

FY 2013 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	<i>Earth-Life Science Institute (ELSI)</i>	Center Director	Kei Hirose

* Prepare this report based on the current (31 March 2014) 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

The Earth-Life Science Institute (hereafter referred to as “ELSI”) is making steady progress toward achieving their planned goals. The following is an overview of the progress status towards attaining the objectives.

1. Management

- Due to his health condition, The Administrative Director stepped down his position on 20 October 2014.
- ELSI ALL meeting is held once a month to share information amongst the ELSI members. The Director updates all staff members in the meeting
- We established the Institute’s unique policy, which is not bound by university regulations, and started an incentive system for those who made special contributions to the Institute, providing rewards to those individuals.
- A roundtable discussion is held once a month with the President, Executive Vice Presidents and ELSI Director to facilitate close collaboration between the university and ELSI.

2. Research Activity We held one international symposium, seven workshops and two forums. As for the visitors, 126 are from overseas out of total 139 visitors. Moreover, achievements include 211 published papers, 13 book publications, and a total of 211 lectures and research presentations at academic societies or symposium. A notable accomplishment was that “Low Core-Mantle Boundary Temperature inferred from the Solidus of Pyrolite,” written by Professor Hirose, the Director, and his colleagues appeared in Science.

○ In addition to sending young researchers to satellite institutions such as Harvard University and the Institute for Advanced Study in Princeton, we are taking part in recruiting and fundraising activities through our satellites and collaborative institutions. and fundraising activities.

3. Open Recruitments, Employment Procedures and Evaluations for Postdocs

- We advertised in Nature Science and ELSI website for 20 posts for young researchers. 135 applications were sent electronically. (125 applications are non Japanese researchers.)

- In January 2014, we conducted an evaluation based on research achievements and future prospects which aims to increase young researcher’s research motivation.

4. Strengthening and Enhancing the Research System and Research Support System

- Three world-renowned principal investigators and 13 excellent researchers were hired (the total number of researchers as of the end of March 2014: 14 principal investigators, 3 associate principal investigators and 20 researchers).
- Four administrative staff members and four educational research assistants were also hired in order to strengthen and enhance research and public relations assistance for the Administrative Division, the total number of the staff as of the end of March 2014: 9 administrators and 4 educational research assistants).
- A research advisory system will be established and three advisors will start working with effect from 1 April, 2014.

5. Promoting Interdisciplinary Research and Interactions

- Five study groups are actively engaged in discussions with various approaches to elucidate the origin of Earth and life.
- A twice-a-week brown bag seminar and a 15-minute daily coffee break session are held to facilitate interdisciplinary interactions with many researchers.

6. Buildings Since the renovation of the ELSI building (2,670m²) was completed, the ELSI has begun full-fledged research and experiments, as well as facilitating active interdisciplinary research interactions by improving the communication space. Moreover, the university has begun construction on a new 5,000m² building that is scheduled to be completed in March 2015.

7. Education and Public Relations Activity Seven public events (two for elementary school students and one for local residents in particular), 20 research publications in newspapers, and 16 book and magazine publications. A centralized publish management system is in the process of implementation.

8. Commitment from the Host Institution One point for a professor from April 2014 to March 2022 was given by 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 & Harvard 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

○ The Steering Committee

Continuing from the previous fiscal year, the Steering Committee (which consists of the Director, the Administrative Director, and two Vice-Directors) provides advice and support to the Director relating to coordination within the university, regulation review, research environment improvement and personnel matters essential to the management of the Institute. While the Steering Committee met once a week at the inception of the Institute, as was necessary to manage the overwhelming number of projects, the frequency of the meetings has gradually decreased to alleviate the burden on the committee. As of the end of FY 2013, the committee meets only once a month. Additionally, we require that Administrative Division personnel at the management level and higher and research related assistants attend the committee meetings in order to share information and improve the system to efficiently implement and fulfill the Institute's decisions.

○ Establishing the Expert Committee

During the beginning period of FY 2013, the Director structured the Institute's management system by establishing the Expert Committee under the Steering Committee.

▪ Science Steering Committee <Continuing from the previous fiscal year>

The committee formulates the mid- and long-term research plans,

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

updates/revises the research master plan and research roadmap based on these plans and promotes interdisciplinary research.

- Public Relations <Continuing from the previous fiscal year>
 - In addition to reviewing public relations activity plans, the Public Relations Department creates/updates the website, disseminates information about the Institute via SNSs, performs outreach activities and collaborates/coordinates with other research centers.
 - Financial Planning Committee <Newly established >
 - The committee prepares a budget draft, compiles the annual budget based on results presented from each committee, and knows the budget implementation status.
 - Building Committee <Newly established >
 - The committee assembles the ELSI building renovation plan and new building construction plan, partakes in daily building management and formulates/implements the experiment infrastructure improvement plan.
 - Computer Network Committee <Newly established committee>
 - The committee builds and updates an information network system in the ELSI buildings and new buildings, takes part in daily maintenance and management, and responds to network issues.
 - Research Interactions Committee <Newly established>
 - The committee plans and holds research meetings, such as symposium and workshops, selects external researchers (visitors), and formulates acceptance plans.
 - Recruitment Committee <Newly established>
 - Based on the employment plan, the committee partakes in activities to recruit young, highly capable researchers and builds/updates the public job opening announcement system. The committee is also responsible for managing applicants documents, screening applications and set interview sessions.
 - In addition to those committees, the Safety and Health Committee, the Information Ethics Committee, the Information Security Committee and the Hazardous Materials Management subcommittee were established in accordance with the regulations and the university rules.
- “ALL ELSI meeting” instead of a monthly PIs meeting
 - Monthly PIs meetings held during the last fiscal year has ceased in November 2013. Beginning in December 2013, ALL ELSI meetings that are directed at all ELSI-affiliated personnel, as the number of newly hired researchers and support staff members has increased. Additionally, principal investigators from overseas participate in the meetings as much as possible via Skype.
 - International Advisory Board

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

In accordance with the plan to increase the number of the international advisory board members, the Director invited Dr. Carl Pilcher, the former director of the NASA Astrobiology Institute, to become a board member; Dr. Pilcher accepted this offer.

The International Advisory Board meeting was held twice during FY 2013, on 13 September and 25 March. Based on the advisory board’s guidance and advice, we implemented measures to strengthen and enhance the ELSI research activities, including developing a risk management plan. Dr. Carl Pilcher, a newly appointed board member, attended the meeting on March 25. As of the end of FY 2013, the following four individuals serve as the International Advisory Board members:

- Masuo Aizawa, Chairperson (Advisor, Japan Science and Technology Agency)
- Douglas Lin, Board Member (Professor, University of California, Santa Cruz)
- Robert Hazen, Board Member (Research scientist, Carnegie Institution)
- Carl Pilcher, Board Member (Former Director, NASA Astrobiology Institute)

○ In order to strengthen collaboration with other institutions, a councilor post was newly set and she/he is in charge of institutional collaboration.

○ Recruiting highly qualified young researchers

In an effort to incorporate tactics used overseas to recruit young researchers to ELSI’s recruiting activities, the Director appointed John Hernlund, a foreign principal investigator who actually began his post at ELSI, to serve as a chairperson for the Recruitment Committee. Under Chairperson Hernlund’s leadership, the committee improved the existing online public job advertise system and expanded the options to announce job offer information (posting on Nature, Science, etc.). Moreover, the Director, the Recruitment Committee and the Public Relations Department collaborated with taking part in recruiting activities, such as setting up booths at international conferences. ELSI received a total of 135 applications since September 2013. One hundred and twenty-five of the 135 applications (92.6%) were by foreign applicants.

○ ELSI hired 13 young researchers in FY 2013, four of them are non-Japanese researchers.

○ Holding an annual evaluation meeting

An annual evaluation meeting was held for two days at the end of January 2014. The evaluation was conducted by both ELSI researchers and principal investigators based on research activity sheets submitted in advance by those to be evaluated and included a 15-20 minute presentation and discussion. The main evaluation criteria consisted of ① the quality of research in which a researcher was undertaking (including academic papers and publications) and its compatibility with the ELSI research objectives; ② whether a researcher was

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.

partaking in research activities that take interdisciplinary studies into consideration; and ③ the researcher's attitude toward advancing his/her research activities independently from his/her principal investigators and mentors (as applied to young researchers). Executive officers including the Director, Vice-Directors, and the Administrative Director compiled the results of the annual evaluation meeting. They then presented the ELSI Incentive Award 2013 to principal investigators, associate principal investigators, and six young researchers who were recognized for promoting excellent studies, and commended them on their achievements. Moreover, the Center Director is planning to conduct a feedback interview with each researcher based on the evaluation results.

These activities were reported at the International Advisory Board meeting held on March 25, 2014. It was also decided to identify the challenges to make a fair evaluation of researchers with different academic disciplines and to continue examining more effective evaluation systems.

- Planning a periodical event to promote interdisciplinary research
In order to overcome the “language barriers” and “cultural barriers” and to promote mutual understanding amongst researchers with various backgrounds, the following events were implemented with the advice by Principal Investigator Piet Hut.
 - ELSI assembly: Research presentations and discussions by ELSI members (Wednesdays)
 - ELSI seminar: Research presentations and discussions by external researchers
 - Brown bag seminar (twice a week) and coffee break meeting (daily)
- (2) Administrative Division
 - While the ELSI operates under the strong leadership of the Director, the Administrative Director was no longer able to fulfill his assigned duties due to health reasons and he stepped down from the post. A new Administrative Director was appointed who assists the Director as well as possesses life science perspectives, experiences in organizational management, and international experiences and viewpoints. As a result, the life science fields are expected to be strengthened and internationalized.
 - An individual who previously held a director level position was recommended by the university and assigned the role of assistant administrative director to support the Administrative Director.
 - One administrative staff member with financial-related experience was designated by the university's administrative office to strengthen and enhance the administrative assistance system.
 - In order to strengthen and enhance research and public relations support for the

Administrative Division, four administrative staff members and four educational research assistants were recently hired (the total number of employees as of the end of March 2014: 9 administrative staff members and 4 educational research assistants).

(3) Satellite Institutes and Collaborating Institutes

○ Satellite Institute—Ehime University

- Continuing from the previous fiscal year, we sponsored studies on the thermal evolution of the Earth and held discussions with the ELSI's researchers.
- ELSI has five study groups with different viewpoints and approaches to elucidating the origin of the Earth and life. The Ehime University Satellite Institute shared responsibility for organizing the "Monthly one day workshop" for Study Group 4, which is studying the topic of solid earth.
- The Satellite Director is actively involved in the ELSI's public relations activities, serving as an ELSI representative and lecturing at science events held in the Shikoku area

○ Satellite Institute—Institute for Advanced Study in Princeton

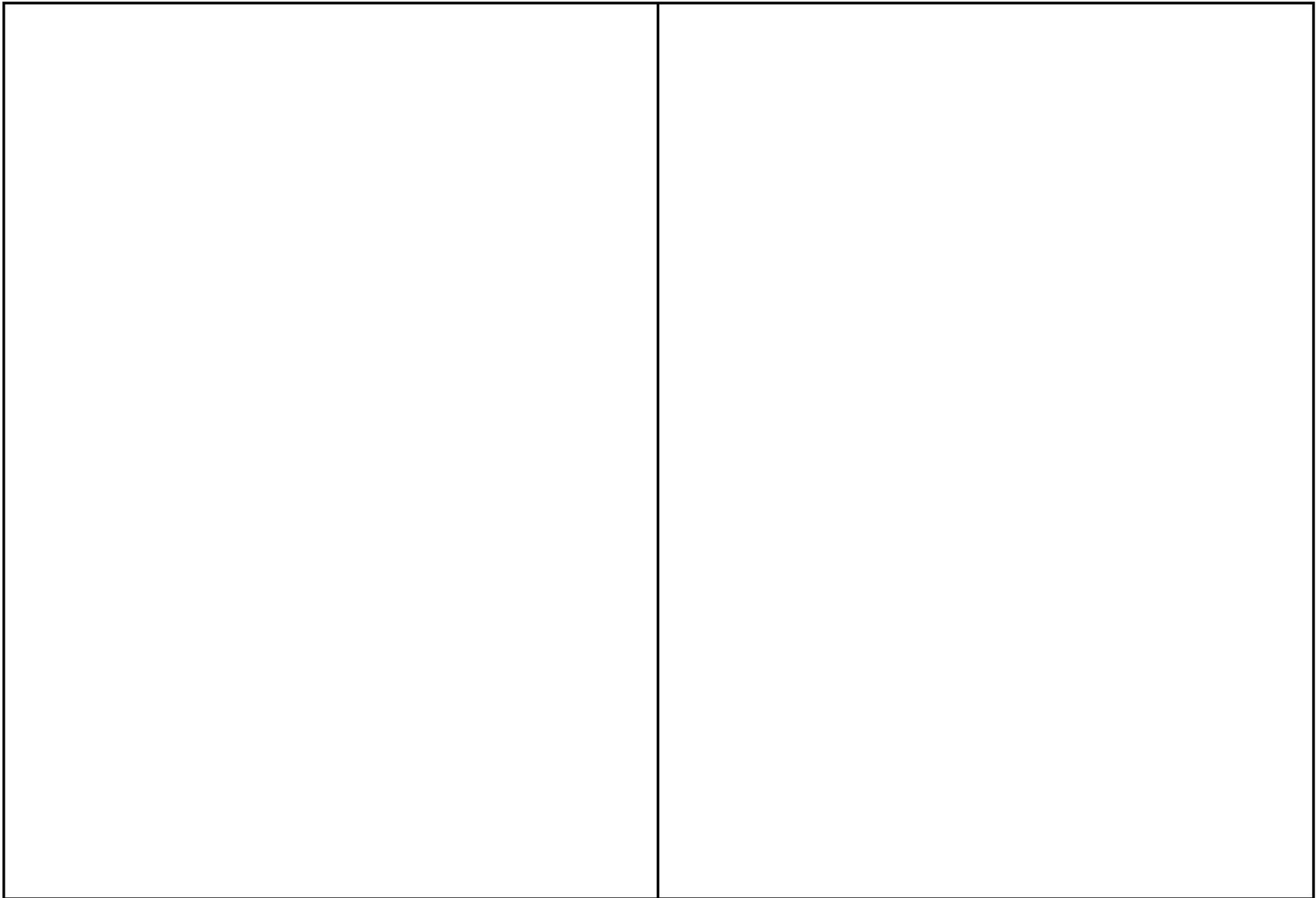
- The Satellite Director made preparations to accept researchers from the ELSI. In response to this development, two young researchers from ELSI (researching chemical evolution and planetary physics/astrobiology, respectively) stayed in Princeton for several months to conduct their research at the Institute for Advanced Study.
- The young researchers staying at the Institute for Advanced Study in Princeton participated in seminars and lunch meetings, introducing ELSI, and cultivated relationships with various researchers.
- Based on the proposals made by the Satellite Director and ELSI's young researchers, the ELSI began discussions toward reaching a partnership agreement with the NASA Astrobiology Institute.
- The Satellite Director conducted investigations on U.S. funding institutions and endowment organizations and, with the Center Director, has been in negotiations with institutions and groups who showed positive interests in assisting the ELSI.
- The Institute for Advanced Study in Princeton serves as a U.S. center for ELSI's recruiting activities. We've received applications for open researcher positions from young researchers who've developed a greater understanding of ELSI's research activities through the Satellite Director and researcher networks at the Institute for Advanced Study in Princeton.

