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Volcanological challenges to understanding explosive large-scale eruptions

Nobuo Geshi*

Abstract

An explosive eruption, associated with the formation of a large ignimbrite sheet and collapsed caldera, is the most severe volcanic disaster on Earth. As modern society has little experience with natural disasters triggered by such events, the integration of volcanological knowledge from geological, petrological, geochemical, and geophysical disciplines is necessary for risk assessment and hazard management planning of large-scale explosive eruptions. Here, I review current volcanological attempts at revealing the mechanisms underlying large-scale explosive eruptions to highlight future objectives. The detection of massive magma storage regions with the potential to generate large-scale explosive eruptions should be the first objective of risk evaluation and assessment for caldera-forming eruption scenarios. This detection requires the development of geophysical techniques used for structural exploration. Geochemical and petrological explorations of leaked gas and magma during precursory eruptions can be useful for investigating the state of a body of underground magma. Evaluation of the eruptibility of a magma chamber is also important for risk assessment, as is the estimation of the timescales of magma accumulation. Defining the triggers that destabilize large volume magma chambers that serve as zones of long-term storage is crucial for being able to provide short-term alerts. Petrological investigations of the magmatic products from past large-scale explosive eruptions are a key tool for such a goal. Modeling the distribution of erupted material, such as huge ignimbrite sheets and co-ignimbrite ash fall, is also crucial for risk assessment of large-scale explosive eruptions. Advancing the understanding of the mechanisms and effects of large-scale explosive eruptions requires development in various fields of volcanology along with the integration of knowledge from multiple disciplines, thus promoting progress and interaction across various areas of volcanology and science and technology.

Keywords: Caldera, Large-scale explosive eruption, Disaster

Introduction

Large-scale explosive eruptions are one of the most serious natural disasters on Earth, as they often result in a large area of devastation and can have a substantial impact on the global climate (e.g., Rampino and Self 1982, Rampino et al. 1988; Sparks et al. 2005; Self 2006, 2015). Collapse caldera surrounded by ignimbrite sheets is the typical geological evidence for large-scale explosive eruption. Volcanological investigations clearly show that the potential risks of these eruptions on our modern society are non-trivial (e.g., Orsi et al. 2004; Tatsumi and Suzuki-Kamata 2014; Papale and Marzocchi 2019). For example, geological investigations reveal that several mega-cities on the Kyushu and Hokkaido islands of Japan are located within areas affected by the late Pleistocene ignimbrite sheets that were ejected from still-active collapse calderas such as Aso, Aira and Shikotsu (Machida and Arai 2003). Italy, New Zealand and other countries with active caldera volcanoes are also at risk of large-scale explosive eruptions (Rhoades et al. 2002; Orsi et al. 2004). However, there is almost no social preparation for the potential disasters induced by these large-scale explosive eruptions because the society regards the frequency

*Correspondence: geshi-nob@aist.go.jp
Research Institute of Earthquake and Volcano Geology, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Site 7, 1-1-1Higashi, Tsukuba, Ibaraki 305-8567, Japan

of these events is as "low" and their risk is "negligibly small".

With a serious gap between social demands and our scientific knowledge, the challenges imposed on volcanology should be the integration of the achievements of volcanology and related research fields of Earth science to present correct views of these large-scale explosive eruptions to society. Interdisciplinary research efforts among the fields of Earth and planetary sciences are required to make precise evaluations of the potential risks of future large-explosive eruptions. Such efforts must undertake analyses of the driving mechanisms of such large explosive eruptions, and evaluation of the potential sites and timing of impending eruptions. As these topics are the general subjects of volcanological research, overview of those studies in recent years will clarify the current achievements of volcanology and the outstanding issues to be tackled in the future.

The large-scale explosive eruptions considered in this paper are of a scale that modern society has rarely experienced but our knowledge shows that these eruptions are by no means rare from the view of volcanology. The largest volcanic eruptions worldwide since the 20th century, which is the history of the monitoring of volcanic activity, are the 1912 Katmai and 1991 Pinatubo eruptions (Hildreth and Fierstein 2012; Newhall and Punongbayan 1996). The intensity of these eruptions is equivalent to that of VEI 6 (Volcanic Explosivity Index; Newhall and Self 1982). It is clear that these eruption scales are by no means "large scales" from the view of geological evidence. There are two main reasons to address these scales of eruptions here. First, the knowledge of the public is generally limited to the largest eruptions experienced by modern societies, and most of the societal activities of disaster preventions are based on the magnitude of such experienced volcanic eruptions. The second reason is that even our knowledge of modern volcanology is also biased by the case studies of most recent eruptions, where instrumental observations have accumulated sufficient data. We should recognize that the history of the monitoring of volcanic activity with modern instruments is limited to at most the last few decades.

