World Premier International Research Center Initiative (WPI)
Executive Summary（Interim Evaluation）

Host Institution	Tokyo Institute of Technology	Host Institution Head	Yoshinao Mishima
Research Center	Earth-Life Science Institute	Center Director	Kei Hirose

*Summarize the Self-Evaluation Report for Interim Evaluation (**within 4 pages** including this page).

1. Summary of State of WPI Center Project Progress

The Earth-Life Science Institute (ELSI) investigates the origin and evolution of the Earth and life, and aims to become a global research hub within the broad theme of "when and where did life emerged on the Earth, and how did they evolve together." More specifically, ELSI aims to study the early Earth environment and its subsequent changes that gave rise to life and sustainable ecological systems and that accommodated their evolution through surveys of microbial ecosystems at the deep see bottoms or of primordial asteroids. Earth science can help us to understand the unique and universal aspects of the Earth and develop into a new life-bioplanetaryology science, to contribute to life exploration for life both inside and outside the Solar System.

Described below is the progress of ELSI since its launch within the context of the four basic objectives of the WPI program. As ELSI research profoundly relies on interdisciplinary activities, we will provide a unified discussion on “Science” and “Fusion”. Our scientific goal is to fill the gap in our knowledge concerning both early Earth and life and to specify medium-range and later research strategies. Following are representative research topics that have advanced at ELSI: 1) Planet habitability with a focus on the key role of "water". 2) "Formation and effectiveness of magnetic fields in the early Earth" related to the origin of life and associated changes in the Earth's atmosphere. 3) Abiotic polymerization of amino acids in prebiotic chemisty. 4) Non-enzymatic rotation of the reductive TCA cycle. 5) Abiotic formation of carbohydrates. 6) Molecular phylogenetic understanding of early ecological systems. These achievements arose through collaboration between heterogeneous researchers and mark the definitive arrival of interdisciplinary research. ELSI has newly defined the "origin of life" as "a transition from Earth-assisted geochemistry to polymer-assisted biochemical networks" and specified medium-range research issues.

ELSI's goal in globalization was to develop the Institute into a global hub for research on the origins and evolution of Earth and life. The recruitment committee headed by a non-Japanese vice director advertises broadly seeks top candidates and has a presence at international meetings to publicize ELSI and to reach out to young researchers. Through these efforts, non-Japanese researchers now comprise 36% of our researchers, including 7 Principal Investigators. Furthermore, ELSI coordinated with the Astrobiology Center at the National Institutes of Natural Sciences (NINS) and launched the Japan Astrobiology Consortium. The Institute also concluded a partnership agreement with NASA Astrobiology Institute and a coordination agreement with JAXA/ISAS, which is a part of the international cooperation framework geared towards Mars exploration in the near future. ELSI will lead the scientific aspect of the Mars Moon (Phobos/Deimos) eXploration (MMX) Mission led by ISAS. Ten Affiliated Centers joined ELSI’s international network and host EON project scientists for collaboration.

ELSI's goals with respect to reform were to develop an organized and comfortable research and living environment under the leadership of the director, particularly for foreign researchers, and to develop an administrative support system that allows researchers to concentrate on their work. For these goals, ELSI branded the “ELSI style” by 1) establishing an open and flat research structure under the belief that all researchers are equal in the eye of “research”; 2) managing and enhancing research equipment and environment through funding from WPI aids, large-scale KAKENHI, and overseas funds; 3) developing the top-down organization with Director empowered with all decision-making; 4) developing a one-stop research support system by the secretaries; and 5) livelihood and language support for foreign researchers through life advisors. With the understanding and support from the host institute, the Tokyo Institute of Technology, ELSI introduced a cross-appointment system, secured tenure positions, implemented a merit-based payroll system, and separated graduate school teaching responsibilities. Referencing the ELSI style to encourage further globalization of the campus and to promote greater involvement of female researchers, the university also began to develop foundational infrastructures, such as a child daycare center, and expanded available housing.

2. Center’s Research Activities

1) Summary of Research Highlights: ELSI research in Phase I has tackled challenging problems related to planet formation, volatile delivery and storage, geomagnetism, early Earth surface environment, prebiotic chemistry, messy chemistries, electro-chemistry, geochemistry-linked microbe ecology, early microbial evolution, and origin of information in chemistry. For example, ELSI employed new planet formation models that provide an improved match to observations, and made predictions of giant impacts that we have now confirmed by astronomical observations in remote young star systems. Experiments and *ab initio* calculations by our researchers indicate that the Earth's core includes approximately 1% hydrogen, which requires wet magma oceans and delivery of a significant amount of volatiles during accretion. ELSI's experiments showing that Earth's core has a high thermal and electrical conductivity threw standard models of deep Earth evolution into a tailspin, but this led us look for alternative models and the discovery that SiO_2 likely crystallized from the early core. Our study of the early atmosphere via geological and biochemical investigations has built a new integrated picture of the Hadean and early Archean environment, and shows that life began in a much more reducing environment than previously thought. The process and environmental conditions of prebiotic chemistry were simulated using experiments such as the "geyser reactor" which enabled ELSI researchers to construct complex molecules such as peptides from simple amino acids. ELSI has made progress in understanding how "messy" chemistry can become organized, such as mapping the most accessible routes to macromolecules through facile reversible polymerization, and the possible roles of branched polyesters in creating early binding motifs or controlled microenvironments. Our electrochemistry laboratory investigates anaerobic catalysis at mineral surfaces and has evaluated pre-biological routes to carbon and nitrogen fixation into biologically accessible molecules. ELSI biology researchers have shown how key functions such as nitrogen fixation, or evolutionary transitions such as the rise of oxygenic photosynthesis, could have occurred more easily than previously expected, and how some units that shape evolution, such as viral genomes, can assume a wider variety of forms. ELSI studies of the structure of evolutionary change have been combined with synthetic-biology methods to understand how genetic-code and protein complexity arises or how new synergies such as membrane functionalization can originate. ELSI theoretical, computational, and laboratory research has shown how heredity can arise in a general way from elementary chemical processes, studied RNA relative to other possible information-carrying systems, and worked on reproducing the transition from minimal oligomeric systems to the extended genetic material comprising modern life.
2) Research for the next five years: Cooperation and interdisciplinary activity has taken root, reaching the next phase where we can overcome the traditional obstacles about research into the origin and evolution of Earth and Life. Specific issues were identified, and our next challenge is to build a foundation for a new system science by addressing these questions and integrating the research outcomes.
3) Appraisal by Society and Scientific Organizations: Both senior researchers and young researchers have been recognized with renowned awards and fellowships, demonstrating the outstanding level of ELSI research.
4) Achievements of center's outreach activities: 1) ELSI has been included in a travel agency's package for high school study excursions. 2) A public lecture, "Investigating Origins," hosted jointly with Kavli IPMU, was well-received (December 2015), marking the kick-off of cooperation with other WPI programs and contributing to the improved visibility of ELSI and WPI programs. 3) The "Tokyo Tech Inspiring Lecture Series" was planned and initiated by the PR team at Tokyo Tech and ELSI. Four ELSI researchers, including the Harvard Satellite Director and Nobel Prize recipient PI Szostak, hosted the seminars. These lectures were well received, and this lecture series now continue to be organized by the University.

3. Interdisciplinary Research Activities

1) State of Strategic (or "Top-down") Undertakings toward Creating New Interdisciplinary Domains: i) Since ELSI's launch, major efforts and strategic plans have been made for acquisition of large-scale research funding to promote fusion. As a result, ELSI and the Ehime satellite succeeded to get a large-scale grant-in-aid program in FY2014 and FY2015 totaling as much as 1.0 billion yen over a five-year period. The biggest success was the "ELSI Origins Network (EON)" project that received the support of an American foundation (33 months, total $5.6 million USD) that started in July 2015. PI and Councilor Hut helped to develop the proposal and used his longstanding network to help in negotiation with the foundation in order to obtain the proposal's acceptance. ii) To promote studies on the origin of life, ELSI aimed to invite a bridge builder who could lead the development of a new interdisciplinary field rather than a specialist. As a result, Dr. Smith and Dr. Kamagata, joined the institution as a PI and an ELSI Fellow, respectively. iii) The Annual Evaluation Meeting is a yearly mandatory event and serves as an

opportunity to enhance mutual understanding and to exchange feedback among researchers. Every member must summarize their activities over the past year and deliver an oral presentation. Evaluation criteria include items such as the eagerness to be involved in an interdisciplinary research, and for young researchers, the willingness to conduct their research independently from PIs. iv) Development of an open and flat research structure and recruiting strategy for young researchers. These form the basis of what creates ELSI's platform for fusion and collaborative work across different disciplines. The young researchers, who play an important role in the interdisciplinary research, should promote their own research independently from PIs together with other researchers within and outside of ELSI. Cares is taken during the recruiting process so that young researchers will not lose sight of their career objectives. Applicants are encouraged to speak with ELSI researchers to fine-tune their research topics before assuming their positions at ELSI.

2) State of "Bottom-up" Undertakings from the Center's researchers toward Creating New Interdisciplinary domains: i) ELSI Director's Fund is used to encourage studies borne out of young researchers' free and flexible ideas or from discussions between researchers with different backgrounds. Proposals including multiple researchers in different disciplines are encouraged. ii) Various meetings are organized to share research targets and foster greater mutual understanding among researchers. Initially, five study groups were set up, and ELSI researchers were asked to belong to at least two groups in order to foster communication between researchers with diverse backgrounds. As the number of researchers increased, the study group activities have been transferred to the ELSI Seminar, ELSI Assembly, and ELSI Youchien. ELSI Seminar is given by external researchers, while ELSI Assembly is a scientific meeting conducted by ELSI researchers. In 2015, the Assembly was organized to host PI Scope sessions in which discussions overviewed by PIs occur and round-table sessions on topics provided by several young researchers are discussed. ELSI Youchien aims to remove the barrier between different disciplines by encouraging young researchers to present their research to other researchers as well as the support staff in simple language. iii) Hosting bottom-up workshops is supported to enhance ELSI's recognition to the outside and to foster fusions between ELSI and external researchers. The Research Interaction Committee reviews the workshop proposals and provides financial support. Some of the workshops' contributions were published in "Physics of the Earth and Planetary Interiors", "Origins of Life and Evolution of Biospheres", and "Geoscience Frontiers".

4. International Research Environment

1) International knowledge circulation takes place through collaboration at the individual level as well as through institutions. Outstanding examples include joint research among ELSI's Deep Earth research team, the University of Minnesota, and the University of California Santa Barbara. In addition, seven cases of international joint research developed by individual researchers are mentioned in the report.

2) Top-rate researchers staying at ELSI include seven PIs from overseas out of total 16 PIs. Four of these seven foreign PIs are based in Japan. ELSI also welcomes visitors from overseas research institutions. ELSI focuses especially on inviting of top-class researchers in the midst of their sabbaticals.

3) With regards to recruitment of young researchers, mentioned in 1, Globalization, our efforts have been fruitful. ELSI has received 216 applications thus far, nearly 90% of which came from foreign researchers. The number of exceptional young foreign researchers selected from the applicant pool totaled 13. Combined with seven foreign PIs (one of whom is a woman), the ratio of foreign researchers at ELSI has increased to 36%.

4) Other environmental preparations: Efforts are made to promote international research environment by hosting international meetings, providing extensive livelihood support for foreigners, assisting in securing competitive funding, and establishing an organization where non-Japanese can feel comfortable.

5. Implementing Organizational Reforms

1) System Reforms: i) New organization management. The so-called ELSI style is formed through introducing open and flat research environment, tenure track system, cross-appointment system, merit-based payroll system, etc. ii) Support for research and daily life by English speaking administrative support staff is established. iii) Efforts for strategic acquisition of research funding. iv) The model practiced by ELSI has spread university-wide, promoting university reform.

2) Support by Host Institution: i) Under the direct jurisdiction of the university president, ELSI is positioned as a permanent research site (special research district), playing a leading role for research reform and system reform, and the university continues to provide personnel and financial assistance, including provision of tenured positions and space utilization. ii) A total of 20 rooms in the university's

International House have been kept for ELSI researchers use, along with the establishment of a daycare center and expansion of lodging. iii) ELSI has decided to introduce first corporate card purchasing system in collaboration with the Tokyo Tech administration.

6. Future Vistas

1) In Tokyo Tech's Mid-Term Plan and Objectives, ELSI is positioned with a "highly strategic ambitious objective and plan" and is directly under the university president's jurisdiction. The university recognizes ELSI as a leader in research reform and during the site visit and program committee meeting, expresses active support in addition to the "commitment by the host institution" at the time of conceptualization.
2) To build on the research grants acquired from overseas and to actively seek further funding from abroad, ELSI is considering to establish an office and incorporating as a non-profit entity overseas.
3) Efforts continue to build the institute into a "world class research hub" after the end of WPI support. ELSI will continue to provide researchers with a place for research, young researcher's development, interaction with the world's top-level researchers, and interdisciplinary research promotion. Furthermore, the support system for foreigners will be further improved and exported to the host.
4) As a host institution, the university positions ELSI as a special research district and continually provides human resources, space, and financial support to keep the perpetual world-class status of ELSI.

7. Others

Acquisition of global fund (EON Project): In July 2015, ELSI secured research funding from the U.S.-based John Templeton Foundation for a 33-month project with a total of US$5.5 million (about 670 million yen). Using this fund as a resource, we launched the EON (the ELSI Origins Network) project to accelerate research related to the origins of life and to build an international research network.

8. Center's Response to Results of FY2015 Follow-up (including Site Visit Results)

8.1 Follow-Up Report and Issues Needing Investigation

1) Research into the origins of life: ELSI has recruited two foreign PIs and one ELSI fellow to promote this research field. Considering the research outcomes to date and future prospects, we newly defined the origin of life and presented three specific issues that should be pursued over the mid-term.
2) Communication with young researchers: In addition to the existing programs such as daily meetings, interviews with the Director after annual evaluations, and the feedback system, various approaches will be taken to enhance communication with engagement of the administrative staffs.
3) Improvements of research funding for foreign researchers: Supported by URAs and PIs, the number of successful applications is steadily increasing. Future support includes covering editing expenses.
4) Improvements in employment of young researchers: In principle, young researchers are employed for three years with the intent to promote circulating intellectual talent, but ELSI offers two-years extension to those with extraordinary achievements or significant contributions. By coordinating with hosting organizations, ELSI also helps them secure tenure positions. ELSI aims to further improve a research and employment environment so that young researchers could develop career through experiences at ELSI.

8.2 FY2015 Site-Visit Report: 6. Response to Demands and Proposals to the Institute

1) Approach to mid-term evaluations: Led by the Director, discussion will be focused on how to present ELSI's research as a single story. ELSI will include bibliometrics analysis in the mid-term evaluation.
2) Updating and sharing the roadmap: We continue to update the roadmap through meetings, share it with all researchers, and encourage researchers to present their achievements along with the roadmap.
3) Proposal of specific approaches into the origins of life: Three key issues include: i) universalization of biochemical reactions, ii) the generation of catalysts and control of organic chemical reactions by catalysts, and iii) the role and history of geoenergy and bioenergy in the transition to the origin of life.
4) Overseas Dispatch Program: In FY2015, to encourage young researchers to develop their research at overseas for a period of time, ELSI established a program to fund part of traveling and residential cost.
5) ELSI's role and contribution in the Phobos/Deimos mission: Based on a cooperative agreement with ISAS/JAXA, ELSI leads science-related plannning in research areas such as planetary and satellite formation theory, astrobiology, and linkages in universal biology.
6) Response to the requests by young researchers (sent to WG): ELSI does not believe that accommodating every single request is the best approach, and the research support, including travel fees, has been defined, applied, and improved accordingly. However, we take this opportunity to engage in additional discussions to support young researchers and practice feasible policies.

7) Support for young foreign researchers for acquisition of competitive funding: Please refer to the section 8.1 3). With the increasing need for research support, including support for young foreign researchers in securing competitive funding, we are increasing the number of URAs to two in FY2016.
8) Realization of employment environment where young researchers can perform research with confidence: Please refer to the section 8.1 4).

World Premier International Research Center Initiative (WPI)
Self-Evaluation Report for Interim Evaluation

Host Institution	Tokyo Institute of Technology	Host Institution Head	Yoshinao Mishima
Research Center	Earth-Life Science Institute	Center Director	Kei Hirose

Common Instructions:
* Please prepare this report based on the current (31 March 2016) situation of your WPI center.
* As a rule, keep the length of your report within the specified number of pages. (The attached forms are in addition to this page count.)
* Use yen (¥) when writing monetary amounts in the report. If an exchange rate is used to calculate the yen amount, give the rate.

1. Summary of State of WPI Center Project Progress (write within 2 pages including this page)

Describe the center's identity and the achievement status of its initially stated goals.
- On the sheets in Appendix 1~5, list the Principle Investigators, and enter the number of center personnel, a chart of the center's management system, a campus map showing the center's locations on the campus, and project funding.

The Earth-Life Science Institute (ELSI) was established as a research hub dedicated to the birth and transition of the Earth and life. The Institute challenges the grand theme of "when did life emerged on the Earth, and how did they evolved together," a question that natural science has continued to ask since the age of Greek philosophy. More specifically, ELSI investigates the birth and evolution of life and its sustainable ecosystem, with emphasis on identifying early Earth's unique environment in which life was born and the environmental changes that followed. The Institute is also committed to empirical research, and studies the early Earth environment by exploring the ecosystems found in deep seas and primordial asteroids. Through such studies of the Earth, ELSI seeks to understand Earth's specificity and universality as a planet with life, expand these efforts into a new life-bioplanetaryology science, and contribute to exploration for life in the solar system and beyond. Conventional research on the origin of life primarily centers on a biochemical approach. The Earth was assumed to be the cradle of life, a support to life rather than a mutually-interacting entity. However, life exists through exchanges of matter and energy with its surrounding environment. Therefore, life activities have an impact on the environment. From this point of view, ELSI emphasizes research on both the Earth and life. This is ELSI's identity. The following section summarizes the progress made since ELSI's establishment in December 2012 and the development of its unique identity as the world's premier international research center committed to understanding the birth and evolution of the Earth and life. The WPI Program's four pillars and the goals set at the time of application to WPI are referenced.

【Science・Fusion】

ELSI's goal with respect to science was to complete the missing link between the early Earth and life, and develop more specific strategies for the research's middle stage and beyond. Since science at ELSI cannot advance without interdisciplinary fusion, science and fusion will be discussed together. The four topics that significantly contributed to the advancement of ELSI science are discussed below.

1) The "How" in the Formation of a Habitable Planet: How did the Earth acquire the water which makes the existence of life possible? How is it blessed with so much water over its surface? Discussions on water in various planets, including the Earth, was one of the most popular topics during the three years of research at ELSI. A research group on the deep Earth empirically found that the majority of water acquired during the formation of the Earth was reduced and absorbed into the core, which has a water volume 80 times that of seawater (Nomura et al. 2014). Another research group on the theories of planetary formation evaluated the solidification process for magma oceans in Earth-like planets. They demonstrated that the early stage of planetary evolution follows one of two path types depending on the location in which the planet was born (Hamano et al. 2013). Type I is a planet that solidifies in a short period of time and forms an ocean; this includes Earth. Type II planets take a very long time to solidify and lose water along the way; this includes Venus. In a study that predicted the probability that rocky planets or ice planets could exist in a habitable zone (HZ) in which liquid-phase water is available, the researchers calculated the probability of ice dust migrating through gas resistance being caught by a primitive planet (Guillot et al. 2014). Because low-mass M dwarfs have a low temperature and the condensation line for ice is closer to the central star, the effect in which ice condensed at a farther location is transported to the inner area through the mutual interaction with the disk becomes important. The group also found that young M dwarfs emit strong ultraviolet rays and water mass

equivalent to the Earth's ocean evaporates in planets at the distance of a HZ, and that M dwarfs in HZs become either planets with deep seas (with great volumes of ocean in the first place) or desert planets (with an ocean masses initially equivalent to or less than that of the Earth) (Tian & Ida 2015).
2) Formation of Strong Magnetic Field in Early Earth and its Impact: The fact that atmosphere existed on the Earth is closely related to the birth of life and its evolution and prosperity. Mars presumably lost its atmosphere due to solar wind, which leaves us with the question as to why the Earth retained its atmosphere. This can be explained by the magnetic field existence. One of the differences between Mars and the Earth is that early Earth formed a strong magnetic field which protected Earth's atmosphere. The presence of magnetites in primitive bacteria has already been confirmed. ELSI introduced a tunnel magnetic junction electron microscope (Kirschvink et al. 2014 Nature) to measure the magnetic strengths of the most ancient rock samples on the Earth. Meanwhile, taking a different approach from that of a geology or paleontology, a deep Earth research team conducted a high-temperature, high-pressure experiment and demonstrated that there was a convection current from the core in the early Earth; this was presumed to have formed Earth's magnetic field (Hirose et al. in prep.; Hernlund & McNamara 2015). The existence of a magnetic field on Earth and the fact that it protected Earth's atmosphere from the solar wind is beginning to be revealed from various points of view. A team led by Principal Investigator (PI) Kirschvink developed a new paleomagnetic method to identify primary minerals and secondary minerals from the early Earth rock samples (Fischer, Kirschvink et al. 2014 PNAS). By combining this method with an atmospheric science tracking method using sulfur isotopes, the team found that the atmospheric change began during the late Archaean era.
3) From Chemistry to Biology: In order to understand the process from chemical evolution to the birth of life, one must investigate how primordial enzymes were created in the Hadean era, how the enzyme reactions were organized into a primordial metabolic system, how genetic information was acquired, and how cells that separated from the environment through a double-membrane based on complex lipids were formed. With regard to the primordial enzyme formation, the polymerization process from amino acids to proteins is experimentally evaluated under the Hadean environment. First, a geyser reactor (intermittent reactor) capable of repeating the heating-cooling cycle was developed to assess the feasibility of oligopeptide synthesis from amino acids under non-equilibrium conditions in which minerals like iron pyrites act as a catalyst (Aono et al. in prep.). Polymerization of amino acids using minerals like iron pyrites as a catalyst assumes that amino acids adsorb onto the mineral surface and condense locally. As such, the team is taking quantitative measurements of the amino acid molecules' adsorption capacity against iron pyrites using an atomic force microscope (Yano et al. in prep.).
Meanwhile, in order to empirically verify the hypothesis that primordial metabolism formed in hydrothermal vents, another study is assessing whether the reduced TCA cycle, which is the starting point for the synthesis of various biological substances, can be operated in a non-enzyme manner by supplying the electro-chemical energy gradient observed in hydrothermal vents (Kameya et al. in prep.). Another theoretical research using computational chemistry is underway to gain insights into how information was memorized and by what types of molecules before RNAs and DNAs appeared. In other words, this research investigates what constituted the primordial genes and how they evolved into nucleic acid-based genetic information (Guttenberg et al. 2015). Furthermore, the process to develop a structure that is essentially a primordial cell membrane is being analyzed biochemically using a model membrane system based on phosphorus lipids (Kuruma et al. 2014).
4) Assessment of the Early Ecosystem: A geological study by Suda et al. (2014) that discovered methane in a rare hydrogen-rich hot spring (Hakuba Onsen) was a defining moment. As such, a hot spring project designed to elucidate the early ecosystem is underway. First, the research team verified that hydrogen and methane are formed chemically (i.e. abiotically) from water and carbon dioxide in the serpentinite layer and that the carbohydrate chain is being elongated (Suda et al. 2014). In order to identify the path for the carbohydrate's abiotic synthesis (carbohydrate chain elongation) in this system, the team developed an isotope isomer analysis method for carbon atoms, thus making progress in analytical chemical research by applying the technique (Gilbert et al. 2013). The team also conducted a simultaneous synthetic experiment and identified the conditions required for abiotic formation of carbohydrates through water and carbon dioxide reactions with serpentinite (Ueda et al. in prep.). Meanwhile, a meta-genome analysis revealed that Hakuba OD1, bacteria with an Archaean metabolism, are quite ancient in terms of molecular phylogeny, and are suspected to reflect the carbon fixation reaction of the early Earth. Evaluations of the early ecosystem centered on bacteria are ongoing (Nishiyama et al. under review).
These findings were products of collaborative works performed by a heterogeneous group of researchers, evidencing that fusions are maturing at ELSI. The achievements in ELSI science during

the first half of the WPI Program will contribute to solving traditional questions on the origins of Earth and life. Through multiple opportunities to revise the roadmap based on the experience, ELSI has newly defined the origin of life as “a transition from Earth-assisted geochemistry to polymer-assisted biochemical networks.” As such, specific research issues for the program’s mid-phase became clear. Science at ELSI is a fundamental science. While today's external funding programs favor innovation-oriented projects, ELSI has worked strategically to secure resources needed for its fundamental research. It should be noted that, as a result of such efforts, two of ELSI's applications were accepted to the large-scale KAKENHI program, the Grant-in-Aid for Scientific Research on Innovative Areas. A grant worth over $5.5 million USD from an overseas foundation was acquired, too.

【Globalization】
ELSI's goal with respect to globalization was to develop the Institute into a global hub for research on the origins and evolution of Earth and life. A measurable goal for ELSI’s globalization was to recruit more foreign researchers and increase their ratio within ELSI researchers to 30% by fall 2015. The recruitment committee headed by a non-Japanese vice director coordinated with the public relations division to host booths at science meetings around the world in order to promote ELSI and provide opportunities to communicate directly with young researchers. Recruitment notices were also placed extensively through public advertisement sites, recruitment advertisements in academic journals, and information sent to mailing lists for relevant academic societies and communities. A special recruitment site was also set up on the ELSI homepage. A recruitment system that accepts job applications 24/7 and reviews applications accordingly was developed and is in operation. Through these efforts, ELSI has received 216 applications thus far, nearly 90% of which came from foreign researchers. The number of exceptional young foreign researchers selected from the applicant pool totaled 13. Combined with seven foreign PIs (one of whom is a woman), the ratio of foreign researchers at ELSI has increased to 36%. To become an international research hub, ELSI coordinated with the Astrobiology Center at the National Institutes of Natural Sciences (NINS) and launched the Japan Astrobiology Consortium. The Institute also concluded a partnership agreement with NASA Astrobiology Institute. These were both major achievements attained during the first half of the WPI Program period. ELSI also concluded a coordination agreement with JAXA/ISAS, which is a part of the international cooperation framework geared towards Mars exploration in the near future. ELSI will lead the scientific aspect of the Mars Moon (Phobos/Deimos) eXploration (MMX) Mission led by ISAS. Combined with an effort to identify ELSI's position within such a large research framework, ELSI also developed a system in which overseas institutions that host the EON project researchers abroad are encouraged to join ELSI's international network as affiliated centers. ELSI is now conducting collaborative research with ten other institutions through this system. During the first half of the past period, it is safe to say ELSI has solidified the foundation to be recognized as an international research hub. Additionally, to serve the general public and the international society as a point of contact with science, ELSI also joined the Social Action for a Grassroots Astrobiology Network (SAGANet), which is renowned for these types of activities. By exercising the SAGANet's policy of “share science, learn science, do science,” ELSI is in a process of learning and practicing the ideal approach to foster discussions between science and society.

【Reform】
ELSI's goals with respect to reform are 1. to develop an organized and comfortable research and living environment under the leadership of the director, particularly for foreign researchers, and 2. to develop an administrative support system that allows researchers to concentrate on their work. ELSI aims at achieving these goals by 1) establishing an open and flat research structure under the belief that all researchers are equal in the eyes of “research”; 2) organizing and expanding the research equipment and environment through funding from WPI aids, large-scale KAKENHI, and overseas funds; 3) developing top-down organization with Director empowered with all decision-making; 4) developing a one-stop research support system by the secretaries; and 5) providing living support for foreign researchers through life advisors. These “ELSI Style” efforts spread across the Tokyo Institute of Technology, the host university, leading to administrative reform for research hubs based on ELSI. In order to help attract top-rate researchers to ELSI, with the understanding and help from the University president, ELSI introduced a cross-appointment system, secured tenure positions, implemented a merit-based payroll system, and separated graduate school teaching responsibilities. Referencing the ELSI style to encourage further globalization of the campus and to promote greater involvement of female researchers, the university also began to develop foundational infrastructures, such as a child

daycare center, and expanded available housing.

2. Center's Research Activities (within 8 pages)

2-1. Research results to date

Provide an overall picture of the Center's research activities and select 5~10 representative results achieved during the period from 2012 through March 2016. Number the results [1] to [10] and provide a description of each.

- In Appendix 2-1, list the papers underscoring each research achievement and provide a description of each of their significance.