○ Satellite Institute—Harvard University

- Young researchers have been sent to Harvard University and have started their

	<p>experiments and research. These researchers are scheduled to conduct their research at Harvard for about nine months, and then continue at the ELSI for three months.</p> <ul style="list-style-type: none">▪ An ELSI associate PI and a young scientist whose research field is synthetic biology methods visited Harvard and had an discussion on collaborative research to be conducted between ELSI and Harvard University. Based on their discussions, we improved the infrastructure at ELSI for better experiments on the origin of life.▪ Seven interested young scientists from Harvard University were invited in March 2014. We hosted a workshop on the origin of life and had in-depth discussions about future research collaboration. <p>○ Collaborating Institutions (Cooperative Institutions)</p> <ul style="list-style-type: none">▪ The Director met with executive officers from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the Research Director of the Institute for Research on Earth Evolution (the Institute is closely related to ELSI's research activities), and the Center for Deep Earth Exploration to discuss a collaborative relationship that would benefit both the ELSI and the JAMSTEC, particularly with regard to interactions among researchers. Moreover, the directors exchanged views on collaborative relationship between organizations (university-organization) based on ELSI and JAMSTEC.▪ An international workshop titled “Magnetospheric Plasmas 2013” was successfully completed in collaboration with the Japan Aerospace Exploration Agency (JAXA).▪ The Director and the Councilor are holding discussions with the JAXA to clarify which the roles the ELSI should play within a broader collaborative research framework, such as the JUICE space mission as referenced by the WPI Committee.▪ Researchers were sent to the California Institute of Technology with the goal of improving transmission electron microscopy analysis techniques and conducting magnetic fine particle measurements. A Principal investigator from the California Institute of Technology stayed at the ELSI for five months and took part in research activities.▪ We accepted one young researcher from the University of Minnesota, which is from where the principal investigator scheduled to assume the post at the ELSI in FY 2015 originates and began collaborative research. <p>[Mission Statement and/or Identity of the Center] (1) Mission Statement</p> <p>○ While the ELSI's mission in the left column remains unchanged, the following streamlined statements shall be shared within the Institute and were reported during the site visit.</p>
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	<p>(Mission 1) Address fundamental questions of “Origin of the Earth” and “Origin of Life on Earth” by linking Earth and Life sciences</p> <p>Elucidate the unique environments on the early Earth, with the main aim to study the origin and early evolution of life in their geological context</p> <p>(Mission 2) Systematize “Astrobiology”: universality of life in the universe</p> <p>Predict possible modes of life on other planets, in our solar system and beyond in collaboration with future observations/explorations</p> <p>(Mission 3) Be an international hub for research on “Origin of the Earth” and “Origin of Life”</p> <p>Build the best research environment to facilitate interdisciplinary research and attract a wide variety of top scientists</p> <p>○ Efforts to become a node Institute Together with the National Institutes of Natural Sciences, ELSI bid to become a partnership organization with the NASA Astrobiology Institute in Japan. As of the end of FY 2013, we are in the final coordination stage towards reaching a partnership agreement. ELSI is expected to act as an intermediary when domestic researchers specializing in related fields take part in research activities in collaboration with the NASA Astrobiology Institute, and to function as a node for astrobiology studies.</p> <p>○ Summer school planning Summer school will be held in August 2014. Local Organizing Committee is formed and they are planning and preparing for the School. The theme of the School is to understand the planetary formation and Early Earth evolution using computer simulation with ELSI super computers.</p>
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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 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,

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

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

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) planned 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 (IFREEE)
- 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 an 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) 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.

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

Research Objectives

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

[Research Plan]

○ Setting a benchmark for the first half of the WPI program and modifying the program roadmap

As a benchmark for the first half period of the WPI program, we ① built the ELSI model on pre-biotic Earth conditions and ② presented and specified the ELSI scenario on the origin of life. For Benchmark ①, a) a top-down approach that uses an earth formation theory model and b) a bottom-up approach that retraces the geological record will be used as a strategy to meet the benchmark. For Benchmark ②, c) a top-down approach which aims to estimate the early stage of the genome and build the cells in the initial stage using genomic science and synthesis biological methods and d) a bottom-up approach which retraces the evolutionary tree experimentally and theoretically will be adopted as a strategy to reach the benchmark. We organized eight interdisciplinary fields to carry out these approaches and illustrated them using a simple roadmap to show a mutual relationship between each discipline and the tasks that need to be undertaken during the process so that each discipline is moving toward achieving the benchmarks (Fig.1).

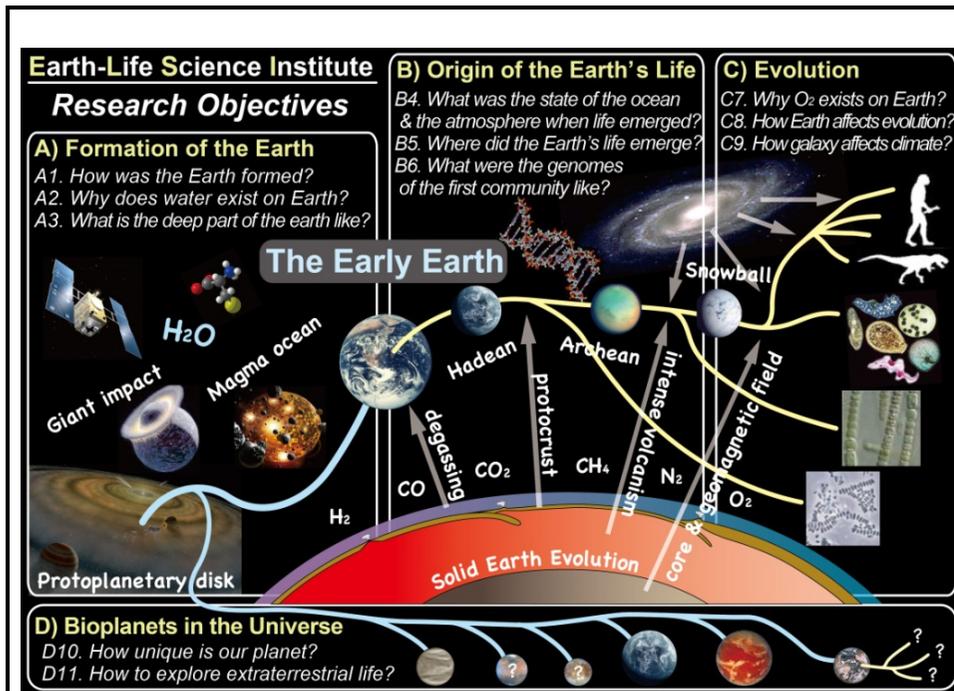


Figure 1. Summary of research objectives.

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 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

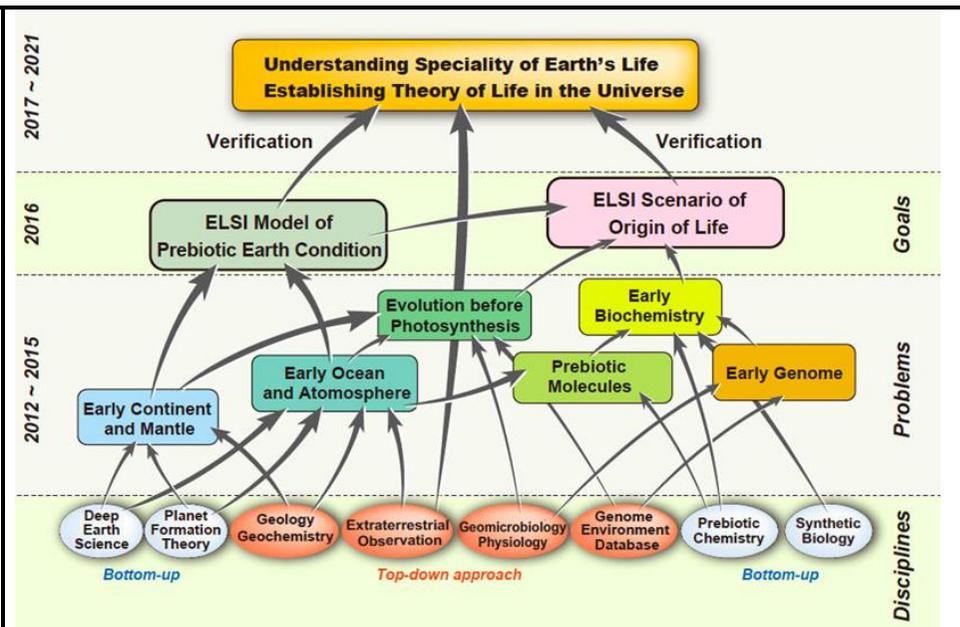


Fig.1 Modified Roadmap

The following sections discuss the research progress made by each of the eight interdisciplinary fields through FY 2013.

Deep Earth Science

The Deep Earth Science area of ELSI includes three approaches to high pressure and temperature mineral physics; laser heated diamond anvil cell experiments, externally heated multi-anvil cell experiments, and ab initio computer simulations of atomic interactions, as well as geodynamics and seismology. This area of ELSI collects geophysical data at both present-day and early Earth conditions to understand the Earth's initial composition and surface environmental conditions during the Hadean when life first developed. Our group has direct collaborations and interactions with the Planet Formation Theory, Geology/Geochemistry, and Extraterrestrial Observations areas of ELSI.

The high pressure-temperature diamond anvil experimental group has made significant progress regarding the chemical composition of the core and its state in the early Earth. This group is led by ELSI Director Kei Hirose and is now managed by Shige Tateno with research performed by Haruka Ozawa, Hitoshi Gomi, and Ryoichi Nomura at the ELSI Tokyo Tech campus. The group's work includes constraining the melting temperature of material similar to that expected for the Earth's primitive lower mantle to around 3570 K at the core-mantle boundary

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 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?

(CMB). Thus, the experiments should provide an upper bound of the CMB temperature because the lowermost mantle is not currently molten. If the CMB temperature is this low today, it suggests that the melting temperature of the Earth's core is lower than expected and could be due to chemical impurities such as hydrogen. Furthermore, this group constructed the thermal equation of state for pure Fe and Fe-Si alloy up to 200 GPa and 300 GPa, respectively. The seismically observed core density can be explained by the presence of 6 wt.% Si, which is consistent with geochemical constraints. This estimated outer core composition is Fe_{93.4}H_{0.6}Si_{6.0} (in weight). In addition, high-pressure electrical resistivity measurements on Fe and Fe-Si alloy indicate that the Earth's core is significantly more conductive than previously thought. When extrapolated back to the early Earth, this result indicates rapid secular core cooling, an inner core younger than 1 Ga, and ubiquitous melting of the lowermost mantle. The group is currently working to understand all of the implications this result has on the Earth's early environment.

The high pressure-temperature multi-anvil experimental group at the ELSI satellite campus at Ehime University's Geodynamics Research Center led by Tetsuo Irifune including Steeve Greaux, Masayuki Nishi, Wei Du, and Yoshinori Tange is working on the properties of proto-planetary chondrites, moon crustal material, and subducting oceanic slabs to understand planetary accretion and crustal evolution. Melting experiments on a C2-type carbonaceous chondrite (Tagish Lake, TL) showed that up to 20 GPa, TL chondrite melted into a homogeneous silicate melt at 2000 K with no metallic iron observed, while at 50 GPa and 2500 K (Mg,Fe)SiO₃ perovskite co-exists with FeS-FeO metal and Ca- and C-rich silicate melt. This is compatible with the differentiation of an hypothetical TL proto-planet into a FeS-core surrounded by a Fe-rich perovskitic mantle and (Ca,Al)-bearing phases located in the crust. The group also determined the phase relations of lunar highland anorthosite and KREEP basalt up to 50 GPa and 2000 K. The derived density profiles indicated anorthosite may sink deep into the lower mantle due to a high density contrast after the CAS phase decompose to Ca-perovskite and corundum, and the less dense KREEP basalt may remain at the depths of the lowermost transition zone. Using ultrasonic interferometry and synchrotron X-ray techniques, the group has measured the sound velocities and thermoelastic properties of CaSiO₃ perovskite, MgSiO₃ majorite and akimotoite, Fe₃Al₂Si₃O₁₂ almandine, Mn₃Al₂Si₃O₁₂ and Ca₃Cr₂Si₃O₁₂ uvarovite garnet. These results will be used to infer the structure of the deep mantle by direct comparison with C. Houser's seismic data. The group's work on subducting slab properties includes measuring the grain boundary diffusion coefficient of Mg in perovskite which may be an effective mechanism for chemical transport in the lower mantle. Results from Si-Al interdiffusion rates in majoritic garnet indicate that low-density metastable regions could exist in the slab due to the low diffusion rate such that the subducted slabs may be buoyantly trapped in

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 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

the mantle transition regions.

The ab initio numerical mineral physics group uses computationally expensive first-principles molecular dynamics calculations of materials at the atomic scale to investigate core and mantle composition. This group includes Renata Wentzcovitch at the University of Minnesota, Koichiro Umemoto at the ELSI Tokyo Tech campus, and Jun Tsuchiya, Taku Tsuchiya, Hiroki Ichikawa, and Xianlong Wang at the Ehime University satellite campus. K. Umemoto performed a series of first-principles molecular dynamics calculations on liquid iron alloys with sulfur at high pressure-temperature conditions corresponding to the outer core of the Earth. These calculations show that density of liquid iron with ~16 wt% sulfur is close to that observed seismically, if sulfur is the only light element alloyed with liquid iron. This data will be analyzed to estimate bulk moduli as functions of pressure, temperature, and sulfur concentration in order to compare with seismic constraints. H. Ichikawa simulated pure liquid iron at the P-T condition of the outer core and constructed an equation of state of liquid iron and calculated bulk sound velocity. The results show that the previously assumed Birch's relation (density - sound velocity relation is linear irrespective of temperature) does not apply for liquid iron. J. Tsuchiya working with experimentalist M. Nishi discovered a new hydrous silicate that could be stable in the Earth's lower mantle in a very cold subducting slab. This new phase provides a mechanism for water to enter the lower mantle which could effect estimates of the Earth's initial water content.

The geodynamics and seismology group led by John Hernlund including Christine Houser and Hiroki Ichikawa combines computer models of Earth's formation with constraints from mineral physics, geochemistry, and seismology to investigate Earth's initial state and consequent evolution. This group is establishing a theoretical framework that links the thermo-chemical evolution of the core-mantle boundary to specific chemical equilibria and makes firm links between seismologically observed features at the core-mantle boundary. The first results are in preparation for publication. H. Ichikawa estimated the subduction rate of continental materials into the deep Earth along ocean-continent margins using 1D numerical model. The results show that an amount of continental materials similar to the present mass of the continental crust could have subducted into the deep Earth. C. Houser took a year maternity leave before joining ELSI, but is now continuing her measurements of seismic velocity in the mantle transition zone, the lower mantle, and outer core. The 1D and 3D seismic velocity patterns in the Earth's interior, when combined with material properties from mineral physics and subsequent dynamics, are used to constrain scenarios of Earth's formation and the development of plate tectonics.

