World Premier International Research Center Initiative (WPI)
FY2016 WPI Project Progress Report (Post-Interim Evaluation)

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Common instructions:
* Unless otherwise specified, prepare this report from the timeline of 31 March 2017.
* So as to base this fiscal year's follow-up review on the document "Post-interim evaluation revised center project," please prepare this report from the perspective of the revised project.
* Use yen (¥) when writing monetary amounts in the report. If an exchange rate is used to calculate the yen amount, give the rate.

Summary of State of WPI Center Project Progress (write within **2 pages**)

1. Conducting research of the highest world level

FY2016 saw continued output of high-profile publications on topics of fundamental importance to the origin and early evolution of the Earth and its extension to exoplanet studies; in addition, ELSI displayed its unique strengths in near-surface geochemistry and molecular biology to connect the long-term co-evolution of the Earth-Life system. Exploration, laboratory measurement, modeling, and basic theory were all represented addressing an integrated set of questions.

Below is the summary of selected research highlights in FY2016.

Origin of the Earth:

- Ohta et al. measured the electrical resistivity (the reciprocal of electrical conductivity) of iron, a primary component of Earth's core, at high temperatures (up to 4,500 kelvin) and pressures (in the range of megabars) matching the Earth's core in a laser-heated diamond-anvil cell. The obtained low electrical resistivity of iron indicates the high thermal conductivity of Earth's core, suggesting **rapid core cooling** and a **young inner core less than 0.7 billion years old**.
- Hirose et al. discovered that the solubility of SiO_2 in liquid iron controls the amounts of silicon and oxygen that are dissolved into the core of a planet as it forms. The precipitation of SiO_2 from the core as the planet cools for billions of years after formation provides a ready and abundant **power source for maintaining planetary magnetic fields** throughout planetary lifetimes.

Birth and evolution of Earth-Life system:

- Ballmer et al. presents the **BEAMS hypothesis** that the lower mantle formed in a way that it is more silica rich than the upper mantle, and that the highly viscous remnants of this ancient mantle control convection today and reconcile many seismic and geochemical observations. The survival of ancient rocks in the convecting mantle has been a long-standing puzzle to many scientists, but may now be resolved as a consequence of inefficient mixing between strong silica-enriched rocks and the much weaker silica-depleted mantle.
- Endo et al. **succeeded in experimentally reproducing the Archean Sulfur Mass-Independent Fractionation** (S-MIF) in the geological record under reducing conditions. This work shows a plausible model of S-MIF yielding reactions, facilitating the reconstruction of the early Earth atmosphere.
- Lin et al. demonstrated that the **ancestors of many modern groups of bacteria were magnetotactic** – they had the genetic ability to make tiny chains of magnetic crystals that turn them into small swimming compass needles. The fact that this ability has survived to the present demonstrates that **Earth has never lost its magnetic field for a significant period of time** in the last 3 billion years.
- Shimizu et al. identified a novel sulfide-responsive transcriptional factor, named SqrR, and described the mechanism by which it responds to sulfides. The findings shed light on early processes in the **evolution and regulation of photosynthesis**, since recent evidence demonstrates that the origins of photosynthesis can be found in deep sea hydrothermal vents, where microbes evolved to obtain energy from ejected hydrogen sulfide and/or methane gases.

Bioplanet in the Universe:

- There are two leading hypotheses to be tested for the origin of the Martian moons: the capture

theory and the giant impact theory. Rosenblatt et al. examined the latter and **succeeded in making Martian moons in the framework of a giant impact theory** for the first time ever.

- In 2015, NASA's New Horizons spacecraft flew by Pluto, and found elongated dark and reddish regions along Pluto's equator. Sekine et al. revealed that these regions are the smoking gun of the **giant impact that made Pluto's satellite Charon** by conducting heating experiments and giant-impact simulations.
- The **maximum entropy production principle** (MEPP) has been both proposed and contested as a law to predict non-equilibrium ordered states, at scales ranging from entire planetary atmospheres to smaller geochemical systems that may have hosted the first life. Bartlett et al. used pattern formation in convecting fluids to show that MEPP cannot be a general principle, demonstrating through parameter variation that the MEPP prediction responds only to boundary fluxes and forces, but does not take into account the constitutive parameters of a system.

2. Advancing fusion of various research fields

In order to advance fusion of various research fields, ELSI researchers work to maintain close communication, understand each other's work and interests, and form an integrated scientific community under the ELSI umbrella of the diverse scope and research topics. We continue to have various opportunities for communication such as ELSI Youchien, ELSI Assembly, ELSI Seminar, and discussion/reading groups; these regular activities were boosted by ad hoc institutional meetings to engage in a dialog about more interdisciplinary topics. ELSI provides an internal funding system, Director's fund, to support the implementation of interdisciplinary research collaboration, which yielded new findings in the study of the origin of life.

ELSI researchers have conceptualized the idea of a new research domain. ELSI aims to crystallize this idea of "Comparative Emergence" in the coming five years.

3. Globalization of the institution

Foreign researchers — including five foreign principle investigators who stay full-time at ELSI — account for around 30 percent of all ELSI researchers. Researchers were sent to overseas satellite organizations and institutions affiliated with the EON project, boosting interaction in research. ELSI held international workshops and symposia, and invited top researchers and students to attend. We also boosted overseas recognition by exhibiting at booths at international conferences and cosponsoring and assisting events, which have attracted outstanding young researchers to the institute. An increasing number of these researchers have obtained full-time positions, prizes and/or competitive funding.

4. Implementing organizational reforms

Tokyo Institute of Technology (Tokyo Tech) is carrying out research, educational and administration reforms. In the area of research reform, for example, ELSI has been designated as a strategic research hub specially approved by the President and under the President's leadership. ELSI and other research center organizations, laboratories and centers have been consolidated into the newly established Institute of Innovative Research (IIR). Tokyo Tech World Research Hub Initiative (WRHI) was created within IIR as an organization that aspires to be a global research hub and promotes interaction among top-level researchers from different fields worldwide.

The WRHI uses ELSI as a model case, and development has progressed with the knowledge gained from running ELSI. This will be reflected in reforms throughout Tokyo Tech as interdisciplinary systems and global cutting-edge researches are promoted.

5. Efforts to secure the center's future development over the mid- to long-term

Tokyo Tech has declared that one of its major goals is to become a member of the world's top ten research universities by 2030. As stipulated in Tokyo Tech's statement of organizational reform plans and in our mid-term goals and plans, ELSI has been assigned a leadership role in Tokyo Tech in terms of research and system reform. For ELSI to remain a top worldwide research center even after the WPI subsidies are finished, we will continue to undertake measures that include personnel support (such as providing tenured positions), financial support with discretionary spending by the President, research space support, and general support for foreign researchers.

Additionally, we have been promoting the establishment of a non-profit corporation in the US to facilitate the acquisition of research funding from more diverse sources.

* Please describe clearly and concisely the progress being made by the WPI center project from the viewpoints below.
- In addressing the below-listed 1-6 criteria, please place emphasis on the following:
  (1) Whether research is being carried out at a top world-level (including whether research advances are being made by fusing fields).
  (2) Whether a proactive effort continues to be made to establish itself as a "truly" world premier international research center.
  (3) Whether a steadfast effort is being made to secure the center's future development over the mid- to long-term.
- Please prepare this report within 10-20 pages (excluding the appendices, and including Summary of State of WPI Center Project Progress (within 2 pages)).

1. Conducting research of the highest world level

* Regarding the criteria used when evaluating the world level of center, please note any updated results using your previous evaluation criteria and methods or any improvements you have made to those criteria and methods.

In FY2016, ELSI has been successful in disseminating research findings and securing competitive research funds as shown in Appendices 1 and 3-1. ELSI also proactively hosted scientific events, which attracted top-level scientists as described in 3. Globalization of the institution. As a result, ELSI and ELSI researchers have received wide recognition, which is described in 3. Globalization of the institution and references therein and Appendix 1 in this report.

ELSI has been making progress in promoting interdisciplinary research and creating a new research domain as described in 2. Advancing fusion of various research fields in this report.

Based on the above judgement, ELSI's research activities in FY2016 are considered to be of the highest world level, and ELSI has been firmly established as a globally visible research center. Described below are selected results in FY2016 along the four major research objectives, from A (Origin of the Earth) to D (Bioplanet in the Universe) in the revised Research Center Project Plan.

(A) Origin of the Earth

The progress and discussion at ELSI during the first five years converged on "magma ocean" processes as a point of focus, and this is highlighted as a new research objective A2 (How did the "magma ocean" phase connect early formation/differentiation to conditions when life emerged, including the essential element of water?) in the revised Research Center Project Plan. ELSI PIs organized a Goldschmidt Conference 2016 offsite workshop "Magma Oceanology" with prominent participants. Other ELSI workshops related to the origin of the Earth include "Jupiter's oscillations with JOVIAL: From observations to theoretical applications" and "Before the Moon."

[Research highlights on the evolution of the Earth's core]

ELSI PIs Hirose, Hernlund, and Helffrich and research scientists have been studying the mechanism of core convection, which resulted in two related publications in Nature in this fiscal year.

The dominant component of the Earth's core is iron, and its electrical and thermal conductivities control the dynamics and thermal evolution of Earth's core. To understand the transport properties of Earth's core, ELSI PI Hirose and others studied the electrical resistivity (the reciprocal of electrical conductivity) of iron at Earth's core conditions (Ohta et al., 2016). The result shows that the iron resistivity is strongly suppressed by the resistivity saturation effect at high temperatures. The low electrical resistivity of iron indicates the high thermal conductivity of Earth's core, suggesting rapid core cooling and a young inner core less than 0.7 billion years old.

The Earth's core is suggested to contain light elements as well as iron (Fe), and many alloys are presumed to be simultaneously present. The proportion of each candidate element is not known, but modeling of core formation at high pressure and high temperature in a deep magma ocean predicts that both silicon (Si) and oxygen (O) are among the impurities in the liquid outer core. Previously, only the binary alloy systems Fe-Si and Fe-O have been studied in detail at high pressures. In this study, ELSI PIs and research scientists report melting experiments on liquid, tertiary alloy Fe-Si-O at high pressure/temperature conditions (Hirose et al., 2017). The data suggests that an initial Fe–Si–O core would be able to crystallize silicon dioxide (SiO_2) as it cools. The calculations show that crystallization of SiO_2 from the core could provide an immense new energy source for powering core convection, which results in producing the Earth's magnetic field.

- Ohta, Kuwayama, Hirose, Shimizu, and Ohishi. 2016. Experimental determination of the electrical resistivity of iron at Earth's core conditions. Nature 534:95-98.
- Hirose, Morard, Sinmyo, Umemoto, Hernlund, Helffrich, and Labrosse. 2017. Crystallization of silicon dioxide and compositional evolution of the Earth's core. Nature 543:99–102.

[Research highlights on planet formation]

Although the classical model of planet formation is based on *in situ* accretion of 1-10 km sized bodies called "planetesimals," a new model of accretion of 1-100 cm bodies called "pebbles" has been proposed. Pebbles are formed in outer regions of protoplanetary disks and migrate inward all through the disks by aerodynamical gas drag. ELSI PI Ida and others have showed that the properties of planetary systems formed by pebble accretion sensitively depend on the detailed structure of the disks, because the pebble accretion is global and regulated by gas drag (Ida et al., 2016).

Pebble accretion is efficient only if planet seeds larger than 1000 km size are formed. ELSI PI Ida and other have found that the formation of the seeds is generally difficult and could be possible only at the snow line at which water icy components sublimate in the protoplanetary disks (Ida and Guillot, 2016).

- Ida, Guillot, and Morbidelli. 2016. The radial dependence of pebble accretion rates: A source of diversity in planetary systems. I. Analytical formulation. Astronomy & Astrophysics 591:A72.
- Ida and Guillot. 2016. Formation of dust-rich planetesimals from sublimated pebbles inside of the snow line. Astronomy & Astrophysics 596:L3.

(B) Birth of Earth-Life system

Bringing several disciplines together, new members at ELSI have expanded the scope and approach to study the birth of Earth-Life system, which is reflected in the revised Center Research Project Plan. We have now multiple, testable hypotheses to investigate the geological conditions that gave rise to the first life, to which geochemical experiments and theoretical simulations provide constraints. We also formulated the questions regarding the first genetic system.

ELSI PIs Kurokawa and Maruyama have been promoting investigations into prebiotic chemistries under the Hadean atmosphere, hydrosphere, and lithosphere through the Hadean Bioscience project (KAKENHI Grant-in-Aid for Scientific Research on Innovative Areas). From November 2016 to January 2017, they organized a series of workshops titled “Hadean Bioscience Forums” at ELSI. Members of the Hadean Bioscience project presented the results of their research projects in key areas of fundamental importance to ELSI and engaged in lively discussion with ELSI researchers.

The studies in this area have been promoted by ELSI’s strength in developing and applying analytical techniques of stable isotopes to study geochemistry and biology. Latest advances were discussed at a Goldschmidt Conference 2016 offsite workshop entitled “New stable isotope techniques and applications to early Earth and life studies” organized by ELSI PIs Yoshida and Ueno and ELSI researchers Foriel, Gilbert, and Nakagawa. ELSI researchers have also actively organized five international workshops to discuss recent findings and approaches in the origin of life studies. ELSI is also adding new fields of analytical expertise through PI hiring and recruiting of junior researchers; they include the elucidation of reaction mechanisms through electrochemical decoupling of proton and electron transfers and through spectroscopic methods, and the development of computational methods to study large reaction networks with a level of analytical control that has previously existed only for individual reactions.

[Research highlight 1. Early Earth’s atmosphere]

Photochemistry of sulfur in atmospheres produces Sulfur Mass-Independent Fractionation (S-MIF). The mechanism of S-MIF is poorly understood. ELSI PI Ueno’s team succeeded in experimentally reproducing the Archean S-MIF by reconsidering the experimental conditions (Endo et al., 2016). Previous experiments were conducted at extremely high partial pressure of sulfur dioxide (SO_2), far different from the presumed reducing Archean atmosphere as indicated by the previous study from Ueno’s team. The present study uses more plausible SO_2 level and presents a plausible model of S-MIF yielding reactions, facilitating the reconstruction of the early Earth atmosphere.

- Endo, Ueno, Aoyama, and Danielache. 2016. Sulfur isotope fractionation by broadband UV radiation to optically thin SO2 under reducing atmosphere. Earth and Planetary Science Letters 453:9-22.

[Research highlight 2. Roles of microbial electron transfer in the Earth-Life coevolution]

In this publication, EON Research Fellow Giovannelli (also affiliated with the Princeton IAS Satellite) and others review the coevolution of microbial electron transfer enzymes with the

biosphere and geosphere, considered at various scales from the protein structure to the geological record (Jelen et al., 2016). The review captures the interest and strength of the ELSI researchers and offers an integrated view of the research objectives B and C in the revised Center Rresearch Project Plan. Some examples of the ongoing work pertinent to this review include the bioenergetic systems and their interaction with the environment, the reconstruction of ancient protein structures, and the change in the environmental redox state and its influence on life.

- Jelen, Giovannelli, and Falkowski. 2016. The Role of Microbial Electron Transfer in the Coevolution of the Biosphere and Geosphere. Annual Review of Microbiology 70:45-62.

(C) Evolution of the Earth-Life system

The Earth's environment has been instrumental for the origin and evolution of life, and life on Earth, in turn, has influenced the evolution of the Earth's environments. Researchers at ELSI aim to understand this two-way nature of the Earth-Life interactions. Our investigations here are directed at three aspects of long-term evolutionary change: (1) major transitions in the bioenergetic systems; (2) what molecular comparative analysis and synthetic biology can tell us about the ancestral state and evolution of core genes and enzymes; and (3) how long-term thermal evolution of the Earth changes the surface environment for life. Described below are research highlights for each topic. Studies of ancient molecular evolution have been a rapidly growing area for ELSI, both in recruiting new post-doctoral interns and in the introduction of new grant proposals and new projects. Although these projects are currently in the beginning stages, ELSI now has active research into both the history and the mechanisms of ancient molecular evolution of several core biochemical and bioenergetics systems. More details are provided in section (D) as two themes are closely linked.