ELSI seeks to address the biggest and deepest questions about Earth and Life: Why did the planet form in the way it did? What factors contributed to the evolution of the planet through time? How did this particular course of planetary evolution create conditions suitable for life? And by which mechanisms did life first begin? By addressing these questions, we will gain historical insights into the processes which resulted in the world we now inhabit; we also gain a more complete understanding of Bio-Planetary relationships in the universe as a whole – knowledge which is requisite to understanding and interpreting data from future space exploration missions. An overarching theme of research conducted at ELSI is that it connects first principal theory with empirical observations, revealing life as a set of responses to geological phenomena. Pertinent to our mission are research fields such as Deep Earth Science, Planet Formation, Geology Geochemistry, Extraterrestrial Observation, Microbial Physiology, Environmental Genomics, Prebiotic Chemistry, Synthetic Biology, and Complex Systems. We have developed a dynamic and collaborative research environment by breaking down existing disciplines, and what is happening at ELSI now is something unique globally: the sustained interactions of highlight motivated thinkers from diverse disciplines each approaching the goal of understanding the Earth-Life system from diverse research angles. This uniqueness has now become autocatalytic and resulted in the attraction of a diversity of superb scientists as well as international awareness of ELSI as the premier center to consider Earth-Life science. In a single institute, our research addresses fundamental questions on 1) Earth's Building Blocks, 2) The Early Crust, Mantle and Core, 3) The Initial Ocean and Atmosphere composition, 4) The Co-evolution of Earth and Life, 5) Geological Supply of Prebiotic Molecules, 6) Proto-metabolism, 7) Proto-cells, and 8) contemporary microbial physiology and evolution. This work accomplishes the goals of ELSI Phase 1 and sets the stage for Phase 2, where ELSI will nurture and establish new multidisciplinary research domains. These multidisciplinary domains will i) revolutionize conventional modes of research operation and ii) achieve ambitious scientific goals including characterization of habitable environments in the universe (ELSI Phase 2). Summarized below are representative research results and highlights to date.

[1] Accretion scenarios and giant impacts: Understanding planetary formation is essential to deciphering the initial conditions of the Earth and other planets, which is directly tied to early environments and geological resources that gave rise to life. ELSI members have investigated the accretion of the terrestrial planets, mostly focusing on the late phase in an attempt to reform conventional models that produce results inconsistent with observations. ELSI explored a variety of terrestrial planet formation models including oligarchic growth (accretion of km-sized bodies) with orbital migration of Jupiter and Saturn, in addition to the newer idea of pebble accretion (accretion of 10-100 cm bodies). With the former model, Mars is formed far from the Earth (Brasser, Ida et al., submitted), consistent with isotopic data. For the latter model, we derived comprehensive formulas for the pebble accretion rate which we simultaneously implemented in our N-body simulation codes. Our results show that the orbital configuration formed by pebble accretion should depend sensitively on the parameters of the nascent protoplanetary disks (Ida et al. Astron. & Astrophys., in press), and H_2O delivery to the Earth sensitively depends on disk structure and timing of the snow line passage [1]. Earth's formation was punctuated by energetic collisions among protoplanets ("giant Impacts"), which led to creation of the Moon [2] and the Martian satellites [3]. Impact-induced warm debris disks from giant impacts were observed by ELSI scientists around other young stars, indicating that this may be a ubiquitous feature of planet formation in the universe. ELSI modelers corrected a shortcoming in simulation algorithms that mistreated the core-mantle interface, which has led to a major revision in impact scenarios consistent with formation of a Moon [2].

[2] Volatile delivery and inventory: Volatile elements such as H and C are fundamental components of organic molecules, but also circulate through Earth's interior and play a critical role in numerous

geological processes. ELSI combines experimental, observational, and theoretical approaches to address issues of volatile accretion during planet formation, outgassing and in-gassing through time, and the reservoirs for volatiles inside the planet. ELSI models have shown that escape of water vapor from magma oceans may result in differences in water content between Earth and Venus [4]. Data obtained from high pressure experiments and *ab initio* calculations indicate that the Earth's core includes ~1 wt.% hydrogen as a predominant light element, yielding a low present-day core temperature and seismic properties consistent with observations [5, 6]. On the other hand, ELSI's seismological prospecting for water in the Earth's mantle has shown that the transition zone is unexpectedly dry (Hauser et al., in press). Integrated modeling to explain all of these results suggests that proto-Earth may have grown to Mars-size with anhydrous enstatite-chodrite-type materials, and then ice-rich materials accreted later, providing ~100 oceans of H_2O. Ongoing accretion modeling efforts by Genda, Hernlund, and others indicates that the magma ocean on proto-Earth may have reacted with hydrogen gas in the proto-atmosphere, modulating both H_2O and FeO content in the growing planet.

[3] Magnetism and Earth evolution: Earth's magnetism is ancient and connects processes deep inside our planet to the surface environment and life. The geomagnetic field is maintained by dynamo action in convection currents in the fluid outer core, and its variations through time influence atmosphere loss, water content, and oxidation state of the surface. The geomagnetic field was exploited by magnetotactic bacteria as a primitive form of eyesight, and may be coupled to dramatic evolutionary changes in the history of life. Experiments in the ELSI's world-leading high pressure laboratory showed that iron alloys in Earth's core should have a very high electrical and thermal conductivity [7, 8], dramatically different from previous estimates. Thermal modeling indicated that these high conductivities imply extremely high core temperatures in the early Earth [7]. This led us to suspect that alternative mechanisms drove the geodynamo in the ancient past, and after more searching we discovered that core alloy containing both Si and O will crystallize SiO_2 (Hirose et al., submitted to Nature). This discovery completely revolutionizes our understanding of core evolution, and can solve the paradox of high core conductivity, in addition to constraining present core composition. Meanwhile, ELSI is deeply involved in paleomagnetism studies that show a rapid change in the latitudes of continents around the same time as the Cambrian explosion (535-515 Ma), thus shedding light upon a phenomenon called "true polar wander" that is hypothesized to be closely linked to rapid episodes of biological evolution [9]. Construction of ELSI's state-of-the-art paleomagnetism laboratory is finishing now, and studies aimed at constraining the geomagnetic field in the Hadean Earth will be a major focus.

[4] Early atmosphere, and geochemistry of present-day proxy environments: An integrated set of ELSI projects has placed new constraints on the composition and chemical dynamics of the atmosphere and subsurface waters of the early Earth. Laboratory investigations of fundamental processes were coupled to field studies of natural systems that serve as present-day proxies for early Archean or Hadean settings. In order to trace the chemistry of the early atmosphere, a new method was developed for determining sulfur isotopes at the nano mole level [10]. Using this technique, new photochemical experiments were conducted at very low $p\,SO_2$ (1-10 Pa) conditions in the presence of CO, successfully reproducing the Archean S-MIF ($\Delta36S/\Delta33S \approx -1$) for the first time [11]. The results suggest that the early Atmosphere was more reducing than previously thought and may have included an appreciable amount of CO. Such reducing atmospheres favor prebiotic synthesis of organic compounds. UV chemistry experiments carried out by our group on the C-H-O system have shown that a CH_4-atmosphere is too reducing to produce building blocks of life compared to CO chemistry. The same experiments suggest that formate was steadily supplied into the early Earth's ocean and could have driven "proto-metabolism." A new experimental system has been constructed which will allow real-time and in situ analysis with a Pulsed-Laser Raman spectrometer. A major ongoing effort has characterized the geology and microbiology of the Hakuba Happo hot springs ophiolite system as a proxy for mantle weathering zones that could have provided chemical energy on the early Earth. H and C isotope studies at Hakuba [12] suggest that both H_2 formation and direct CH_4 formation may characterize surface olivine alteration in these systems. To understand the role of peridotite-hosted modern hot springs as early-earth models, the weathering of komatiitic lavas was studied [13] as a dominant source of alteration fluids on the early Earth, when upper-mantle material would have been less likely to be exposed to surface water. It was found that H_2 evolution by komatiite weathering falls in the range between modern peridotite-hosted and basalt-hosted

systems, depending on melt conditions, enabling the calibration of modern proxy environments to ancient conditions.

[5] Prebiotic chemistry: Investigations into prebiotic chemistry are at the center of studies at ELSI connecting early Earth and Life. Major efforts focused on framing the studies on origins of life. Maruyama and others hypothesize that natural nuclear reactors and their surrounding geysers, which promoted radiation-induced syntheses of organic compounds, were present in the Hadean Earth. Utilizing the gamma radiation facility at Tokyo Tech, the research team led by Aono and Cleaves initiated the radiolysis experiment and succeeded in making formamide from water and acetonitrile (results to be submitted soon), which offers promising prospects for abiotic synthesis of building blocks of life (e.g., amino acids, nucleobases, and lipids). Inspired by the geyser concept, Aono and others developed an intermittent experimental system called a “geyser reactor,” which repeats the wet-dry cycle in a confined flask, and demonstrated amino acid oligomerization by high-temperature heating without a catalyst (results to be submitted soon). Kitadai calculated the thermodynamic behaviors of amino acids over widely diverse temperatures and pH values [14, 15]. These results prove the feasibility of oligopeptide synthesis from amino acids under the Hadean environments. To understand how metal-binding oligopeptides were formed in the presence of minerals and evolved into primordial enzymes, Hara, Yano, and others quantified the interaction force between a single-molecule amino acid and mineral surface using the atomic force microscope (results to be submitted soon). In addition, discussions on what should be excluded and included in the origin of life studies according to physico-chemical constraints promoted systematic experimental investigations by Chandru and others to focus on compounds that can initiate the protometabolic carbon-fixation network and suggested to exclude hydrothermally-driven protometabolism from likely scenarios of the origin of life (manuscript under review). Developments of new computational approaches are of great significance in prebiotic chemistry. Cleaves and others compared the set of 20 genetically encoded amino acids with computationally generated alternative sets and found that the former may represent a largely global optimum, suggesting that the set has been highly influenced by natural selection [16]. Aono and others developed a heuristic search model to solve various constraint satisfaction problems and demonstrated the capacity of the model to simulate unknown chemical reaction kinetics in a semi-quantitative and resource-saving manner [17, 18].

[6] Conceptualizing messy chemistries: Biochemical reaction networks are governed by sophisticated regulatory mechanisms, including enzymatic catalysis, template-directed replication, and signaling. Such mechanisms would not have been present at the early stages of chemical evolution. Prebiotic reaction networks would therefore have been unrestrained and “messy”. Our team combines computational and experimental approaches to understand organization and emergent properties of messy chemical systems, and to map out evolutionary transitions from messy systems to biological organization. Theoretical efforts to relate the topology of a reaction network system to properties of its dynamics have shown how autocatalysis can arise in simple chemistries where it provides focusing and amplification [19]. A dynamical “reservoir” model has also been developed to show how the kind of hereditary memory that enables evolution could have arisen from bulk chemical systems before genomic heredity was possible [20]. Experimental efforts have focused on compounds which undergo facile reversible polymerization, as prebiotic alternatives to proteins for structure and catalysis. These compounds allow for the dynamic recombination of monomers to give large numbers of unique-sequence polymers (combinatorial libraries). Of particular note are hyperbranched polymers (HBPs), which are inherently globular and capable of function without specific folding requirements. HBPs synthesized under prebiotically permissible conditions have exhibited protein-like properties such as metal binding (Mamajanov et al. 2015 Orig. Life Evol. Biosph. 45:123–137). Many projects in this theme are carried out by researchers who have joined ELSI within the past year. We have added a deep expertise in graph-grammar methods for computational chemistry, which introduce an algorithmic framework for generative chemistries. These are currently being extended to include stereochemical properties of molecules including metal centers, and to formalize fundamental concepts such as that of reaction pathways (Andersen, submitted). Ongoing work in HBPs is demonstrating catalysis through modulation of micro-evironments (Mamajanov and Cody, in prep.), and seeks to construct novel dynamic materials that undergo selection based on shape, sequence or function.

[7] Electrochemistry and the origin of life: Hydrothermal activities on the primitive Earth were likely

to be much higher than the present level, and the geo-electrochemical potentials they created could have served as a driving force for CO_2 reduction and the formation of organic compounds that were essential for the origin and early evolution of life [12, 13]. We have established a laboratory that can investigate this type of CO_2 reduction and evaluate catalysts and reaction energetics with an electrochemistry based approach. Ken Takai and others are discovering the diversity and properties of hydrothermal vents, and we are connecting this information to laboratory evaluation of pre-biotic chemistry. Laboratory experiments we are conducting are beginning to constrain the chemical evolution processes between pre-biological and biological systems (e.g. Yamaguchi et al. 2014 Electrochimica Acta 141:311-318) [21], and ELSI is poised to become the leader in data acquisition in this research area by developing a dedicated laboratory for investigating electrochemical reduction properties of hydrothermal vent mineral surfaces (Nunoura et al. 2015 PNAS 112:E1230-E1236). These investigations will provide critical data for evaluating hydrothermal vent hypotheses for the origin of life on Earth and other planets, since the presence of hydrothermal activities has recently been discovered in some extraterrestrial planets/satellites [5]. Our research explores favorable geochemical situations for the geo-electrochemistry-driven proto-metabolism, which provides significant constraints for future space explorations of extraterrestrial life by JAXA and NASA.

[8] Geochemistry-linked microbe ecology, and biology of present-day proxy environments: Biological and geological processes share elaborate linkages, and these links provide motivation that early life was a product of geochemical activity, and by gaining better understandings of past and present matter and energy flows in biological and geological processes, we seek to identify key mechanistic factors and processes that may lead to creation of biological cells on Earth, or other planets. Researchers at ELSI are attacking this area of inquiry from a number of different angles and disciplines. To gain insight into contemporary biological processes, their energy and nutrient requirements, and also to relate these to the formation of the first cells, ELSI has assembled a multidisciplinary set of researchers and faculty with the aim of integrating diverse data sets. We recently appointed Associate Professor Shawn McGlynn who has expertise in microbial physiology, biochemistry, and geochemistry to lead and direct these efforts. By querying the stability of a variety of molecules in different environments, ELSI researchers were able to tabulate possible intermediates and end products of metabolism [15]. To unravel the activities of specific reaction processes for thermodynamic driving forces, advanced isotopic measurement techniques developed at ELSI aid in discrimination between biological and “abiological” processes, resulting in the ability to interpret chemical pathways and fluxes [22]. By creating model systems, ELSI researchers have been able to reduce experimental complexity and investigate critical factors of process evolution [23], and have proposed alternatives to extant biological functionality (e.g. Mamajanov et al. 2014 Macromolecules 47:1334-1343). Finally, by considering chemical instability on other planets [24], and the limits at which this can be detected [25], ELSI researchers have gained insight into where we should and can look for extraterrestrial biology. These studies address key components in the ELSI roadmap Phase I, for example the geological supply of prebiotic compounds and the resultant Co-evolution of the Earth-Life system, as well as protometabolism and the formation of proto-cells.

[9] Early molecular and microbial evolution, and synthetic biology: Inferring the nature of the first life on Earth requires understanding how four billion years of evolution have changed the chemistry and architecture of organisms from forms that were more primitive or significantly different from those in the present. For the era before the beginning of a phylogenetic record, direct historical reconstruction must be replaced with reasoning based on general principles of assembly for living systems. Results in this theme combine genomics and molecular biology with synthetic biology to understand components of evolution and invariant properties of life. An isotopic study of hydrogenotrophic methanogens in modern deep-ocean vents has quantified growth conditions and metal requirements associated with nitrogen fixation in microbial communities inhabiting analogues to Archean hydrothermal systems [26]. The surprising range of energetic costs of N fixation suggests a wider habitat for similar organisms than had been believed. The accessibility of a subsequent major evolutionary transition, from anoxygenic to oxygenic photosynthesis, was demonstrated by a direct-mutagenesis experiment [27], in which purple bacteria (anoxygenic photosynthesizers) evolved the ability to synthesize chlorophyll a, the key pigment required for oxygenic photosynthesis. Fundamental questions about both the deep evolution of genomes, and the nature of earlier RNA and DNA worlds, have been elucidated by recent discoveries of the diversity of architectures in filamentous viruses of thermophilic archaea [28], and by discoveries that thermophilic archaea

viruses are not limited to dsDNA genomes (Mochizuki, unpublished). Two projects in synthetic biology seek to understand the constraints on evolution by re-creating solutions within engineered systems. Biochemical and translation systems with a reduced amino acid inventory and simplified genetic code have been demonstrated by building variant tRNA systems capable of excluding from one to four amino acids relative to the standard code [29], and through the artificial evolution of a Green Fluorescent Protein requiring only 19 amino acids [30]. To understand the complexity of functionalizing the first cell membranes, an in vitro expression system was developed which synthesizes and spontaneously assembles multiple transmembrane proteins, including the SecYEG complex that acts as a transporter for multiple other proteins [24, 31]. Work begun by ELSI members who have joined within the past year focuses on the evolutionary reconstruction of functioning molecular systems beyond mere sequence phylogenies. Two projects seek to reconstruct the histories and functions in vivo of enzymes for major carbon fixation pathways: the reductive citric acid cycle dating back to the oldest life (Kameya, unpublished), and RuBisCO which served the emergence of oxygenic photosynthesis [27].

[10] Origin of information in chemistry: The origin of the RNA world, more specifically, how prebiotic chemistry transitioned to chemical information, is a critical question in the origin of life. Investigations into the physical chemical processes which governed this transition are critical components in ELSI's investigations into the origins of biochemistry. These investigations combine experimental and theoretical efforts to understand the following three transitions in the origin of RNA. 1) Guttenberg and others study the transition from bulk chemistry to the first information containing chemical system. Major efforts in this area focus on simulations of the emergence of hereditable information from elementary chemical processes [32]. 2) The team led by Cleaves studies the selection of RNA from the pool of all possible alternative information carrying systems. Efforts in this area have focused on using computational chemistry to enumerate alternate possibilities and understand what is unique about RNA from among these possible alternatives [33, 34]. 3) Fahrenbach, Szostak, and others study the transition from minimal oligomeric systems to the extended genetic material of modern life. Efforts in this area have focused on understanding the physical chemistry of RNA elongation and replication [35, 36].

2-2. New Challenges

Describe the new challenges befitting a WPI center that have been undertaken.

(1) Graduate Student Advisory by ELSI Faculty Members

Leading researchers at ELSI actively participate in advising graduate students through education and research and help to develop the next generation of researchers.

(2) Introduction to the Research Facility and Equipment Sharing System

ELSI shares its cutting-edge research facilities and equipment with students and researchers from both ELSI and elsewhere in order to promote collaborative research conducted by ELSI researchers, to develop the next generation of talents, and to create a virtuous research cycle.

(3) International Advisory Board

In order to promote premier research activities and international research relationships, ELSI receives assessments and advice on its efforts to be innovative with organizational management development, as well as on its efforts to bolster international recognition through outreach activities, contributions to the Tokyo Institute of Technology (Tokyo Tech), and commitments from the host institution. As such, the Institute is making further progress as a global research center.

(4) Introduction to Research Advisors and the ELSI Fellow System

Top scientists from various disciplines serve as research advisors and ELSI fellows. Based on their expertise, they provide research guidance and advice to research groups and individual researchers.

(5) Introduction to the Research Activity Evaluation System

A two-day annual evaluation is held every year, during which researchers are assessed by all other Institute members based on the contents of research activity sheets submitted prior to the evaluations and 15-minute presentation and discussion sessions. The ELSI Award is given annually to individuals with distinguished research work. The director also conducts a feedback session with each assessed researcher based on the evaluation results, in order to exchange opinions on the evaluation details and to discuss future directions for his or her research.

(6) Acquisition of a Global Fund (EON Project)

ELSI was awarded a research grant worth $5.5 million USD (approx. 670 million yen) from the U.S.-based John Templeton Foundation for the period between July 2015 and March 2018. With this

grant, ELSI launched the “ELSI Origins Network (EON)” project. By acquiring this influential global fund, ELSI will further strengthen its infrastructure and accelerate research to understand the origins of the Earth and life. Building upon the grant acquisition and project launch success, ELSI plans to pursue additional foreign funds. ELSI is also considering an office and incorporation as non-profit entity overseas to be better positioned to acquire further global funds.

(7) Introduction to the Cross-appointment System

Along with Tokyo Tech, ELSI introduced a cross-appointment system in order to acquire top-level researchers in life sciences, in particular to lead research on “origin and evolution of life.” A professor from Osaka University was hired as a principal investigator (PI) through this system. The newly appointed PI's original employer, the Osaka University Graduate School of Information Science and Technology, was also designated as an ELSI satellite to promote research related to the origin of life.

(8) Research for the Next Five Years

The challenges ELSI has faced thus far have been to create a research environment in which unique interdisciplinary research (fusion) can be induced and fostered based on synergies created by the assembled researchers from different backgrounds. In order to promote such a fusion, ELSI introduced an open and flat research structure that departed from the conventional structure in which young researchers assisted PIs under the PIs’ leadership. Instead, young researchers at ELSI form their own networks and seek advice and cooperation from the various PIs and researchers with whom the young researchers’ topics or phases align. Annual evaluation meetings and the ELSI Incentive Award were created in order to share the direction and progress on each research effort and to encourage young researchers who significantly contributed to the development of ELSI science. A Director's Fund was established to promote experimentation with seeds of interdisciplinary research borne out of discussions among young researchers from various disciplines.

The director and vice directors oversaw this research trend. With cooperation from the University, they designed and implemented a cross-appointment system and the ELSI fellow system in order to invite top scientists capable of improving or solving problems and to serve as a bridge between different academic fields. Additionally, a framework was built to appoint notable domestic and international researchers with experience in top research institutions management as international advisory board members and research advisors. They provide advice on multi-angle and objective approaches to ELSI’s research and management and contribute to the advance in young foreign researcher recruitment as well as chemical evolution research.

Given that it is difficult in Japan to find external research funding to support collaborative work and fusion in fundamental science, ELSI faced great challenges in its efforts to acquire global funds with foreign PIs and advisors involved at the core. It took two years, beginning with surveys of overseas funding institutions and foundations. However, the fact that ELSI was able to receive a large research grant from the Templeton Foundation in the U.S. and launch the ELSI Origins Network (EON) project provided momentum for ELSI’s interdisciplinary research promotion.

Finally, the following is a brief summary of the future challenges in promoting interdisciplinary research. As a result of more than three years of various efforts since ELSI’s establishment, collaborative work and interdisciplinary approaches by the assembled researchers from diverse backgrounds have been introduced. The research has entered a phase in which some of the “traditional questions” on the origins and evolution of the Earth and life have begun to be answered. Throughout this process, challenges to the roadmap’s latter phases that remained ambiguous have begun to be broken down into specific questions. While it was difficult to thoroughly investigate such questions in the beginning, these are the questions that could be truly interdisciplinary. The next challenge is to solve these problems and integrate them, or in other words, develop a foundation for a new “origins”-oriented science system.

2-3. Joint Research Advanced

Describe the joint research that the Center has undertaken with research organizations in and outside Japan.

- In Appendix 2-3, list and describe the cooperative research agreements that the Center has with other organizations.

ELSI is involved in a multitude of collaborative research with institutions listed in Appendix 2-1. Some researchers are also actively engaged in collaborative research with other research institutions on an individual basis. None of the major research papers listed in Appendix 2 resulted from closed research within ELSI, but rather from the fruit of collaborative research between ELSI or ELSI researchers and diverse external research institutions. For example, PI Fujimoto is acting as a coordinator between JUICE and the European Space Agency (ESA) to ensure a smooth participation from Japan in a project to explore Jupiter and its icy satellite Europa. This participation includes

developing mounted devices. Researcher Kimura is involved with the team responsible for the laser altimeter mounted on Hayabusa 2 (LIDAR) and the team responsible for the laser altimeter to be mounted on JUICE (GALA). Another young researcher is involved in collaborative research with the Goddard Institute for Space Studies. ELSI members involved in planetary formation theories have been engaging in collaborative research with astronomers related to "ALMA" and "Subaru" (for example, see http://www.jicfus.jp/field5/jp/130320pressrelease/). ELSI is also in discussions with the NASA Astrobiology Institute with regards to concluding a partnership agreement. For the EON project, ten young researchers are actively engaged in collaborative research with overseas institutions on the origin of life.

2-4. Appraisal by Society and Scientific Organizations

Describe how society and/or scientific organizations in and outside Japan have recognized the Center's research achievements.

- In Appendix 2-4, list the awards received and invitational lectures given by the Center's researchers.

As noted in Appendix 2-4, ELSI has earned tremendous recognition from the world as members have received numerous awards and been invited to deliver lectures.

(1) Awards and Fellowships

ELSI's researchers from different generations are held in high esteem at their respective levels. Senior researchers such as PIs have received awards including the Medal of Honor with the Purple Ribbon and the JSPS prize. They have also become fellows of notable societies such as the Royal Institute of Navigation. Meanwhile young researchers have also received awards that target young professionals, such as the IUPAC-SOLVAY International Award for Young Chemists.

(2) Invitations for Lectures

Both the senior researchers and the younger researchers, ELSI members have been invited to deliver a total of 78 presentations at international academic conferences.

(3) Collaborative Workshops with Domestic and International Institutions

Along with satellite institutions including Harvard University and Ehime University, ELSI has held a total of 25 research conferences such as collaborative workshops. The details are discussed in 4-2-1.

2-5. Center's Research Environment including Facilities and Equipment

Describe the Center's research environment including facilities and equipment and the state of its utilization.

(1) ELSI Building 1 and 2

In addition to the Ishikawadai Building #8 (ELSI-2: 2,670㎡), construction for Ishikawadai Building #7 (ELSI-1: 5,000㎡) was completed in March 2015. This added more laboratory rooms and offices for researchers and improved the environment in which researchers could concentrate on their work. A communication space was established in both buildings to remove the underlying "language and cultural barriers" that existed between academic disciplines and to promote mutual understandings between researchers with different backgrounds, thus fostering the development of interdisciplinary research.

(2) Research Equipment Owned by ELSI

- **Earth History Simulator System** is based on the Cray XC30 960 core (Cray Inc.) is used to study the physical state of the Earth's core materials by first principle simulation as well as for simulation studies on Earth's mantle, formation of moons, planetary formation, and galaxy formation.
- **FACS Aria II Cell Sorter** is an apparatus capable of screening and separating cells and artificial membrane vesicles by the size and wavelength of the emitted fluorescent light. It is used for artificial cell research and evolutionary engineering experiments.
- **Xevo G2 XS Q-TOF System** is used for qualitative and quantitative analysis of various organic compounds in chemical and biological studies and can detect trace amounts of polar molecules at the picomole level, enabling precision mass analysis and collision-induced dissociation.
- **High-pressure Micro-sample Analytical System** is powerful in high-temperature, high-pressure experiments to replicate the Earth's interior, processing 10 μm-level microprobes needed to create ultra-high pressure and conduct chemical analyses. It is used almost every day, and has already processed over 500 test materials.
- **Intramolecular Isotopic Distribution Measurement System** is a continuous high-precision stable isotope mass analyzer, measuring the stable isotope ratio for every position of the molecular structure with high precision using a multi-stage gas chromatography. This is one and only system in the world and is used to identify biogenic and abiogenic molecules and prebiotic reaction paths.

(3) Research Equipment Owned by the Satellite Institution (Ehime University

Geodynamics Research Center)

- **3000-ton Multi-anvil High-pressure Apparatus** is the world's largest DIA-type apparatus, used to synthesize materials for physical measurements and phase transition/fusion/element partition experiments, working 300 days a year for high-temperature, high-pressure experiments.
- **Ultrasonic Measurement Apparatus for Elastic Wave Velocity Measurement** is installed in GRC and SPring-8, used for elastic wave velocity experiments by an ultrasonic pulse method under super-high pressure and high-temperature conditions. While it is a unique apparatus, it is used approximately 50 times a year for synchrotron radiation experiments and laboratory experiments.
- **Field Emission Scanning Electron Microscope** is attached to an electron backscatter diffraction device and energy diffusion x-ray analyzer and conducts organizational observation, crystal orientation distribution, and composition analyses for super-high pressure synthetic samples. It is used for analysis 300 days per year.

2-6. Non-WPI Project Funding

Describe the results in securing non- WPI project funding.

- In Appendix 2-6, draw of graph showing the Center's transition in securing non-WPI project funding and list external funding warranting special mention.

Research Project Funds In Addition to WPI Grants

Fiscal Year	funding(unit thousand yen)
2012 (Heisei24)	283,787
2013 (Heisei25)	819,004
2014 (Heisei26)	616,146
2015 (Heisei27)	750,373

Notably, ELSI received a research grant worth $5.5 million USD (670 million yen) from the U.S.-based John Templeton Foundation for a period between July 2015 to March 2018.

2-7. Applications of research results

Describe the applications created from research results, their effect in spawning innovation, intellectual properties (IPs) obtained, and joint research activities conducted with corporations, etc.