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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 structure 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 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

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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 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

Planet Formation Theory

The discovered exoplanets (planets orbiting stars other than the Sun) has increased dramatically in recent years. As of 2014, over 1000 confirmed exoplanets have been discovered by ground telescopes and more than 3600 transiting candidate planets have been found by the Kepler space telescope. 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 large number of discovered planets enables us to discuss statistical distributions of exoplanets. In this status, importance of theoretical studies of planet formation becomes increasingly important. On the other hand, geological and cosmochemical (top-down) approach on early Earth is developing. Bottom-up approach by planet formation theory is demanded to reveal the origin of the Earth, combined with the top-down approach.

The prediction for a frequency of rocky/icy planets in habitable zones, in which liquid water can exist on planetary surface, in exoplanetary systems is one of the most important objectives of planet formation group. Hidenori Genda investigated the habitable zone considering the evolution from an aqua planet (a planet covered with ocean globally, like the Earth) to land planet (a planet with very small amount of water) through water loss (Kodama, Genda Abe in prep). It has been known that a land planet maintains liquid water on its surface at much larger solar radiation than an aqua planet. Therefore, evolution from an aqua planet to land planet is a key to prolong the duration of planetary habitability. Shigeru Ida performed N-body simulations of giant impacts among protoplanets that have migrated from outer regions to the proximity of host stars (Matsumoto, Nagasawa, Ida, in preparation). They incorporated this result into their population synthesis model, which combines multi-step planet formation processes with various physics to predict statistical distributions of exoplanets. They showed that the observed close-in Earths/Super-Earths systems are consistently explained (Ida, Lin, Nagasawa 2013). This model also predicts the frequency of habitable planets in exoplanetary systems, if dynamical conditions for habitable planets are specified (derivation of the conditions itself is an important target of ELSI).

Existence of the Moon may be one of important factors for the Earth to be habitable. The standard model for formation of the Moon is "giant impact" scenario, that is, the Moon was formed by accretion of debris generated by a Mars-size body impact with the proto-Earth. Jun Makino and Takayuki Saitoh developed a novel formulation of smoothed particle hydrodynamics (SPH) (Saitoh and Makino 2013). SPH is widely used in astrophysics and has been applied to the giant impact simulations. However, it has been pointed out recently that the standard SPH (SSPH) cannot properly deal with density discontinuity. This is because SSPH assumes the differentiability of density. Their new code (DISPH) resolves this problem by using "pressure" as a fundamental quantity, since pressure

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 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

is smooth at the contact discontinuity. They extended this formulation for non-ideal gas (Hosono, Saitoh, Makino 2013) to perform the giant impact simulation (Hosono, Saitoh, Makino, Genda and Ida, in preparation). They found that the impact parameters to form the Moon by DISPH differ from those by SSPH and a serious problem of identical isotope ratios between the Earth and the Moon, which has been raised by recent cosmochemical analyses, is potentially solved by the results of DISPH.

The origin of water on the Earth and the effect of the water on planetary evolution are also important objectives of planet formation group. Shigeru Ida worked on the former and proposed a new scenario (Guillot, Ida, Ormel, submitted): Icy dust grains condense in disk outer regions and migrate inward due to gas drag. They found that a small fraction of icy grains are accreted by terrestrial planets and the accretion cross section could regulate the amount of water on the planets. Hidenori Genda investigated the solidification process of magma ocean in the terrestrial planets, and found that the birth place of the planets influences their early evolution in a way that can be categorized into two types (Hamano, Abe & Genda 2013). Type I planets solidify in a short period of time forming oceans, which corresponds to the Earth. Type II planets solidify over a long period of time losing their oceans, which corresponds to Venus. Oxygen which was produced by dissociation of steam would have been absorbed by magma covering Venus' surface. This would solve the longstanding question of why there is no water in Venus and why oxygen did not accumulate in its atmosphere.

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Geology/Geochemistry

PI Maruyama and colleagues published a paper entitled "The naked planet Earth" (Maruyama, Genda, Hirose et al., 2013), which proposed the new model of highly water-depleted planet to evolve into life-sustaining planet, and discussed the origin of water on the Earth. To unfold the origin of life, new model for the birth place of life on Hadean Earth was proposed. Also, new concept of Habitable Trinity was established which indicates necessary environments for emergence of life (Dohm and Maruyama, in press). This concept replaces currently prevailing

planet formation process.

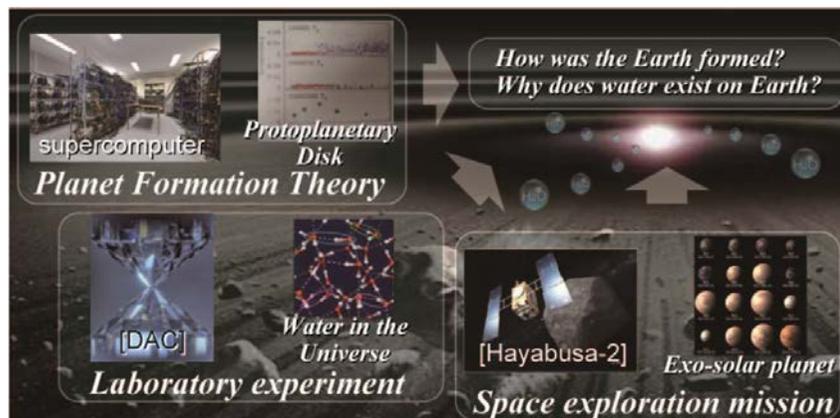


Figure 2. The formation of the Earth in solar system will be examined by a combination of computer simulations of planet formation, with the aid of laboratory experiments and information about extraterrestrial bodies (related to questions A1 & A2).

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, H₂O 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 H₂O water, the ones from well inside 3AU do not contain H₂O ice at all. If this is true, it means that dust material around 1AU from which the Earth is formed did not contain H₂O.

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 H₂O water content of the Earth and creation of life were determined by pure coincidence. 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

concept of habitable zone planet. Also, PI Maruyama and colleagues summarize the series of study of evolution of animal life in a special issue "the Cambrian explosion" published in Gondwana Research (including 11 papers of ELSI researchers).

PIs Maruyama, Kurokawa, Yoshida, APIs Ueno, Hongo and colleagues found abiotic methane from Hakuba Happo Hotspring (Suda et al., 2014). The hot spring water is derived from so-called serpentinization process that should have widely occurred in the Hadean Earth. Hence, the discovered field is very important for further geomicrobiological and organic geochemical studies that have potential to reveal prebiotic reaction took place on the earliest Earth and subsequent first community of life.

PI Yoshida and Guilbert were able to show that intramolecular isotopic measurements by nuclear magnetic resonance were reproducible between different labs and different spectrometer configurations, with a high precision below 2.1‰ (Gilbert et al., 2013). Using isotopic ¹³C NMR, we shown that the intramolecular isotope distribution in natural lipids was not homogeneous, but that differences between positions of up to 20‰ can be observed. This approach will constitute a new tool for a better understanding of lipid biogeochemistry on early Earth. The observed specific patterns for lipids of biological origin may constitute a new potential biomarker.

PI Kirschvink and colleagues documented completely anaerobic conditions in the Koegas formation of South Africa (detrital pyrite and uraninite), along with evidence for primary Mn oxides, just before the Makganyene Snowball Earth in South Africa (Johnson et al., 2013). This argues for the presence of a pre-photosystem II, Mn-oxidizing photosynthetic bacterium just prior to the rise of global oxygenation. The subsequent evolution of Oxygenic photosynthesis is interpreted to have rapidly triggered the Makganyene Snowball Earth planetary disaster.

API Ueno, PI Yoshida and colleagues have systematically studied (1) quadruple sulfur isotopic tracer in order to reconstruct Earth's early biosphere. Spectroscopic analysis of SO₂ isotopologues combined with laboratory UV photolysis experiment newly demonstrated that the observed isotopic anomaly in the Archean rock record can be reproduced by SO₂ photolysis reaction. Based on the estimated fractionation factor and its pressure dependence, we newly indicate that the change in D36S/D33S may reflect partial pressure of SO₂ in the Archean atmosphere decoupled with atmospheric chemistry. Field study of South India and its isotopic analysis suggest that the change occur at 3.0 – 2.8 Ga that may relate to global cooling event.

PIs Takai, Maruyama, Yoshida, API Ueno and colleagues found geological evidence of decreasing CO₂ level at about 2.6 billion years ago based on a geochemical study of Late Archean greenstones (Shibuya et al., 2013). The result indicates continental growth and subsequent increase of nutrient fluxes enhanced

already outlined a new model for reactions between a primitive hydrogen atmosphere and a magma ocean (Genda and Ikoma, 2008). In this model, H₂O is produced by a terrestrial planet itself, thus the existence of oceans on Earth is inevitable and the amount of H₂O 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 H₂O was brought to a planet by some mechanism, or the planet produced H₂O 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 Hayabusa-2 mission plans sample return from a primitive C-type asteroid, which may be formed near the ice boundary, and it will clarify H₂O's behavior in planet formation.

Thus, the conditions for the existence of liquid H₂O are not easy to satisfy. It is well known that, because of its unique character, H₂O's density decreases in the phase transition from liquid to solid phase. Moreover, various icy phases exist under extremely high pressure. By integrating H₂O study in material science and study of celestial bodies in the Solar system that contain H₂O (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 "H₂O 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.

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

biological carbon fixation, leading to CO₂ drawdown, thus demonstrating a key connection between Earth and Life evolution.

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Extraterrestrial Observation

In order to understand how the origins of Earth and Life are related in a universal context, it is crucial to broaden our perspective into the worlds beyond our Earth. Exploration of the solar system and astronomical observations of exo-planets are the very powerful tools that enable us to do so.

Hitoshi Kuninaka has been working hard as the Project Manager of the Japanese mission to a primordial asteroid, Hayabusa2. Hayabusa2 will be launched at the end of 2014. Hayabusa2 is a sample-return mission to the asteroid 1999JU3 which is the only C-type asteroid within the reach that is sample-returnable with reasonable resource for the spacecraft. In-situ observations at the asteroid and analysis of returned-samples will open a new window to see how organic compounds behaved in the proto-solar disk. The studies will focus on the radial range of the disk where the snow line (outside which H₂O forms ice and behave as a dust component) is situated. This region of the proto-solar disk is where early solar system materials, which used to be a mere mixture of rocks and ices, come to put on complexity through chemical reaction under the moderately high temperature within small bodies (planetesimals, the building blocks of the planets). Organic compounds are one of the early solar system materials that will be studied

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 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

intensively by the Hayabusa2 project, and thus, the mission theme is relevant to one of the central theme of ELSI, pre-biochemistry.

JUICE is a mission to icy moons of the planet Jupiter. JUICE will be launched in 2022. Icy moons retain key information with respect to the formation of the Jupiter system which is one of the biggest events in the solar system history. Icy moons hosting sub-surface oceans are potential habitats and could well be more common habitats in the universe than the Earth-like ones. That is, there are two themes that JUICE mission has in common to ELSI, the solar system formation theme and the habitability theme. In response to a call made by JAXA, interested planetary scientists in Japan have submitted a proposal to JAXA that is aimed at making Japanese contribution, both hardware and science, to the JUICE mission. Masaki Fujimoto and Jun Kimura have been working hard to make the proposal in a better shape and a preliminary study phase to be as fruitful as possible. The results of the JAXA AO will be announced in June 2014.

There are various ways that ELSI can contribute to the two missions by enhancing the ties between science communities and the project teams. ELSI-hosted study groups that, with the two missions being at the core, will lead activities which reform planetary science into a better shape would be a good idea. The themes of the study groups will be (1) Jupiter system formation, (2) material science at the snow line and beyond, (3) deep habitats. When some more detailed design is completed, study groups will be formed and discussion will be launched.

Parallel to the mission-enabling effort, Masaki Fujimoto has analyzed Cassini plasma and magnetic field data from the Saturn's bow shock to reveal that relativistic electron acceleration takes place at a parallel part of a high Mach number shock (Masters et al., Nature Physics, 2013). Super-nova remnants are bright in X-rays and indicate that shocks therein are the sources for high energy electrons producing X-rays. Until this discovery, while theoretical consideration tells that parallel shocks are more favored site for electron accelerations, observations at Earth had shown negative results. In the present case at Saturn, unlike those at Earth, the Mach number of the shock was as high as those expected at super-nova shocks. Then, in striking contrast to previous cases, the parallel shock turns out to be a good relativistic electron accelerator. In addition to the new insight obtained with respect to shock acceleration physics, which is one of the most important problems in high-energy astronomy, the study also proves the high-potential of outer-planet mission (such as JUICE) for space plasma physics.

Jun Kimura has constructed a new theory explaining the puzzling diverse difference between the two icy moons of Jupiter, Ganymede and Callisto. While the sizes are mostly the same and their orbits around Jupiter are situated next to each other, Ganymede is so differentiated as to have a core in dynamo action while Callisto is thought to be undifferentiated. In considering evolutionary pathways among large icy moons having similar size and mass (Ganymede, Callisto and Titan), Kimura has taken into consideration an initial hydrous core and its

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 SiO₂ (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.

subsequent dehydration by radiogenic heat. Hydrous state can remove heat effectively but once the dehydration starts, viscosity and temperature of the initial core would rapidly increase. In this scenario, a small difference in the amount of radiogenic heat and the size of a moon possibly explain the diversity in the interior structure (Ganymede has a metallic core while Callisto not).

Detection of exo-planets has enabled us to perform scientific endeavor of habitable planets outside the solar system and habitable planets in a totally different settings from Earth. For this endeavor to be fruitful, one needs to explore the methodology to investigate extrasolar terrestrial planets through astronomical observations, considering the possible variety of terrestrial planets implied from planet formation theories and Earth evolution as well as examining the properties of current Earth.

Yuka Fujii has investigated photometric properties of Solar system planets/satellites in collaboration with researchers of Solar system planets, aiming to provide realistic benchmark cases for future direct imaging observations of Earth-like exoplanets. Fujii surveyed several geological processes that alter the planetary reflectance regionally or globally, including igneous activity, geological ages, fine-grained materials, and interaction with surrounding plasmas. We quantitatively estimate their influences on photometric light curves and found that atmosphere-less planets/satellites can produce 5-60% wavelength-dependent variation in visible/NIR according to spin rotation, which would allow us to infer regional features as well as spin rotation period. These signatures of planetary geology will be useful in characterizing their formation and evolution history, as well as to distinguish Earth-like habitable environment from others.