Potential impact of a large-scale explosive eruption

Geological observations clearly show the presence of much larger explosive eruptions than we have experienced during the past few centuries. Collapse calderas surrounded by ignimbrite sheets provide evidence of explosive eruptions generally larger than VEI 6. Geological investigations of tephra reveal more than ten ignimbrite eruptions, equal or larger than VEI 7, detected within the last 200 ka for the Japanese Archipelago (Machida and Arai 2003). The youngest known eruption with VEI ≥ 7 in the Japanese archipelago is the Kikai-Akahoya eruption that occurred from the Kikai caldera at around 7.3 ka. We also know the eruptions as large as VEI 7 occurred from the calderas of Kikai (95 ka, 7.3 ka), Ata (~ 100 ka), Aira (30 ka), Aso (141 ka, 130 ka, and 90 ka), Toya (~ 114 ka), Shikotsu (46 ka), and Kusharo (~ 120 ka and 40 ka) (Fig. 1). In the Japanese Archipelago, the occurrence of explosive eruptions equal or larger than VEI 7 in the late Pleistocene to Holocene is limited to the Kyushu Island on the northern part of the Ryukyu Arc and Hokkaido Island on the southernmost part of the Kuril Arc.

Eruptions on these scales would inflict severe damage to modern society; an area covered by ignimbrite would be destroyed by the hot blast and rapid sedimentation of massive volumes of pyroclastic material. The ignimbrite sheets produced from the VEI 7 class eruptions listed above would produce ignimbrite at distances approaching ~ 100 km from the caldera. The Aso 4 ignimbrite erupted approximately 90,000 years ago, covered the majority of Kumamoto, Oita, Saga, Fukuoka, and Yamaguchi Prefectures, a total residential area of ten million people currently (Kaneko et al. 2007 and references therein).

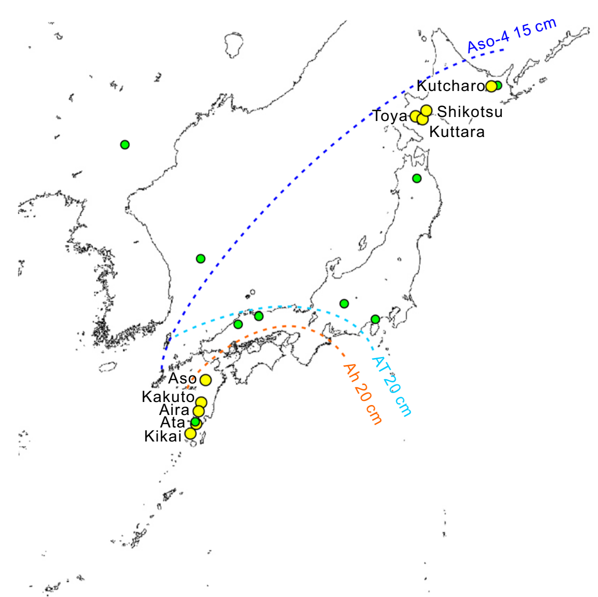

Fig. 1 Locations of volcanoes that have produced VEI > 6 eruptions during the late Pleistocene and Holocene in and around the Japanese archipelago. Yellow circles show the sites of VEI 7 eruptions. Green circles indicate the volcanoes which produced VEI 6 class eruptions. Representative isopach lines of three co-ignimbrite ash falls (Aso-4 at ~ 89 ka from Aso caldera, AT erupted at 30 ka from Aira caldera, and Ah erupted at 7.3 ka from Kikai caldera) are shown

Ashfall from these large-scale explosive eruptions also poses a significant threat to human populations. Both the eruption column from the vent and the ash cloud rising from the spreading pyroclastic flows mainly cover the areas that are downwind from the eruption source. Ashfall deposits can exceed 10 cm at locations greater than 1000 km downwind from the source caldera (Tatsumi and Suzuki-Kamata 2014). The deposition of thick ashfall can inflict severe damage to transportation networks, including roads, railways, air routes, the electrical grid, and agricultural production. Fine ash and aerosols injected into the stratosphere can spread throughout the world and have a severe impact on the global weather patterns (Rampino and Self 1982, Newhall et al. 2018).