[Research highlight 1. Genetic mechanism of the transition in bioenergetic systems]

The team led by ELSI Affiliated Faculty Shinji Masuda identified a novel sulfide-responsive transcriptional repressor, named SqrR in the purple bacterium *Rhodobacter capsulatus*, and described the mechanism by which it responds to sulfides. Unlike many micro-algae and plants that only use water as an electron donor to drive photosynthesis, *R. capsulatus* can switch between energy sources (light or geothermal radiation) and different electron donors depending on their surrounding environment. To do this, the bacterium must carefully control the synthesis of electron transfer proteins in response to changing conditions. They found that when sulfides in the surrounding environment increase, SqrR responds by binding to the sulfide molecules, thereby repressing photosynthetic electron transfer so that the bacterium can survive sulfide stress. In this way, SqrR helps maintain sulfide homeostasis in rapidly-changing environments. The findings shed light on early processes in the evolution and regulation of photosynthesis, since recent evidence demonstrates that the origins of photosynthesis can be found in deep sea hydrothermal vents, where microbes evolved to obtain energy from ejected hydrogen sulfide and/or methane gases.

- Shimizu et al. 2017. Sulfide-responsive transcriptional repressor SqrR functions as a master regulator of sulfide-dependent photosynthesis. Proc. Natl. Acad. Sci. USA 114:2355-2360.

[Research highlight 2. Metagenomic approach to the origin of biomineralization and the geological implication of bacterial magnetotaxis]

Earth's magnetic field deflects the solar wind, and prevents it from stripping away the atmosphere and oceans. However, we do not have good constraints on how old the geodynamo actually is, nor how strong and continuous it might have been during the first two billion years of earth history. In a recent publication co-authored by ELSI PI Kirschvink (Lin et al., 2017), they demonstrate that the ancestors of many modern groups of bacteria were magnetotactic - they had the genetic ability to make tiny chains of magnetic crystals that turn them into small swimming compass needles. Using sophisticated genetic analyses they were able to show that this genetic pathway evolved just once in a distant ancestor of almost all living bacterial groups, sometime before 3 billion years ago. To survive, these bacteria need a magnetic field greater than about 6 μT (~ 10% of the present level), which is easily produced by the magnetic 'stripes' on the ocean floor. However, if the internal field generated by Earth's core were to die away for a few hundred million years, the sea floor with these anomalies would be subducted, causing the magnetotactic bacteria to go extinct. The fact that this ability has survived to the present day demonstrates that Earth has never lost its magnetic field for a significant period of time in the last 3 billion years.

- Lin et al. 2017. Origin of microbial biomineralization and magnetotaxis during the Archean.

Proc. Natl. Acad. Sci. USA 114:2171-2176.

[Research highlights 3. Long-term evolution of the Earth]

The composition of the lower mantle of the Earth remains poorly constrained. Previous models did not consider the effects of variable magnesium/silicon ratios on the viscosity and mixing efficiency of lower-mantle rocks. Through two-dimensional numerical experiments and systematically exploring parametric space of viscosity and density contrast in the mantle, ELSI PIs and researchers identified a regime where large-scale intrinsically strong silica-enriched domains could organize mantle convection patterns for 4.6 billion years or longer (Ballmer et al., 2017). The proposed BEAMS (bridgmanite-enriched ancient mantle structures) hypothesis that the lower mantle formed in a way that it is more silica rich than the upper mantle and that the highly viscous remnants of this ancient mantle control convection today, could reconcile many seismic and geochemical observations. The survival of ancient rocks in the convecting mantle has been a long-standing puzzle to many scientists, but may now be resolved as a consequence of inefficient mixing between strong silica-enriched rocks and the much weaker silica-depleted mantle.

Continental growth affects the thermochemical evolution of the mantle. For instance, subduction along the ocean-continent convergent plate boundaries contributes to the elimination of the granitic continental materials, which supply a large amount of radioactive elements into the deep mantle. In the present western Pacific domain, there are a number of ~600 km scale oceanic microplates with immature oceanic arcs, which are believed to be more common in the Archaean. In order to estimate the subduction rate of granitic materials in oceanic arcs into the mantle, WPI researcher at the Ehime Satellite, Ichikawa, and others conducted numerical simulations of arc subduction by the finite element method and studied the effect of arc's sizes and shapes and slab temperature (Ichikawa et al., 2016). The results show that when the arc is smaller or the temperature of the slab is lower, the subduction rate grows larger owing to competition between upward buoyancy and downward viscous drag from slabs.

- Ballmer, Houser, Hernlund, Wentzcovitch, and Hirose. 2017. Persistence of strong silica-enriched domains in the Earth's lower mantle. Nature Geoscience 10:236–240.
- Ichikawa, Yamamoto, Kawai, and Kameyama. 2016. Estimate of subduction rate of island arcs to the deep mantle. Journal of Geophysical Research 121:5447-5460.

(D) Bioplanet in the Universe

ELSI aims to establish a theoretical framework to search for scenarios for the emergence of life. This is manifested in the newly-introduced research objective D12 in the revised Research Center Project Plan, which is based on theoretical studies at ELSI that focus on defining the abstract properties essential to the origin of life and seek to quantitatively demonstrate conditions for their emergence in a planetary system.

[Research highlights on the satellite formation processes]

Planetary satellites and their formation processes are of great scientific interest in their own right. Additionally, satellites and their habitability are attracting growing interest in astrobiology, and this topic is explored by ELSI Research Scientist Usui and others in Ehlmann et al., 2016. ELSI researchers investigated satellite formation mechanisms and their influence on the satellite environment.

Phobos and Deimos, the two small satellites of Mars, are thought either to be asteroids captured by the planet or to have formed in a disc of debris surrounding Mars following a giant impact. ELSI A-PI Genda and others investigated the formation process of a disk produced by a potential giant impact on Mars, and satellites' formation process from this disk. A huge satellite is quickly formed from this disk first, and it enhances the accretion of Phobos and Deimos in the outer region. After their formation, the huge satellite falls into Mars due to the strong tidal interaction with Mars, and eventually disappears. Only two tiny satellites, that is, Phobos and Deimos were left behind. It was also found that about a half of the disk mass produced by a giant impact originally come from Mars, so that Phobos and Deimos should contain Martian materials. This finding provides further motivation for a sample-return mission from the Martian satellites. Recently, Japan Aerospace Exploration Agency (JAXA) has just started to plan such a sample-return mission from Martian satellite(s), "Martian Moons eXplorer (MMX)," in which ELSI Research Scientist Usui is actively engaged. Returned samples from Martian satellites are expected to have Martian materials.

ELSI A-PI Genda and others revealed that the dark and reddish whale-shaped region — named

"Cthulhu Regio" — observed by NASA's New Horizons spacecraft is the smoking gun of a giant impact on Pluto (Sekine et al. 2017). They conducted heating experiments of water solutions containing simple organic molecules and found that the color of the solution becomes dark and reddish after heating at > 50 °C for several months, which is similar to the color observed in Cthulhu Regio. A-PI Genda carried out many simulations of a giant impact on Pluto and found that the giant impact that created the satellite Charon can also heat the wide regions near Pluto's equator up to > 50 °C. It was concluded that Cthulhu Regio was formed by the Charon-forming giant impact, which also suggests that giant impact events are more ubiquitous across our solar system than previously thought. The research is based on the collaboration between ELSI and researchers at the Department of Earth and Planetary Science in the University of Tokyo, where a new ELSI Satellite will be set up. The new satellite at the University of Tokyo will promote further research interactions.

- Ehlmann et al. 2016. The sustainability of habitability on terrestrial planets: Insights, questions, and needed measurements from Mars for understanding the evolution of Earth-like worlds. Journal of Geophysical Research 121:1927-1961.
- Rosenblatt, Charnoz, Dunseath, Terao-Dunseath, Trinh, Hyodo, Genda, and Toupin. 2016. Accretion of Phobos and Deimos in an extended debris disc stirred by transient moons. Nature Geoscience 9:581-583.
- Sekine, Genda, Kamata, and Funatsu. 2017. The Charon-forming giant impact as a source of Pluto's dark equatorial regions. Nature Astronomy 1:0031

[Research highlight from EON researchers on maximum entropy production principle]

One of the greatest difficulties of moving beyond particular hypothetical scenarios for the origin of life — which will always be doubtful individually — to understand the role of general laws, is the very large number of unknown detailed parameters and variable environments that should be considered. Therefore, an important role of theory is to search for general principles that determine organized states at the level of a whole physical or chemical system, across all values of their detailed parameters. One of the most heavily studied candidates for a general principle has been the "maximum entropy production principle" (MEPP). It showed promise in the 1970s and 1980s as an explanation for the organization of planetary atmospheres, and has been promoted also as a law to describe dynamical organization in geochemistry. However, there are problems with the use of MEPP, which suggest that it is not a general principle but rather only a special case applicable to some kinds of problems. One recent theoretical effort at ELSI grows out of empirical modeling work by EON fellow Bartlett (also affiliated with the Jet Propulsion Laboratory) that has sought to determine whether fluid flow in the thermal gradients of hydrothermal vents can lead to coupled physical and chemical organization (Bartlett and Virgo, 2016). The Lattice Boltzmann Method that Bartlett uses in these simulations, together with an innovative study of independent force- or flux-controlled boundary conditions, provides an ideal platform to test whether the order formed can be explained by an MEPP principle. Recent work by Bartlett and Research Scientist Virgo studies organized Rayleigh-Benard convection in fluid flows where temperature and heat flux can be used independently as control parameters, and where internal fluid properties as well as boundary conditions can be varied to carry out comparative analyses. They find that, whereas the Nusselt number — a dimensionless constant characterizing total heat transport — appears to be maximized by organized convection across a whole range of boundary conditions, entropy production has no special status and is not maximized except at certain finely tuned parameter values. The ability to test theories such as MEPP by parameter variation within a stable class of models is an important contribution to predicting the occurrence of order in dynamical systems where the boundary conditions and many internal properties may be unknown, or may vary across different environments. These modeling efforts may eventually help to link the fluid dynamics with the geochemistry of vent systems to better understand both prebiotic chemistry and current niches for microbial bioenergetics at hydrothermal vents.

- Bartlett and Virgo. 2016. Maximum Entropy Production Is Not a Steady State Attractor for 2D Fluid Convection. Entropy 18:431

2. Advancing fusion of various research fields

In order to advance fusion of various research fields, we (1) discussed areas of potential interest for fusion and (2) have provided communication opportunities and support for interdisciplinary research collaboration. In the following we describe (1 and 2) ELSI's efforts and progress regarding the above two points and (3) research example of interdisciplinary research collaborations. We also conceptualized the idea of "Comparative Emergence" as a new research domain (4).

(1) Areas of fusion

The scope and diversity of research topics under the ELSI umbrella is enormous. To choose strategic priorities within this diversity, a series of topical group meetings was held at ELSI to discuss common interests. Based on these discussions, an ELSI Assembly in September 2016 was held to discuss integrative themes, which could bring together many researchers and interests, and could serve as areas where ELSI commits to make a scientific impact and to influence the research trajectory of the wider community. Suggested integrative themes such as **Comparative Planetology**, **Magma Ocean**, **Messy Chemistry**, **Geometabolism**, and **Progenote** have been incorporated into the revised project plan. In January 2017, the ELSI All-Hands Institutional Strategy Meeting was held to promote interdisciplinary communication and development of new collaborative research ideas.

(2) Communication opportunities and support for interdisciplinary collaboration

ELSI researchers work to actively maintain an "ecosystem" of communication and cross-discipline activities, to help researchers understand each other's work and interests, and to form a more integrated and imaginative scientific community. At the most basic level, the ELSI Youchien (kindergarten) provides welcoming introductions to the main ideas that underpin the origins of Earth and Life. At an intermediate level, the ELSI Assembly allows colleagues to get yearly updates on each other's work, and to provide intermediate, more domain-specific discussions and question/answer sessions. A special series of ELSI Assemblies has started for ELSI researchers to present their research activities conducted in the last year and their latest work-in-progress. This helps researchers to share academic interests and to exchange regular feedback with each other. At the most advanced and topical level, several discussion/reading groups explore current literature, look for trends and emerging syntheses, provide more systematic education in domain basics, and scout directions for next phases of ELSI's work. These groups are spontaneously organized by researchers and cover topics such as planetary interior, magma oceans, mineral-mediated selection of polymers, the origin of life, and molecular systems evolution. Some of these groups were recently formed to follow up on ideas that emerged at the institutional meetings described in 2 (1). The ELSI Seminar is a place for lectures and discussions to which external researchers are invited to present and serves as a good opportunity to set up inter-institutional collaborations.

To provide seed funding and responsive support for innovative and early-stage research ideas, an internal funding system called the Director's fund has been established. Interdisciplinary collaborative research projects proposed by the awardees in this fiscal year include "High-throughput robotics for the exploration of prebiotic chemistry" and "Glycine polymerization on oxide minerals by first principles [refer to 2 (3)]." Some of the Director's fund was used to enhance the analytical system of prebiotic chemistry.

(3) Research example of interdisciplinary research collaborations

Abiotic polymerization of amino acids on mineral surfaces could have played a significant role in the origin of life and is a major topic of a new study group focusing on mineral-mediated selection of polymers [described in 2 (2)]. ELSI Research Scientists Kitadai (organic geochemistry), Umemoto (computational geophysics), Usui (cosmochemistry), and others studied polymerization mechanism of amino acids on minerals using glycine (Gly) and nine oxide minerals as model amino acid–mineral combinations. By combining results of Gly polymerization (by Kitadai) with microscopic observation of Gly–mineral surface interactions (by Usui) and molecular-level knowledge of metals in minerals (by Umemoto), surface structural and electrostatic properties that activate Gly polymerization were inferred (Kitadai et al. 2016). This approach has been further developed and now involves another ELSI Research Scientist Sinmyo (high-pressure geoscience) to predict the best amino acid–mineral combination for peptide bond formation, which is an essential step for the origin of life. This project

has been supported by Director's funds [described in 2 (2)].

- Kitadai, Oonishi, Umemoto, Usui, Fukushi, and Nakashima. 2016. Glycine Polymerization on Oxide Minerals. Origin of Life and Evolution of Biospheres doi:10.1007/s11084-016-9516-z

(4) Comparative Emergence

A common theme in many projects linking Earth and Life is the emergence of new hierarchical levels with properties different from any of those of their components. A second motif shared by these projects is the many advanced methods of comparative analysis, in domains from planetology to biology. ELSI researchers propose to create a new fusion domain by applying comparative analysis to the origin of novel structures and functions across the Earth and Life sciences, to understand common aspects of the emergence of novelty across cases. This study is referred to with the term "Comparative Emergence".

Early-phase work on comparative emergence involves disciplines that are still fairly easy to couple, but surprisingly under-studied to date: the very deep-time evolution of core biochemical pathways and bioenergetics systems. Key problems in this area include 1) the deep reconstruction of historical relations among pathways for carbon fixation and early-stage organosynthesis, and those for bioenergetics systems including sulfate and nitrate reduction coupled to iron or hydrogen oxidation, and the association of these using whole-system models of their interdependencies; 2) the reconstruction of the earliest forms of the enzymes that bring new carbon fixation or bioenergetics pathways into existence, including fundamental differences in very early molecular evolution, using fewer and less substrate-specific enzymes. ELSI researchers (including the Harvard ELSI satellite and colleagues at U. Tokyo) now bring together early-enzyme reconstruction projects for enzymes in the reductive Citric Acid Cycle, the Calvin-Benson cycle, and the Acetyl-CoA pathway, and for Ferredoxin-based, thioester-based, and sulfur- and sulfate-reduction-driven bioenergetics systems. Our work couples bioinformatics and ancient sequence inference, biochemical characterization, isotope studies, and in-vivo enzyme substitution methods by members of a closely-collaborative research group.