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Geomicrobiology / Physiology

Studying evolutionary processes of biological ecosystems is critically important for understanding evolution of early earth and life. Geomicrobiology/Physiology group focuses on birth and early evolution of ancestral ecosystems, origin and evolution of photosynthesis. Ken Takai and his laboratory members, Kentaro Nakamura, Manabu Nishizawa and Takazo Shibuya (all these are external collaborators of ELSI), pursue to understand where and how prebiotic biologically essential elements and molecules would have been synthesized and gathered, where and how prebiotic and protobiotic metabolisms, heredity and compartment would have been originated and organized and where and how our ancestral living ecosystems would have been developed and propagated.

For this purpose, one of the primary research objectives in this group is to estimate the environmental (physical, chemical and biochemical) conditions of

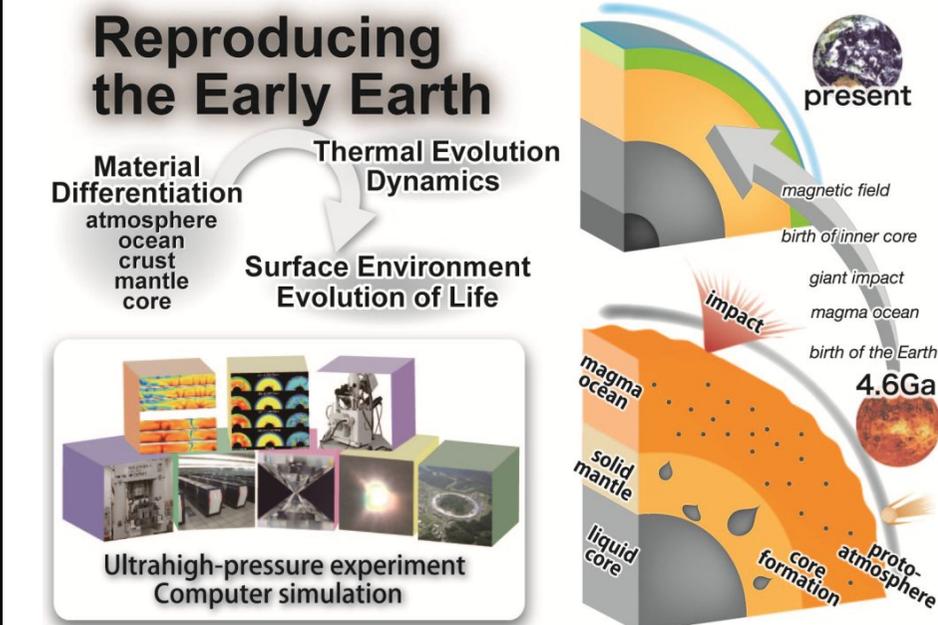


Figure 3. Chemical differentiation within the Earth from core to atmosphere will be reproduced by high-pressure/high-temperature experiments. Subsequent chemical and thermal evolutions inside the Earth will be also examined (related to question A3).

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 H₂O vapor, CO₂ and N₂. As the Earth's surface cooled, H₂O turned to liquid (i.e. ocean), while a CO₂-rich primordial atmosphere remained. Under such a CO₂-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 H₂ and CO due 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 H₂ (Sasaki et al., 2012, in our team). Because these early atmospheric conditions also define the origins of H₂O 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 H₂O 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

cradle places for generation of ancestral living ecosystems and their early evolution. A quantitative estimation of CO₂ concentrations in the atmosphere and ocean during the Hadean and early Archean Earth is also among the scientific goals. Based on the geological and geochemical characterizations of carbonate deposits 2.6 Ga in western Australia, Shibuya et al. (2013a) quantified the potential CO₂ concentrations in the ocean and atmosphere at that time. Since this group already estimated the potential CO₂ concentrations in the ocean and atmosphere 3.5 Ga and 3.2 Ga, the new estimation provided a series of analyzed results in the early Archean from 3.5 to 2.6 Ga. The potential CO₂ concentration in the ocean and atmosphere decreased 1/10 for the 900 million years. In addition, the same group has developed the experimental apparatus to simulate the hydrothermal reaction of crustal rocks during the Earth history. Using the high-temperature and -pressure apparatus, Shibuya et al. (2013b) characterized the chemical compositions of alteration minerals and hydrothermal fluids resulting from the hydrothermal reaction between the CO₂-rich seawater (in the Hadean and early Archean ocean) and the basalt. As previously predicted by the thermodynamic modeling, it was found that the hydrothermal reaction of the CO₂-rich seawater with any of the crustal rock type produced highly alkaline high-temperature hydrothermal fluids together with carbonatization of seawater CO₂ into the alteration minerals that was regarded as a function of geological CO₂ sequestration. In addition, using a newly developed microFTIR spectroscopic technique, this group sought to identify the time and place of early eukaryotic living forms in the history of Earth and Life (Igisu et al., 2013). This group has also promoted a variety of theoretical and experimental investigations on the early evolution of interaction between the earth environments and metabolisms such as nitrogen sources and their assimilation, biologically available energy and biomass production, and the energetics of the Hadean and extraterrestrial submarine hydrothermal systems.

Yusuke Tsukatani and Shinji Masuda have tried to create oxygenic photosynthetic bacteria (artificial proto-cyanobacteria) through genetic recombination of several anoxygenic photosynthetic bacteria, which will provide crucial information on how oxygenic photosynthesis had been evolved and established in the early earth environment. A critical step for establishing oxygenic photosynthesis may be synthesizing chlorophyll a, because oxygenic phototrophs, such as cyanobacteria, use chlorophyll a, although anoxygenic phototrophs, such as purple bacteria and green sulfur bacteria, use bacteriochlorophyll(s), as main pigments. To elucidate what components are required for early evolution of photosynthesis, we have tried to mimic evolution of oxygenic phototrophs from anoxygenic photosynthetic bacteria by direct mutagenesis. Specifically, the purple bacterium *Rhodovulum sulfidophilum*, originally harboring photosystem (PS) II-type reaction center, was used as a host strain to functionally express both PSI- and PSII-types of reaction centers in a single cell. At first, we determined 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 CO₂ concentrations in the 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

whole genome sequence of *R. sulfidophilum*, and identified all genes necessary for photosynthesis (Masuda et al. 2013). Then we modified several photosynthesis genes on the genome. As a result, we succeeded to isolate the genetically modified *R. sulfidophilum* that is capable of synthesizing chlorophyll *a*. For chlorophyll *a* synthesis in the bacterium, genes for photosystem I-type reaction center of green sulfur bacteria as well as galactolipid synthesis were pre-requested. Atsuko Kobayashi started to investigate ultrastructural assessment of bacteria cells and their photosynthetic membrane systems using transmission electron microscopy (TEM). Although TEM studies are still under a way, the available data will tell us the coupling arrangement of chlorophyll synthesis, reaction centers, and membrane lipids for establishing oxygenic photosynthesis in the early earth (Archaean earth) environment. 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. Lipids as structural components of cell membranes are key metabolites to consider origin of life and evolution. We focused on glycolipids, which are major components of photosynthetic membranes in chloroplasts and cyanobacteria. To understand the importance of MGlcDG, which is a characteristic glycolipid in cyanobacterial photosynthetic membranes, we produced a mutant of cyanobacteria in which the cyanobacterial glycolipid biosynthetic pathway is disrupted and substituted by that of higher plants. Under low temperature conditions, the growth of the mutant cyanobacteria was markedly retarded compared with that of WT, although the growth of the mutant was indistinguishable with that of WT at normal growth temperature. Thus, cyanobacterial glycolipid biosynthetic pathway plays an important role for controlling glycolipid amount and composition upon environmental stresses. We speculate that MGlcDG contents are important for the adaptation system of cyanobacteria, which are often found in more extreme environments than are higher plants (Yuzawa et al., 2013).

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., under minor revision). In addition, our research of comparative genome analysis and major lipid analysis suggests that lipid metabolic pathways of *K. flaccidum* are intermediates between algae and land plants.

Lipids also have important roles as a source of lipid derived signaling compounds. We studied on the effect of such a signaling compound on environmental stress responses in land plants. Once plants recognize the signaling

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.

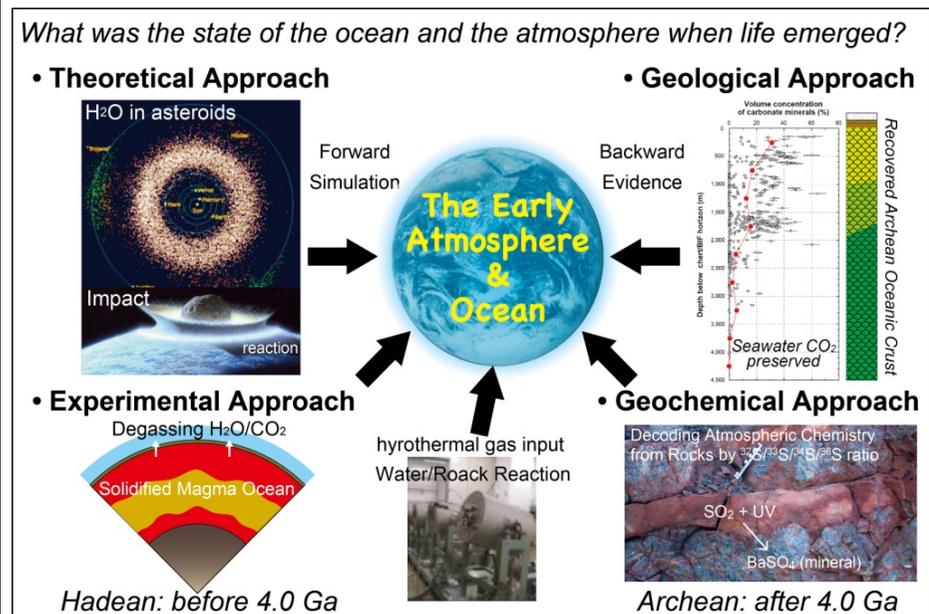


Figure 4. Chemistry of the early atmosphere and oceans will be determined by planet formation theory and tested by geological evidence (related to question B4).

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 subsurface 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.

compound, they start to change their metabolic status to adapt environmental stresses. However, the molecular mechanisms to turn on/off the metabolism under environmental stress conditions are largely unknown. We identified three transcription factors as a molecular switch of stress responses in land plant (Sasaki-Sekimoto et al., 2013, 2014). To understand the adaptation mechanisms of primitive land plants to environmental stresses, Sasaki-Sekimoto launched experimental rooms for biology at ELSI building, and started to investigate the transcriptional responses of *K. flaccidum* under environmental stresses. Comparing the information from *K. flaccidum*, higher plants and algae, we will reveal a fundamental adaptation system against environmental stresses in molecular level.

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

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Genome Environment Database

Investigating the correlation between gene pools derived from modern microbial communities and their surrounding environments is highly important for presuming genetic or gene diversity in the early Earth environments. Genome

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 crust, were abundant and prepared the H₂-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

Environmental Database group focuses on genomics/metagenomics of modern microbial communities, and accumulates the information of both gene pools and environmental contexts (ex. Temperature, pH, etc.) with genomic/metagenomic analyses. On the basis of relationships between gene pools and environmental conditions, pursue to decipher ancient microbial genomes and ecosystems under early Earth environments. Ken Kurokawa and members of his laboratory Takuji Yamada and Hiroshi Mori develop an integrated database for microbes with semantic web technologies named "MicrobeDB.jp". This database integrates microbial gene/genome/metagenome information, taxonomic information and environmental information from both private and publicly available databases. By using this database system, we try to extract correlation indices of metabolic modules and environmental conditions. Yuichi Hongoh and his colleagues investigate how microbial ecosystem had been evolved and established in the early Earth environment through Single-cell genomics studies against unculturable microbes and microbial communities.

In this year (FY2013), we completed the 1st phase of MicrobeDB.jp project (3 years). In this phase, we developed more than 11 billion triples, 6 ontologies and vocabularies and 110 types of STANZA (application for database), and as a result, we succeeded in constructing the integrated database for microbes and environments with full RDF format [MicrobeDB.jp (<http://www.microbedb.jp/>)]. From FY2014, the project goes into the 2nd phase, and we significantly advance the MicrobeDB.jp not only for microbes but also for fungus and algae. We already finished the genome analysis of the purple bacteria *Rhodovulum sulfidophilum* with ELSI Masuda's group [Masuda et al., 2013], the unicellular red algae *Porphyridium purpureum* [Tajima et al., 2014] and the charophyte *Klebsormidium flaccidum* with ELSI Ohta's group [Hori et al., in press]. These genome data are deposited in the MicrobeDB.jp with their environmental contexts.

Results from the group's studies provide fundamental information about the correlation between genes and its surrounding environment to the other group's studies and will become the basis of the collaboration with the Geomicrobiology / Physiology group, Synthetic Biology group and Prebiotic Chemistry group.

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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 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 Nakamura, 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

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Prebiotic Chemistry

Objective of the Prebiotic Chemistry Group

When, where, and how did life emerge from chemical reactions on the early Earth? A number of scenarios for the origin of life have been proposed. However, all require experimental validation as well as further theoretical study. Provided with up-to-date knowledge on plausible conditions on the early Earth, ELSI's Prebiotic Chemistry group focuses on two major questions; 1) how could the components of living systems have been synthesized abiotically? and 2) how could these components have been assembled into living systems?

In FY2013, in order to obtain concrete answers to the critical questions, Masahiko Hara and his laboratory members, Masashi Aono, Jim Cleaves, Alexis Gilbert, Piet Hut, and Norio Kitadai made considerable efforts to optimize chemical reaction conditions on the early Earth and also to develop some schemes/systems to simulate the prebiotic reactions.

Early-Earth Simulator

Masashi Aono and Masahiko Hara designed and developed a flow-type reactor to simulate chemical reactions under various environments of the early Earth. The reactor was designed so as to introduce minerals, gasses (N₂, H₂, CH₄, CO₂) and UV light (UVA/UVB/UVC, selectively) under controlled temperature (~400 °C), pressure (~10 MPa), pH (1~14) and flow rate (1 ~ 100 mL/min). This configuration enabled us to mimic hydrothermal vents on the early Earth's surface. A high-pressure batch-type reactor was also developed to extract chemical soup by boiling minerals.

Masashi Aono with the help of Jim Cleaves constructed an early-Earth-based system of the Miller-Urey experiment (MUE), which enables to synthesize amino acids (AAs) and nucleotide (NT) precursors in reduced atmosphere. The MUE system was designed to simulate not only the synthesis of AAs and NTs but also their polymerization to form proto-proteins (polypeptides) and proto-RNAs (polynucleotides) that exhibit primitive catalytic and self-replicating functions, respectively. For that purpose, he i) introduced various minerals and rocks so that they work as sources of phosphates and their surfaces catalyze the polymerization, avoiding the asphalt problem, ii) create spatial gradients and temporal variations of temperature to induce condensation of AAs and NTs in non-equilibrium conditions, iii) repeatedly alternate between dry and wet conditions on the mineral surface to extend the polymerized chains, and iv) accelerate the polymerization on

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 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

the mineral substrate in the presence of optical near-field interactions occurring at nanoscale structures of the minerals.

