FY 2014 WPI Project Progress Report
World Premier International Research Center Initiative (WPI)

Host Institution	**Tokyo Institute of Technology**	Host Institution Head	**Yoshinao Mishima, President**
Research Center	***Earth-Life Science Institute (ELSI)***	Center Director	**Kei Hirose**

* Prepare this report based on the current (31 March 2015) situation of the WPI Center.
* Amounts of money are to be noted in yen in this report. When necessary to convert other currencies into yen, please give the exchange rate used.

Summary of center project progress

1. Management ○For better operations of expanding Earth-Life Science Institute (ELSI), we appointed a foreign PI as the third Vice Director. They are now in charge of promoting Fusion, Globalization, and Reform.

○ALL ELSI Meeting is held once a month. The Director updates all staff members in the meeting.

○To acquire top-level leading researchers from the life science field, especially in "the origin and evolution of life", a cross-appointment system was established with the host institute. The professor in Osaka University was employed as a PI under this system.

○A monthly discussion is held with the President, the Executive Vice President, and the ELSI Director to facilitate close collaboration between Tokyo Tech and ELSI.

○Through our ongoing fund-raising activities, research fund was acquired from a US Foundation.

2. Research Activity ○The result of interdisciplinary researches to elucidate the source of methane in high-hydrogen-concentration hot-spring water in Hakuba area, Nagano was set as a portfolio of ELSI's research activity.

○International Symposium was held to show ELSI research abilities and activities. This event also increased ELSI's visibility. Besides the symposium, 41 workshops and seminars were held.

○We had 218 visitors, among which 136 were foreign nationals.

○We had 296 scientific papers and 12 books published. Invited talks and poster presentation in the conferences were accumulated to 219.

3. Evaluation of Young Researchers ○We conducted annual evaluation meeting in January 2015 to improve the drive of the young researchers and promote mutual understanding. Evaluations were made based on the research achievements.

4. Strengthening and Enhancing the Research System and the Research Support System ○Three world-renowned PIs (including two non Japanese) and 15 young researchers were hired. The total number of ELSI researchers is 63.

○To improve the origin and evolution of life research, the Graduate School of Information Science and Technology, Osaka University (where the PI hired though the cross-appointment system has an official position) was designated as satellite institute of ELSI. In addition, one each of full associate and assistant professors in life science were hired.

○ Research advisor system was set and seven advisors are actively giving scientific advises

5. Promoting Interdisciplinary Research and Interactions ○Five study groups are actively engaged in discussions with various approaches to elucidate the origin of the Earth and life.

○ELSI Director's Fund was established to support interdisciplinary research team with young researchers from different fields.

○A twice-weekly brown bag seminar and a 15-minute daily coffee break session are held to facilitate interdisciplinary interactions among researchers and visitors.

6. Buildings ○The completion of renovation of the existing ELSI building accelerated the experiments. The new 5,000 m^2 building was completed in March 2015.

7. Education and Public Relations Activity ○Thirty-two public events (seven for especially for school-age children and one for local residents) were held. In addition, 36 research reports were appeared in newspapers, and 25 in books and magazines.

○The first session of "Tokyo Tech Inspiring Lecture Series" a new activity in Tokyo Tech was hosted by ELSI. Four members, including the director and PI Szostak gave lectures on "Origins: Earth and Life"-Science at ELSI-the forefront research at ELSI.

8. Commitment from the Host Institute ○To improve the research system of ELSI, Tokyo Tech provided three staff members in life science (a professor and an associate professor up to 31 March 2022 and a specially appointed professor), and one in earth science (an assistant professor, from 1 April 2015 to 31 March 2022) at the discretion of the President.

1. Summary of center project

<Plan at start of project>

1. Research Objectives

The **Earth-Life Science Institute (ELSI)** aims to answer the fundamental question "**when and where did life originate and how did it evolve**?" This question, which originated with the Greek philosophers, has been one of the most important topics of natural science. We will focus our research on addressing the unique environments on the early Earth that gave birth to life and their subsequent changes, with the main aim to study the origin and early evolution of life and persistent ecological systems in their geological context. We will also approach the primordial environment of the Earth through explorations of deep-sea microbial ecosystems and extraterrestrial primitive asteroids. In addition, we will critically examine the universality of these processes, to determine the uniqueness of our planet, with implications for the search for extraterrestrial life, both in the solar system and beyond.

ELSI will be thoroughly interdisciplinary from the start, integrating three areas in science that are essential for understanding the early stages of Earth and life.

1. Geological sciences, including geology, geochemistry and geophysics of the early Earth, as the sciences that describe the environment in which life first originated, and which shaped, and in turn was shaped by, its further evolution.
2. Biological sciences, ranging from biochemistry and systems biology to environmental microbiology, as the sciences that can investigate the processes that led to the origin and early evolution of life and ecological systems on Earth and elsewhere.
3. Broadly interdisciplinary input from a range of other scientific fields, from mathematics and physics and chemistry all the way to computer science and cognitive science, to shed completely new light on the age old question of how life first appeared and then evolved.

Why these three areas? Clearly, biological sciences are needed to discuss the details of any possible early life forms, and how they managed to become both more complex and more robust. In addition, any discussion about the origin of life needs a detailed description and analysis of the environment in which the building blocks of life came together, and the way in which evolution started to optimize the combinations of those building blocks. Therefore, both geological and biological sciences are essential ingredients.

If there was any good agreement about roughly where and how life formed, those two areas taken together might be enough to produce more and more refined models of the co-evolution of life and environment, right from the appearance of the

<Results/progress/alternations from plan at start of project >

1. Research Objectives

・As shown in the column to the left; no changes.

first living cells. However, currently we are still rather far from such a situation. The debate about how life may have formed continues to range over a huge spectrum of possible environments, together with a wide set of theories of which molecules combined how to produce self-sustaining reactions that were both robust enough to be preserved and flexible enough to admit increasing growth in complexity through early forms of evolution. As long as we don't really have a strong clue as to which ideas are correct, it is a good idea to step back from the immediate details, and to solicit ways of thinking from other areas in science and mathematics. This is where the third area comes in, combining a range of broadly interdisciplinary sciences.

For example, in the last century some well-known physicists have moved into biology and thereby have triggered novel theoretical ways of thinking. In addition, it may well be that abstract modeling of self-sustaining processes, not directly aimed at very specific forms of chemistry, may teach us how to think on higher levels of abstraction about the origin of life. Computer scientists, in turn, can help with the design and execution of simulation methods that also show levels of abstraction not normally encountered in biochemistry. And finally, cognitive scientists with experience in pattern recognition and pattern generation and other cognitive processes may help in other ways: they may approach the interactive needs of the most primitive proto-cells in ways that biologists who are trained to work with current life forms may not easily stumble upon.

More specifically, here are the main research topics at ELSI, focused on the following questions:

(A) Origin of the Earth
A1. How was the earth formed?
A2. Why does water exist on Earth?
A3. What is the deep part of the earth like?

(B) Birth of Earth-Life system
B4. What was the state of the ocean and the atmosphere when life emerged?
B5. Where did the Earth’s life emerge?
B6. What were the genomes of the first community like?

(C) Evolution of Earth-Life system
C7. Why does the Earth’s atmosphere contain oxygen?
C8. How did the thermal evolution of the solid Earth change the ecosystem?
C9. How did galactic events influence the Earth's surface environment?

(D) Bioplanet in the Universe
D10. How unique is our planet?
D11. How should we search for extraterrestrial life?

Our superiority in these studies is clear. We will study the unique environments on the early Earth by combining the research utilizing high-pressure/high-temperature experiments, theory of planet formation, and decoding the Earth's history, all of which are areas in which research at the Tokyo Institute of Technology (Tokyo Tech) is ahead of that at other places, nationally and internationally. In addition, Japanese scientists are also playing a leading role in the research of microbial ecological systems under extreme conditions, including those at deep-sea hydrothermal systems.

Moreover, we already have a rich tradition at Tokyo Tech in addressing many of these issues, based on unprecedented interdisciplinary research on Solid-Earth Science, Planetary Science, Geology, Environmental Biology, and Microbial Genome Science. Such collaborative research has been carried out by teams similar to ours since 2004 through the 21st century COE (Center of Excellence) Program and the Global COE Program. Based on our achievements in these programs, the research at ELSI will emphasize the roles of Earth's interior and the Universe in the origin and evolution of the Earth-life system. The main novel addition will be the even broader interdisciplinary connections in the third area listed above, for which we will make strong international connections with interdisciplinary groups elsewhere, such as the Program in Interdisciplinary Studies at the Institute for Advanced Study in Princeton.

・ Include a chart that illustrates the center's overall structure including its collaborative linkages with other domestic and foreign institutions, and its management framework

2. Organization

The Center is led by the **Center Director**, Prof. Kei Hirose, who has the overall responsibility to create a world-leading research center. He will recruit leading scientists from around the world and give them both clear roles and freedom in research. The Center Director appoints all the research and administrative staff members. The **Steering Committee** will support and advise the Center Director in the overall operation of the Center and evaluation of each research and administrative staff member, in collaboration with the **International Advisory Board**.

We will have sixteen **Principal Investigators**, including six non-Japanese, two women, and three from the Satellite institutes (Ehime Univ., Institute for Advanced Study in Princeton & Hatvard Univ.). Each Principal Investigator has his or her own research group including **post-docs**. The Center will also hire post-docs who have much freedom in research with loose connection to a specific group. The evaluation of research activity by each scientist will be made through an **Annual Evaluation Workshop** in the presence of International Advisory Board members.

Collaborative research is promoted through extensive communications between the different groups. Piet Hut, currently a Professor of Interdisciplinary Studies at the Institute for Advanced Study (Princeton), will organize regular events (daily,

2. Organization
(1) Overall
○Organizational structure
With growing members of Earth-Life Science Institute (ELSI), one of the non Japanese PIs was appointed to the Vice Director for a smooth operation of the institute. In addition, three world-renowned PIs and 15 young and brilliant researchers were hired (the total number at the end of March, 2015: 17 PIs, three associate PIs and 43 researchers).

○Introduction of the cross-appointment system
To acquire leading top-level researchers in the field of life science, especially "the origin and evolution of life," a cross-appointment system was established with Tokyo Tech. A professor from Osaka University was hired as a principal investigator (with effect from 1 November).

○New Satellite Institute
To improve the fields related to life science, especially "the origin and evolution of life," Graduate School of Information Science and Technology, Osaka University was designated a satellite institute of ELSI.

○Director's Office Meeting
The Director's Office Meeting, consisting of the Director, the Vice Directors, the Administrative Director, and the Assistant Director, was reviewed. They are now in

weekly, and monthly) that will stimulate broadly interdisciplinary interactions within the Center itself, as well as between the Center and Tokyo Tech as a whole.

The **Operations and Administration Division** is led by the **Administrative Director**, Dr. Kiyoshi Nakazawa who has rich experience in creating new organizations, in the first few years with the aid of **Executive Administrative Director**. It consists of an International Promotion and Researcher Support Department, an Operations Department, and a Public Relations Department (Figure 10). Proper administrative officers of Tokyo Tech will be assigned to the former two departments, providing the primary interface with existing administration offices of the university. Some administrators will stay at the Institute for Advanced Study in Princeton, our Satellite institute, for a few months to learn their highly efficient administrative system. The functions of the Operations and Administration Division will be carried out by a couple of **Research Advisors** with academic background, who support both researchers and administrators. A **Life Advisor** will be assigned to each non-Japanese family, assisting with immigration, housing, and daily life. **Research Communicators** in the Public Relations Department will be charged with overall outreach activities, including monthly meeting with journalists, a **Summer Internship Program** for high-school students, public lectures on topics of general interest such as Hayabusa missions, etc.

ELSI will have three **Satellites** at Ehime University, the Institute for Advanced Study in Princeton, and Harvard University (Figure 13). We also make strong connections with the Institute of Space and Astronomical Science (ISAS) of the Japan Aerospace Extrapolation Agency (JAXA), and the Japan Agency for Marine Science and Technology (JAMSTEC), where some Principal Investigators are based. These two agencies perform large-scale investigations of extraterrestrial bodies and to deep-sea hydrothermal systems, whose research targets are closely related to our scientific goals. In addition to these institutes, we will collaborate with a number of domestic and over-sea institutions listed in Figure 13. Exchange of scientists with these institutions is an important mission for ELSI in its role to become a world communication center.

Mission Statement and/or Center Identity

So far, discussions about the origin of life on Earth have been mostly limited to the biochemistry of proto-life forms. While the Earth environment has been described as a “cradle of life”, the image of a “cradle” points to a supporting background role, rather than a dynamic interplay. In ELSI, we want to radically broaden these discussions by focusing equally strongly on both sides of Earth and Life. For one thing, life is preserved through a continuous exchange of matter and energy with the surrounding environment. For another, it is a two-way interaction: as soon as life forms are present, they start to influence the environment, just as the environment is influencing life. Our basic outlook is reflected in the name of our proposed center: ELSI stands for Earth-Life Science Institute, in which Earth charge of planning the strategy for ELSI.

○Steering Committee Meeting

Continuing from 2013, the monthly Steering Committee meeting, consisting of the Director, the Administrative Director, and two Vice Directors, provides information from Tokyo Tech, adjustment of the internal rules, the research environment and HR issues that are useful for operation of ELSI. In this meeting, chief administrative staff and secretaries are present for the better sharing of information and seamless daily operation of ELSI.

○Tokyo Tech Internal Council

The Tokyo Tech Internal Council was created to maintain close communications with Tokyo Tech departments regarding items necessary for the management of ELSI, and to manage ELSI efficiently.

○Review of Expert Committees

The Director re-organized Vice Directors’ job distribution to meet the increasing members and the diversity of the work in ELSI. The Director also reviewed the committees and set the management structure in line with the current situation of ELSI.

・Vice Directors responsibilities

In response to the aim of the World Premier International Research Center Initiative (WPI) program, the three Vice Directors are responsible for the promotion and realization of Fusion, Globalization and Reform. They are also responsible for the management of the associated expert committees.

・Director’s Office Meeting <newly established>

Urgent issues and clarification to committees had been handled in Assistant Director’s office meeting with related personnel as required. However due to the increasing and diversification of the problems to be handled, there were some cases in which the problem awareness and information were not necessarily shared within the steering office. To solve this issue Director’s Office Meeting, consisting of the Director, the Vice Directors, the Administrative Director and Assistant Director was newly established and the office took charge of the important issues, problems and sharing updated information. It is also in charge of giving instructions to the committees. In addition, the Director’s Office Meeting absorbed the role of the previous Research Steering Committee, and takes on the role of leading the discussion on research promotion for ELSI, such as development of mid- to long-term research plans, and updates and correction of the research master plan and research roadmap.

・Secretaries Committee <newly established>

The Administrative Director summarized the duties of the Administration Office

sciences and Life sciences will be equally represented.
In addition, we will replace the biology question of the "origin of life" with the more relevant interdisciplinary question regarding the "birth of a persistent ecological system." An important goal in our research will be to clarify the initial ecological system that allowed a stable and persistent existence of life even under the various harsh and violent changes of the environment at the beginning of the Earth's history.

And while we will study life in the context of the early Earth environment, similarly we will also study how the Earth itself was formed and how its conditions changed, inside the Earth as well as on the surface. In the course of these studies, we will critically examine the universality and uniqueness of our planet that gave birth to life as we know it, with implications for the search for extraterrestrial life in both solar and extra-solar systems.

We will perform our research through cutting-edge lab experiments, computer simulations, and field observations. We may also need to develop wider pictures of metabolism and self-reproduction on more abstract meta levels through a broadly interdisciplinary approach. How such abstract models are then implemented on molecular levels may differ between life on Earth and elsewhere.

In contrast to NASA's Astrobiology Institute whose research topics are broadly similar to ours, we emphasize the role of the Earth as a whole in the origin and evolution of life, based on the past achievements of collaborative studies at Tokyo Tech. Most importantly, ELSI will not be a virtual institute. People from different fields will gather together at ELSI to make it a foremost interdisciplinary research institute. We will promote internal communications through a series of daily, weekly, and monthly events, following the Program for Interdisciplinary Studies at the Institute for Advanced Study (IAS) in Princeton as a model. This IAS program will act as a satellite center for ELSI.

The success of ELSI will depend strongly on its research environment, and the recruitment of good scientists. We are planning to build up a strong interdisciplinary program within ELSI. This will attract a wide variety of top scientists to visit ELSI to interact with members there and also with each other. We do not want to define job specifications too strongly beforehand. Rather, we prefer to attract top scientists first, and then to finetune the research program around their skills and interests. In addition to promoting internal communications, the Center Director is responsible for providing the best research environment. PIs joining from Tokyo Tech will be reassigned as Professors of ELSI, in order to be freed at least from the duty of teaching undergraduate students. A very efficient research-oriented administrative system will be created through evaluation and education of administrators.

ELSI will also play a strong role as a communication center. We will promote as the secretarial duties and duties associated with the entire Institute, i.e., duties that require cooperation with the Tokyo Tech headquarters. The responsibility of each administrative staff was clarified. Taking researchers request to consideration, each researcher has now secretary in charge (the contact person). A researcher will contact the secretary in charge and the secretary will handle/respond to the researcher with the support by the Administration Office. This is "One Stop Service". As the secretaries' office became independent of the Administration Office, the secretaries committee was established to share and accumulate the information and knowledge among the secretaries. The Administration Office and secretaries' office have regular liaison meeting and discuss/share information and opinions to make more efficient support for the researchers

・Other committees

Existing expert committees such as the Public Relations Committee, Financial Planning Committee, Building Committee, Computer/Network Committee and Research Interaction Committee, along with the Safety and Health Committee, Information Ethics Committee, Information Security Committee, and Hazardous Materials Management Committee, established in accordance with the laws and regulations/university regulations, has been working to support the research activities. As for Recruitment Committee, because neither continuous nor large-scale recruitment was conducted in the 2014 fiscal year, the Director's Office Meeting tentatively took over the responsibility.

○ALL ELSI Meetings

Continuing from 2014, ALL ELSI Meeting is held once a month. The Director updates/shares the issues and activities happening in ELSI.

○International Advisory Board

One of the International Advisory Board members, Dr Carl Pilcher, the formar director of NASA Astrobiology Institute, had to relinquish the position of Advisory Board member therefore there was no meeting in 2014.
The members comprising the International Advisory Board as of end FY 2014 are the following. One more member will join in fiscal year 2015 and the next meeting is scheduled on 2 September 2015.

・Chairman: Masuo Aizawa (Advisor to Japan Science and Technology Agency)
・Douglas Lin (Professor at University of California at Santa Cruz)
・Robert Hazen (Researcher at Carnegie Institute)

○Research Advisor

Regular meetings are held amongst ELSI members to discuss the medium-term research targets, current research topics, specific research plans, etc., for research. Research advisors give advices from their professional experiences and views based interdisciplinary connections between researchers internationally and nationally. In addition, we will combine our research with outreach and education. Spacecrafts such as Hayabusa and Hayabusa-2, and questions about the formation of Earth and the origin of life, as well as extraterrestrial life are of strong interest to the general public, and thus perfect for outreach. As for education, we will create a Summer Internship Program for high school students, based on nation-wide competitions in high schools in Japan. These activities will also help not only ELSI but also its host, Tokyo Tech, to further increase both its international and domestic visibility.

on those meeting topics. There are seven top-level Research Advisors from various research areas and they actively give suggestions and advices.

Kunihiko Kaneko: Professor at Graduate School of Arts and Sciences, University of Tokyo
Yasushi Sudo: Professor at Graduate School of Science, University of Tokyo
Eiichi Nakamura: Professor at Graduate School of Science, University of Tokyo
Tairo Oshima: Kyowa Kako Co., Ltd., Director at Environmental Microbiology Institute
Ikuo Kushiro: Member at Japan Academy
Mineo Kumazawa: Former professor at Nagoya University
Yoshi Oono (up to July 2014): Professor at University of Illinois

○Recruitment of Young and Brilliant Researchers

Fifteen young researchers were hired in 2014. This is including those who were already selected in previous year's recruitment campaign. Seven of them were foreign nationals.

○Annual Evaluation Meeting

Following the previous year, the mandatory Annual Evaluation Meeting was held over two days at the end of January 2015. Based on criteria on the Research Activity Sheet submitted prior to the evaluation and a 15-minute presentation/discussion, ELSI employed researchers and PIs evaluated each other. The main criteria in the evaluations were as follows: 1) The quality of the research including publications such as papers) and the compatibility with the research purpose of ELSI, 2) if the research is taking interdisciplinary research into consideration, and 3) if, especially young researchers, the researcher conducts research independently. The executive office, the Director, the Vice Directors and Administrative Director summarizes the result of the annual meeting. One PI and an associate professor were awarded the PI Research Award 2014 for promoting excellent research, and nine young researchers were awarded ELSI Incentive Award 2014. In addition, the Director had feedback interview with all the researchers individually based on the evaluation results.

○Planning Regular Events to Promote Interdisciplinary Research

In order to overcome "language barriers" and "cultural barriers" and to promote mutual understanding among researchers with various backgrounds, the following events were implemented.

・ELSI Assembly (twice a month): Research presentations and discussions by ELSI members.
・ELSI Seminar (as needed): Research presentations and discussions by external researchers.
・ELSI Forum (as needed): Panel discussions on ELSI research topics.

・Brown Bag Seminar (twice a week): ELSI members take turns introducing their research and topics to researchers in other fields at lunch time.

・Coffee Break Meeting (daily): Held in the Communication Room at 3 pm to promote communication among researchers in different fields.

(2) Administration Division

〇Organizational structure

The structure of the Administration Division was reviewed. To strengthen public relations, the Public Relations Office in the social cooperation division is under direct supervision of the Director. The secretarial office was also created to strengthen the research support system.

<Members>

Administrative Director, Assistant Administrative Director, and Chief of Secretaries

・Management division and foreign researchers support division (one each of chief of affairs and chief of finances, and three administrators)

・Secretaries’ Office (four administrative staff)

・Public Relations Office (one education research support staff, and one administrative staff)

・One Coordinator for International Initiatives

・One staff in charge of the computer networks

・One staff in charge of research support

(3)Satellite and Collaborating Institutions

〇Satellite Institute—Osaka University

To enhance and strengthen the research on the origin of life at ELSI, as of 1 November, 2014, “Osaka University Satellite Institute” was established at Osaka University Graduate School of Information Science and Technology. Professor Tetsuya Yomo was appointed as the Satellite Director, and Associate Professor Norikazu Ichihashi was appointed as the collaborating researcher. In addition, on 1 March, 2015, Satoshi Fujii, assistant professor, was hired and dispatched to the satellite institute to focus on the research.

This satellite institute collaborates with the researchers at ELSI and aims to elucidate the origin of life from the perspective of synthetic biology. Through the discussion among associated researchers, a research proposal is materializing, and some specific researches have already started.

〇Satellite Institute — Ehime University

・Continuing from the previous fiscal year, we sponsored studies on the thermal evolution of the Earth and held discussions with ELSI’s researchers.

・Management of study groups was facilitated with the collaboration of Ehime

University Satellite Institute since previous year. Based on the discussions among the study groups, joint research resource was secured such as cooperation on the application of Grants-in-Aid for Scientific Research.

・Researchers conducting research at Ehime University Satellite Institute were requested to attend the Annual Evaluation Meeting as part of various research exchanges. Five members including the Satellite Director were evaluated during the evaluation meeting and one young researcher was awarded ELSI Incentive Award 2014.

・ The Satellite Director and researchers presented lectures at scientific events held in Shikoku regions as representatives of ELSI: they are actively engaged in public relations activities as part of ELSI.

〇Satellite Institute—Institute for Advanced Study in Princeton

・Two young researchers from ELSI (specialized in chemical evolution and planetary physics/astrobiology, respectively) stayed in Princeton for several months to conduct their research at the Institute for Advanced Study (see Institute for Advanced Study, Faculty and Members 2013-2014, p 68-69 and https://www.ids.ias.edu/visitors).

・The Satellite Director has made considerable effort to promote the science being pursued at ELSI and improve visibility by organizing the "Modeling Origins of Life Workshops at IAS" from 13 to 15 November, 2014 with the ELSI researchers mentioned above.

・The Satellite Director continued the investigation into foreign funding and charity institutions and won research funds from a US foundation.

〇Satellite Institute—Harvard University

・Continuing from the previous fiscal year, young researchers were sent to Harvard University Satellite Institute, and are currently working on their experimental researches. These researchers will remain at Harvard for about nine months, and spend the rest of the year in ELSI to conduct their researches. In addition, two young researchers conducting research on the origin of life, using the synthetic-biological method with ELSI as base, visited the Satellite and received advice and experimental knowledge from the associated researchers and the Satellite Director.

・The Satellite Directors, Professors Jack W. Szostak, and Dimitar Sasselov (the Director of the Origin of Life Initiative at Harvard University) were invited to the first session of the new lecture series, "Tokyo Tech Inspiring Lecture Series" at the university – "Origins: Earth and Life" Science at ELSI – to present lectures on the forefront research in "origin and evolution of the Earth and life."

・In February 2015, an ELSI-Harvard University joint workshop titled "RNA,

	Peptides, Vesicles and Exoplanets -The Chemical Origins of Life on Early Earth and Other Planetary Bodies" was held at Harvard University Satellite Institute. Five young researchers from ELSI were sent to this workshop. ○ Japan Agency for Marine-Earth Science and Technology (JAMSTEC = collaborating institute) ・The Director met with the Research Director of JAMSTEC and the Center for Deep Earth Exploration (closely related to ELSI's research activities) to discuss a collaborative relationship that would benefit both ELSI and JAMSTEC, particularly with regard to interactions among researchers. In addition, the directors exchanged views on collaborative relationship between organizations (university-organization) based on ELSI and JAMSTEC. ・Cooperation was obtained from JAMSTEC for the research infrastructure at ELSI building to investigate the potential of the origin of life, especially the origin of life in the deep sea hydrothermal system. We placed a young researcher, who is mainly conducting ELSI-JAMSTEC joint research in this field, at ELSI. ・The Administrative Director exchanged opinions with the Research Director in charge on establishing the collaborating relationship such as in the outreach. ○Japan Aerospace Exploration Agency (JAXA = collaborating institute) ・The Director and the Counselor continued their discussions with JAXA to clarify the role ELSI should play within a broader collaborative research framework, such as the JUICE space mission suggested by the WPI Committee. ・ At the launch of "Hayabusa 2" on 2 December, 2014, ELSI hosted a "Live viewing of Hayabusa-2 Launch" event with the image streaming from JAXA, ○California Institute of Technology (Caltech = collaborating institute) ・ Continuing from the previous fiscal year, one researcher was sent to Caltech with the aim of improving the analytical technology of the transmission electron microscope, and magnetic fine particle measurement. ・ The PI from Caltech stayed a total of five months at ELSI to conduct research. This PI gave an opportunity to three students to take a summer course hosted in Caltech and to interact with an ELSI researcher about the research experience at ELSI. ○University of Minnesota (collaborating institute) ・The PI, scheduled to start her employment at ELSI in the 2015 fiscal year, stayed approximately 40 days at ELSI and conducted joint research with associated researchers (elucidation of the material composition of deep Earth by the first principle calculations).

○Effort for a Contract for New Partnership Agreements

・As part of building the global network for the origin of life and astrobiology research, a proposal was prepared for a partnership contract agreement with NASA Astrobiology Institute, and negotiation is in process. As a result, the partnership agreement is to come in effect around June 2015

[Mission statement and/or Identity of the Center]

(1) Mission statement

No change in the column on the left.

(2) Characteristics of the Center

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2. Research fields

<Plan at start of project >

・ Fill in the name of the target research field of the project.
・ Specifying the inter-disciplinary field(s) to which the project may be closely related.

Interdisciplinary Research on Solid-Earth Science, Planetary Science, Geology, Environmental Biology, and Microbial Genome Science

We will promote integrated research in fields related to the formation of the Earth in the early solar system, the environment and the creation of life on the early Earth, and the co-evolution of the Earth-Life system, using the keyword "early Earth". Through the study of Earth, we will clarify both universal and unique aspects of the Earth, from which life emerged and evolved, and we will predict the presence or absence of life on other planets. In order to immediately apply our research results to search for extraterrestrial life, we will work in close cooperation with space exploration missions and astronomical observation teams.

・ Describe the importance of the proposed research field, including domestic and international R&D trends in the field .

Importance and trend of the research field

The life science and Earth science should be linked, simply because life is a phenomenon that can exist only through the exchange of energies and matter with

<Results/progress/alternations from plan at start of project >

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the surrounding environment. We will therefore integrate research on the Earth and life, and explore "how our life can originate and continue on this planet" through a detailed study focused on the early Earth. This is one of the most important questions that natural science, beginning with Greek philosophy, has asked until this modern age. It is amazing and fascinating that so much progress has been made during the last 20 years, in related fields, on a question that has been at the heart of science for 2700 years. Three trends will be described in the following sections.

1. Understanding the Earth

Recently, rapid progress has been made in analyzing the deepest parts of the Earth, and we now have a detailed image of the Earth's interior, including the core of the Earth. One of the major factors in this progress has been a drastic advancement in ultrahigh pressure experiment techniques by Hirose, the Institute manager, and Irifune, the person in charge of the Ehime satellite Center. Ten years ago, most experiments covered a depth of only 2000 km, but currently experiments studying the center of the Earth, 6400 km deep, are being conducted. As a result, Hirose et al. found that the lowermost mantle is composed of a newly-discovered mineral phase, post-perovskite. They also found that the associated phase transition activates convective motion in the mantle. These are great accomplishments achieved in Japan. Furthermore, Hirose et al. have analyzed crystal structures of the inner core of the Earth's deepest part. As a result, the actual state of the Earth's core, which so far had been a topic of speculation, is now becoming a realistic subject of experimentation.

