Chapter 11

Science Plan

Background to the development of Science Plan 2022:

Future Plans and Science Plans 1999 and 2009 were formulated as decadal scale plans. It has been about 10 years since the plan was partially revised during 2014 in response to the 2011 Great East Japan Earthquake Disaster, and a new plan is now being formulated.

In drafting the new plan, the Future Planning Committee has conducted the following surveys and reviews since last year.

1) Confirmation of the contents, process, and background of past future plans and science plans in 1999 and 2009, as well as the history and organizational changes of the ERI prior to Science Plan 1999 and Science Plan 2009.
2) Review of the achievement in terms of the current science plan (Science Plan 2009 and its revision, Science Plan 2009R).
3) Summary of "external review comments in response to the 2009 plan and its revised plan (2009R)" and identification of key issues raised.
4) Survey of plans and movements of various domestic and international solid Earth science institutions and departments.

We have also taken the following additional actions.

5) The framework of Science Plan 2009 is rooted in Science Plan 1999, and Science Plan 2009 focuses on its further implementation and establishing an efficient implementation system,
6) Scientific and technological advances and environments surrounding university research and education have changed drastically and rapidly over the past 20 years.

Considering these points, we have discussed reviewing the framework of the science plan by specifying "Scientific Grand Challenges" (SGCs) that are important for advancing the mission of the ERI, regardless of the time frame for accomplishment or feasibility. As a result, a draft was prepared by the group in charge (Grand Challenge [GC] group) established within the Future Planning Committee, and two symposiums were held for the all ERI members based on the draft. Then, after getting opinions and ideas from the ERI members, we finalized the SGCs.

Position of SGCs in the future plan:

In the section of the Review of Science Plan 2009 and 2009R (Document no. 3-09 of the April 2021 Faculty Meeting), a section "Future Development: Focusing on Interdisciplinary Collaborative Research" was proposed. In this section, we discussed challenges that have been accomplished so far and those yet to be accomplished, as well as the importance of interdisciplinary collaboration, which has been repeatedly pointed out in the previous external review comments. Incorporating these aspects into the new future plan is important for solving problems that have been highlighted and to ensure the continuity and development of current research. In contrast, the SGCs is positioned to provide broad, long-term directions for research and to add new elements to the current science plan and its review through identifying key scientific issues that are important for advancing the mission of the ERI. Considering this position, the following actions were taken.

(A) Various ideas, issues, and concepts were obtained through the GC group discussions and the ERI seminars, and these were used as elements to identify key issues comprehensively to create the SGCs.

(B) A new mid-term science plan was formulated, considering the major directions and new elements given by the SGCs, as well as elements including issues requiring continuing work and development or unachieved issues, as summarized in "Review of Science Plan 2009 and 2009R".

The new science plan was developed as an addition or multiplication of the two directions (the SGCs and the mid-term science plan) to approach key issues. Therefore, the new science plan is more comprehensive than the previous mid-term (10-year) science plans, including long-term and wide-ranging themes and scopes.

The regulations of the University of Tokyo (No. 67, adopted in 2004) and the ERI mission statement (ERI website) state that the purpose of the ERI is to conduct and promote advanced and multidisciplinary research on elucidating and predicting earthquake and volcanic eruption phenomena, preventing and mitigating the resulting disasters, and understanding the dynamics of the Earth's interior, which govern earthquake and volcanic phenomena. The inclusion in the mission statement of the promotion of multidisciplinary research, including of the Earth's interior, is deeply related to the background of the establishment of the ERI. When the reconstruction of “seismology in Japan” became an urgent need following the tragic events of the Great Kanto Earthquake in 1923, Hantaro Nagaoka, Torahiko Terada, and others emphasized the critical importance of understanding earthquakes and seismic phenomena from the standpoint of vibration engineering, physics, geophysics, and other disciplines (based on the “History of ERI” section of the ERI website). Regardless of recent scientific advances and changes in social structure, the history and objectives of the ERI are still important today.

11.1 Earthquake Research Institute Scientific Grand Challenges (SGCs)

The ERI's long-term goals may be itemized as follows:

- Quantitative understanding of the dynamics of the planet Earth
- Scientific understanding and prediction of tectonic events, including earthquake occurrence and volcanic eruptions
- Quantitative prediction of disasters associated with tectonic events and development of mitigation measures.

These items are interrelated and seamless in nature. Earthquakes and volcanoes are manifestations of Earth dynamics. Therefore, the origins of materials, forces, and energy involved in Earth dynamics, as well as the processes through which they are converted into tectonic events, constitute the fundamental mechanisms of earthquakes and volcanoes. Understanding of the mechanisms, along with suitable monitoring, data analysis, and numerical simulations, should lead to accurate reproduction/prediction of earthquake occurrence, volcanic eruptions, and surface events. In turn, this will enable disaster prediction and effective mitigation, and advances in mitigation will result in new needs for observation and analysis, which in turn will lead to further understanding of the fundamental mechanisms.