Jim Cleaves conducted his own MUE to elucidate chemical and physical behaviors of small organic structures and carbonaceous meteorites, of possible relevance to the origin of life on Earth (Parker et al in Press). For comprehensive investigation of the aqueous chemistry of the seemingly simple ternary NH₃ – HCN – HCHO system, he has been specifically examining the kinetics and yield of amino acids of various types and of other small molecules and N-heterocycles derived from this chemistry, and the degree of product overlap with the organics observed in meteorites (Cleaves et al 2013).

Analytical Systems

Alexis Gilbert designed and installed valuable analytical systems for the prebiotic experiments. Nuclear magnetic resonance spectrometer, isotope ratio mass spectrometer, high performance liquid chromatography and gas chromatography mass spectrometry were setup to qualitatively and quantitatively analyze chemical compounds produced through the prebiotic reactions. All of the analytical systems have been ready to be used. Masahiko Hara also designed a novel nano-analytical technique to directly measure interaction forces between biomolecules and minerals using atomic force microscopy, which will be utilized to investigate crystal facet-dependent interactions and so on. Jim Cleaves developed desorption electrospray ionization imaging mass spectrometry to investigate prebiotic model reactions on mineral surfaces (Bennett et al 2013). He also tried to investigate the molecular composition of Titan tholin. This work has been conducted jointly with the CNRS and NASA and has been submitted in two parts to Icarus and the PNAS.

Theoretical Approaches

Along with the experimental approaches, Masashi Aono, Jim Cleaves, Norio Kitadai and Piet Hat developed theoretical approaches to simulate the prebiotic reactions. Masashi Aono modified his amoeba-inspired dynamical system model (Kim et al 2013, Kawai et al 2013, Naruse et al 2013, Aono et al 2013), which quickly found stable solutions to a constraint satisfaction problem. He simulated the formation dynamics of stable organic molecules and RNA secondary structures, aiming at extracting minimal metabolic circuits and self-replicating RNA sequences. Jim Cleaves performed computation of all of the structural isomers of nucleotides and amino acids conceivable (Meringer et al 2013). Norio Kitadai computationally predict thermodynamic behaviors of amino acids over wide ranges of temperature and pH (Kitadai 2014). He calculated the energetics of amino acid synthesis and polymerization as a function of temperature (25–300 °C) and pH (2–12). The energetically most favorable condition for the amino acid synthesis from simple inorganic precursors (CO₂, NH₃, H₂ and H₂S) was found to be slightly acidic pH and lower temperature, whereas that for the polymerization

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 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).

was moderately alkaline pH and higher temperature. These results suggest that the Hadean alkaline hydrothermal setting, where steep pH and temperature gradients between cool, slightly acidic Hadean ocean (pH 5–6, <20 °C) and hot, moderately alkaline hydrothermal fluids (pH 9–11, >200 °C) are expected to exist at the vent–Ocean interface, could have been the most suitable environment for both the synthesis and polymerization of amino acids. Piet Hat tried to establish a community of researchers working on simulations of Artificial Life, with an emphasis on the Origins of Life

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

Jack Szostak, an ELSI PI in Harvard/ MGH, has created new proteins and ribozymes originated from artificial evolutions different from the natural one. He also works for proto cell by construction of artificial compartment containing RNA or peptide. He and Albert Fahrenbach set focus to make use of RNA polymers

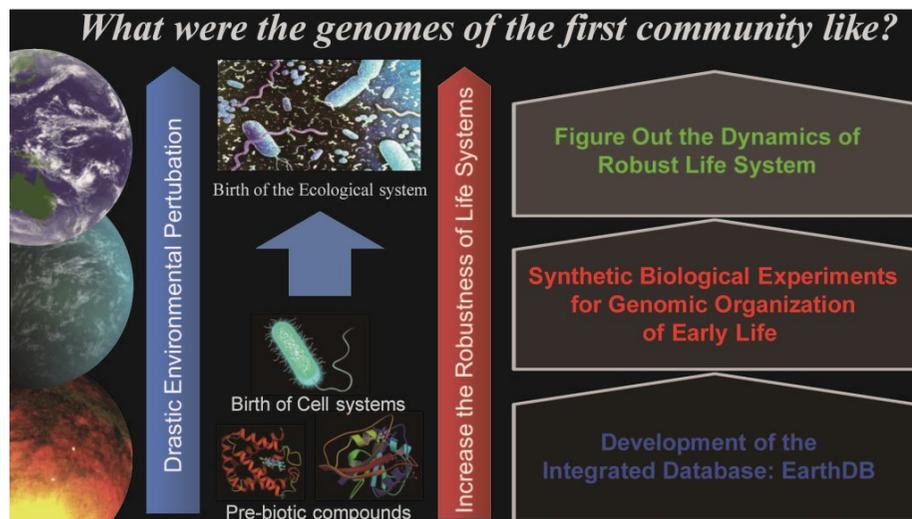


Figure 6. The initial genome born in a unique environment on early Earth will be estimated by using the data base that relates specific environmental factors and the gene pools of microorganisms. With a development of these data base further, the initial ecological system that allowed a stable and persistent 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 evolutionary 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

which can undergo replication within the confines of vesicles. One of the key steps in protocellular replication involves the copying of the RNA polymers which act as the templates for their own syntheses. One of the practical challenges is the fact that the activated RNA monomers are in a high energy state, and react quickly with water before undergoing polymerization on the parent template. Although one of the presumptions of the RNA World hypothesis supposes a time without modern complex molecular machinery that normally powers cellular replication, there may have existed vastly simpler RNA-based machines capable of performing the same functions. These so-called prebiotic molecular machines – capable of doing useful work at the molecular level – may be able to promote template-directed RNA replication. We propose to incorporate covalently the photoactive azobenzene molecule into a functional ribozyme. Azobenzene, a small molecule capable of undergoing cis/trans isomerization upon exposure to ~400 nm light, has the ability to harness the energy of electromagnetic radiation and convert it into a molecular scale contracting motion. Such activated RNA monomers would not be so different from the modern day energy currency used by the cell, namely ATP.

Daisuke Kiga, an ELSI associate PI, 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. As a tool to create primordial protein constituted of limited number of amino acids, he engineered genetic codes to reduce the number to 16 (Amikura et al.; 2013, Amikura and Kiga, in press; Amikura and Kiga, 2013). For these works, he made an oral presentation in Gordon conference for Origins of Life. He also analyzed directed evolution of protein under restriction of the number of amino acid species. Additive effect of beneficial mutations even within the restricted genetic alphabet provides insight into the evolution of primordial proteins.

For resurrection of primordial biological systems, model-based design of biological reaction is important. In our 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. Appropriate gene-overexpression bifurcates basal multistable stable system into monostable one and allocates the single stable-steady point to arbitrary position on the phase space. We experimentally demonstrated that the overexpression induced a monomodal cell distribution, and subsequent overexpression withdrawal generated a bimodal distribution (Ishimatsu et al., 2013).

Yutetsu Kuruma, an ELSI researcher, is a specialist for artificial lipid compartment which represent environment of proto cell. He has produced proteins in his protocells. He also contributed as session organizer in the Fujihara

enzymes and co-factors common to both chemosynthetic and photosynthetic metabolisms. The driving force lies in a strong interrelation between the demand 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

seminar and the Astrobiology workshop. He recently reported a practical model for the construction of artificial cell which enable to autonomously express the cell membrane function by decoding the genes involved in biosynthesis of membrane protein.

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the second half of the project year. Conventional obstacles to this type of research have been metasomatic overprints and contamination of exotic compounds into 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.

Why does the Earth's atmosphere contain oxygen?

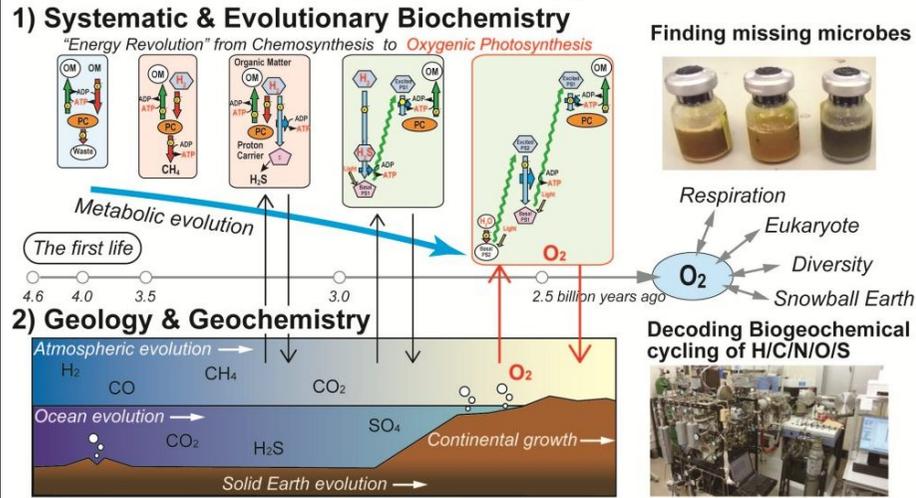


Figure 7. Metabolic evolution from the origin of life to oxygenic photosynthesis will be decoded by systematic and evolutionary biochemistry. The evolution pathway into the oxygenic photosynthesis and its influence on Earth's biosphere will be traced by geological observations (related to question C7).

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 multicellular 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

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.

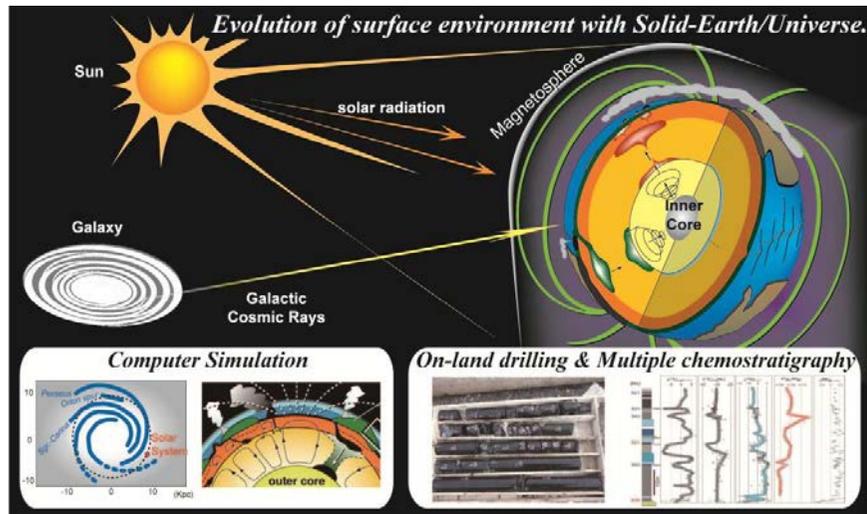


Figure 8. The evolution of the Earth's interior should have affected surface environments through enhancement of geomagnetic field, landmass, and sedimentary rocks. The effect from the Universe such as intensity of cosmic rays may be also important for the change in Earth's surface environment (related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

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 $^{186}\text{Os}/^{188}\text{Os}$ 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

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 data 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.

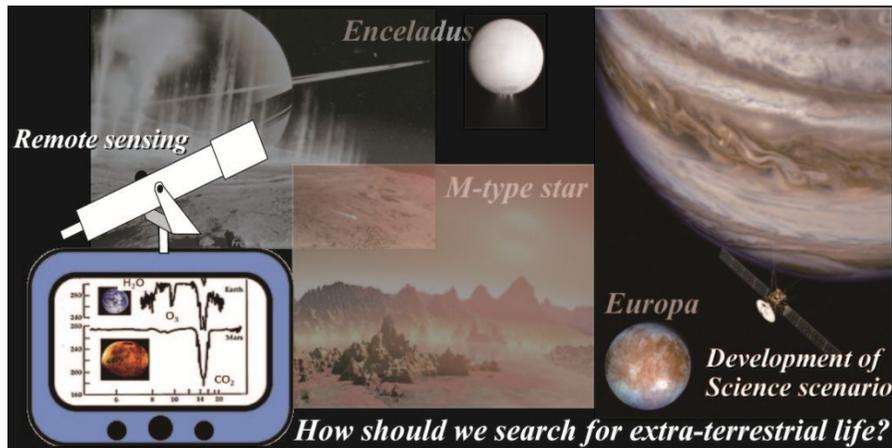


Figure 9. We will participate in future space exploration projects (such as missions to Europa and Enceladus, which have an internal ocean) as well as in projects to look for biomarkers by remote sensing of terrestrial planets outside the solar system (related to questions **D10** & **D11**).

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) Composition of administrative staff

- While ELSI operates under the strong leadership of the Director, the Administrative Director was no longer able to fulfil his assigned duties due to health reasons and he stepped down from the post. A new Administrative Director was appointed who assists the Director as well as possesses life science perspectives, experiences in organizational management, and international experiences and viewpoints. As a result, the life science fields are expected to be strengthened and internationalized.

- In order to strengthen and enhance research and public relations support for the administrative division, four administrative staff members and four educational research assistants were recently hired (the total number of employees as of the end of March 2014: 9 administrative staff members and 4 educational research assistants).

- An individual who held a director-level position with extended work experiences was assigned as an assistant administrative director by the university headquarters. In addition, one individual with extensive financial experience was assigned as a financial chief.

- 2) Decision-making system

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

○ The Steering Committee

Continuing from the previous fiscal year, the Steering Committee (which consists of the Center Director, the Administrative Director, and two Vice-Directors) provides advice and support to the Director relating to coordination within the university, regulation review, research environment improvement and personnel matters essential to the operation of the Institute. While the Steering Committee has met once a week since the inception of the Institute, as was required to manage the overwhelming number of projects, the frequency of the meetings has gradually decreased to alleviate the burden on the committee. As of the end of FY 2013, the committee is meeting only once a month. In addition to requiring that managerial-level personnel and higher from the Administrative Division and research related assistants attend the committee meeting to share information, we improved the system that helps carry out and implement the Institute's decisions efficiently.

○ International Advisory Board

In accordance with the plan to increase the number of International Advisory Board Members, the Director invited Dr. Carl Pilcher, the former director of the NASA Astrobiology Institute, to become a board member; the offer was accepted.

The International Advisory Board meeting was held twice during FY 2013, on 13 September and 25 March. Based on the advisory board's guidance and advice, we implemented measures to strengthen and enhance the ELSI research activities, including developing a risk management plan. Dr. Carl Pilcher, a newly appointed board member, attended the meeting on March 25. As of the end of FY 2013, the following four individuals serve as International Advisory Board members:

- Masuo Aizawa, Chairperson (Advisor, Japan Science and Technology Agency)
- Douglas Lin, Board Member (Professor, University of California, Santa Cruz)
- Robert Hazen, Board Member (Research scientist, Carnegie Institution)
- Carl Pilcher, Board Member (Former Director, NASA Astrobiology Institute)

- A new councilor position was created in order to strengthen collaboration with other institutions.

○ Establishing the Expert Advisory Committee

During the beginning of FY 2013, the Director structured the Institute's management system by establishing the Expert Committee under the Steering Committee.

- Science Steering Committee <Continuing from the previous fiscal year>

The committee formulates the medium and long-term research plans, updates/revises the research master plan and research roadmap based on these plans, and promotes interdisciplinary research

- Public Relations <Continuing from the previous fiscal year>

In addition to reviewing public relations activity plans, the Public Relations

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

Department creates/updates the website, disseminates information about the Institute via SNSs, implements outreach activities, and collaborates/coordinates with other research centers.