Most of the past ultrahigh pressure experiments were conducted for understanding the "current Earth". The research is now targeting "the Earth of the past", and "**the early Earth**". The advancement of a series of ultrahigh pressure experimental techniques enables the ultrahigh temperatures during formation of the Earth to be reproduced. Hirose et al. experimentally confirmed the hypothesis of "Bottom Magma Ocean" where the molten rock, which mostly covered the primitive Earth's surface extended all the way down to the deepest parts of the mantle. In principle, this could allow a much more complete degassing of the volatiles that formed the oceans and atmosphere of the Earth. It is apparent that the extensive differentiation of the Earth due to the magma ocean is a major factor controlling subsequent changes of the Earth, resulting in determining the upheaval of the surface environment.

Complementing these discoveries, the progress of research on geology and geochemistry of the early Earth is remarkable. As a result, on a macro and long-term time scale, it is becoming clear that Life and Earth evolved together. In the 1980's, the Precambrian Paleontology Research Group led by Bill Schopf found many bacterial fossils in Precambrian rocks older than 1 billion years ago. This revealed that life was active on the early Earth. Unfortunately, it was impossible to classify the fossil bacteria based on their simple forms, and it was unknown "what functions and metabolisms were active on the early Earth". After that, the geochemical bio-indicators such as stable isotope ratios of bio-essential elements were established, and certain physiological natures and metabolisms could be continuously read off the geological records. Currently, the biogeochemical cycle of C, N, S, and Fe, etc. can be traced back to 3.8 billion years ago. Furthermore, this research on geochemistry is reaching a level that produces quantitative estimates of the chemical environment on the early Earth, including the atmospheric composition and redox status of the oceans. The "decoding whole-Earth history" project led by Kumazawa and Maruyama, Institute PI, pioneered this research in Japan since 1995. Then, internationally, the Agouron Institute started their scientific drilling project in the Kalahari Desert in South Africa (PI, Kirschvink), followed by the NASA Astrobiology Institute and continental drilling programs of France and Australia, etc. Research programs by Tokyo Institute of Technology COE/G-COE programs also played a role in the research of the evolution of the Earth.

The results of this research uncovered unexpected aspects of atmospheric evolution, such as the Great Oxidation Event, and climate changes, such as Snowball Earth, found by Kirschvink, an Institute PI, implying an important relationship between environmental changes and the evolution of life. The ultimate causes for these environmental changes have not yet been identified; however, changes of the solid Earth (rapid continental growth, increase in sedimentary rocks, intense volcanic activities and geomagnetic field intensity changes), sudden biological evolution of oxygen-releasing photosynthesis, and the impact from galactic events (increase in cosmic rays on Earth), have been discussed actively. A number of new concepts have originated from interdisciplinary research by Tokyo Institute of Technology's G-COE program. To determine the origin and evolution of life on Earth, it is time to pay close attention to the relationship between the thermal evolution of the Earth including its deep mantle and core and long-term changes in the Earth-Life system.

2. Geomicrobiology

Since 1977, when unique microbial and macrofaunal communities were found in the deep-sea hydrothermal system where sunlight does not reach, environments where we can imagine the limits of life and its activity have been extensively explored. Microorganisms are especially good at adapting to extreme physical and chemical conditions, such as temperatures, pressures, pH, and redox state. The investigations of the microorganisms in these extreme environments provided us with confidence that extraterrestrial life may thrive in environments somewhat similar to the Earth's ocean. The impact from the discovery of deep-sea hydrothermal ecosystems immediately led to the hypothesis of "hydrothermal origin of life". Observations of the deep-sea for over 30 years, from 1977, by researchers in Japan, U.S. and Europe, identified that the physical and chemical environments in deep-sea hydrothermal systems are extremely varied. Each hydrothermal ecosystem uniquely depends on its chemical environment, which is ultimately controlled by the geological settings and reactions with the seawater. Therefore, the type of the first ecosystem of this planet must have been controlled by the composition of the primitive crust produced when the magma ocean solidified and by the primitive ocean chemistry. The driving mechanisms of the early ecosystems are based on chemical energy inputs supplied by the Earth's interior. From the standpoints of energy mass balance, Earth and Life cannot be separated and thus consists of a single Earth-Life system. These recognitions led to the establishment of the Biogeoscience division at large-scale academic meetings of Earth and life sciences, such as the American Geophysical Union (AGU), the Japan Geoscience Union (JPGU) and the Golschmidt Conference.

Takai, the Institute PI, led the exploration of deep-sea hydrothermal ecosystems by JAMSTEC, and succeeded to clarify the key role of molecular hydrogen and to establish a new theory of the hydrothermal origin of life. Through his observations, it has been more deeply understood that most life forms exist as a community, not as a single population, and their activity is closely linked to the geologically determined physico-chemical environment. On the other hand, it has been revealed that the ecosystem itself plays an important role in the evolution of the atmosphere and ocean chemistry.

Microbial genome and metagenome sciences are keys to understand the early and modern ecosystems and to extract general principles from the great complexity of ecosystem formation and behavior. Rapid development of next-generation sequencers and data analysis methods enable us to obtain, extract and interpret enormous amount of data and information, expanding our knowledge at unprecedented rates. With engineering developments to synthesize long-chain DNA, synthetic biology has been developed, which enables experiments to determine the function and robustness of the artificially created DNA. In addition, both research targets have been extended to the primitive living system of a community as well as single cells.

3. Discovery of "Earth-like" exo-planets

Since 1995 when extra-solar planets were first found, the number of planets newly discovered has increased drastically. Many terrestrial planets (super-Earths) have been discovered beyond the solar system in the last 17 years, and the size distribution is rapidly expanding, to reach down to the size of the Earth. The most recent observations and theoretical models suggest that more than 20% of percent of solar-type stars have Earth-like planets, resulting in increased discussion about extraterrestrial life within the field of astronomy.

In a parallel development, the discovery of past water traces on Mars, and observational data that strongly suggests the existence of internal oceans in Europa (a satellite of Jupiter) and Enceladus (a satellite of Saturn), gave us great expectations that there may be other celestial bodies in the solar system that might harbor life.

In this manner, the hope of finding life on celestial bodies has now become a concrete expectation. Because of this situation, using current or future observational techniques, we can begin to look for biosignatures of extraterrestrial life, or actual extraterrestrial life. The major idea is to detect atmospheric components of biological origin, such as ozone, by direct spectroscopic observation of light emitted by extra-solar planets. Such observations form one of the highlights for next-generation large ground-based telescopes (Thirty Meter Telescope: TMT and Extremely Large Telescope: ELT) planed by international consortiums. Also, using radio telescopes, organic matter in interstellar molecules has been discovered.

The search for extraterrestrial life includes *in situ* analysis or sample return by space missions in addition to the remote sensing by telescope observations. ”Mars Science Laboratory” which NASA launched last year, will arrive at Mars on August 5 of this year, and has the capability to detect organic matter on the surface of Mars. Also, one of the purposes of “Hayabusa-2” is to detect water and organic matter on a primitive C-type asteroid through a sample return. European Space Agency’s (ESA) “JUICE” mission, which was approved this year, potentially in cooperation with JAXA, is to explore the icy moon Europa. This space mission will explore conditions for the presence of life by capturing water plumes emitted from the icy moon (observed on Enceladus by the Cassini mission) probably originating from an internal ocean.

As just described, science missions searching for extraterrestrial life have already started, and atmospheres of extra-solar Earth-like planets will be investigated through spectroscopic observation within the next 10 years. Thus, the understanding of the universality and uniqueness of our Earth, and the presence or absence of biological activity will dramatically advance. In this way, Earth and planetary sciences will be revolutionized, upon finding habitable planets beyond our current imagination. Before such observations will start, we need to establish a new field of “Bio-planetology” that will predict which types of planets may harbor life and what observation methods should be used for finding them. This should be an urgent issue for earth and planetary sciences and astronomy.

・ If centers in similar fields already exist in Japan or overseas, please list them.

List of centers in similar research fields

International:

- NASA Astrobiology Institute (NAI)
- Extremely large ground-based telescope programs (TMT and ELT)
- Continental drilling programs (France, South Africa, Europe), Deep-sea drilling programs (ODP, etc.)

Domestic:
- Institute for research on Earth Evolution (IFREE)
- Precambrian Ecosystem Laboratory, JAMSTEC
- Tokyo Institute of Technology G-COE

・ Describe why you believe that your project can satisfy the criteria of this call for proposals, especially: “a field in which Japan’s expertise can excel,” “A field that has international appeal,” and “a field that can stand continuously at a top world level by perpetually and strategically spawning related new domains in ways that the field may sustain the future capacity over the relatively long project-funding period of ten years.”

Japanese expertise

In this institute, we first “recreate the Earth” through ultrahigh pressure experiments and simulations based on planet formation theory. We then increase our understanding of the origin and early evolution of the Earth-Life system through geological and microbiological research, and study the universality of life-hosting planets through generalizing from the case of the Earth. Among these, ultrahigh pressure experiments and planet formation theory are, without a doubt, world-renowned specialties of the Japanese in the fields of earth and planetary sciences. In the ultrahigh pressure experiments, the multi-anvil apparatus and diamond (anvil) cell apparatus are the two major high pressure generators that are most widely used. The former apparatus was mainly developed by Naoto Kawai in Osaka University in the 1960’s. The apparatus and experiment techniques have been exported worldwide from Japan. The person at the leading edge of developing these techniques is Irifune, an Institute PI. The latter apparatus has the disadvantage that microscopic samples are used; however, it has become the major apparatus for high pressure earth science with the advent of radiation light facilities. Only the group lead by Hirose, the Institute manager, can realize the ultrahigh pressure and high temperature environment at the center of the Earth. Both groups, led by Irifune and Hirose, have achieved great results based on their world-class ultrahigh pressure experiment techniques, and the superiority of those results will continue for the next 10 years. In addition, particle beams are required to analyze microscopic samples under high pressure. Having the world’s most advanced high pressure sample analysis facilities, such as the world’s largest facility for synchrotron radiation, SPring-8, and the Japan Proton Accelerator Research Complex, J-PARC, form some of Japan’s superior.

Equally leading internationally, planet formation theory began with the solar system formation standard theory, “Kyoto model”, established in the 1980’s. Currently Ida’s group in Tokyo Institute of Technology (an Institute PI) has taken over, and a new “Tokyo Tech model” is being established. That process is closely connected with the development of large scale computer systems. Makino, an Institute PI, has contributed greatly to the development of the world's fastest super computer, by setting clear, scientific goals. This was realized by a unique approach of integrating the development of hardware, algorithms, and software and scientific research, and his expertise will be invaluable.

In the 1990's, a project on "decoding the whole Earth history" was promoted mainly by Maruyama, an Institute PI. In this project, ahead of the inception of the encoding the evolution of life on the early Earth by the NASA Astrobiology Institute, much progress was made in collecting, encoding and analyzing of rocks from the early Earth worldwide. Rock samples collected from all over the world reached a total of over 165000 samples. These samples are stored at Tokyo Institute of Technology and made available for collaborative research all around the world. Collecting rocks in consideration of the changes in the solid Earth is an exclusive part of this project.

For deep-sea hydrothermal exploration, Japan has the best capability in the world, led by the Japan Agency for Marine-Earth Science and Technology. Takai, an Institute PI, et al. have initiated geomicrobiology of the deep-sea hydrothermal systems and have provided basic principles of interaction between the geo- and life-systems through more than 10 years of exploration of his group, utilizing world-class, large-scale research facilities. In addition, he and his colleagues have presented a grand hypothesis describing how the most ancient, continuing community of life originated in the primitive deep ocean and how the early evolution and global propagation of life was successfully achieved in the highly varying and evolving early environments in the primitive ocean.

While Europe and the U.S. lead the way regarding the observation of extra-solar planets in the universe, Japan has also achieved many essential results, such as a sample return from asteroids by Hayabusa and Hayabusa-2, and direct imaging of extra-solar planets by the Subaru Telescope.

In addition to the expertise of each individual researcher, the collective research done in the "project on decoding the Earth evolution", "Tokyo Institute of Technology COE project: the Earth" and "Tokyo Institute of Technology Global COE Project: From the Earth to the Earths", has provided interdisciplinary integrated research by geoscientists, planetary scientists, and life scientists. This research, starting 20 years ago, has firmly established Japan's leading role in these fields, internationally.

International appeal of ELSI

It is obvious that interest in the origin and evolution of Earth and life is common among humankind in all ages and places. The possible existence of life on Mars and the icy moons Europa and Enceladus with potential internal oceans has been extensively discussed as a near future target for space exploration. Recently, a large number of extra-solar planets have been found, and some of them may have oceans like on Earth. In this age when the existence of life in the universe is beginning to be scientifically discussed, we face an increasing importance of understanding the origin of the Earth, from which life has grown.

The program of the NASA Astrobiology Institute systematically began research on extraterrestrial life and the environment on the early Earth, and has greatly contributed to promoting astrobiology. However, the program is a research and development promotion program, and is done by a virtual organization where researchers in different fields do their research separately in their own institutes. In contrast, there are many advantages in having as organization in which the researchers in different fields physically gather, such as in the Tokyo Institute of Technology G-COE program and the system earth and life sciences program, “Precambrian Ecosystem Laboratory”, promoted by JAMSTEC in Japan. These programs have destroyed the walls existing between the research fields, and have succeeded in a real integration of fields, to some extent at least. In fact, the roles of the solid Earth and the universe in influencing the origin and evolution of life have received attention as new key concepts. Based on our existing programs, we seek to become a truly international research institute in this field.

The “early Earth” that we focus on, is an almost untouched field so far, waiting for the experimental and numerical techniques that we plan to use. As there is little direct physical evidence, research on the early Earth is a great challenge for geology and life science. It is clear that the early Earth and early Life have followed a path of joined evolution. An international institute that researches on such unresolved important fields should attract the eyes of the world.

3. Research objectives

< Plan at start of project >

・ Describe in a clear and easy-to-understand manner the research objectives that the project seeks to achieve by the end of the grant period (in 10 years). In describing the objectives, the following should be articulated in an easily understandable manner: What kind of research area do you plan to open up by, for example, fusing various fields? In the process, what world-level scientific and/or technological issues are sought to be resolved? What is the expected impact of the scientific advances to be achieved on society in the future?

We focus on **the early Earth** when life emerged, and will answer the following scientific questions: (A) How was the Earth formed within the solar system? (B)

<Results/progress/alternations from plan at start of project >

[Research Objectives]

As shown in the column on the left, there is no change.

[Research Plan]

Modification of the roadmap

At ELSI, we appropriately review the roadmap in the ELSI forum, etc. under the leadership of the Director based on the research progress/trends and recent findings in the related fields. In the latest roadmap, the subjects to be dealt with during the first half are largely categorized into three groups and subtopics across the subjects are placed under each subject. Complex Systems Science has been newly added to

How was the earth's first ecosystem established, and (C) How can the earth and life evolve after the first state. Through the study of the Earth, we clarify universality and uniqueness of the planet Earth harboring life. Further, we utilize the outcomes of the research (D) to provide guidance for the search for life on other planets and moons. Each of those themes is performed under an interdisciplinary fusion of different fields. Each question to be solved is discussed in detail below.

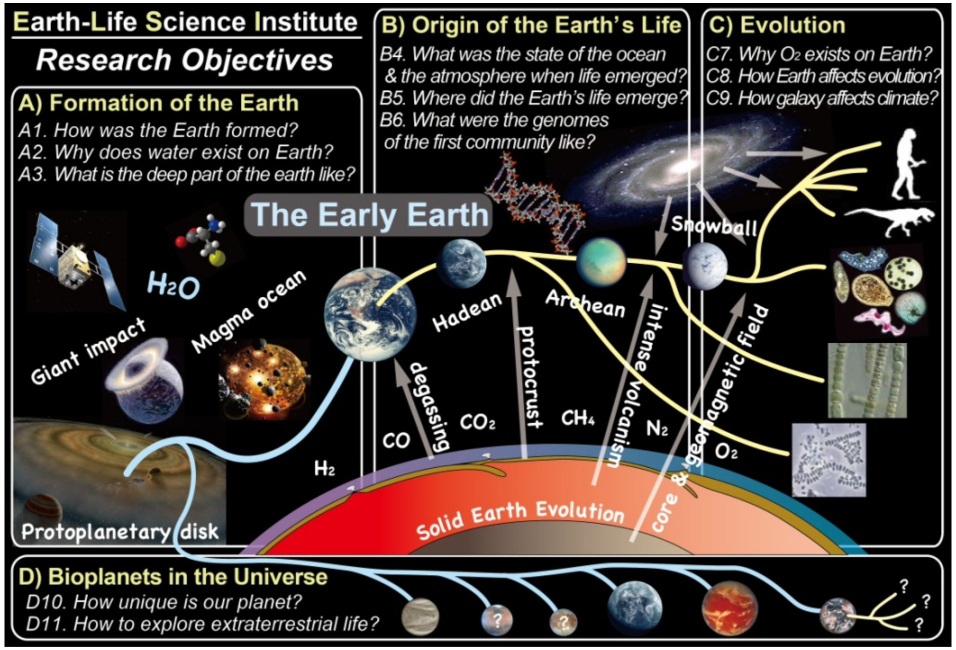

Figure 1. Summary of research objectives.

A) Origin of the Earth

The main goal of our study is to understand how the planet Earth was formed and harbored life. It is critical to determine the first state of the Earth from central core, through mantle and crust, to the ocean and the atmosphere. First, we aim to understand (1) how the earth was formed in the solar system using a theory from first principles, examining the theoretical model from the viewpoint of the chemical composition of the Earth. (2) Breaking through the conventional idea of habitable zone (i.e. just presence of liquid water), we will find out factors which determined the appropriate level of ocean water on the Earth. And finally, (3) we experimentally reproduce material differentiation of the early Earth before and after the birth of life.

A1. How was the earth formed?

The Kyoto Model is well known as the standard model for planet formation in the interfield discipline's challenging subtopics, and research on elucidating proto-metabolic systems towards protocells has been initiated.

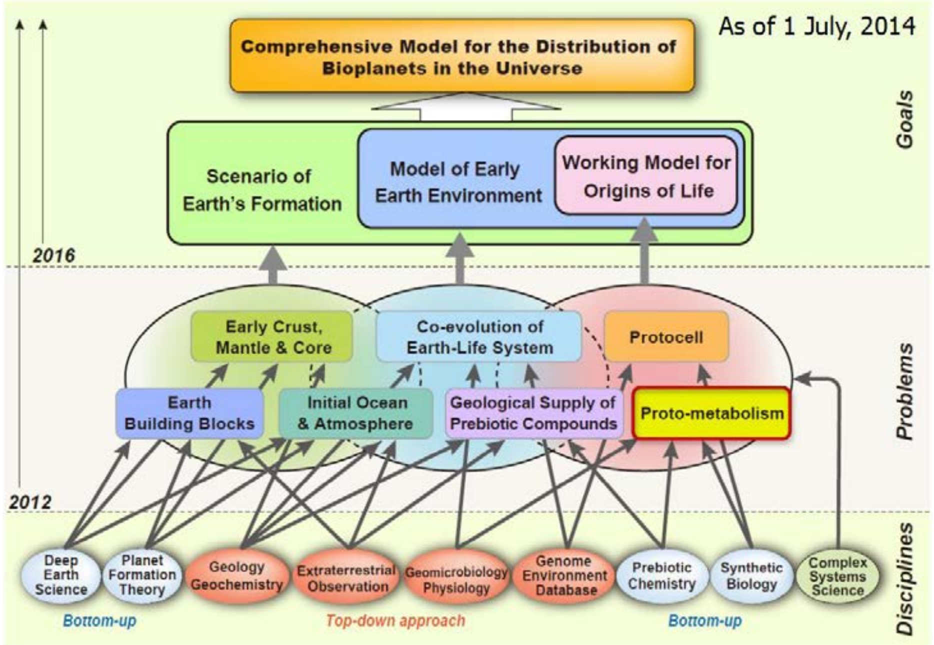

Fig. 1. Modified Roadmap

[Research progress in FY 2014]

Research progress in FY 2014 for each of the eight interfield disciplines, excluding Complex Systems Science, was as follows.

Deep Earth Science

The Deep Earth Science area of ELSI includes three different approaches; high-pressure and high-temperature mineral physics experiment and theory, geodynamics simulations, and seismic observations. This area of ELSI aims to better understand the origin and evolution of the planet Earth, from which we can contribute to addressing several key questions related to the early Earth environments; "When and how did plate tectonics begin?" "From when and how was Earth's magnetic field formed?" "What is the origin of ocean?" Our group has direct collaborations and interactions with the Planet Formation Theory, Geology/Geochemistry, and Extraterrestrial Observations areas of ELSI.

the solar system. However, many problems remain unsolved. In particular, due to the recent finding of many extra-solar planetary systems with quite diverse structures, a more general theory of the planet formation process is now necessary. We abandon many of the simplifications used in conventional models, and rebuild the planet formation theory, in order to understand the planet formation and the evolution processes from first principles. Furthermore, we verify our theoretical models by clarifying the chemical composition of the bulk earth, by determining the composition of the present core and lower mantle of the earth on the basis of super-high-pressure experiments.

A2. Why does water exist on Earth?

Presence of liquid water conventionally has been considered as one of the conditions for habitable planets, and the range of orbital radii in which liquid water can exist is called a habitable zone. However, the factors that determine the amount of water on a planet are not known yet, and coexistence of ocean and land may also be a condition for a planet for life to emerge. Therefore, we investigate the unsolved problem of why this amount of water exists on Earth, from the most recent planet formation theory developed in A1.

A3. What is the deep part of the earth like?

As the magma ocean was formed and solidified, the earth materially differentiated into the core, the mantle, the crust, the ocean, and the atmosphere. Such material differentiation in the early period of the Earth determined the subsequent mantle dynamics and thermal evolution of the Earth. Through volcanic activity, continental growth and magnetic field formation, it should have had a significant influence on changes of the surface environment and the evolution of life. We investigate such a material differentiation by high-pressure experiment and computer simulation.

B) Birth of Earth-Life system

Sustainable life cannot exist as an individual living form (homogeneous origin), but rather as a community (heterogeneous origin) interacting with its surrounding environment. Surely, the so-called "origins of life" should be discussed as entirely different phenomena from the emergence of the most ancient living ecosystem of our ultimate ancestors. We focus on the first Earth-Life system including the atmosphere, the ocean, the rocks, and the biological community that co-evolved finally into the present life. Our goal is to understand when, where and how the Earth-Life system was established. In ELSI, we will try to solve the following three questions.

B4. What was the state of the ocean and the atmosphere when life emerged?

What was the composition of the initial atmosphere, the ocean and the crust at the time of the birth of life? It is still largely an unsolved scientific question. We will build a verifiable model for the first ocean and atmosphere by 1) a forward approach based on the high-temperature experiments and theoretical simulations

It is widely accepted that the Earth was fully molten right after the "Moon-forming giant impact" event and covered with a "magma ocean". The Earth then cooled down rapidly, and consequently its silicate part solidified into a solid mantle and ocean was formed. The solidification of such magma ocean should have produced compositional stratification within the solid mantle. Tateno et al. (2014) has revealed the crystallization of the magma ocean at high pressure by laboratory experiments, suggesting that a deep part of the mantle was originally composed solely of Fe-poor $MgSiO_3$ perovskite, which is buoyant than overlying layer. Subsequently such gravitationally unstable stratification should have led a large-scale overturn in the solid mantle, which strongly controls the early evolution of the solid Earth including surface volcanism, subduction of cold plates (plate tectonics), formation of geomagnetic field, etc. Tateno et al. (2015) has made a new record on the generation of ultrahigh pressure and temperature to 407 GPa and 5960 K by static compression, which is much beyond the condition at the center of the Earth and thus enables experiments that cover the whole Earth.

One of the important goals of ELSI Deep Earth team is to clarify the chemical composition of the Earth's core, which has been strongly controversial since 1952. Since core composition directly depends on Earth's building blocks and planet formation process, it provides key constraints on the origin of the Earth questions. The best way to determine the core composition is to compare P-wave speeds of plausible core materials to seismological observations. Our experimental team (Umemoto et al., 2014) has succeeded in measuring P-wave velocity in a ultrahigh-pressure device called a diamon-anvil cell (to >70 GPa so far) for the first time, which is promising to obtain laboratory data at the Earth's core pressure range (>135 GPa) in the near future. At the same time, ab initio calculations on the P-wave velocity of liquid iron and alloys have been extensively made by ELSI members, which is complementary to the experiments (Ichikawa et al., 2014a JGR). In addition, PI George Helffrich developed model for metallic iron liquid alloy wave speeds for modelling composition of the Earth's core based on the hard-sphere model for dense liquids (Helffrich, 2015, in press). He developed earth accretion model to calculate the core's chemical response to a moon-forming impactor. In collaboration with R. Brasser at ELSI, we plan to extend this model to include actual accretion simulations incorporating impactor masses and timings to add timing and the effects of fluid dynamical processes of mixing in the magma ocean on the partitioning outcomes.

These studies on the Earth's core link with the Earth's magnetic field, which is generated by dynamo action in the core. Because a planet's magnetic field is able to deflect solar charged particles from eroding its atmosphere, a fundamental question for the origin of life is the timing of magnetic fields on earth-like planets. Unfortunately, on earth we do not have a good record of rocks of Hadean age that can give us constraints on the presence of the earliest dynamo. However, we do have tiny grains of the mineral zircon that date back to as far as 4.4 billion years ago, of A1 to A3, and 2) a reverse approach from the geological record. With the technical development of geochemical tracers, we will decode the chemistry of the early ocean and the atmosphere from rock records dating back to 4 billion years ago, and we will test the theoretical model thoroughly.

B5. Where did the Earth's life emerge?

We will elucidate where a sustainable "Earth-Life system" was established by asking the question: "what are the fundamental conditions required for Earth's life?" We explore the conditions, timing and interactive relations behind the generation of the most ancient living ecosystem and the early evolution through interdisciplinary investigations of specific environments in the modern Earth (e.g., hydrothermal systems) that are analogous to those on the early Earth or Mars. Interrelationship between the energy mass balance of the system, the elemental composition, material cycling and the functional and metabolic organization of microbial communities in the system are the keys to answer these questions.

B6. What were the genomes of the first community like?

Starting from simple pre-biotic compounds through complex and functioning large molecules, life was born as a community of living forms. What was the gene set of the first community like? This dates back to the interactive assemblage of genes in the most primitive living forms which later formed the genomes of the modern microbial communities. What are the factors that enabled sustainable and evolvable ecosystems to be built? In addition, where was the initial environment located that was able to utilize 20 kinds of amino acid and genetic codes? How did it become a life system? We approach those fundamental problems experimentally.

C) Evolution of the Earth-Life system

After the emergence of life on Earth, life has evolved in close interaction with surface environmental changes, ultimately linking with the thermal evolution of solid earth and possibly with changes in the galactic environment. We aim to understand these evolutionary aspects of the present-day environment in which organisms including human beings now exist, through decoding the geological record and through systematic evolutionary biology. We will especially focus on three revolutionary events, (1) the onset of photosynthetic oxygen production, (2) the emergence of Eukaryotes and (3) the emergence of multicellular animals (metazoans), and we will try to understand the roles of the thermal evolution of the Earth and galactic events as driving forces of these three steps in biological evolution.

C7. Why does the Earth's atmosphere contain oxygen?

We will elucidate how life on Earth evolved from chemosynthetic life, dependent on the Earth's internal energy supply, to the photosynthetic life dependent on solar irradiation. This "revolution of energy metabolism" was probably driven by environmental changes in the atmosphere and the ocean. The

which are present in a 3.2 billion year-old sandstone in Western Australia. These crystals contain microscopic inclusions of a variety of different minerals, including magnetite. Hence, developing ultra-sensitive magnetic imaging techniques has the potential for placing constraints on the origin of Earth's earliest dynamo. We are building one such imaging system here at ELSI, using Magneto-Tunnel junction technology, with a sub-micron step size.

Unfortunately, there is an extreme debate in the literature about whether or not the basement rocks in West Australia have been thermally metamorphosed to the point where a primary magnetization might not survive in these little zircon grains. Conflicting results have been obtained between groups at ELSI/Caltech/MIT on the one hand, and that of the University of Rochester in New York. We are organizing an international workshop of all participants involved in this problem to sort out the fundamental constraints, to be held in Japan during October or November 2015. ELSI provides a beautiful framework for addressing fundamental problems of this sort.

The experimental group of Ehime satellite has studied sound velocities of high-pressure minerals constituting the lower mantle, particularly focusing on those of MgSiO3 perovskite (bridgmanite) up to 27 GPa by a combination of multianvil apparatus, synchrotron in situ X-ray observations, and ultrasonic measurements. The results show that the chemical composition of the lower mantle is made of pyrolitic rather than chondritic/perovskititic compositions as reported by an earlier study based on Brillouin scattering measurements, suggesting that the bulk mantle was significantly depleted in silicon. Although this result should be further confirmed by additional experiments at higher pressures, theoretical mineral physics group of Ehime satellite also predicted that the lower mantle would have compositions rather depleted in silicon, based on first-principle calculations. Elastic properties of another important high-pressure phase in the lower mantle, $CaSiO_3$-perovskite, has also been studied theoretically and experimentally, both of which demonstrate this phase has shear wave velocities lower than those of the previous studies.

Melting relations and element partitioning in Tagish lake carbonaceous chondrite have been studied from 12 to 50 GPa using multianvil apparatus. Analyses of the partially molten samples demonstrate that Si-rich phases, stishovite and bridgmanite, are the liqudus phases at relatively high pressures, due presumably to the effects of volatile components. The Fe-Ni metallic aggregates are accompanied mainly by S and O with no detectable Si, suggesting the former two elements may be important light elements in the Earth's core. In addition to the carbonaceous chondrite, a corresponding study on an enstatite chondrite has also been started to simulate the origin and the chemical evolution of the early Earth.

As for the missing anorthosite and KREEP basalt materials, which could have existed in the early Earth (Maruyama et al., 2013), experimental and theoretical studies by a Tokyo-Ehime joint team have been made on the phase relations and density changes in these compositions. These studies demonstrated that both of key approach is a combination of (1) the systematic and evolutionary biochemistry of energy metabolisms and (2) geology/geochemistry decoding of newly emerging rock records for testing the scenario. The fusion of these studies will answer the following questions: When, where, and why did the oxygen-producing photosynthesis emerge? When and how was the atmosphere oxidized? Was the birth of eukaryotes really caused by the ascent of oxygen?