Research at ELSI is within the realms of pure science. It is not intended for commercialization through collaborative efforts with corporations or to seek innovations. The following are examples of ELSI research relevant to this section. 1. A proposal and patent application for a new freezing technology developed by researcher Atsuko Kobayashi, which focused on magnetite particles inside organisms during research involving observation and experiments with biological samples. Information is now being exchanged with several companies for possible collaborative research. 2. A possible patent application developed by Associate PI Aono for a new calculation method and a device to be applied to a highly efficient chemical reaction simulator and protein simulators. ELSI will provide full support for the development of potential practical applications of technical seeds borne out of research. However, the Institution maintains its belief that its mission is to contribute to the general public's scientific literacy by communicating our achievements.

2-8. Achievements of Center's outreach activities

- In Appendix 2-8, list and describe media coverage resulting from press releases and reporting.

As noted in Appendix 2-8, a public relations (PR) office was established at ELSI in 2015 to manage outreach activities and media announcements.

(1) ELSI International Symposium: In 2016, ELSI utilized a service "SAGAnet" to broadcast the fourth International Symposium to SAGAnet members around the world (including the general public). This service was well-received.

(2) Outreach Activities to Raise Awareness for the WPI Program: ELSI is involved in outreach activities conducted by the WPI Program, including the AAAS annual meeting, SSH student research presentations, and WPI joint symposia. Public relations are provided not only for ELSI, but for the entire program as well.

(3) Outreach to Elementary, Middle, and High School Students: As of March 2016, ELSI had conducted 11 outreach activities domestically, including hosting visits from 243 individuals and ten outreach classes. ELSI has been included in a travel agency's package for high school study excursions. As a result of PR activities with schools, such as distributing leaflets and newsletters, school students from across the country have visited the Institute, thus improving public awareness for ELSI. ELSI has

also hosted two overseas visits, welcoming students from China and Vietnam.

(4) Public Seminars and Science Cafe, and Coordination with the Tokyo Tech Alumni Association, the Alumni Association of Hitotsubashi University, and the Asahi Culture Center: As of March 2016, ELSI had organized 18 public events, either on its own or in collaboration with another organization. A total of 1,220 people attended these events. One event was streamed by Niconico Douga and was viewed 337 times. ELSI researchers have also held a total of 38 talks at non-ELSI events. Whether Japanese or non-Japanese, ELSI researchers are actively involved in outreach activities. Talks are tailored specifically to the target audience at each event. For example, at events intended for high school students, ELSI's young researchers and relevant graduate students serve as lecturers and set up a booth at which they offer advice on research careers and researchers' everyday lives. In an attempt to capture new interest from society's younger generations, and with the U.S. Embassy's help and a permission from 20th Century Fox Media, ELSI organized a seminar with Jim Green, the head of NASA's Planetary Science Department, who supervised the movie "Odyssey." Over 60% of the 110 participants had never heard of ELSI before the event. Over half of the participants attended the event due to the movie, confirming success in raising awareness among a new public segment. As such, ELSI not only hosts seminars with its own researchers, but also hosts events involving foreign researchers, including NASA directors and professors from the University of Washington and the University of Utah among others. In coordination with alumni associations and specific groups, ELSI researchers have also held a lecture series. Such activities have helped to develop greater understanding for ELSI's research activities and to generate donations from members of outside groups.

(5) SNS: ELSI's official Twitter account has issued 630 tweets, and has 880 followers, which is the greatest number of followers for any WPI center. ELSI's Twitter provides updates on the Center's activities and news. The team tweets news related to research on the origins of life and the Earth, thus promoting a greater understanding and deeper interest in the field.

(6) Broadcasting ELSI Research to the World: Articles on ELSI research are written in Japanese and English and published on the ELSI website and in newsletters, thus broadcasting the Institute's activities to domestic and international research communities and the general public. Japanese articles are written at a level understandable by high school students and above, while English articles are written at a level understandable by researchers from different disciplines. To ensure the articles are usable by the media, permission for reprinting videos, charts, and photos used in the articles is generally granted. Important research achievements are announced via press releases and press conferences. However, in an effort to expediently broadcast to the media around the world, news is uploaded onto Vocus, a media release distribution website.

(7) Visits from Overseas Institutions: ELSI hosted 13 visits with a total of 124 individuals from foreign embassies, universities, and research institutions. In addition to introductory videos and presentations on the Institute, ELSI also provides facility tours for the visitors.

(8) Others

1. Coordination with Other Research Centers (2015.12.10 ELSI/Kavli IPMU Joint Public Seminar "Questions toward the Origin"): ELSI co-hosted a public event with Kavli IPMU, another WPI Center, at the National Museum of Emerging Science and Innovation. Directors from both Centers and a philosophy professor delivered the lecture and talk session on the concept of origin. The number of applicants exceeded the hall's capacity, therefore, 298 people were selected by lottery to attend. Ten media companies also attended the event and the site of the lectures was published in magazines, which was a significant achievement in terms of PR for both Centers and WPI overall.

2. "Tokyo Tech Inspiring Lecture Series": This event was planned and initiated by the PR team for Tokyo Tech and ELSI. Four ELSI researchers, including the Harvard Satellite Director and Nobel Prize recipient PI Szostak, hosted the seminars. Three hundred and forty people participated in the seminars, a remarkable number for a university event discussing the latest research. Events now continue to be organized by the University.

3. Interdisciplinary Research Activities(within 2 pages)

3-1. State of Strategic (or "Top-down") Undertakings toward Creating New Interdisciplinary Domains

(1) Efforts to Acquire Large Research Funding

Science at ELSI is impossible without fusion. It is a deeply fundamental science. A respectable amount of research funds need to be secured in order to advance the interdisciplinary research in a stable fashion. However, current trends in competitive research funding favor innovation-oriented and exit-orient research grant programs. This is an admittedly difficult situation for ELSI. ELSI's top management has extensively discussed how to acquire large research funds for interdisciplinary research since the beginning and acted accordingly.

As a result, in 2014 a research proposal titled "Hadean Bioscience" was created and accepted for KAKENHI's Grant-in-Aid for Scientific Research on Innovative Areas (representative: Vice Director Kurokawa, 500 million Yen was allocated for ELSI members). The aim of this research project was to create a new academic area to identify when, where, and how life was created through an assembly of cutting-edge planet earth science, life science, and organic chemistry, with a focus on the Hadean era (i.e. the first 600 million years after the birth of the Earth; 4.6 billion - 4.0 billion years ago). The Ehime satellite also organized a similar effort. In 2015, they launched another Scientific Research on Innovative Areas initiative title "Interaction and Coevolution of the Core and Mantle Toward Integrated Deep Earth Science," with Affiliate Faculty Tsuchiya as the representative (approx. 1.09 billion yen for five years). This area aims to identify the evolution timeframe by determining element allocation and isotope fractionation at the Deep Earth level through both experiments and theories, and to understand the mutual interaction and evolution of the core-mantle that dominates the dynamics in Deep Earth. The project is expected to contribute greatly to the advancements of ELSI's research on the origins and evolution of life.

The greatest success to date has been the launch of ELSI Origins Network (EON) project, which began in July 2015 with support from an American foundation (33 months, total $5.6 million USD). PI and Councilor Hut helped to develop the proposal and used his longstanding network to help in negotiation with the foundation in order to obtain the proposal's acceptance. While the funds acquired for the EON project attracted the talents and resources needed for interdisciplinary research, it is also a success benchmark case as it helped ELSI gain knowledge on how to acquire overseas funds. Based on the experience in securing the funds for the EON project, ELSI established a "Fund Raising Committee," which has been tasked with investigating overseas funds and making preparations to set up an overseas office.

(2) Invitation to a Bridge Builder

Adding PI-level researchers capable of leading research on the origin of life has been a challenge since ELSI's establishment. It is an issue that the Program Committee and the Working Group have cited in the past. Rather than finding a top leader in a particular discipline related to the origin of life, ELSI chose to focus instead on inviting a bridge builder. This would be a human resource with a great vision who would be capable of leading the development of a roadmap for a new interdisciplinary field by coordinating the existing collaborative research led by researchers from various backgrounds. While it took some time, two bridge builders with whom ELSI could share its strategy, Dr. Smith and Dr. Kamagata, joined the institution as a PI and an ELSI Fellow, respectively. PI Smith identified the positioning of microbiology within ELSI and the approach towards the evolution of early-stage metabolism. He broke down the challenges outlined in the roadmap, "primitive bio-system" and "transformation to a more complex system," into more specific levels. Fellow Kamagata is serving a role in which he relates the primitive energy conservation system, a clue to understanding the evolution of the early-stage metabolism network, to today's energy conservation system. Chemistry and biology are starting to be bridged by their presence. As such, ELSI has defined the "Origin of Life" as "a transition from Earth-assisted geochemistry to polymer-assisted biochemical networks."

(3) Annual Evaluation = Promotion of Mutual Understanding

When researchers from different backgrounds work together, the first effort should be to share the research and language of his/her own research with each other. As detailed later, ELSI hosts various opportunities for researchers from different backgrounds to converse and network. This includes the annual evaluation, an event led by the top management, in which all researchers at ELSI (including those at satellites) participate. Every member must summarize their activities over the past year on paper (research activity sheet) and deliver a 15 to 20-minute presentation. Researchers evaluate each other in two directions, as score and comment sheets are distributed. Young researchers evaluate PIs while PIs evaluate all researchers so that each researcher can gain a deeper understanding of each other's research and receive feedback on their respective projects. Evaluation criteria include items such as the eagerness to be involved in an interdisciplinary research, and for

young researchers, the willingness to conduct their research independently from PIs. For individual researchers, this is an opportunity to become acquainted with how others view his/her own research. Top management can grasp the research progress at ELSI and utilize it as the base to discuss roadmap updates, to validate whether researchers are able to work together across disciplines in an open research structure, and to identify any areas in which improvements are needed. Based on the score sheets, young researchers who are deemed to be contributing to the development of science at ELSI will be awarded with an Incentive Award, which includes research funding allocation, an award, and an employment period extension. This is provided as an effort to maintain and raise their research motivations. Additionally, after the annual evaluation, the director will conduct a meeting with every Institution member based on his or her score sheet and use the occasion to listen to any honest opinions or requests of the Institute's management.

(4) Development of an Open and Flat Research Structure and Recruiting Strategy for Young Researchers

While it may be the subtlest effort of all, constructing an open and flat research structure and the strategy to recruit young researchers are what creates ELSI's platform for fusion and collaborative work across different disciplines. As noted in "2-2. New Challenges," since its beginning, ELSI has never had a structure similar to the lecture system commonly found in Japan. As the bearers of interdisciplinary research, young researchers are not assigned to any particular PIs. They work on their research by collaborating with other researchers within and outside ELSI. PIs, including the director, will serve as mentors to the young researchers. However, with regard to research, they have made efforts to avoid interjecting the superior-subordinate relationship.

The recruiting process is also emphasized at ELSI to ensure that ambitious young researchers who join ELSI's open research environment will not lose sight of their positions within the Institute. Those young researchers who pass the paper selection phase and are invited to the meeting selection phase must present at an ELSI seminar. They are provided with an opportunity to speak with researchers engaged in similar or related research themes. Young researchers who are accepted will fine-tune their research topics before assuming their positions at ELSI. These efforts have been successful, as ELSI has begun to naturally move away from closed and isolated research projects.

3-2. State of "Bottom-up" Undertakings from the Center's researchers toward Creating New Interdisciplinary Domains

(1) ELSI Director's Fund

ELSI Director's Fund was established to encourage feasibility studies for concepts borne out of young researchers' free and flexible ideas or from discussions between researchers with different backgrounds. The Fund is also meant to help grow these research seedlings and encourage those with practical potential to delve further into serious development and acquire competitive funds such as KAKENHI. This system is meant to uncover interdisciplinary research seedlings and support their development. Proposals from individuals are not accepted. The requirement is that the development proposals come from multiple researchers from different disciplines. Originally, applications for the Fund were available once a year, with limited eligibility of up to 1 million yen per year per challenge. Based on suggestions from the Working Group and requests from young researchers, opportunities to apply were open to every spring and fall. The fund limits were diversified into an upper limit of 3 M, 1 M, and 500,000 yen per challenge in order to make the Funds accessible to both experimental researchers and theoretical researchers. Thus far, a total of 19 proposals have been accepted. There have been unique proposals from unlikely combinations of researchers. ELSI looks forward to further development in the future. As some researchers assisted by the Fund in the early stages have applied for external funding programs like KAKENHI, tracking surveys to evaluate accepted proposals are planned in order to determine how the funding system should be managed in later stages.

(2) Study Groups, ELSI Seminar, ELSI Assembly, ELSI Youchien

Over the course of less than two years, from ELSI's establishment to the adequate assembling of research talents, five study groups have been initiated as opportunities in which to share research targets and foster greater mutual understanding among researchers. The study group topics include planetary water, pre bio-chemistry, biosphere evolution, solid earth, and planetary exploration and life. Researchers that joined the Institute in the beginning belong to at least two groups in order to foster communication between diverse researchers through study sessions and to develop a blueprint for working together. Members from the Ehime satellite also participate in the solid earth group, sharing the "Monthly One Day Workshop" responsibilities. One of the large-scale KAKENHI projects

based at the Ehime University satellite was borne out of this study group. The same could be said for another large-scale KAKENHI project, Hadean Biosciences, as well as the EON project.
As the number of researchers increased, the multidisciplinary needs for shared foundational knowledge of each other's fields and research increased, the study group activities were developed into several types, ELSI Seminar, ELSI Assembly, and ELSI Youchien, to better meet the learning demands of the researchers, from basic level to understanding the cutting edge ideas in the various fields. ELSI Seminar is a place for lectures and discussions to which external researchers are invited to speak, while ELSI Assembly is a science meeting conducted by ELSI researchers. In 2015, the Assembly was organized to alternately host PI Scope sessions in which discussions overviewed by PIs occur and round-table sessions on topics provided by several young researchers are discussed. ELSI Youchien (Youchien is the Japanese word for kindergarten) aims to remove the barrier that exists between different principles. Young researchers present their research and specialties to other researchers as well as the support staff in simple language.
ELSI's interdisciplinary research style has developed by providing opportunities to listen to the presentations from various researchers in diverse forms and discuss. For example, proposals of "the birth place of life on the Hadean Earth" and "three step model for evolution of first life in a geryser driven by natural nuclear reactor" are particularly striking results.

(3) Hosting Support for Bottom-Up Workshops
While the efforts outlined in (2) are intended to create fusions within ELSI, the efforts cited in the title are designed to promote ELSI research to the outside and to foster fusions with external researchers. The Research Interaction Committee reviews the workshops proposed by researchers and provides financial support for those approved. The committee has provided assistance 17 times thus far, which has contributed to simultaneously sparking new interdisciplinary collaborative research between ELSI and external researchers and to improving ELSI's reputation. Additionally, some of the workshops' achievements have also been published in journals such as "Physics of the Earth and Planetary Interiors", "Origins of Life and Evolution of Biospheres", and in the Special Issue of "Geoscience Frontiers".

4. International Research Environment (within 4 pages)

4-1. International Circulation of the Best Brains

4-1-1. Results of International Joint Research (other than with the satellite)

(1) Collaborative Research with ELSI
ELSI and its satellites are engaged in various international collaborative research projects. This section summarizes four major projects in which ELSI acted as the leader and for which the research feedback has already been shared with the ELSI research teams. Some of the collaborative research were motivated by things that were seemingly distant from the science at ELSI. However, the ELSI science acted as a catalyst and blossomed into an international collaborative research that contributed to the science's advancement. These cases also demonstrate that ELSI is beginning to function as an international research hub.

◆ **Deep Earth (University of Minnesota, University of California, Santa Barbara)**
This international collaborative research group is working on research to discover the composition of the Earth's core and mantle at an atomic scale through first principles calculations of various materials. By applying a series of first-principles calculations to molten metal alloys containing sulfur under a temperature and pressure condition equivalent to the Earth's outer core, the group obtained values for the density of the alloy containing 16% sulfur by weight. This was very close to the values from seismological observations based on the assumption that the light element in the alloy is sulfur only. In the future, the data derived in the research will be used for bulk coefficient estimation as a function of pressure, temperature, and sulfur concentration to compare with seismological constraints. Furthermore, the group also conducted a simulation of pure molten iron under the temperature and pressure of the outer core, and attempted to calculate the acoustic velocity of the bulk by developing a state equation of the molten iron. As a result, molten iron was found not to follow Birch's Law (a linear relationship exists between density and acoustic velocity, regardless of the temperature), which was previously assumed to be applicable to molten iron. Additionally, through cooperation between theoretical and empirical research, the group also found

a new hydrous silicate that is thought to be stable in the lower mantle, a part of a very low-temperature sinking slab. This new phase provides a mechanism in which water enters the lower mantle. It is an achievement that enables the estimation of water content in the early Earth.
[Major Publication] Umemoto K, Himmetoglu B, Wang J-P, Wentzcovitch RM, Cococcioni M. 2015. Searching for high magnetization density in bulk Fe: the new metastable Fe-6 phase. Journal of Physics-Condensed Matter, 27. DOI: 10.1088/0953-8984/27/1/016001.

◆ Formation of the Earth's Magnetic Field (California Institute of Technology, Massachusetts Institute of Technology)

A planet's magnetic field offsets charged particles from the sun that cause atmospheric erosion. The fundamental problems in understanding the origin of life could also be thought of as the question of when the magnetic field was formed on a planet similar to Earth. With respect to Earth, no favorable rock records from Hadean era exists that limit the first dynamo effect. However, 3.2 billion year-old sandstones sampled from Western Australia contain trace amounts of zircon mineral particles from at least 4.4 billion years ago. The zircon minerals also include trace amounts of magnetites and other minerals. Therefore, high-resolution magnetic imaging technology may provide restrictions over the search for the origin of the Earth's dynamo. This international research group aims identify the Earth's magnetic field's formation process by applying magnetic tunnel junction technology to develop a system capable of imaging at sub-micron intervals in order to analyze zircon minerals. Conversely, there is an intense debate as to whether the basement rocks in Western Australia were thermally deformed through a temperature level in which the initial magnetization could no longer be conserved within the zircon. Therefore, the group is also working on the grand problem of "formation of the magnetic field on the Earth" by extending beyond the framework of an international collaborative research. They organized an international workshop in fall 2015 to which they invited researchers to work on the problem, including a group from the University of Rochester that adheres to a view which is different from that of the ELSI group.
[Major Publication] International Workshop "Geophysical & Geochemical Constraints on Early Planetary Dynamos," September 15-19, 2015, Kawaguchiko

◆ Chemical Evolution (Cleveland State University, National Institute for Materials Science, Institute of Physical and Chemical Research)

This international collaborative research group addresses the fundamental question of "how the structural components of biological bodies were inorganically synthesized" through a theoretical approach in which pre-biological reactions are simulated. The group also improved on a dynamic system model, which took a clue from a slime mold *Physarum polycephalum*, and developed a unique model capable of quickly finding a stable solution for constraint satisfaction problems. Utilizing such progresses, the group is now working on a simulation for the formation dynamics of stable organic molecules and a secondary RNA structure to gain minimal metabolic pathways and self-replicating RNA arrays. While there are many scenarios with respect to the origin of life, they all require empirical validation or theoretical research. This international collaborative research is making empirical verification backed by theoretical research a possibility.
[Major Publication] Aono M, Kim SJ, Hara M, Munakata T. 2014. Amoeba-inspired Tug-of-War algorithms for exploration-exploitation dilemma in extended Bandit Problem. Biosystems, 117: 1-9. DOI: 10.1016/j.biosystems.2013.12.007.

◆ Synthetic Biology (Massachusetts Institute of Technology, Massachusetts General Hospital)

This international collaborative research group is working on research on primitive cells by artificially creating micromembranes with RNAs and peptides. In particular, the RNA controls a series of processes, along with the execution of metabolic processes through functions such as a template for replicating the next generation of primitive cells from the current generation. This suggests the possibility for a first bootstrap towards the Darwinist evolution mechanism, in which a catalyst that merely originated from a template effect eventually transitioned to today's replication system. Once there is a basic understanding of a non-enzyme, template-dependent RNA replication mechanism, important understanding on various origins of life on the Earth could be gained from the RNAs. In 2014, PI Szostak and research member Fahrenbach worked on RNA replication research by surveying the thermodynamics in the bonding of an RNA monomer template to primer complexes, as well as the speed of the ensuing chemical reaction that follows the template.
[Major Publication] Izgu EC, Fahrenbach AC, Zhang N, Li L, Zhang W, Larsen AT, Blain JC, Szostak JW. 2015. Uncovering the thermodynamics of monomer binding for RNA replication. Journal of the

American Chemical Society, 137: 6373-6382. DOI: 10.1021/jacs.5b02707.

(2) Collaborative Research by Individual Researchers

Deep Earth: A team led by Project Assistant Professor Ballmer, with researchers from the University of Hawaii and University of Nevada, are studying the mode of mantle rise and volcanic activities, delays in lithosphere's descent into the deep mantle, and chemical heterogeneity inside the plume rising from the deep mantle. (For example, Ballmer MD, Conrad CP, Smith EI, Johnsen R. 2015. Intraplate volcanism at the edges of the Colorado Plateau sustained by a combination of triggered edge-driven convection and shear-driven upwelling. Geochemistry Geophysics Geosystems, 16: 366-379. DOI: 10.1002/2014gc005641.)

Theories of Planetary Formation: Identifying the origin of water on Earth and the impact of water in planetary evolution is a crucial research topic for the planetary formation theory group. With researchers from University of California, Santa Cruz, and the University of Beijing, a group led by PI Ida verified past scenarios and evaluated new scenarios with respect to “condensation of icy dust particles at the outer disk followed by their migration into the inner disk by gas resistance.” The group was able to verify the accretion of trace amounts of ice particles on an Earth-like planet, and the possibility that the accretion cross section controlled the amount of water available on the planet. (For example, Ida S, Lin DNC, Nagasawa M. 2013. Toward a deterministic model of planetary formation. vii. eccentricity distribution of gas giants. Astrophysical Journal, 775. DOI: 10.1088/0004-637x/775/1/42.)

Planetary Exploration 1: PI Fujimoto and researchers from the Imperial College of London, Athenes Academy, Los Alamos National Research Center, Observ St. Maur, CNRS, Boston University, and University College of London analyzed data from plasma and magnetic fields generated by Saturn’s arc-like shock waves to identify relativistic electron acceleration that occurs in the parallel part of the high-Mach number shock waves, as discovered by Masters et al. (2013). These waves were measured by the Saturn explorer Cassini. The remains of the supernova shined in an X-ray. Thus, the research revealed that the moment in which the shock wave occurs is the source of high-energy electrons that create X-rays. Previous theories suggested that parallel shock waves were the desirable place for electron acceleration. However, the observations from the Earth indicated otherwise. Unlike the Earth, Saturn today has the same level of shock waves predicted to accompany supernova explosions. As a result, contrary to the past research, parallel shock waves were found to accelerate relativistic electrons. This study not only uncovered new knowledge in shock wave acceleration physics, which was one of the most important problems in high-energy astronomy, it also significantly revealed the great possibility for space plasma physics in outer planetary missions like JUICE. (For example, Masters A, Stawarz L, Fujimoto M, Schwartz SJ, Sergis N, Thomsen MF, Retino A, Hasegawa H, Zieger B, Lewis GR, Coates AJ, Canu P, Dougherty MK. 2013. Electron acceleration to relativistic energies at a strong quasi-parallel shock wave. Nature Physics, 9: 164-167.**)**

Planetary Exploration 2: Project Assistant Professor Fujii, along with researchers from the University of Toronto, co-authored a paper that highlighted the impact of satellites in identifying bio-markers in exoplanets. The paper noted that, in a case in which an Earth-like planet has a satellite with atmosphere like Titan, the spectrum cannot be separated using today’s observation equipment or that of the near future. It cites that the indicator which shows that the “atmosphere is greatly unbalanced since oxygen and methane coexists” will not be usable. The paper also discussed the conditions required to separate the two and the possibilities for removing false positives. The research brought attention to a problem that was previously overlooked in identifying atmospheric composition in exoplanets. (Rein H, Fujii Y, Spiegel DS. 2014. Some inconvenient truths about biosignatures involving two chemical species on Earth-like exoplanets. Proceedings of the National Academy of Sciences of the United States of America, 111: 6871-6875. DOI: 10.1073/pnas.1401816111.)

Geology and Earth Chemistry 1: PI Kirschvink and others worked with researchers from University of Washington and St. Andrews University to develop a new paleomagnetic method to identify primary minerals and secondary minerals in rock samples from the early Earth*. Combining this method with a tracking method in atmospheric chemistry that utilizes sulfur isotopes, the study also reported via the journal Nature that atmospheric change started in the late Archaean era**. (*Fisher, W. W, Fike, D. A., Johnson, J. E., Raub, T. D., Guan, Y., Kirschvink, J. L., Eiler, J. M., SQUID-SIMS, a useful approach to uncover primary signals in the Archean sulfur cycle. Proceedings of the Natural Academy of Sciences, 111(15), 5468-5473, 2014.

www.pnas.org/cgi/doi/10.1073/pnas.1322577111 and Kirschvink JL. 2014. Sensory biology radio waves zap the biomagnetic compass. Nature, 509: 296-297.)

Geology and Earth Chemistry 2: PI Yoshida and Project Assistant Professor Gilbert worked with researchers from CNRS and University of Nantes to demonstrate that the measurement of intramolecular isotopes from nuclear magnetic resonance (NMR) can be reproduced using different labs and different spectrometers with a high accuracy of less than 2.1‰ errors. From the NMR measurements of ^{13}C isotopes, the project observed that intramolecular isotope distribution in natural lipids are not uniform, and that the difference in distribution by positional difference was up to 20‰. This method will likely be a part of a new tool that deepens our understanding of lipids in the early Earth from a biochemical perspective. The unique lipid distribution pattern from the origins of the organisms observed in the study could be treated as a new biomarker. (For example, Bayle K, Gilbert A, Julien M, Yamada K, Silvestre V, Robins RJ, Akoka S, Yoshida N, Remaud GS. 2014. Conditions to obtain precise and true measurements of the intramolecular C-13 distribution in organic molecules by isotopic C-13 nuclear magnetic resonance spectrometry. Analytica Chimica Acta, 846: 1-7. DOI: 10.1016/j.aca.2014.07.018.)

Chemical Evolution: Project Associate Professor Cleaves and others worked with researchers from University of Copenhagen, University of Hawaii, German Aerospace Center, University of Maryland at Baltimore County, and Jackson State University to develop a new method in computational science. They compared a set of 20 amino acids used by today's organisms with multiple sets randomly selected from the 2000 amino acids that can exist, and demonstrated that the set of 20 amino acids is capable of covering a wide range of space occupied by multiple physical and chemical characteristics (Ilardo M, Meringer M, Freeland S, Rasulev B, Cleaves HJ. 2015. Extraordinarily adaptive properties of the genetically encoded amino acids. Scientific Reports, 5: 6. DOI: 10.1038/srep09414.)

4-1-2. State of Top World-level Researchers residing at the Center

Describe the participation of overseas Principle Investigators, the short-term stays of joint researchers, and the state of participation in symposiums sponsored by the Center.

- In Appendix 4-2, enter the number of researchers from abroad within the total number of the Center's researchers, and their annual transition

ELSI's management has been ardent about meeting the requirements to be a world premier international research center, including 1. inviting attractive leaders; 2. acquiring exceptional talents (researchers) from around the world; and 3. developing a research environment and foundation needed to achieve 1. and 2. Today, seven out of 17 PIs are foreign researchers with proven track records from overseas. Four of these seven foreign PIs are based in Japan. This number is a testament to ELSI's quality as a research center at which the world's top-class scientists gather, rather than a mere fulfillment of number requirements. PI Eric Smith cited his reason for moving to ELSI on a permanent basis was that "ELSI is a place in which, in addition to 1-3, scientists can engage in the world's top-level research on the origin of the Earth and the origin of life." His comment is a testament to the research environment developed at ELSI as a world premier research center.

In parallel with the effort to increase the presence of foreign researchers, ELSI is also working to welcome more visitors from overseas research institutions. In particular, visitors that stay anywhere from a few months to a year are essential to the advancement and deepening of the science at ELSI. They propel forward the collaborative research with ELSI researchers, bring new perspectives or problem-solving clues for ELSI's young researchers, and even serve as bridge builders between researchers. From this viewpoint, ELSI focuses especially on inviting of top-class researchers in the midst of their sabbaticals.

4-1-3. Utilization and Employment Situation of Young Researchers

Describe the utilization and employment situation of young researchers including postdoctoral researchers.