Longer-term collaborations under development include whole-genome metabolic modeling which uses computational-chemistry methods to develop stable-isotope fingerprints that relate kinetic isotope effects of enzymes, or labeled-feeding protocols, and physiological branching ratios, to environmentally detectable isotope signatures in the rock record.

3. Globalization of the institution

* Describe what's been accomplished or recognized in the efforts to raise the center's international recognition as a genuine top world-level research institute, along with innovative efforts proactively being taken in accordance with the development stage of the center, including the following points, for example:

- Efforts being developed based on the analysis of number and state of world-leading, frontline researchers; number and state of visiting researchers; exchanges with overseas entities
- Proactive efforts to raise the level of the center's international recognition
- Efforts to make the center into one that attracts excellent young researchers from around the world (such as efforts fostering young researchers and contributing to advancing their career paths)

(1) Efforts being developed based on the analysis of number and state of world-leading, frontline researchers; number and state of visiting researchers; exchanges with overseas entities

For the 2017 academic year, eight of ELSI's fifteen principal investigators will be non-Japanese, and five of them will stay full-time at the Institute. In addition to those researchers (Appendix 4) who are working closely with satellite organizations, ten EON project postdoctoral fellows are shuttling back and forth between ELSI and affiliated overseas centers to carry out joint research. Additionally, visits of people from around the world, from the world's top researchers to foreign students, have been accepted (Appendix 5). Along with holding international research meetings — such as "Magma Oceanology," "Before the Moon," and the "From Minerals to Enzymes: The EON Workshop on Electrochemistry at the Origin of Life" — cutting-edge research results were presented at the "Synthetic Approach for the Study of the Origin of Life" EON workshop hosted in Glasgow, UK. Conferences that sought to explore new interdisciplinary fields were also held. Young Researchers' Day was also held prior to the ELSI International Symposium, and attracted more than fifty young researchers and students, who engaged in animated discussions (Appendix 3-1).

(2) Proactive efforts to raise the level of the center's international recognition

ELSI set up an exhibition booth at the Goldschmidt Conference in Yokohama, and numerous foreign researchers attended the workshop ELSI sponsored, "New Stable Isotope Techniques and Applications to Early Earth and Life Studies." ELSI researchers also participated in numerous international conferences, giving keynote presentations and invited lectures (Appendix 1). We plan to carry out promotion activities at science meetings held overseas next year as well, primarily through our foreign Vice Director and the public relations office. Additionally, we will raise the Institute's profile by introducing it to science and technology personnel from overseas partner universities, funding organizations, and foreign embassies.

(3) Efforts to make the center into one that attracts excellent young researchers from around the world (such as efforts fostering young researchers and contributing to advancing their career paths)

Thanks to public relations efforts that leveraged the above-mentioned visitors and international conferences, around 60 percent of the applicants for this year's international recruitment of young researchers were non-Japanese. As of the end of the 2016 academic year (Appendix 3-1), foreign researchers account for 30 percent of the researchers at ELSI, including a number of principle investigators. Five young researchers have received informal notice regarding full-time positions at other institutes this year, and one's accomplishments included winning the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science, and Technology's Young Scientist's Prize (Appendix 1). In addition, young researchers and mentors would periodically hold discussions.

(4) Others

ELSI launched the Japan Astrobiology Consortium in cooperation with the National Institutes of Natural Sciences' Astrobiology Center, and signed a partnership agreement with NASA's Astrobiology Institute.

We continue to provide daily life assistance, Japanese-language classes, and research support to foreign researchers. More and more researchers of foreign nationality are being selected for competitive funding, and six have secured new Grants-in-Aid for Scientific Research, along with two being awarded other research funds this fiscal year.

4. Implementing organizational reforms

* If innovated system reforms generated by the center have had a ripple effect on other departments of the host institutions or on other research institutions, clearly describe in what ways.

(1) Top-down decision-making systems

A system has been set up so that the Director of ELSI makes decisions about the Institute's management and operations, including personnel and budget implementation. ELSI has been designated in Tokyo Tech as a strategic research hub specially approved by the President and under the President's leadership. ELSI is playing a central role in the research reforms throughout Tokyo Tech, promoting the organization plan, establishment, and advancement of flexible research systems. The emphasis is on building ideas beyond conventional practices, and increasing the level of international recognition by carrying out research that attracts the world's top researchers.

Tokyo Tech is carrying out reforms that aim at spreading cross-disciplinary systems throughout the university to strengthen Tokyo Tech's research capabilities and promote cutting-edge global research by establishing research hubs similar to ELSI.

(2) Implementing research reforms: Forming a true global research hub as a means of carrying out international research efforts

Tokyo Tech has been implementing research reforms since April 2016, consolidating four

affiliated laboratories and other research centers to establish the Institute of Innovative Research (IIR), accelerating interdisciplinary research and increasing personnel mobility. The Tokyo Tech World Research Hub Initiative (WRHI) was established within IIR as an organization to promote interaction among top worldwide researchers in different fields and will serve as a world research hub that strives to produce innovative scientific technology. WRHI invites top worldwide researchers from overseas to conduct joint research with IIR's researchers and engage in cross-disciplinary interactions.

IIR and WRHI use ELSI as a model case, and development has progressed with the knowledge gained from running ELSI. This will be reflected in reforms throughout Tokyo Tech.

(3) System reforms for international research efforts

The reforms that ELSI has adopted to promote internationally competitive research and attract outstanding researchers from around the world — including a merit-based salary system and the provision of incentives based on performance appraisals, making English the common language, and strengthening support for foreign researchers — have had a strong impact on Tokyo Tech's reforms.

- New personnel system
  Tokyo Tech has adopted for the first time in ELSI a cross-appointment arrangement and a merit-based salary system.

- English-language support environment
  English is used as the common language at ELSI, and work-related interactions in the administrative departments are carried out in both English and Japanese. Along with the expanded use of English in campus documents and email notices at the university, Tokyo Tech set up an assistance service on general campus affairs in FY2016, providing full-time staff that could handle inquiries in English by phone, email, or in person.

Regarding facets of life support for foreign researchers, new English-language counseling will be established in April 2017. In addition, lodging facilities for foreign researchers in Tokyo Tech 80th Anniversary Hall and Senzokuike House, the university's new women's dormitory that is available to female students and researchers, will be established by Tokyo Tech in April 2017.

5. Efforts to secure the center's future development over the mid- to long-term

* Please address the following items, which are essential to mid- to long-term center development:
- Future Prospects with regard to the research plan, research organization and PI composition; prospects for the fostering and securing of next-generation researchers
- Prospects for securing resources such as permanent positions and revenues; plan and/or implementation for defining the center's role and/or positioning the center within the host institution's institutional structure
- Measures to sustain the center as a world premier international research center after program funding ends (including measures of support by the host institution)

5-1. Future Prospects with regard to the research plan, research organization and PI composition; prospects for the fostering and securing of next-generation researchers

(1) Research plan

The research plan has been revised to reflect the changes in the PI composition and the research developments and trends both at and outside of ELSI since its launch. The Science Steering Committee led the process of the revision based on the discussion over research direction, goals, and strategies at ELSI Assemblies. Figure 1 illustrates the changes in research objectives. ELSI researchers conceptualized the idea for a new research domain, now designated as "Comparative Emergence."

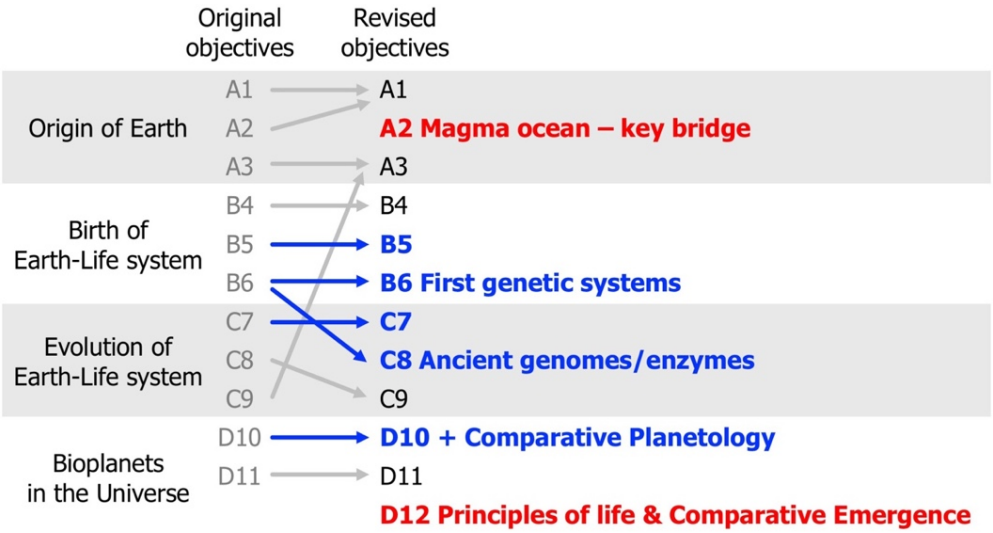

Figure 1. Overview of the revised research objectives.
Research objectives in red are newly defined in the revised plan. Those in blue were reviewed and revised to present integrative perspectives and new approaches to expand and deepen the framework in which each question is addressed.

(2) Research organization

We have reviewed the research organization in response to the midterm evaluation results, and the organization structure and several systems were revised to secure the mid- to long-term development of ELSI.

Renewed organizational structure, ELSI Organization "ELSI 3.0," has become effective on October 1, 2016 to increase academic productivity (Appendix 3-1). In this new organization, roles and functions of committees and meetings and their interrelationships are further clarified, and more effort and consideration were made to enable researchers to concentrate on research.

Cross-appointment and ELSI Fellow systems were designed and implemented in order to invite top scientists to engage in the research activities at ELSI. ELSI Fellows provide research guidance and advice to research groups and individual researchers. Another framework that has been adopted is to appoint notable domestic and international researchers with rich experience in top research institution management as International Advisory Board members. They provide advice on multi-directional and objective approaches to ELSI's research and management.

A mentoring system was recently introduced to complement the open and flat research structure and to help career development of researchers. In the open and flat research structure, young researchers at ELSI, called Research Scientists, have much freedom in research with loose connection to a specific group. Laboratories and equipment are shared at ELSI, and lab managers ensure the safe and effective operation and assist experiments carried out by laboratory members and visitors. In the recently introduced mentoring system, each researcher will have a mutually-agreed mentor who will interact with him or her throughout the year. A longer-term interaction between the mentor and mentee will lead to mutual trust and constructive feedback. This helps each researcher achieve a favorable outcome in his or her career at ELSI and beyond.

The annual evaluation system of researchers was revised to ensure the objectivity and independence of the assessment. In the revised system, the evaluation process is structured in several layers. Firstly, researchers review their activities and submit a report on publications in academic journals, the scientific merit of his or her research, their contribution to ELSI's overall activities, and the acquisition of external competitive funds. Then mentors add statements and forward the assessment results to senior PIs and Director's office. For outstanding research outcomes or contributions, ELSI will provide better research environments (space, financial support, etc.) and treatment (salary raise and extension of contract) as incentives.

(3) PI composition

In April 2016, Shawn McGlynn joined ELSI as a new PI, and associate PI Yuichiro Ueno was promoted to PI (Appendix 2- attachments). PI McGlynn will lead microbiological and bioenergetics projects and promote international collaborations. PI Ueno's strong expertise and research in

geochemistry and astrobiology is crucial in integrating diverse research fields and interest at ELSI and developing a clear vision and strategy.

We have clarified the roles of PIs in response to the midterm evaluation results, and the PIs in a revised organization are expected to play leading roles to achieve ELSI's scientific missions. From April 2017 onwards, PIs will be required to stay at ELSI for a certain amount of time to be regularly involved in ELSI's activities and management duties. In accordance with this provision, several of the current PIs will participate as ELSI Fellows from April 2017 and continue to maintain collaborative relationship with ELSI through providing expert advice and feedback.

The 15 PIs from April 2017 of diverse backgrounds and each with academic expertise and high recognition represent a broad range of scientific interests and lead interdisciplinary studies at ELSI.

(4) Fostering and securing of next-generation researchers

Through open international solicitations, ELSI hires Research Scientists [described in 5. 5-1. (2)]. Their academic independence is guaranteed in ELSI's open and flat research structure, and they work on their research by collaborating with other researchers within and outside ELSI. Their mentors provide support and guidance for their career development. In addition, the Directors regularly communicate with Research Scientists and exchange opinions on and to discuss future directions for his or her research.

An annual budget of 500,000 yen is allocated to young researchers hired with WPI expenditures to cover their startup costs. This funding 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 (although acceptance is not compulsory).

ELSI has been making steady progress in contributing to graduate education. Some non-Japanese PIs and associate professors are now becoming affiliated with Tokyo Tech schools and departments across campus, as main or sub supervisors. ELSI has been supervising students on site and is eager to recruit more prospective PhD students. ELSI researchers will also participate in teaching classes and working toward setting up an international educational program. By doing so, such PhD students and supervisors will simultaneously develop interdisciplinary research both at ELSI and other departments.

5-2. Prospects for securing resources such as permanent positions and revenues; plan and/or implementation for defining the center's role and/or positioning the center within the host institution's institutional structure

In its statement on the organizational plan, Tokyo Tech has stipulated that ELSI is a strategic research hub specially approved by the President, designating it a "highly strategic, ambitious project" in the university's midterm goals and plans. Tokyo Tech specifies that "the Earth-Life Science Institute, a global top level research center, shall focus on the Earth in its early stages, seeking to mutually link and elucidate the origins and evolution of Earth and life, with full support from discretionary resources provided by the President," positioning it in a leadership role in research and system reform.

Moreover, we are promoting the establishment of a non-profit corporation in the US to obtain research funding and to support various activities of Tokyo Tech outside Japan. Other ways of fundraising will also be investigated, using funding acquisition strategies and examples from other universities or WPI centers for reference.

5-3. Measures to sustain the center as a world premier international research center after program funding ends

Tokyo Tech has declared to become a member of the world's top ten research universities by 2030 as a major goal, positioning ELSI in a leadership role in research and system reform, and is taking the following steps to ensure that ELSI remains a top global research hub even after the WPI subsidies end:

- Arrangements have been made to secure ten full-time equivalent principal investigators (of

which six have been already tenured) and the necessary administrative staff, as well as for the continuing support required for the management of the institute, including discretionary funding and research space from the President.
- We will continue to provide a full-scale research environment in which the research staff can concentrate on scientific activities, supervise graduate students and other young researchers, interact with the world's top researchers, and pursue interdisciplinary research.
- We will provide an environment in which foreign researchers get support for daily life and are able to focus on their research. We will assign a life advisor for them, and will give support for foreigners in terms of housing, etc.
- Collaborating with the Research Promotion Department and public relations and outreach office of Tokyo Tech as well as with other WPI centers, we will maintain and expand various kinds of expertise acquired through this program to ensure that our top-level global research hub continues.
- The ELSI Director meets every month with the President and the two Executive Vice Presidents to discuss the steps required to ensure that ELSI remains a top-level global research hub.

6. Others

* In addition to the above 1-5 evaluation items, only if there is anything else that deserves mention regarding the center project's progress, please note it.

5th ELSI International Symposium (2017 Jan 11-13): 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 5th symposium was organized under the theme of "Expanding views on the emergence of the biosphere". Invited speakers came from Harvard University, Georgia Institute of Technology, University of Cambridge, NASA's Ames Research Center, and many major institutes around the world. 167 participants joined the event. Prior to the three-day main event, ELSI organized Young Researchers' Day for Earth Life Science. This year's symposium was followed by four "Aftershop" meetings, each exploring a hot topic to the depth that is not available during the symposium and trying to generate new collaborative research ideas.