Research targets on large-scale explosive eruptions

Evaluations of the potential sites and timing of large-scale explosive eruptions are required for assessing the risk of disasters induced by these events. Because large-scale explosive eruptions have evolutionary stages with different timescales and phenomena, we should set different objectives and methods to detect the processes of each (Table 1 and Fig. 2). Factors complicating the problem are that the timescales of the preparatory processes prior to these eruptions are case-by-case, and the order of these preparatory processes may not be constant, though Table 1 has been simplified for explanation of model case.

The following sections give an overview of these topics and consider how the technologies and knowledge in the fields of Earth science can be applied.

Detection of magma chambers

To make a preliminary evaluation of the potential for a large-scale explosive eruption, we should identify the potential sites and timing of an eruption. Because large-scale explosive eruption requires the accumulation of a certain volume of magma within a storage zone at shallow depth in the Earth's crust (Fig. 2-1), detection of the location and size of a magma chamber is crucial for evaluating the potential site of a large-scale explosive eruption. Many caldera volcanoes are sites of recurrent large-scale explosive eruptions, and are therefore candidates for the source of future eruptions. Since magma accumulation for future large-scale pyroclastic eruptions may be progressing in places that do not exactly coincide with the current locations of caldera volcanoes, detection of new magma chambers is also an important endeavor (e.g., Hamling et al. 2016). The presence of a shallow magma chamber of a certain volume, therefore, indicates a site with the potential for a large-scale explosive eruption.

There are several geophysical approaches for detecting hidden magma chambers. The region of magma storage is expected to be manifest as a low-velocity zone for seismic waves; the detection of a low-velocity zone can thus reveal a zone of magma storage (e.g., the low-velocity zone beneath Valles Caldera; Roberto et al. 1991). Seismic wave reflections between the magma body and surrounding host rocks can also potentially detect the roof of the magma chamber (e.g., the Campi Flegrei caldera; Zollo et al. 2008). Recent developments in surveys of electrical resistivity enable the detection of the presence of a low-resistivity zone beneath some calderas in which magma can be stored (Heise et al. 2010). Especially, regional three-dimensional electrical resistivity structure surveys covering several caldera areas are expected to be carried out over a wide area in the future as a powerful exploration method for detecting the potential locations of magma chambers beneath caldera volcanoes (e.g., Hata et al. 2020).

Petrological investigations of the erupted products of past volcanic eruptions can also constrain the depths of magma storage. If a portion of a large volume magma source is leaked during a relatively small-scale eruption, the petrological characteristics of the erupted magma can serve as an indicator of the magma storage conditions and the potential of future large-scale eruptions. Several past large-scale eruptions have had precursory minor eruptions prior to the main caldera-forming eruption (Nagaoka 1988). Herein, some key petrological tools for defining magma storage depths are reviewed. Volatile element (H_2O and CO_2) concentrations in glass inclusions trapped in phenocrysts within erupted magmas are used for estimating the pressure conditions of the magma storage (Lowenstern and Hurwitz 2008). The solubility of volatiles in silicate magmas is dependent on pressure; the volatile concentration in magma is thus correlated to the pressure that is exerted on the magma (e.g., Liu et al. 2005). Phenocrysts, which are formed inside a magma chamber, trap silicate which then melts inside the crystal. When a crystal is erupted with its surrounding magma, the melt cools within the crystal and forms a solid, glassy inclusion. The volatile element concentration in glass inclusions can record the pressure within the magma chamber when the melt was trapped in the crystal and if the melt was saturated in the volatile species. Many high-pressure experiments have been conducted to confirm the relationship between pressure and solubility of volatile elements. The chemical composition of melts is also an important factor in determining the solubility of volatile species. Actual volatile element concentrations in glass inclusions are measured by microscale analytical techniques, including Fourier Transform Infrared (FTIR) micro-spectrometry (Nichols and Wysoczanski 2007),

Table 1 Objectives and methods for different evolutional stages of large-scale explosive eruptions