C8. How did the thermal evolution of the solid Earth change the ecosystem?

We will explore how the long-term cooling of the solid Earth influenced the co-evolution of life, atmosphere and ocean. We will elucidate the changes in the chemically-stratified structure of the Earth's interior over time based on convection simulations with parameters defined by our high pressure experiments (A3), and we will evaluate the intensity of the volcanic activities and growth rate of continents. Using the physical properties of the core determined by A3, we will perform numerical simulations of the convection in the core and its change through time. We will estimate the timing of the birth of the inner core, which probably changed the geomagnetic intensity. In addition, using the geological samples, we will analyze paleogeomagnetic intensity through time, large-scale volcanic activity, continental growth, and we will thoroughly verify the simulation results. Taking the surface environmental changes brought by the solid earth evolution into account, we will re-evaluate the causes of the two evolutionary events: the emergence of eukaryotes and the emergence of metazoans.

C9. How did galactic events influence the Earth's surface environment?

We will estimate the changes in our galactic environment during the 4.6 billion years history of our solar system based on theories and observations. Recently, the understanding of the disk and spiral stricture of our galaxy has substantially changed. The travel history of our solar system within the galaxy and its relation to the Earth's history is still largely unknown. We will elucidate this issue based on new theoretical simulations and astronomical observations of our galaxy, and we will evaluate the influences on the Earth's surface environment. Furthermore, by using deep-sea sediments of specific ages and developing cosmochemical techniques, we will try to locate evidence of these galactic events, to further clarify the influence on the climate and the Earth's biological evolution.

D) Bioplanet in the universe

D10. How unique is our planet?

Through the study of Earth, obtained from A1 to C9, we will clarify both universal and unique aspects of the Earth. We will generalize them and construct a "Bio-Planetology" that has the potential to predict the presence or absence of life on other planets.

D11. How should we search for extraterrestrial life?

We will work closely with those in the fields of space missions and astronomical observations, in order to apply the research results of the above

these compositions would have densities significantly higher than the surrounding pyrolitic lower mantle materials, suggesting that these components may have been accumulated at the bottom region of the lower mantle. In addition, a new hydrous phase, phase H, was discovered as a collaboration of experimental and theoretical mineral physics groups in Ehime satellite, whose detailed stability field, crystal structure, and effects of Al and Fe have been clarified experimentally. It has been strongly suggested that this new phase should play an important role in the circulation of water in the deep lower mantle and have significant influences on the structures and dynamics of this region of the lower mantle.

A new research collaboration using nano-polycrystalline diamond (NPD) invented by the Ehime satellite group has started with the scientists of ELSI to access the local structures of melts at very high pressure. NPD has unique features of ultra-hardness and polycrystalline nature, the latter having been shown great advantage in obtaining high-quality data in synchrotron X-ray absorption measurements over single crystal diamond. This joint study would lead to development of new techniques to address the nature and the role of the deep magmas in the Earth's evolution and dynamics.

The geodynamical modeling team at ELSI uses fluid dynamics theory and computational approaches to study the integrated physical and chemical processes involved in Earth's formation and their influence upon its subsequent evolution. The information provided by the mineral physics teams is essential for constraining input parameters of geodynamical models, and forms the basis for a very close collaboration between these teams. This modeling team is proposing and testing new hypotheses by comparing model predictions with available observations, and additionally employs large-scale seismic imaging of Earth's interior to seek relics of early Earth processes buried deep inside our planet at the present day. An extensive review written by PI Hernlund was recently accepted for publication in the Treatise on Geophysics and outlines the cutting edge issues and grand challenges for deep Earth research and connections to issues of formation and evolution. Dr. Maxim Ballmer has been publishing studies on modes of upwelling and volcanism in the Earth's mantle (Ballmer et al., 2015a), the inhibition of lithosphere descending into the deep mantle (Motoki and Ballmer, 2015), and chemical heterogeneities inside upwelling plumes from the deep mantle (Ballmer et al., 2015b; Cheng et al., 2015). PI Hernlund, and Drs. Christine Houser and Maxim Ballmer are developing a model in which lower mantle structure and chemistry can be explained by silica enriched local domains that are remnants of solidification after the moon-forming giant impact, which can help solve numerous problems in deep Earth studies and establish new connections between the present and ancient Earth. Dr. Hiroki Ichikawa at Ehime satellite reported the results of work on the influence of mantle mineralogy upon Earth's internal dynamics (Ichikawa et al., 2014b), joined a study on the effects of variable transport properties deep inside a planet (Miyauchi et al., 2014), and is currently working on publishing a study with PI Hernlund on temperatures in points A to C for the detection of life on planets, moons and similar objects. Within the next 10 years, spectroscopic observations will start to yield information about the atmospheres of extra-solar Earth-like planets in the habitable zones, which may contain oceans. Before that, we will establish criteria for life-harboring planets using the results of our explorations on the early Earth and its subsequent evolution.

[Social Impact]

The ultimate goal of this study is to go back to the origin of science, and ask ourselves "why are we here?" There is no question that the results of our research activities will revolutionize our views of Earth and life, as state-of-the-art scientific achievements and the most advanced attainments of intellectual and cultural activity of human beings. Our research will stimulate young people who will carry the future of the scientific nation of Japan by reminding them of the intellectual desire and curiosity that is the original instinct of human beings, through which they distinguished themselves from other creatures.

Each type of research is conducted with clear scientific objectives while developing new advanced techniques. As a result, there are countless effects on the society in the short term. For example, development of techniques for ultra-high-pressure and ultra-high-temperature experiments; development of high speed large-scale computer systems; design and development of organic molecules on the basis of chemical evolution experiments; finding previously unrecognized factors controlling global environmental change; innovation of advanced techniques of environmental measurements, analysis and decoding; discovery and a wide spectrum of application of novel and unique extremophilic microorganisms; large-scale acquisition of microbial genetic information and resources; developing, analyzing and mining enormous quantities of genomic data; making progress in space exploration technology driven by the intellectual desire of human beings, and so on. However, these short-term impacts are only by-products of this program.

・ Describe concretely the research plan to achieve these objectives and any related past achievements related to the proposal.

[Research plan]

We will try to answer the above 11 questions from A1 to D11 through interdisciplinary investigations. Each research plan is described in detail below.

A1. How was the earth formed?

We aim at a theoretical understanding of the planet formation process by means of a three-dimensional global simulation of protoplanetary disks consisting of gas magma oceans during core formation. Dr. Matthieu Laneuville has published a study on the early evolution of the Moon and its magnetic field (Laneuville et al., 2014) and is finishing a study with Hernlund on the ability for stratification in the core-mantle boundary region resulting from a moon-forming giant impact event to explain the longevity of Earth’s geomagnetic field and major deep Earth structures as relics.

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and dust. For such study we need to perform long-term three-dimensional simulations of differentially rotating gas disks with sufficient accuracy, which has been considered impossible. The artificial transport of energy and angular momentum due to the finite resolution causes changes in the spatial structure of gas disks on a dynamical timescale. It is not clear if we can achieve the necessary accuracy to prevent such numerical artifacts. Even if we could, the long timescale requires very long integration times, and therefore very large amounts of computer resources.

Recent advances in computer technology have solved at least partially the problem of computing resources. Thus, the problem of accuracy has become more important. We are currently working on the improvement of the SPH (smoothed particle hydrodynamics) method, in order to reduce the artificial transport and to improve resolution.

In ELSI, we will take the following approach. We try to understand the diversity of the planet formation process by global simulations with appropriate modeling of required physical processes, instead of the traditional approach in which we construct a global view by combining our understanding of processes obtained by local simulations.

We have been leading the research of the planet formation process for the last two decades, since Ida and Makino (1992). Moreover, we have developed special-purpose computers for N-body simulations and new parallel algorithms, and we have been leading the world in the simulation of galactic disks, similar to protoplanetary disks since they are also rotating systems of particles and fluids.

In addition to these advantages in computational science, we form one of the leading centers in the world, for theoretical research on planet formation. Therefore, it is expected that there will be new developments by combining theoretical studies and large-scale simulations. The PI, Ida and his colleagues have done numerous studies on elementary processes. As for the global simulation of the gas disk, we have been working on large-scale simulations of the galactic disk beginning with Saitoh et al. (2008).

Numerous extra-solar planets very close to central stars have been found, and this strongly suggests that the formed planets migrated inward through the interaction with the disk gas. However, our solar system cannot be reproduced if we incorporate such migrations with the existing formulas. In order to resolve this contradiction, we must simultaneously solve the evolution of the disk structure and planet formation. These global simulations will become extremely important for the understanding of events such as the late heavy bombardment and water transportation into the early Earth by the impact of asteroids or comets.

On the other hand, it is important to identify the chemical composition of the lower mantle, which accounts for 60% of the volume of the earth and the light element content in the metallic core, in order to elucidating the original composition of the Earth. Our ultra-high-pressure experiments with geochemical/geophysical

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Planet Formation Theory

Nearly 2000 confirmed exoplanets (planets orbiting stars other than the Sun) and more than 3600 transiting planetary candidates have been discovered as of 2015. These detections show that Earth-mass planets are quite common around solar-type stars in our galaxy, while the diversity of planetary systems is much larger than was expected from studies our own Solar System.

The prediction for a frequency of rocky/icy planets in habitable zone (HZ), in which liquid water can exist on planetary surface, in exoplanetary systems and their characterization are the important objectives of planet formation group.

Shiegru Ida (PI) derived the capture probability of icy grains migrating due to aerodynamic gas drag by a protoplanets (Guillot, Ida & Ormel 2014). Around low-mass stars (M dwarfs), water delivery by planet orbital migration due to disk-planet intereraction is also important due to the close proximity of ice-condensation line to the host stars. On the other hand, strong UV photoevaporation by young M dwarfs removes ocean mass comparable to the Earth ocean from Earth-mass planets in HZ, which means that the planets in HZs around M dwarfs are either “deep ocean” planets or “dune” planets (Tian & Ida 2015).

Carbon and Nitrogen are essential elements for life. However, they are condenced and incorporated into planetary bodies only in very cold regions (<100K). How to deliver C and N to planets in HZ is a very important problem. Ramon Brasser (reseach scientists) and Shigeru Ida started N-body simulation of scattering of planetesimals by giant planets and study accompanied delivery of to e C and N to inner regions (Matsumura et al. 2015).

Note that the importance of orbital migration of planets requires global N-body simulation. The global simulation has been computationally too expensive to be actually performed so far. Jun Makino (PI) has developed massively-parallel N-body simulation code for simulation of planetary formation, which runs with high efficiency on the K computer and started global simulation.

Satellietes are by-product of planet formation. They show clues of planet formation. They also affect habitability of their host planets through tidal interactions. Takayuki Saitoh (research scientist), Hidenori Genda (research scientist), Jun Makino and Shgeru Ida revisited formation of the Earth’s Moon by a giant impacts with their renovated Smoothed Particle Hydrodyamics code and found that the Moon-forming impact is significantly different from that has been identified information can constrain the original concentration of volatile elements such as O, S and Si in the metallic core, resulting in great progress in the elucidation of the Earth's building blocks. This makes it possible to establish important boundary conditions for the simulation of the formation process of the early solar system, and elucidate how the Earth was formed, and its uniqueness and universality in the planet formation process.

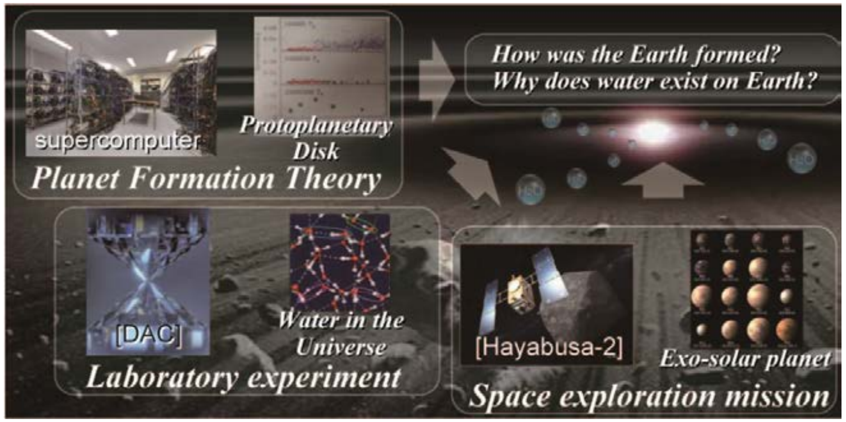

Figure 2. The formation of the Earth in solar system will be examined by a combination of computer simulations of planet formation, with the aid of laboratory experiments and information about extraterrestrial bodies (related to questions **A1** & **A2**).

A2. Why does water exist on Earth?

In the conventional planet formation theory, it is extremely difficult to explain how the Earth came to have an ocean of 1/10000 of the planet mass, a very fine-tuned amount. In a protoplanetary disk, H_2O ice dust can be condensed from the disk gas only in a low temperature range (below 160-170K) beyond 3AU. Actually, while asteroids originating from the region near 3AU include about 10wt% of H_2O water, the ones from well inside 3AU do not contain H_2O ice at all. If this is true, it means that dust material around 1AU from which the Earth is formed did not contain H_2O.

Conventionally, research has mostly focused on the theory that water was brought to the Earth by accidental collisions with asteroids or comets formed beyond 3AU. For instance, there is a simulation, which studied possible scattering of icy planetesimals by the formation of Jupiter. However, as scattering phenomena are chaotic, each simulation generated a different outcome, resulting in tens of wt% as Earth's water content in one simulation, and zero water content in another. If this approach is correct, the Earth's water content is unpredictable and the H_2O water content of the Earth and creation of life were determined by pure coincidence. (Hosono et al. 2015). Hidenori Genda and Shigeru Ida found that Phobos and Deimos of Mars can be formed by a giant impact (Citron et al. 2015). These simulations are revising the view of satellite formation in our Solar system.

Hadean Earth experienced many asteroid and/or comet bombardments, and some amount of seawater should be splashed into the space. Some fraction of salt dissolved in Hadean seawater should spread over the Moon's surface. Hidenori Genda and other ELSI researchers in geology and geochemistray investigated the feasibility of this hypothesis, and discussed how to test this hypothesis.

Remote sensing of exoplanets is a big target of future large telescopes such as TMT(Thirty Meter Telescope). Yuka Fujii (research scientist) and Jun Kimura (research scientist) investigated photometric properties of planets with various surface environments using existing data of Solar system bodies, with geologists (Fujii et al. 2014). Jun Kimura also showed with an ELSI chemist, Norio Kitadai, that polymerization of organic monomers could proceed spontaneously in the environment of icy moons based on thermodynamic calculations (Kimura & Kitadai 2015). Shigeru Ida has started simulation of complex organic molecules in interstellar moldecules, which could be life-forming materials on the Earth. The results should be compared wiith data by new large scale radio telescope, ALMA.

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Geology/Geochemistry

PI Maruyama and colleagues developed "The naked early Earth scenario" and proposed that delivery of water into dry early Earth triggered chemical reactions

However, this "asteroid/comet collision model" is yet to set out a scenario consistent with the hydrogen and oxygen isotope ratios of the Earth. Based upon an improved planet formation theory constructed in A1, we will discuss this "coincidental collision theory."

We will also consider other possibilities than the collision model. We have already outlined a new model for reactions between a primitive hydrogen atmosphere and a magma ocean (Genda and Ikoma, 2008). In this model, H_2O is produced by a terrestrial planet itself, thus the existence of oceans on Earth is inevitable and the amount of H_2O is determined by the planetary parameters.

The habitable zone is a range in orbital radius in which a planet can have liquid water under an atmosphere. However, unless H_2O was brought to a planet by some mechanism, or the planet produced H_2O by itself, an ocean cannot have existed and neither could life have emerged. In order to investigate why and how life was created on Earth, as well as to estimate the possibility of the existence of life on planets in habitable zones in planetary systems outside the Solar system, it is very important to elucidate why water exists on the Earth in the current amount.

We also address this issue by contributing to the scientific mission plan of JAXA's Hayabusa-2. The Hayabuya-2 mission plans sample return from a primitive C-type asteroid, which may be formed near the ice boundary, and it will clarify H_2O's behavior in planet formation.

Thus, the conditions for the existence of liquid H_2O are not easy to satisfy. It is well known that, because of its unique character, H_2O's density decreases in the phase transition from liquid to solid phase. Moreover, various icy phases exist under extremely high pressure. By integrating H_2O study in material science and study of celestial bodies in the Solar system that contain H_2O (not only oceans on the Earth, but also in asteroids, comets, icy satellites, Uranus and Neptune), we expect that there will be a new field "H_2O in the universe" and its relationship with life.

Because ELSI will include leading scientists in planet formation theory (S. Ida) and extremely high pressure experiments (K. Hirose), and leaders in science and engineering parts of HAYABUSA 2 (M. Fujimoto and H. Kuninaka), we can form a strong group to investigate this new and important problem.

A3. What is the deep part of the earth like?

Lower mantle**:** First, we need to clarify the chemical composition of the lower mantle, which composes 60% of Earth in mass. We will carry out experiments on realistic model compounds by employing the multi-anvil apparatus, in order to precisely determine the phase transition, element partitioning, density, and elastic wave velocity under high-pressure and -temperature conditions of the lower mantle. By comparing the results with seismological data, we will then clarify the lower mantle chemical composition. This provides important constraints to the chemical differentiation that occurred inside the Earth, the origin of layered structure, as well as its dynamics and evolution.

resulting in the birth of life (Maruyama, Genda, Hirose et al., 2013; Dohm and Maruyama, in press). This research direction result in an acquisition of newly funded SHINGAKUJUTSU grant "Hadean Bioscience." In this project, prebiotic chemistries under Hadean atmosphere, hydrosphere, and lithosphere are systematically studied in the viewpoint of the earliest geological evolution of Earth.

PI Kirschvink and colleagues developed a new paleogeomagnetic technique for distinguishing primary and secondary minerals from early Earth's rock samples (Fischer, Kirschvink et al., 2014 PNAS). The results were combined with a fingerprinting technique for atmospheric chemistry based on sulfur isotopes and demonstrated atmospheric fluctuation occurred in Late Archean period. Furthermore, PI Kirschvink successfully installed a Magneto Tunnel Junction (MTJ) scanning microscope this year in ELSI for obtaining high spatial resolution magnetic image from geological and biological samples (Kirschvink, 2014 Nature). The new technique allow us to unravel a number of problems, for example early evolution of Earth's geomagnetic field based on the analysis of the oldest rocks and minerals. Also, this year, PI Kirschvink published a book for summarizing a new research direction of early Earth research (Ward & Kirschvink, 2014).

PI Takai and colleagues discovered that hyperthermophilic methanogen can fix nitrogen under the condition of deep sea hot spring (Nishizawa, Takai et al., 2014 GCA). The results of this study demonstrated that the methanogens can convert N_2 into biologically-useful nitrogen compounds at a rate 10 times faster than a marine phototrophs, a typical nitrogen fixation organism in the modern ocean. Furthermore, the nitrogen isotopic fractionation observed in the studied methanogens are similar to those reported from 3.5-billion-years-old hydrothermal deposit, suggesting that microbial nitrogen fixation operated at the early Earth's deep-sea vent. In addition, PIs Takai, Yoshida, A-PI Ueno and colleagues studied methane generated by similar thermophilic methanogens and showed that hydrogen isotopic composition of the microbially-produced methane not only reflect isotopic composition of substrate water, but also that of molecular hydrogen (Kawagucci, Takai, Ueno, Yoshida, et al., 2014). These investigations are important to explore the first microbial community appeared on Earth and its early metabolic evolution.

PI Yoshida and ELSI research scientist Gilbert developed a fingerprinting technique by using intramolecular isotopic composition (Yamada, Gilbert, Yoshida et al., 2014). Gilbert, Yoshida and A-PI Ueno have implemented an apparatus to measure position-specific ^{13}C isotope composition within hydrocarbon molecules, that is expected to lead to new information about their origin and mechanism of formation. Preliminary results indicate that the position-specific ^{13}C isotope composition of propane seems to vary between different sources. This technique is now applied into the gas collected from Hakuba Happo hot spring that has been studied by ELSI's ONSEN project for understanding the geochemical processes producing hydrocarbons abiologically. A-PI Ueno and colleagues now identified abiological methane from the Happo site (Suda, Ueno, Yoshida, Maruyama,

Core composition: The chemical composition of the core is one of the most important problems in the solid Earth science. It will be obtained on the basis of diamond-anvil cell experiments by measuring the sound velocity and density of liquid Fe-alloys using synchrotron X-rays, differentiation of light elements at the inner core boundary, and the dissolution of light elements from the molten mantle into the core at the giant impact events on the early Earth.

The determination of chemical compositions of the lower mantle and core will elucidate the bulk Earth composition. Then, comparing the result with cosmic abundances of refractory elements, we can examine consistency with the theoretically-derived Earth-formation scenarios obtained in A1 above.

Magma ocean and proto-crust: We also examine the primordial layered structure inside the Earth, from the core to the proto-crust. We will reproduce experimentally the solidification of the magma ocean, which most likely extended to the whole mantle at the time of the Moon-forming giant impact event. While it has been believed that its solidification occurred from the bottom, recent experimental studies suggest that it started at the middle of the mantle, eventually spreading upward and downward, which changes the whole view of the solidification process.

The chemical composition of the Earth's proto-crust forming from the final residual melt after extensive crystallization of the magma ocean may have been significantly enriched in incompatible elements including phosphorus, the essential element for life. Indeed, the unusual type of rock called KREEP (K, REE, P-enriched) is found on the Moon's crust, but it can be different from the Earth's.

Core evolution and geomagnetic field: Finally, we study the thermal and dynamical evolution of the Earth's core based on its physical properties, from which we can estimate changes in geomagnetic field intensity through Earth's history. With the chemical composition of the core obtained above, we can determine temperature, thermal conductivity, effects of chemical buoyancy for convection, and possibly viscosity of the core, all of which are important for modeling.

At the same time, by using vast amounts of Precambrian rock samples collected by our geology team, changes in paleomagnetic intensity will be examined. We will apply new techniques developed mainly by the PI, Kirschvink to improve the database of paleogeomagnetic intensity for Precambrian times, and thereby test the predicted changes. Numerous intrusive complexes from large igneous provinces are being discovered and dated accurately with U/Pb techniques, and simple shallow drilling operations could provide pristine samples amenable to the modified Thellier/Thellier techniques needed for robust paleointensity determinations. Magnetic microscopy using Superconducting Quantum Interference Device (SQuID) technology may even allow these techniques to be used on detrital grains of Hadean age. These studies are link with the theme C8.

ELSI is fully equipped and ready to investigate the solidification of the magma

Kurokawa et al., 2014a, b). This year, A-PI Ueno and colleagues successfully detected smaller amount of hydrocarbons (ethane, propane and butane) from the Happo site. The preliminary results showed that ^{13}C-distribution pattern of these hydrocarbons and their relative abundance are very similar to typical serpentinization site (i.e. candidate environment for emergence of life on the early Earth) like deep sea Lost City field. Thus, we can now investigate the abiological processes for producing organic compounds on the early seafloor based on the on-land hot spring in Japan.

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ocean and chemically-stratified structure of the mantle, as well as to determine the primordial crust composition. Studies on core and lower mantle described above are primarily based on property measurements of iron alloys and silicate minerals, employing high pressure and temperature (*P*-*T*) experiments. At this point, the Hirose team is the only group in the world which can simultaneously create extreme high *P*-*T* conditions that exceed that of the center of the Earth (364 GPa, ~6000 K) by static experiments using the diamond-anvil cell (Tateno, Hirose et al., 2010, Science). Combining such leading-edge technology and synchrotron radiation X-rays, the group has achieved several outstanding results. These include the discovery of post-perovskite, a major mineral in the lowest mantle (Murakami, Hirose et al., 2004, Science), determination of the crystal structure of iron in the inner core, the discovery of a phase transition of FeO under outer-core pressure (Ozawa, Hirose et al., 2011, Science), and the discovery of the cubic structural phase of SiO_2 (Kuwayama, Hirose et al., 2005, Science). Furthermore, we have developed a new methodology for measuring properties such as the electrical and thermal conductivity (Ohta et al., 2008, Science), seismic velocity (Murakami et al., 2012, Nature), and element partitioning (Nomura et al., 2011, Nature) under high pressure, which resulted in making major breakthroughs. Also, pioneering research has been conducted on mantle materials by Irifune's team based on precise measurements in a multi-anvil apparatus (Irifune, 1994, Nature; Irifune et al., 1998; 2010, Science; Irifune et al., 2008, Nature; Irifune and Isshiki, 1998, Nature). More recently, they succeeded in making the first measurements of elastic wave velocity under lower mantle *P*-*T* conditions. Meanwhile, as reported in Irifune et al. (2003, Nature), the team started applying the world's hardest nano-polycrystalline diamond for the multi-anvil apparatus. This technology is expected to enable precise experiments under the entire range of mantle conditions.

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Extraterrestrial Observation

[Hayabusa 2]

Hayabusa 2 is an asteroid sample return mission targeting a primordial C-type asteroid, 1999JU3, in which PI Kuninaka worked as the project manager. Launch site operations started at the Kagoshima Space Center in Tanegashima in September. Deployable equipments (a capsule, an impactor, an isolated camera, four rovers, and a sampler horn) were mounted properly, the tanks were filled by fuel, which made a probe with a mass of 600 kg prepared for its launch. Although the launch was postponed twice because of bad weather, Hayabusa 2 was successfully launched by H-2A rocket No. 26 on December 3 at 13:22:04 (Japan time) and kicked into deep space by re-ignition of the rocket. As initial operations, the confirmation of initial conditions and adjustment were conducted for several months, and sequential acceleration using ion engines over a period of three weeks succeeded in enabling it to start cruising towards the asteroid in March. It is expected that Hayabusa 2 will rendezvous with asteroid 1999JU3 in 2018, take off after sample collection, and then return to Earth at the end of 2020, after staying close to the asteroid for approximately a year and a half.

Dr. Kimura is a part of the team responsible for the laser altimeter onboard Hayabusa 2 (LIDAR (light detection and ranging)). The LIDAR measures the distance between the probe and objects using a laser beam and contributes to identification of the overall shape and surface undulations of the asteroid as well as searching for the optimal landing sites and improving the accuracy with which the probe position is determined. In particular, Kimura developed a model for deriving overall 3-D shapes from a limited number of distance measuring points and a model for inferring the regolith distribution on a surface based on the asteroid's shape and gravitational potential. Because asteroid 1999JU3 is extremely small, approximately 500 m in radius, and neither the shape nor the surface conditions are known as of now, it is essential for successfulu probe landing and sample collection that prompt comprehensive analysis of the features obtained through LIDAR upon the approach to the target asteroid. A paper describing scientific objectives of LIDAR was published in a scientific article before launch. The instrument status has been favorable after the launch. In addition, Hayabusa 2 is an international joint mission in which Germany and France are participating. PI Fujimoto served as the chair of

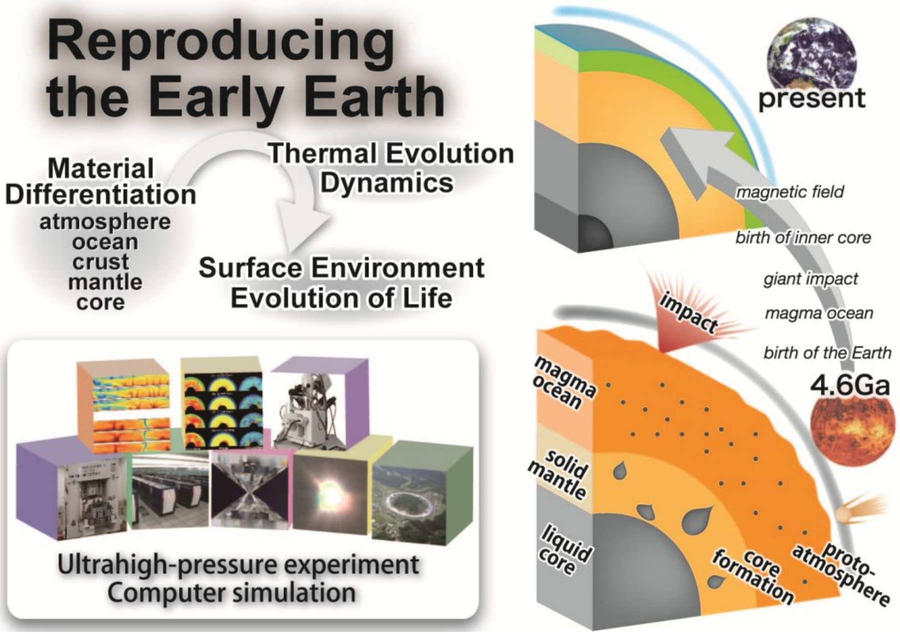

Figure 3. Chemical differentiation within the Earth from core to atmosphere will be reproduced by high-pressure/high-temperature experiments. Subsequent chemical and thermal evolutions inside the Earth will be also examined (related to question **A3**).

B4. What was the state of the ocean and the atmosphere when life emerged?

By extending the high-temperature experiments and theoretical computations of A1-3, we will make forward estimations of the composition of the atmosphere and oceans. To verify our theoretical predictions on the basis of geological evidence, we will analyze the early geological record dating back to 4 billion years ago.

Theoretical and Experimental Approach: Our objective is to specify the physico-chemical environment of the primordial Earth on which life emerged. According to the conventional theoretical model, the Earth's primordial atmosphere formed from volatiles (secondary atmosphere) produced by the degassing of planetesimals, the building blocks of the Earth. It is generally believed that the degassed volatiles consisted primarily of H_2O vapor, CO_2 and N_2. As the Earth's surface cooled, H_2O turned to liquid (i.e. ocean), while a CO_2-rich primordial atmosphere remained. Under such a CO_2-rich (i.e. oxidizing) atmosphere, however, it is extremely difficult to follow pre-biotic synthesis of organic matters that are necessary for the emergence of life. On the other hand, recent research results rather suggest a more reducing primary atmosphere, possibly rich in H_2 and CO due to

the international meeting for Hayabusa 2 to promote publication of important results by Hayabusa 2 for the planetary science of the world.