Coordination with other research centers — ELSI / Kavli IPMU Joint Public Lecture "Quest for Origins" (2017 Jan 22): ELSI co-hosted a public event with Kavli IPMU, another WPI Center, at Ito Hall at the University of Tokyo. Kei Hirose (ELSI), Hiroshi Ooguri (Kavli IPMU), and Noburu Notomi (Professor of Philosophy, University of Tokyo) delivered lectures respectively and they gave a tripartite talk about human intelligent activities "Quest for Origins" from their own viewpoints. This was the second joint public event for ELSI and Kavli IPMU. The number of applicants nearly doubled this time, and twelve media companies attended the event, suggesting the increase in public interest, not only in research fields of both institutes but also interaction between them. This was a significant achievement in terms of PR and outreach for both Centers and WPI overall.

7. Center's response to the site-visit report

* Transcribe each item from the "Actions required and recommendations" section and note how the center has responded to them. However, if you have already provided this information, please indicate where in the report.

(1) Response to the comment *"Dr. Hirose reported that he will be cross-appointed with the University of Tokyo from the next fiscal year under the plan for an effort ratio of 85% for Tokyo Tech and 15% for U. Tokyo. This may be a good opportunity to incorporate activities of geo science at U. Tokyo into ELSI as a satellite. We sincerely hope that he will make every effort to keep focused on the activities of ELSI over the next 5 years."*

In April 2017, ELSI will launch a new satellite in the Department of Earth and Planetary Science (EPS) at the University of Tokyo (EPS/U.Tokyo). The Institute Director Hirose will promote his own research on the formation and early evolution of our planet in collaboration with experts in geochemistry and thermal evolution modeling at the EPS/U.Tokyo and lead collaborative research between ELSI and EPS/U.Tokyo. In order to facilitate the launch of this

new satellite, Director Hirose will be cross-appointed by the University of Tokyo as of April 2017 and will work 20% of time at the EPS/U.Tokyo. The EPS/U.Tokyo has strong research groups in astrobiology, planetary science, solar system exploration, early Earth geology & geochemistry, and the evolution of life. Importantly, their research is complementary to that of current ELSI members, and they will contribute substantially to one of ELSI's focus areas in next five years, "magma ocean" processes that determined the early Earth environment. ELSI and EPS/U.Tokyo have already agreed to start research collaborations in the study of the formation, evolution, and habitability of planets in solar and extrasolar systems, and the study of geology, geochemistry, and life on the early Earth. These joint research projects will be actively promoted by Director Hirose's leadership through hiring research scientists who work at both campuses, co-hosting visitors, and co-organizing international workshops.

It should be noted that ELSI is based on the previous Global Center of Excellence (G-COE) program, which was a collaborative project between Tokyo Tech and the University of Tokyo. This GCOE program was titled "From the Earth to "Earths," led by ELSI Vice Director Shigeru Ida during the period of FY2009 to FY2013. It focused on the relationship between environmental changes and the evolution of life on Earth, motivating us to expand this to exploring the relationship between the early Earth and the origin of life — a key concept of ELSI. This is just one of many collaborative efforts with EPS/U.Tokyo which illustrates that EPS/U.Tokyo and ELSI are fully prepared to initiate a new plan. The Institute Director Hirose will take the initiative to make every effort towards success of the new satellite at EPS/U.Tokyo.

(2) Response to the comment *"A "flat" presentation in which every work is explained in only a brief time for each work is not so good for conveying the essential progress being made. A more structured presentation with a clear focus is desirable at the next site visit."*

The presentations were made based on our firm belief that all researchers are equal in the eyes of "research," which is best represented in our open and flat research structure. Towards the ambitious goals to understand the origin and evolution of Earth and life, the researchers at ELSI are undertaking diverse approaches, and our sincere efforts at the site visit to encompass a broad range of the research activities may have resulted in a too short presentation time for each topic and a bigger picture as a whole, giving a flat impression. Considering the limited time available at the site visit, we will be thoughtful to illustrate the overview of our research activities in an easily comprehensible manner.

(3) Response to the comment *"We understand that it is important to conduct various approaches to tackle ELSI's big science goals in the ramp-up phase, but at the same time, we think that the project should have more definitive strategies for the next 5 years. This effort should be undertaken in a sufficiently quick manner so as to allow its effective implementation. The plan could and probably should include continuing currently successful and promising lines of investigation, but in addition, serious consideration should be given to initiating new research programs."*

ELSI's transition into a second phase of focused research goals is progressing both on the large scale of defining integrative themes, which tie together early-Earth and first-Life sciences, and on the small scale where development efforts that have been ongoing for the past two years have led to the attainment of deep expertise and in some cases to ELSI's being the leading institution in the world in new research domains. We summarize below the two efforts in this order.

ELSI saw the FY2016 site visit as a good opportunity to vigorously review research activities in the first 5-year period, and researchers at ELSI worked together to clarify the most important questions in their areas of expertise in the origin and evolution of Earth and life and to select the areas where they think ELSI should focus effort. The content of these discussions was shared at ELSI Assembly and other institutional meetings so that every ELSI researcher can have input on the research strategy, and we collected input from as wide a range of ELSI researchers as possible in order to arrive at the most informed possible set of scientific goals for strategic development for ELSI's second 5-year period and beyond. The Science Steering Committee organized these suggestions and provided them to the Director as a basis for internal funding allocations and strategic hiring.

The Assembly strategic planning exercises in late 2016 and early 2017 led to the identification of the high-level strategic goals that have been presented earlier in this report and in the Director's presentation at the FY2016 Program Committee under the headings of "magma ocean", "progenote studies", and "messy chemistry. Other focused themes include a comparative approach to planetology unifying Earth-science and exoplanet studies, and a theme we refer to as "geometabolism", which is a unified study of early biochemistry and bioenergetics with geological conditions both as the ongoing context for life, and as a prebiotic analogue. These areas build on ELSI's existing strengths and our strong local collaborations with institutions such as JAMSTEC, JAXA/ISAS, and RIKEN, but they emphasize original areas of integration such as bottleneck phases of planetary formation (the magma ocean phase) or bridging gaps in current scientific work in order to extend analytic theories that exist for local processes, to address diversity and complexity at the system level that has formerly been treated mostly descriptively (messy chemistry and comparative planetology). Some projects are ongoing, and details are provided in the revised Research Center Project Plan, and new collaborative projects are under discussion at study groups. The common theme of the formation of new types of dynamical order as components are assembled into systems has been the basis of our proposal for a new integrative research domain, presented under the heading 2 (4) Comparative Emergence in this report.

Two other areas merit notice as the fulfillment of ELSI's goals to become a world-class or world-leading institution in problems of the Origin of Life or early evolution. As a result of strategic hires of research scientists, establishment of cooperative research with the Harvard satellite leading to recruitment of top graduate students and postdoctoral fellows to Tokyo Tech and ELSI, and success in recent high-level international grant competitions, ELSI now has projects reconstructing the ancestral forms of all three dominant carbon fixation pathways (rTCA, acetyl-CoA, and Calvin-Benson) and all major sulfur-based bioenergetic systems. Paleoenzyme and ancestral-state reconstruction is one of the most compelling forefronts of research to study early evolution and major transitions in early life, and ELSI is currently the home of *all* leading work in this area for ancient metabolisms. A second area, which developed from earlier work in electrochemistry at ELSI and in collaboration with JAMSTEC, is the hiring of PI Nakamura and ongoing recruitment of several new postdoctoral fellows within Japan and abroad, to develop world-leading expertise in coupled proton-electron transfer processes and spectroscopy. These competences in characterizing reaction mechanisms fill out the expertise in analytic chemistry gained by the strategic hiring of PI Mamajanov in 2015. The development of deep group-level expertise and original projects in these areas stands as a parallel, in chemical and life-science domains at ELSI, to the established expertise in the labs of Director Hirose on deep-earth dynamics, and PIs Yoshida and Ueno in near-surface geochemistry, which have been sources of much of ELSI's most-recognized work.

(4) Response to the comment *"Graduate students are still not a part of ELSI activities, though some of the center's researchers mentor students in the university's graduate school. Both Director Hirose and President Mishima mentioned that incorporating ELSI into the graduate program is being planned. This should be quickly implemented, particularly so that non-Japanese PI's have chances to get involved in graduate education."*

In our long-term vision of ELSI, the importance of nurturing next-generation scientists is recognized. They will advance our understanding of the origins of the Earth and life, evolving and circulating ELSI's innovative institutional practices within and beyond Tokyo Tech. ELSI is making steady progress in contributing to graduate-course education, and Tokyo Tech will support establishing ELSI's unique international educational system. Some non-Japanese PIs and associate professors are now becoming affiliated with Tokyo Tech schools and departments across campus, as main or sub supervisors. ELSI is eager to recruit more prospective PhD students and has been supervising students on site. ELSI researchers will also participate in teaching classes and working toward setting up an international educational program. By doing so, such PhD students and supervisors will simultaneously develop interdisciplinary research both at ELSI and other departments.

(5) Response to the comment *"We heard again some young researchers expressing a demand for the upgrading of experimental facilities and employment of excellent technicians. We consider*

some aspects of their requests to be reasonable. We want to ask the ELSI center members to engage in more effective communication."

To meet diverse experimental scientists' needs at ELSI, researchers themselves actively engage in laboratory management and safety/compliance issues. This is led by the Lab Management Committee, which consists of a PI, lab managers and technical and administrative staff. We increased the number of WPI-employed technical support staff, and from April 2017, at least one technical staff works in each laboratory and assists in laboratory management.

Directors and PIs continue their ongoing efforts to communicate with young researchers daily during a tea break. Chairs of various committees (Lab Management, Computer and Network, etc.) act as an invaluable reference source for Directors to understand researchers' needs relevant to specific issues. In addition, administrative staff contribute to the enhancement of internal communication; new Administrative Director interviewed researchers and administrative members individually, and we increased the number of research administrators to bridge the gap between researchers and administration more effectively. The recently-introduced mentoring system also shows beneficial effects on taking researcher's point and concerns. Through these diversified means, we expect to see smoother communication and be more closely coordinated with each researcher.

(6) Response to the comment *"In this interim evaluation, progress at the Ehime satellite was little presented although some poster presentations were made. The challenge and role of the Ehime satellite over next 5 years should be clarified and re-discussed. Effort to promote interaction between the Ehime people and ELSI Tokyo Tech people should be considered seriously."*

The progress at the Ehime satellite was presented in two oral presentations given by PIs Hirose and Hernlund as well as in several poster presentations. We will continue to present the research activity at the Ehime satellite in future site visits.

In order to clarify the challenge and role of the Ehime satellite over the next 5 years, Tetsuo Irifune, ELSI PI based at the Ehime satellite, had several face-to-face meetings and exchanged ideas with Directors and ELSI-resident PIs. The researchers at the Ehime satellite also joined the institutional strategic meetings held at ELSI to discuss and share the vision for the future together. We will continue to promote research interactions between ELSI and the Ehime satellite, and researchers at the Ehime satellite will spend more time at ELSI to facilitate the interaction.

The productive collaboration between ELSI and the Ehime satellite was further reinforced by the successful acquisition of a large KAKENHI grant "Interaction and Coevolution of the Core and Mantle – Towards Integrated Deep Earth Science (MEXT Grant-in-Aid for Scientific Research on Innovative Areas)." Taku Tsuchiya, an affiliated researcher to ELSI at the Ehime satellite, is the leader of this project. The project's goal is in line with ELSI's, and several researchers at ELSI as well as the new satellite from April 2017 at the University of Tokyo are members of this project, creating more opportunities for collaborations among ELSI, the satellites, and other institutions.

World Premier International Research Center Initiative (WPI)
Appendix 1 FY2016 List of Center's Research Results and Main Awards

A. Refereed Papers

- List only the Center's papers published in 2016. (Note: The list should be for the calendar year, not the fiscal year.)

(1) WPI papers
List papers whose author(s) can be identified as affiliated with the WPI program (e.g., that state the name of his/her WPI center) (Not including papers whose acknowledgements contain the names of persons affiliated with the WPI program.)

Order of Listing
1. Original articles
2. Review articles
3. Proceedings
4. Other English articles
5. Articles written in other than English

(2) Method of listing paper
- List only referred papers. Divide them into categories (e.g., original articles, reviews, proceedings).
- 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. (The names of the center researchers do not need to be underlined.)
- If a paper has many authors (say, more than 20), all of their names do not need to be listed.
- If the papers are written in languages other than English, divide them into language categories when listing them.
- Assign a serial number to each paper to be used to identify it throughout the system.

(3) Submission of electronic data
- In addition to the above, for each paper provide a .csv file output from the Web of Science (e.g.) or other database giving the paper's raw data including Document ID. (Note: the Document ID is assigned by paper database.)
- These files do not need to be divided into paper categories.

(4) Use in assessments
- The lists of papers will be used in assessing the state of WPI project's progress in FY 2016.
- They will be used as reference in analyzing the trends and states of research in all the WPI centers, not to evaluate individual researcher performance.
- The special characteristics of each research domain will be considered when conducting assessments.

(5) Additional documents
- After all documents, including these paper listings, showing the state of research progress have been submitted, additional documents may be requested.

WPI papers

1. Original articles

1. Aoki, Y., Y. Okamura, H. Ohta, K. Kinoshita, and T. Obayashi. 2016. "ALCOdb: Gene Coexpression Database for Microalgae." Plant and Cell Physiology 57 (1):9. doi: 10.1093/pcp/pcv190.
2. Baba, J., K. Morokuma-Matsui, Y. Miyamoto, F. Egusa, and N. Kuno. 2016. "Gas velocity patterns in simulated galaxies: observational diagnostics of spiral structure theories." Monthly Notices of the Royal Astronomical Society 460 (3):2472-2481. doi: 10.1093/mnras/stw987.
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4. Other English articles

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132. Yada, T., M. Abe, T. Okada, H. Yurimoto, M. Uesugi, Y. Karouji, A. Nakato, M. Hashiguchi, T. Matsumoto, M. Nishimura, K. Kumagai, S. Matsui, M. Yoshitake, K. Sakamoto, Y. Nakano, N. Kawasaki, and M. Fujimoto. 2016. "CURATORIAL WORKS FOR THE HAYABUSA-RETURNED SAMPLES AND PREPARATION FOR HAYABUSA2 SAMPLE CURATION." Meteoritics & Planetary Science 51:A677-A677.