Stage	Possible timescale before climactic eruption	Magma process	Research targets	Possible observation techniques
Stable	Up to 10^4–10^5 years	* Generation of silicic magmas by fractionation and/or crustal melting. * Accumulation of silicic magma within a shallow level of the earth's crust	* Presence of magma chamber * Magma eruptability within the magma chamber *Prior eruptions from this volcano	* Seismic tomography * Electrical resistivity survey * Geological and petrological investigation of previous eruptions of this volcano
Unrest	Less than 1 year (probably months)—years	* Destabilization of silicic magma chamber * Diking of the host rock and magma intrusion toward the surface	* Pressure condition inside the magma chamber * Dike intrusion process * Degassing during magma ascent	* Geodetic monitoring (ground and remote) * Seismicity monitoring * Gas geochemistry
Onset of eruption	Less than 1 week—up to years	* Leaking of magma from the chamber * Decompression of magma chamber for collapse	* Pressure condition inside the magma chamber * Magma discharge rate and accumulative volume of erupting magma	* Geodetic monitoring (ground and remote) * Petrological investigation of erupted magmas * Seismicity monitoring * Gas geochemistry * Rader sensing (radar interferometry and single-shot views through clouds)
Climactic eruption	N/A	* Extraction of magma from main body of the magma chamber * Collapse of the roof of magma chamber *Spreading of ignimbrite sheet	* Pressure condition inside the magma chamber * Magma discharge rate and accumulative volume of erupting magma * Behavior of ignimbrite	* Geodetic and seismic monitoring (if stations still alive) * Satellite remote sensing of ignimbrite spreading and of ash clouds and sulfate aerosol

*Note that the stages 2 and 3 can revert back to stages 1 and 2 before any eventual climactic eruption