[Research on the outer planets of the solar system]

JUICE, a mission to Jupiter and its icy moons led by ESA (European Space Agency), is a project that will become very important in planetary sciences. Fujimoto has been coordinating Japanese participation to the mission. Kimura is a part of the team responsible for the laser altimeter to be carried on JUICE (GALA (Ganymede Laser Altimeter)). The GALA measures the distance between the probe and objects using a laser beam, and contributes to an understanding of the surface undulations of Jupiter's icy moons, and elucidating the overall aspects of ice tectonics as well as confirming the existence of subsurface oceans suggested to be present by monitoring the deformation of the moon due to tidal forces. In the GALA team effort shared beweeen Japan and Europe, Kimura was in charge of drafting scientific objectives as the leader for science reviewing in the Japan team.

Kimura examined the possibility of amino acid polymerization and nucleoside formation under the low-temperature environment on a surface of an icy moon by thermodynamic calculation, in collaboration with researchers specializing in organic geochemistry, which can lead to an understanding of evolution from organic monomers to polymers in extraterrestrial astronomical environments. It has been recently demonstrated by observations and experimental studies that among major life precursors, simple amino acids are generated non-biologically and universally exist in space in comets and cosmic dust. The possibility that on icy moons these substances are continuously supplied from its outer-space over a long period of time as well as being synthesized after mutual collision on the moon surface or by reactions in sub-surface ocean has been suggested. Kimura found that glycine polymerization and nucleoside formation spontaneously proceed in low-temperature regions up to several kilometers below the surface when expected temperature and pressure environments in the interior of the icy moons were taken into account. This study discussed the possibility based only on thermodynamic calculation and requires a future study of reaction kinetics in order to discuss the possibility of the reactions in reality. Furthermore, salts, including magnesium sulfate existing on the surface of icy moons, may promote reactions as catalysts. Experimental verification will be conducted in low-temperature environments.

In collaboration with researchers specializing in infrared astronomy and planetary atmosphere, Kimura discovered a new phenomenon—Jupiter's moons shine imperceptibly in Jupiter's shadow. Although detailed causes have been under investigation, the most probable cause is that sunlight scattered by the "mist" existing in Jupiter's upper atmosphere indirectly provides light on the moons (similar to the phenomenon of Earth's moon glowing red during a total lunar eclipse). "Mist" is a key entity in the dynamics of Jupiter's atmosphere and cloud generation, but neither its 3-D distribution nor composition is known, owing to delayed dispersion and capture of nebula hydrogen (Genda and Ikoma, 2008, in our team) and resetting the conditions in the atmosphere by reactions with meteorites that fell during the Late Heavy Bombardment (LHB), some 4 billion years ago (Hashimoto et al., 2007; Schefer and Fegley, 2010). Additionally, our research at G-COE has suggested the possibility that the moon-forming impact ejected fragments that returned to Earth during 100 million years after the impact. These re-entering fragments may be large enough (10 to 100 times larger than impact from the LHB event) to have converted a substantial amount of primordial ocean into H_2 (Sasaki et al., 2012, in our team). Because these early atmospheric conditions also define the origins of H_2O on Earth, they are extremely important for understanding the origins of seawater and its total volume as discussed in A2. For re-evaluating these new scenarios, we will first perform numerical simulations by extending the planet formation theories developed in A1 and A2. In particular, the H_2O content of planetesimals and their accumulation process after solidification of the magma ocean are important aspects on which we will focus in our simulations. Furthermore, the mass of the early atmosphere and oceans is controlled by the cooling process of the magma ocean that we can constrain by using the high-pressure experiments of A3.

In addition, the composition of the atmosphere was modified by gases released from the mantle through volcanic activity. This process has been studied on the basis of research using today's subaerial volcanoes. The early Earth, however, was covered with oceans and had almost no land. Hence, input to the atmosphere and ocean system would come not from high-temperature volcanic gases, but from submarine hydrothermal gases resulting from reactions between rock and seawater. Hence, we will perform hydrothermal experiments on rock types from the Earth's earliest oceanic crust determined by A3 to systematically understand the volatile and elemental flux into the early atmosphere and oceans. The experimental setup has already been developed and utilized to study this issue by the group of the PIs, Takai and Maruyama (e.g., Yoshizaki et al., 2010).

Geological and Geochemical approach: Our theoretical predictions must be thoroughly verified on the basis of geological evidence. Unfortunately, the means for such verification for the Earth's environment during the Hadean (before 4.0 billion years ago) are extremely limited because there is no geological record except for tiny mineral grains in clastic rocks. In the past ten years, however, dramatic advances in research on the early ocean and atmosphere during the Archean (4.0 to 2.5 billion years ago) have been made by rapidly developing chemical and isotopic indicators recorded in sedimentary rocks that now provide useful boundary conditions to verify the Hadean environment. In particular, 1) over 10 years of geologic mapping of the PI, Maruyama's group has identified many fragments of the past oceanic crust in Archean cratons and their comprehensive metamorphic petrology, making it now possible to quantify the CO_2 concentrations in the

observation difficulties. This study proposes a new technique by which information about Jupiter's "mist" can be obtained through observation of the "eclipse" of Jupiter's moon. Simultaneously, this study leads to research on the atmosphere of extrasolar planets as the technique is similar to the transit method for extrasolar planets in terms of astronomical observation with "transmitted light."

PI Fujimoto analyzed the results of spectroscopic observation of the gas released from Jupiter's moon, Io, in the ultraviolet region, which were obtained by "Hisaki," a small scientific satellite operated by JAXA. His findings led to an understanding that the space proximal to Jupiter functions as the strongest particle accelerator in the solar system. In addition, by analyzing combined data obtained by "Hisaki" and the Hubble Space Telescope, he found that activity in the space surrounding Jupiter not only depends on the external factor of solar wind, but that it is also a result of a combination of the planet's high-speed rotation and mass addition due to gas released from Io within the magnetosphere region. These study results accumulate with other findings towards our better elucidating the space environments surrounding icy moons.

[Study on extrasolar planets]

Research Assistant Professor Fujii wrote a survey paper on the photometric characteristics of planets in the solar system aiming at characterization of extrasolar telluric planets, which had been initiated in the previous year in collaboration with Kimura. Fujii also wrote a paper pointing out the effects of moons in the identification of biomarkers of extrasolar planets in collaboration with researchers in the US. This paper points out that when a terrestrial planet is accompanied by a moon that has an atmosphere, such as Titan, their spectra cannot be separated as being derived from two origins with any observation device used in the near future, as this would cause indices—for example, an index to determine "The atmosphere is largely non-equilibrium because of coexistence of oxygen and methane."—to become unusable. Observation conditions required for separating them and the possibility of excluding false positives are also discussed in the paper. This study highlighted a problem with identifying the atmospheric composition of extrasolar planets, which had not been taken into account. Based on the fact that identification of atmospheric composition in super-Earth planets would be focused by using a next-generation, super ground-based telescope, such as NASA's James Webb Space Telescope (JWST). Fujii has initiated a study to investigate the climate on terrestrial extrasolar planets and its observatory signs in collaboration with global climate experts.

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Archean ocean (e.g., Nakamura et al., 2004; Shibuya et al., 2007; 2012, in our team). Moreover, 2) after the discovery of a sulfur isotope anomaly in Archean sedimentary rocks that proved extremely low oxygen levels of the Archean atmosphere (Farquhar et al., 2000), recent advances in research on the isotope fractionation of photochemistry makes it possible to quantify not only oxygen levels but also the concentration of green-house gases and volcanic flux into the atmosphere (Lyons, 2007; Danielache et al., 2008; Ueno et al., 2009, in our team).

In this context, we will reproduce the composition of the Archean oceans by using systematic chemical and isotopic analysis with thermodynamic computations on the rock samples. Tokyo Tech's earth history archives already house numerous Archean oceanic crust samples. While we have already obtained fixed-point data based primarily on detailed field mapping in designated regions and metamorphic petrology, we will now significantly broaden our scope in order to describe temporal changes across the entire Archean. For decoding the Archean atmosphere, while much data has been collected on isotopic anomalies regarding their role as atmospheric proxies, the inherent potential of this research has not been fully realized because the basic mechanisms for producing the isotope anomaly are still inadequately understood. Hence we will conduct spectroscopic studies and reaction experiments with numerical simulations of photochemical reactions to understand the dependencies of UV wavelength, atmospheric composition, temperature and pressure on the isotopic effects in order to constrain the Archean atmosphere quantitatively. The PI, Yoshida and his group has determined photochemical isotope effects by a number of key reaction steps (e.g., Danielache et al., 2008; Ueno et al., 2009; Hattori et al., 2011; Enghoff et al., 2012) and will extend this research to produce testable models of the Archean atmosphere by using geologically preserved isotope anomalies.

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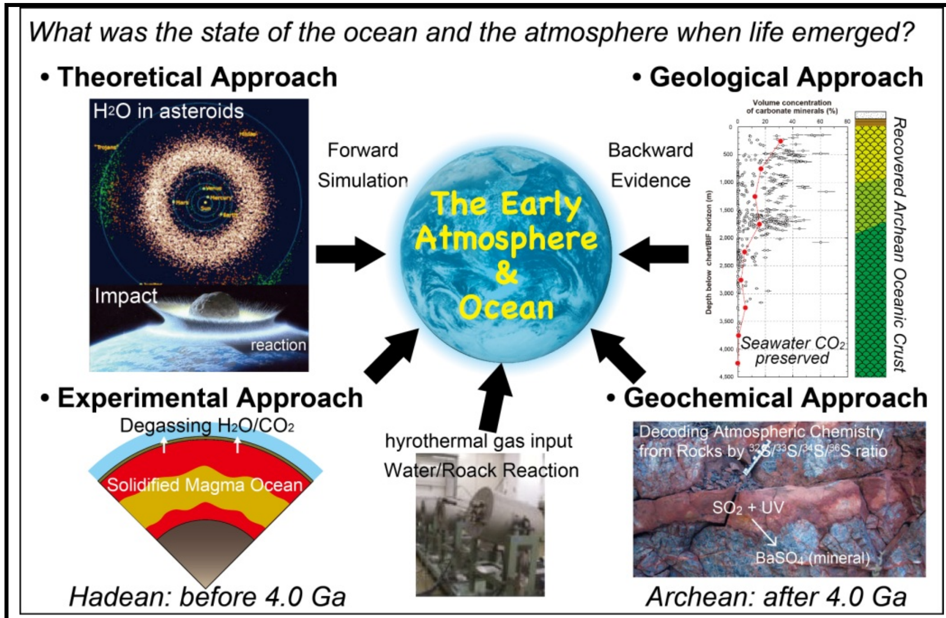

Figure 4. Chemistry of the early atmosphere and oceans will be determined by planet formation theory and tested by geological evidence (related to question **B4**).

B5. Where did the Earth's life emerge?

We will try to determine what environmental conditions can give birth to the most ancient living ecosystem via the organization of energy mass balance, elemental flux, mineral availability, prebiotic organic synthesis to lead to the birth of our ancestors. We will also explore the concrete place for a cradle of the most primordial sustainable living ecosystem through the interdisciplinary exploration of modern sites, similar to locations on the early Earth (e.g., seafloor and subseafloor hydrothermal systems, serpentinite hot springs, chains of crater lakes, etc.). Interrelationships between the energy mass balance of the system, the elemental composition and availability of the system and the functional and metabolic formation of microbial community in the system are keys to answering the most crucial questions.

The habitable physical-chemical environment formed the basis from which life emerged on Earth. The nature of the environment for the emergence of the most ancient living ecosystems relevant to us today can be addressed by estimation of the likelihood for such ancestral life to emerge in a given environment, and the universality in incidence of that environment. As a result of recent advances in research on the submarine hydrothermal systems, we are convinced that the Hadean seafloor hydrothermal systems, hosted by ultramafic rocks widespread in the ocean

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<u>Geomicrobiology / Physiology</u>

How oxygenic photosynthesis was established from anoxygenic photosynthesis in the course of evolution is a fundamental question for elucidating early earth environment and its transition. To elucidate what components are required for the early evolution of photosynthesis, Yusuke Tsukatani and Shinji Masuda have tried to create artificial oxygenic phototrophs, what we call "proto-cyanobacteria", by genetically engineering anoxygenic photosynthetic bacteria. One of the critical factors to achieve oxygenic photosynthesis is acquisition of chlorophyll biosynthesis, because chlorophylls absorb much higher energy from sunlight than bacteriochlorophylls do. The purple bacterium *Rhodovulum sulfidophilum* having photosystem (PS) II-type reaction centers was chosen as a host strain for the mutagenesis, because we determined the whole genome sequence of *R. sulfidophilum* and identified all genes necessary for photosynthesis. We succeeded to isolate the genetically engineered purple bacterium that is capable of synthesizing chlorophyll *a*. For chlorophyll *a* biosynthesis in purple photosynthetic bacteria, genes for photosystem I-type reaction centers and galactolipid synthase as well as chlorophyll synthase were pre-requested. The results demonstrate the concerted acquirement of Chl synthesis, reaction centers, and membrane glycolipids for establishing oxygenic photosynthesis in the course of evolution.

Atsuko Kobayashi investigates ultrastructural assessment of bacterial cells and photosynthetic membrane systems using transmission electron microscopy (TEM). The information from the first group for early earth biological ecosystems is also incorporated to develop new and sophisticated scenarios for co-evolution of the Earth and life.

Hiroyuki Ohta and Yuko Sasaki-Sekimoto investigate how photosynthetic organisms have evolved and influenced the Earth's ecosystem. Initiation of land colonization by plants was a key event in the evolution of life. It is generally accepted that the ancestor(s) of current terrestrial plants was closely related to present-day Charophytes. To elucidate transition of biological systems from aquatic algae to land plants, we investigated *Klebsormidium flaccidum* (Division Charophyta, Order Klebsormidiales), which is a filamentous terrestrial alga and also can survive in fresh water. We determined the draft genome sequence of the *K. flaccidum* (Hori et al., 2014).

Lipids play a key role to adapt environmental stresses. When cultivated under stress conditions, many plants and algae accumulate oil. A model unicellular green alga *Chlamydomonas reinhardtii* accumulates triacylglycerols (TAGs) during crust, were abundant and prepared the H_2-rich environments that potentially offered the best energetic habitability. Institute PI Takai has already proposed a hypothesis that such ultramafics-associated deep-sea hydrothermal environments nurtured hydrogenotrophic energy metabolisms capable of habitability and sustainability of the most ancient living ecosystem (Takai et al., 2006).

Along these lines, the institute PI Kirschvink (2003) proposed another scenario (i.e. Martian origin of life). Early Mars was clearly not a water world like Earth, and in addition to hydrothermal systems would have had numerous environments like Death Valley in which periodic wet/dry cycles could promote polymer formation via dehydration reactions, as well as providing a borate-stabilized pathway for RNA synthesis. This theory also makes use of the more reducing nature of the Martian mantle (at the Iron/Wüstite buffer), and a surface layer more oxidizing than the Earth's.

While both hypotheses focus on energy and prebiotic chemical synthesis, other researchers have noted the great potential of primordial continental rift valley considering the supply and availability of essential elements and nutrients necessary for formation of functional substrates of life (Maruyama, 2012). Indeed, this notion is supported by the latest research, in which the common compositional pattern of essential elements has systematically pointed to the cytoplasmic constituents and the hydrothermally altered clay pools in terrestrial hot springs (Mulkidjanian et al., 2012). In any case, the plausible places of environments must be verified on all points through quantitative estimates of the likelihood for most an ancient living ecosystem to be generated and sustained, and the universality in the incidence of such environments on the early Earth. ELSI will include leading researchers behind each of these hypotheses. Their vigorous debates and joint research can be expected to produce new world-leading hypothetical models and theories.

To define the chemical environments for oceanic hydrothermal systems on the primitive Earth and even the primitive Mars, research will be conducted with a forward approach using simulations and reproducing experiments of hydrothermal reactions between the ancient ocean crust and seawater. Here we adopt a reverse approach as well. In short, we will identify the microbial community composition, distribution and function, the metabolic processes and networks, and the composition and function of elements and minerals in present-day analogous environments that could share operative principles in common with the candidate early environments. The methodology is amenable to multifaceted analyses combining in-situ chemical sensing and probing, high-sensitivity/quantitative in-situ metabolic activity measurement, isotope-tracer experiments, and metatranscriptomic and metabioelemental analysis. Preparatory research has been ongoing, and the underlying technologies, methodologies and accumulated data are in place.

Under the Center's precursor G-COE program, microbiologists, genome scientists, environmental chemists, and geologists engaged jointly in research on terrestrial hot spring environments, advancing interdisciplinary cooperation on the

nutrient stress conditions. Using this characteristics, we succeeded to enhance oil accumulation in the algal cells under nutrient deprivation especially phosphate deprived conditions (Iwai et al., 2014).

We have started study on algal cell surface structures to adapt land conditions. Yuko Sasaki-Sekimoto set up GC-MS/MS system to analyze cell surface lipids extracted from *K. flaccidum*. We identified that *K. flaccidum* has TAGs on the surface of their cells in dry conditions. In collaboration with Atsuko Kobayashi, we have started to observe the cell surface structure of *K. flaccidum* using scanning electron microscope (SEM).

Results from the group's studies are combined to develop new and sophisticated scenarios for co-evolution of the Earth and life though the intimate collaboration with the Geology / Geochemistry group.

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subject of early Earth-like hot environments. Making full use of Japan's world-leading large-scale research facilities for deep-ocean surveying and drilling, Takai's Precambrian Ecosystem Lab has already collected multiple lines of quantitative mass data and modeled geo-bio interactions of nearly all types of deep-ocean hydrothermal activities that exist on Earth today, pursuing a reverse approach from the present to the Hadean (Takai and Nakamuara, 2010; 2011).

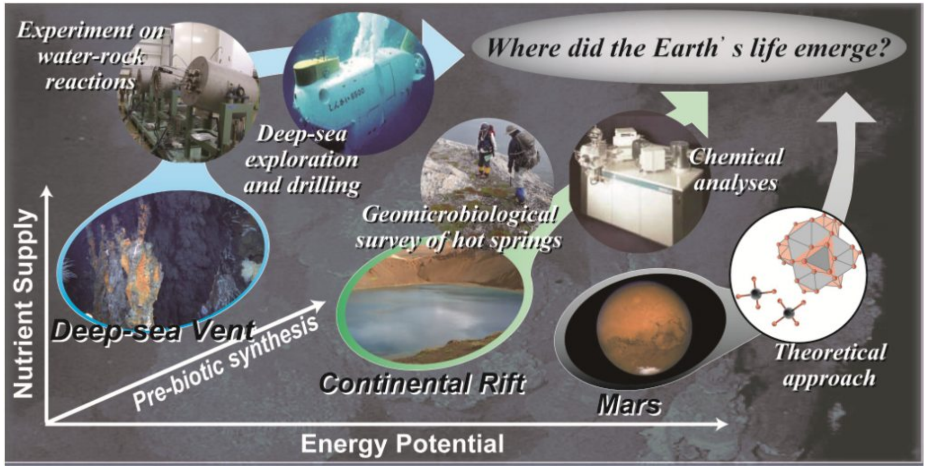

Figure 5. The first life on Earth may have emerged at deep-sea or continental hydrothermal system. Alternatively, possibly life originated on Mars and was then transported to Earth (related to question **B5**).

B6. What were the genomes of the first community like?

Following its emergence on Earth, early life may have faced various environmental disruptions. To achieve a sustainable and stable existence without extinction, a robust life system was necessary, consisting of both cellular and ecological systems, to develop in order that life could cope with these environmental disruptions. While research on the robustness of cellular systems has progressed in the life sciences, very little research has focused on robustness of ecological systems. This area of research will elucidate dynamics that produce ecosystems that are both sustainable and capable of evolving. The following research will be undertaken with the objective of tracing genomic diversification and ecosystem formation since the emergence of life.

***Comprehensive Earth Database (EarthDB)*:** To reveal relationships between environmental factors and genetics, we will build a comprehensive database, EarthDB. In conjunction with projects in B4 and B5, we will thoroughly collect genetic data with environmental information from all environments including those

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Genome Environment Database

Investigation of the relationship between the gene pools extracted from living microbial populations and their surrounding environmental conditions is very important in order to infer genetic diversity on early Earth. The Genome Environment Database group conducted genomic/metagenomic analyses with a focus on living microbial populations as well as a concentration on accumulating information about genetic pools and environmental conditions including temperature and pH. On the basis of the relationship between genetic pools and environmental conditions, the group has begun to infer genomes of ancient microbes and ecosystems under environments on early Earth. Kurokawa, the group PI, developed an integrated database of microbes, called “MicrobeDB.jp,” with Semantic Web techniques. MicrobeDB.jp is a database of information about microbe genes/genomes/metagenomic, and taxonomic and environmental information collected/integrated from available databases belonging to individuals and public organizations. The group has been developing extractions of correlation indices between metabolic modules and environmental conditions using this database. The group’s collaborator, Hongoh, has been studying how microbe ecosystems evolved/became established by analyzing single-cell genomics, targeting unculturable microbes. The following is a summary of the studies conducted by this group in FY 2014.

In the “Program for promoting integration” by JST NBDC (National Bioscience Database Center of Japan Science and Technology agency), a three-year research and development study, “Promotion of ultra-upgrading microbe DB by integration of genomic/metagenomic information,” has been launched. This study subject aims to expand the integrated microbe database, “MicrobeDB.jp,” developed by the group, and integrate more and various information to develop a database system that similar to the early Earth. Genomic information for isolated prokaryotes in these environments will also be included in EarthDB. We will also perform metagenomic analysis on soils, oceans, and other present-day environments to fully reveal relationships between genetics and environmental factors. PI Kurokawa has already developed MicrobeDB.jp, a comprehensive database of microbial genomes and metagenomes (http://microbedb.jp/). MicrobeDB.jp not only captures genomes, metagenomes, and metadata but also has led the world in developing a vocabulary that provides definitions of terms used in descriptions of microbial habitats and thorough descriptions of semantic relationships between terms (MEO), making it possible to speculate on relationships between genetics and environmental factors. Moreover, with respect to microbial genomic and especially metagenomic analysis, by publishing results of large-scale human metagenomic analyses (Kurokawa et al., 2007), Kurokawa's group has established itself as one of the world's leading research groups and made it possible to discover new knowledge by analyzing large data sets (Mori et al., 2010; Arumugam et al., 2011).

Synthetic Biological Experiments for Inference of Missing Enzymes and Genomic Organization of Early Life: By using EarthDB, it will become possible to use the environmental factors in our reconstructions of early environments on Earth to infer gene groups necessary to maintain life, as well as gene groups necessary for specific environments. Though the inferred gene groups will include many genes with unknown functions, missing enzymes can be identified by finding the rate of cross-environmental co-occurrence of genes and expected metabolites. By combining these, we can form conjectures about early life genomes capable of inhabiting the Earth's early environments. PI Kurokawa's group has already published on methods for inferring missing genomes from bacterial genome information (Yamada et al., 2012).

By artificially synthesizing the inferred missing enzymes, the function of the artificial genes can be confirmed by introducing them into microbes from which the corresponding genes are missing or into microbes for which the genes have become thermosensitive. After purification of a product of artificial genes, their functions will be measured in vitro.

Because a genome has so many genes, early stages of our research will focus on genes for amino acid metabolism and protein synthesis. During that time, we will develop research methods by which we will pursue a whole genome understanding of early life. Proteins, which are the functional macromolecules in life today, rely on the functional variety of 20 types of amino acid to achieve their diverse range of functions. However, the lack of enzymes for today's amino acid metabolism and protein synthesis in some microbes suggests that not all 20 types were used to make up proteins around the time of early life's creation. For an amino acid to be newly incorporated into early life, despite the absence of that amino acid, requires the existence of enzymes that synthesize the amino acid, as well as enzymes for protein facilitates knowledge discovery from big data.

Basic information on the correlation between genes and their surrounding environments that has been studied/collected by the Genome Environment Database group is expected to be provided for other research groups as well as become a future basis of collaboration by the Geomicrobiology/Physiology group, the Synthetic Biology group, and the Prebiotic Chemistry group.

Kurokawa was granted approximately one billion yen over five years as the total budget for the entire research area for the research subject, "Creation of Hadean Bioscience," in the form of a Grants-in-aid for Scientific Research in new scientific fields (research field proposals) in FY 2014. Hongoh obtained a large grant for the study subject "Development of a micro device for single-cell genomic analysis of environmental microbes" from JST CREST and has been developing a semi-automatic micro device for single-cell genomic analysis with high accuracy at low cost.

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synthesis that utilize the amino acid. Utilizing EarthDB, this research will identify "late amino acid" candidates that might either be lost in a given environment or have been incorporated into the system around the time of life's emergence. This research complements approaches that rely on modern-day life data for such identification by taking an approach that focuses on data for amino acid sets available to early life as a result of the Earth's chemical evolution.

Using wet experiments to synthesize the missing enzymes, we will first synthesize them using all 20 types of amino acid. Moreover, we will generate evidence that the enzymes can function even when several late-period amino acids are missing by tracing the artificial evolution of proteins that in fact lack those late-period amino acids.

Kiga in our team has already created an enzyme that acts in ways not seen on Earth and has measured its activity. Moreover, by introducing this enzyme into *in vitro* reaction systems or cells, he has expanded the function of protein synthesis to use 21 types of amino acid (Kiga et al., 2002). By a non-natural combination of proteins and nucleic acids, he has also developed a system with multi-step reactions that proceed autonomously (Ayukawa et al., 2012).

***Dynamics of a Robust Life System (Ecosystem)*:** We will show how a robust life system, or ecosystem, is created and evolves by positioning a multi-agent-modeled microbial colony simulation within a model of collective evolution. To correspond to the computer-based simulation, we add artificial genetic networks to the microbes described above to perform a culture experiment using living microbial cells. By examining differences between behavior under the simulation and that of living microbial cells, we will improve precision of the simulation. The above research will enable us not only to infer the genomes of early life, but also to argue how an environmentally robust ecosystem can be produced. The PI Kurokawa has already developed a simulator, "SimMicrobiome", capable of multi-agent simulations of colony behavior under changing environmental conditions modeled on bacteria colony dynamics, making it possible to express microbial ecosystems *in silico*. By introducing artificial genetic networks into *E. coli*, Kiga in our team has already developed a multi-cellular system in which *E. coli* populations with identical genetic sets diversify autonomously through cell-to-cell communication (Sekine et al., 2011).

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Prebiotic Chemistry

♦ Objective of the Prebiotic Chemistry group

The objective of this group is to elucidate the processes by which life components are synthesized from relatively simple molecules and come to have primitive life functions. Although there are no unified views on the definition of life, understanding that life is a system satisfying the following three conditions is generally recognized among most scientists.

(A) "Compartmentation": Possessing a boundary dividing the self from others.
(B) "Metabolism": Up-taking and efficiently using energy for the self's activities (chemical reactions).
(C) "Self-replication": Leaving copies of the self for the next generation.

As a material basis having each of these three life functions, present-day organisms use cell membrane, protein, and DNA/RNA, respectively, and their constituting components are organic compounds, fatty acids, amino acids and

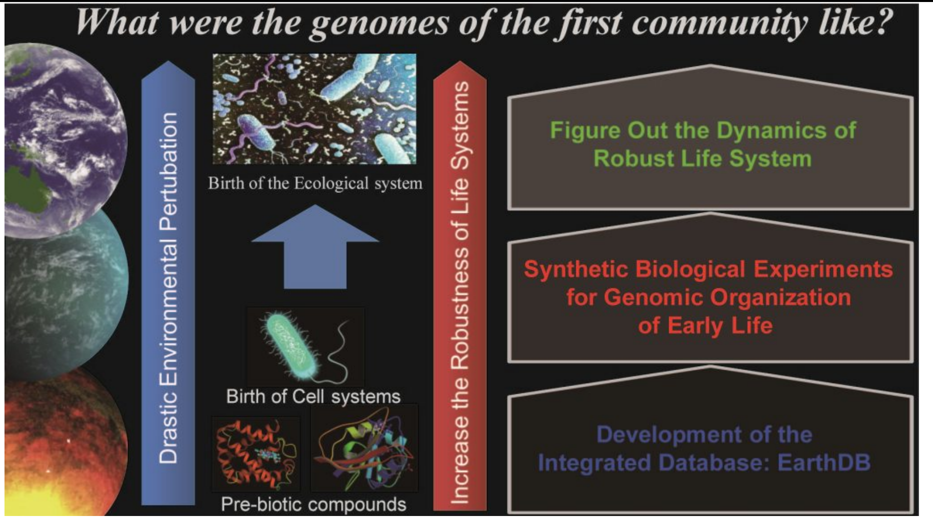

Figure 6. The initial genome born in a unique environment on early Earth will be estimated by using the data base that relates specific environmental factors and the gene pools of microorganisms. With a development of these data base further, the initial ecological system that allowed a stable and persistent existence of life will be clarified (related to question **B6**).

C7. Why does the Earth's atmosphere contain oxygen?

We combine the systematic and evolutionary biochemistry with high-resolution decoding of geological records to unravel the evolutional processes from the chemosynthetic energy conversion for life dependent on the Earth interior energy supply to the photosynthetic energy conversion for life dependent on solar irradiation driven by the environmental changes in the atmosphere and ocean. In addition, we will investigate the following questions in ELSI. When, where, and how did oxygenic photosynthesis begin? When and how did the atmosphere first become oxidized? Did the elevation of oxygen levels really cause the first snowball earth and trigger the birth of eukaryotes? Placing geological and geochemical constraints on this transition is a major goal of PI Kirschvink and his group.