5. Articles written in other than English

None

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

- List up to 10 main presentations during FY2016 in order from most recent.
- For each, write the lecturer/presenter's name, presentation title, conference name and date(s)

1) Joseph L. Kirschvink
"Constraints on the Archean and Early Proterozoic Paleoenvironment: A Paleomagnetic and Biomagnetic Perspective"
Precambrian World 2017, Fukuoka, 3-10 March, 2017

2) Tomohiro Usui
"The Evolution of Water in the Martian Atmosphere, Hydrosphere, and Cryosphere: Insights from Hydrogen Isotopes"
AGU Fall Meeting, San Francisco, 12-16 December, 2016

3) Alexis Gilbert
"Recent insights into intramolecular 13C isotope composition of biomolecules"
AGU Fall meeting 2016, San Francisco, 12-16 December, 2016

4) Albert Fahrenbach
"Radiolytic Synthesis of RNA Precursors"
XIIth Rencontres du Vietnam - Search for life: From Early Earth to Exoplanets -, Quy Nhon, Vietnam, 11-16 December, 2016

5) Ruiqin Yi and Masashi Aono
"Production of water-alternative solvents and informational polymers by radioactive minerals on the Hadean Earth"
Proto-computation and Proto-life workshop, Harvard University, Boston, 10-11 December, 2016

6) Shigeru Ida
"Planet Formation and Volatile Delivery to Terrestrial Planets"
KVA-JSPS seminar, Lund Univ., Stockholm Univ., and Uppsala Univ., 12, 17, 18 October, 2016

7) Yuichiro Ueno
"Prebiotic compounds supplied from early atmospheres of Earth and Mars"
Geochemical Society of Japan Annual Meeting, Osaka, 14-16 September, 2016

8) Shigenori Maruyama
"Initiation of plate tectonics on the Hadean Earth"
Workshop on the origin and evolution of plate tectonics, Monte Verita, Switzerland, 17-22 July, 2016

9) Kei Hirose
"Mantle Melting in Earth and Planetary Interiors"
Goldschmidt 2016, Yokohama, 26 June - 1 July, 2016

10) Tetsuo Irifune
"Deep mantle mineralogy and novel materials synthesis using multianvil high-pressure Technology"
European Geosciences Union General Assembly 2016, Austria Center Vienna, 20 April, 2016

C. Major Awards

- List up to 10 main awards received during FY2016 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) Shawn McGlynn, Awarded the grant from Research Foundation for Opto-Science and Technology, 2016
2) Kosuke Fujishima, WIRED Audi INNOVATION AWARD, 2016
3) Kuhan Chandru, Best Poster of American Chemical Society (ACS) Symposium, 2016
4) Kosuke Fujishima, iGEM 2016 Best Measurement project (Participated as a team advisor for the Stanford-Brown University team hosted by Lynn Rothschild lab at NASA Ames), 2016
5) Stuart Bartlett, Best paper award at the Fifteenth International Conference on the Synthesis and Simulation of Living Systems, 2016
6) Yutetsu Kuruma, SFS Research Award 2015, given at June 2016
7) Kei Hirose, 57th Fujihara Award, 2016
8) Masashi Aono, The Young Scientists' Prize, Commendation by the Minister of MEXT, Japan, 2016
9) Tetsuo Irifune, Robert Wilhelm Bunsen Medal, 2016

World Premier International Research Center Initiative (WPI)
Appendix 2　FY 2016 List of Principal Investigators

NOTE:
・Underline names of principal investigators who belong to an overseas research institution.
・In case of researchers not listed in the latest report, attach “Biographical Sketch of a New Principal Investigator”.

<Results at the end of FY2016>　　Principal Investigators Total: 19

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 (49)	Director, 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 (67)	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 (56)	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 (64)	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 (54)	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 (62)	Professor, Department of Chemical Science 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 (48)	Professor, Center for Information Biology National Institute of Genetics	Ph.D., Metagenomics, Bioinformatics	15%	5%	60%	20%	From start	Stays at the center once a month	
Tetsuo IRIFUNE (62)	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 (63)	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 (44)	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 (52)	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 (47)	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 (56)	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 (64)	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 (64)	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 from July 2014	
Eric SMITH (51)	Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., High-enery/particle Physics	75%	10%	10%	5%	From February, 2015	Usually stays at the center from February 2015	
Irena MAMAJANOV (41)	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 from January 2016	
Yuichiro UENO (42)	Associate Professor, Department of Earth and Planetary Sciences, Tokyo Institute of Technology	Doctor of Science, Geochemistry	40%	20%	10%	30%	From April, 2016	Usually stays at the center from April 2016	
Shawn McGLYNN (33)	Assosiate Professor, Earth-Life Science Institute, Tokyo Institute of Technology	Ph.D., Evolutionary biology, Microbial biochemistry	70%	10%	10%	10%	From April, 2016	Usually stays at the center from April 2016	

e.g., a) usually stays at the center, b) stays at the center once a month, at XX satellite three times a week, and XX satellite once a year, c) joins a videoconference from another institution two times a week.

e.g., send/accept young scientists to/from the WPI center (number/period)

World Premier International Research Center Initiative (WPI)
Appendix 2- attachment
FY2016 Biographical Sketch of a New Principal Investigator

Name (Age)	Shawn McGlynn (33)
Affiliation (Position title, department, organization)	PI (Associate Professor), Earth Life Science Institute, Tokyo Institute of Technology
Academic degree, specialty	Ph.D., Biochemistry, microbial ecology and evolution

[Research and education history]

Research:

- April 2016 – Present, **PI (Associate Professor)**, Earth-Life Science Institute, Tokyo Institute of Technology, Tokyo, Japan.
- October 2014 – March 31 2016, **Associate Professor of Biology**, Department of Biological Sciences, Tokyo Metropolitan University, Tokyo, Japan.
- March 2016 – Present, **Visitor in Geobiology**, Geological and Planetary Sciences, California Institute of Technology, California, USA.
- February 2015 – Present, **Visiting Scientist**, Biofunctional Catalyst Research Team, RIKEN Center for Sustainable Resource Science, Yokohama, Japan.
- June 2014 – Present, **Research Scientist**, Blue Marble Space Institute of Science, Seattle Washington, USA.
- October 2013 – October 2014, **Senior Postdoctoral Scholar in Geobiology**.
  October 2010 – October 2013, **Postdoctoral Scholar in Geobiology**.
  June 2011 – June 2012, **Agouron Postdoctoral Scholar in Geobiology**.
  Division of Geological and Planetary Sciences, California Institute of Technology, California, USA
  Advisor: Dr. Victoria J. Orphan
- Summer 2008, **NASA Planetary Biology Internship**, Planetary Science Division, Jet Propulsion Laboratory, Pasadena, California, USA.
  Supervisor: Dr. Michael Russel
  Final Report: Isolation and Analysis of In Vitro Iron Sulfide Chimneys in Off-axis Submarine Hydrothermal Vent Simulations
- Summer 2005, **DAAD Undergraduate Scholar**, Institute of Chemical Technology, University Campus Vaihingen, Stuttgart, Germany.
  Supervisor: Constanze Fritsch, Prof. Jens Weitkamp
  Final Report: Gas expanded liquid oxidation of 1-pentanol

Education:

- 2006 – 2010, Montana State University
  Ph.D., Biochemistry (2010)
  NSF-IGERT Fellow in Geobiological Systems
  Thesis Advisor: Dr. John W. Peters
  Thesis Title: Investigations on [FeFe]-hydrogenase active site biosynthesis
- 2001 – 2005, Montana State University
  B.S., Chemistry with High Honors (2005)
  2004 – 2005, Undergraduate Study at Montana State University – Bozeman
  2003 – 2004, Undergraduate Study at the University of Canterbury, Christchurch, New Zealand
  2001 – 2002, Undergraduate Study at Montana State University – Billings

[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.)

Shawn McGlynn received training in anaerobic biochemistry and microbial ecology. His interests concern redox reactions as they relate to i) isotope fractionation, ii) microbial interactions, and iii) to the origin of life. With regards to i), he was named a NASA Early Career Fellow while at Caltech, and is currently pursuing the research described in that award– which concerns identifying the catalytic determinants of sulfur isotope signals from the level of enzymes at ELSI. With regards to ii), he played a major role in the discovery of a new mode of archaea-bacteria interactions based on direct electron exchange while at Caltech (McGlynn *et al*. Nature 2015; Scheller, Yu, Chadwick, McGlynn, and Orphan 2016 Science). These investigations not only revealed a new mode of microbial interaction, but also pave the way for being able to understand and construct microbial ecosystems theory from the basis of individuals, rather than from populations which is typically done in absence of individual cell resolution experiments. With regards to iii) He is currently continuing work which was started while at the NASA Jet Propulsion laboratory, where McGlynn developed flow systems to mimic and allow the study of hydrothermal vents as they may have occurred in the Hadean ocean (McGlynn *et al*. 2013 Proc. Roy. Soc. A).

Honors and Awards:

- 2014, NASA Early Career Fellowship Award.
- 2011, Agouron Institute Post-Doctoral Scholar in Geobiology, California Institute of Technology.
- 2011, University of Hawaii Winter Astrobiology School Attendee.
- 2010, AbGradCon Travel Award for Research Presentation.
- 2009, NASA Astrobiology Institute Santander Summer School Scholar.
- 2008, Planetary Biology Internship – Research conducted at Jet Propulsion Laboratory.
- 2008, European Astrobiology Network Travel Award.
- 2008, International Society for Astrobiology Travel Award.
- 2006 – 2010, NSF-IGERT Fellow in Geobiological Systems.
- Dean's List, All years of University.
- 2005, DAAD (German academic exchange service) RISE Scholar.
- 2005, Minerva "Tommy" Morgan Scholarship.
- 2005, Montana State University Fry Scholarship.
- 2005, Award for Academic Excellence.
- 2003, National Society of Collegiate Scholars Member.
- 2003, Golden Key Award, Montana State University Bozeman Chapter.
- 2003, W.E. Mares Scholarship, Montana State University Bozeman.
- 2002, University Bonhomme Scholarship, Montana State University Bozeman.
- 2001, Haynes Foundation Chancellor's Scholarship; President's Award for Educational Excellence.
- 2001, Outstanding Academic Performance Award on ACT.

[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.

Guest Lectures, Conference Attendance, and Synergistic Activity:

- 2017, **Invited Speaker** at Solar Fuels Workshop, Seoul National University, Seoul, Korea.
- 2016, **Invited Speaker** at Solar Fuels Workshop, Seoul National University, Seoul, Korea.
- 2016, **Invited speaker** at the Japanese society of microbial ecology annual meeting, Yokosuka, Japan.
- 2016, **Invited speaker** at the EON Workshop on Electrochemistry and the origin of life (From Minerals to Enzymes), Earth-Life Science Institute, Tokyo Institute of Technology, Japan.
- 2015, **Invited Attendee** at Microenergy-Workshop, Denmark.
- 2015, **Invited Seminar Speaker**, Tohoku University Geosciences, Japan.
- 2015, **Invited Seminar Speaker**, Earth-Life Science Institute, Tokyo Institute of Technology, Japan.
- 2015, **Invited Seminar Speaker**, Biofunctional Catalyst Research Team, RIKEN, Japan.
- 2015, **Invited lecture** at the 2015 American Society of Microbiologists in New Orleans, USA.
- 2015, **Invited Seminar Speaker**, Department of Marine Sciences UNC Chapel Hill, USA.
- 2014, **Conference session co-organizer** at the American Geophysical Union, USA.
- 2014, **Invited participant** in the NSF Center for Dark Energy Biosphere investigations (C-DEBI)

"Limits to life" workshop, Redondo Beach, California, USA.
- 2011, **Invited participant** in the NSF Center for Dark Energy Biosphere investigations (C-DEBI) "Limits to life" workshop, Redondo Beach, California, USA.

Selected Other Activities:
- Editorial board of *Frontiers in Microbiology*, *Microbial Physiology and Metabolism*.
- *Ad Hoc* Reviewer of *Environmental Microbiology Reports*; *Astrobiology*; *Origins of Life and Evolution of Biospheres*; *Nature Geosciences*; *Frontiers in Microbiology*; *FEMS Microbiology Ecology*.
- 2011 – 2014, Student Councilor. International Society of the Study of the Origin of Life and Astrobiology Society (ISSOL).

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

1. Opto-Science foundation. PI. ¥4 million in direct costs. Title: Direct electron transfer as a mechanism to facilitate metabolic and ecological stability between multiple species. FY2017-2018.
2. Kakenhi "Challenging" Award. PI. ¥2.9 million in direct costs. Title: Species interaction by direct electron transfer in syntrophic communities. FY2015-2016.
3. NASA Exobiology. Science PI. US $ 193,062 in direct costs. Title: Assay of dissimilatory sulfate reduction enzymes in- vitro and analysis of sulfur isotope fractionation. FY2014-2017.

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

Number of citations searched using Google Scholar	**Times cited**
Rebecca C. Driesener, Martin R. Challand, **Shawn E. McGlynn**, Eric M. Shepard, Eric S. Boyd, Joan B. Broderick, John W. Peters and Peter L. Roach. [FeFe]-Hydrogenase Cyanide Ligands Derived From *S*-Adenosylmethionine Dependent Cleavage of Tyrosine. *Angewandte Chemie. 2010, Feb 9:1687-1690*	**117**
Shawn E. McGlynn, Eric M. Shepard, Mark A. Winslow, Anatoli V. Naumov, Kaitlin S. Duschene, Matthew C. Posewitz, William E. Broderick, Joan B. Broderick, and John W. Peters. HydF as a scaffold protein in [FeFe] hydrogenase maturation. *FEBS Lett. 2008 Jun 25;582(15):2183-7*	**105**
Eric M. Shepard, **Shawn E. McGlynn**, Alexandra L. Bueling, Celestine S. Grady-Smith, Simon J. George, Mark A. Winslow, Stephen P. Cramer, John W. Peters, and Joan B. Broderick. Synthesis of the 2Fe-subcluster of the [FeFe]-hydrogenase H- cluster on the HydF scaffold. *PNAS, 2010 Jun 8;107(23):10448-53.*	**98**
Eric M. Shepard, Benjamin R. Duffus, Simon J. George, **Shawn E. McGlynn**, Martin R. Challand, Kevin D Swanson, Peter L. Roach, Stephen P. Cramer, John W. Peters, and Joan B. Broderick. [FeFe]-Hydrogenase Maturation: HydG-Catalyzed Synthesis of Carbon Monoxide. *JACS, 2010 Jul 14;132(27):9247-9.*	**94**
Other notable publications	
Shawn E. McGlynn, Grayson L. Chadwick, Christopher P. Kempes, and Victoria J. Orphan. Single cell activity reveals direct electron transfer in methanotrophic consortia. *Nature, 2015 526, 531–535.*	**59**
Elizabeth Trembath-Reichert, Jonathan P Wilson, **Shawn E McGlynn**, Woodward W Fischer. Four hundred million years of silica biomineralization in land plants. *PNAS.* 2015 112, 5449-5454	**20**
Silvan Scheller, Hang Yu, Grayson L. Chadwick, **Shawn E. McGlynn**, Victoria J. Orphan. Artificial electron acceptors decouple archaeal methane oxidation from sulfate reduction. *Science 2016*, 351 (6274). pp. 703-707.	**26**

Number of papers published: 26
Sum of the Times Cited: 1053
Average Citations per Item: 40.5
h-index : 17

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

World Premier International Research Center Initiative (WPI)
Appendix 2- attachment
FY2016 Biographical Sketch of a New Principal Investigator

Name (Age)	Yuichiro Ueno (42)
Affiliation (Position title, department, organization)	Associate Professor, Department of Earth and Planetary Sciences, Tokyo Tech.
Academic degree, specialty	Doctor of Science, Geochemistry

[Research and education history]

Research:

2002-2004:JSPS Research Fellow, Department of Earth Science & Astronomy, Univ. Tokyo
2003-2005:Visiting Researcher, Geophysical Laboratory, Carnegie Institution of Washington, USA.
2004-2007:21COE Assistant Professor, Department of Environmental Science and Technology, Tokyo Institute of Technology
2007-2010: Assistant Professor, Global Edge Institute, Tokyo Institute of Technology
2008-present: Guest Researcher, Precambrian Ecosystems Laboratory, JAMSTEC

Education:

2010-present:Associate Professor, Department of Earth and Planetary Sciences, Tokyo Institute of Technology.
2012-2016:Associate-PI, Earth-Life Science Institute, Tokyo Institute of Technology.
2016-present: PI, Earth-Life Science Institute, Tokyo Institute of Technology.

[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.)

Ueno's research interests center on the early evolution of Earth's biosphere and its interaction with atmosphere and ocean, especially older than 2.5 billion years (Archean). For the better understanding of biogeochemistry of the early Earth, Ueno has tried to integrate several independent approaches including stable isotope geochemistry (C and S), micro-paleontology, and field geology.