- Financial Planning Committee <Newly established >

The committee prepares a budget draft, compiles the annual budget based on results presented by each committee, and knows the budget implementation status.

- Building Committee <Newly established>

The committee puts together the ELSI building renovation plan and new building construction plan, partakes in daily building management, and formulates/implements the experiment infrastructure improvement plan.

- Computer Network Committee <Newly established >

The committee builds and updates an information network system in ELSI buildings and new buildings, takes part in daily maintenance and management, and responds to network issues.

- Research Interactions Committee <Newly established>

The committee plans and holds research meetings, such as symposium and workshops, selects external researchers (visitors), and formulates acceptance plans.

- Recruitment Committee <Newly established>

Based on the employment plan, the committee partakes in activities to recruit young, highly capable researchers and builds/updates the public job opening announcement system. The committee is also responsible for managing applicants documents, screening applications and set interview sessions.

In addition to those committees, the Safety and Health Committee, the Information Ethics Committee, the Information Security Committee and the Hazardous Materials Management subcommittee were established in accordance with the regulations and the university rules.

3) Allocation of authority between center director and host institution

- We established the Institute's unique policies, which are not bound by the university rules, and created a reward system for those who made special contributions at the Institute, and provided rewards two individuals.

- In January 2014, we conducted an evaluation based on research achievements and future prospects using the ELSI Evaluation that aims to increase young researchers' research motivation; evaluation results were used to increase researchers' compensations.

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).

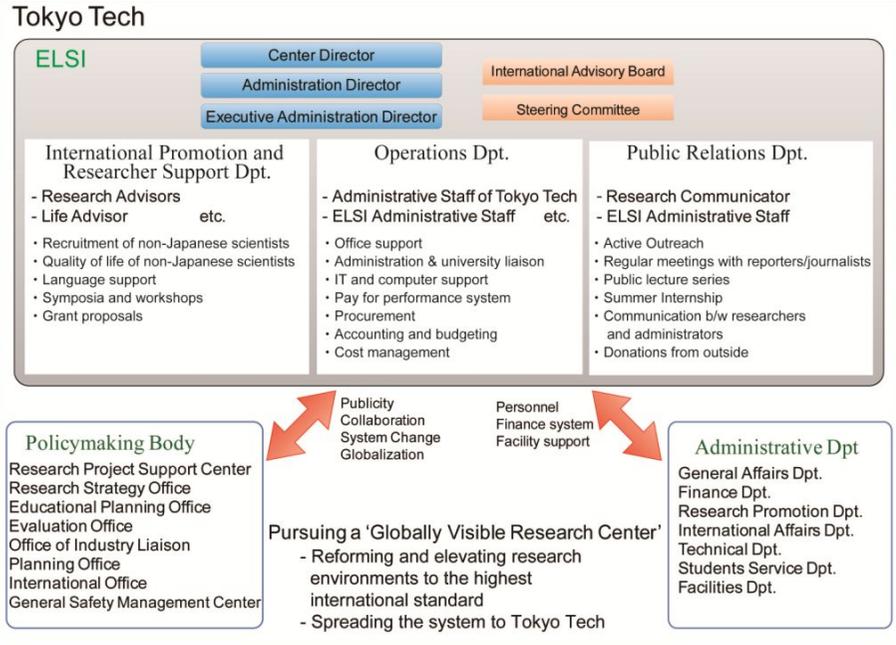


Figure 10. Structure of Operations and Administration Division of Earth-Life Science Institute.

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 2013	Results at end of April 2014
Researchers from within host institution	6	6 (October,2015)	8	7
Foreign researchers invited from abroad	3	6 (October,2015)	2	2
Researchers invited from other Japanese institutions	4	4 (October,2015)	4	5
Total principal investigators	13	16 (October,2015)	14	14

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 2013	Results at end of April 2014
Researchers	23 < 3 , 13 %>	71 (October,2015) < 24 , 33 %>	41 < 10 , 21 %> [8 , 20 %]	49 < 10 , 20 %> [9 , 18 %]
Principal investigators	13 < 3 , 23 %>	16 (October,2015) < 6 , 37 %>	14 < 4 , 29 %> [0 , 0 %]	14 < 4 , 29 %> [0 , 0 %]
Other researchers	10 < 0 , 0 %>	55 (October,2015) < 18 , 33 %>	27 < 6 , 22 %> [8 , 30 %]	35 < 6 , 17 %> [9 , 26 %]
Research support staffs	0	34	9	8
Administrative staffs	5	10	18 (14 , 78 %)	18 (14 , 78 %)
Total	28	115	68	75

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.

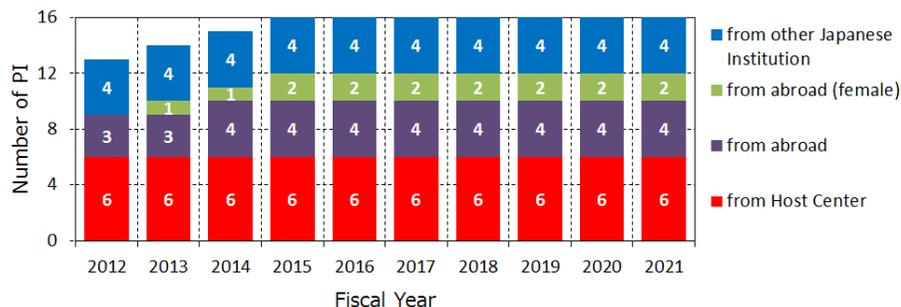


Figure 11. Plan for the participation of non-Japanese Principal Investigators.

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 Investigators (Equivalent to professor and associate professor levels)

- Principal investigator John Hernlund arrived ELSI in August 2013 as the initial schedule was accelerated. Hernlund is a foreign principal investigator working full-time at ELSI.
- As of the end of FY 2013, ELSI had 14 principal investigators and four of them are foreign principal investigators, this is 28% of the total principal investigators. Numbers of associate principal investigators, which is consistent with the previous fiscal year as three.
- Based on the WPI Committee and the International Advisory Board's advice, ELSI reviewed the plan to secure life science researchers. It is essential to invite first class researchers as principal investigators to attract young researchers. We created a list of first class researchers in the area of life science research and active in his research. Full-fledged negotiations are scheduled to take place after FY 2014.
- As for Dr. Lisa KALTENGER who is scheduled to start her post as a principal investigator in October 2014, has started to work with new institute. We need to change her duration of employment as a principal investigator at ELSI.
- Principal Investigator Makino will be transferred to the RIKEN HPCI Program for Computational Life Sciences from April 2014. He will be participating in the ELSI as an external principal investigator.

b) Overall Plan

- As of the end of FY 2013, the ELSI had 47 researchers (14 principal investigators, 3 associate principal investigators, 19 WPI-employed researchers, and 11 collaborating researchers), including 11 foreign researchers (23% of the overall researchers) and eight female researchers (17% of the overall researchers). ELSI has a total of 58 researchers, including 11 researchers who have been selected during FY 2013 and will be starting their posts after April 2014; this indicates that the number of researchers has been increasing almost as initially planned. Meanwhile, increasing the ratios of foreign and female researchers is a task that needs to be achieved.
- One foreign researcher who started his post in February 2012 obtained an associate professor position at another university. This researcher will continue to participate in ELSI's research activities as an affiliated scientist.

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%.

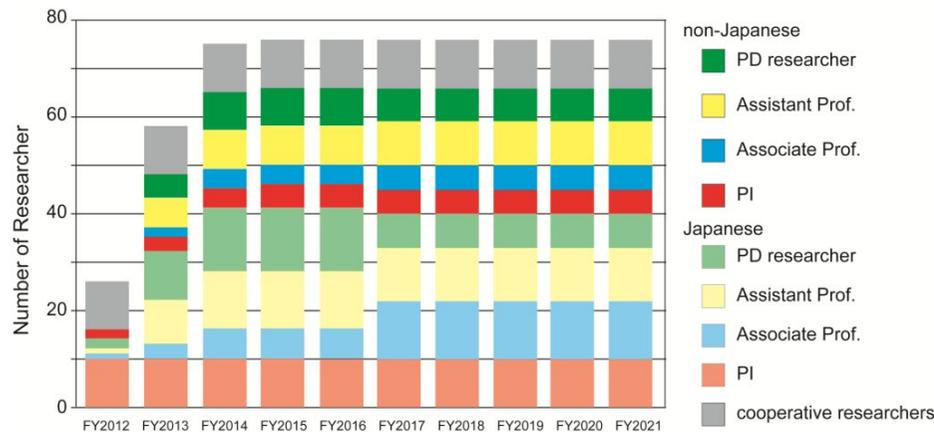


Figure 12. Expected number of researchers at ELSI.

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.

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

- Satellite organizations

[Performance for 2013 / progress status / changes since establishment]

Organization name (1): Geodynamics Research Center, Ehime University

<Roles>

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

<Personnel and organization>

Personnel makeup as of the end of 2013 is as described below.

- Satellite Director and Principal Investigator Professor Tetsuo Irifune (Director of Geodynamics Research Center (GRC), Ehime University)
- WPI Member
 - Steeve Greaux (Member, GRC, Ehime University)
 - Hiroki Ichikawa (Member, GRC, Ehime University)
 - Masayuki Nishi (postdoctoral fellow, GRC)
- Cooperative researchers
 - Taku Tsuchiya (Professor, GRC, Ehime University)
 - Jun Tsuchiya (Associate Professor, GRC, Ehime University)
 - Yoshinori Tange (Assistant Professor, GRC, Ehime University)
 - Xianlong Wang (postdoctoral fellow, GRC)

<Collaboration Framework>

- To arrange a Study Group 4 together with ELSI for exchanging and discussions on daily research activities approximately once a month.
- To recruit young researchers using a researcher network called “TANDEM” (The Asian Network in Deep Earth Mineralogy) which has been fostered to date by Professor Irifune and others.
- To cooperate to ELSI’s public relations activities, in particular science events held in the Western Japan regions.

Organization name (2): The Interdisciplinary Program, the Institute for Advanced Study in Princeton

<Roles>

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

<Personnel and organization>

Personnel makeup as of the end of 2013 is as described below.

- Satellite Director and Principal Investigator
 - Professor Piet Hut (Head of the Interdisciplinary Program, the Institute for

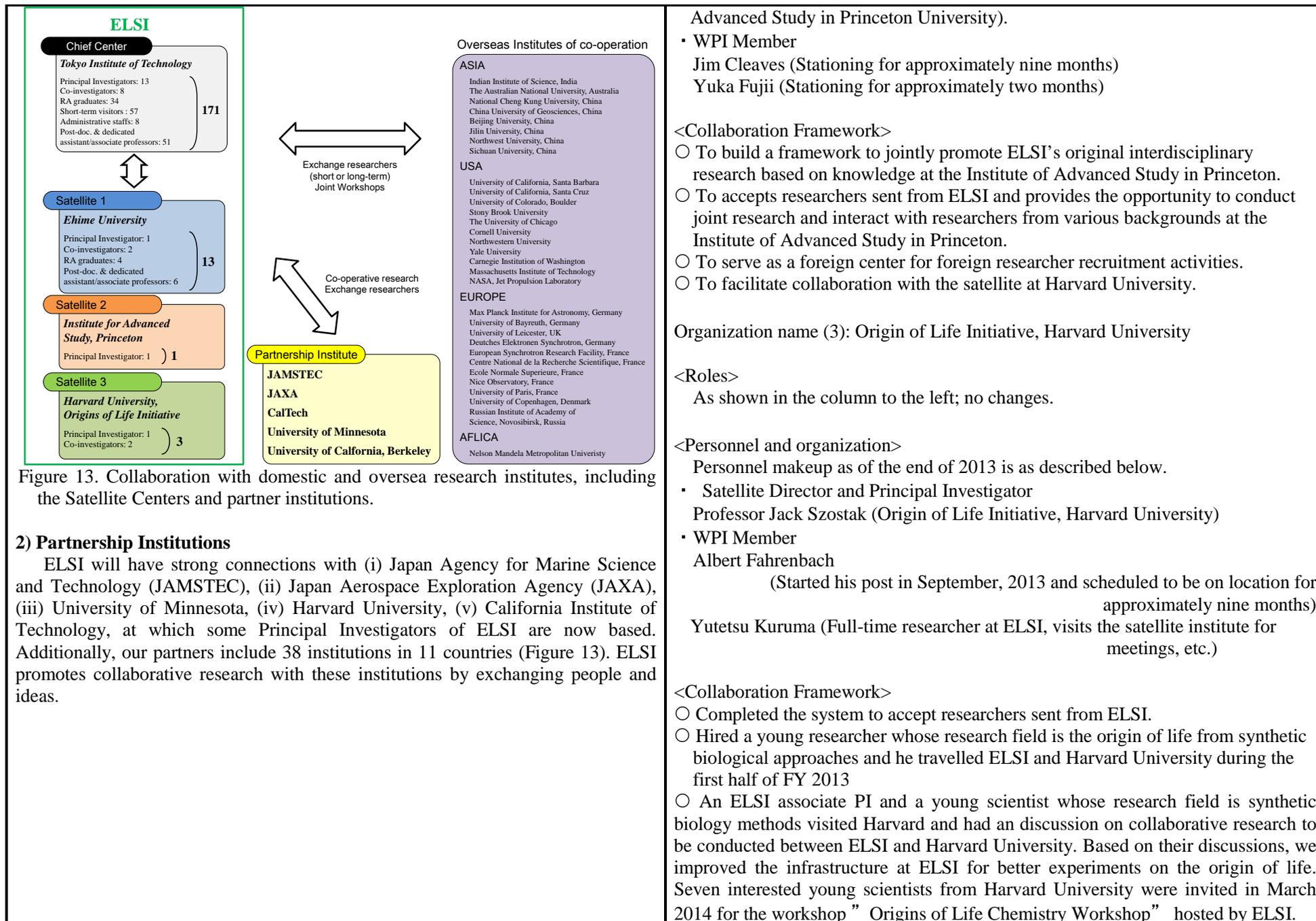


Figure 13. Collaboration with domestic and overseas research institutes, including the Satellite Centers and partner institutions.

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.

○ To promote collaboration with Institute for Advanced Study in Princeton.

[Performance for 2013 / progress status / changes since establishment]

Organization name (1): Japan Agency for Marine-Earth Science and Technology

<Roles>

① The agency conducts thorough investigations on where and how the substances (elements and molecules) which 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 them to the task intended to analyze biological evolution from geological records.

<Personnel and organization>

Personnel makeup as of the end of 2013 are as described below:

- Principal Investigator

Ken Takai, Program Director (Ocean Subsurface Geobiology and Advanced research Project at the Institute of Biogeosciences).

- Associate Principal Investigator

Naohiko Okochi, Program Director (Ocean Subsurface Biology and Advanced research Project at the Institute of Biogeosciences).