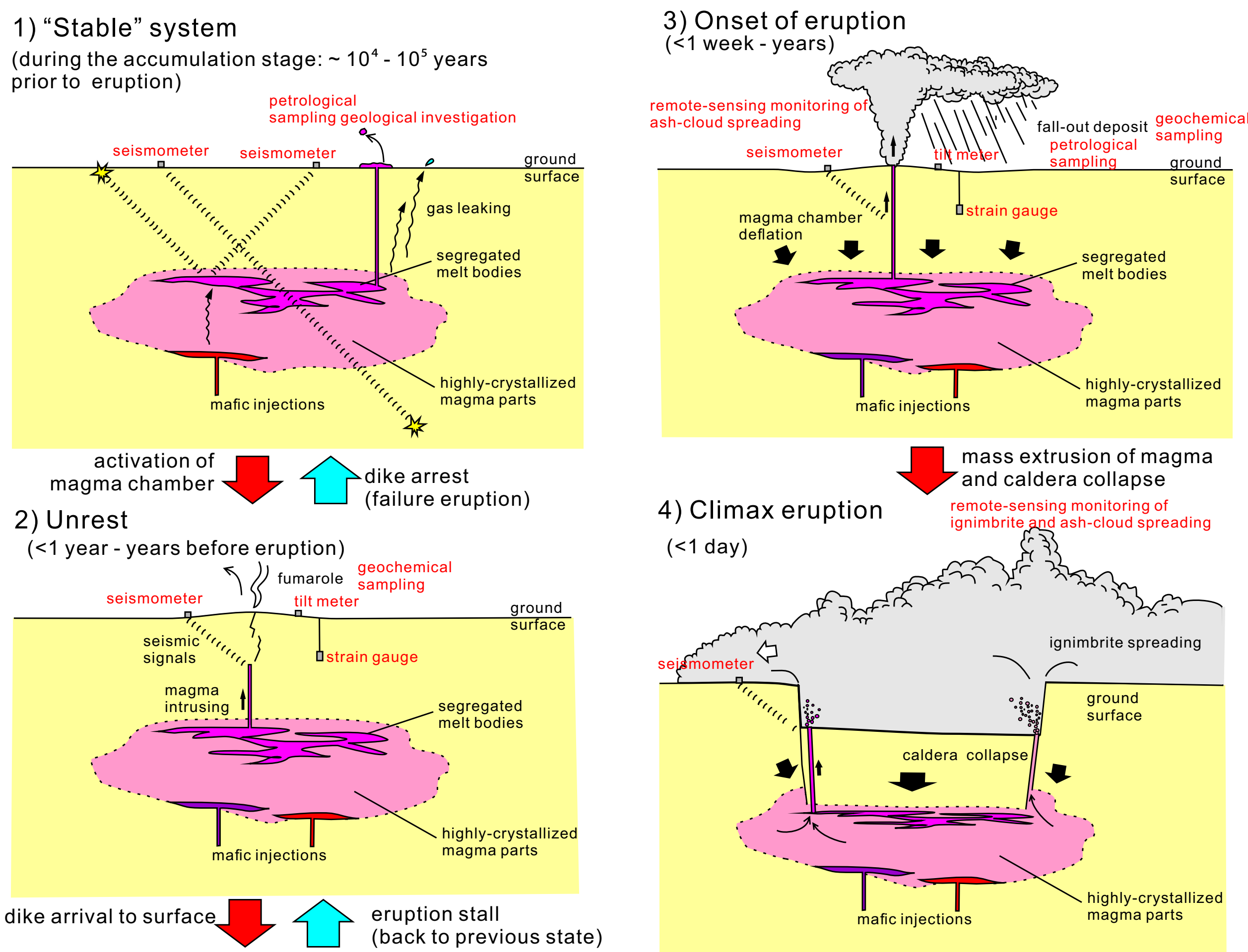

Fig. 2 Summary of volcanological phenomena associated with large-scale explosive eruptions and the methods used for their detection. (1) During the stable accumulation stage, detection of the magma chamber prior to eruption is crucial. Some geophysical explorations of massive liquid zones (potential magma chamber) can be useful. Geochemical and petrological investigations on the leaked materials (magma and gases) from the magma chamber also can be potential methods to monitor the state of magma chamber. (2) Diking from the activated magma chamber may cause "unrest" of the volcanic system. Detection of the ground deformation and seismic activities can detect the progress of diking from the magma chamber toward the ground surface. Geochemical investigations of fumarole gas and ground gas emission may be also useful. Eruption does not occur when the propagating dike is arrested within the host rock. (3) After onset of eruption, monitoring of the eruption cloud will be useful to detect the magma discharge rate. Syn-eruptive ground deformation also shows the deflation of magma chamber by magma extraction. Geochemical and petrological investigations on the erupted magma can provide direct information about the magma storage which is feeding the eruption. Many eruptions may stall by various factors and the system back to the previous state. (4) After the eruption reaches to climax eruption (VEI 6 or larger), rapid deflation of magma chamber results collapse of the roof of magma chamber which can be detected by geodetic data and seismic signals. Monitoring of the behavior of ignimbrite and co-ignimbrite ash fall by remote-sensing methods is useful for evaluating widespread impacts

Raman micro-spectrometry (Thomas 2000; Di Muro et al. 2006), and Secondary Ion Microprobe Spectrometry (SIMS) (Hauri 2002; Hauri et al. 2002).

The assemblage of minerals within erupted magmas, based on phase equilibria, is also used to estimate magma storage temperature and pressure conditions (e.g., Putirka 2005, 2008; Waters and Lange 2015). Applying assumptions of the density of the host rock, lithostatic pressure levels can be converted into an estimation of depth from the ground surface to the magma storage region. Phase diagrams show the equilibrium mineral assemblage at a given pressure, temperature, and composition (with volatile elements). The rhyolite-MELTS software package (Gualda et al. 2012) is widely used to determine the phase equilibration at a given combination of temperature, pressure, and volatile element concentration.

Evaluation of the eruption potential of magma chambers

Evaluation of the eruptibility of a magma chamber (Stolper and Walker 1980) is also an important issue for assessing the potential of a large-scale explosive eruption. Though a magma chamber in the crust may be a potential source of a large-scale explosive eruption in the future, we do not know which magma chambers can produce large-scale pyroclastic eruptions in the near future. One magma chamber may be still in the early stages of preparation for a large-scale pyroclastic eruption, while another magma chamber is already consolidating into an intrusive body in the final stage of its life cycle. Understanding the state of such magma chambers and assessing the possibility of an eruption are key aspects of being able to accurately evaluate the potential of large-scale explosive eruptions.

Since a long-lived body of magma residing in the crust is expected to be highly crystallized (Koyaguchi and Kaneko 1999), the geophysical methods employed for detection may in fact detect these highly crystallized and non-eruptible bodies of magma. Detection of an eruptible magma batch(es) within such a highly crystallized magma body (Cashman and Giordano 2014) is the present task and a challenge in volcanology.