Ueno has studied geology and geochemistry of Pilbara Craton, Western Australia and first revealed that seafloor hydrothermal systems has been inhabited by micro-organisms since about 3.5 billion years ago (e.g., Ueno et al., 2001a). In order to trace the past microbial activities, Ueno has further developed several new methods for C, N and S stable isotope analysis of these ancient rocks. His ion microprobe C isotope analysis first revealed that the organic matter preserved in the Archean hydrothermal deposit is highly depleted in ^{13}C, suggesting autotrophic carbon-fixation via reductive acetyl-CoA pathway would have been responsible for the primary production in the Archean seafloor (Ueno et al., 2001b IGR; 2004 GCA). Furthermore, he was succeeded to extract tiny amount of methane preserved in the hydrothermal deposit and to measure its carbon isotopic ratio. The results indicate that methanogenic Archaea was involved in the microbial community of the Archean seafloor (Ueno et al., 2006 Nature). This is the oldest known evidence of domain Archaea living on the Earth. Also, his new quadruple sulfur isotope analysis and nitrogen isotope analysis of the deposit clarified that sulfate-reducing prokaryote and nitrogen-fixing organisms were also in active at that time (Nishizawa et al., 2007 EPSL; Ueno et al., 2008 GCA). These methods developed by his pioneering studies are now indispensable for wide range of geomicrobiological studies on early Earth, as well as important technique for astrobiology.

Ueno also contributed paloatmospheric study using sulfur isotopic anomaly recorded in Archean sediments. Anomalous fractionation of four stable sulfur isotopes were known to occur in photochemistry of few sulfur species. A series of spectroscopic experiments determined absorption spectra of each sulfur isotopologues of SO_2 for the first time (Danielache et al., 2008 JGR; Endo et al., 2015 JGR), that demonstrated photodissociation of SO_2 can cause the isotopic anomaly and provide fundamental data for simulating chemistry of early atmosphere. Further photochemical experiments of SO_2 succeeded to reproduce fractionations for all the four stable sulfur isotopes observed in geological record (Endo et al., 2016 EPSL). Based on these experimental results with a number of

analysis of Archean rock samples, Archean atmosphere would have been more reducing than previously thought (Ueno et al., 2009 PNAS). Hence, Ueno and colleagues provide a new insight of Earth's early atmosphere.

[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.

Ueno Y (2008) Spectroscopic and Stable Isotopic Fingerprints of Prokaryotic Fossils, ***World Summit on Ancient Microscopic Fossils***, UCLA, USA (Representative of Japan)

Ueno Y (2010) Stable isotopic fingerprints of greenhouse gasses before the rise of oxygen. ***Goldschmidt Conference***, Knoxville, USA (Keynote)

Ueno Y (2014) Archean Geology. ***Gordon Research Conference (Origins of Life)***, Galveston, USA (Invited)

Ueno Y (2015), Biogeochemistry of life-inhabited planets: Lessons from Early Earth, ***JPGU Geoscience Ahead***, Makuhari, Japan (Keynote)

Ueno Y, Kawade W and Zang X (2016) Prebiotic compounds supplied from early atmospheres of Earth and Mars, ***Geochemical Society of Japan***, Osaka (Keynote)

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

JSPS Funding Program for Next Generation World-Leading Researchers (FY2010-2013) JPY143,000,000

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

Number of citations searched using Web of Knowledge **Times cited**

1. Ueno Y, Yamada K, Yoshida N, Maruyama S, Isozaki Y (2006)
   "Evidence from fluid inclusions for microbial methanogenesis in the early Archaean era"
   Nature 440: 516-519 **157**
2. Ueno Y, Isozaki Y, Yurimoto H, Maruyama S (2001)
   "Carbon isotopic signatures of individual Archean microfossils (?) from Western Australia"
   International Geology Review 43: 196-212 **105**
3. Ueno Y, Yoshioka H, Maruyama S, Isozaki Y (2004)
   "Carbon isotopes and petrography of kerogens in ~3.5-Ga hydrothermal silica dikes in the North Pole area, Western Australia"
   Geochimica et Cosmochimica Acta 68: 573-589. **93**
4. Ueno Y, Ono S, Rumble D, Maruyama S (2008)
   "Quadruple sulfur isotope analysis of ca. 3.5 Ga Dresser Formation: new evidence for microbial sulfate reduction in the Early Archean"
   Geochimica et Cosmochimica Acta 72: 5675-5691 **82**
5. Ueno Y, Johnson MS, Danielache SO, Eskebjerg C, Pandey A, Yoshida N (2009)
   "Geological sulfur isotopes indicate elevated OCS in the Archean atmosphere, solving faint young sun paradox"
   Proceedings of the National Academy of Sciences of USA 106: 14784-14789 **63**

Number of papers published in 2001-2016: 66
Sum of the Times Cited: 1427
Average Citations per Item: 21.62
h-index: 21

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

Japanese-French Frontier of Science Symposium, Program Group Member 2007-2008

World Premier International Research Center Initiative (WPI)

Appendix 3-1 FY2016 Records of Center Activities

1. Researchers and center staffs, satellites, partner institutions

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

- Enter the total number of people in the columns below. In the "Researchers" column, put the number and percentage of overseas researchers in the < > brackets and the number and percentage of female researchers in the [ ] brackets.
- In the "Administrative staffs" column, put the number and percentage of bilingual staffs in the ( ) brackets.
- In the "Final Goal" column, enter the currently projected goal and the estimated date for achieving it [OO month, OO year].

		Goal set in the "Post-interim evaluation revised center project"	Results at end of FY 2016	Final goal (Date: 10 month, 2019 year)
Researchers		70 < 35,50 %> [16,23 %]	63 < 29,46 %> [11,17 %]	70 < 35,50 %> [16,23 %]
	Principal investigators	16 < 9,56 %> [1,6 %]	19 < 8,42 %> [1,5 %]	16 < 9,56 %> [1,6 %]
	Other researchers	54 <27,50 %> [15,28 %]	44 < 21,48 %> [10,23 %]	54 < 27,50 %> [15,28 %]
Research support staff		29	29	29
Administrative staff		25 (24, 96 %)	25 (24, 96 %)	25 (24, 96%)
Total		124	117	124

Other matters of special mention

- Enter matters warranting special mention, such as concrete plans for achieving the Center's goals, established schedules for employing main researchers, particularly principal investigators.
- As background to how the Center is working to mobilize/circulate the world's best brains, give good examples, if any, of how career paths are being established for the Center's researchers; that is, from which top-world research institutions do researchers come to the Center and to which research institutions do the Center's researchers go, and how long are their stays at those institutions.

1-2. Satellites and partner institutions

- List the satellite and partner institutions in the table below.
- Indicate newly added and deleted institutions in the "Notes" column.
- If satellite institutions have been established, describe by satellite the Center's achievements in coauthored papers and researcher exchanges in Appendix 4.

<Satellite institutions>

Institution name	Principal Investigator(s), if any	Notes
Ehime University	Tetsuo Irifune	
Institute for Advanced Study in Princeton	Piet Hut	
Harvard University	Jack W. Szostak	

< Partner institutions>

Institution name	Principal Investigator(s), if any	Notes
(Institute of Space and Astronautical Science) ISAS/Japan Aerospace Exploration Agency (JAXA)	Masaki Fujimoto, Hitoshi Kuninaka	
Astrobiology Center, National		

Institute of Natural Sciences (NINS)		
Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	Ken Takai	
California Institute of Technology	Joseph L. Kirschvink	
NASA Astrobiology Institute		
University of Minnesota		

2. Securing competitive research funding

Competitive and other research funding secured in FY2016

Total: 626,333,119 yen

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

KAKENHI Grant-in-Aid for Specially Promoted Research 71,600,000 yen

Global fund from John Templeton Foundation 159,714,248 yen

3. International research conferences or symposiums held to bring world's leading researchers together

- Indicate the number of international research conferences or symposiums held in FY2016 and give up to three examples of the most representative ones using the table below.

FY 2016: 16 meetings

Major examples (meeting titles and places held)	Number of participants
New Stable Isotope Techniques and Applications to Early Earth and Life Studies, Pre-Goldschmidt workshop Tokyo Institute of Technology 25th June 2016 http://www.elsi.jp/en/research/activities/workshops/2016/06/20160625.html	From domestic institutions: 27 From overseas institutions: 27 Total 54
Symposium on the Origin of Consciousness Tokyo Institute of Technology 25th-26th July 2016 http://originofconsciousness.jimdo.com/	From domestic institutions: 85 From overseas institutions: 24 Total 109
5th ELSI International Symposium: Expanding Views on the Emergence of the Biosphere Tokyo Institute of Technology 11th-13th January 2017 http://elsi5sympo.com/	From domestic institutions: 78 From overseas institutions: 89 Total 167

4. Center's management system

- Please diagram management system in an easily understood manner.
- If any changes have been made in the management system from that in the "Post-interim evaluation revised center project," please describe them. Please describe any changes made in the administrative director, head of host institution, and officer(s) in charge at the host institution (e.g., executive vice president for research)

- Appointment of new administrative director

Motonori Hoshi, the former administrative director, decided to leave this job because of personal reasons, and Takashi Sakurai, previously at the National Astronomical Observatory of Japan serving as the vice director general, was appointed as the successor on 13 April 2016. He is experienced with the management of research organizations and international research coordination, and is expected to continue supporting the director seamlessly from his predecessor.

- Establishment of the Research Promotion Committee

A new committee, the Research Promotion Committee, has been established to carry out the following functions: to define and improve the methods of evaluation of individual researchers, to assign reviewers for Director's funds etc., to recommend candidates for the incentive awards to the Director, and to discuss ways to improve research environment.

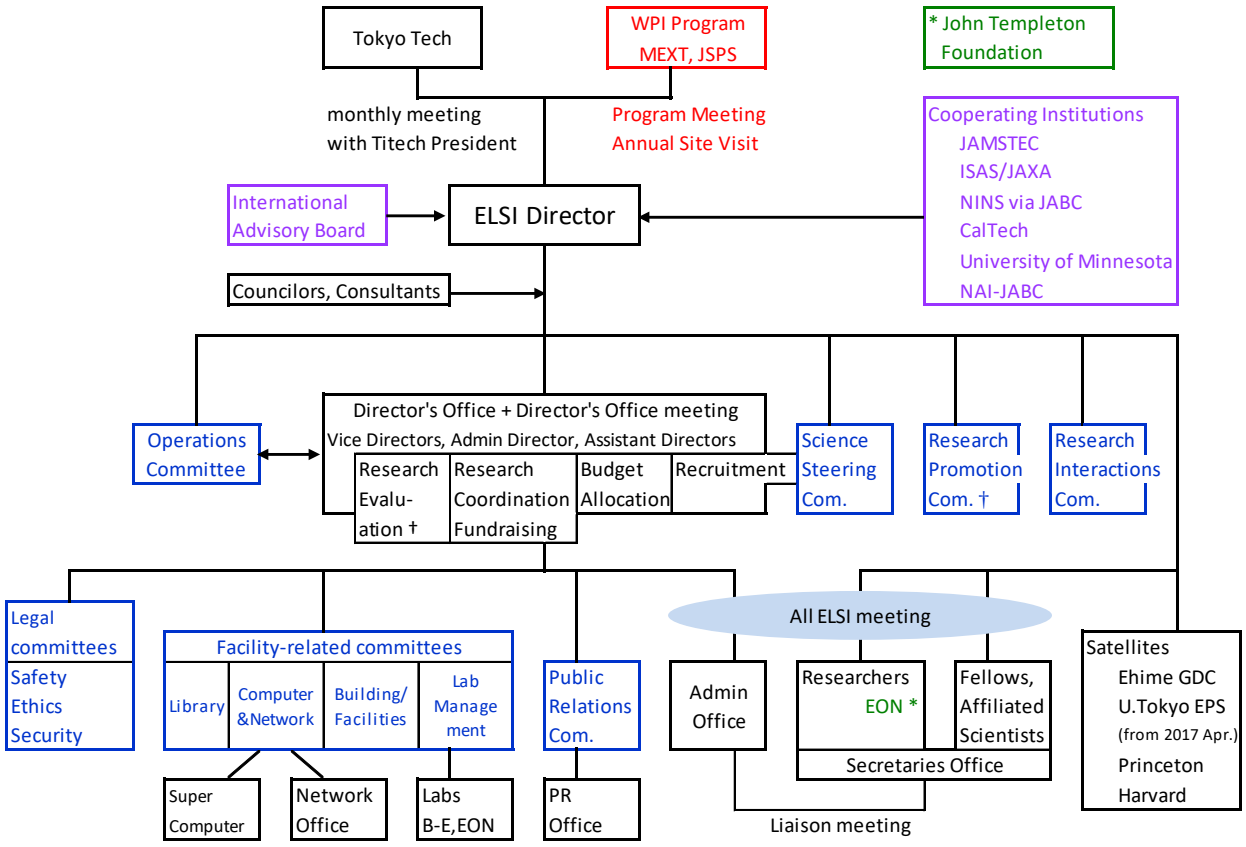
- New satellite at the University of Tokyo

ELSI signed the contract with the department of Earth and Planetary Science (EPS), the University of Tokyo, in order to promote cooperative researches on the formation, evolution, and habitability of planets and satellites in the Solar System and other stellar environments, and geological, geochemical and biological researches on the early history of the Earth. The satellite office of ELSI is established in the University of Tokyo, starting from April 2017.

- New research coordination

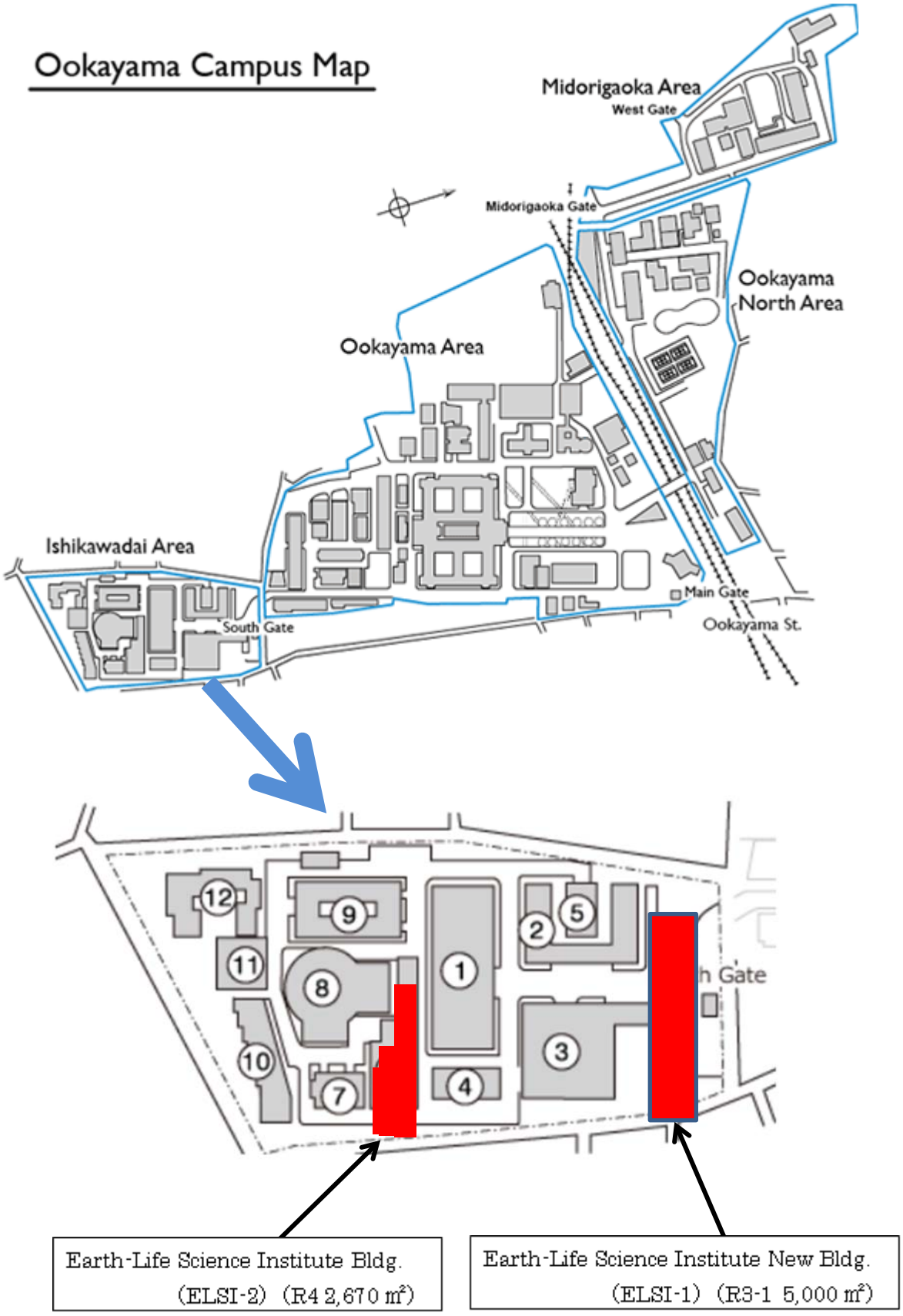
ELSI established the Japan Astrobiology Consortium (JABC) together with the Astrobiology Center of National Institutes for Natural Sciences (NINS) in 2015. JABC became an international partner of NASA Astrobiology Institute in 2015 August, and is working on cooperative research, joint international workshops and schools, and student education.