- In Appendix 4-3, enter the state of international recruitment for postdoctoral researchers, applications received, and selections made
- In Appendix 4-4, enter the percentage of postdoctoral researchers from abroad
- In Appendix 4-5, enter the state of postdoctoral researchers' employment

ELSI has sought to recruit individuals who are able to assess their questions' scope and confront problems with ideas and approaches not confined to conventional concepts. A recruiting committee headed by a foreign PI promoted the selection policy, and established a unique ELSI method for recruiting young researchers, which is modeled after the Western recruiting style. As shown in the

Appendix 4-3 and 4-4, international advertisements were placed in journals including JST (JREC-IN), Nature, Science, and ELSI Web, and also sent to mailing lists for relevant academic societies and communities. From these efforts, ELSI received 206 applications from 31 countries around the world, most of which (86%) were from young foreign researchers. The employment period at ELSI is typically three years. However, young researchers with exceptional results may extend their stay by two years based on the outcomes of the annual evaluation. As shown in Appendix 4-5, 17 out of 51 young researchers hired by ELSI have been promoted at the world's top research institutions following their research experience at ELSI. This is a proof that ELSI is recognized as a career-path institution.

4-1-4. Other

Describe the Center's policy for sending Japanese researchers overseas to gain international experience, and give examples of how the Center is working to create career paths for its researchers within a global environment of researcher mobility.

(1) Overseas Dispatch Program was established to encourage young researchers to develop their research overseas for a period of time by funding part of the traveling and residential fees for proposals that include plans to a) visit an overseas research institution that the applicant has not previously visited; and b) either continue the research on his or her own for at least several weeks at the target institution or conduct collaborative research with the hosting researcher.

(2) Key Points in the EON Project Design: Upon designing the research system for the EON project, post-doctorate researchers were required to submit research plans in which they spend approximately half of their contract terms at overseas institutions in order to pursue their research. With acceptance from hosting overseas institutions as a prerequisite for the EON project membership application, ELSI was able to secure forward-thinking young researchers with the willingness to gain international experiences. As a result, more welcoming attitude towards the prospects of conducting research at overseas institutions began to take root within the Institute.

4-2. Creating the Center's Environment

4-2-1. Holding International Research Meetings

Describe the results obtained from holding the Center's main international research meetings.

- In Appendix 4-6, enter the number of international research conferences or symposiums held and give up to two examples of the most representative ones.

(1) ELSI "Kick-off" Symposium: ELSI's first international symposium was organized followed by ELSI's opening ceremony in Kuramae-Hall, Tokyo Tech, for 2 and half days starting on 27 March 2013. Participants joined from Tokyo Tech, ELSI's satellite institute such as Ehime U., IAS and Harvard U as well as overseas institutes, Caltech, U. of Minnesota and UC Berkeley. Domestic institutes, JAMSTEC, JAXA and total 30 institutions gathered in the event with over 140 participants. All the participants discussed actively for better understanding of various research areas as well as the strategy of future ELSI.

(2) ELSI International Symposia: ELSI International Symposium is annual event for ELSI and every year the symposium offers the chance to gather invited speakers from abroad and Japan to tackle some of the most pressing issues related to the science at ELSI. The 2nd symposium took place in March 2014 with the theme of "Origin & Evolution of the Earth-Life System". Invited speakers came from Michigan State U., CNRS, Weizmann Institute of Science, Observatoire de la Cote d'Azure and many major institutes around the world. 145 participants joined the event. The 3rd symposium was organized with the title of "Life in the Universe" and 144 participants from various research institutes, such as U. of Glasgow, ESA, Utrecht U., UNAM and Ames/ NASA joined and discussed the fundamental question: "Is there life in the Universe, outside Earth?" Each day saw a different set of posters being exhibited, on the theme of that day. The 4th symposium was 3-½-day event unlike the previous 3 symposia. "Early Earth, Venus & Mars Three Experiments in Biological Origins" was the title and symposium investigated how comparative planetary science can help our understanding of early Earth and the origins of life. Indeed we have only one example of a biotic planet, but we can use Mars and Venus as examples of failed origins of life. Attended by 149 participants.

(3) International Workshops/ Seminars organized by ELSI members: Starting from "Kick-off Symposium" in 2013, ELSI has hosted many international workshops and conferences throughout the years, 7 in 2013, 9 in 2014 and 9 in 2015. Major workshops are listed below.

"Workshop on Transport Properties in the Earth's Core" (2013; Kawaguchi-ko Lake, Yamanashi,

Japan; 29 participants 18 from foreign institutes) was organized by Kei Hirose, the ELSI director with the goal to bring together key researchers to discuss both the differences in our results, and to consider together the robustness of upward revisions in core conductivity in the context of their implications for the dynamics of the core and evolution of the deep Earth system.
“The International Astrobiology Workshop 2013, 6th Japan Astrobiology Network Workshop (JABN6)” (2013; Sagamihara, Kanagawa, Japan; 157 participants 23 from foreign institutes) was arranged for two days in JAXA/ ISAS Sagamihara campus and aimed to promote interdisciplinary interactions among astrobiology researchers and advancement of this field in Japan.
“Modeling Origins of Life Workshop at IAS” (2014; Princeton, NJ, USA; 10 participants 4 from overseas), organized by Piet Hut, ELSI PI and councilor, was held in IAS, one of ELSI’s satellites in US as a follow-up workshop with the ELSI summer school. The invited speaker includes Chris Adami (Michigan State University), well known for developing Avida, an artificial life simulation program.
“RNA, Peptides, Vesicles and Exoplanets -The Chemical Origins of Life on Early Earth and Other Planetary Bodies” (2014; Cambridge, MA, USA; 25 participants 10 from foreign institutes) was jointly sponsored by both ELSI as well as the Harvard University Origins of Life Initiative with the help of Albert Fahrenbach, who spends part of the year in Jack Szostak's lab at Harvard and part of the year at ELSI in Tokyo. The workshop itself allowed for experts in origins research to gather and discuss past, current, and future work towards understanding the origin of life.
“What Can Synthetic Biology offer to Artificial intelligence? - ECAL2015 satellite workshop “SB-AI”” (2015; York, UK; 20 participants 19 from foreign institutes) was organized by Yutetsu Kuruma, ELSI research scientist as the following session of two international conferences, ECAL 2013 in Sicily, Italy and ALIFE 2015 in New York, USA.
“Geophysical & Geochemical Constraints on Early Planetary Dynamos" (2015; Kawaguchi-ko, Yamanashi, Japan; 21 participants 10 from foreign institutes) was organized by Joseph Kirschvink, ELSI PI, specifically on the problem of early planetary dynamos arises from recent attempts to push back our knowledge of primary magnetic fields in the Solar System.

(4) ELSI Summer School: ELSI summer school is the co-sponsored event with RIKEN/ AICS and ELSI started in 2013 in Center of Planetary Science or CPS in Kobe for five weeks. Piet Hut, PI and councilor and Junichiro Makino, PI of ELSI organized the school with the concept of very informal "working workshop" on the topic of Large-Scale Simulations of the Formation and Evolution of Planetary Systems. 30 participants, 8 joined internationally. The highlights of the event were the two invited talks, by two visitors from the Southwest Research Institute in Boulder, CO, USA: by Bill Bottke on "Exploring the Early Bombardment of the Solar System" and by Hal Levison, on "Tackling Some Issues in Planet Formation -- From Mars's Size to a Fast Formation of Neptune".
With the success of the first school, the following year’s event, entitled "Modeling the Origins of Life", were held at ELSI (first two weeks) and in CPS, Kobe (next three weeks). 16 attended and 10 were from overseas. The goal was to build a community around a new idea and it was well achieved. In 2015, the number of participants increased to 38 and 13 came from foreign institutes. With the title of “Towards an Integrative Approach to the Study of Awareness”, lecturers joined from U. of Memphis, Monash U. and U of Exeter etc. ELSI Origins Network, funded by John Templeton Foundation and started July 2015, was also the co-sponsor besides ELSI and RIKEN/ AICS.

(5) Other events sponsored by ELSI

ELSI has been not only organizing but also sponsoring several high profile international conferences such as Gordon Research Conference (GRC), Origins of Life and Nara Origins 2014 to make ELSI’s presence visible in the scientific community, especially in the Origin of Life field.
ELSI scientists attended to those conferences and actively promoted ELSI’s interdisciplinary research to the attendees around the world.

4-2-2. Support System for Overseas Researchers

(1) Support for Living in Japan (Including Visa Applications)

In order to ensure that foreign researchers can concentrate on their work as soon as possible upon arriving in Japan, ELSI provides pre-arrival support for various matters, including visa applications and searches for housing and child daycare services. ELSI also assists foreign researchers with address registration and opening bank accounts to help them settle into life in Japan. Additional services are provided as needed, including searching and making appointments for hospitals and

signing contracts for cell phones and credit cards. In case of emergency, ELSI also has a contract with a 24-hour interpretation service available by phone that foreign researchers can access at any time through their mobile phones. ELSI also provides assistance to visitors in the event that they encounter problems during their time at ELSI.

(2) Japanese Language Classes

As a part of the support for living in Japan, ELSI provides Japanese lessons at a level that foreign researchers can use in their everyday lives in order to mitigate the stress of living in a different cultural environment. Rather than outsourcing the service, lessons are taught by the ELSI life advisor. Two classes are available: one for beginners and one for conversational level learners. Both classes are held twice a week, and have typically four to nine participants. Anyone can join at his or her convenience, including short-term residents. ELSI also ensures that the Japanese class itself will not be a burden to the researchers. As requested by the researchers, no homework is assigned. Instead, the class approach is hands-on, thus offering participants ample opportunities to speak during the classes. In particular, researchers with children have many opportunities to speak in Japanese outside of work. ELSI answers any questions regarding Japanese via emails. An environment in which foreign researchers can casually learn Japanese has helped improve the odds that they can respond in Japanese in the event of an emergency. This also improves their lives in Japan, as it facilitates an environment in which researchers can concentrate on their work.

(3) Daycare Service

An increasing number of foreign researchers are joining the Institute, along with the University's globalization efforts. As such, in April 2017, a daycare service will open inside the International House, which is the closest building to ELSI. This will allow researchers that need day care services and postnatal researchers to able to concentrate on their work with ease.

(4) Support for Acquisition of Competitive Funds

ELSI hosts KAKENHI seminars in English conducted by a Japanese PI with abundant experience in obtaining KAKENHI. In addition, translation services are available to assist with application documents. These services are provided by Japanese researchers, graduate students, and the full-time URA (Assistant Director) whose research fields are similar to that of the applicant. In light of the low number of accepted applications, in 2015 ELSI began a program in which the Institute has asked young foreign researchers with plans to apply to submit their research plans by fall. This allows the PIs to review and return the documents with recommendations. For other competitive funding programs and foundation grants, ELSI staff, including the URA, collect and analyze the information, and introduce relevant information to foreign researchers based on their research fields. As with KAKENHI, URA provides advice to ensure the applications are in proper agreement with the program objectives and assists with Japanese translation of the documents. Thus far, these efforts have been productive, as the number of accepted proposals has risen since 2014.

(5) Safety Management Training

Along with the University's General Safety Management Center, ELSI hosts an annual "briefing session on rules and precautions for experiments" in English for non-Japanese researchers. First hosted in 2014, the goals of the sessions are for researchers to understand the University's rules and system, and to develop an environment in which they can easily communicate with the University staff directly regarding any questions or concerns. This year's briefing session was held on February 1. Twelve non-Japanese and seven Japanese researchers attended. Videos of the briefing session and printed handouts will be provided for foreign researchers to be appointed at a later date.

5. Implementing Organizational Reforms (within 3 pages)

5-1. Operation carried out under the Center Director's Leadership

Describe the division of roles and authority between the Center and its host institution, and the state of the Center director's presence at the Center.

(1) Separation of Power Between the Institute Director and the Host Institution

Appointment and dismissal of the director is determined by the head of the hosting institution, i.e. the president of the Tokyo Institute of Technology. Other managerial decisions are decided by the director. Vice directors support the director. Opinions are exchanged once a month with the University executives in order to maintain close coordination between the University and ELSI.

(2) Decision-Making System within the Institute

・The director makes administrative decisions for ELSI based on discussions held by organizational

bodies under the director's purview. This includes the director's office meetings, steering committee meetings, and relevant committee meetings. The director also receives advice from an International Advisory Board on promoting the world's top level academic research activities and developing international research exchanges.

・ To meet the needs from increasing number of Institute members and to manage operations more reasonably, one new non-Japanese PI was appointed as a vice director, increasing the number of vice directors to three. Each vice director is responsible for developing academic fusion, globalization, and reform.

・Director's office meetings are held once a week and attended by the director, three vice directors, and the administrative director. The purpose of the meetings is to share the latest information and issues related to important ELSI matters, to unify the order system, and to ensure operations are smoothly executed.

・Steering committee meetings are held once a month involving the director, administrative director, and two vice directors. During these meetings, the director receives advice and support on internal adjustments, policy organization, research environment organization, and human resource matters needed to manage the Institute. The administrative staff above the chief-level and research secretaries are required to attend these meetings in order to ensure information is shared and decision-making related to the Institute is smoothly executed. Various committees are also established to meet the needs that arise from different ELSI management functions, ensuring that tasks are executed smoothly.

5-2. Administrative Personnel who facilitate the use of English in the Work Process

(1) Reorganization of the Administrative Office

To clarify each staff member's responsibilities, the administrative office work was re-organized into secretarial duties and tasks that are either related to the entire Institute or require coordination with the University's headquarters. Based on requests from researchers, a contact person was also assigned to each research unit to create a one-stop service for researchers. Along with the separation of secretaries from the administrative office, a secretary office was also established to accumulate and share information and knowledge among secretaries. Based on this approach, the University enacted "Policies on concentration of accounting tasks for research offices" to converge accounting tasks and strengthen check functionalities, thus enriching educational research as well. The administrative office and the secretary office periodically hold liaison meetings to share information and discuss possible improvements to their workflow. The PR department that was formerly established within the administrative office as a social coordination division was reorganized as an organization directly under the director in order to strengthen domestic and international PR activities and outreach activities.

(2) Structure of the Support Department

The administrative department consists of a total 16 staff members, including seven staff members from the operational department and the foreign researcher support department, four secretaries, three public relations staff members, one international coordinator, and one network staff member. Fourteen staff members are bilingual. Work-related communications are created in both Japanese and English. ELSI is bolstering its support for foreign researchers in terms of financial tasks, secretarial tasks, and support for living.

5-3. System Reforms and Their Ripple Effect within the Host Institution

Describe the following:

- Reforms to the Center's research operation advanced by way of the WPI Program's research-results evaluation system
- Reforms to the Center's operation made by introducing a merit-based salary system
- Ripple effects of the Center's system reforms within the host institution

(1) Top-Down Decision Making: ELSI follows a top-down management approach that begins at the director level. The Institute has developed a system in which researchers are able to concentrate on their work without being involved in daily managerial tasks. The President has approved and positioned ELSI directly under his research-based organization (research hub). The intent is to establish and develop a flexible research system that breaks away from conventional rules and operational structures. As such, ELSI will be regarded as a front-runner in research reform and as an organization that pursues research that attracts researchers from all over the world, while raising its international profile. The president has already declared a plan to establish two more research organizations within the University with structures similar to that of ELSI. The president also aims to

extend ELSI's system reforms throughout the University in order to strengthen the University's research capacity and further internationalize the campus.

(2) Realization of "World Research Hub" the for Development of International Research Activities: Through the advanced development of international student and faculty member engagement and a strengthened international network, Tokyo Tech strives to be a "truly globalized" university by becoming a research hub for a global current of knowledge and human resources in science and technology. This is achieved by inviting top-class researchers and research groups from around the world and implementing a "Tokyo Tech World Research Hub Initiative (WRHI)" based on the knowledge accumulated at ELSI, an Institute of Innovative Research that strives to create new research areas and seedlings for next-generation industries.

(3) Promotion of Interdisciplinary Research Across Different Disciplines

Promotion of Communications Across Different Disciplines: ELSI offers many opportunities to remove the "language and cultural barriers" between different disciplines and to promote mutual understandings between researchers from various backgrounds. These include twice-weekly lunch talks and tea time at 15:00 every day to encourage researchers and visitors to engage in discussions. ELSI aims to incorporate such initiatives across the Institution.

Study Groups: In order to identify the origins of the Earth and life through various approaches, ELSI organized five study groups in which researchers from different fields participate in discussions. This initiative is regarded as the blueprint for promoting interdisciplinary research at Tokyo Tech.

(4) Implementation of the Tenure System: The University has designated eight tenure positions for ELSI. Three additional tenure positions will be designated in 2016. This policy is the result of ELSI's recognition as a strategically emphasized education and research area from the University's mid- and long-term perspectives.

(5) Introduction of a Meritocratic Payroll System: ELSI employs a merit-based salary system, based on the stipulations found in "Rules regarding the salary of hired staff with limited periods at the Earth Life-Science Institute, Tokyo Institute of Technology." An annual evaluation meeting is conducted every year. At that time, as determined by the executives including the director, vice directors, and the administrative director, those recognized for distinguished progress in research are presented with an award and their salaries revised. ELSI also established an incentive system in which those who have made significant contributions to the Institute are awarded with a financial prize. (Number of recipients: 3 in 2013, 9 in 2014, 8 in 2015)

(6) Introduction of a Cross-appointment System: A cross-appointment system was organized with the University to acquire top-level researchers in life sciences, particularly to lead research in the "origin and evolution of life." For the first time, a professor was hired as a University PI through the system. The cross-appointment system will be utilized by Tokyo Tech in the future with the intent to acquire more distinguished faculty members.

(7) Acquisition of a Global Fund (EON Project): ELSI acquired a sum of $5.5 million USD (approx. 670 million yen) from the John Templeton Foundation (US) for the period from July 2015 to March 2018. Tokyo Tech has acquired a global fund in such a large sum for the first time and is considering developing an overseas office with persona sui juris to further acquire overseas funds.

(8) Introduction of a Corporate Card: ELSI has decided to introduce a corporate card with the intent to lessen the burden for researchers when they need to purchase supplies for research activities overseas (for which the researchers had to pay on behalf of the Institute under the current process) and to also prevent accounting fraud with research expenses.

(9) Participation in Graduate School Education for the World's Leading Researchers

Director Hirose, and full-time academic staff members Professor Ida and Professor Kurokawa, mentor undergraduates pursuing thesis research and graduate students. These faculty members are entrusted with same level of authority and responsibilities as the department faculty members. ELSI actively engages in advising graduate students through education and research based on the belief that such activities will help develop the next generation of researchers.

(10) Others: The President aims to propagate an interdisciplinary system similar to ELSI's system in order to strengthen the University's research capacity.

5-4. Support by Host Institution

Besides the state and effectiveness of the host institution's support for the Center, describe the Center's positioning within the host institution's mid- to long-term plans.

- In Appendix 5-1, describe specific support measures being taken by the host institution.

(1) Tokyo Tech Mid-Term Plan: The mid-term plan, which outlines Tokyo Tech's mid-term research

objectives, cites that "the University will provide resources as deemed fit by the president to the world premier international research center, the 'Earth Life-Science Institute', which will conduct research that focuses on the early Earth and studies the origins and evolution of the Earth and life in relation to each other." It has been positioned as "a highly strategic and ambitious objective and plan."
In order to accomplish the mid-term plan, ELSI is positioned directly under the president as a research center organization (research hub) approved by the president. ELSI is expected to establish and develop a flexible research system free from conventional practices, while raising its international profile. It is regarded as a front-runner in academic reform and as an organization capable of attracting scientists from around the world through its research. ELSI strives to conduct research to understand the origins and evolution of the Earth and life. It receives support such as academic posts, spaces, and expenses approved at the president's discretion. The president also declared a commitment for additional support, including human resources and material support for site visits and program committees, in addition to the previous commitment as a hosting institution during the concept stage.
(2) Human Resources Support to the Center: Tokyo Tech enacted an "agreement on mobility of staff and faculty at the Tokyo Institute of Technology Earth Life-Science Institute." Five faculty members were assigned on a permanent basis, while PIs were exempt from educational duties for undergraduates. At the same time, at the president's discretion, Tokyo Tech hired three new faculty members for previous departments to develop undergraduate education and avoid disruption. Two administrative staff members were also assigned to ELSI. The University also provided ELSI with two posts (professor and associate professor, from April 1, 2014 to March 31, 2022) to bolster the life-science fields, particularly with respect to the "origin and evolution of life." A post for an assistant professor was also added with the intent to strengthen and enrich the graduate school program.
Three tenure positions will also be sanctioned in 2016.
(3) Provision of Research Spaces: An existing building on the University campus (2,670 m^2) was designated as the Earth Life-Science Institute Building (ELSI-2). Additionally, a new research building was also built (ELSI-1: 5,000 m^2) in 2014 on a property provided by the University. Twenty rooms at the International House are also reserved for preferential occupancy by ELSI's foreign researchers.
(4) Preferential Financial Measures: ELSI receives 90 million yen annually. This expense sanctioned by the president as the cost for developing an existing center. ELSI also received financial support for facility updates, such as air conditioners. It was exempt from 40-million-yen worth of president-sanctioned space leasing fees provided by the University. The University provided additional support for the direct payroll of four PIs and two full-time administrative staff members.
(5) Daycare Service: Due to the increasing number of foreign researchers joining the Institute, along with the University's globalization, in April 2017 a daycare service will open inside the International House, the closest building to ELSI. This service will allow researchers that need day care services and post-natal researchers to be able to concentrate on their work with ease.

5-5. Others

5-5-1. Efforts to Foster Young Researchers (e.g., startup funding)

An annual fee of 500,000 yen is allocated to young researchers hired with WPI expenditures to cover their startup costs. This fee is to ensure that young researchers who join ELSI can start their research smoothly. It is intended as a support until they acquire external funds. Given the purpose of the WPI Program and with the intent to encourage swift transitions into research funded by external funds, researchers with allocated startup funds are required to apply for at least one external funding program every year, including KAKENHI (acceptance is not taken into account). ELSI recognizes that the amount of startup expense per person is insufficient. However, like an OJT program, the intent is for young professionals to gain the essential knowledge on how to plan carefully, utilize other funds like the Director's Fund, and become independent researchers capable of acquiring competitive funds. As noted in 2-8, young researchers are encouraged to join ELSI's outreach activities so long as they do not disrupt their research activities. The intention is for young professionals to understand the importance and pleasure of dialogues between science and society at an early stage in their careers, and become trained in the ability to explain the research funded by the public to society.

5-5-2. Appointment of Female Researchers

- In Appendix 5-2, give the transition in the number of female researchers.

In order to encourage the employment of women, the director and vice directors are promoting ELSI's top-level research environment and future prospects through various opportunities. They

promote open recruitment internationally through the website, JST (jREC-IN), the Society of Evolution Studies, and the Japanese Society of Cell Synthesis Research. Additionally, ELSI supports PI-class female researchers upon their appointment so that they can start their research smoothly. This includes allocating base startup expenses with a premium, preferential hiring for post-doctorate positions, and preferential accommodations for research spaces. As shown in Appendix 5-2, the gender ratio today is 24% (6% for PIs, 29% for other researchers).

6. Future Vistas (within 2 pages)

6-1. Future Policies and Plans for Advancing the Center's Operation and Project

(1) Tokyo Tech Mid-Term Plan

The mid-term plan, which defines the mid-term objective for research at Tokyo Tech, clearly cites that, "as a world's top-level research base, the 'Earth-Life Science Institute' will focus on the early Earth, and, through resources provided at the president's discretion, promote research that aims to understand the origins and evolution of the Earth and life in relation to each other." It positions the Institute as a "highly strategic and ambitious objective and plan."

In order to execute the plan, ELSI is positioned directly under the president as a research-based organization (research hub) approved by the president. ELSI is expected to establish and develop a flexible research system that is not restricted by conventional practices or operational structures. It will be regarded as a front-runner in research reform and as an organization that pursues research that attracts researchers from all over the world, while raising its international profile. ELSI strives to conduct research to understand the origins and evolution of the Earth and life with support including academic posts, spaces, and expenses approved at the president's discretion. The president also declared a commitment to ELSI management for additional support from the University. This includes human resources and material support during site visits and program committees. This is in addition to the previous "commitment as a hosting institution" during the conceptual stage.

(2) Funding Plans

In order to build on the research grants acquired from the John Templeton Foundation in the U.S. and to actively seek further funding from abroad, ELSI is considering establishing an office and incorporation as a non-profit entity overseas.

6-2. Measures to sustain the center as a World Premier International Research Center after Program Funding Ends

(1) Enhanced Research Environment

ELSI will continue to provide researchers with a place for their own research, including an adequate environment in which they can concentrate. This environment will support young researcher development, including graduate student education, exchanges with the world's top-level researchers, and interdisciplinary research promotion.

(2) Support for Foreign Researchers

ELSI provides support to help foreign researchers settle into life in Japan prior to their arrival. This includes help with visa applications, address registrations, bank account openings, searches for and appointments with hospitals, housing searches, and contracts for cell phones and credit cards. ELSI has also contracted a 24-hour interpretation service (Cross Language, Inc.) that in the event of an emergency foreign researchers can access at any time through their mobile phones. ELSI provides foreign researchers with an environment in which they can concentrate on their work and feel at ease even before they arrive.

(3) Support from the Host Institution

Tokyo Tech will continue to provide the following support in order to maintain ELSI as a "one of the world's top-level research hub" even after the end of WPI support.

1. Provide human resources, space, and financial support
2. Designate ELSI as a permanent "research base organization (research hub)"
3. Consider to establish an office and incorporating as a non-profit entity overseas to actively seek further funding from abroad

(4) Establishment of a Future Concept Assessment Committee

A committee to develop a future concept of ELSI beyond the end of WPI Program will be installed at the University. The aim of the committee will be to discuss approaches to maintain ELSI as a world premier international research center.

(5) Coordination with Research Centers

ELSI will seek to coordinate with other WPI centers with respect to their outreach activities and management.

7. Others (within 1 page)

* In addition to the above 1-6 evaluation items, only if there is anything else that deserves mention regarding the center project's progress, please note it.

(1) Acquisition of a Global Fund (EON project)

ELSI acquired a sum of $5.5 million USD (approx. 670 million yen) from the U.S.-based John Templeton Foundation for the period from July 2015 to March 2018. By acquiring this influential global fund, ELSI will further strengthen its infrastructure and accelerate research to understand the origins of the Earth and life. A project titled "ELSI Origins Network (EON)" was launched using the fund. Through this project, ELSI serves as a hub to strengthen and expand a global network of researchers pertaining to the origin of life. The EON project's first major activity was to organize and host an international workshop that was held from August 26th to 28th, 2015. Building on the success in acquiring the grant and launching the project, ELSI plans to pursue additional foreign funds. The EON project's achievements will be fed into ELSI's research which expected to accelerate studies on the origins of the Earth and life, a realm unknown to mankind for many years. The development of an office and incorporation as a non-profit entity overseas to acquire further global funds is also being considered.

(2) Streaming Lectures Online

On October 7, 2015, Tokyo Tech began streaming the first lecture by Tokyo Tech's first MOOC: "Introduction to Deep Earth Science - Part1 (GeoS101x) Outer." ELSI Director and Professor Kei Hirose was selected to deliver a lecture for the very first streaming. In his lecture, he discussed "the internal structure of the Earth" with the world in English. Using the lecture recordings and texts available online, 5,402 registered students from 159 countries are learning the details about global, top-level research.

8. Center's Response to Results of FY2015 Follow-up (including Site Visit Results) (Use as Many Pages as needed.)

Describe the Center's Response to Results of FY2015 Follow-up. Note: If you have already provided this information, please indicate where in the report.

8-1. Follow-Up Report and Issues Needing Investigation

(1) Research into the Origins of Life

As noted at the beginning of this report, studies on the origin of life at ELSI are based on a unique point of view: "Past studies on the origin of life were primarily based on a biochemical perspective that assumed that the Earth was the cradle of life and a support to, rather than an entity that mutually interacts with, life. Life is an entity that exists upon exchanges of substances and energies with the surrounding environment. As a result, not only does the environment affect life activities, life activities also affect the environment. From this standpoint, ELSI emphasizes research on both the Earth and life. It is a based on a unique viewpoint of (1. reprint from the overview of the research center plan)." For this reason, researchers, the research structure, and infrastructure all had to start from ground floor. In fact, a significant amount the efforts and investments to develop "science," one of the four pillars of the WPI Program, was applied to research on the origin of life. Under the belief that "first-class research cannot be achieved without first-class scientists and first-class laboratories," "first-class researchers" that matched the ELSI's research on the origin of life were recruited as PIs and ELSI fellows. Additionally, first-class human resources were secured in various ways. Invitations were issued to top-contenders in the midst of sabbaticals. As a result, an interdisciplinary research team was formed. Based on discussions led by key individuals, past research achievements, and the future research outlook, the origin of life was uniquely defined by ELSI as follows: "The 'origin of life' is a transition from Earth-assisted geochemistry to polymer-assisted biochemical networks." In order to pursue this important change, problems will be broken down into more specific research issues, including 1. extraction of universal properties in biochemical reactions; 2. creation of catalysts and control of organic chemical reactions by catalysts; and 3. the role and history of geo-energy and bio-energy in transitions towards the origin of life. Specific and elaborate experiments will be planned to address each issue. In order to promote these challenges, two foreign researchers with creative and distinguished achievements in disciplines including organic physical chemistry will be welcomed as PIs from January to June 2016. The ideal structure for

pursuing the most challenging issues in context of ELSI's science development is nearly complete, and great steps forward can be expected in the mid-phase of the WPI Program.