Monitoring of ground deformation induced by pressure changes in a magma chamber can be an indicator of the stability of a magma chamber (Williams-Jones and Rymer 2002). An active magma chamber with injection and extraction of magma may experience pressure disturbance, and cause ground deformation in the vicinity of the magma chamber. The repeated leveling in and around the Aira caldera since 1891 AD, in correlation with the activity of the Sakurajima volcano, reveals the deflation and inflation of a pressure source at around 10 km beneath the center of the Aira caldera (Iguchi 2013). This indicates the presence of an active magma chamber beneath the caldera. GNSS and tilt meter network, satellite-based interferometric synthetic aperture radar (InSAR), and microgravity measurement may also be useful to detect the ground deformation induced by the instability of magma chambers.

Though ground deformation is a powerful tool to evaluate the activity of magma chamber, one of the difficulties in detecting magma chamber activity by geodetic methods is that volcanic ground deformation is caused by magma chamber pressure changes as well as magma intrusion and hydrothermal activity at shallower levels. Many ground deformation events observed in the Campi Flegrei caldera are considered the result of the activity of geothermal fluid (Battaglia et al. 2006), and magma intrusion at shallow depths (D'Auria et al. 2015; Di Vito et al. 2016). Therefore, to detect the activity of a magma chamber from geodetic data, the signal from the pressure change of a magma chamber must be extracted from the ground deformation caused by shallow level magma intrusion and hydrothermal activity.

Timescales of magma accumulation

Determining the length of time between the destabilization of a magma chamber and the occurrence of a large-scale pyroclastic eruption is an important aspect of volcanological research. Destabilization of magma chambers is expected to induce various precursory phenomena such as an increase in seismic activity, rapid crustal deformation, activation of volcanic fluid, and preceding small-scale leakage of magmas. Therefore, capturing such phenomena and clarifying the precursory processes for large-scale pyroclastic eruptions are essential tasks for short-term risk assessment and eruption warning notification (e.g., Illsley-Kemp et al. 2020).

The accumulation time of silicic magmas related to large-scale explosive eruptions depends on the mass and thermal flux of the system. The volume of silicic magma involved in large catastrophic caldera-forming eruptions must accumulate over periods of 10^5 to 10^6 years judging from the relatively low rates of magma production in island arcs and continental extensional settings (Jellinek and DePaolo 2003). Detailed chronological analysis of minerals and eruption ages suggests that most eruptions of magma < 10 km^3 have residence times < 100 ky, and those > 100 km^3 have longer residences, some up to 300–500 ky (Costa 2008). Other examples provide evidence for rapid assembly of large magma sources, such as for the ~ 25 ka Oruanui eruption at Taupo volcano, New Zealand. Whereas growth of the magma body occurred over a period of ~ 40,000 years, the main melt-dominant body of magma was extracted less than 3000 years before the eruption (Wilson and Charlier 2009). Crystal growth and mafic magma injections occurred within a few centuries leading up to the eruption (Allan et al. 2019).

Some large-scale explosive eruptions have smaller "precursory" eruptions leaking a part of accumulating magma (Di Renzo et al. 2011). The time difference between the oldest precursory eruption and the large-scale explosive eruption constrains the minimum duration of magma chamber growth prior to large-scale explosive eruptions. Detailed stratigraphical analysis and absolute age dating of sequences of erupted products are required to determine the lifetime of the magma chamber leading up to large-scale explosive eruptions.

The zoning structure found in phenocrysts can record the storage process in a magma chamber. Recent microscale dating via laser ablation techniques can determine the age of each compositional zone of a crystal. Diffusion profiles found at the compositional boundaries inside a crystal can be an indicator of the time a crystal has been a resident within a magma if the temperature and diffusion coefficients of the elements in the mineral are known (Morgan et al. 2004; Chamberlain et al. 2014; Barker et al. 2016). The timescale of the reshaping of melt inclusion in minerals is also used for the estimation of magma storage time (Pamukcu et al. 2015; Carrasco-Núñez et al. 2018).

Triggers of large-scale explosive eruptions

Recognizing and defining the mechanisms that trigger eruptions from magma chambers that have served as long-term storage zones is a key objective for the research of large-scale explosive eruptions. As a large-scale explosive eruption follows a long process of magma accumulation within a magma chamber, the eruption of voluminous magma from a stable storage environment requires a process of destabilization within the magma chamber. Many efforts have been made to reconstruct the triggers of eruptions from petrological evidence recorded in ejected magma. Eruption triggers are also inferred from changes in the geophysical and geochemical signatures that precede large-scale explosive eruptions.