Systematic and evolutionary biochemistry will be applied for understanding how the energy revolution developed from chemosynthesis to photosynthesis. The study of the step-wise evolution of extending metabolic pathways by the team led by PI Takai has been advancing by degrees. The team has analyzed the simplest diversification scenario of metabolic pathways by the minimum innovation (evolution) of catalytic components and the molecular evolution of catalytic enzymes and co-factors common to both chemosynthetic and photosynthetic metabolisms. The driving force lies in a strong interrelation between the demand

nucleosides, respectively.

(1) Under what conditions can these components be synthesized?
(2) Under what conditions can these components be organized as a system having primitive life functions (A), (B), and (C)?

Reproducing experiments for answering the questions should be conducted under the conditions conformable to environments presumed to have existed on early Earth. Various usable minerals in such environments may have exerted unknown catalytic abilities to promote a variety of interesting reactions. Consequently, this group has devised experimental equipment that facilitates unhindered regulation/changing of various temperatures, pressures, pH values, catalytic minerals, energy sources, etc. and has been conducting studies aimed at discovering how life originated.

In FY 2014, a new study scheme was established to reproduce a particular chemical reaction network that presumably can become a prototype for (B) "Metabolism," and the preparation of experimental equipment and analytic devices is now complete.

♦ Primitive metabolism

Research Associate Professor Aono and Kitadai et al. have focused on a part of the pathway in the reductive citric acid cycle as a reaction network that presumably can become a prototype for metabolism (Aono et al., in press). The reaction network, called "primitive metabolism," is a pathway in which acetic acid (CH_3COOH) is used as a starting material, and by carboxylation to extend its carbon chain, citrate (C6) is synthesized in the end through metabolites such as acetate (C2) → pyruvate (C3) → oxaloacetate (C4) → α-ketoglutarate (C5). In present-day organisms, these carboxylation reactions are optimized by the intervention of enzymes, and carbohydrates, amino acids, fatty acids, and nucleobases are synthesized from each metabolite in the downstream reactions. If this primitive metabolic pathway can be constructed by utilizing catalysts such as minerals that had existed or energy sources that had been available on early Earth instead of enzymes, we will be able to advance an understanding of the process in which the system continuously producing life components originated. However, realization of such a primitive metabolism had been difficult because of roughly the following two factors: (1) These carboxylation reactions do not easily occur in terms of energy. (2) Without the intervention of enzymes that catalyze reactions to selectively generate specific metabolites only, products become diverse and a reaction network is unable to be stably maintained. These problems are expected to be overcome because under the conditions of atmosphere/ocean/continents on early Earth, inferred by Associate Professor Ueno et al. in the Geology/Geochemistry group, (i) ultraviolet radiation and supply of energy in the early evolution of the earth environments and the ancient ecosystems. The necessity of innovation in the energy metabolisms is also closely linked to the propagation of the early microbial communities from the limited habitats in the deep ocean to the global ocean environments at those times. Our approach, however, is still in an early phase, and we intend to pursue it further. Another important question is why very few types of chemosynthetic phototrophs (e.g., only anoxygenic green-sulfur and purple bacteria) are known as the evolutionary intermediate metabolisms in any of the microbial communities in the modern Earth. There are two possible answers to this question. One is that such evolutionarily intermediate energy metabolisms and the host microbes have not been discovered by the present methods and techniques in the modern microbial communities; the other is that such evolutionarily intermediate energy metabolisms and the host microbes never emerged. To investigate the first possibility, we need to take advantage of the results of B4 above, and design previously untested experiments for detection and estimation of evolutionary intermediate energy metabolisms under the potential initial environments such as a CO atmosphere and ocean. This kind of approach may find a missing link of evolution between chemosynthesis and photosynthesis. Behind the second possible answer is a hypothesis that a precursor or primitive photosynthetic metabolic system already existed almost immediately after the early continuing living ecosystems came into existence. In connection with B4, B5, and B6 above, we will work toward unraveling these mysteries.

Geology and geochemistry will be applied to trace the evolution from chemosynthesis to photosynthesis. The transition from chemosynthesis to photosynthesis must be recorded in Archean geological records. Recent development of stable isotope geochemistry has enabled us to identify the activity of some anaerobic metabolisms (e.g., methanogenesis and sulfate reduction) from isotopic information of Precambrian rocks. PI Yoshida's group, Ohkouchi and Ueno in our team have developed novel isotopic techniques to trace specific metabolic activities from geological rock samples (e.g., Ueno et al., 2006; 2008; Ohkouchi et al., 2007) Still, we have obtained relatively little information about anaerobic photosynthesis and other key metabolisms of anaerobic organisms, which must have existed before the emergence of oxygenic photosynthesis. In the nitrogen cycle, for example, nitrogen fixation, which must have been crucial from the beginning of microbial ecosystem, have not been adequately traced from geological records. We will newly explore proxies of biological metabolism in an analogous environment to anoxic early Earth and incubation experiments during the first half of the project. And we will also apply new techniques currently under development to geologic samples of isotope systematics (e.g., H, C, N, O, S, Fe) at the same time or during the second half of the project year. Conventional obstacles to this type of research have been metasomatic overprints and contamination of exotic compounds into

and electrochemical potential can be obtained as energy sources, (ii) inorganic compounds obtained from sulfide minerals, phosphate minerals, borate minerals, etc. can be used as catalysts, and (iii) in the repeated condition of rapid heating/cooling, thermal non-equilibrium states can be generated. Therefore, a scheme for conducting experiments under these conditions was established and the equipment for the study was developed. In addition, for product identification/quantitation, the installation of analytical equipment including LC-QToF (liquid chromatography-quadrupole time-of flight), HPLC (high performance liquid chromatography), GC-MS (gas chromatography-mass spectrometry), was completed. The experimental facility and analytical equipment are now fully in operation and experimental results are currently being obtained.

♦ Catalytic activity of mineral surfaces

There are a variety of crystal planes on the surface of minerals, even simple substances, and the specific structure is present locally in each crystal plane. In order to identify interaction sites involved in adsorption/polymerization of life components on mineral surfaces, the interaction between mineral surfaces and organic compounds needs to be measured/analyzed with high-resolution and high-efficiency at the nanoscale. Assistant Professor Yano and collaborators Hara et al. developed a technique by which interaction forces between amino acids and mineral surfaces are quantitatively analyzed at nanoscale using an atomic force microscope (AFM), which is highly sensitive in detecting forces. Measuring interaction forces while controlling the distance between a given amino acid molecule bound to the probe tip of AFM and a mineral surface at an angstrom scale by AFM enabled them to quantitatively analyze adsorption forces between the mineral surface and amino acid molecules. They analyzed adsorption states between amino acids and sulfide mineral surfaces (iron pyrite, etc.) via temperature programmed desorption gas spectroscopy. The analysis results revealed that amino acid adsorption amounts depend on the temperature of the mineral surface at the time of adsorption and the states through which the iron pyrite surface changes depending on the temperature. They will conduct similar experiments under temperature environments on primitive Earth to elucidate the correlation between the surface states of minerals and amino acid adsorption amounts.

♦ Embodiment of environments under which life originated on early Earth

PI Maruyama et al., from the Geology/Geochemistry group, studied feasible conditions of the surface environment on early Earth in detail and proposed that geysers, which are presumed to have existed in the crust of primitive continents, are, indeed, optimum places for a variety of life components to be synthesized. In addition to above conditions (i), (ii), and (iii), in geysers, (iv) reactions whose energy sources are gamma rays, etc. from mineral deposits of radioactive elements sedimentary rocks long after deposition. There have also been technical obstacles that have prevented us from obtaining information from carbonaceous macromolecules (kerogen) in sediments, which should not be affected by post-depositional petroleum migration. Developing a method to overcome these technical difficulties is key. We will establish a new reliable geochemical method of extraction that focuses on organic nitrogen, hydrogen, and sulfur, and we will strive to develop techniques that can test for their syngenetic origin within their host rock. Consequently, we will unravel the evolution from chemosynthesis to photosynthesis in the realm of microorganisms based on geological evidence.

We will carefully select a specific stratigraphic horizon for thorough geochemical analysis particularly focusing on the time before and after the period of changes. The best potential locations are as follows: (1) The Kaapvaal craton in South Africa to probe the emergence of oxygenic photosynthesis (3~2.8 or 2.4~2.2 billion years ago) (2) Gabon in Africa to probe the emergence of eukaryotes (about 2 billion years ago) through field mapping and targeted drilling. Other international research projects including the NAI and Agouron Institute led by PI Kirschvink have done similar projects to study the period 2.5 billion years ago when oxygen levels elevated. Our research will differ from these studies, since it is vital to look at the subject matter from a different angle. In our view, the emergence of photosynthesis, elevation of atmospheric oxygen levels, and birth of eukaryotes were not isolated events, and possibly the 1 billion year period, between 3 billion and 2 billion years ago was a transition phase whose beginning and end were crucial. PI Kirschvink disagrees with this view, and this disagreement will in itself give rise to investigating and vigorous discussions within ELSI.

Based on the results of our research, we will develop a biological scenario (focusing on internal factors) of the origins of photosynthesis, oxygen atmosphere, and eukaryotes to describe actual environmental changes. C8 and C9 below are meant to identify external factors that led to the emergence of photosynthesis, oxygen atmosphere, and eukaryotes.

(uranium, etc.) in the crust are accelerated, and (v) repeated wet-dry cycles are realized during the periodical circulation of reaction solution between the crust and ground surface, which allows product polymerization and enrichment. Kitadai comprehensively investigated processes in which life components synthesized in the geysers are capable of providing these various reaction conditions and systematically summarized them (Kitadai and Maruyama, in preparation).

♦ Computational approaches

Research Associate Professor Cleaves et al. developed a new technique in computational sciences and demonstrated that the set of 20 amino acids used in present-day organisms are extremely “adaptive” in that it is able to cover a broad area of the space containing multiple physicochemical features, compared to other sets that were randomly selected from approximately 2,000 existable amino acids (Illardo et al., 2015). Research Associate Professor Aono et al. developed a dynamics model that expresses chemical reaction processes in which multiple atoms bind to form stable molecules as dynamic solutions satisfying given limiting conditions and for which search is conducted in a combination optimization problem. The developed model enables the expression of organic electronic reaction mechanisms (polarization, ionization, and radical reactions) based on the findings obtained from the simulation model of organic compound formation processes in the space studied by PI Ida in the Planet Formation Theory group (Aono and Wakabayashi, in press).

♦ Research network

PI Hut et al. constructed a network of researchers involved in the study on computational modeling of origins of life, “Modeling Origins of Life (MOL),” and holds workshops at the Institute of Physical and Chemical Research (RIKEN) and the Institute for Advanced Study, Princeton (ELSI Satellite) to promote related studies inside and outside of Japan and to expand the related human network.

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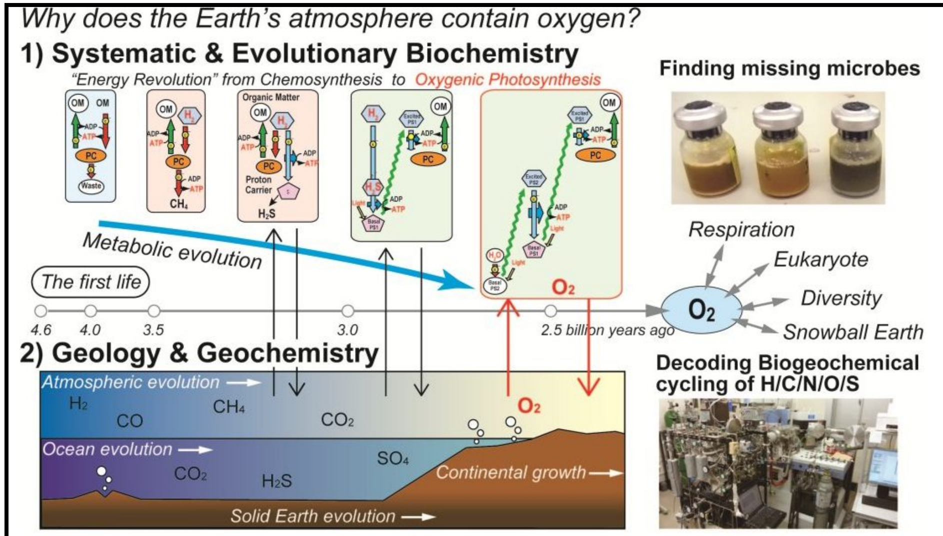

Figure 7. Metabolic evolution from the origin of life to oxygenic photosynthesis will be decoded by systematic and evolutionary biochemistry. The evolution pathway into the oxygenic photosynthesis and its influence on Earth's biosphere will be traced by geological observations (related to question **C7**).

C8. How did the thermal evolution of the solid Earth change the ecosystem?

The long-range evolution of the biosphere as well as the atmosphere and ocean is deeply connected with the thermal evolution of the solid Earth. The links between these categories of evolution have been dramatically reconsidered in recent years. Subject matters that have been revisited include the following: (1) Changes in and evolution of atmospheric composition through volcanic activity and differentiation of the Earth's crust and mantle. (2) Changes in the supracrustal material cycle through plate tectonics, and the link with the emergence of multicellur animals. (3) Effects of the inner core formation and resulting changes in geomagnetic field intensity on the biosphere. (4) True Polar Wander and the Snowball Earth hypothesis (Kirschvink). The driving force in these is related to the differentiation of the solid Earth through the cooling of the Earth. The record of the Earth's history reveals that there were drastic changes in the Sr isotopic composition at 2.1 billion and 600 million years ago. These changes in composition imply the onset of extensive weathering of continents, increase in sedimentary rocks owing to the expanded land areas, and the supply of nutrients to the ocean. The times of the changes appear to coincide with the emergence of eukaryotes and of metazoan animals when the levels of oxygen increased. These coincidences imply possible causal links between these climatic and evolutionary events that may ultimately reflect the thermal evolution of solid Earth. Particularly, the increase in oxygen

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Synthetic Biology

By combination of biomolecules such as protein, DNA, RNA, and lipid, synthetic biology approach allows design and construction of reaction systems which represents proto cells or what life could be. Since the same reaction can be realized by different combinations of biomolecules, information from geology and levels 600 million years ago may have been an inevitable physical trajectory of a cooling planet.

We will clarify how the Earth's core, mantle, and crust differentiated over 4.6 billion years, and especially when radiogenic heat sources were first distributed, and subsequently spread by mantle convection. To do so, we will first determine the physical properties of key substances and their elemental partitioning in the Earth's interior based on the results of experiments under high temperature and pressure in A3 above. Using these parameters, we will simulate the convection of the mantle through time to identify when the convection transformed, and we will identify when the inner core was formed. In addition, we will conduct a dynamo simulation of the metallic core to understand how the geomagnetic field intensity changed by the formation of the inner core.

These simulations should be compared with actual observational evidence. We will measure paleomagnetic intensity of rock specimens from various times in the history of the Earth to study the link between the core evolution and magnetic fields. PI Kirschvink established a method of analyzing measured paleomagnetism as described in A3. PI Maruyama and his team discovered that continental growth was episodic throughout the history of the Earth (Rino et al., 2008). Igneous activity is closely linked to the thermal evolution of the solid Earth. Comparing the implied solid Earth evolution with the surface environmental changes shown in the study of drill core samples will establish links between the Earth's interior and surface environment. In regard to direct influence of environmental changes on the biosphere, we will examine changes in composition of the atmosphere and ocean by extending the method described in B4 and C7. To study links between plate tectonics and the biosphere, we will conduct a geochemical analysis and model biogeochemical cycling of key elements not only within biosphere but also include crust and mantle in a longer timescale. PI Maruyama and his team studied changes in temperature and pressure of subducted plates in regional metamorphic belts, and arrived at the conclusion that, as the Earth cooled, subducted oceanic plates carried water to the mantle, and the total quantity of seawater decreased thereafter (Maruyama et al., 1996; 1997; Maruyama and Liou, 2005). The decrease in seawater exposed vast areas of continent above sea surface. The denudation of the continents increased the supply of nutrients to the ocean and substantial organic carbon burial into sediments, possibly triggering the elevation of oxygen levels that may have triggered emergence of animals at 600 million years ago.

Focusing on the times 600 million years ago, our G-COE project has carried out continental drilling over 10 sites and performed thorough geochemical and paleontological analyses (e.g., Sawaki et al., 2010). In this project, we will focus on even earlier times to obtain pristine drill core samples of critical events, as described in C7.

metagenomic database is important to study origins of life by constructive approach.

Jack Szostak, an ELSI PI in Harvard/ MGH, works for proto cell by construction of artificial compartment containing RNA or peptide. Especially, RNA was running the show, carrying out metabolic processes while simultaneously serving as its own template for genetic replication from one generation of “protocells” to the next. It is possible that the catalysis derived from nothing more than these template effects provided the initial bootstraps for the mechanisms of Darwinian evolution that eventually gave way to modern systems of genetic replication. A fundamental understanding of the mechanisms of nonenzymatic template-directed RNA replication will provide key insights into the possible origins of life on Earth from RNA. During the past year, Jack Szostak and Albert Fahrenbach have studied prebiotic mechanisms of template-directed syntheses, namely RNA replication, by investigating the thermodynamics of binding of the RNA monomers to the template-primer complexes, as well as the kinetic rates of their subsequent reactions along the template.

Daisuke Kiga, an ELSI associate PI, and Kazuaki Amikura has engineered a genetic code which translates genetic information written by a nucleotide sequence on RNA to functional information written in an amino acid sequence on a protein. Instead of 20 amino acids used in the Universal genetic code, less than 20 amino acids are used in his engineered genetic code which represents ancient form of a code in a proto cell. They developed newly molecular biology technique to evolve the protein without specific kinds of amino acids. It is useful as an engineering tool to make ancient protein encoding fewer than 19 amino acids with activity. These works are collaborated in part with Rajat Banerjee (ELSI visitor, University of Calcutta).

ELSI has researchers for artificial lipid compartment which represent environment of proto cell. Yutetsu Kuruma, an ELSI researcher, havs succeeded to synthesize SecYEG translocon by synthesizing its component proteins in vitro. Because SecYEG controls protein membrane insertion and secretion on the cell membrane, this would be a fundamental membrane device for the construction of artificial cell, which is a good model to study a very early stage of cellular life. This work has been accepted by the journal of Angewandte Chemie. He made the press release and presentation about this achievement, and received much attention from a lot of media. He also has purified nine enzymes involved in fatty acid synthesis pathway. Purification of additional three enzymes will allow him to reconstruct the fatty acid synthesis inside cell size vesicles. The goal of this work is the development of self-reproducing artificial cell. Tetsuya Yomo, PI on the satellite of ELSI at Osaka Univ, synthesized and evolved an artificial model experimentally. He currently focuss on the development of an experimental setup to evolve a membrane protein to facilitate fusion (growth) and division of lipid vesicles. In the last three month, he confirmed some membrane proteins showed an activity of membrane fusion slightly higher than the background level. The

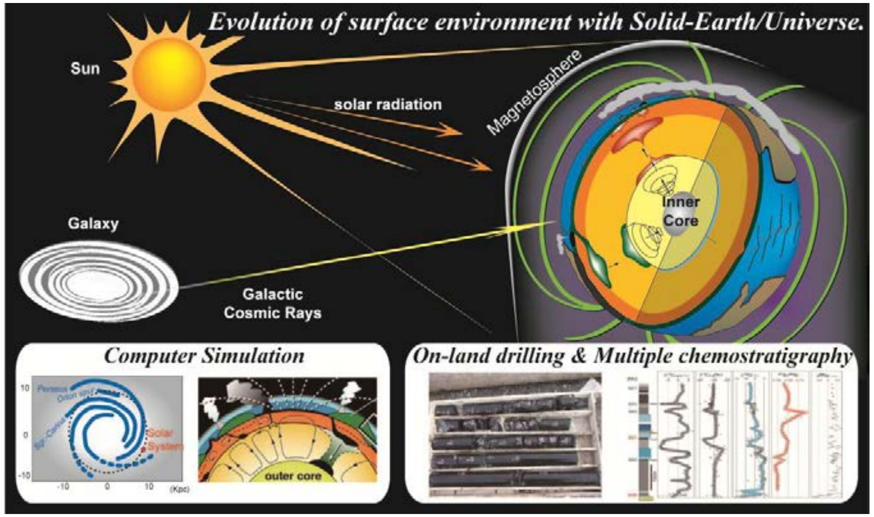

Figure 8. The evolution of the Earth's interior should have affected surface environments through enhancement of geomagnetic field, landmass, and sedimentary rocks. The effect from the Universe such as intensity of cosmic rays may be also important for the change in Earth's surface environment (related to questions **C8** & **C9**).

C9. How did galactic events influence the Earth's surface environment?

Cosmic forcing may change the surface environment on Earth. This has been shown in daily meteorological changes (links between cosmic rays flux, solar activity and cloud formation), and suggested even the freezing of the entire globe due to changes in galactic environment. The connection between the Earth and outer space has long been pointed out, but it has been treated as a hypothesis that could not be examined due to the scarcity of specific evidence. However, as astronomical observations have advanced in recent years, ages, masses, and locations of stars, galaxies, and molecular clouds have rapidly been identified in detail. Moreover, advances in simulation technologies led by PI Makino and his team have enabled us to theoretically analyze the origin and evolution of our Milky Way Galaxy, leading to a view significantly different from common belief (e.g., Baba et al., 2012). The conventional theory is that the sun circulates within the Galaxy, periodically meeting Spiral Arms that are in steady state. Recent observations, however, found a high probability that the sun's movement may be nowhere near circulation, and that its radial movement within the Galaxy may be the cause of considerable changes in the Earth's surface environment. The Spiral Arms also undergo significant temporal variations, far from steady state conditions. Also, recent observations discovered that the Galaxy has a large bar-like structure that may influence the movements of

existence of the slight activity implies that he can apply an evolutionary optimization for the fusion of lipid vesicles.

For study of primordial biological systems, model-based understanding of biological reaction is important. In Kiga's recent work in synthetic genetic network field, a genetic switch for differentiation of cells can be initialized by overproduction of gene regulation, as mathematical model predicts. He also introduced notion of impedance in genetic circuit. By evolution experiments using E.coli, Yomo aim to observe how the bacterium adapts to survive in severe selection conditions. He found a bacterium strategy for exhibiting sustainability to unexperienced environmental changes.

In order to establish ELSI presence in this research field, ELSI people actively organized meetings. Kiga was a LOC member for ORIGNS2014 meeting. Kuruma organized the workshop about synthetic biology in the international conference, ALIFE2014, in New York. He also organized another meeting, Open Questions of the Origin of Life (OQOL) 2014, which held in Nara just after the ORIGNS2014. After that, He served as an editor of OLEB journal for the special issue of the OQOL2014 meeting.¥

Interaction with general public is quite important for synthetic biology including origins of life research. Szostak made public lecture in Tokyo tech, which was attractive for general public so that a large conference hall was filled to capacity. Kiga organized, with ELSI support, a summer school and a workshop in this field. He also served as a committee member for evaluation of recombinant DNA technology from viewpoints of bio-diversity.

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the sun and the Spiral Arms.

In this project, we simulate the dynamics of the Galaxy based on numerical calculations to predict galactic events that the solar system experienced in the Galaxy, as well as the timing of the events. The project has already started and has stimulated links between a 150-million-years cycle of changes in Earth's climate and in the position of the solar system in our galaxy. Now, we re-examine the role of the universe in the history of the Earth quantitatively. Events in the Galaxy that can influence the Earth's climate may be the following: (1) Major changes in star-formation rates, (2) A collision between molecular clouds and the solar system, and (3) A supernova explosion in the vicinity of the solar system. Astronomical observations by HIPPARCOS and other projects revealed a considerable increase in star-formation rates at 4.6 billion, 2.3 billion, and 0.7 billion years ago. The new picture of the galactic disk prompts us to re-interpret the data from HIPPARCOS. Time scales for encounters with molecular clouds vary due to their size and are estimated up to be several million years. Based on recent estimates by PI Maruyama and his group, the effects of a supernova explosion on Earth's climate last 10,000 years or shorter (e.g., Kataoka et al., 2012).

Will these galactic events leave any traces in the Earth's geologic record? It is known that the deep ocean covering the Earth helps preserve extraterrestrial material in deep-sea sediments. If the Earth ever encountered any molecular clouds, dust particles from the clouds can be preserved in deep-sea sediments. Therefore, a project to find and separate extraterrestrial or extra-solar material is under way, examining deep-sea deposits collected from around the world, in accordance with our project of decoding Earth's history developed by Tokyo Institute of Technology. As evidence of a supernova explosion, the ^{60}Fe isotope anomaly was reported in deep-sea sediments from the late Pliocene when the Ice Age began that indicated the occurrence of a supernova explosion in the vicinity of the solar system (Fields et al., 2005). Isotopic cosmochemistry is crucial to find extraterrestrial material and to develop and refine theories of stellar evolution. Yokoyama and Usui in our team have developed an ultra-high-precision technology to measure trace isotopes. For example, they reported the world's first measurements of high-precision $^{186}Os/^{188}Os$ isotope ratios from natural sedimentary rock specimens to detect potential extraterrestrial or even extra-solar input (Yokoyama, JPGU2012). Searches for the past extraterrestrial or even extra-solar input into the Earth will enable us to demonstrate cosmic effects on the history of the Earth that cannot be identified merely through the theory and simulation of a galactic disk relying only on astronomical observations.

D10. How unique is our planet?

Fundamental questions in history such as "What is special about human beings?" and **"How unique is our planet?"** can now be addressed in quantitative ways based on actual observations, experiments and simulations. At first, we clarify

Dale, A. C. Fahrenbach, J. F. Stoddart. Relative Contractile Motion of the Rings in a Switchable Palindromic [3]Rotaxane in Aqueous Solution Driven by Radical-Pairing Interactions. Org. Biomol. Chem. 2014, 12, 6089.

A. C. Fahrenbach. Template-Directed Nonenzymatic Oligonucleotide Synthesis: Lessons from Synthetic Chemistry. Pure Appl. Chem. 2015, *in press*.

conditions for the origin of life systems and their subsequent evolution, and identify their dependency. These considerations will be used to observe extra-solar planets, which will enable us to compare simulation results for extra-solar planet formation and observation data. We will review and synthesize results concerning the composition of the atmosphere, the amount of ocean (sea versus ocean ratio), plate tectonics, magnetic field generation, evolution of planet's interior, positional relationships of the planet and effects from the Galaxy. We promote the study of the Earth, while being aware of unique aspects of the Earth at any time. These achievements will be published as an English book entitled by "Bio-Planetology" by the end of the WPI program.

D11. How should we search for extraterrestrial life?

The research outcomes from the above A to C will be utilized for space exploration missions, particularly for search for life on the icy satellites, Europe and Enceladus, that have subsurface oceans. The European Space Agency has just announced its new mission named the Jupiter Icy moons Explorer (JUICE) to visit Jovian satellites. JAXA has discussed corporation with this project since before the pre-proposal phase 6 years before. Japanese researchers also cooperate in the project to promote scientific studies of icy satellites. As pre-exploration preparation, we will study the possibility of existence of life forms on icy satellites with inner seas. We focus on developing scientific scenarios, rather than mission details. We will also commit to scientific scenarios for Hayabusa-2 that also aims at detection of organic materials in the C-type asteroid.

Furthermore, spectroscopic observation of the atmosphere of extra-solar terrestrial planets in habitable zones will be available in the near future. We will establish methods for remote sensing of biosignatures on these planets. We will pursue original ideas as well as detailed discussions of ideas that have already been proposed.

As for a discussion of life diversity, we will link data on life in extreme environmental conditions on Earth and data from searches for extraterrestrial life with date from geology, discussions of planetary condition based on state-of-art planet formation theory, the history of the Earth, and Earth's interior physics. To be more specific, as case studies, we will consider the possibility of existence of life on celestial bodies with subsurface oceans and planets in habitable zones around M-type stars. Compared to our sun, M-type stars are so faint that the habitable zones are very close to the central stars. Owing to tidal actions, the planet's rotation and revolution should be synchronized, with one particular side facing the central star. The planets receive intense X-rays and ultraviolet fluxes owing to its proximity to the central star. These planets, although they are in habitable zones, have environment, that differ significantly from that of the Earth.

Figure 9. We will participate in future space exploration projects (such as missions to Europa and Enceladus, which have an internal ocean) as well as in projects to look for biomarkers by remote sensing of terrestrial planets outside the solar system (related to questions **D10** & **D11**).

4. Management

<Plan at start of project >

1) Composition of administrative staff

i) Prospective center director

・ Provide the name of the prospective center director, his/her age (as of 1 December 2012), current affiliation and position title, and specialties. Describe his/her qualifications to be the center director.

Name of prospective Center Director:

Name: **Kei Hirose**

Age: 44

Current position: Professor, Department of Earth and Planetary Science, Graduate School of Science and Engineering, Tokyo Tech

Field of expertise: High-pressure Geoscience

Reasons for eligibility as Center Director:

Kei Hirose is only 44 years old but has already accomplished several milestones

<Results/progress/alternations from plan at start of project >

1) Structure of Administration Division

Please see Chapter 1: 2. Organization (2) Administration Division

2) The decision-making system at the Center

Please see Chapter 1: 2. Organization (1) General

3) Division of Authority Between the Center Director and the Host Institute

○ At ELSI, to attract world-renowned researchers in the field of life science, especially in “the origin and evolution of life,” the newly created cross-appointment system at Tokyo Tech was applied, a professor from Osaka University was hired as the new PI. In addition, an agreement was made that Graduate School of Information Science and Technology, Osaka University would be a satellite institute of ELSI.

○The Annual Evaluation Meeting was held in January 2015 to improve the motivation of the young researchers. Evaluations were made based on the research achievements and future potential. The evaluation reflects the researchers promotions and salaries.

in high-pressure mineral physics and petrology, which include 1) the first determination of melt composition formed by direct partial melting in the Earth's uppermost mantle, 2) discovery of post-perovskite, the principal mineral in the lowermost mantle, 3) the first static experiments at ultrahigh-pressure and -temperature beyond the conditions at the center of the Earth, and 4) the first measurements of transport properties (electrical and thermal conductivity) at deep mantle conditions. These are the products of his strong enthusiasm on research, and his ability of long-term planning & execution. Though Kei is still young, he is a person of great insight into the essential part of the problem.