(2) Communication with Young Researchers:

Daily communications between ELSI's top management or PIs and young researchers occur during the aforementioned lunch meetings, tea times, and Izakaya ELSI. Communication also takes place during specialized internal committee activities in which senior figures, such as vice directors, serve as the committee chairs. This includes the recruitment committee, the research interactions committee, and the public relations committee. Additionally, since 2014, the director has also conducted face-to-face interviews with all researchers following the annual evaluation meetings. ELSI is also coordinating efforts, such as installing an "electronic comment box," in order to address absorbing matters and concerns that are difficult to communicate directly. However, ELSI does not assume that such efforts have been sufficient. Therefore, the Institute, especially the top management, will assess further approaches to diversified communications in order to meet the various contextual needs. Furthermore, non-research positions such as administrative and support roles, including the administrative director and research administrator, will also take part in further enhancing communication with young researchers.

(3) Improvements of Research Funding for Foreign Researchers:

Specific past efforts are noted in "4-2. Organization of the Environment (4) Support for Acquiring Competitive Funding." For example, many of the screening results for the 2014 Fall KAKENHI were came close to be approved. ELSI is making progress towards improving the acceptance rate. During the application season for fall 2015, foreign researchers were advised to take part in research plans with collaborative research partners from within and outside ELSI.

In the three years since its establishment, the greatest fear for ELSI is to be overtaken by discouragement. Based on the applications for funding programs like KAKENHI, for which judgment results are accessible, ELSI intends to maintain and improve the foreign researchers' motivations by developing a plan to provide some level of the financial support needed to polish research proposals that were rejected by narrow margins.

(4) Improvements in Employment of Young Researchers:

Since its conceptual stage, ELSI has been recruiting young researchers for three years with the intent to play a role in circulating intellectual talent by developing unique talents well-versed in origin and evolution. ELSI aims to secure research talents who meet the needs of the Institute's constantly evolving overall research phase. For those who have been deemed through the annual evaluation to have made either extraordinary achievements or significant contributions, ELSI has established a system to either extend their employment periods by two years, or to coordinate with hosting organizations to help them secure tenure positions. ELSI has emphasized the development of an environment in which more young researchers can comfortably and fully engage in their research. At the risk of being misunderstood, it must be said that, considering the Japanese regulations for employment contract and the employment trends for young researchers around the world, it might be impossible for ELSI alone to construct an employment system that satisfies the needs of all young researchers. However, ELSI will not falter. Instead, the Institute aims to create and improve a research and employment environment in which more young researchers will be able to view their experiences at ELSI as beneficial to their career development. In the three years since ELSI's establishment, it is true that some young researchers who have been with the Institution since the beginning will leave ELSI after completing their contract period. However, this is only a few researchers. As stated before, it should be noted that there are many researchers who have boosted their careers based on their achievements at ELSI, and many others who have chosen to extend their stays by receiving the Incentive Award.

8-2. FY2015 Site-Visit Report: 6. Response to Demands and Proposals to the Institute

1) For the forthcoming interim evaluation, careful arrangement of presentations is highly recommended so as to make clear ELSI's identity. Also, publication metrics should be better provided as reference to the center's scientific achievements. The presentations should better highlight the progress that ELSI has made since the start of its program.

The Science Committee, led by the director, including the vice directors and major PIs, has been

discussing the appropriate approach to promote the science developed at ELSI as a cohesive story as they prepare for a series of interim evaluations. The first evaluation will begin with a site visit on June 2016. In late March 2016, the Science Committee invited ELSI researchers to organize and share the major discussion points that should be promoted. Following the comments received, at the interim evaluation ELSI will provide results from an objective, i.e. bibliometric, analysis of past publications along with a summary of its science.

2) Many members of the working group think that the institute's current roadmap is much better than the previous one. However, a more conscious effort is needed by all ELSI members to identify the place and direction of their research within the ELSI roadmap.

ELSI grasps the progress made by every researcher at the aforementioned annual evaluation. The Science Committee has been revised the roadmap accordingly. ELSI understands that such efforts have been well-received. The effort to update the roadmap will continue. ELSI views this comment both as an encouraging implication that the "roadmap updates" are essential efforts towards the promotion and qualitative improvement of ELSI's science, and as an indication that ELSI's previous science appeal was somewhat disorganized. This also relates to the point discussed in 1). ELSI intends to ensure that the roadmap is shared with all of its members, and will make the effort to promote our achievements in a consistent and structured manner that takes the roadmap into account.

3) The WG understands well that solving the "origin of life" problem is very difficult and quite a big challenge. Nevertheless, in next year's interim evaluation, ELSI is expected to give some clues on how it is moving forward in tackling this challenge.

ELSI recognizes the third challenge in the breakdown of our own definition of "origin of life" as the "clue" to which the comment refers. This challenge is described in (1) "Research on the Origin of Life" from "8. Response for Follow-up Results (including On-Site Visitation Report) and its Outcome." Achievements, challenges, and future outlooks for these three challenges will be presented and discussed at the interim evaluation.

4) ELSI remains much more focused on "import" (of visitors) than on "export" (of its scientists) to overseas institutions.

While ELSI recognizes that a consistent flow of researchers from ELSI to overseas institutions would be evidence that ELSI is truly a global research hub, it must be noted that ELSI has been biased towards inviting distinguished researchers from overseas to strengthen its research infrastructure. Three years have passed since the Institute has been established, and some of the researchers that joined ELSI at its early stage have begun to move abroad to overseas research institutions, using the research they began at ELSI to their advantage (for example, in 2015, Project Assistant Professor Ballmer accepted a position at ETH as a tenure-track assistant professor, and Project Assistant Professor Fujii [a woman] was accepted as a NASA Postdoctoral Fellow). Conversely, based on the need to strengthen efforts for ELSI researchers to develop research activities at overseas institutions on a short- or mid-term basis, ELSI created and recently initiated an overseas dispatch program, as noted in 4-1-4. Additionally, the majority of the EON project researchers are required to spend 50% of their employment period at overseas institutions in order to develop their research. ELSI will ensure that past achievements and efforts will be shared with the entire Institute, and will consider developing a plan in which young Japanese researchers can proactively choose to continue their research abroad at overseas institutions.

5) While the importance of collaboration with ISAS/JAXA on the Phobos/Deimos mission is understandable in general terms, more specific and convincing reasons for how that collaboration is relevant to ELSI's objectives was not presented. ELSI should clarify its view on the role it hopes to play and the research benefits it hopes to obtain from such collaboration.

As it is widely known, the Mars Moon (Phobos/Deimos) eXploration (MMX) Mission is a foundation for future exploration on Mars (and life on Mars) to which Japan can contribute from engineering and scientific perspectives within an internationally collaborative framework. Just as the glimpses of the birth of the Earth could be seen from the exploration of moon and its samples, combining the

exploration and sampling of Mars satellites like Phobos and Deimos (i.e. the Phobos/Deimos mission) with our knowledge from material evidences will help advance comparative satellite studies and understanding towards the origin and evolution of the Mars itself. ELSI will lead and practice scientific discussions by taking into the account theories of planetary and satellite formation, astrobiology, as well as the universal biology that lies ahead. ELSI has already assigned two project associate professors as science leaders at MMX. ELSI also hosted an international symposium in February 2016 that was organized by these two professors and PI Fujimoto, and began drawing an scientific image of future Mars explorations, including the Phobos/Deimos mission.

6) The WG received a request from young researchers for more travel support. They also wanted to see the development of experimental facilities and employment of excellent technicians. We understand that some parts of their requests are reasonable while others are difficult given the present funding system. We want to ask the ELSI center members to carry out appropriate communication with an eye to working toward satisfying the young researchers' desires.

It is important, not only to young researchers but also to ELSI itself, that the Institute support young researchers' pursuits of research activities in a global environment and their self-improvements. Conversely, ELSI does not believe that accommodating every single request is the best approach, not only in terms of the funding limitations, but also in terms of developing young researchers. Thus the research funding menu, including travel fees, have been defined, applied, and improved accordingly. For example, the opportunity to apply for the Director's Fund was initially defined as once a year but later changed to once every spring and fall. Additional efforts are being made to set three stages of upper-limits to the allocated funds in order to meet individual needs. During the budgeting phase, ELSI also secured funds that may be used at the Research Interactions Committee discretion and established a new overseas dispatch program. However, the comment implies the possibility that there is a mismatch between ELSI and young researchers. Please refer to the details discussed in "(2) Communication with Young Researchers" in "8. Response for Follow-up Results (including Site-Visit Report) and its Outcome." This is an opportunity to re-assess the current communication with young researchers in which approaches to their support, including traveling fee support, will be assessed through PDCA cycles. The Institute will discuss these assessments with the young researchers, begin implementing feasible policies, and make improvements accordingly.

7) The young foreign researches are having some trouble acquiring research funds, such as KAKENHI. It is important for Japanese administrative staffs to assist them in improving their research proposals. They also need to be informed about research funding offered by private foundations.

As previously noted in "4-2. Organization of the Environment; (4) Support for Acquiring Competitive Funding" and "8. Response for Follow-up Results (including Site-Visit Report) and its Outcome; (3) Improvements in Research Funding for Foreign Researchers," ELSI is working on providing support to acquire external funds for young foreign researchers. The research administrator and the research support team are actively engaged in such support. Research conducted at ELSI is a fundamental science, which often does not match the intentions of the external funding programs that seek innovation-oriented research or foundation grant programs. This puts our researchers at a disadvantage in terms of the external funding programs to which we can apply. ELSI will continue to meticulously provide information and support application document development, including translation into Japanese. Since there has been a greater need to increase research support, including support for young foreign researchers to acquire competitive funding, another research administrator will join the staff in 2016. ELSI will assist researchers with a two-person support system.

8) Crossing disciplinary boundaries is notoriously difficult, time consuming and ultimately risky (project success rates are far lower than with purely single discipline efforts). Young researchers who must face the job market within 1 to 2 years are at a career stage that makes it very awkward for them to take on such gambles, especially in today's very unfavorable job market. This appears to be a major source of stress and even discontent among ELSI postdocs and other young researchers. The problem could be substantially alleviated by making ELSI postdoctoral appointments carry a normal or expected duration of five years (with renewal subject to adequate performance, of course). In addition to giving young researchers at ELSI the "room" they need to take risks without gambling away their careers, such a system would be an extremely powerful

recruitment tool for hiring the very best young scientists into positions at ELSI. Management should very seriously consider implementing such long-duration postdoctoral appointments as the norm at ELSI.

Please refer to the details discussed in “8. Response for Follow-up Results (including On-Site Visitation Report) and its Outcome;(4) Improvements in Employment of Young Researchers.”

World Premier International Research Center Initiative (WPI)

Appendix 1-1. FY 2015 List of Principal Investigators

NOTE:
・Underline names of investigators who belong to an overseas research institution. Place an asterisk (*) by names of investigators considered to be ranked among world's top researchers.
・In case of researchers not listed in the latest report, attach "Biographical Sketch of a New Principal Investigator".

<Results at the end of FY2015>

Principal Investigators Total:17

Name (Age)	Affiliation (Position title, department, organization)	Academic degree, specialty	Working hours (Total working hours: 100%)				Starting date of project participation	Status of project participation (Describe in concrete terms)	Contributions by PIs from overseas research institutions
			Work on center project		Others				
			Research activities	Other activities	Research activities	Other activities			
Center director Kei HIROSE* (47)	Director, Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., High-pressure Geoscience	50%	40%	0%	10%	From start	Usually stays at the center	
Shigenori MARUYAMA* (65)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Geology, Tectonics, History of Life and the Earth	70%	10%	0%	20%	From start	Usually stays at the center	
Shigeru IDA* (55)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Planetary Sciences, Planetary Physics.	70%	10%	0%	20%	From start	Usually stays at the center	
Piet HUT* (63)	Full professor, Institute for Advanced Study, Princeton, Program of Interdisciplinary Studies Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Theoretical Astrophysics, Interdisciplinary Studies	40%	10%	40%	10%	From start	Stays at the center for five months, other than that, at Princeton Satellite	- Accept young ELSI scientists to the Satellite (5 months, 7 months) - Facilitate interdisciplinary research - Organize Workshops - Recruit young scientists

Junichiro MAKINO* (52)	Team Leader, Particle Simulator Research Team, RIKEN Advanced Institute for Computational Science	Ph.D., Computational Astronomy	35%	5%	40%	20%	From start	Stays at the center once a week	
Naohiro YOSHIDA* (60)	Professor, Interdisciplinary Graduate School of Science and Engineering, Department of Environmental Chemistry and Engineering, Tokyo Institute of Technology	Doctor of Science, Environmental Chemistry, Global Change Analysis	70%	10%	0%	20%	From start	Stays at the center three times a week	
Ken KUROKAWA* (47)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D. Metagenomics, Bioinformatics	70%	10%	0%	20%	From start	Usually stays at the center	
Tetsuo IRIFUNE* (61)	Professor, Geodynamics Research Center, Ehime University	Ph.D. High-pressure geosciences, Materials sciences	56%	10%	14%	20%	From start	Usually stays at Ehime satellite	
Joseph Lynn KIRSCHVINK* (62)	Professor, Division of Geological and Planetary Sciences, California Institute of Technology Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D. Geobiology, Paleo-magnetism, Biophysics, Neurobiology	40%	10%	40%	10%	From start	Stays at the center for five months, regularly communicates with us by email	- Research fieldwork and prepare customize equipment for research
John HERNLUND (42)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D. Geophysical Modeling, Fluid and Solid Dynamics	90%	10%	0%	0%	From August, 2013	Usually stays at the center from August 2013	

Masaki FUJIMOTO* (49)	Professor, Department of Solar System Sciences, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency	Ph.D. Solar System Plasma Physics	25%	5%	25%	45%	From start	Stays at the center once a week	
Ken TAKAI* (44)	Program Director, Institute for Biogeosciences and Precambrian Ecosystem Laboratory, Japan Agency for Marine-Earth Science and Technology	Ph.D. Geobiology and Astrobiology	45%	5%	45%	5%	From start	Stays at the center several times a month, regularly communicates with us by email	
Hitoshi KUNINAKA (54)	Professor, Lunar and Planetary Exploration Program Group, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency	Ph.D. Aerospace Engineering Electric Propulsion	25%	5%	25%	45%	From start	Stays at the center several times a month, regularly communicates with us by email	
Jack William Szostak* (62)	Professor of Genetics, Harvard Medical School	Ph.D. Molecular biology Synthetic biology	50%	10%	10%	30%	From start	Usually stays at Harvard satellite	- Accept a young ELSI scientist to the Satellite (5 months) - Mutual dispatch of young scientists between two institutes
George HELFFRICH* (62)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Geological Sciences	75%	10%	10%	5%	From July, 2014	Usually stays at the center	
Eric SMITH* (49)	P Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D. Aerospace Engineering Electric Propulsion	75%	10%	10%	5%	From February, 2015	Usually stays at the center	
Irena MAMAJANOV* (40)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Physical Chemistry	85%	15%	0%	0%	From January, 2016	Usually stays at the center	

Researchers unable to participate in project in FY 2015

Name	Affiliation (Position title, department, organization)	Starting date of project participation	Reasons	Measures taken
Renata WENTZCOVITCH* (59)	Professor of Materials Science and Engineering, Department of Chemical Engineering and Materials Science, University of Minnesota	From October, 2015 Rescheduling starting date	Due to family reasons	
Tetsuya YOMO* (52)	Professor, Graduate School of Information Science and Technology, Tokyo Institute of Technology Professor, Earth-Life Science Institute, Tokyo Institute of Technology Cross-appointment system Osaka University 75% / Tokyo Institute of Technology 25%	From November, 2014	Period of the satellite contract between Tokyo Institute of Technology and Osaka University was terminated.	

World Premier International Research Center Initiative (WPI)

Biographical Sketch of a New Principal Investigator

Name (Age) *NOTE: Place an asterisk (*) by the name of investigators considered to be ranked among the world's top researchers.*	Irena Mamajanov (40)
Current affiliation (Position title, department, organization)	Tokyo Institute of Technology (Earth and Life Science Institute)
Academic degree, specialty	Ph.D Systems Chemistry, Polymer Science

Research and education history

Research:

Principal Investigator/ Project Professor, Earth and Life Science Institute, Tokyo Institute of Technology 2016-present

• *Areas of Research:* Origins of Life, Functional Polymers, Structural Investigation of Heterogeneous Prebiotically Plausible Polymers, Emergence of Enzymes, Hyperbranched Polymers.

Research Fellow, Carnegie Institution for Science 2014-2015

• Was awarded the Simons Foundation Collaboration on the Origin of Life Fellowship to investigate the prebiotic potential of hyperbranched polyesters

• Trained and mentored summer interns

Research Scientist, Georgia Institute of Technology 2012-2013

• Conducted research in the fields of far-from-equilibrium functional polymers and dynamic combinatorial chemistry

• Mentored graduate and undergraduate students

Postdoctoral Fellow, Georgia Institute of Technology 2009 – 2012

• Conducted research in the fields of nucleic acid biophysics, chemical evolution and novel anhydrous solvents

Research and Teaching Assistant, Brandeis University 2002-2008

• *Dissertation:* Potentially Biogenic Polymers

• *Courses Taught:* General Chemistry, Art and Chemistry, Physical Chemistry Laboratory

Research and Teaching Assistant, Hebrew University 1999-2001

• *Thesis:* Petroleum Bioremediation by Cyanobacterial Mats

• *Courses Taught:* General Chemistry Laboratory for Medicine and Biology Students, Inorganic Chemistry Laboratory, Advanced Chemistry Experiments

Education:

2008	PhD, Physical Chemistry Brandeis University, Waltham, MA, USA
2001	M. Sc., Organic Chemistry Hebrew University, Jerusalem, Israel
1997	B. Sc., Chemistry Hebrew University, Jerusalem, Israel

Achievements and highlights of past research activities *(Describe qualifications as a top-caliber researcher if he/she is considered to be ranked among the world's top researchers.)*

Irena Mamajanov is a spectroscopist with interests in systems chemistry, polymer science and biomimetics. She was involved in origins of life research since grad school where she worked under the tutelage of Judith Herzfeld on structure elucidation of hydrogen cyanide (HCN) polymers via solid state NMR (Mamajanov and Herzfeld, 2009). HCN polymers have been long postulated to contain peptide-like structures; the notion proved to be inconsistent with ^{13}C and ^{15}N NMR spectra collected. Alternatively, the data suggested that the polymers were formed by simple monomer addition, first in head-to-tail fashion to form linear conjugated chains and then laterally to construct saturated two-dimensional networks. Moreover, the data verifiably pointed towards radical initiation mechanism in concert with previously published EPR data and autocatalytic nature of HCN polymerization.

Upon completion of her Ph.D program, Mamajanov moved to a new postdoc, later research scientist, position at the Georgia Institute of Technology. Her interests shifted towards the prebiotic "water problem": condensation dehydration polymer, such as nucleic acid, peptide and polysaccharide, formation under thermodynamically unfavorable water solution conditions. Mamajanov conducted a number of experiments in attempt to synthesize nucleosides (Sheng *et al.*, 2009), polyesters (Mamajanov *et al.*, 2014) and polypeptides (Forsythe *et al.*, 2015) under low water activity conditions. The polypeptide formation is particularly noteworthy since it overcomes the thermodynamic hurdle by invoking an alternative to condensation transamidation mechanism. As an unconventional approach to the "water problem" Mamajanov investigated nucleic acid behavior in non-aqueous solvents. This work led to seminal publications describing DNA and RNA reversible folding and unusual structure dynamics in an anhydrous deep eutectic solvent comprised of choline chloride and urea (Mamajanov *et al.*, 2010; Lannan *et al.*, 2012).

In 2013 Mamajanov was awarded a prestigious Simons Foundation Collaboration on the Origin of Life fellowship. She then moved to Carnegie Institution for Science to conduct her research on the origin of enzymatic catalysis. The premise of her project based on the structural similarity of polymers with high degree of branching (hyperbranched or dendritic polymers) and globular proteins. Mamajanov had successfully synthesized hypebranched polyesters under prebiotically plausible conditions and demonstrated the propensity of these polymers to bind metal ions. She showed that addition of metal ions during the polymerization process influenced the sub-unit sequence, in effect creating a system with rudimentary smart material properties (Mamajanov *et al.*, 2015). Moreover, in a proof-of-principle experiment Mamajanov demonstrated that a heterogeneous mixture of short branched oligoesters was capable of catalyzing Kemp elimination reaction by providing low water activity microenvironments (Mamajanov *et al.*, in preparation).

In summary, Mamajanov's accomplishments include: 1) structure elucidation of HCN polymers; 2) determining constraints of prebiotically plausible nucleoside and polyester synthesis; 3) successful demonstration of peptide formation though transamidation mechanism; 4) demonstration of reversible DNA and RNA folding in non-aqueous solvent; 5) affirmation of biomimetic properties of hyperbranched polymers under prebiotically plausible conditions. At her new position at ELSI, Mamajanov intends to further investigate the catalytic properties of hyperbranched polymers, develop spectroscopic and chromatographic methods for heterogeneous polymer structure analysis, as well as study systems chemistry as it pertains to origin of life research.

Achievements

(1) International influence *a) Guest speaker, chair, director, or honorary member of a major international academic society in the subject field, b) Holder of a prestigious lectureship, c) Member of a scholarly academy in a major country, d) Recipient of an international award(s) , e) Editor of an influential journal etc.*

Invited speaker at Gordon, Abscicon and MOL conferences

(2) Receipt of large-scale competitive funding *(over past 5 years)*

Simons Foundation Collaboration on the Origin of Life Fellowship ($90,000/year, 3years)

(3) Article citations *(Titles of major publications, and number of citations.)*

Mamajanov, I; Cody, G.D. Protoenzymes: The Case of Hyperbranched Polyesters, *in preparation*

Mamajanov, I; Callahan, M. P.; Dworkin, J. P.; Cody, G. D. (2015) Prebtiotic Alternatives to Proteins: Structure and Function of Hypebranched Polyesters. *Origins Life Evol. Biosph.*, 45(1-2):123-37

Mamajanov, I; McDonald, P. J.; Duncanson, D. M.; Jingya, Y.; Walker, C. A.; Grover, M. A.; Hud, N .V.; Schork F. J. (2014) Ester Formation and Hydrolysis during Wet–Dry Cycles: Generation of Far-from-Equilibrium Polymers in a Model Prebiotic Reaction*. Macromolecules,* 47(4), 1334-43 **12 citations**

Mamajanov, I.; Engelhart A. E.; Bean, H. D.; Hud, N. V. (2010). DNA and RNA in Anhydrous Media: Duplex, Triplex, and G-Quadruplex Secondary Structures in a Deep Eutectic Solvent. *Ang. Chem. Int. Ed. 49* (36), 6310-4 **68 citations**

Forsythe, J. G.; Yu, S.-S.; Mamajanov, I.; Krishnamurthy, R.; Grover, M. A.; Fernández, F. M.; Hud, N .V. (2015) Ester-Mediated Amide Bond Formation and the Prebiotic Origin of Peptides, *Ang. Chem. Int. Ed.*, 127(34), 10009–10013 **4 citations**

Lannan, F. M.; Mamajanov, I.; Hud, N. V. (2012). Human Telomere Sequence DNA in Water-Free and High-Viscosity Solvents: G-quadruplex Folding Governed by Kramers Rate Theory. *J. Am. Chem. Soc., 134* (37), 15324–15330 **36 citations**

Chen, M. C.; Cafferty, B. J.; Mamajanov, I.; Gállego, I.; Khanam, J.; Krishnamurthy, R.; Hud, N. V. (2014) Spontaneous Prebiotic Formation of a β-Ribofuranoside That Self-Assembles with a Complementary Heterocycle. *J. Am. Chem. Soc.*, 136 (14), 5640-6 **21 citations**

Mamajanov, I. and Hud, N. V. (2011) DNA, In *Encyclopedia of Astrobiology (Gargaud, M., Cernicharo, J., Viso, M., Cleaves II, H. J., Pinti, D., Amils, R., and Kobayashi, K., Eds.), Springer, New York, NY*, 443-447.

Mamajanov, I. and Herzfeld, J. (2011) HCN polymer, In *Encyclopedia of Astrobiology (Gargaud, M., Cernicharo, J., Viso, M., Cleaves II, H. J., Pinti, D., Amils, R., and Kobayashi, K., Eds.), Springer, New York, NY*, 730-732

Herzfeld, J.; Rand, D.; Daviso, E.; Mak-Jurkauskas, M.; Mamajanov, I. (2011). Molecular Structure of Humin and Melaniodin via Solid State NMR. *J. Phys. Chem. B* 19, 5741-5 **8 citations**

Sheng, Y.; Bean, H. D.; Mamajanov, I.; Hud, N. V.; Leszczynski, J. (2009). Comprehensive investigation of the energetics of pyrimidine nucleoside formation in a model prebiotic reaction. *J. Am. Chem. Soc.* 131 (44), 16088-95 **17 citations**

Mamajanov, I., Herzfeld, J. (2009). HCN polymers characterized by solid state NMR: chains and sheets formed in the neat liquid. *J. Chem. Phys.*, *130* (13), 134503 **20 citations**

Mamajanov, I., Herzfeld, J. (2009). HCN polymers characterized by SSNMR: Solid state reaction of crystalline tetramer (diaminomaleonitrile). *J. Chem. Phys.*, *130* (13), 134504 **9 citations**

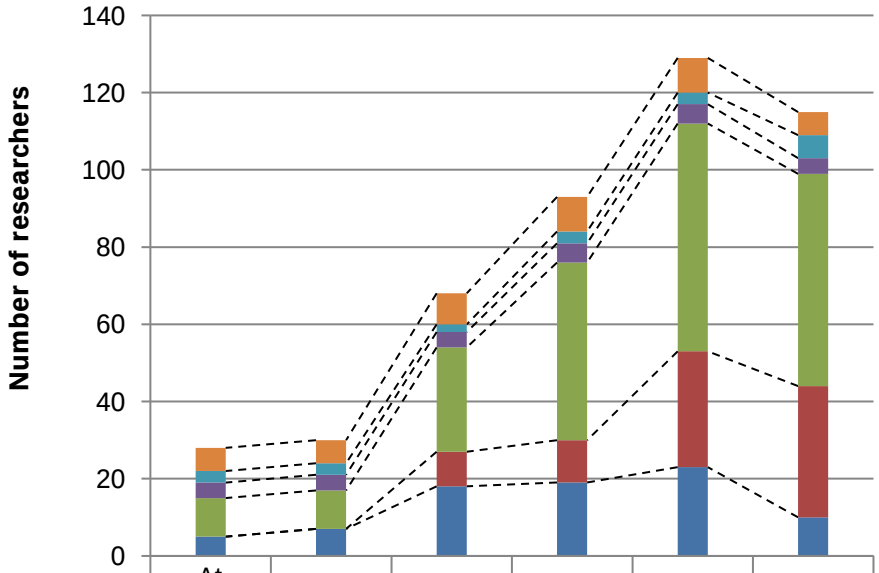
(4) Others *(Other achievements that indicate qualification as a top-caliber researcher, if any.)*

World Premier International Research Center Initiative (WPI)

Appendix 1-2. Number of researchers in the "core" established within the host institution

*Make a graph of the annual transition in the number of center personnel since the start of project.

