounded in the perspective that Archean plate tectonics are similar to a present one seen in the western Pacific region, suggesting that the Earth’s surface was covered with about 400 micro-plates, and continental rocks derived from ocean island crust accumulated.
along the plate convergent boundary. At 2.0 Ga, the size of the plate was 3,000 km across on average, and an embryonal continental crust had begun to form, indicating that the mode of mantle convection had shifted from double-layer convection to whole mantle convection. Around 2–1.8 Ga, the supercontinent Nuna appeared. Subsequently, the number of continents increased until 600 Ma when the total land area was almost the same as the present Earth. On the other hand, the Hadean primordial continent covering most of the surface of the Earth was assumed to have disappeared by 4.0 Ga, based on the age-frequency distribution of detrital zircon, suggesting that Hadean tectonic erosion could have been as dynamic as erosion today. The next research target in this field is to identify where the huge amount of Haden primordial continent accumulated, which would unravel the thermal history of the Earth.

Finally, Tsutsumi et al. (2018) introduce new technology that enables the rapid collection and analysis of Hadean zircon. Previously, analyses of zircon required mounting and polishing samples for dating, which necessitated time and patience. However, the development of new equipment to substitute for manual labor is effective for mass analyses.

In the following Special issue volume 2, we focus on the birthplace of life on the Earth, such as the chemical evolution of primordial oceans and atmospheres, in order to discuss how prebiotic chemical evolution progressed in the Hadean surface environment. In Volume 3, the birth of life and early evolution are the focus. We hope a series of special issues will cue further research and discussions.

References
Bell, E.A., Boehnke, P., Harrison, T.M. and Mao, W.L. (2015): Potentially biogenic carbon preserved in a 4.1 billion-year-old zircon. Proceedings of the National Academy of Sciences, 112, 14518–14521.
Borg, L.E., Gaffney, A.M. and Shearer, C.K. (2015): A review of lunar chronology revealing a preponderance of 4.34–4.37 Ga ages. Meteoritics & Planetary Science, 50, 715–732.
Dohm, J. and Maruyama, S. (2018): Newly proposed Habitable Trinity concept and the possibility of life on Mars, Europa, and Titan. Journal of Geography (Chigaku Zasshi), 127, 609–618. (in Japanese with English abstract)
Ebisuzaki, T. (2018): Tandem planetary formation theory. Journal of Geography (Chigaku Zasshi), 127, 577–607. (in Japanese with English abstract)
Ichikawa, H. and Tsuchiya, T. (2018): Chemical composition of the outer core. Journal of Geography (Chigaku Zasshi), 127, 631–646. (in Japanese with English abstract)
Komiya, T., Aoki, S. and Yoshida, S. (2018): Geology and geochronology of Nulliak supracrustal rocks in Labrador, Canada: The oldest supracrustal rocks and evidence for the operation of plate tectonics. Journal of Geography (Chigaku Zasshi), 127, 683–704. (in Japanese with English abstract)
Maruyama, S., Ebisuzaki, T. and Tange, Y. (2018): ABEL model of the two-step formation of the Earth and the significance of ABEL bombardment to produce a Habitable planet. Journal of Geography (Chigaku Zasshi), 127, 647–682. (in Japanese with English abstract)
Saal, A.E., Hauri, E.H., Cascio, M.L., Van Orman, J.A., Rutherford, M.C. and Cooper, R.F. (2008): Volatile content of lunar volcanic glasses and the presence of water in the Moon’s interior. Nature, 454, 192.
Sawada, H., Isozaki, Y. and Maruyama, S. (2018): Pattern of continental growth and its secular change. Journal of Geography (Chigaku Zasshi), 127, 705–721. (in Japanese with English abstract)
Tsutsumi, Y., Sawada, H. and Isozaki, Y. (2018): Search for Hadean zircon: Decreasing the time required for pre-analyzing processes and age analyses. Journal of Geography (Chigaku Zasshi), 127, 723–734. (in Japanese with English abstract)
Wetzel, D.T., Hauri, E.H., Saal, A.E. and Rutherford, M.J. (2015): Carbon content and degassing history of the lunar volcanic glasses. Nature Geoscience, 8, 755.
Wilde, S.A., Valley, J.W., Peck, W.H. and Graham, C.M. (2001): Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. Nature, 409, 175–178.
Zhao, D., Arai, T., Liu, L. and Ohtani, E. (2012): Seismic tomography and geochemical evidence for lunar mantle heterogeneity: Comparing with Earth. Global and Planetary Change, 90, 29–36.
Zhao, D., Maruyama, S. and Isozaki, Y. (2018): Lunar seismic tomography and the early Earth. Journal of Geography (Chigaku Zasshi), 127, 619–629. (in Japanese with English abstract)