Kei has been appointed a Power User of SPring-8, the world-largest synchrotron radiation facility, since 2003 until now. During that period, the beamline BL10XU was reconstructed to a world-leading beamline for high-pressure sciences under his strong leadership as the Power User, which is a big benefit to the relevant communities in the world.

Professor Hirose is a recipient of the Japan Academy Prize, the most honorable academic award in Japan, and the Ringwood medal from European Association of Geochemistry for these outstanding achievements. He was also elected a Fellow of the American Geophysical Union at the age of 40, the world-largest society in geoscience. Kei is also well recognized internationally as an Editor of *Physics of the Earth and Planetary Interiors* (an Elsevier journal) and a member of the Board of Reviewing Editors of *Science*.

Dr. H-K. Mao, one of the pioneers and leaders of high-pressure experiments using the diamond-anvil cell, mentioned Professor Hirose's personality and leadership in his letter of support, which ensure the recruitment of world-leading scientists for unexplored new researches at ELSI. His strong motivation in research, leadership in the community, and international recognition will certainly make Professor Hirose an ideal Center Director.

ii) Prospective administrative director

・ Provide the name of the prospective administrative director, his/her age (as of 1 December 2012), current affiliation and position title. Describe his/her qualifications to be the administrative director.

Name of prospective Administrative Director:

Name: **Kiyoshi Nakazawa**

Age: 69

Current position: Dedicated Professor, Global COE Program, Department of Earth and Planetary Sciences, Graduate School of Science and Engineering, Tokyo Tech

Field of expertise: Planet Formation

Reasons for eligibility as Administrative Director:

Dr Nakazawa has displayed an outstanding capability in launching a new organization and creating a sustainable system. In 1992, he founded the Department of Earth and Planetary Sciences in the Faculty of Science at Tokyo Institute of Technology. At that time he was a professor of general studies at Tokyo Institute of Technology. Under his strong leadership, the university succeeded in recruiting promising faculty members within Japan as well as from the University of California. The principal members of this Department were all recruited by him from the University of Tokyo when they were young. He also established a system to conduct an annual external evaluation of lecturers' activities that was unheard of in Japan at the time. In addition, he introduced systems such as syllabus creation and evaluation of lectures by undergraduates, which had also not been done in Japanese universities in those days. Although heavily criticized at that time, these are now common in the Tokyo Institute of Technology as well as other Japanese universities. Therefore, it could be said that Dr Nakazawa took the lead in reforming university systems in the Department of Earth and Planetary Sciences. As a result of these reforms, the Department of Earth and Planetary Sciences at Tokyo Institute of Technology has achieved world-leading research results already shortly after its establishment, and is widely acknowledged as one of the leading departments in its research field in Japan.

Furthermore, in 1998, he established another new organization, the Interactive Research Center of Science at the graduate school of Tokyo Institute of Technology. The Interactive Research Center of Science consists of promising young lecturers and world's leading established scientists. They are exempted from all duties other than research (e.g., university management and lecturing) and thus they can concentrate solely on their research. It could be said that this organization is a pioneer for the WPI program. Excellent scientists including Dr Makino, an internationally recognized computer scientist, are working in this organization.

Dr Nakazawa is also known as a founder of the Japan Society of Planetary Science. He created a firm foundation for the society. Serving as the first administrative director together with the first president, he launched the academic journal "Yuseijin" and established a membership system mainly by himself.

Thus, his planning and management skills and future perspectives are outstanding. He has a number of achievements in introducing new sustainable systems as well. The great success of the Department of Earth and Planetary Sciences at Tokyo Institute of Technology as well as that of the Japan Society of Planetary Science established by him indicate that Dr Nakazawa is the most suitable candidate for the administrative director of the institute.

Dr Nakazawa has made two stipulations. Firstly, he would not interfere in research. Secondly, he would serve as the Administrative Director only during the initial period following the launch of the institute. Therefore, Executive

Administrative Director who has a background with an exquisite experience as a Director of the Administration Bureau of Tokyo Tech who also has a background as rich experience as a public official will work together with Dr Nakazawa to lay the foundation of the center in the first two to three years and replace him as Administrative Director after that. ・ Attach a CV of the prospective administrative director (free format). iii) Administrative staff composition ・ Concretely describe how the administrative staff is organized. The Operations and Administration Division will consist of three departments: 1) International Promotion and Researcher Support Department 2) Operations Department 3) Public Relations Department Their functions will be promoted by a couple of Research Advisors, who have academic background and support both researchers and administrators. Existing administration offices of the university, Research Project Support Center, Research Strategy Office, Educational Planning Office, Evaluation Office, Office of Industry Liaison, Planning Office, and International Office, will also provide full support for the operation of the Center's Administrative Division (Figure 10).	

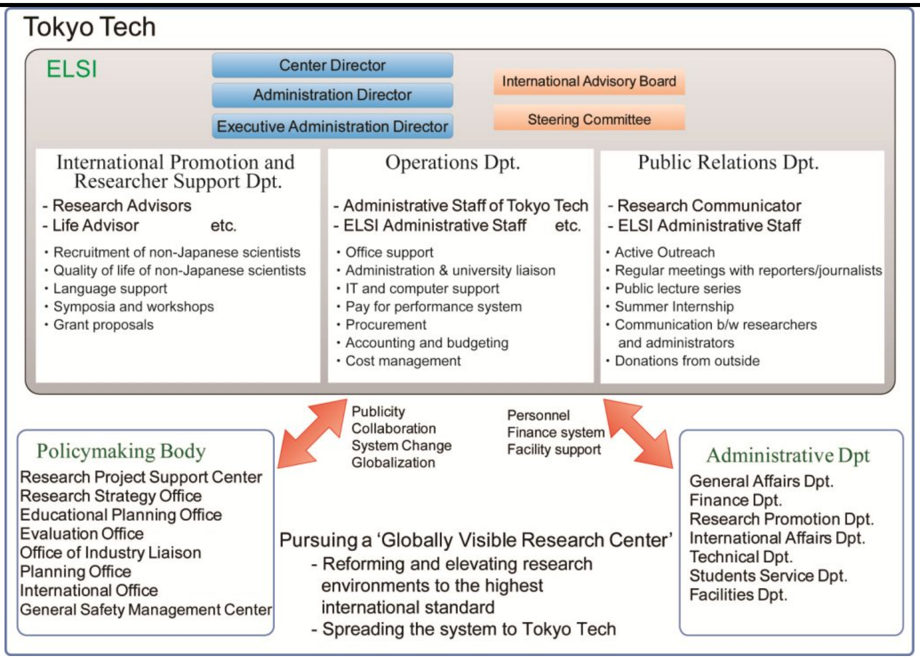

Figure 10. Structure of Operations and Administration Division of Earth-Life Science Institute.

International Promotion and Researcher Support Department

This department is responsible for connections between the Center and the outside world and for supporting the researchers during their stay at the Center. The manager and supporting Research Advisors are in charge of international recruiting, support and retention of non-Japanese staff members and visitors. With a "Japanese lifestyle adviser" assigned to each family, they offer assistance with immigration, housing, and daily life concerns. They also provide language support for non-Japanese scientists and their families. This department will manage a series of international seminars and workshops, both smaller in-house seminars and international conferences. Their role includes assistance with preparation of external research grant proposals by researchers from abroad.

The key areas of responsibility for International Promotion and Researcher Support are:
- Recruitment of non-Japanese scientists
- Quality of life of non-Japanese scientists
- Language support
- Symposia and workshops

- Grant proposals

Operations Department

This department will handle the internal operations tasks of the Center, such as financial accounting and budgeting, running the daily, weekly, and monthly events, etc. It will provide the primary administrative interface with the rest of Tokyo Tech, particularly including facilities, information technology infrastructure, and procurement.

The key areas of responsibility for the Operations Department are:
- Office support
- Administration & university liaison
- IT and computer support
- Pay for performance system
- Procurement
- Accounting and budgeting
- Cost management

Public Relations Department

This department is responsible for Center's outreach activity. We will hire Research Communicators with an academic background as a contact person to/from the outside. They regularly will send out information about the Center's research achievements to the general public in both English and Japanese through a website, encourage press releases by the Center's staff, organize monthly meetings with reporters, journalists, and science communicators, and hold lecture series as monthly events, etc. This department also will organize the Summer Internship Program for high-school students. To regularly inform the Center's administrators about the latest research outcomes is also an important task for the Research Communicators. They also seek donations from the foundations and enterprises, in collaboration with Center Director. We will be able to provide the teaching materials to companies for education.

The key areas of responsibility for Public Relations are:
- Active Outreach
- Regular meetings with reporters/journalists
- Public lecture series
- Summer Internship
- Communication between researchers and administrators
- Donations from outside

iv) Decision-making system

・ Concretely describe the center’s decision-making system.

The Center Director will have the authority to make all decisions except those concerning the final selection/removal of the Center Director himself. The responsibilities of the Center Director include the operation and management, fully assisted by the Administrative Director. This will enable a flexible and fast decision-making system.

The Center has a Steering Committee consisting of the Center Director as a chair person, Administrative Director, Directors of Satellite Centers, and two other Principal Investigators, to assist the Center Director in making decisions on a wide range of matters. The International Advisory Board members, two Japanese and three non-Japanese, also advise from an international perspective. The Advisory board meetings will be held twice a year. The Center Director receives advice from them, but makes final decisions by himself.

v) Allocation of authority between center director and host institution

・ Concretely describe how authority is allocated between the center director and host institution.

The President of Tokyo Tech is the chief representative of the university, and will be able to exercise strong leadership in management strategy. While the President will have the authority concerning the final selection/removal of the Center Director, the Center Director will be empowered to appoint all the research and administrative staff members of the Center, decide annual salaries and incentives, write a budget, etc, in consultation with the Center’s Steering Committee and the International Advisory Board.

5. Researchers and center staffs

i) "Core" to be established within host institution

Principal investigators

	At beginning	Final goal (Date: month, year)	Results at end of FY 2014	Results at end of April 2015
Researchers from within host institution	6	6 (October,2015)	9	8
Foreign researchers invited from abroad	3	6 (October,2015)	3	3
Researchers invited from other Japanese institutions	4	4 (October,2015)	5	5
Total principal investigators	13	16 (October,2015)	17	16

All members

- In the "Researchers" column, put the number and percentage of overseas researchers in the < > brackets and the number and percentage of female researchers in the [ ] brackets.
- In the "Administrative staffs" column, put the number and percentage of bilingual staffs in the ( ) brackets.

	At beginning	Final goal (Date: month, year)	Results at end of FY 2014	Results at end of April 2015
Researchers	23 < 3 ,13 %>	71 (October,2015) < 24 ,33 %>	63 〈20, 32 %〉 [11, 17 %]	63 〈20, 32 %〉 [12, 19 %]
Principal investigators	13 < 3 ,23%>	16 (October,2015) < 6 ,37 %>	17 〈6, 35 %〉 [0 , 0 %]	16 〈6, 38 %〉 [0 , 0 %]
Other researchers	10 < 0,0 %>	55 (October,2015) < 18 ,33 %>	46 〈13, 28 %〉 [11, 24 %]	47 〈13, 28 %〉 [12, 26 %]
Research support staffs	0	34	11	10
Administrative staffs	5	10	19 (17, 89 %)	20 (18, 90 %)
Total	28	115	93	93

Table 1 and Figure 11 show the expected number of Principal Investigators (PIs) at the beginning of the program and at the end of FY 2012, as well as the number set as the final target on October, 2015. At the start of ELSI, two PIs will be invited from overseas. We will invite 2 female non-Japanese PIs in 2013 and 2015, and a full-time non-Japanese PI in 2014. We assign a Japanese PI at the Satellite Center in Ehime University and also invite 3 Japanese PIs from Japan Aerospace Exploration Agency (2 PIs) and Japan Agency for Marine-Earth Science and Technology. The ratio of non-Japanese PIs of ELSI will grow from 23 % (3 out of 13 at the beginning) to 37 % (6 out of 16) by the time of October, 2015.

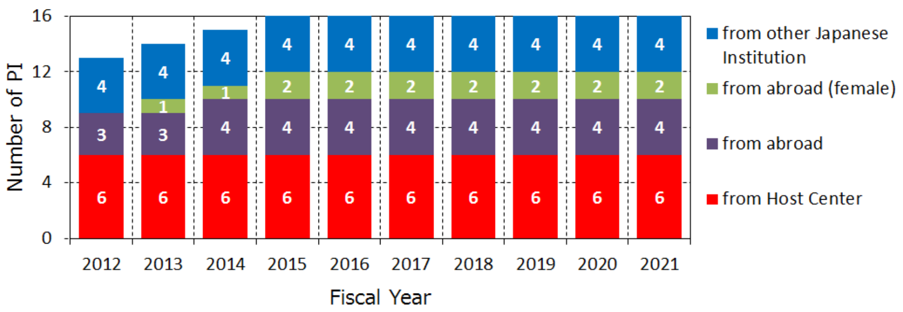

Figure 11. Plan for the participation of non-Japanese Principal Investigators.

b) Total members

Table 2. Plan to achieve the final staffing goal.

	Numbers			
	At beginning		At end of FY 2012	Final goal (Date: month, year) (October, 2015)
		Those in existing center-building project		
Researchers	23 < 3,13 %> [0, 0 %]	10 < 0, 0 %> [0, 0 %]	23 < 3, 13 %> [0, 0 %]	71 < 24, 33 %> [13, 18 %]
Principal investigators	13 < 3, 23 %> [0, 0 %]	7 < 0, 0 %> [0, 0 %]	13 < 3, 23 %> [0, 0 %]	16 < 6, 37 %> [2, 12 %]
Other researchers	10 < 0, 0 %> [0, 0 %]	3 < 0, 0 %> [0, 0 %]	10 < 0, 0 %> [0, 0 %]	55 < 18, 33 %> [11, 20 %]

a) Principal Investigator, PI (Equivalent to professor and associate professor levels)

○ PI George Helffrich, PI Tetsuya Yomo and PI Eric Smith were appointed to ELSI in July 2014, in November 2014 and in February 2015, respectively. They are 100% ELSI employees and two of them are foreign nationals.

○ ELSI is with 17 PIs as of the end of fiscal year 2014, six out of 17 are foreign nationals, this is 35% of the total cohort of PIs. The number of associate PIs remained at three.

○ Measures to secure life science researchers were reviewed based on the advice from the WPI Committee and the International Advisory Board. As a result, it was deemed essential to invite first class researchers as PIs and to attract young researchers. We created a list of first class researchers in the life science field, who have remarkable track records and are also currently active in their research. After the careful review of the list and discussion, Professor Tetsuya Yomo of from Graduate School of Information Science and Technology, Osaka University was hired under the cross-appointment system to strengthen the “origin and evolution of life” research. Furthermore, Osaka University, where the PI Yomo has an official post, agreed to be a satellite institute of ELSI. In addition to him, an associate professor and an assistant professor in the field of life science were hired.

○ Dr. Lisa Kaltenegger, who had been scheduled to take up her post as a PI in October 2014, was offered a professorship at Cornell University and it was difficult for her to join ELSI as a PI. However, she continues research exchange and joint research while staying in close contact, such as hosting the “2014 German-Japanese Exoplanet Conference” in Heidelberg, Germany, in November 2014, which was mainly organized by Dr. Kaltenegger and PI Ida.

○ PI Makino was transferred to the HPCI Program for Computational Life Sciences, RIKEN in fiscal year 2014. He continues to collaborate with ELSI as an external PI. In addition, PI Maruyama retired at the end of fiscal year 2014, but he will continue to collaborate with ELSI as a specially appointed professor.

b) Overall plan

○ As of the end of fiscal year 2014, ELSI had 78 researchers (17 PIs, three associate PIs, 35 WPI-employed researchers and 23 affiliated scientists). Twenty-seven researchers were foreign nationals (35% of the total number of researchers), and 13 were female (17%). The number of researchers is increasing as initially planned. Meanwhile, increasing the ratio of female researchers (especially at PI level) is a key that we are still striving to achieve.

Research support staffs (incl. Research Assistant)	0	0	0	34
Administrative staffs	5	0	8	10
Total number of people who form the "core" of the research center	28	10	31	115

By October 2015, the total number of researchers will reach 71, including 24 non-Japanese researchers (33%). At this point we set the final staffing goal (Table 2 and Figure 12).

Our final goal consists of 10 collaborative researchers, 5 young and promising researchers at high-performance level (Associate Prof. level), and 40 young resourceful researchers (Assistant Prof. or postdoc level). Young researchers ranked at Associate Prof. level will lead their teams like a PI. Each PI will work closely with the newly appointed researchers ranked at Assistant Prof. or postdoc level. Most of the young researchers will be newly employed by international open recruitment adapted according to the Western recruiting calendar.

We will have a 5-year review of center operations in FY2016 and execute the ELSI reform agenda for next 5 years.

We will drastically reform our staff structure in accordance with the review in FY2017. After the reform we expect the fraction of non-Japanese researchers to be up to about 40%.

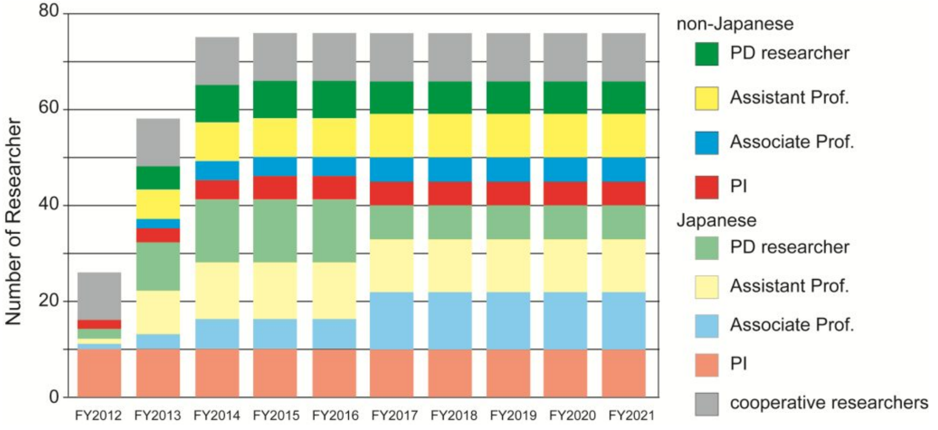

Figure 12. Expected number of researchers at ELSI.

ii) Satellites

1) Satellite Center

ELSI has three Satellite Centers, i) at the Geodynamics Research Center, Ehime University, (ii) at the Interdisciplinary Program, Institute for Advanced Study in Princeton, and (iii) at the Origin of Life Initiative, Harvard University. Each satellite function is as follows.

Geodynamics Research Center (GRC), Ehime University

GRC has shown globally leading research results in the fields of deep Earth science. Prof. Tetsuo Irifune will join ELSI as a Principal Investigator and Satellite Director. The other five GRC members (one female) will also join this Satellite Center (see Figure 13).

The main role of this Satellite Center at Ehime University is to conduct research on the origin and evolution of the solid Earth, primarily based on the high-pressure/high-temperature experiments using multi-anvil apparatus (large-volume press). Such multi-anvil experiments have a great advantage in controlling sample temperature over experiments by other techniques such as a laser-heated diamond-anvil cell, although the experimental pressure-temperature range is limited. The combination of both diamond-anvil experiments (K. Hirose at Tokyo Tech) and multi-anvil experiments (T. Irifune at Ehime Univ.) would provide the best answers to questions on the deep Earth structure and dynamics.

Interdisciplinary Program, Institute for Advanced Study (IAS) in Princeton

Prof. Piet Hut is based at the IAS in Princeton. He will divide his time between Tokyo Tech and Princeton, half and half. During his stay at Princeton, the Institute for Advanced Study will host both scientists and administrators from ELSI. The IAS is, of course, a world-leading research institute, always hosting more than hundred visitors from around the world. This is an ideal place for scientists to exchange ideas and establish their own personal connections. It is also a good place for administrators to learn about an efficient system at such a top-class institute.

Origin of Life Initiative, Harvard University

Prof. Jack Szostak will participate as a Principal Investigator and a Satellite Director on behalf of Harvard University Origin of Life Initiative. He is a world-leading scientist in synthetic biology. We will exchange young scientists to explore the origin of life, based on new information about the early Earth environments that will be examined by the main body of ELSI.

[Achievements, progresses and alterations from the plan at the start of the project: Fiscal year 2014]

○ New Satellite Institutes

In addition to the three existing institutes, Graduate School of Information Science and Technology, Osaka University was newly designated as a satellite institute of ELSI to strengthen the field of life science, especially areas associated with “the origin and evolution of life,”

Organization Name (1): Graduate School of Information Science and Technology, Osaka University

<Roles>

○ To elucidate the origin of life from the perspective of synthetic biology.

<Personnel and organization>

○ Personnel makeup as of the end of 2014 is as described below.

・Satellite Director and PI

Professor Tetsuya Yomo (Graduate School of Information Science and Technology, Osaka University /ELSI Tokyo Institute of Technology (under cross-appointment system)

・WPI Researchers

Assistant Professor Satoshi Fujii (ELSI, Tokyo Institute of Technology)

・Affiliated Scientist

Associate Professor Norikazu Hitotsubashi (Graduate School of Information Science and Technology, Osaka University)

<Collaboration Framework>

○ Promoting the research to elucidate the origin of life from the perspective of synthetic biology by collaborating and discussing with the researchers of ELSI.

Organization name (2): Geodynamics Research Center, Ehime University

<Roles>

○ Development of the accurate experiment technique for elastic wave velocity under the lower mantle condition and formulation of the estimation of heat conductivity under high temperature/high pressure condition, which is important to understand the thermal evolution of the Earth.

<Personnel and organization>

○ Personnel makeup as of the end of 2014 is as described below.

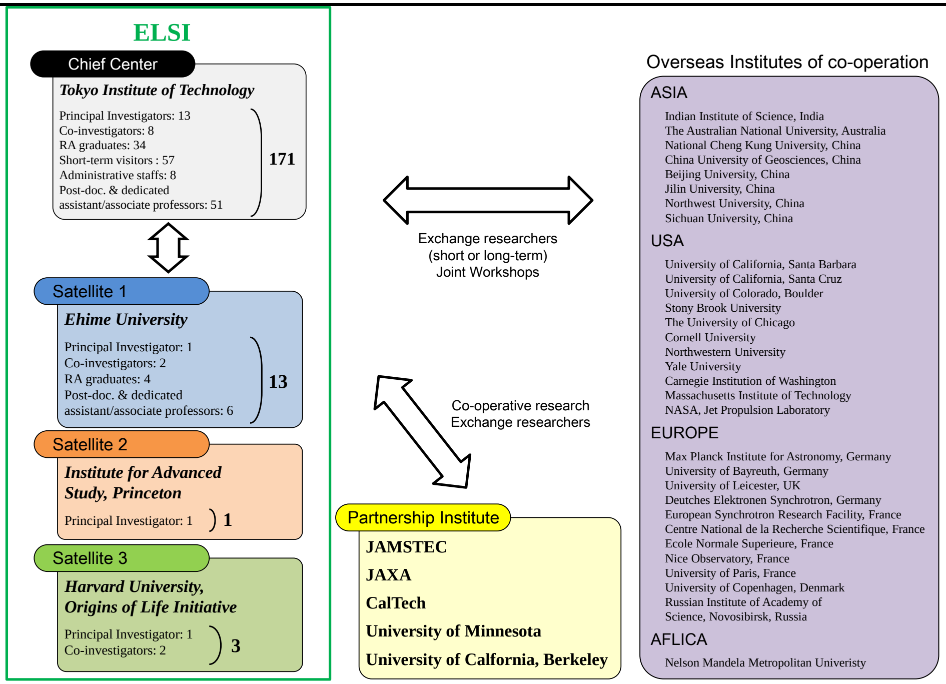

Figure 13. Collaboration with domestic and oversea research institutes, including the Satellite Centers and partner institutions.

2) Partnership Institutions

ELSI will have strong connections with (i) Japan Agency for Marine Science and Technology (JAMSTEC), (ii) Japan Aerospace Exploration Agency (JAXA), (iii) University of Minnesota, (iv) Harvard University, (v) California Institute of Technology, at which some Principal Investigators of ELSI are now based. Additionally, our partners include 38 institutions in 11 countries (Figure 13). ELSI promotes collaborative research with these institutions by exchanging people and ideas.

・ Satellite Director and Principal Investigator
Professor Tetsuo Irifune (Director, Geodynamics Research Center(GRC), Ehime University)

・WPI Researchers
Hiroki Ichikawa
Steeve Gréaux
Vincenzo Stagno
Wei Du

・Affiliated Scientists
Professor Taku Tsuchiya (GRC, Ehime University)
Associate Professor Jun Tsuchiya (GRC, Ehime University)
Associate Professor Yoshinori Tange (GRC, Ehime University)
Assistant Professor Masayuki Nishi (GRC, Ehime University)
Xianlong Wang (GRC, Ehime University /JSPS researcher)

<Collaboration Framework>
○ After the monthly discussion in the study groups, they plan the collaboration research and secure the funding for research.
○ A researchers' network, "TANDEM (The Asian Network in Deep Earth Mineralogy)," established by professor Irifune and other researchers is currently used to recruit young researchers.
○ Collaborations are being made through public relations activities of ELSI such as giving lecturers at scientific events in western Japan.

Organization name (3): The Interdisciplinary Program, the Institute for Advanced Study (IAS)

<Roles>
○ As shown in the column on the left, no changes.

<Personnel and organization>
○ Personnel makeup as of the end of 2014 is as described below.
・ Satellite Director and PI
Professor Piet Hut (Director of The Interdisciplinary Program, the Institute for Advanced Study)

・WPI Researchers
Jim Cleaves (stayed approximately nine months)
Yuka Fujii (stayed approximately five months at Goddard Institute for Space

	Studies (GISS) while stationed in IAS) <Collaboration Framework> ○ Continuing from the previous fiscal year, ELSI's unique way to promote interdisciplinary research was further established with knowledge and experience of IAS. ○ IAS welcomed ELSI researchers and offered opportunities for exchange views and collaboration with their researchers with various backgrounds. ○ IAS is a hub for recruiting foreign researchers. <u>Organization name (4): </u>Origin of Life Initiative, Harvard University <Roles> ○ As shown in the column on the left, no changes. <Personnel and organization> ○ Personnel makeup as of the end of 2014 is as described below. ・Satellite Director and PI Professor Jack Szostak (Origin of Life Initiative, Harvard Medical School) ・WPI Researchers Albert Fahrenbach (Appointed in September 2013 and scheduled to stay for nine months in a year) Yutetsu Kuruma (ELSI-based scientist, visits satellite institute for research meetings) <Collaboration Framework> ○ ELSI-hired young researchers visited both ELSI and Harvard University satellite institutes, and studied the origin of life from the view of synthetic biology. ○ ELSI-based young research scientists were given advice and support for their experiments. ○ The workshop "Origins of Life Chemistry Workshop" was held with the topic focusing on the research into the origin of life from the perspective of synthetic biology, while promoting exchange of researchers between ELSI and Harvard University satellite institute, the communities of the research field were expanded. [Achievements, progress and alterations from the plan at the start of the project: Fiscal year 2014] <u>Organization name (1): </u>Japan Agency for Marine-Earth Science and Technology (JAMSTEC)

	<Roles> (1) The agency conducts thorough investigations on where and how the substances (elements and molecules) that led to the early stage of life were synthesized and accumulated. In addition, the agency takes part in close examinations on how the initial period of ecosystems was created and evolved. (2) The agency builds methods to measure new stable isotopes and isotopomers and apply the method to analyze biological evolution from geological records. <Personnel and organization> ・PI: Ken Takai, Program Director (Extremobiosphere Research Program, Institute of Biogeosciences) ・Associate PI: Naohiko Ohkochi, Program Director (Marine Environment and Biosphere Transition Process Research Program, Institute of Biogeosciences) <Collaboration Framework> ○PI Takai and his laboratory staff are mainly responsible for role (1), while associate PI Ohkouchi and PI Yoshida's group are responsible for role (2). ○ In October 2014, young researchers were hired at ELSI to develop part of the joint research topics role (1). ○ Discussions are continuing for exchanging researchers and comprehensive collaborations going beyond the framework between the institutes. Organization name (2): Japan Aerospace Exploration Agency (JAXA) <Roles> ○ The Agency comprehends the process of planetary formation and the origin of minor planets as material celestial bodies with observation data on universally crucial characteristics and phenomena found on planetary/satellite surfaces or in the surrounding outer space (surface topography, composition, gravitational field, shock wave, magnetospheric dynamics, plasma motion, etc.), as well as remote sensing of the terrestrial planets. In addition, the Agency examines the possibility of the existence of life on icy satellites, which are believed to have oceans. Further, the Agency participates in examining technologies required for the next generation of space exploration, in order to contribute to planetary exploration as part of the medium- and long-term objectives. <Personnel and organization> ・ PI: Professor Masaki Fujimoto (Department of Space Plasma Physics, Institute of Space and Astronautical Science, JAXA) ・ PI: Professor Hitoshi Kuninaka (Department of Space Transportation, Institute of Space and Astronautical Science, JAXA)

	<Collaboration Framework> ○ Not only promoting joint research among ELSI researchers, the JUICE mission, where both PIs Fujimoto and Kuninaka are part of leading team, holds workshops to promote both the Hayabusa 2 project and ELSI science. Organization name (3): University of Minnesota <Roles> ○ The university examines the material compositions that comprise deep earth and the quantity in which such substances exist, based on a simulation using molecular dynamics first principles methods. <Personnel and organization> ○ Researcher: Professor Renata Wentzcovitch (Department of Chemical Engineering and Materials Science, University of Minnesota) <Collaboration Framework> ○ A theoretical model based on the origin of the Earth will be reviewed and adjusted by comparing the results of experimental research conducted at ELSI and seismic wave measurement data to the calculation results obtained at the University of Minnesota. Professor Wentzcovitch spent 40 days at ELSI in the fiscal year 2014 and promoted the research. ELSI young researchers were encouraged through seminars and group discussions. ○ One young researcher was assigned to help connect ELSI's experimental research with the University of Minnesota's theoretical studies. Organization name (4): California Institute of Technology (Caltech) <Roles> ○ The university presents a verifiable model of the early stage of the ocean, the atmosphere and the crust by retracing geological records. In particular, the continental distribution in the Hadean and the chemical composition of the atmosphere and the ocean in their initial stages will be thoroughly investigated. <Personnel and organization> ○ PI: Professor Joseph Lynn Kirschvink (Division of Geological and Planetary Sciences, California Institute of Technology) <Collaboration Framework> ○ PI Joseph Lynn Kirschvink stayed in ELSI for over five months in fiscal year 2014 as he had done so in the previous fiscal year and made adjustments to

	magnetic microscopes to search for traces of life in Martian meteorites, and conducted preliminary experiments. ○ PI Kirschvink accepted ELSI researchers to Caltech, and provided a learning opportunity for cutting edge research technology such as transmission electron microscope analysis and sample preparation methods. ○ ELSI accepted three Caltech students supervised by PI Kirschvink, and provided an opportunity for research exchange with other young researchers in ELSI. Discontinued collaboration Dr. Lisa Kaltenegger of Harvard University had been scheduled to begin her post as PI sometime during fiscal year of 2014. However, she was appointed a fulltime professorship at Carnegie University. She left Harvard University and the situation made her appointment at ELSI difficult. Therefore we came to the decision to discontinue the collaboration work. As mentioned earlier, Dr. Kaltenegger plans to continue with her effort to expand the astrobiology community and joint research with ELSI researches, especially with PI Ida's group.