This section presents the Scientific Grand Challenges (SGCs) that the ERI will follow to achieve the above objectives. Firstly, this section covers the key issues by considering perspectives (A–G) below, which are the pillars of the SGCs. Secondly, a few particularly challenging tasks that warrant conscious attention are highlighted. Finally, with these tasks in mind, research directions are proposed that should be strengthened in the ERI in terms of perspectives (A–G).

(A) Determining the structure and state of Earth's interior

(B) Understanding global dynamics

(C) Understanding and predicting earthquakes and volcanic eruptions, and the causative processes

(D) Understanding disaster mechanisms and assessing associated risk

(E) Advancement of observational and computational technology

(F) A platform connecting (A–D) and integrated modeling

(G) Establishing a system that enables serendipitous discovery

(A–D) represent scientific objectives and (E–F) are approaches to achieving these objectives. Clearly, crisscrossing connections exist among (A–F). This section first starts by elaborating on perspectives (A–F), with emphasis on the connections among (A–D). In geosciences, which is concerned with the behavior of the planet Earth, it is essential to know what is present, where, in what quantities, and in what physical state (temperature, fluid pressure, and stress) within the heterogeneous Earth (i.e., perspective A). The spatial resolution that is required varies with the nature of the process governing the target phenomenon, and can be determined by evaluating the component sensitivities of the system behavior in the dynamic models constructed in (B–C).

Global dynamics (i.e., perspective B) is the driving force behind the processes leading to earthquakes and volcanic eruptions (i.e., perspective C). Although (B) and (C) are inherently seamless, the key processes and spatiotemporal scales are very different. Global dynamics (B) can be formulated within the framework of continuum mechanics, provided that heterogeneities in the relevant physical properties are macroscopic (i.e., amenable to deterministic description). The validity of the models in (B) can be mainly tested by the extent to which they explain the actual structural evolution of Earth through to its current state of mantle convection and plate tectonics. As such, for (A) it is necessary to elucidate how the structure and state of Earth's interior and nature of tectonic events have changed through Earth's history. In addition, studies of the tectonics of other planets are important for comparison with Earth, and such efforts would deepen the understanding of (B). In contrast, (C) is concerned with much shorter timescales, ranging from sequences of recurring earthquakes/volcanic eruptions through to fault slip during earthquakes and magma motion during eruptions, during which localized structures such as faults and volcanic conduits have an essential role. In particular, during earthquakes and eruptions, the dynamics are dominated by extremely discontinuous, nonlinear changes such as rupture and vesiculation constrained by preexisting complex structures. The validity of the models in (C) can be tested by comparison with observations on various timescales, including detailed history during each event, monitoring records of mass transport and the physical state during inter-event periods, and variations in event intervals.

Elucidating the history of tectonic events is also an important contribution from geoscience to hazard assessment, as such information is an essential input to (D). Research in perspective (D) aims to further incorporate the propagation mechanism of the effects of tectonic events and the response characteristics of the structures that might be affected. These contributions from (D) will yield two main benefits: assessing the likely damage, which is a prerequisite for implementing effective mitigation measures; and the real-time prediction of likely damage that can be communicated immediately after an event has started, which would help guide an efficient and rapid response.

To realize (A–D), observational and experimental data and interpretation techniques need to be extended or newly pioneered. Given that science and technology progress in unison, it is necessary to continuously improve technologies (i.e., perspecive E) for observations and experiments, and analysis and simulations, including the creation of innovative techniques and improvement of existing ones. To verify that models correctly reflect real processes, observations and experiments need to achieve greater accuracy, and their window (i.e., variety of independent information) needs to be expanded. Correspondingly, data interpretation needs to involve efficient methods for the simultaneous analysis and reproduction of large and diverse datasets. Furthermore, given the seamless nature of the processes in (A–D) and that the same observation reflects multiple structures and processes while reliable estimation of a structure or a process needs observations of different items, it is necessary to develop a platform (i.e., perspective F) for interdisciplinary collaboration. This platform will enable observations, data analysis, and modeling to be shared and integrated from perspectives (A–D), thereby dramatically promoting and sharing advances in each individual field.

Implicit in the above elaboration on perspectives (A–F) was a deductive approach, where everything from global evolution to seismic/volcanic disasters is modeled as a combination of processes based on the laws of physics and chemistry and are thence tested against observations and actual data. However, considering that many scientific revolutions are founded on entirely unexpected discoveries, an inductive approach is also important, whereby phenomena and data are examined for unknown correlations. The steady accumulation of a wide variety of observations and the availability of researchers with time to examine these are prerequisites for serendipitous discoveries. As such, it is important to establish a system (i.e., perspective G) that encourages serendipitous discoveries.

The following sections address the current understanding of Earth and the directions that need to be strengthened regarding perspectives (A–G). As such, it is important to note some key scientific challenges that must be addressed in order to approach the objectives identified at the beginning of section 11.1. Three of especially challenging tasks, which might be unaddressed forever if not given conscious attention, are described below.