Annual Transition in the Number of Members



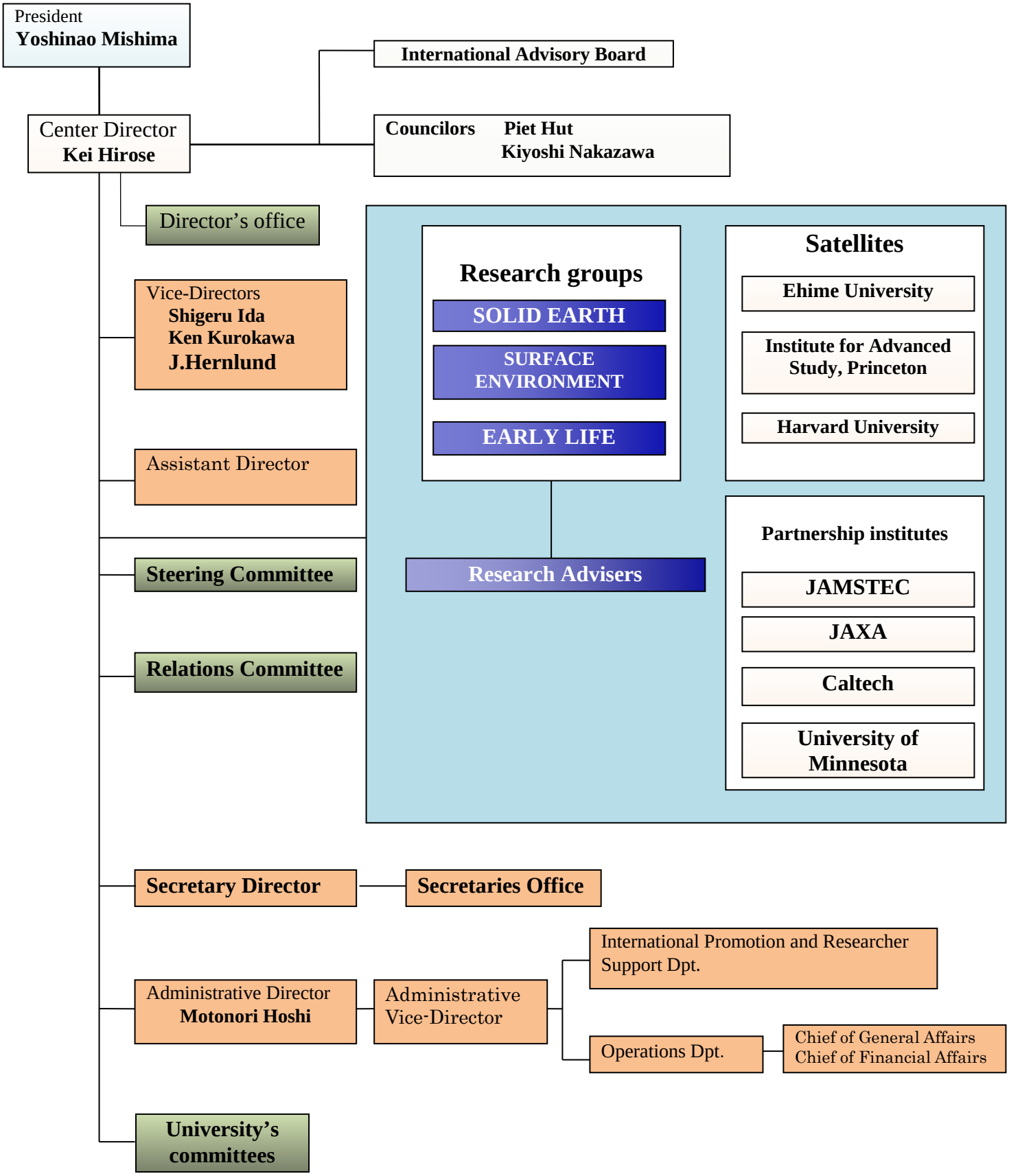
	At beginning	FY2012	FY2013	FY2014	FY2015	Final goal
PI : Researchers from within host institution	6	6	8	9	9	6
PI : Foreign researchers invited from abroad	3	3	2	3	3	6
PI : Researchers invited from other Japanese institutions	4	4	4	5	5	4
Other researchers	10	10	27	46	59	55
Research support staffs	0	0	9	11	30	34
Administrative staffs	5	7	18	19	23	10

- Enter matters warranting special mention, such as concrete plans for achieving the Center's goals, established schedules for employing main researchers, particularly principal investigators.

World Premier International Research Center Initiative (WPI)

Appendix 1-3. Center's Management System

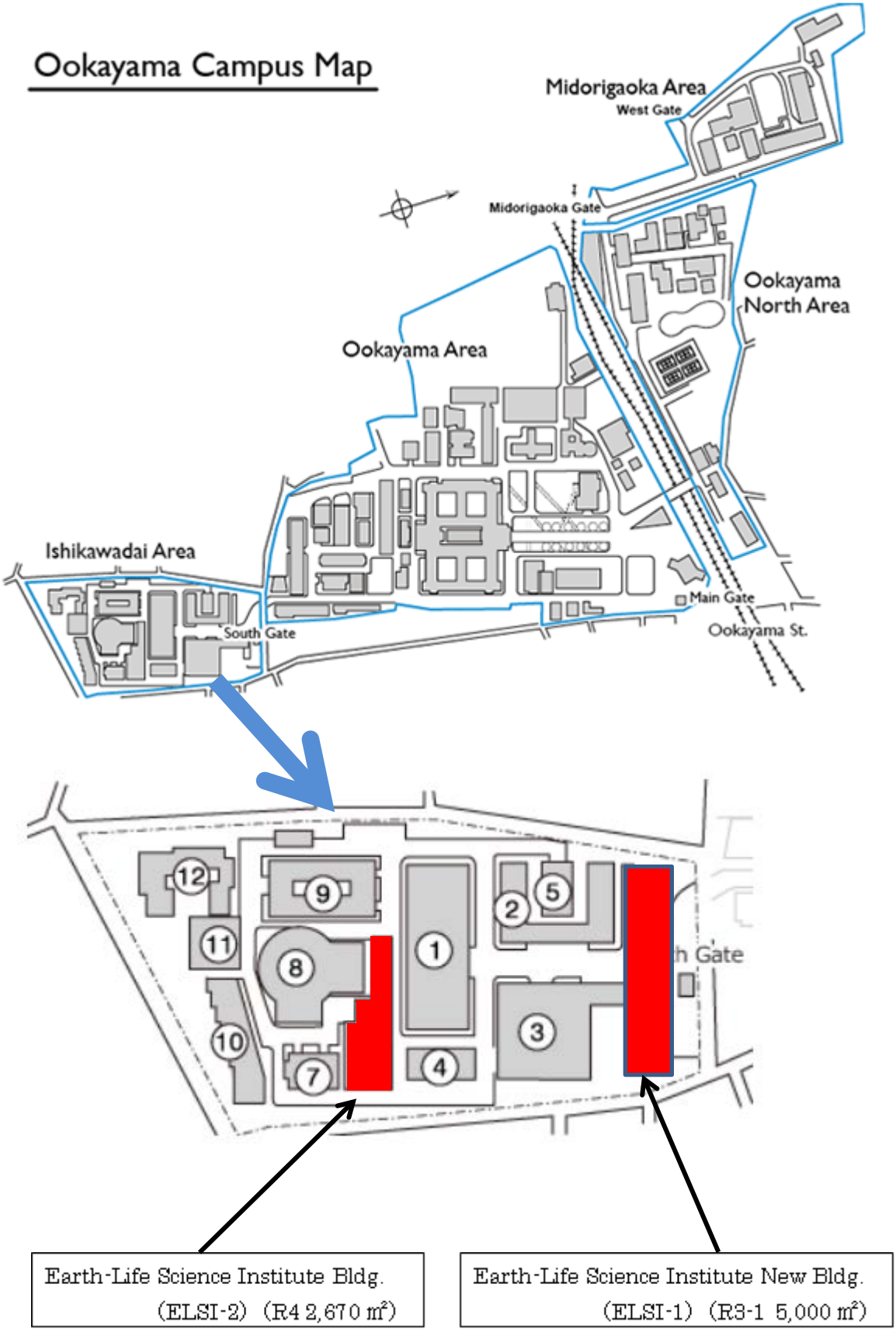
- Please diagram management system in an easily understood manner.



World Premier International Research Center Initiative (WPI)

Appendix 1-4. Campus Map

– Please draw a simple map of the campus showing where the main office and principle investigator(s) are located.

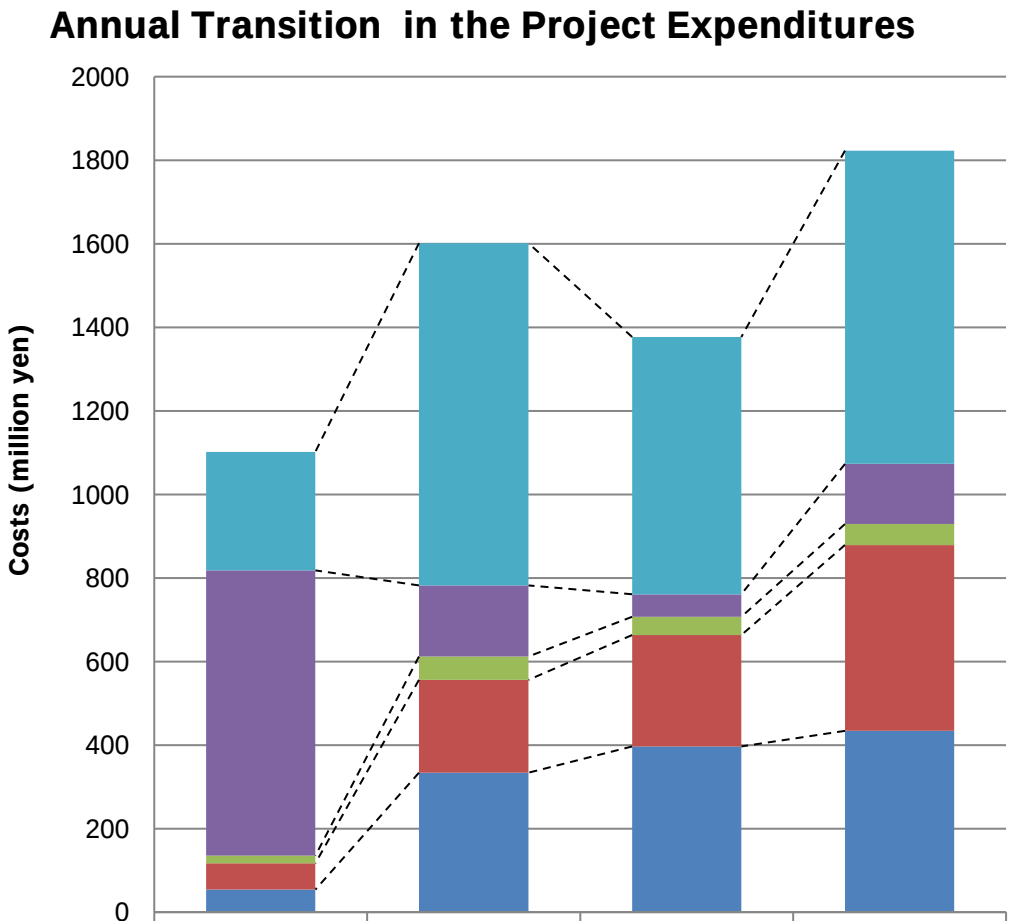


World Premier International Research Center Initiative (WPI)

Appendix 1-5-1. Annual transition in the project expenditures

*Make a graph of the transition in the number of overall project funding.

(Example)



	FY2012	FY2013	FY2014	FY2015
Researchprojects	284	819	616	750
Equipment	683	170	54	144
Travel	18	56	44	50
Projectactivities	63	222	266	445
Personnel	54	334	397	434

- To date, what has the Center's thinking been about spending project funding, and how has the funding been spent?

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

-Holding of an International Symposium and International Workshops

-Research Startup Funding (Including Promoting Interdisciplinary Research and Interactions)
-Overseas Dispatch Program for Researchers of the young people
-Outreach Activities for the WPI Program and ELSI
-Recruitment of Brilliant Researchers (Setting up booths at well-known international conferences and Carrying charge for a ELSI logo)

World Premier International Research Center Initiative (WPI)

Appendix 1-5-2. FY2015 Project Expenditures (the exchange rate used: 1USD= 110JPY)

i) Overall project funding

Cost Items	Details	Costs (million yen)
Personnel	Center director and Administrative director	23
	Principal investigators (no. of persons):10	87
	Other researchers (no. of persons):42	228
	Research support staffs (no. of persons):14	29
	Administrative staffs (no. of persons):16	64
	Total	431
Project activities	Gratuities and honoraria paid to invited principal investigators (no. of persons):5	1
	Cost of dispatching scientists (no. of persons):0	
	Research startup cost (no. of persons):32	29
	Cost of satellite organizations (no. of satellite organizations):1	50
	Cost of international symposiums (no. of symposiums):1	3
	Rental fees for facilities	156
	Cost of consumables	51
	Cost of utilities	0
	Other costs	156
	Total	446
Travel	Domestic travel costs	3
	Overseas travel costs	11
	Travel and accommodations cost for invited scientists (no. of domestic scientists):32 (no. of overseas scientists):104	34
	Travel cost for scientists on secondment (no. of domestic scientists):0 (no. of overseas scientists):3	2
	Total	50
Equipment	Depreciation of buildings	12
	Depreciation of equipment	226
	Total	238
Other research projects	Projects supported by other government subsidies, etc.	275
	Commissioned research projects, etc.	72
	Grants-in-Aid for Scientific Research, etc.	403
	Total	750
Total		1915

million yen

WPI grant			565
Costs of establishing and maintaining facilities			0
Establishing new facilities (Number of facilities: , m²)	Costs paid:		
Repairing facilities (Number of facilities: , m²)	Costs paid:		
Others			
Cost of equipment procured			30
Name of equipment: Fume hood Number of units: 5	Costs paid:		16
Name of equipment:ACQUITY APC System Number of units: 1	Costs paid:		10
Name of equipment:HPLC System Number of units: 1	Costs paid:		4
Name of equipment:High-speed network system Number of units: 1	Costs paid:		11
Name of equipment:Videoconferencing system Number of units: 1	Costs paid:		22
Others			63

ii) Costs of Satellites and Partner institutions

Cost Items	Details	Costs (million yen)
Personnel	Principal investigators (no. of persons):1	
	Other researchers (no. of persons):9	
	Research support staffs (no. of persons):0	
	Administrative staffs (no. of persons):1	
	Total	33
Project activities		9
Travel		4
Equipment		4
Other research projects		77
Total		127

World Premier International Research Center Initiative (WPI)

Appendix 2-1. List of papers underscoring each research achievement

- List papers underscoring each research achievement listed in the item 2-1 "Research results to date" (up to 40 papers) and provide a description of the significance of each (within 10 lines).
- For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is the same.
- If a paper has many authors, underline those affiliated with the Center.
- If a paper has many authors (say, more than 10), all of their names do not need to be listed.

Research results [1] Accretion scenarios and giant impacts

1. Sato T, Okuzumi S, Ida S. 2016. On the water delivery to terrestrial embryos by ice pebble accretion. Astronomy and Astrophysics, 589: A15.

Standard accretion disk models suggest that the snow line in the solar nebula migrated interior to the Earth's orbit in a late stage of nebula evolution, when icy pebbles could have been delivered to 1 AU from outer regions. This raises the question why the present Earth is so depleted of water. This study evaluates the amount of icy pebbles accreted by terrestrial embryos after the migration of the snow line using a simplified version of the coagulation equation. This study finds that the final mass and water content of terrestrial embryos strongly depends on the radial extent of the gas disk, the strength of disk turbulence, and the time at which the snow lines arrives at 1 AU. If the solar nebula extended to 300 AU, initially rocky embryos would have evolved into icy planets of 1–10 Earth masses unless the snow-line migration was slow. If the proto-Earth contained water of ~1 wt%, the formation of the proto-Earth was possible with weaker turbulence and with earlier (>0.5–2 Myr) snow-line migration.

2. Hosono N, Saitoh TR, Makino J, Genda H, Ida S. 2016. The giant impact simulations with density independent smoothed particle hydrodynamics. Icarus, 271: 131-157.

At present, the giant impact (GI) is the most widely accepted model for the origin of the Moon. Most of the numerical simulations of GI have been carried out with the smoothed particle hydrodynamics (SPH) method. Recently, however, it was pointed out that standard formulation of SPH (SSPH) has difficulties in the treatment of a contact discontinuity and a free surface. This difficulty comes from the assumption of differentiability of density in SSPH. The team previously developed an alternative formulation of SPH, density independent SPH (DISPH), which is based on differentiability of pressure instead of density to solve the problem of a contact discontinuity. This study reports the results of the GI simulations with DISPH and compare them with those obtained with SSPH. The disk properties, such as mass and angular momentum produced by DISPH is different from that of standard SPH. The findings suggest that careful considerations should be taken for results obtained from numerical simulations for giant impact.

3. Citron RI, Genda H, Ida S. 2015. Formation of Phobos and Deimos via a giant impact. Icarus, 252: 334-338.

Although the two moons of Mars, Phobos and Deimos, have long been thought to be captured asteroids, recent observations of their compositions and orbits suggest that they may have formed from debris generated by one or more giant impacts of bodies with ~ 0.01 x target mass. Recent studies have both analytically estimated debris produced by giant impacts on Mars and numerically examined the evolution of circum-Mars debris disks. This study reports a numerical study (Smoothed Particle Hydrodynamics simulation) of debris retention from giant impacts onto Mars, particularly in relation to a Borealis-scale giant impact capable of producing the Borealis basin. This study finds that a Borealis-scale impact is capable of producing a disk of mass ~ 5 x 10^{20} kg, sufficient debris to form at least one of the martian moons. These results can serve as inputs for future studies of martian debris disk evolution.

Research results [2] Volatile delivery and inventory

4. Hamano K, Abe Y, Genda H. 2013. Emergence of two types of terrestrial planet on solidification of magma ocean. Nature, 497: 607-610.

In the Solar System, Venus has a similar size and bulk composition to those of Earth, but it lacks water. Because a richer variety of exoplanets is expected to be discovered, prediction of their atmospheres and surface environments requires a general framework for planetary evolution. By radiative–convective equilibrium calculations and modeling, this study shows that terrestrial planets can be divided into two distinct types on the basis of their evolutionary history during solidification from the initially hot molten state. A type I planet, which is formed beyond a certain critical distance from the host star, solidifies within several million years. If the planet acquires water during formation, most of this water is retained and forms the earliest oceans. In contrast, on a type II planet, which is formed inside the critical distance, a magma ocean can be sustained for longer, even with a larger initial amount of water. Earth is categorized as type I, while Venus may be representative of type II planets.

5. Nomura R, Hirose K, Uesugi K, Ohishi Y, Tsuchiyama A, Miyake A, Ueno Y. 2014. Low Core-Mantle Boundary Temperature Inferred from the Solidus of Pyrolite. Science, 343: 522-525.

Through high-pressure experiments and three-dimensional x-ray microtomographic imaging, this study showed that the solidus temperature of a primitive (pyrolitic) mantle is as low as 3570 ± 200 kelvin at pressures expected near the boundary between the Earth's mantle and its outer core. The finding implies that the post-perovskite phase is present in wide areas of the lowermost mantle and that the melting temperature of the outer core is depressed largely by impurities such as hydrogen. This study suggests that some phases typically thought to lose stability in the lowermost mantle may be more widely distributed than expected.

6. Umemoto K, Hirose K. 2015. Liquid iron-hydrogen alloys at outer core conditions by first-principles calculations. Geophysical Research Letters, 42: 7513-7520.

The preliminary reference Earth model (PREM) deduced from seismic data predicts the presence of substantial amounts of light alloying elements in the Earth's liquid core, however, the identification of light elements in the core remains controversial. This study reports first-principles molecular dynamics calculations of liquid iron-hydrogen alloys under the Earth's outer core conditions. Approximately 1% hydrogen concentration in the outer core is found to reproduce seismological observations, including density and bulk sound velocity. This study suggests that hydrogen could be a primary light element in the core.

Research results [3] Magnetism and Earth evolution

7. Gomi H, Ohta K, Hirose K, Labrosse S, Caracas R, Verstraete MJ, Hernlund JW. 2013. The high conductivity of iron and thermal evolution of the Earth's core. Physics of the Earth and Planetary Interiors, 224: 88-103.

This study measured the electrical resistivity of iron and iron-silicon alloy to 100 GPa. The resistivity of iron was also calculated to core pressures. Combined with the first geophysical model accounting for saturation resistivity of core metal, the present results show that the thermal conductivity of the outermost core is greater than 90 W/m/K. These values are significantly higher than conventional estimates, implying rapid secular core cooling, an inner core younger than 1 Ga, and ubiquitous melting of the lowermost mantle during the early Earth. These findings suggest that the lowermost mantle must have been molten during the early Earth, which is consistent with the basal magma ocean model and numerous recent experimental determinations of Earth's mantle solidus.

8. Ohta K, Kuwayama Y, Hirose K, Shimizu K, Ohishi Y. 2016. Experimental determination of the electrical resistivity of iron at Earth's core conditions. Nature, in press.

The Earth continuously generates a dipole magnetic field in its convecting liquid outer core by a self-sustained dynamo action. Since metallic iron is a dominant component, its electrical and thermal conductivity controls the dynamics and thermal evolution of the Earth's core. However, such transport properties of iron under core conditions are still controversial. Since free electrons are a primary carrier of both electric current and heat, the electron scattering mechanism in iron under high pressure and temperature (P-T) holds the key to understanding the transport properties of planetary cores. This study measured the electrical resistivity under the conditions relevant to the Earth's core in a laser-heated

diamond-anvil cell (DAC). The observed low electrical resistivity of iron suggests rapid core cooling and a young inner core less than 0.7 Gyr old, undermining the conventional theory relating an abrupt increase in palaeomagnetic field intensity around 1.3 Gyr to the birth of the inner core.

9. Mitchell RN, Raub TD, Silva SC, Kirschvink JL. 2015. Was the Cambrian explosion both an effect and an artifact of true polar wander? American Journal of Science, 315: 945-957.

Recent, initially controversial hypothesis that repeated true polar wander (TPW) triggered the Ediacaran-Cambrian explosion of animal life has been supported by numerous paleomagnetic and geochronologic refinements. These data imply □75° of TPW between 535 and 515 million years ago, coinciding with the paleontologically observed rise in metazoan diversity and disparity. This study shows that this evolutionary trend is explained simply by the well known ecology-driven increase of diversity in low latitudes, coupled by other ecological effects as well as the enhanced deposition of sedimentary rocks during TPW-driven sea-level transgressions. Diversity changes by quadrential TPW offers a unifying explanation for why rates of Early Cambrian origination and extinction simultaneously increased and why origination prevailed.

Research results [4] Early atmosphere, and geochemistry of present-day proxy environments

10. Ueno Y, Aoyama S, Endo Y, Matsu'ura F, Foriel J. 2015. Rapid quadruple sulfur isotope analysis at the sub-micromole level by a flash heating with CoF_3. Chemical Geology, 419: 29-35.

Stable sulfur isotope ratio has been useful for tracing a wide range of biogeochemical processes. The conventional SF6 method enables high-precision analyses of all four of the stable sulfur isotopes (32S/33S/34S/36S), although the fluorination step is time consuming and requires the hazardous elemental fluorine (F2). This article reports development of a new flash fluorination method for sulfur isotope analysis. The new cobalt fluoride flash-fluorination technique provides a fast, convenient and safe procedure for high-precision analysis of quadruple sulfur isotopes at the sub-micromole level.

11. Endo Y, Danielache SO, Ueno Y, Hattori S, Johnson MS, Yoshida N, Kjaergaard HG. 2015. Photoabsorption cross-section measurements of ^{32}S, ^{33}S, ^{34}S, and ^{36}S sulfur dioxide from 190 to 220 nm. Journal of Geophysical Research-Atmospheres, 120: 2546-2557.

The ultraviolet absorption cross sections of the SO_2 isotopologues are essential to understanding the photochemical fractionation of sulfur isotopes in planetary atmospheres. This report improves previously measured spectra and extends them to $^{36}SO_2$. The obtained results suggest that UV photodissociation of SO_2 reproduces the isotopic imprint in the Archean sedimentary record.

12. Suda K, Ueno Y, Yoshizaki M, Nakamura H, Kurokawa K, Nishiyama E, Yoshino K, Hongoh Y, Kawachi K, Omori S, Yamada K, Yoshida N, Maruyama S. 2014. Origin of methane in serpentinite-hosted hydrothermal systems: The CH_4-H_2-H_2O hydrogen isotope systematics of the Hakuba Happo hot spring. Earth and Planetary Science Letters, 386: 112-125.

This study reports a systematic isotopic study of a new serpentinite-hosted system suggested that abiotic methane production directly from water without mediation by hydrogen gas may be more common, leading to a reconsideration of the origins of methane in serpentinite-hosted systems.

13. Shibuya T, Yoshizaki M, Sato M, Shimizu K, Nakamura K, Omori S, Suzuki K, Takai K, Tsunakawa H, Maruyama S. 2015. Hydrogen-rich hydrothermal environments in the Hadean ocean inferred from serpentinization of komatiites at 300 °C and 500 bar. Progress in Earth Planetary Science, 2: 46.

This work is at the center of studies at ELSI connecting early Earth and early Life. It seeks to constrain the geochemical environments in the ocean and sub-surface in the Hadean eon, which are primary candidates for the environments in which life first formed. The study of weathering of ancient lavas (komatiites) which have not been produced on Earth for billions of years is central to the question of planetary habitability: in which ways was the environment on early Earth similar to, or different from, the environment on modern Earth, that were essential to the emergence of a biosphere? The work falls under the roadmap areas of Early Ocean & Atmosphere, and Geological Supply of Prebiotic

Compounds, and emphasizes both Whole Planet Reaction Networks and Emergence of a Biosphere.

Research results [5] Prebiotic chemistry

14. Kitadai N. 2015. Energetics of Amino Acid Synthesis in Alkaline Hydrothermal Environments. Origins of Life and Evolution of Biospheres, 45: 377-409.

This study estimated the thermodynamic properties of amino acids at high temperatures and alkaline pH using experimental high-temperature volume and heat capacity data reported in the literature for several amino acids, together with correlation algorithms and the revised Helgeson–Kirkham–Flowers (HKF) equations of state. The results suggested that Hadean alkaline hydrothermal settings, where steep pH and temperature gradients may have existed between cool, slightly acidic Hadean ocean water and hot, alkaline hydrothermal fluids at the vent–ocean interface, may be energetically the most suitable environment for the synthesis and polymerization of amino acids.

15. Kitadai N. 2016. Predicting Thermodynamic Behaviors of Non-Protein Amino Acids as a Function of Temperature and pH. Origins of Life and Evolution of Biospheres, 46: 3-18.

Why does life use α-amino acids exclusively as building blocks of proteins? This study addresses this fundamental question from an energetic perspective, by estimating the standard molal thermodynamic data for three non-α-amino acids and α-amino acid in their zwitterionic, negative, and positive ionization states based on the corresponding experimental measurements reported in the literature. The results suggest that the energetic cost of synthesis is not an important selection pressure to incorporate α-amino acids into biological systems. This study has useful implications on discussion about why life exclusively uses α-amino acids.

16. Ilardo M, Meringer M, Freeland S, Rasulev B, Cleaves HJ, II. 2015. Extraordinarily Adaptive Properties of the Genetically Encoded Amino Acids. Scientific Reports, 5: 9414.

Diverse protein polymers consists of a set of just 20 genetically encoded amino acids, used nearly universally in life on Earth. While previous studies have found strong support for the idea that the 20 genetically encoded amino acids exhibit non-random, adaptive properties as a set, the strength of these findings is limited by the scope of alternative amino acids considered. Using novel advances in computational chemistry, this study compared the set of genetically encoded amino acids to a far larger and more comprehensive set of chemical possibilities than was previously available and demonstrated the former has been highly influenced by natural selection. This study also begins to explore for the first time some “better sets,” which, given their adaptive qualities, might be plausible candidates for alternative biochemistries.

17. Aono M, Kasai S, Kim SJ, Wakabayashi M, Miwa H, Naruse M. 2015. Amoeba-inspired nanoarchitectonic computing implemented using electrical Brownian ratchets. Nanotechnology, 26: 234001.

This study extracted the essential spatiotemporal dynamics that allow an amoeboid organism to solve a computationally demanding problem and adapt to its environment, thereby proposing a bio-inspired algorithm to search for solutions to various constraint satisfaction problems and their physical implementations to develop nanoarchitectonic computing systems.

18. Aono M, Wakabayashi M. 2015. Amoeba-Inspired Heuristic Search Dynamics for Exploring Chemical Reaction Paths. Origins of Life and Evolution of Biospheres, 45: 339-345.

When simulated for longer than a few microseconds, huge computational costs are required to undertake ab-initio approaches for the quantitative estimation of the chemical kinetics of unknown reactions. This study extended the bio-inspired algorithm for solving an NP-complete constraint satisfaction problem and introduced a heuristic approach for modeling a reaction as probabilistic dynamics to explore the optimal combinations of the bonding states of atoms, which allows us to estimate the unknown kinetics in a semi-quantitative manner that saves computational resources.