- ELSI Organization chart:



5. 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 3-2 6. Project Expenditures (the exchange rate used: 1USD= 100JPY)

1) Overall project funding

Cost Items	Details	Costs (Ten thousand dollars)
Personnel	Center director and Administrative director	20
	Principal investigators (no. of persons):8	74
	Other researchers (no. of persons):36	222
	Research support staffs (no. of persons):15	40
	Administrative staffs (no. of persons):17	76
	Total	432
Project activities	Gratuities and honoraria paid to invited principal investigators (no. of persons):23	1
	Cost of dispatching scientists (no. of persons):0	0
	Research startup cost (no. of persons):27	12
	Cost of satellite organizations (no. of satellite organizations):1	40
	Cost of international symposiums (no. of symposiums):1	1
	Rental fees for facilities	155
	Cost of consumables	10
	Cost of utilities	0
	Other costs	61
	Total	280
Travel	Domestic travel costs	1
	Overseas travel costs	8
	Travel and accommodations cost for invited scientists (no. of domestic scientists):11 (no. of overseas scientists):116	31
	Travel cost for scientists on secondment (no. of domestic scientists):0 (no. of overseas scientists):0	0
	Total	40
Equipment	Depreciation of buildings	10
	Depreciation of equipment	140
	Total	150
Other research projects	Projects supported by other government subsidies, etc.	97
	Commissioned research projects, etc.	111
	Grants-in-Aid for Scientific Research, etc.	264
	Joint reserch funds	13
	Donation	
	Total	485
Total		1387

	Costs (Ten thousand dollars)
WPI grant	585
Costs of establishing and maintaining facilities	0
Cost of equipment procured	41

2) Costs of Satellites and Partner institutions

Cost Items	Details	Costs (Ten thousand dollars)
Personnel	Principal investigators (no. of persons):1	
	Other researchers (no. of persons):5	
	Research support staffs (no. of persons):1	
	Administrative staffs (no. of persons):1	
	Total	30
Project activities		6
Travel		2
Equipment		1
Other research projects		0
Total		39

World Premier International Research Center Initiative (WPI)
Appendix4 FY2016 Status of Collaboration with Overseas Satellites

1. Coauthored Papers

- List the refereed papers published in FY2016 that were coauthored between the center's researcher(s) in domestic institution(s) and overseas satellite institution(s). List them by overseas satellite institution in the below blocks.
- Transcribe data in same format as in Appendix 1. Italicize the names of authors affiliated with overseas satellite institutions.
- For reference write the Appendix 1 item number in parentheses after the item number in the blocks below. Let it free, if the paper is published in between Jan.-Mar. 2017 and not described in Appendix 1.

Overseas Satellite 1: Interdisciplinary Program, Institute of Advanced Study (IAS) in Princeton (Total: 7 papers)

1) [3] Bada, J. L., J. H. Chalmers, and *H. J. Cleaves*. 2016. "Is formamide a geochemically plausible prebiotic solvent?" Physical Chemistry Chemical Physics 18 (30):20085-20090. doi: 10.1039/c6cp03290g.
2) [11] Chandru, K., A. Gilbert, C. Butch, M. Aono, and *H. J. Cleaves*. 2016. "The Abiotic Chemistry of Thiolated Acetate Derivatives and the Origin of Life." Scientific Reports 6:11. doi: 10.1038/srep29883.
3) [19] Fairen, A. G., J. M. Dohm, J. A. P. Rodriguez, E. R. Uceda, J. Kargel, R. Soare, *H. J. Cleaves*, D. Oehler, D. Schulze-Makuch, E. Essefi, M. E. Banks, G. Komatsu, W. Fink, S. Robbins, J. G. Yan, H. Miyamoto, S. Maruyama, and V. R. Baker. 2016. "The Argyre Region as a Prime Target for in situ Astrobiological Exploration of Mars." Astrobiology 16 (2):143-158. doi: 10.1089/ast.2015.1396.
4) [25] *Giovannelli, D.*, G. d'Errico, F. Fiorentino, D. Fattorini, F. Regoli, L. Angeletti, T. Bakran-Petricioli, C. Vetriani, M. Yucel, M. Taviani, and E. Manini. 2016. "Diversity and Distribution of Prokaryotes within a Shallow-Water Pockmark Field." Frontiers in Microbiology 7:21. doi: 10.3389/fmicb.2016.00941.
5) [62] Ledesma-Mateos, I., and *H. J. Cleaves*. 2016. "Alfonso Luis Herrera and the Beginnings of Evolutionism and Studies in the Origin of Life in Mexico." Journal of Molecular Evolution 83 (5-6):193-203. doi: 10.1007/s00239-016-9771-7.
6) [88] Parker, E. T., *H. J. Cleaves*, J. L. Bada, and F. M. Fernandez. 2016. "Quantitation of alpha-hydroxy acids in complex prebiotic mixtures via liquid chromatography/tandem mass spectrometry." Rapid Communications in Mass Spectrometry 30 (18):2043-2051. doi: 10.1002/rcm.7684.
7) [120] Jelen, B. I., *D. Giovannelli*, and P. G. Falkowski. 2016. "The Role of Microbial Electron Transfer in the Coevolution of the Biosphere and Geosphere." In Annual Review of Microbiology, Vol 70, edited by S. Gottesman, 45-+. Palo Alto: Annual Reviews.

Overseas Satellite 2: Origin of Life Initiative, Harvard University (Total: 2 papers)

1) [16] Domagal-Goldman, S. D., K. E. Wright, K. Adamala, L. A. de la Rubia, J. Bond, L. R. Dartnell, A. D. Goldman, K. Lynch, M. E. Naud, I. G. Paulino-Lima, K. Singer, M. Walter-Antonio, X. C. Abrevaya, R. Anderson, G. Arney, D. Atri, A. Azua-Bustos, J. S. Bowman, W. J. Brazelton, G. A. Brennecka, R. Carns, A. Chopra, J. Colangelo-Lillis, C. J. Crockett, J. DeMarines, E. A. Frank, C. Frantz, E. de la Fuente, D. Galante, J. Glass, D. Gleeson, C. R. Glein, C. Goldblatt, R. Horak, L. Horodyskyj, *B. Kacar*, A. Kereszturi, E. Knowles, P. Mayeur, S. McGlynn, Y. Miguel, M. Montgomery, C. Neish, L. Noack, S. Rugheimer, E. E. Stuken, P. Tamez-Hidalgo, S. I. Walker, and T. Wong. 2016. "The Astrobiology Primer v2.0." Astrobiology 16 (8):561-653. doi: 10.1089/ast.2015.1460.
2) [46] *Jia, T. Z.*, A. C. Fahrenbach, N. P. Kamat, K. P. Adamala, and *J. W. Szostak*. 2016. "Oligoarginine peptides slow strand annealing and assist non-enzymatic RNA replication." Nature Chemistry 8 (10):915-921. doi: 10.1038/nchem.2551.

2. Status of Researcher Exchanges

- Using the below tables, indicate the number and length of researcher exchanges in FY2016. Enter by institution and length of exchange.
- Write the number of principal investigator visits in the top of each space and the number of other researchers in the bottom.

Overseas Satellite 1: Institute of Advanced Study (IAS) in Princeton

<To satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2016	0	0	0	0	0
	2	1	2	1	6

<From satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2016	0	0	0	0	0
	0	0	0	0	0

Overseas Satellite 2: Harvard University

<To satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2016	0	0	0	0	0
	2	5	0	0	7

<From satellite>

	Under 1 week	From 1 week to 1 month	From 1 month to 3 months	3 months or longer	Total
FY2016	0	0	0	0	0
	3	4	0	0	7

World Premier International Research Center Initiative (WPI)
Appendix 5 FY 2016 Visit Records of World Top-caliber Researchers from Abroad

Researchers Total: 50

	Name	Age	Affiliation (Position title, department, organization)	Academic degree, specialty	Record of research activities (Awards record, etc.)	Time, duration	Summary of activities during stay at center (e.g., participation as principal investigator; short-term stay for joint research; participation in symposium)
1	Joseph Moran		Director, Laboratory of Chemical Catalysis, Institut de Science et d' Ingénierie Supramolé culaires, University of Strasbourg	Ph.D. Catalysis, Organic Chemistry		2016-04-11 to 2016-04-22	Participation in ELSI Seminar, Research meeting
2	Christophe Sotin		Chief Scientist, Solar System Exploration Directorate, JPL/Caltech	Ph.D. Planetary Science	Asteroid 54963 named Sotin (February 2012) NASA Group Achievement Awards: 2009 – Cassini Titan Orbiter Science Team (TOST) 2009 – Visual and Infrared Mapping Spectrometer (VIMS) Team 2004 – Aerial Regional-scale Environmental Survey of Mars (ARES) Mission Concept Development Team Medal 'Runcorn-Florensky' of the European Union of Geosciences (2008)	2016-05-30 to 2016-06-03	Research meeting
3	Brian Kennett		Professor, Research Shool of Earth Sciences, Australian National University	Ph.D. Seismology	Chair of Acess Committee, ANSIR National Research Facility (Director 2002-2014) Past President, International Association of Seismology and Physics of the Earth's Interior (IASPEI)	2016-05-31 to 2016-05-31	Research meeting
4	Mary Voytek		NASA Senior Scientist for Astrobiology, NASA's Astrobiology Program, NASA	Ph.D. Astrobiology	Board member of the American Geophysical Union	○2016-06-13 to 2016-07-01 ○2016-11-08 to 2016-11-18 ○2017-01-05 to 2017-01-18	○Participation in Site Visit, Research meeting ○Participation in Workshop, Research meeting ○Participation in ELSI Symposium, Research meeting
5	Douglas Lin		Professor, PBSci-Astronomy & Astrophysics Dept., University of California Santa Cruz	Ph.D. Astronomy and Astrophysics	Guggenheim Fellow, Otto Schmidt Medal, von Humboldt Fellow Sackler Fellow, Member of American Academy of Arts and Sciences Director, Kavli Institute for Astronomy and Astrophysics	○2016-06-14 to 2016-06-25 ○2016-11-20 to 2016-11-24	○Participation in International Advisory Board Meeting, Research meeting ○Research meeting
6	Caleb Sharf		Director of Astrobiology, Columbia Astrophysics Laboratory, Columbia University	Ph.D. Astrobiology	2011 Chambliss Medal/Award for Astronomical Writing, American Astronomical Society	2016-06-15 to 2016-06-28	Research meeting
7	Mark Thiemens		Distinguished Professor of Chemistry and Biochemistry, Dean, Division of Physical Sciences, University of California, San Diego	Ph.D. Atmospheric chemistry: physical chemistry of isotope effects; solar system formation	2011 Cozarelli Prize, 2010 Selected one of 100 distinguished alumni in 100 years. Florida State University, 2009 Goldschmidt Medal The Geochemical Society, 2007 Asteroid (7004) Markthiemens named in his honor, International Astronomical Union, 2006 Elected, National Academy of Sciences	2016-06-23 to 2016-07-08	Participation in ELSI Seminar, Research meeting
8	Michael Russell		Supervisor, Planetary Chemistry and Astrobiology Group, NASA JPL, Caltech	Ph.D. Mineral Deposit Geochemistry	William Smith Medal, 2009, Geological Society of London Nature 2009, feature in 459, 316-319 (Whitfield; Nascence Man)	○2016-06-28 to 2016-07-28 ○2016-11-08 to 2016-11-11	○Participation in Workshop, Research meeting ○Participation in Workshop
9	Stéphane Labrosse		Professor, ENS de Lyon	Ph.D. Geophysics	2000: Doistau-Blutet prize from the french academy of science. 2002: Doornbos memorial prize from the SEDI.	2016-07-08 to 2016-07-13	Research meeting
10	Thomas Henning		Director, Max Planck Institute for Astronomy Heidelberg Origins of Life Initiative	Ph.D. Physics, Astronomy	Fellow of the German Academy of Sciences Leopoldina. Honorary Professor at Heidelberg University. The asteroid 30882 has been named "Tomhenning" in his honour.	2016-08-24 to 2016-08-26	Research meeting
11	Terrence Deacon		Professor, Biological Anthropology, University of California, Berkeley	Ph.D. Human evolutionary biology and neuroscience	Merit Scholar / Lehman Fellow, Harvard University Psychiatric Neuroscience Fellow, Harvard Medical School Centenary Alumni Award, Western Washington University 69th James Arthur Lecturer, American Museum of Natural History J. I. Staley Prize 2005, School of American Research	2016-08-24 to 2016-08-26	Participation in Workshop
12	Michel Morange		Professor in Biology, University Paris 6, Ecole normale supé rieure	Ph.D. Biochemistry and molecular biology		2016-08-24 to 2016-08-26	Participation in Workshop
13	Athelstan Cornish-Bowden		Directeur de Recherche (Émérite), Centre National de la Recherche Scientifique	Doctor of Science, Properties of multienzyme systems	Hermann Niemeyer Professor, Facultad de Ciencias, Universidad de Chile, Santiago, Chile, 1992 (first holder of the Chair) and 1993. 2003. Elected corresponding member of the Academia Chilena de Ciencias. 2005. Elected Honorary Professor, Facultad de Ciencias, Universidad de Chile, Santiago, Chile	2016-08-24 to 2016-08-26	Participation in Workshop
14	Antonio Lazcano		Professor, School of Sciences, National Autonomous University of Mexico	Ph.D. Evolutionary biology	Past president of the International Society for the Study of the Origin of Life, "ISSOL"	2016-08-24 to 2016-08-26	Participation in Workshop
15	Michael Lachmann		Professor, Santa Fe Institute	Ph.D. Theoretical biology		2016-08-24 to 2016-09-04	Participation in Workshop, Research meeting