6. Summary of center's research environment

< Plan at start of project >	<Results/progress/alternations from plan at start of project>
1) Environment in which researchers can devote themselves to their research **Earth-Life Science Institute (ELSI)** will try to provide the best environment for Principal Investigators (PIs) to concentrate on research. Two to three post-docs or dedicated assistant professors will be hired for each PI to form his/her research group. A couple of Research Advisors with academic background provide additional support in order for them to avoid miscellaneous tasks. They will also help non-Japanese PIs in general ways, including assistance in writing a proposal, communicating with external Japanese scientists, etc. PIs joining from Tokyo Tech will be reassigned as Professors of ELSI, which grant them a reduction in non-research responsibilities. They must be exempted from at least the duty of teaching undergraduate students. The Center Director is responsible for minimizing the administrative work by all researchers at the Center. For this purpose, a very efficient research-oriented administrative division will be created through several unique systems. Each administrator will be evaluated annually and given incentives, similarly to scientists. The Center holds a regular event to inform administrators of the Center's latest research results, which will lead to smooth communications between researchers and administrators and more importantly will motivate the administrators to work	1) Environment in which researchers can devote themselves to their research (1) Researcher oriented Environment The structure of the Administration Division was reviewed. To strengthen public relations, the Public Relations Office in the social cooperation division goes under direct supervision of the Director. The secretarial office was also created to strengthen the research support system. <Members> The Administrative Director, the Assistant Administrative Director and the Chief of the Secretaries Management division and foreign researchers support division (one each of chief of affairs and chief of finances, and three administrators) ・Secretaries' Office (four administrative staff) ・Public Relations Office (one education research support staff, and one administrative staff) ・One Coordinator for International Initiatives ・One staff in charge of the computer networks ・One staff in charge of research support

for the research. Some of the administrators will stay at the Institute for Advanced Study in Princeton, our satellite institute, for a few months to learn their highly effective administration system.

2) Startup research funding

Each PI invited from overseas will be granted JPY5 to 10 million, depending on theoretical or experimental work, to start up his/her research project. For the second year, another JPY5 to 10 million will be provided. Further support is possibly given until he/she obtains external funds based on the discussion with the Center Director. The Center will provide non-Japanese PIs a full range of support to acquire large-scale competitive funds in Japan. We also provide JPY6 million start-up funds to dedicated research associate professors.

3) Postdoctoral positions through open international solicitations

The Center will hire three ranks of researchers besides PIs; 1) post-docs, 2) dedicated research assistant professors, and 3) dedicated research associate professors. More than half of the post-docs and dedicated assistant professors will work with one of the PIs, while the rest of them have more freedom in their research with only loose connections to specific groups. All dedicated associate professors are independent (assistant professors in Japanese universities are traditionally not independent). These three classes of researchers are recruited through open international solicitations. The Center Director will make their best efforts to advertise the recruitment internationally.

4) Administrative personnel who can facilitate the use of English in the work process

The official language must be English for non-Japanese and Japanese alike. Every document will be written in English. A few officers of Tokyo Tech who can use English will be assigned to the Center as a priority. We will also hire excellent English-speaking staff members from outside, and we will actively encourage the employment of staff, Japanese and non-Japanese, with international experience. In addition, some of the administrative staff at the Center will stay for three months at the Institute for Advanced Study in Princeton, our Satellite institute, in order to experience and learn their highly efficient administrative system and its operation.

5) Rigorous system for evaluating research and system of merit-based compensation

The evaluation of the research activity by each scientist will be made annually. It will be based on publications in academic journals and on the scientific merit of his/her research. The Annual Evaluation Workshop will be held in March for the latter purpose.

(2) Research Startup Funding

○Based on the funding provided by our WPI budget and Tokyo Tech's support, we set aside 500,000 to five million yen expenses for PIs and researchers recruited from other institutes.

○We established the ELSI Director's Fund and built a support system for interdisciplinary research teams consisting of young researchers with various fields of expertise. (Maximum ceiling of three million yen)

(3) International Postdoctoral Recruitment System

○ There were no continuous and large-scale recruitment campaign in the fiscal year 2014. As international recruitment is planned for next year and beyond, we focused on showcasing the appeal of ELSI to young researchers gathered from various nations by setting up booths at well-known international conferences.

(4) Administrative Personnel with high English communication skills

○Currently, 11 administrators and secretaries are bilingual out of total 15 administrators and secretaries (11 administrative staff and four research support staff). They communicate with researchers both in Japanese and English. We attempted to strengthen and enhance foreign researcher support especially in accounting and administrations and daily life support.

Further, the Secretaries' Office was created to establish a support system that foreign researchers can feel comfortable and easy to ask for their support.

In addition, we accepted nine foreign researchers and 136 visitors, and held 42 international workshops and conferences.

○Implementation of Japanese education

We offer Japanese Language training twice a week for foreign researchers to gain day-to-day communication skills to live in Japan.

○We held "experiment rules and regulations session" in English with Tokyo Tech for researchers involved in experiments in order to build safe and secure experimental environment.

(5) Introduction of Research Achievement Evaluation System and Performance-based Salary System

○Based on the provision of the incentive scheme for those who contributed significantly to ELSI, we offered monetary rewards to nine, including two administrative staff.

○Holding of Annual Evaluation Meeting

Following the previous year, the mandatory Annual Evaluation Meeting was held over two days at the end of January 2015. Based on criteria on the Research Activity Sheet submitted prior to the evaluation and a 15 to 20-minute presentation/discussion, ELSI employed researchers and PIs evaluated each other.

The Center secures better salaries for PIs than their previous employment conditions. Their annual salary will be determined on the basis of their research output, contributions to Center's overall activities, and the acquisition of external competitive funds. For outstanding research outcomes or contributions by all scientists, the Center will provide better research environments (space, financial support, post-docs, etc) as incentives.

Not only researchers but also administrators will be evaluated annually. For their superior works, the Center will give them an opportunity to be dispatched to our oversea satellite institute.

6) Equipment and facilities, including laboratory space, appropriate to a top world-level research center

Tokyo Tech will secure sufficient research space (about 1500 m^2 from start and additionally up to approximately 2100 m^2 by 2015) for the Center at the Ookayama Campus, close to the building of the Department of Earth and Planetary Sciences. In addition to research space (offices, laboratories), we will prepare a Common room to promote internal communications, which is key for interdisciplinary studies. People gather in this room for their short break and for daily and weekly events organized by Research Advisors.

The access to research equipments, in particular to large scale parallel computers for simulations, is abundant. The computer center of Tokyo Tech (GSIC) has the most advanced supercomputer in the research institutes in Japan. In addition, GRAPE series of custom-built supercomputers, developed by J. Makino's group, will be accessible to researchers of the Center. Also, 10-Petaflops K computer and other supercomputers in national research institutes, including National Astronomical Observatory, JAXA and JAMSTEC are accessible through PIs.

7) International research conferences or symposiums held regularly to bring world's leading researchers together

International symposium will be held annually. They will cover a wide range of topics, with different clear-cut key concepts in each year, based on original research at the Center. More than twenty world-leading scientists and young active researchers will be invited from abroad with and without travel support. The symposia will be held in autumn, the best season to recruit promising young researchers. Other relatively small symposiums on specific hot topics as well as interdisciplinary topics will be held several times each year.

Additionally, Annual Evaluation Workshop will be held in March, at the end of the Japanese fiscal year, in which all the scientists at the Center must present on their research made in corresponding year. Only a small number of key scientists and International Advisory Board members will be invited. The primary purpose of this workshop is to evaluate the research activity by each scientist and to redirect the

The main criteria in the evaluations were as follows: 1) The quality of the research including publications such as papers) and the compatibility with the research purpose of ELSI, 2) if the research is taking interdisciplinary research into consideration, and 3) if, especially young researchers, the researcher conducts research independently. The executive office, the Director, the Vice Directors and Administrative Director summarizes the result of the annual meeting. One PI and an associate professor were awarded the PI Research Award 2014 for promoting excellent research, and nine young researchers were awarded ELSI Incentive Award 2014. In addition, the Director had feedback interview with all the researchers individually based on the evaluation results.

(6) Establishing Facilities and Environment for the World's Top-Level Researchers

○Active research interactions are continuing through twice-weekly brown bag seminars and daily coffee break in the existing building (2,670m^2) in Ookayama Campus (Ishikawadai area). The renovation of the building completed in previous fiscal year.

○In addition to the ELSI building, a new 5,000 m^2 building with research facilities was completed in March 2015.

○The layout arrangement of the research facilities and the preparation of relocation were mainly taken care of by Building Committee in fiscal year 2014. The procurement and setting up of the research facilities were completed in fiscal year 2014 as per planned earlier, and the various types of equipment are operating smoothly.

(7) International Conferences and Symposiums held Regularly to Bring the World's Leading Researchers Together

○One international symposium and 41 international workshops and seminars were held in fiscal year 2014. Five study groups (SGs) regularly held research meetings.

○Further, in August 2014, a summer school was held for practical training on the numerical model that uses the computing resources of ELSI regarding planetary formation and the evolution of the early Earth. Twenty-four graduate students and young researchers, from both domestic and international institutes, participated, leading to a resounding success.

(8) Other Activities

○In order to contribute to promoting the world's top-level interdisciplinary research activities, seven research advisors actively offered research guidance and advice from their professional standpoint.

○ The Research Strategy Promotion Center and the Assistant Director, who also serves as a Research Administrator, are providing support to secure external funds for all researchers.

emphasis of the Center's research if necessary.

8) Other measures, if any

Living conditions will probably be the biggest concern for most non-Japanese scientists. To best serve them and their families, the Center will assign a "Life adviser" to each family even before they move to Japan. This adviser will guide them through all the difficult processes and will always be available to advise on procedures such as visa, school, bank account, special diets, garbage, transportation, taxes, pension, etc. The adviser essentially acts as a personal assistant for non-Japanese scientists when needed. Tokyo Tech has an accommodation facility called the 100th Anniversary International House with 100 single rooms and 20 family rooms in its Ookayama Campus. It can be temporally used for non-Japanese scientists and families until they find a place to live outside.

Another challenge for non-Japanese scientists will be the acquisition of external funds for their research. Both Research Advisors and other Center staff members in related fields will be strongly involved in their preparation of proposals. The university's Research Project Support Center and Research Strategy Office will also support non-Japanese scientists to acquire competitive funds.

7. Criteria and methods used to evaluate center's global standing

< Plan at start of project >

i) Criteria and methods to be used for evaluating the center's global standing in the subject field

Our research is highly academic. Even for such academic accomplishments, evaluation requires comprehensive assessment with various criteria and methods. However, the evaluation is often made on the basis of publications. It may be still useful to assure the activity, quality, and recognition of research.

Here we indicate ELSI's global standing from the perspective of "research activity" and "research quality". To evaluate such perspectives, assessment referring to the number of published articles and their citations is one of the most primary and objective criteria. Thomson Reuters have developed a database for this purpose. Here we used the University Science Indicator (USI) as the most authoritative index to compare the research levels of world-top universities in each field.

ii) Results of current assessment made using said criteria and methods

a. Number of papers per faculty staff (PI) per year

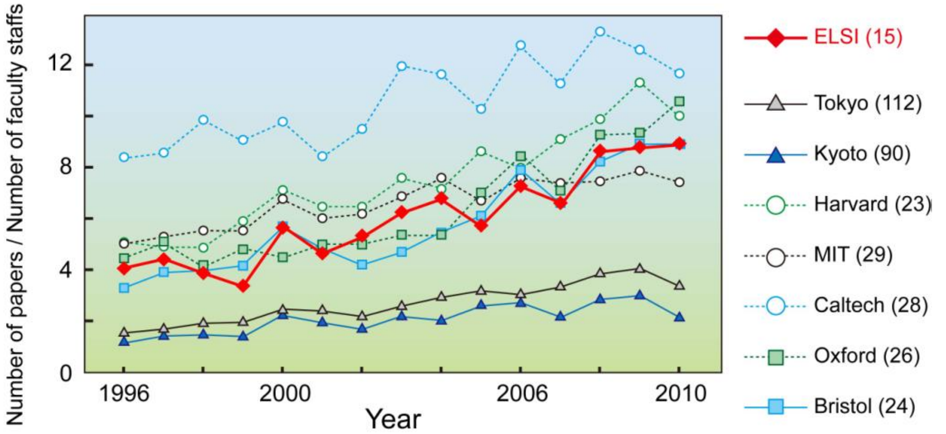

Figure 14. Research activity defined by (Numbers of papers) / (Number of faculty staffs) in the top universities in Japan, U.S. and UK (Thomson Reuters, USI Database 1996-2010, results from the fields of Geology, Geochemistry & Geophysics, Environmental Science, and Geoscience, Multidisciplinary). The number of faculty staff at each institute is from its website in 2007. Productivity of papers by PIs of ELSI is at a global top standard.

In order to assess our research activity, we adopt (Numbers of papers) /

<Current assessment>

i) Criteria and Methods to be used to Evaluate the Center's Global Standing in the Subject Field

○ As shown in the column on the left, no changes.

ii) Current Evaluation Based on the Aforementioned Evaluation Indices and Methods

○ There were 175 peer-reviewed papers with ELSI mentioned as the author affiliation during 2014 (279 including ELSI-related papers). There were also 12 books, inclusive of textbooks and 17 reviews.

○ It takes at least several years following the publication of a paper for research activity and research quality to become significant in terms of statistics and bibliometrics. Based on this fact, Web of Science by Thomson Reuters was used to survey the number of citations.

○ The papers forming the subject of this survey were those published between 2012 to 2014. There were 200 papers with ELSI as the author affiliation. Six papers were among the top 1% of the most cited papers, while 24 were in the top 10%.

○ One of ELSI's missions is to become a global hub that handles researches on the origin and evolution of Earth and life. As indicated by this goal, the research fields that ELSI directs are still minor compared to the global scientific community. Under such circumstances, the fact that 15% of the total number of papers fall within the top 10% of cited papers or better is quite a positive result for a fairly new laboratory.

○ According to the Japanese University benchmarks 2011, which focus on research papers (NISTEP, 2012), the world's top class universities have one in about four to five papers falling in the top 10% of cited papers. The current goal is for the number of citations for the papers originating from ELSI to reach such numbers.

iii) Goals to be Achieved Through the Project (at interim and final evaluations)

○ As shown in the column on the left, no changes.

(Number of faculty staffs) for each year. Figure 14 above shows the change in this index during 1996 to 2010, for the world-class Earth and Planetary Science departments at universities in US, UK, and Japan, in comparison with that by our PIs at ELSI. It clearly shows that the research activity of our PIs far exceeds those at Japanese two major universities, and is indeed comparable to those at world-leading institutes.

b. Impact of papers in subject area

We use an index of (Number of citations per publication in a given field) / (Total number of citations for all publications in that field) to assess our "research impact". We chose Geochemistry & Geophysics for papers by our PIs, except for S. Maruyama (Geology), N. Yoshida (Environmental science), and P. Hut and J. Kirschvink (Geoscience, multidisciplinary). We calculated average values of 4 fields for leading universities and ELSI. The results are shown in Figure 15 below, for the year of publications.

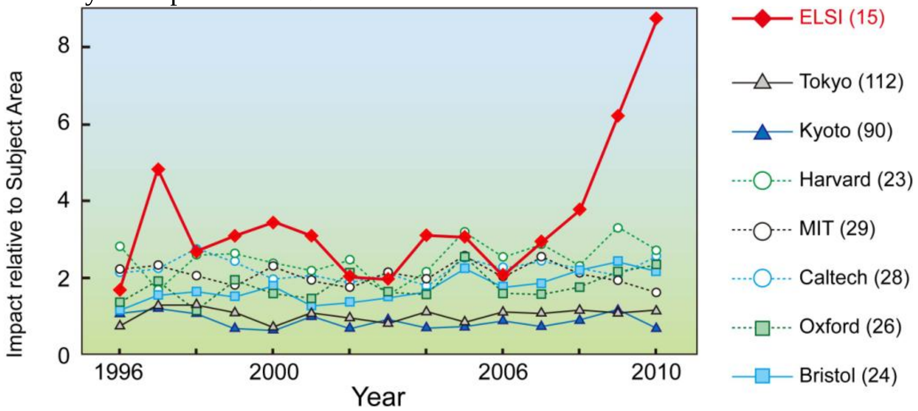

Figure 15. Research impact defined by (Average number of citations per publication in a given field) / (Total number of citations for all publications in that field) for papers published in a specific year (Relative Impact Factor, Thomson Reuters, USI database). The number of citations for papers by our PIs is indeed world-leading.

This plot shows that papers published by our PIs have been well cited in each corresponding field. Sudden increase after 2009 was caused primarily by a hot paper published by the group led by R. Wentzcovitch. Even without this paper, our publications have been cited more times than those reported from the world top-level departments in Earth and Planetary Sciences, indicating that our research impact is really world leading.

Additionally, 8 out of 15 PIs in ELSI have "h-index" higher than 35 (see

Biographical sketches). It is clear that ELSI exhibits a strong prospective to stand out globally as top-level research center in the world.

iii) Goals to be achieved through the project (at time of interim and final evaluations)

Once ELSI is established and starts research fully with world-top level and young promising scientists, we can naturally expect that our research activity will be enhanced substantially. ELSI should be top in the world in both research activity and impact defined above in five years. Each scientist of ELSI will pursue ambitious interdisciplinary sciences, with retaining their excellencies in each individual field.

Additionally, Tokyo Tech has well known experts in the field of project assessment or scientometrics. In cooperation with the university's Research Strategy Office, ELSI will utilize new objective assessment program to assure the quality of research, as well as to advance research and research policy, by giving feedback to our community and funders.

Measure or Indicator	5 Year Target	10 Year Target
World leadership, relevance and quality (Annual review)	・Globally competitive	・The only world-leading center in all of its subject fields
Research activity*1 and Research impact*2	・Top in the world in both Research activity and impact	・Same
Business Development	・Develop trend analysis for research funds ・Establish framework for collecting donations ・Young researchers annually obtain competitive funds of JPY 110M.	・Stable operation of collecting donations ・Young researchers annually obtain competitive funds of JPY 175M.
Development of Research Talent	・40% of young researchers come from overseas	・More than 30% of young researchers are female
Effective support for international visitors	・80% of visitors assess support as outstanding	・Same

$$^{*1}\text{Research activity} = \frac{\text{Numbers of papers}}{\text{Number of faculty staffs}}$$

$$^{*2}\text{Research impact} = \frac{\text{Number of citations per publication in a given field}}{\text{Total number of citations for all publications in that field}}$$

Figure. Goals to be achieved through the project

8. Securing competitive research funding

<Plan at start of project >

i) Past record

Ten Japanese PIs have secured a lot of research funds including Grand-in-Aid for Science Research (KAKENHI), sponsored research funds, collaborative research funds, and university grants/operating subsidies. The amount of obtained funds between FY2007 and FY2011 are summarized in Table 3 (the effort ratios of PIs are taken into account). Prospective funds for FY2012 and FY2013 are also listed.

The dominant fund is KAKENHI. Indeed, the 10 Japanese PIs have constantly acquired large-scale KAKENHI programs such as Specially Promoted Research, Scientific Research on Priority Areas, Scientific Research on Innovative Areas, and Scientific Research(S). The annual average of the total amount of KAKENHI between FY2007 and FY2011 is JPY 294 million, and we can see that the amounts of KAKENHI have been demonstrating an upward trend. Also, the 10 Japanese PIs have obtained sponsored research funds and collaborative research funds. Especially in FY2011, they see a remarkable increase in those funds.

The annual average of the total research funds obtained by the 10 Japanese PIs between FY2007 to FY2011 is about JPY 670 million/year and this is equivalent to about 96% of our requesting WPI grants (JPY 700 million).

Figure 16 shows the total amount of funds obtained by the 10 Japanese PIs and another 8 Japanese researchers who will join ELSI from the beginning. The annual average from FY2007 to FY2011 becomes about JPY 980 million/year, which exceeds our requested level of WPI grants.

We conclude that ELSI's capabilities of securing research funding are substantially matched to the WPI program.

Table 3. Total amount of research funds obtained by 10 Japanese PIs over the past five years (FY2007 - 2011), with promised funds for FY2012 and FY2013.

Unit : million yen

	FY2007	FY2008	FY2009	FY2010	FY2011	FY2012	FY2013
Grants-in-Aid for Scientific Research (KAKENHI)	272.30	262.84	271.26	305.23	359.61	458.45	509.80
Sponsored Research	114.09	117.51	72.17	64.48	296.07	221.73	221.73
Collaborative Research	29.70	25.85	30.80	36.30	105.88	92.13	77.83
University Grants/ Operating Subsidy	189.18	255.29	168.77	177.29	215.14	182.22	181.73
Total	605.26	661.49	543.00	583.29	976.69	954.52	991.08

※1 provisional data identified at 30 June, 2012

<Results/progress/alternations from plan at start of project>

i) Past record

No changes

Research funding acquired during fiscal year 2014 (The amount takes into account the effort put forward by ELSI)

6.16 million USD (616 million yen) Conversion rate:1 USD =100 JPY

ii) Outlook Following the Establishment of the Research Institute

○ No changes at the time of institute establishment.

○ Main activities related to securing competitive funds in fiscal year 2014.

- In order to assist researchers to apply for as many funding programs as possible, we made an effort to disseminate available information about funding program opportunities besides focusing on improving the environment to help them concentrate on their research.
- A start-up budget was provided as planned to new researchers to start their research smoothly. The budget was allocated to them contingent upon applying for external funding opportunities.
- We set up a support system for foreign researchers applying for Grants-in-Aid for Scientific Research. In particular, the system provides guidance on selecting the application items, handles administrative procedures for them, prepares the research overview section of the application in Japanese at minimum, and assists in preparing a budget plan by taking Japanese business practices into consideration. Similar support was also provided to young Japanese researchers who do not have prior experience in applying for Grants-in-Aid for Scientific Research. We also make use of seminars to apply for the Grants-in-Aid for Scientific Research hosted by Tokyo Tech Research Strategy Promotion Center.
- Through our ongoing fund-raising activities, research fund was acquired from a US Foundation.

○ The Research Strategy Promotion Center and the Assistant Director in charge of the research administration support all researchers to acquire external funding.

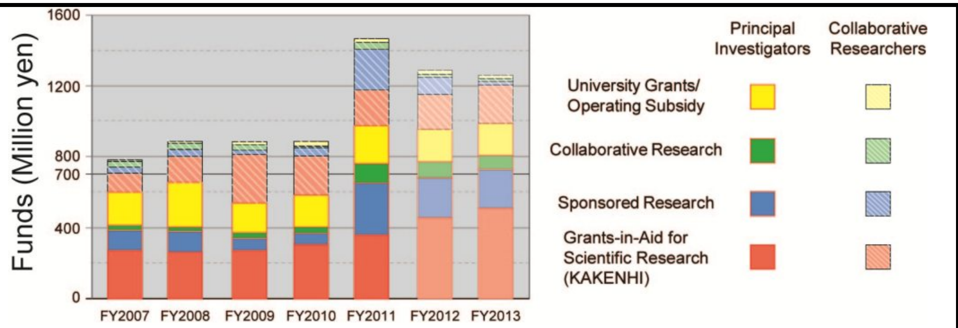

Figure 16. Annual variations in the total research funds obtained by the 10 Japanese PIs and another 8 collaborative researchers between FY2007 and FY2011. The dashed bars of FY2012 and FY2013 indicate those informally-promised by the end of June 2012.

ii) Prospects after establishment of the center

We expect funds acquired by the 10 Japanese PIs and by the other 8 Japanese independent researchers should be at least JPY 600 million/year and JPY 300 million/year, respectively. Based on results in the past 5 years and the current trend (in the preceding section), we think these figures are probably realized. Note that the sum of these figures, which is JPY 900 million/year, already exceeds the amount of funds from the WPI program. In addition, we expect other members of ELSI including the foreign PIs (5), adjunct associate professors (10), adjunct assistant professors (20), and PDs (21), whom ELSI will recruit, to annually obtain JPY 140 million (2.5 million yen/person) or more by FY2015 and beyond. In total, we expect the funding that all the members of ELSI will obtain should be more than JPY 1000 million/year (Figure 16).

In order to ensure that the expected funding appears, we provide the following structured and strategic efforts to all researchers in ELSI.

- By creating an environment in which all researchers in ELSI can concentrate on research, we will allow them to apply for more competitive funding programs.
- Research Advisors will fully assist PIs in acquiring funds, including arranging financial support and applications with the help of the project support center of Tokyo Institute of Technology.
- We will provide comprehensive support to individual investigators in preparing competitive grant proposals to funding agencies in Japan and elsewhere, including: start-up funding for feasibility studies; English and Japanese language editorial support; opportunity identification; training and mentoring of early-career staff in proposal development; brokering of internal and external collaborations; and rigorous internal review prior to proposal submission.

The operation and administrative directors should regularly develop some trend analysis of national policy objectives, related subsidies, and competitive funding programs with the help of the policy making body of Tokyo Institute of Technology. This will ensure a cost-effective approach to support basic funding applications and the more complicated and demanding approach necessary for foundations and other large sources of funds. We will propose new future-oriented large-scale projects to the government on the basis of the trend analysis.

One of ELSI's challenging subjects is to secure endowed research funds. The public relations departments will examine possibilities of donations from education business communities and a framework for collecting small donations from individuals and corporations in ELSI operations. We aim at raising our collaborative research funds including endowed funds to more than JPY 150 million by FY2019.

The Tokyo Institute of Technology will cover funds for the labor expenses for internally hired researchers (PIs: 6 professors and associate professors with 80 to 90% effort rate (= Effort 1); co-researchers: 8 professors and associate professors with 50% effort rate) and administrative staff members, and will provide large equipment, etc., that should be worth about JPY 145 million a year.

In summary, we expect to secure resources greater than the amount allocated as WPI grants throughout the implementation period with the funds acquired through the above efforts (Figure 17).

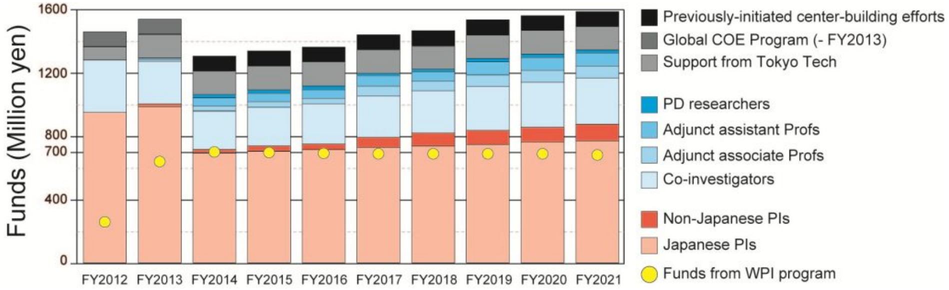

Figure 17. Prospects of research funds. The total amounts of KAKENHI, sponsored research funds, collaborative funds, and university grants/operating subsidies will far exceed the amount of requested fund from the WPI program (yellow balls). Additionally, this figure includes the support from G-COE program until FY2013 and its compensation from the President's discretionary fund after FY2014.

(8) Exploiting the results of previously-initiated center-building efforts (when applicable)

Program name: Global Center Of Excellence program (G-COE)

Project title: From the Earth to "Earths"

Representative's name: Shigeru Ida
Funding period: FS2009-2013

Related to the G-COE program above, the university provided the following support for our activity:

Financial support

- FS2009 JPY9,150,057
- FS2010 JPY5,632,000
- FS2011 JPY4,063,000
- FS2012 JPY4,161,000

Provision of research space

- Room 403, 404, 405 in Ishikawadai no.6 Building in Ookayama campus
- Room 009, 011, 017 in G1 Building in Suzukakedai campus

Total 10 units (1 unit: ~26 m^2)

・Describe why you believe that you can yield a top world-level center by applying new concepts to the heretofore results of your previously-initiated center-building efforts.