(1) Measurement of key dynamics parameters (i.e., materials, temperature, absolute stress, fluid pressure, and strength)

The understanding that plate motion is a manifestation of large-scale solid convection, island arc magmatism is mass transfer derived from subduction, and that earthquakes are rapid shear ruptures caused by plate motion loading the schizosphere provides a unified explanation for the diverse observations to date. However, predictions of earthquake occurrences and volcanic eruptions are not as advanced as other scientific predictions methods such as weather forecasting. Weather forecasting with physics-based models is robust because atmospheric pressure, temperature, and humidity are measured over nearly the entire system. In contrast, the key parameters of the dynamics leading to earthquakes and eruptions (i.e., materials, temperature, absolute stress, fluid pressure, and strength) in Earth's interior are difficult to constrain from surface observations. Direct measurement of these parameters is also difficult even in relatively shallow structures, including faults and volcanic conduits, due to the difficulty of drilling beyond a few kilometers in depth. Although this is a difficult task that requires the creation of innovative technologies, it is necessary to obtain robust values of these key parameters at pivotal locations, as they are used as ground truth (cornerstone facts) to determine the processes that should be incorporated into physical models.

(2) Reconstructing the history of structural evolution and tectonic events

To validate the dynamics models of perspectives (B) and (C), an accurate knowledge of the past behavior of Earth is required. For perspective (B), it is necessary to know the irreversible and, in some cases, one-off changes associated with the cooling of Earth, such as the development of island arc–back-arc systems and the global evolution of the internal structure throughout Earth's history. For unambiguous determination of this history, it is important to use multiple disciplines, including geophysical modeling, geology, material sciences, and comparative planetology. For perspective (C), it is necessary to know the event history of earthquakes and eruptions that have recurred in a certain time and place in Earth's history. It is desirable to have as long and detailed record as possible for the same tectonic system. To achieve this, it is necessary to create innovative methods that overcome the limitations of current research. In parallel with such efforts, international cooperation should be further promoted to increase the number of case studies and areas covered, and to eliminate observational gaps.

(3) Frontiers of physics

Some key processes in seismogenesis and volcanic eruptions cannot be properly considered by existing physical laws. For seismic faulting, it has been observed that rupture growth resistance (per unit area) increases as the rupture progresses. This means that the rupture growth resistance is not known until the rupture is complete and the size of the earthquake has been fixed. Existing fracture mechanics, which assumes that rupture growth resistance is prescribed, cannot describe the dynamics of a fault rupture. Elucidating the physical conditions that control the size of an earthquake is a major challenge in seismogenesis, and it is necessary to create new fracture mechanics that is applicable to fractal structures, such that the entire rupture process can be modeled, from the beginning to the end of an earthquake proceeding on faults with multi-scale complex structures.

During volcanic eruptions, rapid changes in magma viscosity and permeability by many orders of magnitude occur due to phase changes associated with depressurization and cooling, as well as major changes in magma deformation and fracture modes. These processes are responsible for the observed diversity of surface phenomena and ejecta, but no constitutive law has been established that can capture such state transitions. A physics framework that can describe magma behavior from the shallow crust to the surface must be developed by combining experiments, theories, and observations of natural volcanic systems.

With tasks (1–3) described above in mind, the important Earth science problems that the ERI should address from perspectives (A)–(G) are now discussed, and new directions are proposed that should be strengthened in future research.

(A) Determining the structure and state of Earth's interior and (B) Understanding global dynamics

Once the distributions of composition, microstructures, and temperature are determined, the dynamics of solid flow in the lower crust and deeper in Earth can be described by the equations of motion, state, and chemical kinetics. Such a model can further incorporate the long-term tectonics of the shallow schizosphere to form a comprehensive physical system. The objective is to elucidate the distribution of materials and states that can explain actual observations (task 2) of the long-term evolution of Earth's internal structure and tectonics. New research directions that are necessary to achieve this include the acquisition of ground truth via the creation of robust measurement methods of key parameters, such as materials, temperature, and absolute stress (task 1), and strengthening the parameter constraints by comprehensive multi-physics simulations. Inclusion of the lower mantle (or even deeper Earth) in the modeled system would help suppress modeling arbitrariness.

(A) Determining the structure and state of Earth's interior and (C) Understanding and predicting earthquakes and volcanic eruptions, and the causative processes

The absolute level of stress that results in fault rupture remains enigmatic. It is necessary to measure the absolute stress and pore fluid pressure in the vicinity of faults (task 1). These parameters need to be measured not only at seismogenic depths, but also in ductile shear zones, which are considered to be the direct loading source of seismogenic faults. Furthermore, obtaining spectral information regarding stress heterogeneity through intensive measurements in the vicinity of a fault, in addition to the creation of fractal rupture mechanics (task 3), will greatly advance our understanding of earthquake predictability.