Many silicic products of large-scale eruptions provide evidence for injection, just before eruption, of hot and mafic magmas (Eichelberger 1980). Heating of crystal-rich felsic magma in a shallow magma chamber via injection of hot mafic magma may reduce the viscosity of felsic magma via the melting of crystals. Mixing with mafic magma also reduces viscosity by changes in melt composition and a decrease of crystal contents in the hybrid magma (Pallister et al. 1996). Injection of mafic magma may be recorded in the outermost part of the phenocrysts if the crystal continues overgrowth after the mafic injection. The “resorbed texture” on the crystal surface also serves as supporting evidence for mafic injection. Diffusion profiles found in mineral crystals of the ejecta show both long and short periods of diffusion between injections of mafic magma and eruption, as long as centuries to decades (Costa 2008; Barker et al. 2016) and as short as days or weeks (Druitt et al. 2014; Allan et al. 2019). Mafic injection into a silicic magma chamber is thus considered a primary trigger for eruption of silicic magma.

A rise in excess magmatic pressure (i.e., the difference between lithostatic pressure in host rock and magmatic pressure within the chamber) can cause fracturing of the host rock and promote injection of magma into the fracture, and is therefore another principal trigger for eruption. Injection of mafic magma into a silicic magma chamber is one of the causes of generating excess magmatic pressure. Oversaturation of volatiles in a silicic magma chamber may also serve as a trigger for eruption (Blake 1984, Stock et al. 2016).

The time difference between the trigger (e.g., mafic injection) and the eruption is crucial for the risk management of eruptions. As mentioned above, diffusion profiles found in the phenocrysts of hybrid magmas are generally narrow; therefore, the time between mafic injection and eruption is considered to be relatively short. However, some eruptions have been preceded by inflation of the magma chamber, likely caused by the injection of mafic magma, over a period of years (Druitt et al. 2014). In any case, rise of the magmatic pressure in a shallow magma chamber is expected before the onset of diking from a magma chamber (Fig. 2-2). Therefore, well-designed ground-based geodetic monitoring and remote-sensing monitoring can be an effective method to catch the precursory signal for the eruption (Reath et al. 2019). Dense seismic monitoring also can detect the onset and propagation of diking from a magma chamber to the ground surface.

A troublesome point from the view of risk assessment is that these triggers occur universally in various eruptions and are not unique to large-scale pyroclastic eruptions. And, there should be many “unfired trigger” that could not result in any eruption. Injection of mafic magma into a silicic magma chamber is commonly observed in many silicic magma products associated with various types of eruption, from lava-dome effusion (Soufrière Hills; Plail et al. 2014) to large-scale Plinian eruptions (e.g., Schmitt et al. 2001). Inflation of an edifice, which is thought to be due to increased pressure in the magma chamber, is also generally observed prior to many types of eruptions, from explosive to effusive. Therefore, identification of the unique triggers for large-scale explosive eruptions is crucial for risk assessment in such settings. It is necessary to promote research on the mechanism that controls the magnitude of an eruption; can the scale of an eruption be estimated prior to its occurrence and, if so, how long before the eruption can such estimation be made?

As eruptions of large-scale ignimbrite are associated with the formation of collapse caldera, caldera collapse also plays a critical role in large-scale explosive eruptions. The subsiding of the roof rocks into the magma chamber can push out the magmas stored in the chamber and cause eruption of ignimbrite sheet by rapid ejection of fragmented magmas. Decompression in the magma chamber is necessary for the subsidence of the caldera block into the magma chamber. Even in the case of non-caldera-forming eruption, change of magma chamber overpressure and volume of the chamber are the important factors for the evolution of eruption (Kozono et al. 2013), as the magmatic overpressure in magma chamber is one of the main driving forces for magma discharge. Therefore, real-time monitoring of the pressure reduction in the erupting magma chamber by geodetic methods might be a key tool for forecasting the evolution of an eruption, such as the onset of caldera collapse and eruption of the main ignimbrite phase (Fig. 2-3, -4).