Previous G-COE programs have focused on the relationship between environmental change and evolution of life on Earth. Our focus was particularly on organisms in the Cambrian explosion and Snowball earth event 500 - 600 million years ago. We have carried out studies including geological decoding of environmental change before and after the snowball Earth event and genome analysis of photosynthetic organisms in relation to adaptation to land. We also looked at the evolution from prokaryotes to eukaryotes 1.9 – 2.0 billion years ago. Generalizing these results, we have tried to discuss requirements for enlargement of life and adaptation to land on extra-solar terrestrial planets. We recognized the role of solid Earth and environmental influences in the galaxy (influences of the universe) for variation of the Earth surface environments. This motivated us to make a project plan of ELSI with emphasis on the role of solid Earth led by a solid-earth geophysicist, Prof. Hirose as a leader. Research in ELSI will also highlight the early Earth as the place of origin of life. Therefore, not only solid earth science, but also a theory of planet formation would play an important role.

Using our experience to explore the relation between the snowball Earth event and discontinuous biological evolution, ELSI will explore the relationship between the early Earth and the origin of life. We have already been focusing on Japanese geothermal and serpentine hydrothermal areas - Hakuba hot springs, which are thought to be modern analogues of hydrothermal area on the ocean floor, a promising location for the origin of life. We have collected microorganisms living in those extreme environments and we have analyzed their genomes.

In addition, data on life in extreme environments would be required to make our discussion of the origin of life on the early Earth scientifically reliable. To achieve this, research projects in ELSI will closely link to the national projects of a sample return mission for a primitive asteroid by JAXA's "Hayabusa-2", a possible future mission to icy satellites, and exploration of deep-sea hydrothermal organisms by Japan's renowned "Shinkai 6500", which is run by the Japan agency for marine-earth science and technology (JAMSTEC). It is the Earth that links deep ocean to deep space (satellites of Jupiter and Saturn) in terms of life. The obtained knowledge would lead to understanding of life in a myriad of extra-solar terrestrial planets in the Galaxy.

The precursor programs 21COE - How to build habitable planets? (2004 -2008) as well as G-COE - From the Earth to "Earths" (2009-2013) have achieved results by active collaboration of the history of the Earth, a theory of planet formation and ultra-high pressure experiments, which are Japanese specialty, with life science. Based on these results obtained by wide-field interdisciplinary collaboration, ELSI will much further proceed this line with emphasis on the role of solid Earth and universe. It will also focus on not only the evolution of life but also the origin of life by involving "Hayabusa-2" and "Shinkai 6500". Thereby, we believe that ELSI will become a world-leading institute.

- Describe concretely your prospects for securing the same scale of the measured amount through independent resources after that funding eventually ends in future.

After the funding from the above-mentioned G-COE program ends in 2013, the university has promised that they will provide US$1,125,000 every year after 2014 until the end of this WPI program from the president's discretion money. This amount of money is equivalent to the support from the G-COE program.

9. Other important measures taken to create a world premier international research center

<Plan at start of project >

1) Activities after the end of the program period

The Center Director will do his utmost best to seek donations to ELSI from international nonprofit corporations and from companies with close relations to Tokyo Tech. Several research topics of ELSI, such as extraterrestrial life and the space craft "Hayabusa" are of general interest to the public, which may help us to

<Results/progress/alternations from plan at start of project>

(1) Activities Following the Completion of the Funding Period

○To make ELSI a permanent institute, Tokyo Tech shall continue to view ELSI as its main institute by providing assistance with funding, research space and personnel. Tokyo Tech takes donations as the most fundamental source of funding.

collect donations.

After the end of the support under the WPI program, the activity of ELSI will continue based on 1) external funds acquired by Principal Investigators and other members, 2) continued support from the university, and 3) donations from outside.

2) Effects on other institutions

Internationalization is one of the important goals of this program. 1) English-based administration, 2) merit-based annual salary & incentive, 3) non-Japanese family support systems will be secured at the Center. These can be models for other institutions to host researchers from abroad.

ELSI will be highly research-oriented institute. For this purpose,

- Annual Evaluation Workshops will be held to evaluate the research results by each scientist, which reflect in the annual salary and incentive given by the Center Director.
- Research Advisors with academic background will provide a wide range of support to all scientists.
- PIs from Tokyo Tech will be reassigned to the Center, in order to be exempted from the duty of teaching undergraduate students.
- A research-oriented Administrative Division will be created through 1) evaluation by researchers, 2) consequent merit-based incentives, 3) dissemination of the latest research results, 4) stays at the overseas satellite center to learn efficient system.

These unique systems may be helpful for other organizations to become more highly research-oriented.

ELSI will have strong connections to the general public.

- Research Communicators with full academic background will be in charge of overall outreach activities.
- They will organize 1) press releases, 2) regular meetings with reporters/journalists, 3) a Summer Internship Program for high-school students, etc.

Active outreach will make the ELSI and the host institute more visible from the outside, which will be a big advantage for each institute.

3) Other plans important for the establishment of a leading global research center

ELSI will be a world communication center in related research fields. We will invite top-level professors on sabbatical leave to stay for half a year or a year as well as support short stays by both established and young active scientists. At the same time, the Center will encourage all scientists including PhD students to stay at oversea partner institutions for a while to exchange ideas and collaborative research.

○ Through our ongoing fund-raising activities to foreign institutes with focus on interdisciplinary research, promotion of international joint research, and finding excellent talent, we were able to receive research funding from a US foundation.

(2) Influence on Other Institutes

1) Internationalization

○ Currently, 11 administrators and secretaries are bilingual out of total 15 administrators and secretaries (11 administrative staff and four research support staff). They communicate with researchers both in Japanese and English. We attempted to strengthen and enhance foreign researcher support especially in accounting and administrations and daily life support.

Further, the Secretaries' Office was created to establish a support system that foreign researchers can feel comfortable and easy to ask for their support.

In addition, we accepted nine foreign researchers and 136 visitors, and held 42 international workshops and conferences.

○ Implementation of Japanese education

We offer Japanese Language training twice a week for foreign researchers to gain day-to-day communication skills to live in Japan.

2) Research Direction

○ To attract world-renowned researchers in the field of life science, especially in "the origin and evolution of life," the newly created cross- appointment system at Tokyo Tech was applied, a professor from Osaka University was hired as the new PI. In addition, an agreement was made that Graduate School of Information Science and Technology, Osaka University would be a satellite institute of ELSI. One associate professor and one assistant professor in the life sciences were hired.

○Annual Evaluation Meeting and ELSI Incentive Award

As reported in 2. Organization (1) General, Following the previous year, the mandatory Annual Evaluation Meeting was held over two days at the end of January 2015. Based on criteria on the Research Activity Sheet submitted prior to the evaluation and a 15-minute presentation/discussion, ELSI employed researchers and PIs evaluated each other. Nine researchers who were deemed superior in their research activity for the year were given ELSI Incentive Awards. To encourage the researchers who won the awards, research funds and extension of their employment contract were given.

○In order to contribute to promote the world's top-level interdisciplinary research activities, seven top-level researchers from various research areas were appointed as Research Advisors and they actively give suggestions and advices.

○ Based on the provision of the incentive scheme for researchers who contribute the most at ELSI, nine were given monetary rewards.

3) Outreach Activities

We will also dispatch administrators to our oversea satellite institute (Institute for Advanced Study in Princeton).

Researchers at ELSI will be actively encouraged to organize sessions closely related to their research topics at relevant international conferences. The Goldschmidt Conference, which gathers 4000 researchers from all around the world, will be held in Japan in 2016, which is a good opportunity to summarize our research results in the midst of the project.

We already have nine years of experience of interdisciplinary research between geoscience and life science through 21st-Century COE and G-COE programs. Additionally, ELSI will have several plans to unite the team to explore the early Earth and life. First of all, we need to promote internal communications within ELSI. We will therefore prepare a Common room as well as daily, weekly, and monthly events following the model of IAS, Princeton, where Prof. Piet Hut, one of PIs, is based. Second, we may replace some PIs after midterm evaluation, based on their research performance. And third, the Director will co-supervise each young scientist. Under the supervison by the Director, they will interact not only with their main advisor but also with other PIs to promote interdisciplinary research.

ELSI will have several young active Associate PIs in addition to PIs. They will make significant scientific contributions in environmental chemistry and synthetic biology. Such Associate PIs will have their own research group at ELSI.

(1) The outreach system was reinforced to focus on to make ELSI’s activities more visible to overseas.
(2) Research communicators with sufficient scientific background handled the overall ELSI’s outreach activities.
(3) We conducted outreach activities with research communicator in (2) playing the central role. Specifically, a) press releases, b) regular conferences between researchers and media staff/journalists, c) laboratory visits by the local elementary schools (experiment class), and seminars and lectures for local residents.
(4) Thirty-two public events (seven for especially for school-age children and one for local residents) were held. In addition, 36 research reports were appeared in newspapers, and 25 in books and magazines. Papers and research update information generated at ELSI were collected monthly and published on our website.
(5) The first session of “Tokyo Tech Inspiring Lecture Series” a new activity in Tokyo Tech was hosted by ELSI. Four members, including the director and PI Szostak, gave lectures on “Origins: Earth and Life”-Science at ELSI-the forefront research at ELSI.

(3) Other

1) Overseas Exchange Opportunities for Researchers

○ During fiscal year 2014, a total of 218 researchers were invited (136 foreign researchers) for approximately one week to one month, and they had discussions on the promotion of joint researches with ELSI researchers, and research cooperation for the next year and beyond. The invited researchers were requested to lecture and present topics at ELSI seminars and brown bag seminars; These opportunities provide ELSI researchers with interacting with researchers from different fields.

2) Announcing Research Achievements

○ We presented the affiliated researchers’ research achievements at the 3-day International Symposium held from 13 to 15 January 2015. Participants discussed ELSI’s research strategy by taking these achievements into consideration.

3) Improving the Research Environment

○ We created a roadmap that clearly indicates the current position and future direction taking the aspects specified by the Program Committee.

○ ALL ELSI meetings instead of a monthly PI meeting

With the newly hired researchers and increase in the support staff, ALL ELSI meetings were held with all ELSI-affiliated staff The Director provided updates happening in ELSI

	○ In order to overcome “language barriers” and “cultural barriers” and to promote mutual understanding among researchers with various backgrounds, the following events were implemented. ・ELSI Assembly (twice a month): Research presentations and discussions by ELSI members. ・ELSI Seminar (as needed): Research presentations and discussions by external researchers. ・ELSI Forum (as needed): Panel discussions on ELSI research topics. ・Brown Bag Seminar (twice a week): ELSI members take turns introducing their research and topics to researchers in other fields at lunch time. ・Coffee Break Meeting (daily): Held in the Communication Room at 3 pm to promote communication among researchers in different fields. ○ Active research interactions are continuing through twice-weekly brown bag seminars and daily coffee break in the existing building (2,670m2) in Ookayama Campus (Ishikawadai area). The renovation of the building completed in previous fiscal year. ○ We held “experiment rules and regulations session” in English with Tokyo Tech for researchers involved in experiments in order to build safe and secure experimental environment. ○ In addition to the ELSI building, a new 5,000 m2 building with research facilities was completed in March 2015. ○ Researchers from various fields participated in five SGs. They conducted interdisciplinary research by having regular meetings. ○ The layout arrangement of the research facilities and the preparation of relocation were mainly taken care of by Building Committee in fiscal year 2014. The procurement and setting up of the research facilities were completed in fiscal year 2014 as per planned earlier, and the various types of equipment are operating smoothly.

10. Host institution’s commitment

<Plan at start of project >	<Results/progress/alternations from plan at start of project>
-Provision in host institution’s mid-to-long-term plan Tokyo Institute of Technology (herein after “Tokyo Tech”) has formulated the long-term vision “Vision 2009” as well as the mid-term targets and plans as follows. **[Tokyo Institute of Technology Vision 2009]** The Vision 2009: A Vision for the Future of Tokyo Institute of Technology	- Provision of the host institution’s mid-to-long term plan ○ Medium-to-long-term plan ・ No change in 2014 ○ Specific Measures The specific accommodations offered by the host institute can be categorized into the following five areas.

(herein after “Tokyo Tech”), which focuses on the next ten years, is a view to enable Tokyo Tech to fulfill this mission over the long-term and contribute to ongoing world development in the midst of the unprecedented difficulties facing humankind. We have set the followings as goals for the item “III. Research”:

1. Create new academic fields

Pay adequate attention to securing the research funds and space necessary to promote basic and challenging research that conventionally should be encouraged by Tokyo Tech as a university.

2. Create new values by systematically strengthening research

Select research fields in which Tokyo Tech can demonstrate its strengths on a university/departmental basis, and strengthen the Institute’s research capacity by concentrating investments on resources in these areas, etc.

3. Establish a hub for international collaborative research

Rally researchers with diverse global perspectives and establish an international collaborative research hub to contribute to addressing social needs and solving global issues.

[Medium-term targets/plan]

- The forewords of the medium-term plan (2010 to 2015) define the basic principles of Tokyo Tech as follows: “Based on the recognition that the basis of the sustainable development of Japan and contribution to the world lies in “human resources”, Tokyo Tech will stabilize its position as a global education and research base through nurturing “knowledgeable, skilled, ambitious, peace-minded and harmony-seeking scientific creators of the times”.
- “Target concerning research level and results” of the medium-term target states, “Based on the variety of creative research results in the basic and fundamental areas backed by a long-term viewpoint, Tokyo Tech will create new values including integrated areas and new areas.”
- “Target concerning research implementation structure, etc.” states, “Establish a structure for flexible implementation of organizational research utilizing the knowledge and resources of Tokyo Tech.”

The **Earth-Life Science Institute (ELSI)** will integrate the research in various disciplines and gather world-leading researchers to solve one of the most fundamental questions of humankind: how did life originate and evolve on Earth. The establishment of ELSI and associated innovations in science and technology match the above-mentioned vision and medium-term targets and plan. Therefore, the university will promptly revise to include ELSI in the medium-term targets and plan.

(1) Approving the unique operation system at ELSI by the university administration bureau.

(2) Providing necessary space

(3) Offering personnel support to the Institute

(4) Making arrangements with the Institute to conduct educational research activities in other departments to gather the researchers to the Institute

(5) Giving preferential financial treatment

The specific measures are described as follows.

(1) Approving the unique operation system at ELSI by the university administration bureau.

In order to help ELSI implement a unique and flexible operation, ELSI is operated with unique policies. The following is a list of the main policies that have been approved by the university administration bureau.

○ A round table discussion is held once a month with the President, Executive Vice President for Research, Executive Vice President for Finance and Public Relations and the Director to foster close collaboration with Tokyo Tech.

○ ELSI established unique policies, which is not bound by Tokyo Tech rules and regulations. Incentive system for those who make special contributions to ELSI, was implemented and nine researchers were awarded.

○Annual Evaluation Meeting

As reported in 2. Organization (1) General, Annual Evaluation Meeting was held. It is functioning well as a good opportunity to learn each other’s research, and a measure provide merit-based support for young researchers.

○Other supports have been provided as per previous year.

(2) Providing necessary space

○ Tokyo Tech provided the current ELSI building on campus to ELSI. Research and experiments were promoted at full-scale in this building. Researchers from various fields interact very well in the renovated rooms/ spaces in the renovated building. In addition, land was secured on Ookayama campus for ELSI and a new 5,000 m^2 building was completed in March 2015.

(3) Offering personnel support to the Institute

○ To strengthen the field of life science, especially “the origin and evolution of life,” two posts were provided by Tokyo Tech at the discretion of the President (a professor and an associate professor, from 1 April, 2014 to 31 March, 2022).

○ PI Maruyama retired at the end of fiscal year 2014; however, Tokyo Tech provide specially appointed professor position and he will continue to be a PI at ELSI.

○ To enhance earth science researches and the education of graduate students, a

-Concrete Measures

(1) Competitive grants obtained by researchers participating in the project and in-kind contributions, etc.

From the start, ELSI will be competitive in its ability to attract external grants, given the excellent track record of its PIs, who have already brought in a level of funding comparable to what WPI can provide. In addition to that very promising outlook, we will add additional support in the following ways.

a) Concrete support for acquiring and utilizing competitive funding

We will provide extensive guidance, in terms of advice, coaching and language support to the foreign members of ELSI, to enable them, too, to be competitive in applying for Grants-in-Aid for Scientific Research (KAKENHI). This will make ELSI an unusually attractive place for foreigners to work, given the existing barriers in language and culture in most other Japanese research institutes.

In addition to these concrete scientific and administrative forms of support, we will also provide an equally concrete financial form of support: part of the indirect expense of acquired research grants (KAKENHI) will be provided directly to the researchers at ELSI.

b) Concrete measures to increase research time for ELSI members

We fully understand that the main goal of a WPI institute is the creation of a place where scientists can concentrate on their research, in an international and interdisciplinary setting. The university will work toward this goal in two ways. First, the PIs employed by Tokyo Tech will be transferred to ELSI to reduce their current duties. Second, we will provide members from our own administrative staff at no cost to ELSI, to build up an independent Administrative Division (for general affairs and planning, research support, financing and facilities, etc.). In doing so, we will select staff members with excellent linguistic abilities and extensive administrative experience. In short, we will shield ELSI members from much of the day-to-day chores interfering with research, both by lightening their non-research work load and by providing administrators of high caliber to help them focus on establishing an ideal research environment.

c) Concrete continued funding through discretionary funds

After the current Global Center of Excellence (herein after G-COE) Program is terminated, about 100 million yen (the same amount as the operating cost of the existing G-COE program) will be provided to ELSI from discretionary funds by the President of Tokyo Tech.

post was provided by Tokyo Tech at the discretion of the President (an assistant professorship, 1 April 1, 2015 to 31 March, 2022).

○ In order to acquire top-level researchers in the life science field, especially “the origin and evolution of life,” Tokyo Tech established a new cross-appointment system established. One professor from Osaka university was newly hired as a PI under they cross-appointment system.

○ ELSI received personnel expense support for four PIs and for two full-time administrative staff from Tokyo Tech.

○ As PIs are exempted from undergraduate teaching at Tokyo Tech, three teaching posts were provided to the department where PIs had teaching duty, at the discretion of the President to prevent any problems arising in undergraduate education.

○ We continue to examine the introduction of a research track system.

(4) Making arrangements with the Institute to conduct educational research activities in other departments to gather researchers to the Institute

○ Remote Learning opportunities are provided through Massive Open Online Course (MOOC). The first lecture was given by the Director, Kei Hirose and is to be broadcasted globally.

○ We continued with the review process for establishing an “International Center” to strengthen the centralized support system for foreign researchers and students.

(5) Giving preferential financial treatment

○ Tokyo Tech continued to support ELSI with budget of 90 million yen as support for establishment of the institute.

○ Ten million yen was set aside in Tokyo Tech’s budget as the operating cost for ELSI new building.

○ ELSI was exempted approximately 40 million yen space charge for the President’s discretionary space provided by Tokyo Tech.

○ Building the day care facilities to assist female researchers is still consideration.

(6) Other

○ In addition to “Host Institute’s commitment” made by Tokyo Tech at ELSI’s planning stage, the President made it clear during the Site Visit and WPI Program Committee Meeting to actively support, not only providing personnel and material support but over all assistance for ELSI.

○ Tokyo Tech emphasized that various system reforms and administrative organization reforms at ELSI will be the first step for Tokyo Tech reforms.

○ ELSI was highlighted at the first lecture of the new Tokyo Tech lecture series, “Tokyo Tech Inspiring Lecture Series”. A lecture on “Origins: Earth and Life" - Science at ELSI was given to introduce the forefront research at ELSI.

(2) System under which the center's director is able to make substantive personnel and budget allocation decisions - ELSI will be established as an independent organization inside Tokyo Tech. The prospective Center Director of ELSI will have authority to make all decisions related to the Cenetr, including personnel affairs (excluding hiring and firing of the Center Director him/herself) and execution of the budget, etc. He receives advice from the Steering Committee, for which the Center Director him/herself serves as the Chairperson, but makes final decisions by himself. - The Center Director will evaluate both researchers and administrative staff members, and can provide them with extra incentives, depending on their performance. (3) Support for the center director in coordinating with other departments at host institution when recruiting researchers, while giving reasonable regard to the educational and research activities of those departments - We will make arrangements directly with those departments that provide one or more researchers belonging to ELSI, to ensure that those researchers will have unusual amounts of time and freedom to concentrate on their research, for example by appointing substitute professors for educational activities. (4) Revamping host institution's internal systems to allow introducing of new management methods (e.g., English-language environment, merit-based pay, top-down decision making) unfettered by conventional modes of operation - English will be used as the primary language inside ELSI. - Some departments of Tokyo Tech have internationally recruited researchers and provided support for them in English for research and administration. Utilizing such know-how, international recruiting will be conducted for all research positions in ELSI, to prepare a top-notch internationally inviting environment. - We will support the dispatch and extended visits for several months of the administrative staff in ELSI to an overseas satellite. In addition, exchange visits of part of the administrative staff of the satellite center to Tokyo Tech will be encouraged. - Tokyo Tech has already introduced a salary system that provides extra financial incentives for researchers and administrative staff members in recognition of their proven abilities and performance. For the overseas Principal Investigators, an annual salary system will be adopted. - Additional incentives will be made available for members of ELSI, based on their	○ ELSI will continue to collaborate closely with Tokyo Tech.

performance, such as improvements in research facilities for researchers, and opportunities to be dispatched overseas for administrative staff members (if they so desire). Decisions will be made depending on presentation of results held at the Annual Evaluation Workshop that will be the end of every academic year.
- Except for cases of hiring and firing of personnel or a drastic revision of financial projects, the Center Director of ELSI will be given the freedom to follow a streamlined and flexible policy in which he/she can make decisions without the need to consult the Steering Committee.
- In addition to these specifics, in general we will operate its existing systems in flexible ways, leaving room for revisions and additions when required by ELSI.

(5) Accommodation of center's requirements for infrastructural support (facilities, e.g., laboratory space; equipment; land, etc.)

- The board of Tokyo Tech assured approximately 1500 m^2 of floor space for ELSI at the start-up and additionally up to approximately 2100 m^2 by 2015 in an existing building. The building is located closely to the building of the Department of Earth and Planetary Sciences that ELSI is most closely related. This will include research labs, offices for clerical work, and a presentation room for an audience of 150, as well as meeting rooms on each floor. Research can be carried out there from the opening day of ELSI. Moreover, renovation of the building will create an environment encouraging researchers from different fields to communicate frequently and comfortably on a daily basis.
- Moreover, approximately 500 m^2 of research space is currently used by the existing G-COE program. In addition, ELSI will be eligible for the system already established at Tokyo Tech that provides space preferentially to researchers who acquire large competitive funding. These additional spaces will enable researchers of ELSI and related graduate students of Tokyo Tech to conduct joint research.
- Depending on additional growth of ELSI, we are prepared to provide more space on its campus.
- The Ookayama Campus of Tokyo Tech, housing ELSI, is located near a train station about 30-minutes away from the center of Tokyo. It has a number of large and small conference halls that can hold an international symposium, a main hall, a library, and a restaurant. Therefore, the campus is suited for meetings of world-leading researchers. We will provide support for preferential usage of such common spaces.
- Meeting spaces and the lecture hall in our Tamachi Campus, located in the heart of Tokyo, is convenient for researchers from abroad and from locals who are working with a tight schedule. We will provide support for preferential usage of such spaces as well.

- We will encourage researchers of ELSI to use the most advanced research equipment available at Tokyo Tech in coordination with each department.
- Our on-campus accommodation, the International House, offers single and family rooms for young overseas researchers and short-term visitors. It is conveniently located right next to the building of ELSI and provides a preferable environment for researchers. 20 rooms of which will be preferentially secured for ELSI use. Off-campus accommodations will be also arranged.

(6) Support for other types of assistance

- ELSI's goal is to become an established institute where superior geoscientists and biologists gather from around the world when the WPI-grant period ends. With ELSI forming a significant face for Tokyo Tech as a leading research center, we will in turn continue to provide support, such as funding and space.
- In addition, we will aid ELSI in obtaining continuous support from outside of Tokyo Tech, in terms of competitive funding, and contribution from foundations and enterprises.
- Already before the end of the WPI program, Tokyo Tech as a whole will internally adopt widely those parts of ELSI's innovative systems that have proven to be effective.
- We will encourage ELSI to coordinate with centers of other programs at Tokyo Tech that have a similar structure to provide stronger ties with higher efficiencies and more leverage.
- In order to develop ELSI into a truly global research institute, it is very important to publicize the activities of ELSI both inside and outside of Japan, in order to highlight its presence. From such a viewpoint, the Research Strategy Office, the Planning Office, the International Office, and the Center for Public Relations will all collaborate to plan public relations strategies of Tokyo Tech to effectively advertise the research activities and results of ELSI.
- While integrating the PR activities of ELSI with the PR activities of Tokyo Tech, the PR activities of Tokyo Tech will be strengthened in line with public relations strategies.

11. Efforts to improve points indicated as requiring improvement in application review and results of such efforts

- Major points to be improved	<Efforts taken during the fiscal year 2014 and the result of such efforts>
• Although the revised Roadmap is very clear and easy to understand, it is still important to clarify what is stated in the Roadmap. What is meant by “working model for the origin of life,” “model of early Earth environment,” and “scenario	1. In order to revise the roadmap, we focused on identifying the problems confronting in the first half of the year and the relations between the sub-topics and the nine inter-related disciplines. On the other hand, in the latter half, we set three

of Earth's formation." • ELSI should continue making effort to increase the number of senior-level female scientists. • For ELSI, it is worth considering more observational studies of protoplanetary disks ALMA, SUBARU, and other telescopes. Also, recent results from the observation of extrasolar planets are very important for ELSI activities. Collaboration with astronomers studying planet formation will be very useful. • It would be useful to record and report ELSI's "export" as well as its "import" activities in terms of internationalization. In other words, ELSI should put an emphasis not only on hosting researchers from abroad but also on sending its researchers abroad to research centers around the world.	problems: "Working hypothesis of the origin of life," "A model of early Earth environment", and "Scenario of the formation of the Earth" not to make our roadmap more complicated. The roadmap is updated twice yearly at ELSI Forums. In the next roadmap revising, we take the latest research trend into consideration along with the newest research achievement of ELSI, and make the comments and feedbacks clearer in the roadmap. 2. ELSI takes the comments very seriously and mesurements are discussed in the recruitment process. However, the solutions are not yet found. In the meantime, ELSI make it more flexible to shortlist the female researcher candidates who are willing to station in ELSI more than half of a year, not necessary fulltime. Alternatively, we may introduce a summer salary system to set up flexible hiring conditions to secure senior-level female researchers as well. In addition, considering that it would help to secure female researchers, we decided to invite a European female researcher who is playing an active role in the field of astrobiology to become a member of our International Advisory Board. 3. Theoretical researchers researching the formation of planets at ELSI have already been conducting joint research with astronomers using "ALMA" and "Subaru" (e.g., http://www.jicfus.jp/field5/jp/130320pressrelease/). On the other hand, as was pointed out, there is room to examine joint research that contributes to the foundation of the science at ELSI. As was reported in the above-noted "2. Organization (3) Satellite Institutes and Collaborating Institutes," ELSI submitted a proposal with National Astronomical Observatory of Japan to NASA Astrobiology Institute for a partnership agreement. Thus, we will discuss joint researches that are not sporadic, and the collaborating relationship toward core formation in our field. One young researcher was sent to GISS to conduct research with the support of astronomers. In relation to point #4, Research Interaction Committee is looking into the best effective way to support the research collaborations. 4. The Directors' Office and Research Interaction Committee are discussing the support for ELSI's young resident researchers to conduct research at foreign institutes for certain period of time. The new support program is to start to support the young researchers travel costs as long as they can fulfill two points (a) the researcher visits the foreign research institute for the first time, and b) the researcher stays at the institute for at least several weeks and works on his/her research topic, and conducts joint research with the host researcher.

12. FY 2014 funding

i) Overall project funding

(Unit: 1 million yen)

Cost Items	Details	Costs (1 million yen)
Personnel	Center director and Administrative director	23
	Principal investigators (no. of persons): 10	69
	Other researchers (no. of persons): 33	226
	Research support staffs (no. of persons): 6	21
	Administrative staffs (no. of persons): 12	58
	Total	397
Project activities	Gratuities and honoraria paid to invited principal investigators (no. of persons): 3	0
	Cost of dispatching scientists (no. of persons): 0	0
	Research startup cost (no. of persons): 33	16
	Cost of satellite organizations (no. of satellite organizations): 2	56
	Cost of international symposiums (no. of symposiums): 1	8
	Rental fees for facilities	16
	Cost of consumables	14
	Cost of utilities	0
	Other costs	156
	Total	266
Travel	Domestic travel costs	4
	Overseas travel costs	12
	Travel and accommodations cost for invited scientists (no. of domestic scientists): 28 (no. of overseas scientists): 95	26
	Travel cost for scientists on secondment (no. of domestic scientists): 1 (no. of overseas scientists): 2	2
	Total	44
Equipment	Depreciation of buildings	13
	Depreciation of equipment	34
	Total	47
Other research projects	Projects supported by other government subsidies, etc.	141
	Commissioned research projects, etc.	74
	Grants-in-Aid for Scientific Research, etc.	355
	Total	570
Total		1324

WPI grant for FY 2014		510
Costs of establishing and maintaining facilities in FY 2014		0
Establishing new facilities		
(Number of facilities: , m²)	Costs paid:	
Repairing facilities		
(Number of facilities: , m²)	Costs paid:	
Others		
Cost of equipment procured in FY 2014		27
Name of equipment: Full automatic cleaner Number of units: 1	Costs paid:	2
Name of equipment: Video conference system Number of units: 1	Costs paid:	2
Name of equipment: Floor-model ultra centrifuge Number of units: 1	Costs paid:	9
Name of equipment: Fume hood Number of units: 1	Costs paid:	4
Name of equipment: CryoTrap ControllerLN2 Number of units: 1	Costs paid:	1
Name of equipment: VT64 Cluster system Number of units: 1	Costs paid:	3
Others		6

ii) Costs of Satellites and Partner institutions

Cost Items	Details	Costs (1 million yen)
Personnel	Principal investigators (no. of persons): 1	
	Other researchers (no. of persons): 9	
	Research support staffs (no. of persons): 0	
	Administrative staffs (no. of persons): 0	
	Total	29
Project activities		21
Travel		4
Equipment		1
Other research projects		46
Total		101