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Evaluation of Eruption Potential

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Synopsis

This manuscript proposed a concept 'eruption potential' and discussed its contents and data and knowledge necessary for its evaluation. As one example, eruption potential at Sakurajima volcano was shown: possibility of eruption in a few decades, possible styles of eruption, eruption scenarios and expected hazards. In Japan, similar evaluation as Sakurajima might be possible at about 20 volcanoes among 108 active volcanoes. At other volcanoes, it is difficult to evaluate eruption potential.

Keywords: eruption potential, middle-term prediction, volcanic hazards, Sakurajima

1. Introduction

There are 108 active volcanoes in Japan. Most of volcanoes erupt after a dormant time of a few decades to several thousands years, and larger eruption at a volcano in general needs longer rest. Volcanic eruptions are generally 'unexpected and unpredictable': Clear indication of eruptions, for example, swarm of felt earthquakes appears immediately before the onset of eruptions, 10 minutes to several days （e.g. Ishihara, 1997）, though abnormal sign may be issued a few years before eruption. For example, a submarine eruption was unexpectedly generated in 1989 at Izu peninsula, where remarkable earthquake swarms had been frequently repeated since 1978. However, few scientists expected possibility of eruption until just before the eruption, as the former eruption occurred about 2000 years ago, and the eruption site was fairly apart from the location of the previous eruption. Therefore, we need some arrangements before volcanic crises to mitigate volcanic hazards, even though no eruption was recorded in historical time.

The strategy for the mitigation of volcanic disasters should be composed of the following four items.

[1] Volcano monitoring and the system for quick transfer of information on volcanic activity, including short-term prediction of volcanic eruption.

[2] Volcanic hazards map, and education for people on volcanic activity and hazards.

[3] Plan for volcanic crisis management and city planning around volcanoes.

[4] Middle-to-long term evaluation of volcanic activity based on geological survey and geophysical observation.

Here, middle-term evaluation means activity expected in a few decades, and long-term one does activity in a few centuries.

In Japan, the first one [1] has been done the Japan Meteorological Agency (JMA) and the Coordinating Committee of Prediction of Volcanic Eruptions (CCPVE) since 1974. At present, JMA conducts continuous volcano monitoring at 25 volcanoes. The second [2] and third ones [3] have been systematically improved by national and local governments in cooperation with scientists since 1992, and volcanic hazards maps have been published for more than 30 volcanoes.

The most important one is the last [4]. The former three are 'explicitly or implicitly' based on scientific knowledge and experience of experts in volcanology and volcanic hazards. For example, volcanic hazards maps are made using mainly geological data on history of volcanoes: time, sites, style and size of eruptions, and volcanic hazards. The plan for volcano monitoring is also effectively designed by middle-term evaluation of volcanic activity. For example, Usu volcano observatory, Hokkaido University was established just before the 1977 eruption according to the strong recommendation from Geodesy Counsel (1975) to national government based on a report by volcanologists (Yokoyama et. al., 1973). The report included approximate time of eruption and eruption scenarios. As a result, evacuation at the 1977 eruption was well managed as well as the 2000 eruption.

Thus, middle term evaluation on volcanic activity is effective and important for both the prediction of volcanic eruptions and mitigation of volcanic hazards. Such efforts have been however done until now by a small group of scientists for limited number of active volcanoes.

In this paper, we introduce the concept ‘Eruption potential’ corresponding to middle-term evaluation on volcanic activity, and discuss its contents and method of evaluation.

2. Eruption Potential

‘Eruption potential’ discussed here is capability of a volcano to induce eruption in a certain range of time in near future. The contents of eruption potential should ideally include the following information:

[1] Possibility of eruption in forthcoming decades or in a century

[2] Scenarios of possible eruptions: size, style, and location of eruption, and volcanic process expected before eruption.

[3] Possible hazards and affected area by eruption

These are mainly deduced from geological studies of t past eruptions and volcano monitoring data. In this paper, the previous studies related to eruption potentials are reviewed, and the possibility, difficulty and limitation on evaluation of eruption potentials are discussed, focusing mainly on evaluation of possibility of eruption in a few decades.

2.1 Recurrent Period

A few numbers of active volcanoes in Japan have repeated significant eruptions with a fairly regular time interval.

For example, Usu volcano erupted 5 times with the interval of 31 to 57 years from 1769 to 1943. Yokoyama et.al. (1973) estimated that the next eruption would occur 30 to 50 years after the 1943 eruption. The expected eruption started in 1977, 34 years after the former eruption. However, the 2000 eruption recorded the shortest dormant time of 23 years.

Miyakejima volcano erupted 9 times from 1643 to 1983 with the time interval of 21 to 69 years. Miyazaki (1984) found an empirical formula on the periodicity of eruption: recurrent period=n(22∓2.5) years. Here, n= 1, 2 and 3. And it was also recognized close relationship between the amount of materials ejected by eruption and the dormant time, as illustrated in Fig. 1. However, the last eruption occurred in 2000, earlier than expected from the above empirical formula, 17 years after the 1983 eruption.

Thus, the recurrent time of past eruptions should be noted as a useful but tentative scale for rough estimation on the time of forthcoming eruption. We need additional information or other tools to evaluate possibility of eruption in near future, as recurrent time of eruption at most of Japanese volcano seems to be at random or uncertain.