With regards to the interseismic processes of an earthquake cycle, it is important to describe in the framework of continuum mechanics the complex stress state and heterogeneous distribution of fluid and physical properties around the fault. This and monitoring and data assimilation would allow interseismic processes to be tracked and predicted over time. This is equivalent to the physics-based prediction of temperature, pressure, and vapor distribution in weather forecasting. However, for dynamic rupturing during earthquakes (task 3), a basic scientific problem remains. Even if this problem could be solved, the physical scenario is too complex to be described and predicted deterministically with a deductive model. Even for weather forecasting, the eventual precipitation forecast is based on statistics. A similar approach is needed for earthquake forecasting.

The migration and phase changes of magmas and fluids dominate the preparatory processes toward eruption, but the actual nature of the magma ascent path and accumulation field has not been elucidated. To understand the location, shape, and extent of magma and fluids, technological innovations that surpass the resolution of conventional exploration techniques are needed. It is also necessary to pioneer methods (task 2) that can decipher the entire magmatic history recorded in volcanic ejecta with high precision. During an eruption, significant changes are expected due to the movement of large amounts of high-temperature material and phase changes that occur over a relatively short time. In fact, various precursory phenomena are known to occur. It is necessary to undertake well-resolved spatial–temporal monitoring of magma transport from the mantle, excess pressure in upper crustal magma reservoirs, and the detailed properties of the ascending magma, including the temperature, volatile components and contents, volatile saturation, and solid–gas–liquid fractions. Such monitoring from the build-up to the end of an eruption, along with approaches based on an understanding of the magma state transitions (task 3) and ejecta analysis, will lead to more reliable, quantitative physical models of magma and fluid behavior and eruptive processes. This will greatly improve our understanding of volcanic eruption mechanisms and improve predictions of short-term transitions in volcanic activity.

(D) Understanding disaster mechanisms and assessing associated risk

In formulating disaster risk assessments and earthquake mitigation measures, preventing overlooking is important and hence we need to have a broad perspective. In addition to capturing infrequent but highly destructive phenomena by enhancing knowledge of the long-term history of faults, earthquakes, tsunamis, and volcanic activity (task 2), it is also necessary to conduct a quantitative assessment of the potential for various complex disasters and theoretically predictable, but currently unrecognized, types of disasters.

With regards to earthquakes, the main prediction targets are seismic ground motion, fault displacement, tsunamis, and damage to ground, buildings, and infrastructure. The physical mechanisms by which seismic source radiation causes disasters are relatively well understood. A future goal is to improve the reliability of disaster prediction to a level where it will be more helpful to society. To achieve this, in addition to the refinement of damage prediction through the efficient collection of the properties of building and ground, etc., technological innovations that enable a rapid response following an event are needed, both in quality and quantity. They include the immediate prediction of wave fields through real-time data assimilation and the immediate acquisition of infrastructure conditions.

For volcanic eruptions, the causes of damage are pyroclastic flows and plumes, which are both complex, high-velocity multiphase flows. To further understand these processes, it is necessary to have methods to observe their internal conditions (task 1). In addition, because large-scale eruptions have long-term effects on the atmosphere, hydrosphere, and biosphere, improvements in the assessment and immediate tracking of materials and heat are needed, which requires collaboration with disciplines outside of solid earth sciences.

(E) Advancement of observational and computational technology, (F) A platform connecting (A–D) and integrated modeling, and (G) Establishing a system that enables serendipitous discovery

To meet the observational needs of (A–D), technological challenges must be addressed, including in unexplored/extreme environments, such as those beyond the geosphere. It is also necessary to implement new observational quantities, and enhance the quantity, precision, and accuracy of observations and measurements. For numerical computational technology, it is necessary to be aware of the approaches aimed to make high-resolution inferences of the state and motion of matter, by simultaneous fitting to the abundant and diverse data that are becoming available due to innovations in observational technology. Such approaches will lead to a better understanding and prediction of phenomena of the ERI's concern. The research directions to be strengthened include: (1) the development of ultra-high speed computational methods to allow large-scale detailed analysis that can resolve local phenomena in large domains and over long periods of time; (2) mathematical and information science methods, such as data assimilation, to efficiently estimate model parameters, while taking into account uncertainties in the observed data; (3) computer architectures that can perform these calculations at high speed; and (4) methods that can simulate pre- and post-disaster societal situations. At the same time, these computational technologies are essential for seamlessly connecting perspectives (A–D), and thereby constructing an integrated model of Earth (perspective F).

Diverse and researcher-driven experiments and observations are the source of serendipitous discoveries (i.e., perspective G). In addition, steady data accumulation over long periods of time is important in earthquake and volcano science, which deals with processes over long timescales. The common platform (F), which accumulates these data, thereby increases the chance of serendipitous discoveries. Furthermore, the platform augments human's ability to grasp the diverse data, again helping serendipity. One approach for data utilization in this way is the search for correlations between different phenomena, which uses data science rather than human's physical intuition. Combined inductive and deductive approaches in simulations, such as estimating physical laws by data-driven assimilation modeling, should also be explored. Serendipitous discoveries will generate new scientific questions, leading to the acquisition of new observational and experimental data.