(Geobiosphere Evolution Research Program at the Institute of Biogeosciences)

<Collaboration Framework>

○ Principal Investigator Takai and his laboratory staff members primarily take responsibility for Role ①, while Associate Principal Investigator Ohkouchi and a group led by Principal Investigator Yoshida are primarily in charge of Role ②.

○ The agency has started exploring research personnel interactions and comprehensive collaboration between institutions beyond the framework of collaborative research.

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 using the observation data on universally crucial characteristics and phenomena found on the planetary/satellite surface 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. Additionally, the Agency examines the possibility of the existence of life on icy satellites, which are believed to have oceans.

Moreover, 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 mid- and long-term objectives.

<Personnel and organization>

Personnel makeup as of the end of 2013 are as described below:

- Principal Investigator Professor Masaki Fujimoto (Department of Space Plasma Physics, Institute of Space and Astronautical Science, JAXA)
- Principal Investigator Hitoshi Kuninaka (Department of Space Transportation, Institute of Space and Astronautical Science, JAXA)

<Collaboration Framework>

○ Not only simply taking part in collaborative research with ELSI's researchers, Principal Investigators Fujimoto and Kuninaka held workshops to develop the JUICE plan and the Hayabusa 2 plan,

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 first principles molecular dynamics methods.

<Personnel and organization>

Personnel makeup as of the end of 2013 are as described below:

Principal Investigator 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 the ELSI and seismic wave measurement data to the calculation results obtained at the University of Minnesota.
- One young researcher was assigned to help connect the ELSI's experimental research with the University of Minnesota's theoretical studies.

Organization name (4): Harvard University

<Roles>

○ The university anticipates the achievement of spectral observation of exoplanets in the habitable zone and is investigating effective indices to determine the presence of life by targeting a red dwarf (M) type star in the habitable zone.

<Personnel and organization>

Personnel makeup as of the end of 2013 are as described below:
Principal Investigator Lisa KALTENEGGER (Research Associate)
(Harvard Smithsonian Center for Astrophysics)

<Collaboration Framework>

- Collaborative research between two groups, one led by Principal Investigator Ida and the other led by Principal Investigator Kaltenegger is underway.
- Principal Investigators Ida, Principal Investigator Kaltenegger, and others will organize the “Exoplanet Conference” scheduled to be held in Germany in November 2014. For this event, both groups are cooperating and making an effort to expand the astrobiology communities.

Organization name (5): California Institute of Technology

<Roles>

- The university presents a verifiable model of the ocean, the atmosphere, and the crust in the early stage by retracing geological record. 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>

Personnel makeup as of the end of 2013 are as described below:
Principal Investigator Professor Joseph Lynn KIRSCHVINK (Division of
Geological and Planetary Sciences, California Institute of Technology)

<Collaboration Framework>

- Principal Investigator Joseph Lynn KIRSCHVINK stayed at the ELSI for slightly longer than five months during FY 2013 and took part in collaborative research with Principal Investigator Maruyama and Associate Principal Investigator Ueno.
- Principal Investigator Joseph Lynn KIRSCHVINK received ELSI’s researchers at the California Institute of Technology, his principal place of employment, and provided the opportunity for the researchers to acquire the most advanced research techniques, such as transmission electron microscopy analysis, sample preparation methods, etc.

6. Summary of center's research environment

< 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 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

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

1) Environment in which researchers can devote themselves to their research

- We integrated the administrative desk offices for researchers and established a one-stop support system for them.
- "ALL ELSI meeting" instead of a monthly PIs meeting
Monthly PIs meetings held during the last fiscal year has ceased in November 2013. Beginning in December 2013, ALL ELSI meeting started. Principal investigators from overseas participate in the meetings as much as possible via Skype.

2) Startup research funding

- 500,000 yen to five million yen were allocated to principal investigators and researchers hired from outside the university.

3) Postdoctoral positions through open international recruitment

- In an effort to incorporate tactics used overseas to recruit young researchers to ELSI's recruiting activities, the Director appointed John Hernlund, a foreign principal investigator to serve as a chairperson for the Recruitment Committee. With Hernlund's leadership, the committee improved the existing online public job advertising system and expanded the options to announce job offer information (posting on Nature, Science, etc.). Moreover, the Director, the Recruitment Committee and the Public Relations Department collaborated with recruiting activities, such as setting up booths at international conferences. ELSI received a total of 135 applications since September 2013. One hundred and twenty-five of the 135 applications (92.6%) were by foreign applicants.
- ELSI hired 13 young researchers in FY 2013, four of whom were foreign researchers.

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

- We strengthened and enhanced the administrative management by adding three people with sufficient English language skills as the personnel in charge of financial related tasks and research related administrative tasks to support foreign researchers. Eleven of the 15 employees are bilingual (the total number of employees as of the end of March 2014 in the administrative division: 11 administrative staff members and 4 research assistants).

W provided support for employment procedure for seven foreign researchers, assisted 126 visitors, and held ten international conferences.

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.

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 overseas 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 m² from start and additionally up to approximately 2100 m² 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

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

- An incentive system was established for those who made special contributions to the Institute. A reward was given to two individuals.

○ Holding an annual evaluation meeting

An annual evaluation meeting was held for two days at the end of January 2014. The evaluation was done by both ELSI researchers and principal investigators based on the research activity report, a 15-20 minute presentation and discussion. The main evaluation criteria consisted of ① the quality of the research (including academic papers and publications) and feasibility with the ELSI research objectives; ② the participation in activities to promote interdisciplinary studies; and ③ the researcher's independence to conduct his/her own research (applied to young researchers). One Principal investigator, one associate principal investigator and six young researchers were awarded for 2013. The Director is planning to conduct a feedback interview with each researcher based on the evaluation results.

These activities were reported at the International Advisory Board meeting held on March 25, 2014. It was also decided to identify the challenges to make a fair evaluation of researchers with different academic disciplines and to continue examining more effective evaluation systems.

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

- As the renovation work on the existing buildings (2,670m²) was completed, full-fledged research activities began. A communication space was set up in which we actively provide the opportunity for interdisciplinary research interactions that go beyond specialized academic fields via a twice-a-week brown bag lunch session and a daily coffee break meeting.
- In addition to the ELSI building, new building 5,000m² building is now under construction. It is scheduled to be completed in March 2015.
- Equipment essential to promote ELSI's science (such as transmission electron microscopes [TEMs], computer resources for simulations/database, next generation sequencers, cell sorters, etc) was introduced as scheduled. With the university's cooperation, we also accelerated the initial plans to expand the life science and chemistry related experiment space and improve the infrastructure for experimentation.

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

- We hosted the International Symposium, as well as nine other international

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 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.

symposium and various seminars in FY2013. Five study groups (SGs) hold research seminars on a daily basis.

8) Other measures, if any

- In order to help promote the world's top-level interdisciplinary research activities, we established a research advisory system to provide research guidance and advice from professional standpoints. Three advisors are scheduled to start the post on 1 April 2014.
- We integrated the administrative desk offices for researchers and established a one-stop support system for them.
- The Research Strategy Promotion Center and the Assistant Director, who also serves as a research administrator, are providing support to secure external funds for foreign researchers.

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

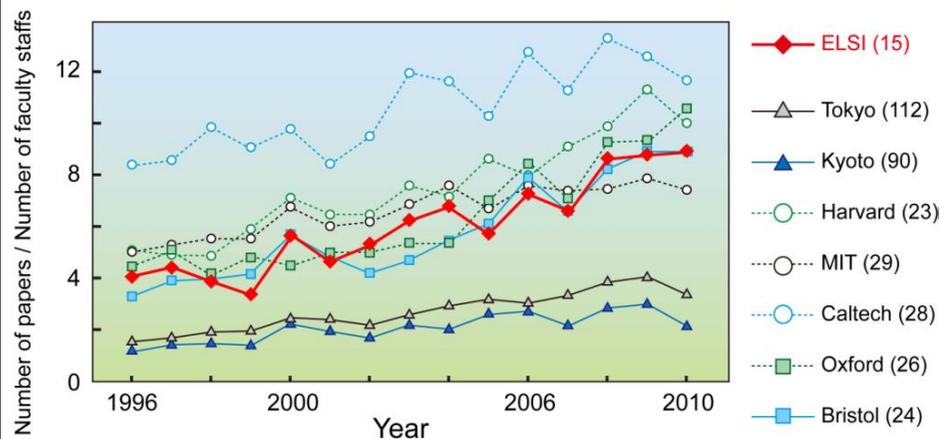


Figure 14. Research activity defined by (Numbers of papers) / (Number of faculty staffs) in the top universities in Japan, U.S. and UK (Thomson Reuters, USI Database 1996-2010, results from the fields of Geology, Geochemistry & Geophysics, Environmental Science, and Geoscience, Multidisciplinary). The 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 for evaluating the center's global standing in the subject field

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

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

- It takes several years after a paper is published before research activities and research quality become significant from statistical and bibliometric perspectives. Therefore, current self-evaluations of research quality, an index based on the number of citations made from the paper in particular, shall be conducted after the following fiscal year.
- In addition to reviewing "Altmetrics," a method to instantly measure the degree of influence from a recently published paper, within the Institute we participated in the "GRIPS University Benchmarking Seminar," hosted by the National Graduate Institute for Policy Studies, and discussed the issue with responsible parties from other institutions. Therefore we decided not to conduct current evaluations only using "Altmetrics" at this point.
- During 2013, 91 published papers cited "ELSI" as the author's affiliated institution, including Science (one publication), Nature (one publication) and Nature Geoscience (two publications).

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

- As shown in the column to 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.

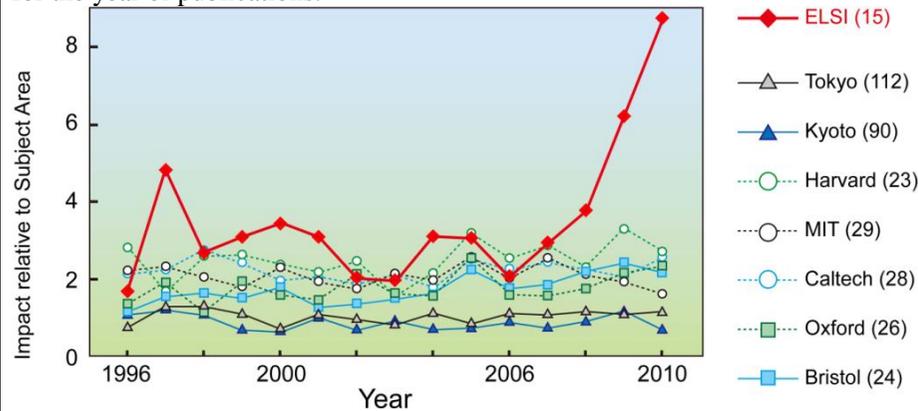


Figure 15. Research impact defined by (Average number of citations per publication in a given field) / (Total number of citations for all publications in that field) for papers published in a specific year (Relative Impact Factor, Thomson Reuters, USI database). The number of citations for papers by 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)	<ul style="list-style-type: none"> Globally competitive 	<ul style="list-style-type: none"> The only world-leading center in all of its subject fields
Research activity ^{*1} and Research impact ^{*2}	<ul style="list-style-type: none"> Top in the world in both Research activity and impact 	<ul style="list-style-type: none"> Same
Business Development	<ul style="list-style-type: none"> Develop trend analysis for research funds Establish framework for collecting donations Young researchers annually obtain competitive funds of JPY 110M. 	<ul style="list-style-type: none"> Stable operation of collecting donations Young researchers annually obtain competitive funds of JPY 175M.
Development of Research Talent	<ul style="list-style-type: none"> 40% of young researchers come from overseas 	<ul style="list-style-type: none"> More than 30% of young researchers are female
Effective support for international visitors	<ul style="list-style-type: none"> 80% of visitors assess support as outstanding 	<ul style="list-style-type: none"> 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 Change

Research funding acquired during the fiscal year 2013 (The amount has taken in account the effort put forward by ELSI)

8,310,000 USD (831,000,000 yen) Conversion rate:1 USD =100 JPY

ii) The Outlook Following the Establishment of the Research Institute

○ No changes at the time of institute establishment.

○ Main activities related to securing competitive funds in FY 2013.

- In order to assist researchers in applying for as many funding programs as possible, we made an effort to disseminate available information about funding program opportunities, in addition to focusing on improving the environment that helps them concentrate on their research.
- A start-up budget was provided to new researchers to start their research smoothly as planned. The budget was only allocated to them contingent upon applying for external funding opportunities.
- Set up the assisting system to foreign researchers when applying for Grants-in-Aid for Scientific Research. In particular, the system provides guidance on selecting the application items, handles administrative procedures for them, at minimum prepares the research overview section of the application in Japanese, 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 a 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 the university's Research Strategy Promotion Center.
- The Director, the Administrative Director and the Councilor are in negotiation with foundations in the U.S. supported by Institute of Advanced Study in Princeton.

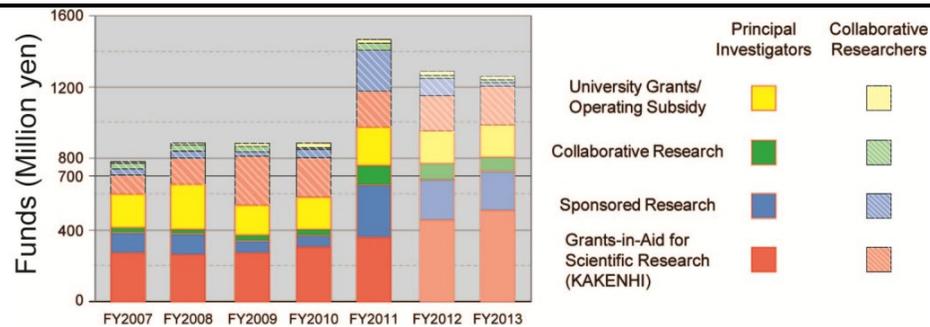


Figure 16. Annual variations in the total research funds obtained by the 10 Japanese PIs and another 8 collaborative researchers between FY2007 and FY2011. The dashed bars of FY2012 and FY2013 indicate those informally-promised by the end of June 2012.

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).

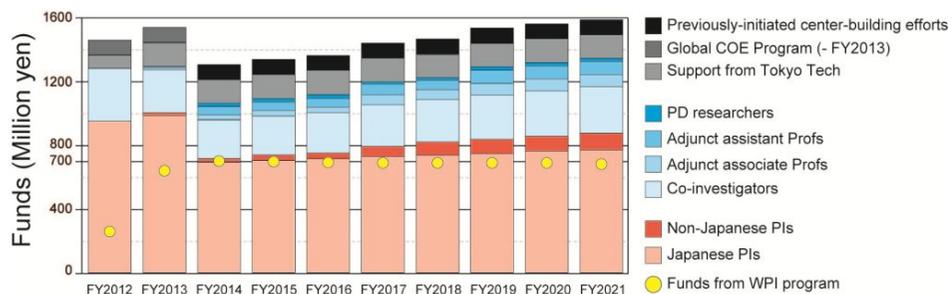


Figure 17. Prospects of research funds. The total amounts of KAKENHI, sponsored research funds, collaborative funds, and university grants/operating subsidies will far exceed the amount of requested fund from the WPI program (yellow balls). Additionally, this figure includes the support from G-COE program 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 m²)

- 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 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.