Research results [6] Conceptualizing messy chemistries

19. Virgo N, Ikegami T, McGregor S. 2016. Complex Autocatalysis in Simple Chemistries. Artificial Life, 2: 1-15.

Life on Earth must originally have arisen from abiotic chemistry. This study shows that even very simple chemistries in the thermodynamically reversible regime can self-organize to form complex autocatalytic cycles, with the catalytic effects emerging from the network structure using a very simple but thermodynamically reasonable artificial chemistry model. Modulation of the cycle can lead to nonlinear phenomena such as oscillations and bistability, the latter of which is of particular interest regarding the origins of life.

20. Virgo N, Guttenberg M. 2015. Heredity in Messy Chemistries. Proceedings of the European Conference on Artificial Life 2015, 325–332.

One of the outstanding questions in the origin of life is how natural selection emerges from chemistry. And for natural selection to progress, it requires a sufficiently large evolutionary space to explore. In systems with template-based replication, such as heredity, this space needs to be combinatorially large in the length of the information-carrying molecules. This opens the question of how the structure of a reaction network relates to the number of heritable states it can support, and in particular, how the number of heritable states scales with system size for a given network topology. This study shows that it is possible to detect the set of independent autocatalytic subnetworks that can operate in the vicinity of a fixed point. This study also shows that the number of cores scales at best as log N in the case of unstructured networks, but that adding a strong energy constraint on the network topology allows it to scale linearly, which is the best possible case.

Research results [7] Electrochemistry and the origin of life

21. Aono M, Kitadai N, Oono Y. 2015. A Principled Approach to the Origin Problem. Origins of Life and Evolution of Biospheres, 45: 327-338.

Claiming that the key issue of origins of life is the origin of a complex system rather than the abiotic formation of various building blocks of life, this paper suggests how to construct a non-enzymatic carbon-fixation network called "protometabolism" for the experimental investigations of the origin of the complex system.

Research results [8] Geochemistry-linked microbe ecology, and biology of present-day proxy environments

22. Yamazaki T, Hozuki T, Arai K, Toyoda S, Koba K, Fujiwara T, Yoshida N. 2014. Isotopomeric characterization of nitrous oxide produced by reaction of enzymes extracted from nitrifying and denitrifying bacteria. Biogeosciences, 11: 2679-2689.

Nitrous oxide (N_2O) is a potent greenhouse gas and produced in denitrification and nitrification by various microorganisms. Site preference (SP) of ^{15}N in N_2O has been reported to be a useful tool to quantitatively distinguish N_2O production pathways. By measuring SP of N_2O produced in different biological pathways, this study revealed that previous in vivo studies might have underestimated the SP value for the NH_2OH oxidation pathway possibly due to a small contribution of NO_2^- reduction pathway. Further evaluation of isotopomer signatures of N_2O using common enzymes of other processes related to N_2O would improve the isotopomer analysis of N_2O in various environments.

23. Matsubayashi H, Kuruma Y, Ueda T. 2014. In Vitro Synthesis of the E. coli Sec Translocon from DNA. Angewandte Chemie-International Edition, 53: 7535-7538.

An artificial living cell is a sustainable and reproducible cell-like entity composed of biological components, such as proteins, DNA, RNA, and phospholipids. The practical strategy for producing such an artificial cell is assembling biomolecules that imitate the architectures and functions of biosystems in living organisms. This study reports construction of the Sec translocon membrane channel in the

membrane of lipid vesicles through in vitro expression of its component proteins. The synthesized *E. coli* Sec translocon successfully mediated the membrane translocation of membrane proteins. These finding demonstrate the feasible construction of artificial cells, the membranes of which can be functionalized by directly decoding genetic information into membrane functions.

24. Kimura J, Kitadai N. 2015. Polymerization of Building Blocks of Life on Europa and Other Icy Moons. Astrobiology, 15: 430-441.

This study shows that polymerization of amino acids and nucleotides could proceed spontaneously in the cold environment of icy moons (e.g., Europa) based on thermodynamic calculations, providing good constraints on the origin and early evolution of extraterrestrial life.

25. Rein H, Fujii Y, Spiegel DS. 2014. Some inconvenient truths about biosignatures involving two chemical species on Earth-like exoplanets. Proceedings of the National Academy of Sciences of the United States of America, 111: 6871-6875.

The detection of strong thermochemical disequilibrium in the atmosphere of an extrasolar planet is thought to be a potential sign of life. This study describes a previously unidentified scenario for a possible false positive due to the presence of a moon orbiting the exoplanet that can mimic a disequilibrium or any other biosignature associated with this method. Given the most optimistic spectral resolution, discriminating between a single planet and a planet–moon system is in general unlikely to be possible. This study also discusses two possibilities that can provide genuine biosignatures.

Research results [9] Early molecular and microbial evolution, and synthetic biology

26. Nishizawa M, Miyazaki J, Makabe A, Koba K, Takai K. 2014. Physiological and isotopic characteristics of nitrogen fixation by hyperthermophilic methanogens: Key insights into nitrogen anabolism of the microbial communities in Archean hydrothermal systems. Geochimica Et Cosmochimica Acta, 138: 117-135.

This study reports, for the first time, the physiological properties and isotopic characteristics of nitrogen anabolisms, including nitrogen fixation, in hyperthermophilic and thermophilic methanogenic genera found in global hydrothermal environments (*Methanocaldococcus*and *Methanothermococcus* spp.). These methanogens, together with anaerobic archaeal methanotrophs, are known to encode for nitrogenase homologs that do not cluster phylogenetically with previously characterised nitrogenases with iron–molybdenum, iron–vanadium or iron–iron cofactors. Cultivation experiments were conducted under various conditions to potentially reproduce present and past oceanic and hydrothermal environments. The results include the novel finding that diazotrophic methanogens produce biomass that is more depleted in ^{15}N than diazotrophic photosynthetic prokaryotes. The relatively large isotopic fractionation effect of the methanogens and its evolutionary implications are also discussed.

27. Tsukatani Y, Masuda S. 2015. Elucidation of Genetic Backgrounds Necessary for Chlorophyll a Biosynthesis Toward Artificial Creation of Oxygenic Photosynthesis. Origins of Life and Evolution of Biospheres, 45: 367-369.

This work seeks to experimentally characterize the genomic context that was necessary for the emergence of modern phototrophic pigments. The evolution of new function is generally made possible only by the creation of new molecular contexts by the assembly of existing functions. This paper is parallel and complementary to the work by Kacar et al. (Reconstructing the phylogenetic history of RuBiSCO proteins. 2015. LPI Contributions, 7580) in emphasizing the systems biology of evolutionary innovation for photosynthetic systems. The work falls under the roadmap area of Co-Evolution of Earth-Life System, and emphasizes Major Earth-Life Transitions.

28. Rensen EI, Mochizuki T, Quemin E, Schouten S, Krupovic M, Prangishvili D. 2016. A virus of hyperthermophilic archaea with a unique architecture among DNA viruses. Proceedings of the National Academy of Sciences of the United States of America, 113: 2478-2483.

This work is central to understanding two aspects of early life and evolution: 1) it seeks to understand

the partial independence of genomic and cellular lineages that is expressed in the history of the virosphere, and 2) it seeks to characterize the limits of forms of assembly that simple nucleic-acid/protein structures can take. Information about thermal limits, and the structures that achieve them, in simple DNA and RNA systems may be relevant to dynamics in the RNA world before the emergence of modern protein translation. Several hypotheses about early life include key roles for viruses as an independent class of lineages from cells, perhaps instrumental in major transitions such as the origin of DNA. The work falls under the roadmap area of Co-Evolution of Earth-Life System, and emphasizes Major Earth-Life Transitions, Ancient Biosystems, and Nature of the Living State.

29. Amikura K, Sakai Y, Asami S, Kiga D. 2014. Multiple Amino Acid-Excluded Genetic Codes for Protein Engineering Using Multiple Sets of tRNA Variants. Acs Synthetic Biology, 3: 140-144.

This work is concerned particularly with simpler stages of the biological amino acid inventory and the genetic code, which could have preceded the modern inventory and code. More generally, it is an example of ELSI researchers using synthetic-biology approaches to re-discover evolutionary solutions to problems of biological function. In this way we hope to understand constraints on evolution that cannot be directly reconstructed by historical inference. Such a capability is particularly important for the origin of the genetic code, since this likely took place in a time before stable genomic lineages existed. The work falls under the roadmap area of Proto-Cell, and emphasizes the Transition to Complexity.

30. Kawahara-Kobayashi A, Hitotsuyanagi M, Amikura K, Kiga D. 2014. Experimental Evolution of a Green Fluorescent Protein Composed of 19 Unique Amino Acids without Tryptophan. Origins of Life and Evolution of Biospheres, 44: 75-86.

This study reports creation of active green fluorescent proteins (GFPs) composed of 19 amino acids without troptophan using directed evolution with repeated rounds of random mutagenesis and selection. The original mutant GFP protein was less active but gained activity by accumulating beneficial mutations through two rounds of experimental evolution. Recording the improvement in the activity of the 19-amino-acid protein without Trp using experimental evolution, where it is easy to observe the accumulation of beneficial mutations, would provide additional insights into the late stages of protein evolution.

31. Kuruma Y. 2015. Creation of Simple Biochemical Systems to Study Early Cellular Life. Origins of Life and Evolution of Biospheres, 45: 359-360.

This work reports the development of cell-free experimental systems to study the expression of translocation proteins. It is a second example (together with the work by Amikura et al. [29]) of systems biology approaches to recreate central biological functions in artificial systems. The work falls under the roadmap area of Proto-cell.

Research results [10] Origin of information in chemistry

32. Guttenberg N, Laneuville M, Ilardo M, Aubert-Kato N. 2015. Transferable Measurements of Heredity in Models of the Origins of Life. Plos One, 10: e0140663.

One of the milestones of a theory of the Origins of Life is the understanding of how to bridge the gap between abiotic conditions and the onset of evolution. Along with replication, the mechanics of Darwinian evolution require that the system be capable of heritable variation and also be subject to selective pressures. This study presents a principal component analysis (PCA)-based heredity metric which can be used to compute the amount of heritable variation enabled by a given dynamical system. This metric accurately detects the number of species or modules present in artificially prepared test systems and also accurately reproduces prior measurements of compositional heritability in a non-trivial model system.

33. Cleaves HJ, Meringer M, Goodwin J. 2015. 227 Views of RNA: Is RNA Unique in Its Chemical Isomer Space? Astrobiology, 15: 538-558.

The RNA world hypothesis is widely accepted, however, prebiotic synthesis of RNA is not well

understood despite active studies over the last 50 years. Bu using a computational approach, this study enumerated the structures of all the potential isomers of the ribosides and a set of analogues derived from them and evaluated the feasibility of polymerization as well as the physicochemical properties of the resulting structures. Several databases have been queried to determine whether any of the computed isomers had been synthesized previously, revealing that very few of the molecules that emerge from this structure set have been previously described. We concluded that ribonucleosides may have competed with a multitude of alternative structures whose potential proto-biochemical roles and abiotic syntheses remain to be explored.

34. Wang J, Bonnesen PV, Rangel E, Vallejo E, Sanchez-Castillo A, Cleaves II HJ, Baddorf AP, Sumpter BG, Pan M, Maksymovych P, Fuentes-Cabrera M. 2016. Supramolecular polymerization of a prebiotic nucleoside provides insights into the creation of sequence-controlled polymers. Scientific reports, 6: 18891-18891.

This report studies self-assembly of a nucleoside on Au(111) to ascertain whether polymerization on well-defined substrates constitutes a promising approach for making sequence-controlled polymers. Scanning tunneling microscopy and density functional theory were used to investigate the self-assembly on Au(111) of (*RS*)-N^9-(2,3-dihydroxypropyl)adenine (DHPA), a plausibly prebiotic nucleoside analog of adenosine. This study found that DHPA molecules self-assemble into a hydrogen-bonded polymer that grows almost exclusively along the herringbone reconstruction pattern, has a two component sequence that is repeated over hundreds of nanometers, and is erasable with electron-induced excitation. Polymerization occurs on a substrate in a dry environment and can be gauged with high-resolution imaging and accurate modeling techniques. These characteristics make nucleoside self-assembly on a substrate an attractive approach for designing sequence-controlled polymers.

35. Izgu EC, Fahrenbach AC, Zhang N, Li L, Zhang W, Larsen AT, Blain JC, Szostak JW. 2015. Uncovering the Thermodynamics of Monomer Binding for RNA Replication. Journal of the American Chemical Society, 137: 6373-6382.

The nonenzymatic replication of primordial RNA is thought to have been a critical step in the origin of life. However, despite decades of effort, the poor rate and fidelity of model template copying reactions have thus far prevented an experimental demonstration of nonenzymatic RNA replication. This study presents the results of the noncovalent binding of ribonucleotide monophosphates (rNMPs) to both RNA and DNA primer–template complexes using ^{1}H NMR spectroscopy supplemented by molecular dynamics structural calculations. This study provides insight into nonenzymatic template-directed RNA polymerization by allowing the binding event to be separated from the subsequent chemical steps of primer extension. The accurate measurements of the thermodynamic association constants for ribonucleotides obtained in this study will be useful for designing higher fidelity, more effective RNA replication systems.

36. Larsen AT, Fahrenbach AC, Sheng J, Pian J, Szostak JW. 2015. Thermodynamic insights into 2-thiouridine-enhanced RNA hybridization. Nucleic Acids Research, 43: 7675-7687.

Essential and diverse roles of RNA require many well-defined 3D structures. Nucleobase modifications diversifies nucleic acid structure and thermodynamics. This study focuses on 2-thiouridine (s2U), a modified nucleobase found in tRNAs and known to stabilize U:A base pairs and destabilize U:G wobble pairs and presents thermodynamic evaluations of formation of RNA duplexes containing internal s2U:A and s2U:U pairs and their native counterparts. This study also evaluates the effect of s2U on single strand conformation and on nucleoside conformation experimentally. These results provide insights into the effects that nucleobase modification has on RNA structure and thermodynamics and inform efforts toward improving both ribozyme-catalyzed and nonenzymatic RNA copying.

World Premier International Research Center Initiative (WPI)

Appendix 2-3. List of the cooperative research agreements in and outside Japan

1. Counterpart of an Agreement : Ehime University
   Name of an Agreement : Joint Research Agreement for Experimental and Theoretical Research Related to Deep Earth Chemical Composition and Evolutionary Process
   Dates of an Agreement : December 7, 2012
   Summary of an Agreement : It makes use of the world's largest, most diverse characteristic multi-anvil device group held by the Ehime University Geodynamics Research Center and pursues the origin and evolution of the solid Earth, materials circulation, thermal structure, etc., based on leading first-principle simulation calculations.

2. Counterpart of an Agreement : Japan Agency for Marine-Earth Science and Technology
   Name of an Agreement : Joint Research Agreement for Materials Science Research Related to the Early Earth, Biomolecules, and the Crust and Mantle
   Dates of an Agreement : April 1, 2014
   Summary of an Agreement : A clear understanding of early Earth biomolecules, the crust, mantle, constituent substances, and chemical characteristics is necessary and essential for determining the early environmental evolution of the solid Earth and of early life. This joint research aims to analyze the early crust, early oceans, and early life history.

3. Counterpart of an Agreement : Japan Aerospace Exploration Agency, Institute of Space and Astronautical Science
   Name of an Agreement : Compact for Promotion of Collaboration and Cooperation in "Basic Science for Planetary Life Exploration"
   Dates of an Agreement : August 26, 2015
   Summary of an Agreement : The goal is to explore for life beyond Earth and to return samples for analysis, through the expansion of basic and fundamental science, the setting of novel and original science exploration objectives based on the samples, and the identification and cultivation of young researchers to support exploration.

4. Counterpart of an Agreement : Keio University
   Name of an Agreement : Joint Research Agreement for Astrobiological Research Related to Synthesis and Evolution of Biorelated Macromolecules in Primordial Earth Environment
   Dates of an Agreement : February 18, 2016
   Summary of an Agreement : The study uses advanced chemical analytical devices, such as a liquid chromatography mass spectrometer (LCMS) and a capillary electrophoresis mass spectrometer (CE-MS) held at the Keio University Institute for Advanced Biosciences. This equipment will be used to obtain quantitative data evaluating the types of organic compounds and their changes over time. Samples will be obtained through simulations of deep sea hydrothermal reactions performed at ELSI. This will lead to the development of research into the molecular evolutionary processes that take place in a primordial ocean environment that fostered the origin of life on Earth.

World Premier International Research Center Initiative (WPI)

Appendix 2-4. Major Awards, Invited Lectures, Plenary Addresses (etc.)

1. Major Awards

- List main internationally-acclaimed awards received/unofficially announced in order from the most recent.
- For each, write the recipient's name, name of award, and year issued.
  In case of multiple recipients, underline those affiliated with the center.

1) Kei Hirose、Fellow of the American Geochemical Society、2014
2) Kei Hirose、Fellow of The European Association for Geochemistry、2014
3) Shigenori Maruyama、Fellow of the Japan Geoscience Union、2014
4) Joseph Kirschvink、Fellow of the Japan Geoscience Union、2014
5) Albert C. Fahrenbach、IUPAC-SOLVAY International Award for Young Chemists、2014
6) Tetsuo Irifune、A. E. Ringwood Medal、2014
7) Ryuichi Nomura、SPRUC 2014 Young Scientist Award、2014
8) Shigenori Maruyama、GSA Honorary Fellow、2014
9) Taku Tsuchiya、Japan Association of Mineralogical Sciences Award、2014
10) Joseph Kirschvink、George P. Woollard Award、2014
11) Ryuichi Nomura、Spring-8 Seeds Research Award、2014
12) Masayuki Nishi、The Japan Society of High Pressure Science and Technology Award、2014
13) Ryuichi Nomura、Inoue Research Award for Young Scientists、2014
14) Hiroki Ichikawa、Minister of Education, Culture, Sports, Science and Technology Prize, Science and Technology Award、2015
15) Joseph Kirschvink、Royal Institute of Navigation Fellow、2015
16) Joseph Kirschvink、Geological Society of America Fellow、2015
17) Tetsuo Irifune、The Medal with Purple Ribbon、2015
18) Tetsuo Irifune、R.W. Bunsen Medal (EGU)、2015
19) Yuka Fujii、Inoue Research Award for Young Scientists、2016
20) Daisuke Kiga、Japan Society for the Promotion of Science Prize、2016

2. Invited Lectures, Plenary Addresses (etc.) at International Conferences and International Research Meetings

- List up to 10 main presentations in order from most recent.
- For each, write the lecturer/presenter's name, presentation title, conference name and date(s)

1) Masashi Aono "Oligopeptide formation in geysers"、 [Invited talk] Gordon Research Conference on Origins of Life, Galveston, Texas, Jan. 19, 2016.
2) Daisuke Kiga "Simplification of the genetic code: Restricted diversity of genetically encoded amino acids"、[Invited talk] Chemical approaches to astrobiology, Pacifichem 2015, Honolulu, HI, USA, Dec 20, 2015
3) Kirschvink, J.L. & Kobayashi, A., "Biophysical Puzzles Concerning Magnetite-Based Magnetoreception in the Common Nematode, *Caenorhabditis elegans*"、[Invited talk] AGU Fall Meeting, San Francisco, Dec. 2015l
   https://agu.confex.com/agu/fm15/meetingapp.cgi/Paper/59724
4) David Eric Smith "Phase transitions in the origin of the biosphere"、 [Keynote talk] Workshop "Reconceptualizing the Origin of Life", Carnegie Institution of Washington, November 15, 2015
5) Ken Kurokawa "Small Bugs, Big Data": Developing an integrated database for microbes with semantic web technologies" [Invited talk] ICSTI 2014 General Assembly & Annual Conference in Tokyo, Oct 20 2014
6) Tetsuo Irifune "Multi-anvil high-pressure technology and mineralogy of the deep mantle" [keynote, invited] Australian Earth Sciences Convention 2014, Canberra, July 2014
7) Kei Hirose "The discovery of post-perovskite and its unique physical property" [keynote talk] A meeting for the 10th anniversary of the discovery of post-perovskite, Bristol, UK, June 2014

8) Shigeru Ida “Planetary Dynamics: Semi-Analytical Approach” [Invited talk] Secind ISSI Meeting, Bern Switzerland, June 2014
9) Yuichiro Ueno Ueno Y. “Archean geology” [Invited talk] Gordon Research Conference, Galveston, USA , January, 2014
10) Masaki Fujimoto “BepiColombo MMO” [Invited talk] AOGS Meeting, Brisbane, Australia, June 24-28, 2013

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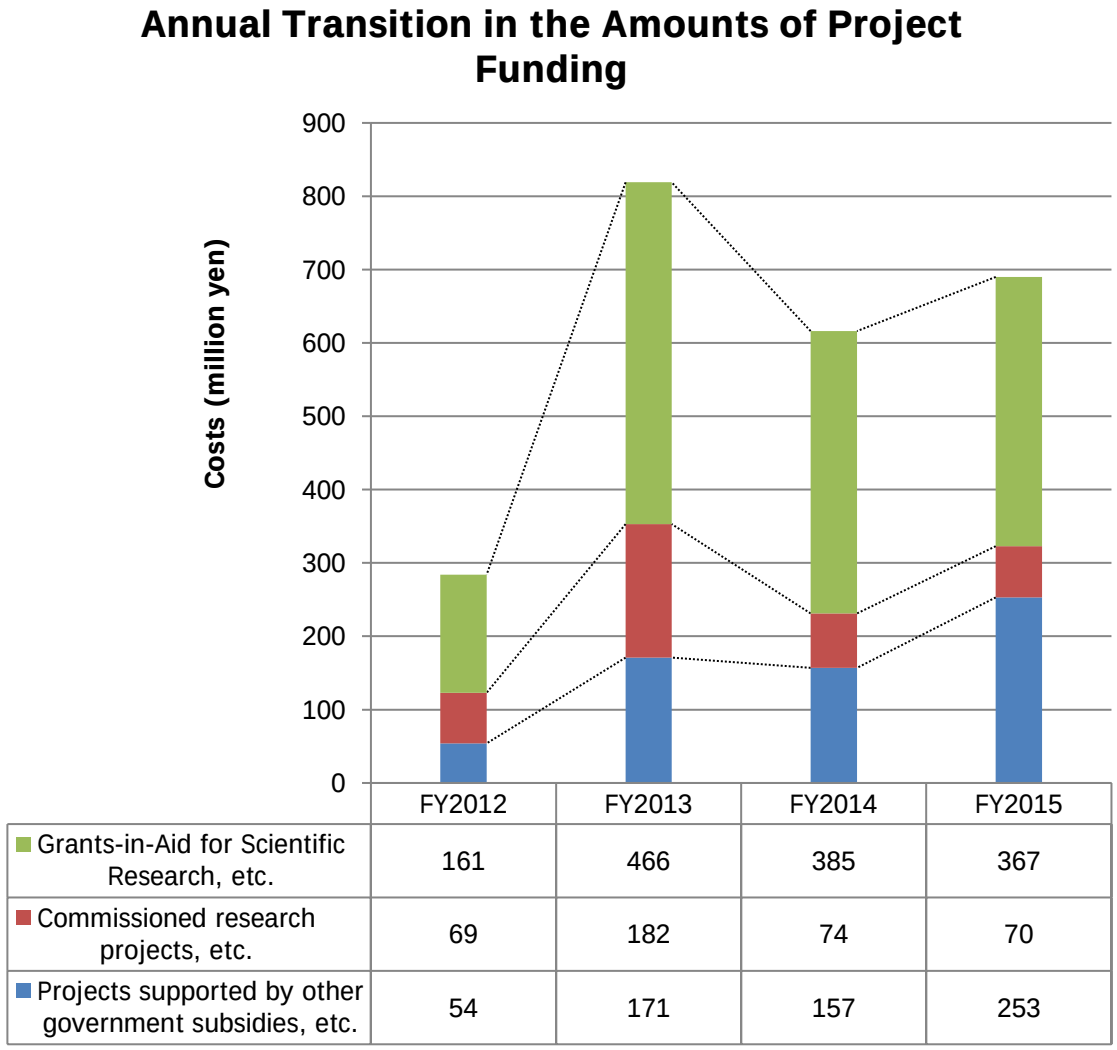
Appendix 2-6. Amounts of Non-WPI project funding (grants)

*Make a graph of the annual transition in non-WPI project funding (grants).

（Example）



	FY2012	FY2013	FY2014	FY2015
Grants-in-Aid for Scientific Research, etc.	161	466	385	367
Commissioned research projects, etc.	69	182	74	70
Projects supported by other government subsidies, etc.	54	171	157	253

- Describe external funding warranting special mention. Include the name and total amount of each grant.

FY2012
・
・
・
FY2013
KAKENHI　Grant-in-Aid for Specially　Promoted Research　165,000,000YEN
・
・
FY2014
KAKENHI　Grant-in-Aid for Scientific　Research on Innovative Areas　68,200,000YEN
・
・
FY2015
Global fund from John Templeton Foundation　88,104,017YEN
・

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Appendix 2-8. FY 2015 List of Project's Media Coverage

- Select main items of coverage, and list them within these 2 pages.

No.	Date	Type media (e.g., newspaper, television)	Description
1	2015/4/13	NHK General (TV)	Close-up Gendai "Found at Last!? Scientists Grapple with Life Beyond Earth"
2	2015/4/14	NHK Radio 1 (Radio)	Looking Ahead! Evening News "Searching for Heavenly Bodies Most Likely To Harbor Life"
3	2015/5/19	Iwanami Shoten (Books)	Fresh New Earths—Conditions for the Birth of Life
4	2015/5/19	Bisho-sha (Books)	Listening to Japan's Top-Level Researchers
5	2015/7/16	GrassRoots Community Network (TV)	Aspen Science Highlights - "New Theories on the Origin of Life" with Eric Smith, Ph.D.
6	2015/7/31	University of Tokyo Press (Books)	Theory of Life in the Universe　Life in the Universe
7	2015/8/8	Mainichi News Yahoo! News LabOnline etc (Newspaper, WEB News)	Tokyo Institute of Technology: American Foundation Makes 670 Million Yen Donation Tokyo Institute of Technology Earth-Life Science Institute obtains about 670 million yen in research funding from American charitable foundation! A new search for the origin of life
8	2015/8/17	Nature Japan	＜Scientific Reports＞ Decision-Making Based on a Single Photon
9	2015/9/25	Shinchosha (Books)	A Resume for the Earth
10	2015/10/1	NHK BS Premium (TV)	Cosmic Front☆NEXT "Mystery of Earth's Birth"
11	2015/10/5	BBC、Huffington Post Science News etc (TV, Newspaper, WEB News)	The tsunami that engulfed an island Ancient Tsunami Was Nearly As Tall As The Eiffel Tower, Scientists Say Ancient tsunami heaved 700-ton boulders over island cliffs

12	2015/10/28	Nikkei Biotech ONLINE (WEB News)	Tokyo Institute of Technology, Clues to Reproducing the Atmospheric Environment of the Early Earth—UV Absorption Spectrum in Sulfur Dioxide Determined by All Isotopes
13	2015/10/29	Shinano Mainichi News Ohito Times (Newspaper)	Tokyo Institute of Technology, Prof. Kurokawa's Lecture at Hakuba High School, "Searching for the Roots of Life in Hakuba Serpentinite." Happo is a valuable research site
14	2015/11/18	Phys.org Nikkei Biotech ONLINE (WEB News)	Researchers provide a unified explanation of changes in volume of ice Tokyo Institute of Technology, Understanding the Essence of the Ice Volume Isotope Effect—Successful Construction of a Unified Theory and Experimental Demonstration
15	2015/11/24	EurekAlert! (WEB News)	Liquid acoustics half way to the Earth's core
16	2015/12/7	W. W. Norton & Company (Books)	A Brief History of Creation: Science and the Search for the Origin of Life
17	2016/1/4	Scientific American (Magazine)	The Search for the Origin of Life
18	2016/1/14	Nikkei Sangyo Shimbun (Newspaper)	Origin of Life, Applying a Clear Understanding
19	2016/1/14	Kawade Shobo Shinsha (Books)	Why Living Things Were Born: Latest Science on the Origin and Evolution of Life
20	2016/1/16	Bungeishunju Ltd. (Magazine)	Bungeishunju February Issue <New Leader Conditions> 125 Outstanding Persons Enlivening Japan
21	2016/2/5	Nature Digest (Magazine)	＜News in Japan＞ Birth of New Site for Searching Space for Key to the Origins of Life!
22	2016/2/5	Monthly AstroArts (Magazine)	Challenging Primordial Questions about Humanity
23	2016/2/12	ITmedia (WEB News)	＜New Trends in Space Business＞ Do you know the Japanese who are researching "Life Beyond Earth" and "Mars Migration?"
24	2016/2/14	E Tele (TV)	Science ZERO "Birth of a Planet! Giant Impact"

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Appendix 3. List of papers of representative of interdisciplinary research activities

- List up to 10 papers that underscoring each interdisciplinary research activity and give brief accounts (within 10 lines).
- For each, write the author name(s); year of publication; journal name, volume, page(s), and article title. Any listing order may be used as long as format is the same.
  If a paper has many authors, underline those affiliated with the Center.
- If a paper has many authors (say, more than 10), all of their names do not need to be listed.