11.2 Mid-term Science Plan

(A) Understanding the structure and state of Earth's interior

Knowledge of Earth's constituent materials and their physicochemical states (i.e., temperature, stress, and fluid pressure) is essential for understanding processes in Earth's interior. The spatial resolution that is needed varies with the nature of the process, ranging from the atomic scale for studies of phase equilibria and reactions, microscopic scale for microstructures in faults and the solid–liquid distribution geometry during melt generation, to global-scale for subduction zones that are the sites of earthquake and volcanic activity. In the ERI, researchers from various fields of solid Earth sciences are working in these fields using different methods of observation (including direct drilling observations), analysis, experiments, and theory. However, to understand a wide dynamic range of structures and states from the atomic to global scale, including solid–liquid phases, it is necessary to integrate diverse disciplines and methods. For example, in addition to seismic constraints, the electrical conductivity and properties of melts and deep fluids are essential for determining the distribution of magma and fluids.

"Inter-disciplinary collaboration" will be promoted, which has been a part of the Science Plan for the past 10 years and aims to robustly constrain the structure and state of Earth's interior using the integrated approach described above. In the field of global dynamics, the seismic velocity, attenuation, anisotropy, and electrical conductivity from the upper mantle to the transition zone, including oceanic regions and subduction zones, will be determined by broadband ocean–land mobile observations, including international collaborations such as the Pacific Array. Based on these multi-dimensional data, the state and behavior of the lithosphere–asthenosphere system, and distribution of water and melting in the mantle will be determined. An understanding of the deformation and anelasticity of crustal and mantle materials obtained through laboratory experiments, and the composition and chemical state of materials obtained by analysis, will constrain material cycling and dynamics in subduction zones on a local and global scale, including the evolution of Earth.

In the fields of seismology and volcanology, to understand the spatiotemporal changes in the physical and chemical conditions of regions that generate earthquakes and volcanic eruptions, the spatiotemporal evolution of the seismic activity, fault slip, stress field, deformation field, temperature field, gravity field, seismic wave velocity structure, attenuation structure, electrical conductivity structure, heat flow, and fluid and gas upwelling will be determined at high resolution using nationwide observation networks, mobile dense observation networks, borehole observations, and remote sensing. A quantitative understanding of the structures of seismogenic zones and volcanoes from deep to shallow depths will be undertaken using an integrated approach involving geology, materials science, and geophysics. This will reveal the underlying processes that cause the variability and complexity of seismic and volcanic phenomena. Particular attention will be paid to the internal structures of fault systems and zones, and their development and growth patterns, frictional and deformational characteristics, stress loading processes and fluid pressure changes on faults, magma generation and accumulation in reservoirs, ascent and migration pathways of fluids and magmas, and distribution of groundwater systems.

(B) Global dynamics

The internal structure, state, and activity of the present-day Earth are the result of its thermal and material evolution since its formation, and contain information regarding Earth's history. To deepen our understanding of the dynamics of Earth's interior, it remains important to elucidate the multi-scale dynamics from microscopic to global scales through an integrated approach involving observational science that includes instrument development, materials science, condensed matter physics, and computational science, as has been conducted at the ERI for many years. These advances will be continued with an emphasis on integrating individual studies. If structures or states emerging from global-scale dynamics including the deep mantle as a broad-scale field, subduction zones are one of the important components included within the global-scale. This framework will provide the background for understanding the driving forces of catastrophic phenomena such as earthquakes and volcanic eruptions in island arc systems. The dynamics of island arc systems, based on global-scale dynamics, will be used as a foundation for understanding global dynamics as part of perspective (F). A further objective is to understand the deformation of the entire Earth system, including coupling between the solid Earth, atmosphere, and ocean, with a view to undertaking comparisons with other planets.

Efforts will continue to promote international, large-scale, multidisciplinary, broad-band mobile observations on the seafloor and land, as well as laboratory experiments on the deformation and inelasticity of mantle materials under upper mantle conditions. By integrating these approaches, a new model of oceanic mantle dynamics and an improved understanding of the oceanic mantle will be obtained. In addition to clarifying spatial variations in dynamics, temporal variations will be reconstructed from the information preserved in structures. Knowledge of material circulation in the entire mantle and subduction zones will improve our understanding of the structure and dynamics of the mantle by viewing the subduction zone as an entry point for mantle convection into which the lithosphere–asthenosphere system is subducted. For example, large-scale mobile observations on the seafloor, covering the outer-rise side of a subduction zone, may be conducted in addition to the regular observation network deployed throughout the islands of Japan and continental shelf regions. The current structure and kinematics obtained from these observations, as well as their evolution, will be constrained based on knowledge of materials science and modeling of crustal and mantle dynamics. New observational targets for multidisciplinary verification, based on geophysics, material science, and geochemistry, will be identified. A deeper understanding of Earth as a planet and its dynamics, in terms of the evolution of the mantle–core system, will be developed by studies of the long-term thermal history of Earth.