16	Patrick Forterre		Professor, Department of Microbiology, Pasteur Institute	Ph.D. Evolutionary Biology, Microbiology, Virology		2016-09-08 to 2016-09-09	Participation in Workshop
17	Eugene Koonin		Senior Investigator, National Center for Biotechnology Information (NCBI), National Library of Medicine (NLM), National Institutes of Health (NIH)	Ph.D. Evolutionary and computational biology	Elected to the National Academy of Sciences (2016)	2016-09-08 to 2016-09-09	Participation in Workshop
18	David Prangishvili		Group leader, Pasteur Institute	Ph.D. Virology	Prize of Council of Ministers of the USSR for Excellence in Science and Technology in 1989	2016-09-08 to 2016-09-09	Participation in Workshop
19	Hubert Klahr		Group head, Planet and Star Formation Dept., Max Planck Institute for Astronomy	Ph.D. Computational physics		2016-09-22 to 2016-09-24	Research meeting
20	Jan Amend		Professor of Earth Sciences and Biological Sciences, University of Southern California	Ph.D. Geochemistry		2016-10-04 to 2016-10-07	Participation in Workshop
21	James Badro		CNRS Research Director, Institut de Physique du Globe de Paris	Ph.D. Cosmochemistry, Astrophysics and Geophysical Experimentation	Fellow of the American Geophysical Union Fellow of the Mineralogical Society of America Grand Prix "Louis Gentil - Emile Bourcart", French Academy of Sciences, 2009 Macelwane Medal, American Geophysical Union, 2008	2016-10-28 to 2016-10-28	Participation in ELSI Seminar
22	Trevor Ireland		Professor, Research Shool of Earth Sciences, Australian National University	Ph.D. Isotope Geochemistry, Planetary Sciences	Hayabusa II Joint Science Committee (2014 -) Vice President, The Meteoritical Society (2015-16)	2016-11-06 to 2016-11-10	Participation in Workshop
23	Steve Mojzsis		Professor, Department of Geological Sciences, University of Colorado	Ph.D. Earth Sciences	ASSETT Award of Excellence in Technology in Teaching, University of Colorado, 2014 Distinguished Visiting Professor, Hungarian Academy of Sciences (Hungary), 2013-present Fulbright Faculty Scholar (France), 2007-2008	2016-11-06 to 2016-11-10	Participation in Workshop
24	Richard W. Carlson		Director, Department of Terrestrial Magnetism, Carnegie Institution for Science	Ph.D. Earth Sciences	Distinguished Lecturer, Mineralogical Society of America, 2015-16 Arthur L. Day Medal, Geological Society of America, 2013 Member, National Academy of Sciences, 2012	2016-11-06 to 2016-11-10	Participation in Workshop
25	Qing-Zhu Yin		Professor, Earth and Planetary Sciences Department, University of California, Davis	Ph.D. Geochemistry		2016-11-06 to 2016-11-10	Participation in Workshop
26	Marc Chaussidon		CNRS Research Director, Institut de Physique du Globe de Paris	Ph.D. Cosmochemistry, Astrophysics and Geophysical Experimentation	Fellow of Geochemical Society et de l'European Association for Geochemistry (2007) and Meteoritical Society (2010) Asteroid 7048 named after Chaussidon (International Astronomical Union, 2002)	2016-11-06 to 2016-11-10	Participation in Workshop
27	Kevin McKeegan		Professor, Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles	Ph.D. Geochemistry and Cosmochemistry	Science team leader for isotope measurements of the returned microscopic samples of comet P/Wild-2 Asteroid 5663 has been named McKeegan by the International Astronomical Union	2016-11-06 to 2016-11-10	Participation in Workshop
28	Hisayoshi Yurimoto		Professor, Faculty of Science, Department of Natural History Sciences, Earth and Planetary System Science, Hokkaido University	Ph.D. Geochemistry and Cosmochemistry		2016-11-06 to 2016-11-10	Participation in Workshop
29	Gary Huss		Director of W. M. Keck Cosmochemistry Laboratory, University of Hawaii	Ph.D. Cosmochemistry		2016-11-06 to 2016-11-10	Participation in Workshop
30	Alycia Weinberger		Staff Scientist, Department of Terrestrial Magnetism, Carnegie Institution of Washington	Ph.D. Physics	Distinguished Visitor, Haverford College, 2013 Beatrice Tinsley Visiting Fellow at University of Texas Austin (2011)	2016-11-14 to 2016-11-18	Participation in Workshop
31	Renata Wentzcovitch		Professor, University of Minnesota	Ph.D. Physics	Fellow of the American Physical Society Fellow of the American Geophysical Union Fellow of the Mineralogical Society of America Fellow of the American Association for Advancement of Science Fellow of the American Academy of Arts and Sciences 2008 Alexander von Humboldt Award for Senior US Scientists 2008 Japan Society for Promotion of Science Fellowship	2016-12-17 to 2016-12-23	Research meeting

32	Peter F. Stadler		Professor, University of Leipzig	Ph.D. Chemistry	Novartis Preis für Chemie 2002. Co-head (2005-2006), then Senior Scientific Advisor (since 2007) of the RNomics Group at the Fraunhofer Institute for Cell Therapy and Immunology. External Scientific Member of the Max Planck Society, affliated with the MPI Mathematics in the Sciences" in Leipzig since March 2009. Corresponding Member Abroad of the Austrian Academy of Sciences since 2010.	2017-01-06 to 2017-01-15	Participation in ELSI Symposium, Research meeting
33	Christoph Flamm		Professor, Institute for Theoretical Chemistry, University of Vienna	Ph.D. Biochemistry, Mathematical Chemistry, Theoretical Chemistry		2017-01-06 to 2017-01-19	Participation in ELSI Symposium, Research meeting
34	Reidar G. Trø nnes		Professor, Natural History Museum, University of Oslo	Ph.D. Geology, Experimental Petrology		2017-01-08 to 2017-01-15	Participation in ELSI Symposium, Research meeting
35	Mark Jellinek		Professor, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia	Ph.D Geophysical Fluid Dynamics	2003 Elected Scholar, Canadian Institute for Advanced Research	2017-01-08 to 2017-01-15	Participation in ELSI Symposium, Research meeting
36	Emmanuelle J. Javaux		Associate Lecturer, Department of Geology, University of Liege	Ph.D. Geology		2017-01-08 to 2017-01-15	Participation in ELSI Symposium, Research meeting
37	Carmen Gaina		Professor, Department of Geosciences, University of Oslo	Ph.D. Earth evolution and dynamics		2017-01-08 to 2017-01-16	Participation in ELSI Symposium, Research meeting
38	Joseph Nuth		Senior Scientist, NASA, Goddard Space Flight Center	Ph.D. Chemistry	NASA Group Achievement Award-Astrobiology Roadmap Team (2009) Elected a Fellow of the Meteoritical Society (2004)	2017-01-09 to 2017-01-15	Participation in ELSI Symposium, Research meeting
39	Costantino Vetriani		Professor, Institute of Marine and Coastal Sciences, Rutgers University	Ph.D. Molecular Biology		2017-01-09 to 2017-01-15	Participation in ELSI Symposium, Research meeting
40	Marc Hirschmann		George and Orpha Gibson Chair of Earth and Planetary Sciences, Professor, Department of Earth Sciences, University of Minnesota	Ph.D. Experimental Petrology	Fellow, Mineralogical Society of America 2003 McKnight-Land Grant Professorship 1999-2001	2017-01-09 to 2017-01-16	Participation in ELSI Symposium, Research meeting
41	Andrew Knoll		Fisher Professor of Natural History and Professor of Earth and Planetary Sciences, Harvard University	Ph.D. Geology	Walcott Medal, Mary Clark Thompson Medal of the National Academy of Sciences, Phi Beta Kappa Book Award in Science, Moore Medal of the Society for Sedimentary Geology, Paleontological Society Medal, and Wollaston Medal of the Geological Society of London	2017-01-09 to 2017-01-20	Participation in ELSI Symposium, Research meeting
42	Martha Grover		Professor of Chemical & Biomolecular Engineering, Georgia Institute of Technology	Ph.D. Chemical evolution, polymer organic electronics		2017-01-10 to 2017-01-14	Participation in ELSI Symposium
43	Nicholas Hud		Professor, School of Chemistry and Biochemistry, Georgia Institute of Technology	Ph.D. Biology, Biotechnology, Biochemistry	Fellow of the International Society for the Study of the Origin of Life in 2014. Sigma Xi Distinguished Lecturer.	2017-01-10 to 2017-01-15	Participation in ELSI Symposium
44	Simon Conway Morris		Professor, Department of Earth Sciences, University of Cambridge	Ph.D. Palaeobiology and Palaeoecology	The Walcott Medal 1987 PS Charles Schuchert Award 1989 GSL Charles Lyell Medal 1998 Trotter Prize 2007	2017-01-10 to 2017-01-16	Participation in ELSI Symposium, Research meeting
45	Lynn Rothschild		Senior Scientist, NASA Ames Research Center	Ph.D. Evolutionary Biology, Microbiology	2013 NIAC Fellow, NASA 2013 Lecture, Royal Swedish Academy of Sciences-Molecular Frontiers, May 2012 CEO Award, Gen9 G-Prize	2017-01-10 to 2017-01-17	Participation in ELSI Symposium, Research meeting
46	Loren Williams		Professor, School of Chemistry and Biochemistry, Georgia Institute of Technology	Ph.D. Physical Chemistry	Director of the NASA Astrobiology Institute from 2008 to 2015	2017-01-10 to 2017-01-19	Participation in ELSI Symposium, Research meeting
47	Sijbren Otto		Professor of Systems Chemistry University of Groningen	Ph.D. Systems Chemistry	2013 Elected Fellow of the Royal Society of Chemistry	2017-01-11 to 2017-01-14	Participation in ELSI Symposium
48	Marcelo Gleiser		Professor of Physics and Astronomy, Appleton Professorship of Natural Philosophy, Dartmouth College	Ph.D. Cosmology	Fellow and General Councilor of the American Physical Society. Recipient of the Presidential Faculty Fellows Award from the White House and NSF.	2017-01-11 to 2017-01-14	Participation in ELSI Symposium

49	David Yuen		Professor, Department of Earth Sciences, University of Minnesota	Ph.D. Geophysics and Geology	2010, Senior Visiting Professor, Graduate University of Chinese Academy of Sciences 2005, Fellow, American Geophysics Union	2017-02-13 to 2017-02-17	Research meeting
50	Razvan Caracas		Senior Researcher, CNRS Laboratoire de G éologie de Lyon	Ph.D. Material Physics	Ad-Astra Award for excellence in Research, Earth and Space Sciences, 2016 ERC Consolidator Grant “IMPACT: The Giant Impact and the Earth and Moon Formation”, 2015 Research Excellence Medal of the European Mineralogical Union, 2013 Prix Henri Buttgenbach, 2012, Academie Royale des sciences, des letters et des beaux-arts de Belgique, Bruxelles, Belgium	2017-02-17 to 2017-03-05	Research meeting

World Premier International Research Center Initiative (WPI)
Appendix 6 FY2016 State of Outreach Activities

Using the table below, show the achievements of the Center's outreach activities in FY2016(number of activities, times held).
※Describe those activities that have yielded novel results or that warrant special mention in the "Special Achievements" space below.
※In appendix 7, list and describe media coverage (e.g., articles published, programs aired) in FY2016 resulting from press releases and reporting.

Activities	FY2016(number of activities, times held)
PR brochure, pamphlet	2
Lectures, seminars for general public	25
Teaching, experiments, training for elementary, secondary and high school students	11
Science café	1
Open houses	1
Participating, exhibiting in events	3
Press releases	17

<Special Achievements>

■Events for Elementary, Middle, and High School Students

・Practice for high school students' reading acaedmic English paper

We put on a tour program for ten students from Fukushima Prefectural Iwaki High School, a designated SSH(Super Science High school), on February 22, 2017. In a first for our Institute, we had the students practice their reading comprehension with a thesis written in English by ELSI researcher Dr. Tomohiro Mochizuki. He himself gave a presentation to explain the background research before the reading comprehension drill, and explained the main points paragraph by paragraph as the students read. We had the students read the abstract of Mochizuki's thesis both before and after the drill, and according to their self-assessments, their levels of comprehension broadly improved following the drill. We received praise from their teacher, who said: "The students enjoyed the presentation about viruses and realized new things by reading the thesis in English, so you provided them with a very good experience."

■Public Lectures

・Kuramae Seminar co-hosted by Tokyo Tech Alumni Association and ELSI
"The Wonder of the Earth and Life -To What Extent Have We Discovered the Origin of Life? How Probable Does the Life Exist in the Universe? -"

・The 5th ELSI International Symposium Public Lecture
"We Don't Know "How We Began" Yet - Quest of Astrobiology for Origin of Life" / January 11, 2017

・Kavli IPMU-ELSI Joint Public Lecture
"Quest for "Origins"" / January 22, 2017

■Social Media for general public

・Facebook page "PR for PR room at ELSI" https://www.facebook.com/ELSIPRPR/ (since Oct. 2017)

■Books for general public

・Ida, S., *NHK Culture Radio - Science and Human "Seeking Exoplanets"*, NHK Publishing, 2016

・Ida, S., *Exoplanets and the Earth*, Iwanami Shoten, 2017

・Ida, S., Maruyama, S., et al., *Questions to 18 Scientists: Is There Anyone in the Universe?*, Kawade Shobo, 2017

World Premier International Research Center Initiative (WPI)
Appendix 7 FY 2016 List of Project's Media Coverage

	Date	Types of Media (e.g., newspaper, television)	Description
1	2016/4/21	TV	Scientific simulation movie made by Dr. Saito was introduced in the NHK BS program "Cosmic Front - NEXT "Mystery of Globular Clusters - Ancient Cities of the Universe"
2	2016/5/12	magazine	Dr. Fujishima was introduced in the article about human challenge to immigrate to the Mars in "Kodomo-no-Kagaku (Science for Kids)".
3	2016/5/28	newspaper	The Yomiuri Newspapers reported that the 57th Fujihara Prize was given to the Center Director, Professor Hirose.
4	2016/6/27	newspaper	The NIKKEI reported that Dr. Usui's comment was cited where he explaned about the water of Mars.
5	2016/7/2	radio	Dr. Fujishima appered as a gest in the radio program "Hiroshi Kume "Radio-Nan-Desu-Kedo" (This is a radio problem. Any problem?)".
6	2016/7/3	TV	Scientific simulation movie made by Dr. Saito was introduced in the NHK TV program "Sciense ZERO".
7	2016/7/5	newspaper	The Mainichi Newspapers reported that Dr. Genda and his colleagues had found that the two satellites of Mars had been made by collision with a celestial body.
8	2016/7/7	web article	Nature Planetary Science focused on Dr. Genda's research about formation of Martian moons in "This week's Research Highlights".
9	2016/9/11	TV	NHK educational TV program "Science ZERO" introduced ELSI collaborator, Vladimir Airapetian.
10	2016/9/27	TV	Nippon Television program "ZIP" cited comments of Dr. Kimura about NASA's announce on Europa.
11	2016/11/13	TV	Dr. Kurokawa, H. appeared as a guest in the TV program "Mirai-no-Kigen (Origin of future)" by TBS.
12	2016/11/17	TV	Dr. Genda appeared as a guest in the NHK BS program "Cosmic Front - NEXT" and mentioned about Venus.
13	2016/11/28	newspaper	The Mainichi Newspapers reported that ELSI had been donated 5.5 million dollars by an US foundation among many universities in Japan suffering from their serious financial situation.
14	2016/12/7	newspaper	Cutting edge technology and culture magazine "WIRED" reported that Dr. Fujishima had won WIRED Audi Innovation Award 2016.
15	2017/2/2	web article	Selected from scientific literatures "Pluto's dark equator explained", Dr. Genda's paper was also introduced at Nature's Research highlights.
16	2017/2/2	newspaper	The Asahi Newspapers reported the Dr. Genda's work to explain formation of the whale-like pattern of the surface of Pluto by collision with other planetary body.
17	2017/2/3	web article	Nature Astronomy reported the ELSI's workshop about exoplanets.
18	2017/2/3	web article	The Huffington Post mentioned about the 5th ELSI symposium in the article titled "The New Evolutionary Biology".
19	2017/2/9	newspaper	Dr. Genda explained in the article of the Mainichi Newspaper that there is major controverse about the mechanism of the emergence of the moon.
20	2017/2/23	newspaper(web article)	NIKKEI on the web reported that professor Hirose and his colleagues had found that the magnetic field of the earth existed even at the very beginning of the earth, which was generated by convection of iron, caused by separation of silicon dyoxide.