1. Tian F, Ida S. 2015. Water contents of Earth-mass planets around M dwarfs. Nature Geoscience, 8: 177-180.

Efforts to identify habitable extrasolar planets have focused on systems around M dwarfs, faint stars with less than half the solar mass. Habitable planets around M dwarfs are thought to be more plentiful and easier to detect than those orbiting Sun-like G dwarfs. However, unlike G dwarfs, M dwarfs experience a prolonged decline in luminosity early in their history, leading to an inward migration of the habitable zone and subsequent water loss. This study combines a numerical planet population synthesis model with a model for water loss and shows that the evolution of stellar luminosity leads to two types of planets of Earth-like mass in the habitable zones around M dwarfs: ocean planets without continents, and desert planets, on which there are orders of magnitude less surface water than on Earth. The simulations suggest that stars close to the size of the Sun (G-dwarfs) should be the primary targets for detecting Earth-like planets.

2. Nakajima Y, Imada S, Hirose K, Komabayashi T, Ozawa H, Tateno S, Tsutsui S, Kuwayama Y, Baron AQR. 2015. Carbon-depleted outer core revealed by sound velocity measurements of liquid iron-carbon alloy. Nature Communications, 6: 8942.

The relative abundance of light elements in the Earth's core has long been controversial. Recently, the presence of carbon in the core has been emphasized, because the density and sound velocities of the inner core may be consistent with solid Fe_7C_3. This study reports the longitudinal wave velocity of liquid $Fe_{84}C_{16}$ up to 70 GPa based on inelastic X-ray scattering measurements. The velocity was found substantially slower than that of solid iron and Fe_3C and faster than that of liquid iron. The thermodynamic equation of state for liquid $Fe_{84}C_{16}$ was also obtained from the velocity data combined with previous density measurements at 1 bar. The longitudinal velocity of the outer core, about 4% faster than that of liquid iron, is consistent with the presence of 4–5 at.% carbon. However, that amount of carbon is too small to account for the outer core density deficit, suggesting that carbon cannot be a predominant light element in the core.

3. Nishizawa M, Miyazaki J, Makabe A, Koba K, Takai K. 2014. Physiological and isotopic characteristics of nitrogen fixation by hyperthermophilic methanogens: Key insights into nitrogen anabolism of the microbial communities in Archean hydrothermal systems. Geochimica Et Cosmochimica Acta, 138: 117-135.

This study reports, for the first time, the physiological properties and isotopic characteristics of nitrogen anabolisms, including nitrogen fixation, in hyperthermophilic and thermophilic methanogenic genera found in global hydrothermal environments (*Methanocaldococcus* and *Methanothermococcus* strains). These methanogens, together with anaerobic archaeal methanotrophs, are known to encode for nitrogenase homologs that do not cluster phylogenetically with previously characterised nitrogenases with iron–molybdenum, iron–vanadium or iron–iron cofactors. Cultivation experiments were conducted under various conditions to potentially reproduce present and past oceanic and hydrothermal environments. The results include the novel finding that diazotrophic methanogens produce biomass that is more depleted in ^{15}N than diazotrophic photosynthetic prokaryotes. The relatively large isotopic fractionation effect of the methanogens and its evolutionary implications are also discussed.

4. Aono M, Kitadai N, Oono Y. 2015. A Principled Approach to the Origin Problem. Origins of Life and Evolution of Biospheres, 45: 327-338.

Claiming that the key issue of origins of life is the origin of a complex system rather than the abiotic formation of various building blocks of life, this paper suggests how to construct a non-enzymatic

carbon-fixation network called "protometabolism" for the experimental investigations of the origin of the complex system.

5. Suda K, Ueno Y, Yoshizaki M, Nakamura H, Kurokawa K, Nishiyama E, Yoshino K, Hongoh Y, Yoshida N, Maruyama S, et al. 2014. Origin of methane in serpentinite-hosted hydrothermal systems: The CH4-H-2-H2O hydrogen isotope systematics of the Hakuba Happo hot spring. Earth and Planetary Science Letters, 386: 112-125.

This study reports a systematic isotopic study of a new serpentinite-hosted system suggested that abiotic methane production directly from water without mediation by hydrogen gas may be more common, leading to a reconsideration of the origins of methane in serpentinite-hosted systems.

6. Tahata M, Sawaki Y, Ueno Y, Nishizawa M, Yoshida N, Ebisuzaki T, Komiya T, Maruyama S. 2015. Three-step modernization of the ocean: Modeling of carbon cycles and the revolution of ecological systems in the Ediacaran/Cambrian periods. Geoscience Frontiers, 6: 121-136.

Important ecological changes of the Earth (oxidization of the atmosphere and the ocean) increase in nutrient supply due to the break-up of the super continent (Rodinia) and the appearance of multi-cellular organisms (macroscopic algae and metazoan) took place in the Ediacaran period, priming the Cambrian explosion. This study constructed a numerical model (BFM), which reproduces the carbon records in the Ediacaran–early Cambrian period. BFM reveals that the Shuram excursion is related to three major changes in the carbon cycle or the global ecological system of the Earth: (1) increase in the coefficient of remineralization, corresponding to a change in the dominant metabolism from anaerobic to aerobic respiration, (2) increase of carbon fractionation index, corresponding to the change in the primary producer from cyanobacteria to macro algae, and (3) increase in the coefficient of the organic carbon burial, corresponding to the onset of a biological pump driven by the metazoan and zooplankton.

7. Kimura J, Kitadai N. 2015. Polymerization of Building Blocks of Life on Europa and Other Icy Moons. Astrobiology, 15: 430-441.

This study shows that polymerization of amino acids and nucleotides could proceed spontaneously in the cold environment of icy moons (e.g., Europa) based on thermodynamic calculations, providing good constraints on the origin and early evolution of extraterrestrial life.

8. Mitchell RN, Raub TD, Silva SC, Kirschvink JL. 2015. Was the Cambrian explosion both an effect and an artifact of true polar wander? American Journal of Science, 315: 945-957.

Recent, initially controversial hypothesis that repeated true polar wander (TPW) triggered the Ediacaran-Cambrian explosion of animal life has been supported by numerous paleomagnetic and geochronologic refinements. These data imply □ 75° of TPW between 535 and 515 million years ago, coinciding with the paleontologically observed rise in metazoan diversity and disparity. This study shows that this evolutionary trend is explained simply by the well known ecology-driven increase of diversity in low latitudes, coupled by other ecological effects as well as the enhanced deposition of sedimentary rocks during TPW-driven sea-level transgressions. Diversity changes by quadrential TPW offers a unifying explanation for why rates of Early Cambrian origination and extinction simultaneously increased and why origination prevailed.

9. Wang J, Bonnesen PV, Rangel E, Vallejo E, Sanchez-Castillo A, James Cleaves II H, Baddorf AP, Sumpter BG, Pan M, Maksymovych P, Fuentes-Cabrera M. 2016. Supramolecular polymerization of a prebiotic nucleoside provides insights into the creation of sequence-controlled polymers. Scientific reports, 6: 18891.

This report studies self-assembly of a nucleoside on Au(111) to ascertain whether polymerization on well-defined substrates constitutes a promising approach for making sequence-controlled polymers. Scanning tunneling microscopy and density functional theory were used to investigate the self-assembly on Au(111) of (*RS*)-N^9-(2,3-dihydroxypropyl)adenine (DHPA), a plausibly prebiotic nucleoside analog of adenosine. This study found that DHPA molecules self-assemble into a hydrogen-bonded polymer that grows almost exclusively along the herringbone reconstruction pattern, has a two component sequence

that is repeated over hundreds of nanometers, and is erasable with electron-induced excitation. Polymerization occurs on a substrate in a dry environment and can be gauged with high-resolution imaging and accurate modeling techniques. These characteristics make nucleoside self-assembly on a substrate an attractive approach for designing sequence-controlled polymers.

10. Endo Y, Danielache SO, Ueno Y, Hattori S, Johnson MS, Yoshida N, Kjaergaard HG. 2015. Photoabsorption cross-section measurements of ^{32}S, ^{33}S, ^{34}S, and ^{36}S sulfur dioxide from 190 to 220 nm. Journal of Geophysical Research-Atmospheres, 120: 2546-2557.

The ultraviolet absorption cross sections of the SO_2 isotopologues are essential to understanding the photochemical fractionation of sulfur isotopes in planetary atmospheres. This report improves previously measured spectra and extends them to $^{36}SO_2$. The obtained results suggest that UV photodissociation of SO_2 reproduces the isotopic imprint in the Archean sedimentary record.

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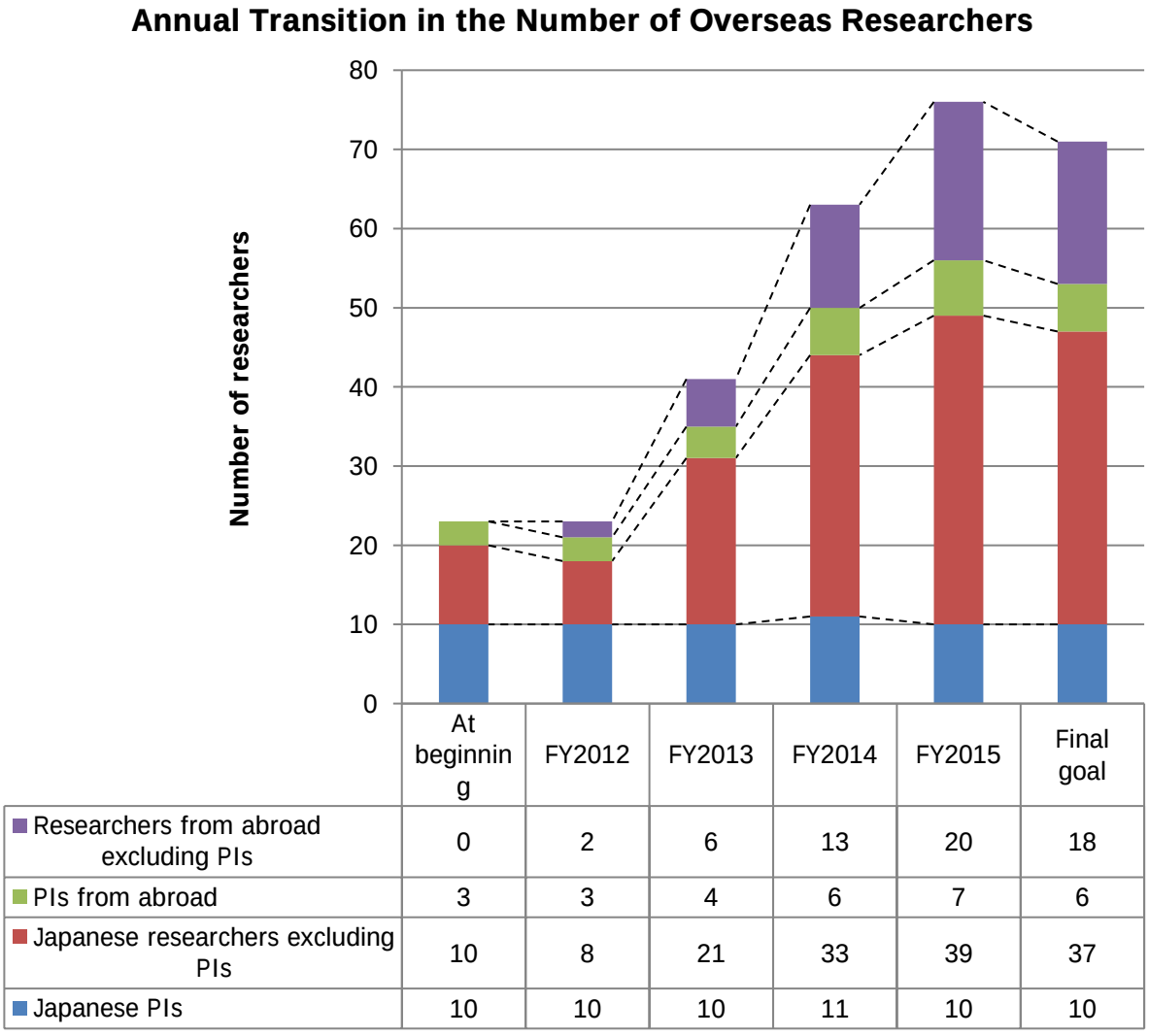
Appendix 4-2. Number of overseas researchers and annual transition

*Make a graph of the transition in the number of overseas researchers since the application.



	At beginning	FY2012	FY2013	FY2014	FY2015	Final goal
Researchers from abroad excluding PIs	0	2	6	13	20	18
PIs from abroad	3	3	4	6	7	6
Japanese researchers excluding PIs	10	8	21	33	39	37
Japanese PIs	10	10	10	11	10	10

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Appendix 4-3. Postdoctoral positions through open international solicitations

- In the “number of applications” and “number of selection” columns, put the number and percentage of overseas researchers in the < > brackets.

FY	Number of Applications	Number of Selection
FY2012	N/A < , %>	N/A < , %>
FY2013	134 < 125, 93%>	10 < 8, 80%>
FY2014	N/A < , %>	N/A < , %>
FY2015	72 < 52, 72%>	8 < 6, 75%>

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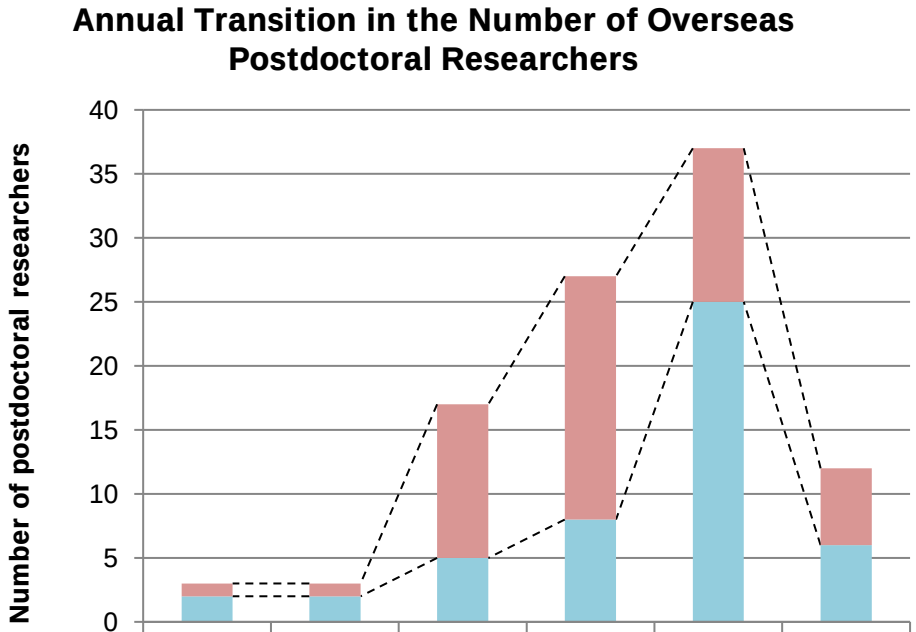
Appendix 4-4. Number of overseas postdoctoral researchers

* Make a graph of the transition in the number of overseas postdoctoral researchers since the project application was submitted.



	At beginning	FY2012	FY2013	FY2014	FY2015	Final goal
Japanese postdoctoral researchers	1	1	12	19	12	6
Overseas postdoctoral researchers	2	2	5	8	25	6

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Appendix 4-5. Status of postdoctoral researchers' employment at institutions

- List each researcher in 1 line. If the list exceeds this form, please add extra pages.

Period of project participation	Previous Affiliation (organization, *country)	Next Affiliation (Position title, organization, *country)	Nationality
2013.3.8-2014.3.31	University of Arizona, U.S.A	Associate Professor, University of Tokyo, Japan	U.S.A
2013.4.1-2015.10.31	University of Tokyo(Graduate Student), Japan	NASA Postdoctoral Program Fellow, NASA GISS, U.S.A	Japan
2013.4.1-2016.3.31	RIKEN, Japan	Research Scientist, Tokyo Tech, Japan	Japan
2013.4.1-2016.3.31	Tokyo Tech, Japan	Research Scientist, National Institute of Genetics, Japan	Japan
2013.4.1-2016.3.31	Tokyo Tech, Japan	Research Scientist, Kyushu University, Japan	Japan
2013.4.1-2015.8.31	JAMSTEC, Japan	Research Scientist, Okayama University, Japan	Japan
2014.4.1-2016.3.31	Tokyo Tech(Graduate Student), Japan	Research Scientist, Ehime University, Japan	Japan
2014.4.1-2015.9.30	Hiroshima University, Japan	Technical Research Scientist, JAMSTEC, Japan	Japan
2014.4.1-2015.7.31	Tokyo Tech(Graduate Student), Japan	Assistant Professor, University of Tokyo, Japan	Japan
2014.6.1-2015.3.31	Tokyo Tech, Japan	Research Scientist, Tokyo Tech, Japan	Japan
2014.9.1-2015.7.31	University of Hawaii, U.S.A	Senior Scientist, ETH, Switzerland	Germany
2014.4.1-2016.3.31	Tokyo Tech, Japan	Research Scientist, Advanced Industrial Science and Technology, Japan	Japan
2014.4.1-2014.8.31	Tokyo Tech, Japan	Research Scientist, RIKEN, Japan	Japan
2014.4.1-2014.8.31	Tokyo Tech(Graduate Student), Japan	Postdoctoral fellow, Carnegie Institution for Science, U.S.A	Japan
2015.4.1-2016.3.31	Hiroshima University(Graduate Student), Japan	JSPS Research Fellow, Kyushu University, Japan	Japan
2015.4.1-2015.6.30	Nagoya University(Graduate Student), Japan	Postdoctoral fellow, Niels Bohr Institute - University of Copenhagen, Denmark	Japan
2015.4.1-2015.9.30	Tokyo Tech(Graduate Student), Japan	Research Scientist, Japan Synchrotron Radiation Research Institute, Japan	Japan

* The country in which the organization is physically located.

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Appendix 4-6. Holding International Research Meetings

For each fiscal year, indicate the number of international research conferences or symposiums held and give up to two examples of the most representative ones using the table below.

FY 2012-2013: 7 meetings

Major examples (meeting title and place held)	Number of participants
Workshop on Transport Properties in the Earth's Core Kawaguchi-ko Lake, Yamanashi Prefecture, Japan	From domestic institutions: 11 From overseas institutions: 18
The International Astrobiology Workshop 2013 ISAS/ JAXA Sagamihara Campus, Sagamihara, Kanagawa Prefecture, Japan	From domestic institutions: 134 From overseas institutions: 23

FY 2014: 9 meetings

Major examples (meeting title and place held)	Number of participants
Modeling Origins of Life Workshop at IAS Institute for Advanced Study, Princeton, NJ, USA	From domestic institutions: 10 From overseas institutions: 4
RNA, Peptides, Vesicles and Exoplanets -The Chemical Origins of Life on Early Earth and Other Planetary Bodies Harvard University, Cambridge, MA, USA	From domestic institutions: 15 From overseas institutions: 10

FY 2015: 9 meetings

Major examples (meeting title and place held)	Number of participants
What Can Synthetic Biology offer to Artificial intelligence? - ECAL2015 satellite workshop “SB-AI” York Centre for Complex Systems Analysis at The University of York, York, UK	From domestic institutions: 1 From overseas institutions: 19
Geophysical & Geochemical Constraints on Early Planetary Dynamos Kawaguchi-ko Lake, Yamanashi Prefecture, Japan	From domestic institutions: 11 From overseas institutions: 10

World Premier International Research Center Initiative (WPI)

Appendix 5-1. Host institution's commitment

1. In-kind contributions from host institution

(personnel, laboratory space, etc.)

(1) Introduction of Flexible Teaching Staff System

After adoption of the WPI, the Tokyo Institute of Technology instituted the "Agreement Related to Flexible Teaching Staff at the Tokyo Institute of Technology Earth-Life Science Institute," installing a permanent teaching staff of five persons at ELSI as a flexible teaching staff and exempting senor researchers from teaching undergraduate courses. In addition, three teaching posts are being staffed at the university president's discretion in the original departments, to serve as supplemental teaching staff for those departments in order to fulfill academic education requirements.

(2) University President Discretionary Posts

To strengthen the life-related fields and particularly the origin and evolution of life, the Tokyo Institute of Technology has provided to ELSI two university president discretionary posts (professor and assistant professor (from April 1, 2014 to March 31, 2022) and one assistant professor post for strengthening and completing the graduate school education requirements. In addition, two administrative personnel positions were added at ELSI.

(3) Support for Personnel Expenses

Tokyo Institute of Technology assists with personnel expenses for four principle investigators and two specialist administrative personnel from the university.

(4) Allocation of Tenured Posts

In FY2016, three new tenured positions are to be added.

(5) Preferential Budgeting Measures

Tokyo Institute of Technology provides ELSI with 90 million yen each year from the university president discretionary expenses for existing site development. It also supports to repair air conditioners etc., and about 40 million yen is exempted from the university president discretionary space fees provided by the university.

2. System under which the center's director is able to make substantive personnel and budget allocation decisions

Tokyo Institute of Technology considers ELSI as a research site organization (research district) particularly recognized by the university president. It is under the university president's jurisdiction and promotes the building, establishment, and development of a flexible research system wholly unlike conventional practices or operations systems. It is also positioned as a leader in research reform, increasing the degree of international recognition and implementing research that attracts the world's finest researchers. Based on this policy, ELSI has the authority to run the site, including personnel and budget implementation.

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

After adoption of the WPI, the "Agreement Related to Flexible Teaching Staff at the Tokyo Institute of Technology Earth-Life Science Institute" was instituted, installing a permanent teaching staff of five persons at ELSI as a flexible teaching staff and exempting principle investigators from teaching undergraduate courses. In addition, three teaching posts are being staffed at the university president's discretion in the original departments, to serve as supplemental teaching staff for those departments in order to fulfill academic education requirements. This action enabled more teaching staff from other departments to participate in research at ELSI.

4. Revamping host institution's internal systems to allow introducing of new management methods

(e.g., English-language environment, merit-based pay, cross appointment, top-down decision making unfettered by conventional modes of operation)

(1) Introduction of Research Performance Evaluation System and Skills-Linked Wage System

ELSI has adopted a wage system based on the "Bylaws Related to Wages for Special Fixed-Term Employment Staff at the Tokyo Institute of Technology Earth-Life Science Institute" and also based on skills. An Annual Evaluation Meeting is implemented each year by the Director, Assistant Director,

Administrative Department Director, and others in the Executive Office to honor persons deemed to have conducted particularly excellent research and to perform wage adjustments.
In addition, a bonus system was established for persons who have contributed significantly to the Institute. The bonuses are then dispersed. Bonuses for the past three years were distributed as: FY2013: 3 persons, FY2014: 9 persons, and FY2015: 8 persons,

(2) Introduction of Cross-Appointment System

To acquire top-level researchers who can advance the life science fields and particularly the life origins and evolution area, we have implemented a cross-appointment system and have utilized this to employ a professor at Osaka University as principle investigator. Furthermore, Osaka University Graduate School of Information Science, where the principle investigator was originally based, has become a satellite of ELSI to promote research related to the origins of life.

(3) Promotion of Interdisciplinary Research

The promotion of interdisciplinary research and internationalization, the research support system, and other efforts developed at ELSI (ELSI-Style) provide a guide for internationalization and the strengthening of research at the university. In the long term, ELSI-Style will mean a standard research style at the university while being engaged in interdisciplinary efforts with other research site organizations. We expect that the new graduate school and Institute of Innovative Research at Tokyo Institute of Technology derives and benefit from ELSI-Style.

5. Utilities and other infrastructure support provided by host institution.

(facilities, e.g., laboratory space; equipment; land, etc.)

(1) Support for Space Utilization

Tokyo Institute of Technology provided existing buildings (2,670 m2) on the campus for the Earth-Life Science Institute wing (ELSI-2). With the receipt of university land, a new research wing (ELSI-1: 5,000 m2) was launched in FY2014. In addition, a total of 20 rooms in the university's International Exchange Hall are set aside as priority residences for foreign researchers at ELSI.

(2) Exemption for University President Discretionary Space Contribution

For the new Earth-Life Science Institute wing, the university president discretionary space (new buildings contributing 20%) contribution was exempted.

(3) Establishment of Child Daycare Center

With the globalization of the university, the arrival of young foreign researchers is increasing. To prepare an environment for researchers with children, a daycare center inside the International House nearest to ELSI will be opened in April 2017. These young researchers can then concentrate on their research with confidence.

6. Support for other types of assistance

(1) Tokyo Institute of Technology Medium-Term Plan, Etc.

In the medium-term plan and the objectives related to research at the Tokyo Institute of Technology, ELSI is stated to be focusing on the early Earth at the world-class research site 'Earth-Life Science Institute' and promoting research at the discretion of the university president, with the objective of clarifying the mutual relationship of the origins and evolution of the Earth and life. It is positioned as having a highly strategic, ambitious objective and plan.
To reach the medium-term plan objectives, ELSI has been positioned as a research site organization (research district) recognized by the university president. It is an organization under the university president's jurisdiction and promotes the building, establishment, and development of a flexible research system wholly unlike conventional practices or operations systems. As a leader in research reform, it also increases international recognition and implements research that attracts the world's finest researchers. ELSI researchers also help to educate the next generation of researchers and actively participate in education research guidance for graduate school students. In addition, efforts at ELSI to achieve advanced results are incorporated into the Institute of Innovative Research and other organizations and are reflected in improvement in the university's general research standards.
ELSI receives university president discretionary posts, university president discretionary space, and university president discretionary expenses for research into the understanding of the origin and evolution of the Earth and life. In addition to the commitment by the host institution at the formation of ELSI, the university president has expressed active support that does not end with the personnel and physical assistance for site visits and program committees.

(2) Outlook After the End of WPI

As indicated by the name, Earth-Life Science Institute, ELSI has, since its founding, promoted

detailed research related to the origins of life within a framework of planets, and, particularly, to the origin of the Earth. The research to date has integrated various fields, including geophysics, Earth physics, Earth chemistry, biochemistry, microbiology, and evolutionary biology, etc. These are already good examples of interdisciplinary fusion research. At present, ELSI is fast becoming a research hub for the pursuit of the origins of life through such integrated research.

Recently, at ELSI, research incorporating new interdisciplinary topics has started. This research uses simulations based on our knowledge of the origins of life on Earth to pursue the more universal origins of complex living systems. The aim is to normalize the origins of life on Earth and pursue the origins of life on extrasolar and other planets.

Currently, the biochemistry of life on other planets (life beyond Earth) is unknown. Our goal is to search for elements that are essential for life processes beyond an Earth-type carbon/water-based life and to normalize knowledge related to Earth-type life. This attempt at exploring universal biology will in the future enable interpretation of data when chemical observation results hinting at the existence of life beyond Earth are obtained.

When the WPI program period has come to an end, the focus of research at ELSI will have moved from the initial Earth to space and to the establishment of a firm position leading to the ambitious challenge of systematizing astrobiology.

The next research phase at ELSI will see the development of close and wide-ranging cooperation with JAXA, NASA, ESA, and other such institutions engaged in space exploration. Among these, ELSI expects to become a unique research hub for universal biology, sketching out a general image of the vast extent of astrobiology.

As a host institution for this kind of large-scale research, Tokyo Institute of Technology recognizes the need for study of the WPI-academy and of joint operations between ELSI and other research institutions in Japan and abroad.

(3) Development of Graduate School Education Research

ELSI researchers are at the forefront of research in the Earth-life sciences, and their methods and findings are of use in the education of the next generation of researchers. Tokyo Institute of Technology has been building a system enabling active participation in education research guidance for graduate school students.

World Premier International Research Center Initiative (WPI)

Appendix 5-2. Female researchers

*Enter the number and percentage of female researchers in the top of each space and the total number of all the researchers in the bottom.

		FY2012	FY2013	FY2014	FY2015	Final goal
Researchers		1, 4%	8, 20%	11, 17%	18, 24%	13, 18%
		23	41	63	76	71
	Principal investigators	0, 0%	0, 0%	0, 0%	1, 6%	2, 12%
		13	14	17	17	16
	Other researchers	1, 10%	8, 30%	11, 24%	17, 29%	11, 20%
		10	27	46	59	55