In addition to constraints from both the oceanic mantle system and land–ocean asymmetry, earthquake and volcanic activity in subduction zones will be assessed by considering the heterogeneity of material subducted along oceanic trenches and the heterogeneous distributions of earthquakes and volcanoes. By considering the area from the subduction zone to the back-arc as a single island-arc system, and attempting to understand deformation over a wide area and at various depths in an integrated fashion, a deeper knowledge of island arc dynamics and fluid circulation will be obtained on long temporal and spatial scales.

(C) Understanding and forecasting earthquakes and volcanic eruptions, and causative processes

Earthquakes and volcanic eruptions occur over shorter timescales than are considered in perspective (B), and the spatial and temporal evolution of these events is strongly dependent on localized and complex structures and states, such as faults and volcanic conduits. As a result, it is key to elucidate temporal changes that are extremely discontinuous and nonlinear. To understand and forecast earthquakes and volcanic eruptions, it is important to constrain the diversity and complexity of events, the basic processes that results in these events, and construct earthquake generation and volcanic eruption models.

To understand the processes leading to an earthquake, it is necessary to clarify how a fault begins to move and transition to dynamic rupture processes. To this end, physics-based models of earthquake generation at multiple scales will be used to constrain fault slip and deformation at different spatial–temporal scales that progress in the source region and modeling of various observed fault slip phenomena and complex dynamic rupture processes. To improve the reliability of earthquake forecasts, it is important to know the stress state and strength of faults. In addition to nationwide observation networks on land and sea, data from mobile dense stations and drill holes will be used to determine the stress state, pore fluid pressure, and their temporal and spatial changes near faults. This will allow direct comparisons of seismic activity (including slow earthquakes) and fault slip, thereby revealing the basic processes that cause earthquake rupture. Furthermore, by combining the monitoring results with physical models through data assimilation, the spatial–temporal evolution of fault slips and slow earthquakes will be forecasted. Statistical models of seismicity will be improved by focusing on the relationship between seismicity and the structure and state of the source region.

To understand the processes that lead to volcanic eruptions, it is necessary to constrain the state transitions of magmatic fluids at shallow depths (i.e., from the upper crust to the volcanic edifice at the surface). The parameters that control eruptions, such as the viscosity and phase changes of magmatic fluid in volcanic conduits, will be estimated to develop physics-based models and verify these through observations, experiments, and numerical simulations. Volcanic plume column and magma ascent models will be further developed until these can be directly compared with surface observations, and models for other surface phenomena such as pyroclastic flows will be developed. For physical processes at greater depths, an integrated model will be adopted that includes magma ascent from the deep magma chamber to the surface. It is essential to constrain the mechanical aspects of magma ascent and eruption, as well as the composition and physical properties of magma and the phase changes associated with varying temperature and pressure. This integrated approach will involve geophysics and materials science, and incorporate cutting-edge observational and analytical techniques.

For the forecasting of earthquakes and volcanic eruptions, and validation of physical models, it is necessary to determine the magnitude and history of past earthquakes and volcanic eruptions for long time periods. Detailed geological, historical, and archaeological data will be compiled that document the occurrence of past earthquakes and volcanic eruptions in Japan and abroad, which can be integrated with recent observational data and findings. The efficiency of event detection rates and homogeneity of the event catalog will be improved by revising the methodologies for identification and evaluation of past events. Furthermore, to elucidate the processes on a larger spatiotemporal scale, it is necessary to determine the deformational stress field, thermal structure, and magma and fluid distribution, as well as their temporal changes, in and around the earthquake source region and volcanoes, which will be undertaken in collaboration with perspectives (B) and (F).

(D) Understanding and forecasting of disaster mechanisms

To understand and mitigate disasters caused by earthquakes and volcanic eruptions, it is necessary to make forecasts for the periods immediately before, immediately after, and subsequent to a disaster. High-density ocean and land observational data will be used to assess the physical mechanisms of disasters and evaluate the hazards related to earthquakes, tsunamis, and volcanic eruptions that pose a threat to modern society. To prepare for earthquakes and volcanic eruptions, a real-time disaster forecasting system will be constructed to promptly identify the scale of the event, foresee future disasters, and assess their long-term impact on society.