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

(1) Activities Following the Completion of WPI fundingPeriod

- In order to help operate the ELSI permanently, the university shall continue to view the ELSI as its main institute by providing assistance with funding, research space, personnel matters and place. Obtaining donations would be as one of the basic sources of funding.
- We are considering the option of obtaining donations from foreign institutions with the Councilor—who is in charge of promoting interdisciplinary studies and international collaborative research, and examining how to acquire excellent talent—playing a leading role in this matter.

(2) Influences to other institutes

1) Internationalization

- ① We strengthened and enhanced the administrative management by adding five people with sufficient English language skills to the personnel in charge of financially- related tasks and research related administrative tasks in order to support foreign researchers. Eleven of the 15 employees are bilingual (the total number of employees as of the end of March 2014 in the Administrative Division: 11 administrative workers and 4 research assistants). We provided support for employment of seven foreign researchers, assisted 126 visitors, and held ten international conferences.
- ② An incentive system was established for those who made special contributions to the Institute. A reward was given to two individuals.
- ③ We integrated the administrative desk offices for researchers and established a one-stop support system for them.

2) Research Direction

- Holding an annual evaluation meeting

An annual evaluation meeting was held for two days at the end of January 2014. The evaluation was done by both ELSI researchers and principal investigators based on the research activity report, a 15-20 minute presentation and discussion. The main evaluation criteria consisted of ① the quality of the research (including academic papers and publications) and feasibility with the ELSI research objectives; ② the participation in activities to promote interdisciplinary studies; and ③ the researcher's independence to conduct his/her own research (applied to young researchers). One Principal investigator, one associate principal investigator and six young researchers were awarded for 2013. The Director is planning to conduct a feedback interview with each researcher based on the evaluation results.

These activities were reported at the International Advisory Board meeting

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. 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 supervision 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.

held on March 25, 2014. It was also decided to identify the challenges to make a fair evaluation of researchers with different academic disciplines and to continue examining more effective evaluation systems.

○ In order to help promote the world's top-level interdisciplinary research activities, we established a research advisory system to provide research guidance and advice from professional standpoints. Three advisors are scheduled to start the post on April 1, 2014.

3) Active Outreach Activities

○ We conducted active outreach activities. This can be used as a reference by other institutions in terms of returning research achievements to the society.

① We strengthened and enhanced the public relations system by hiring two public relations personnel.

② Research communicators with sufficient scientific background will take responsibility for the overall ELSI outreach activities.

③ We conducted outreach activities with the research communicators mentioned in ② playing a leading role in those activities. Specific activities include a) issuing press releases; b) holding a periodic round-table conference with reporters, journalists and researchers; c) welcoming visits to the laboratory from local elementary school students (experiment workshops) and holding a lecture that mainly targets local residents.

④ Seven events were conducted for the general public (two events for elementary school students and one event for local residents in particular) while there were 23 publications and 14 publications of research achievements in newspapers and in books/magazines, respectively. Moreover, we are currently building a centralized management and disclosure system for paper publications and research information from the Institute.

(3) Other

1) Overseas Exchange Opportunities for Researchers

○ During FY 2013, a total of 139 researchers (126 of whom were foreign researchers) were invited for a time ranging from one week to one month to discuss the promotion of collaborative research with the ELSI researchers and research cooperation for the following year and thereafter. We made an effort to provide research exchange opportunities that are not limited to the interested parties by requesting that visiting researchers lecture or present relevant topics at the ELSI seminar or at a brown bag session.

2) Announcing Research Achievements

○ We presented the affiliated researchers' research achievements at the

international symposium held for three days from 24 to 26 March, 2014, and discussed the ELSI 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 by incorporating the aspects specified by the Program Committee.

○ “ALL ELSI meeting” instead of a monthly PIs meeting

Monthly PIs meetings held during the last fiscal year has ceased in November 2013. Beginning in December 2013, ALL ELSI meeting started. Principal investigators from overseas participate in the meetings as much as possible via Skype.

○ In order to overcome the “language barriers” and “cultural barriers” and to promote mutual understanding amongst researchers with various backgrounds, the following events were implemented with the advice by Principal Investigator Piet Hut.

- ELSI assembly: Research presentations and discussions by ELSI members (Wednesdays)

- ELSI seminar: Research presentations and discussions by external researchers

- Brown bag seminar (twice a week) and coffee break meeting (daily)

○ As the renovation work on the existing buildings (2,670m²) was completed, full-fledged research activities began. A communication space was set up in which we actively provide the opportunity for interdisciplinary research interactions that go beyond specialized academic fields via a twice-a-week brown bag lunch session and a daily coffee break meeting.

○ In addition to the ELSI building, new building 5,000m² building is now under construction. It is scheduled to be completed in March 2015.

○ Researchers from different academic fields participate in the five study groups (SGs) and take part in interdisciplinary research by holding research seminars on a daily basis.

○ Equipment essential to promoting ELSI’s science (such as transmission electron microscopes [TEMs], computer resources for simulations/database, next generation sequencers, cell sorters, etc) was introduced as scheduled. With the university’s cooperation, we also accelerated the initial plans to expand the life science and chemistry related experiment space and improve the infrastructure for experimentation.

10. Host institution's commitment

<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 (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

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

- Provision of the host institution's mid-to-long term plan

No Change

○ Specific Measurements

The specific accommodations offered by the host institution can be categorized into the following five areas.

- ① Approving the unique operation system at ELSI by the university administration bureau.
- ② Providing necessary space.
- ③ Offering personnel support to the Center
- ④ Making arrangements with the Institute to take educational research activities in other departments for gathering the researchers to the Institute
- ⑤ Giving a preferential financial treatment

The specific measurements are described as follows.

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

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

- A round table discussion is held once a month with the President, Executive Vice President for Research and the Director to foster close collaboration with the university.
- We established the Institute's unique policy, which is not bound by the university regulations, created an incentive system for those who made special contributions to the Institute, and provided rewards to two individuals.
- Holding an annual evaluation meeting

An annual evaluation meeting was held for two days at the end of January 2014. The evaluation was done by both ELSI researchers and principal investigators based on the research activity report, a 15-20 minute presentation and discussion. The main evaluation criteria consisted of ① the quality of the research (including academic papers and publications) and feasibility with the ELSI research objectives; ② the participation in activities to promote interdisciplinary studies; and ③ the researcher's independence to conduct his/her own research (applied to young researchers). One Principal investigator, one associate principal investigator and six young researchers were awarded for 2013. The Director is planning to conduct a feedback interview with each researcher based on the evaluation results.

These activities were reported at the International Advisory Board meeting held on

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.

-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

March 25, 2014. It was also decided to identify the challenges to make a fair evaluation of researchers with different academic disciplines and to continue examining more effective evaluation systems.

○ In addition, we continued to implement the same measures as last year.

② Providing necessary space

○ As the renovation work on the existing buildings (2,670m²) was completed, full-fledged research activities began. A communication space was set up in which we actively provide the opportunity for interdisciplinary research interactions that go beyond specialized academic fields.

○ In addition to the ELSI building, construction work has begun on a new 5,000m² building for the Institute. It is scheduled to be completed in March 2015.

③ Offering personnel support to the Institute

○ In order to strengthen the life science fields, particularly in the area of “the origin and evolution of life,” at the President’s discretion, the university accommodated the ELSI’s request for an additional professor to serve from 1 April 2014 to 31 March, 2022.

○ Continuing from the previous fiscal year, we received the university’s assistance with salaries for a total of seven personnel, including five principal investigators and one affiliated administrative staff member, in addition to one affiliated administrative staff member added during FY 2013.

○ As principal investigators are exempted from teaching undergraduate education courses, the department which received approval for three faculty posts at the President’s discretion is aiming to strengthen its undergraduate education by adding faculty members in order to prevent disruptions to its curriculum

○ We began the review process for the introduction of the research track system.

④ Making arrangements with the Institute to take educational research activities in other departments for gathering the researchers to the Institute

○ As part of developing the next generation of researchers, principal investigators from the university participating in activities at the Institute are now allowed to provide research guidance for undergraduate theses.

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

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.

(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 Center, 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

⑤ Giving preferential financial treatment

- We are exempted of 60 million yen space charges for the President's discretionary space provided by the university.
- Eighteen million yen was provided to assist in repairing the air conditioning units in the ELSI building.
- We began the review process for creating a day care facility to assist female researchers.

⑥ Others

In addition to "Host Institute's commitment" made by the university at the Institute's planning stage, the President announced active support for the operation of the Institute, along with personnel and material assistance for the Site Visit Committee and the Program Committee. The university emphasized that various system reforms and administrative organization reforms at the ELSI will be the first step toward university reforms.

We will continue to collaborate closely with the university.

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 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 m² of floor space for ELSI at the start-up and additionally up to approximately 2100 m² 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 m² 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

- The road map of ELSI is an important guideline for all ELSI researchers as well as for visitors. It is recommended to make a simplified map that clearly indicates the present location and future direction.
- Recruiting the first “class” of young foreign scientists should be considered one of the most important goals of ELSI over the next 6 months or so, and it should be explicitly raised to this level of priority by ELSI management.
- Activities of female scientists are not apparent in the leadership roles at ELSI. It also appears that female scientists who are actually active on a routine level are restricted to junior ranks. Vigorous efforts are needed to promote activities of female scientists.
- In describing ELSI’s participation within a larger collaboration, for example, the JUICE space mission or advanced computing hardware development, ELSI needs to state clearly what its contribution would be.
- ELSI has, as a whole, impressive expertise in deep earth science, planetary research, genomics and phylogenetics, but needs to reinforce its research in prebiotic chemistry and evolutionary biochemistry, which are a major component in current discussions on the origins of life.

<Responses to Areas Requiring Improvement and the Outcomes in FY 2013>

1. As previously reported, the roadmap was reviewed with the Director and the Science Steering Committee playing a leading role in the task. First, the benchmark for the first half of the WPI Program was set. The unique aspect of ELSI science is that it attempts to examine the origin and evolution of the Earth and life by applying both bottom-up and top-down approaches, thus providing the missing link that exists between these two approaches. We set up eight interdisciplinary fields in which specific research activities take place based on the two approaches (an understanding of the current situations), and then formulated a simple roadmap to connect the fields with the tasks that need to be performed in order to reach the benchmarks.
2. ELSI’s efforts to fill publicly job openings were re-evaluated with overseas academic calendar and a foreign principal investigator who is familiar with researcher recruitment was appointed as a chairperson of the Recruitment Committee. In addition, the chairperson is to be replaced periodically rather than serving permanently in the position. In other words, we appoint a foreign researcher of the field that needs to be strengthened to be chairperson by balancing the researchers’ specialized fields at ELSI.
3. To have full-time female researchers at the ELSI with leadership role, we have been examining measures to achieve the goal. However, we have not yet found a solution. We are aiming to such researchers by providing higher startup funds by emphasizing our support program for living in Japan, which to date has been positively received by foreign researchers.
4. Focusing on large-scale international collaborative research, such as the JUICE project in which JAXA’s principal investigators have been taking a leading role in Japan, the Director and the Councilor have begun discussions to identify specific contributions that the ELSI can make and topics that are beneficial to both sides. By the first half of FY 2014, they aim to clarify the ELSI’s contributions to and roles in large-scale international research projects and the expected scientific benefits.

	<p>5. We shared with the host institution the fields that we need to improve. In order to facilitate experimental research in relevant fields, we have accelerated the initial plan to improve experiment infrastructure by expanding the experimentation space with the university's assistance. Moreover, the President provided one faculty post to the ELSI in order to invite a professor who specializes in the relevant research fields.</p> <p>As for the recruitment of young researchers, we decided to give hiring priority to a researcher who assumes research activities in the relevant fields. A foreign researcher serving as the chairperson of the Recruitment Committee with the background in the Earth Science field was replaced by a foreign researcher who is playing a leading role in research activities in Life Science, particularly in the area of chemical evolution.</p> <p>Top-rated researchers, who are scheduled to stay at the ELSI for approximately one year from the second half of FY 2013, have had a significant impact at the ELSI on studies in their relevant fields and continue to encourage young researchers. The ELSI views this "finding" as an important element and strives to focus on inviting world-renowned researchers who can take long-term sabbaticals to stay at the ELSI.</p>
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12. FY 2013 funding

(the exchange rate used:)

i) Overall project funding

1 million yen

Cost Items	Details	Costs (1 million yen)
Personnel	Center director and Administrative director	22
	Principal investigators (8 persons):	56
	Other researchers (19 persons):	106
	Research support staffs (5 persons):	27
	Administrative staffs (12 persons):	49
	Total	260
Project activities	Gratuities and honoraria paid to invited principal investigators	0
	Cost of dispatching scientists (0 person):	0
	Research startup cost (19 persons):	6
	Cost of satellite organizations (1 satellite organization):	52
	Cost of international symposiums (1 symposium):	4
	Rental fees for facilities	102
	Cost of consumables	28
	Cost of utilities	0
	Other costs	20
	Total	212
Travel	Domestic travel costs	2
	Overseas travel costs	11
	Travel and accommodations cost for invited scientists (22 domestic scientists): (89 overseas scientists):	29
	Travel cost for scientists on secondment (0 domestic scientist): (1 overseas scientist):	1
	Total	43
Equipment	Depreciation of buildings	133
	Depreciation of equipment	86
	Total	219
Other research projects	Projects supported by other government subsidies, etc.	133
	Commissioned research projects, etc.	189
	Grants-in-Aid for Scientific Research, etc.	426
	Total	748
Total		1482

WPI grant for FY 2013

Costs of establishing and maintaining facilities in FY 2013

133

Repairing facilities
(1 facilities: 2,670m²)

Costs paid:

133

Cost of equipment procured in FY 2013

523

High Resolution Analytical Transmission Electron Microscope : Number of units : 1 130

Simulator System for the History of Earth : Number of units : 1 71

High performance computer system for Earth-Life Database : Number of units : 1 48

multicolor cell sorter : Number of units : 1 40

High throughput DNA sequencing system for genomics and metagenomics : Number of units : 1 33

Direct-injection-type Mass Spectroscopy System : Number of units : 1 28

Flow Reactor for Early-earth Simulation : Number of units : 1 14

Batch Reactor for Early-earth Simulation : Number of units : 1 13

Gas Chromatography Mass Spectrometry : Number of units : 1 12

Spectrum image measuring system : Number of units : 1 12

Simulator System for the formation process of Earth : Number of units : 1 9

High speed network System : Number of units : 1 9

Hydrogen-Pressuring System : Number of units : 1 9

fume cupboard : Number of units : 1 7

Nucleic acid and Protein Extraction System : Number of units : 1 6

Others 82

ii) Costs of Satellites and Partner institutions

Cost Items	Details	Costs (1million yen)
Personnel	Principal investigators (1 person):	/
	Other researchers (4 persons):	
	Research support staffs (5 persons):	
	Administrative staffs (0 person):	
	Total	
Project activities		27
Travel		3
Equipment		3
Other research projects		71
Total		122