Effects of and potential disasters arising from large-scale explosive eruptions

Determining the impact of large-scale explosive eruptions on the environment and society is also key objective of volcanology. The relationship between the range and pattern of ignimbrite spreading and the source processes (e.g., eruption volume, magma flux, the geometry of vent) are still poorly modeled. To approach this question, integration of numerical models of pyroclastic flows is required (e.g., Doronzo et al. 2011); the compilation of field data of real spreading patterns of ignimbrite sheets is also required. Impact of ignimbrite flow on artificial structures such as buildings and other infrastructure needs to be examined by researching both the dynamics of pyroclastic flows and also building mechanics (Valentine 1998, Spence et al. 2004, Zuccaro et al. 2008; Giordano et al. 2018). The survivability of very important structures, such as nuclear facilities, should specifically be examined; their planning has never accounted for the impact of ignimbrite, despite some facilities being located in areas covered by a large-scale explosive eruption's ignimbrites (e.g., the 30-ka Aira-Ito ignimbrite covers the site of the Sendai nuclear power plant). The geological evidence (i.e., deposits) of the ignimbrite (particularly in the peripheral areas of its distribution) may be eliminated due to erosion during the post-eruption period, hence making it difficult to evaluate the real risk posed by a large-scale explosive eruption's pyroclastic flows. Observation of modern examples of human exposure to pyroclastic flow indicates that pyroclastic surge without any thick deposit may also result in fatal damage by heat and dynamic pressure (Spence et al. 2004). However, it is very difficult to evaluate the extent of damage from a pyroclastic surge beyond the area of thick deposition of the main part of the ignimbrite.

Because the injection of voluminous fine ash and aerosols in the atmosphere also has a serious impact on the global environment, the impacts of large-explosive eruption on the climate system have been intensively studied (Rampino and Self, 1982, 1984; Rampino et al. 1988; Self et al. 2004; Sparks et al., 2005; Self 2006, 2015). Ash clouds rising from spreading ignimbrites bring voluminous fine-grained volcanic ash to the downwind side of the caldera, which causes heavy precipitation of ash there. A layer of ashfall can be traced up to ~ 1000 km from the source caldera for some large-scale explosive eruptions and can measure more than a centimeter in thickness in the geological section (Machida and Arai 1976). This means that the amount of ashfall can exceed 20 kg in an area of one square meter. Ashfall deposits of this thickness may prevent the flow of traffic in the absence of any road cleaning activity. Networks of electrical power lines may also be damaged from the heavy ashfall. The deposition of volcanic ash on land can inflict severe damage to agricultural activity by covering land with ash and choking off the water supply (Wilson et al. 2011). The drifting of fine ash particles in the atmosphere may block air traffic for weeks. The spread of very fine ash and sulfate aerosol particles in the global atmosphere may also have a serious impact on the global climate.

The potential of various engineering approaches to deal with disasters involving heavy ashfall is a current topic of interest in volcanic disaster prevention. Health hazards caused by the drifting of fine ash particles are also being examined by public health authorities. Since engineering and medical planning for volcanic ash disasters are based on models that estimate the intensity of ashfall in the targeted area, precise modeling of the dispersion of volcanic ash, based on various volcanological and environmental parameters, is crucial (e.g., Barker et al. 2019).

Conclusions

Evaluation of the potential risks of large-scale explosive eruptions is one of the major scientific objectives of modern volcanology. Integrated modeling utilizing various fields of volcanology is necessary to understand the mechanisms of large-scale explosive eruptions, as we have little direct experience and observation of such events. In specific, identifying the presence of large volume magma chambers at shallow crustal levels is the first objective for evaluating the potential of future large-scale explosive eruptions. For a large-scale explosive eruption of voluminous eruptible magma, a triggering event resulting in the destabilization of the magma chamber is necessary. To assess the potential of large-scale explosive eruption from a magma chamber, we should identify the specific triggering system behind large-scale explosive eruptions, as distinguished from the triggers associated with smaller scale eruptions. To prepare for hazard management of future large-scale explosive eruptions, we need to combine knowledge not only from volcanology but also from engineering technology, medical science, and other fields of science and technology. Such a multidisciplinary approach is required to ensure that we are resilient to hazards that have never been experienced by modern society.

Abbreviations

VEI: Volcanic Explosivity Index, defined by Newhall and Self (1982); ka: Kilo annum; AD: Anno Domini.

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