In addition to high-density observational data obtained on land, new observational data from seafloor observational networks (e.g., DONET and S-net) and DAS will deepen our understanding of the physical mechanisms of earthquakes, tsunamis, and volcanic eruptions that result in disasters. In particular, earthquake source studies that use dense seismic observational data and dynamic rupture simulations to elucidate the causes of strong ground motions in the vicinity of fault zones will be undertaken, similar to the approach used for the 2016 Kumamoto earthquake. In addition, the relationship between strain accumulation (i.e., fault lock and slip) and dynamic rupture processes at shallow depths at the plate boundary that generated the giant tsunami of the 2011 Tohoku-Oki earthquake will be investigated. This will clarify the state and structure of the deeper plate boundary region that generated the strong ground motions. Observational, experimental, and modeling approaches will be used to conduct a comprehensive evaluation of the mechanisms of various disasters associated with volcanic eruptions, such as ash falls, lava flows, pyroclastic flows, mud flows, and mountain collapse. This will identify the magma supply system and internal structure of volcanoes, which will reveal disaster-prone areas, constrain magma accumulation, movement, and ascent by monitoring, and enable forecasting of the timing and magnitude of eruptions. A data archive will be constructed for the long-term preservation and utilization of continuous observational data during normal periods, disaster occurrences, and post-disaster periods.

In response to the change in the social environment and the diversification of man-made structures, a strong-motion simulation technique and source–subsurface structural model will be developed that can forecast broadband strong motion, such as very short-period ground motion that causes soil damage, strong motion in the vicinity of faults including permanent displacement, pulsing waves that can lead to the collapse of wooden houses, and long-period ground motion that affects skyscrapers. Utilizing a simulation-based ground motion forecasting system that will replace the current empirical strong motion predictions, forecasts will be made of strong motion in the vicinity of faults where observational data are sparse. Based on knowledge of the source physics and structural heterogeneity of the crust, a forecasting technique that can contribute to an earthquake-resistant design by quantitatively evaluating the uncertainty of forecasts will be developed.

By assimilating real-time observational data with high-speed simulations, an overall picture of an earthquake or volcanic eruption in the immediate aftermath will be constructed that also allows a real-time forecast of what will happen in the minutes to days afterwards. Based on various disaster scenarios utilizing numerical simulations and data science, a practical forecast technology that guarantees immediacy, reliability, and accurateness will be developed. Furthermore, new observational and analysis techniques will be developed to allow the early detection of large earthquakes based on changes in gravity, and the forecasting of distant tsunamis using atmospheric gravity waves. New technologies (e.g., building sensors and UAVs) will be used to develop a building damage assessment system for the period immediately after a disaster, as well as on an annual timescale. The observation systems and analytical methods for forecasting changes in volcanic activity, based on a model that combines observational data during volcanic eruptions with ongoing subsurface phenomena, will be strengthened. In addition, global effects, such as pumice stone damage, tsunamis generated by undersea eruptions, and meteotsunamis caused by atmospheric oscillations from volcanic eruptions, will be investigated.

(E) Development of innovative observational and computational technology

Earth science is a discipline rooted in observation. In recent years, the importance of data obtained using state-of-the-art observation techniques has increased. The ERI has already proposed three directions for technological development: (1) development of observational techniques with higher precision and sensitivity; (2) observations in new domains by the application of new observational technologies; and (3) innovative observations involving new observational quantities. These directions will be maintained in the future.

In recent years, new science has been pioneered by the availability of vast amounts of observational data. Furthermore, innovative numerical analysis techniques utilizing advances in computational, computer, information, and mathematical sciences have been developed, with which observational and analysis technologies are being integrated. In this science plan, development of innovative analytical and computational techniques that can contribute to new observations has been added. This includes innovative simulation methods, data acquisition methods, and analysis of large amounts of observational data, which are essential for simulation, modularization of observational and measurement systems, packaging of analytical software, and development of distribution systems for observational data. Some specific examples of this future development are listed below.

(1) Development of observational techniques with higher precision and sensitivity

- Observations of crustal strain, gravity, and ground motion using fiber optic sensing technology
- Data acquisition over a wider frequency range, at a higher sampling rate, and with a higher signal-to-noise ratio from small vibrational to strong ground motions
- Application of muography technology and satellite observations to integrated volcanic research

(2) Extension of observations into new domains by the application of new observational technologies

- Developments that enable observations in regions where measurements are difficult using current technologies, such as marine areas and active volcanoes
- Development of a wide variety of oceanic observational techniques, including acquisition of unmeasured physical quantities
- Observations using drones and other flying vehicles
- Application of exploration and analytical technologies used in planetary exploration to remote observations and chemical analysis in the field

(3) Innovative observations using new observational quantities

- Observations of the density structure of Earth’s interior and its variations using high-energy elementary particles such as muons

(4) Development of innovative analytical and computational techniques for new observations

- Processing of spatially dense, continuous, real-time observational data such as fiber optic sensing measurements
- Numerical simulations based on optimization methods and physical models with extremely high resolution
- Innovative simulations that would be difficult to achieve with current technology
- Innovative detection of earthquakes and tremors, and modeling of the seismic velocity structure in combination with data assimilation and machine learning

To develop these novel observational and computational technologies to obtain new scientific knowledge, researchers in the ERI need to closely cooperate with scientists and engineers. A system will be developed to construct new technologies rapidly and efficiently in the ERI, and promote collaboration and implementation of these developed technologies.

Furthermore, interdisciplinary collaboration based on the mathematical and computational sciences will be encouraged, and research collaborations on related events (e.g., economic losses and climate disaster) that also require social implementation will be explored.

(F) Platform and integrated modeling that connects (A–D)

For perspectives (A–D), a particular observation covers multiple structures and processes, and to reliably estimate them requires a range of observations. Therefore, it is necessary to develop a platform or framework for interdisciplinary collaboration and to share or integrate the observations, data analysis, and modeling. As a result, this is expected to simultaneously and rapidly advance the individual research fields, as well as to act as a foundation for open scientific discussions. The construction of a platform to systematically and efficiently acquire, share, and analyze large amounts of multidimensional data in conjunction with perspective (E) is related to (A–D). In particular, to establish collaborations between science, engineering, and disaster prevention, it is important to seamlessly capture real-time changes, forecast event occurrence, forecast phenomena obtained by data assimilation, and undertake statistical evaluation based on Bayesian methods using an appropriate network, computational methods, and storage environment.

Data and interpretations of volcanic and subvolcanic structures, as well as eruptive and magmatic activity, have been obtained by a variety of methods, including satellite, geodetic, seismic, electromagnetic, gravity, heat flow, and muon geophysical observations. Simulations of eruption dynamics and magma production and ascent have been obtained using physical properties, chemical and isotopic compositions of rocks, magma, and fluids, and advanced material and data analysis. However, it is difficult to predict the processes and disasters related to magma generation, ascent, and eruption with sufficient accuracy simply by analyzing and interpreting these diverse data in isolation. For example, to determine where and how much magma exists and to identify the magma reservoir, seismic wave analysis is not sufficient, and it is necessary to integrate and interpret the various observations and data within a single platform. This is true for magma beneath volcanoes and for faults and other structures containing aqueous or supercritical fluids.

Such a platform is also essential for the construction of an integrated model of island arc dynamics that describes the processes from magma generation and ascent to eruption, earthquakes, crustal deformation, and even the formation and evolution of an arc, including the Japan arc, as a single dynamic system. The subducting plate–subducted island arc–back arc are considered within the framework of the island arc dynamics model, which aims to provide an integrated understanding of processes from deep to shallow depths. An understanding of global structures and processes will be promoted by: (1) accurately capturing the lithosphere–asthenosphere system; (2) reconstructing plate motions; (3) predicting geological phenomena through dynamic modeling of the crust–mantle system including material cycling (e.g., water); and (4) verifying these phenomena through geophysical and geochemical observations.

By establishing this platform, the gap between scientific/engineering research in the ERI and the engineering/societal demands for disaster mitigation will be bridged. Participation of a wide range of research fields in the ERI, along with collaborations within the university, including the CIDIR and Interfaculty Initiative in Disaster Prevention and Revitalization Research, and collaborations with the DPRI (Kyoto University) will enable interdisciplinary research in the fields of earthquake source physics, tsunami prediction, and disaster mitigation. This will result in socially relevant, innovative, observational and analytical technology systems that enable the immediate estimation of structural damage.

(G) Schemes for serendipitous discoveries

Excellent research is often a function of the outstanding talent and efforts of individuals. Unexpected discoveries can occur through trial and error, based on new ideas and research activities designed for other purposes. Recent advances in digital transformation (DX) in academic research have dramatically enhanced the data collection capabilities of researchers by enhancing methods for processing large amounts of observational data and extracting information from the processed data. This facilitates serendipitous exploration of data archives. The platform and integrated model developed in perspective (F) will promote interdisciplinary collaboration in modeling–verification research, and the data collection, analysis, and display capabilities will expand human cognitive abilities, and could also be used for other research such as data science. Researchers need a secure research environment that allows them to have sufficient free time, and be willing to take advantage of it, to produce groundbreaking and original results. It is desirable to encourage researchers to establish challenging tasks on an individual-level, and take on challenges even if failure is one possible outcome.

It is well known that the free and frank exchange of ideas amongst researchers often leads to new collaborative research, and discussions between those in different research fields can directly identify the solution to a problem in a specific research field. SGC seminars will be held periodically as a mechanism for such an exchange of ideas. In some cases, the application of observational techniques and analytical methods in other fields of Earth science, or even in other disciplines, may bring about new advancements in the solid Earth sciences. This exchange between related fields and the transfer of new technologies with data sharing via international observational campaigns will create both openness and competition amongst researchers, which will increase opportunities for new discoveries.

The development of observational technologies with enhanced accuracy and sensitivity, and that enable “anytime” and “anywhere” observations and measurement of new observational quantities (perspective E), are the key to serendipitous discoveries. In addition, the solid Earth science research projects listed in perspectives (A–D) are the foundation for future serendipitous discoveries.