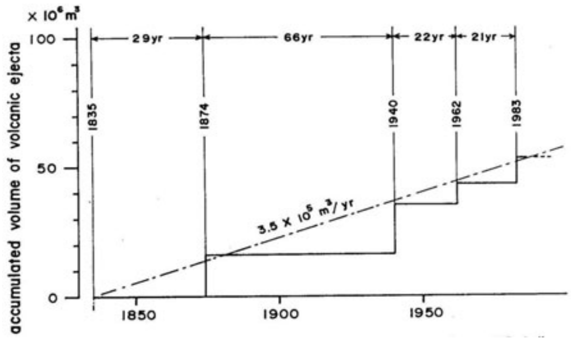

Fig. 1 Accumulated volume of volcanic ejecta at Miyakejima volcano (Ishihara et.al., 1984)

2.2 Seismic activity

It is expected that seismic activity may increas around a volcano, if magma is accumulated to a certain level or intrudes under the volcano.

The working group on long-term prediction of CCPVE examined the possibility of eruption at Usu and Miyake volcanoes in 1997, using data on eruption history and other data. The working group paid attention on a n insignificant but gradual increase in annual number of volcanic earthquakes, as illustrated in Fig. 2, and judged that eruption would probably occur within 10 years, earlier than expected from recurrent time in the past, as a similar trend was also recognized before the 1977 eruption. The expected eruption occurred in 2000 accompanied with remarkable and expected earthquake swarm from 3 days before the eruption. However, note that *exact estimation of the year of eruption is impossible even at Usu volcano.*

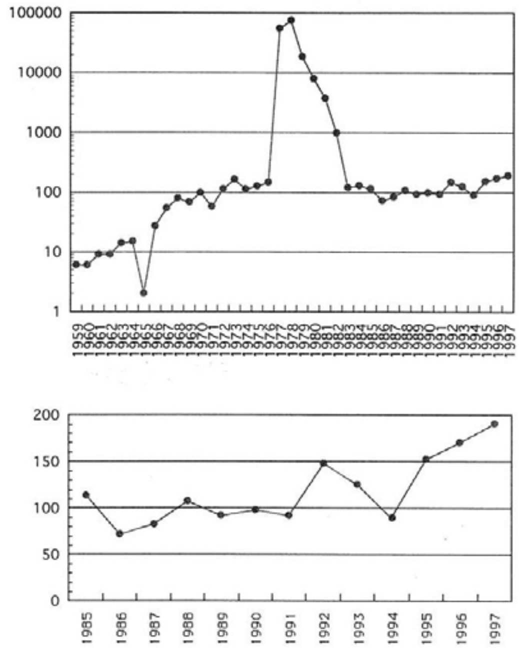

Fig. 2 Annual number of volcanic earthquakes at Usu volcano (Hokkaido University, 1997). Rapid increase in 1977 related to the 1977 eruption.

At some other volcanoes, seismic activity gradually increases on the volcano or around it a few years to several decades before eruption. For example, significant earthquake swarms have been frequently repeated 10 to 20 km west of the Unzen volcano since 1922 and migration of earthquakes toward the volcano was observed before the 1990 eruption, as similar as the 1989 submarine eruption at the Izu peninsula.

These examples suggest that gradual increase of seismic activity on volcanoes and significant seismic activity around volcanoes are not the direct indication of eruption, but might be one of signs issued by volcanoes which are going to erupt in a few decades. It should be stressed that it is difficult to evaluate abnormal seismic activity in relation to volcanic activity with monitoring data of short time. We need accumulation of data at least over 10 years. Note also that *some volcanoes may not indicate any increase in seismic activity before eruptions.* For example, no abnormal seismic activity was observed before the onset of the 1983 and 2000 eruptions at Miyakejima volcano.

2.3 Ground Deformation

Monitoring of the ground deformation around the volcanoes is probably the most direct tool to observe and evaluate accumulation of magma under volcanic areas.

The typical example is the ground deformation around the Aira caldera associated with the eruptive activity of Sakurajima volcano. The ground around the caldera subsided remarkably just after the 1914 eruption which extruded 1.9 km^3 of lava, ash and pumice. Just after summit eruption started in 1955, Sassa (1956) drew one figure on the relationship between the ground deformation of the Aira caldera and eruptions using leveling data, as illustrated in Fig. 2, and suggested a continuous magma supply to the underground of the caldera. This figure stresses that summit eruption continues or large eruption will be inevitable in near future. As he expected, summit eruption has continued for more than half a century.

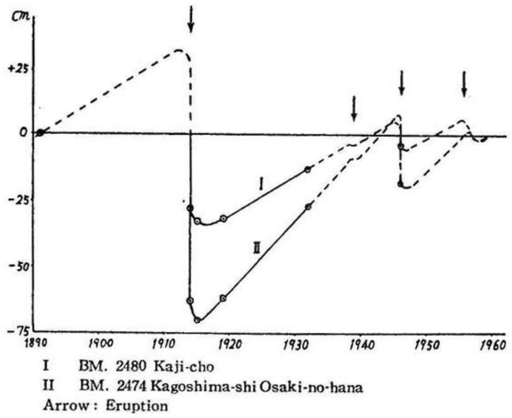

Fig. 3 Relationship between the ground deformation of the Aira caldera and eruptions of Sakurajima (Sassa, 1956)

Similar pattern of the ground deformation was also observed at Miyakejima volcano (Fig. 4). The ground around the southern part subsided after the 1983 eruption, and recovery process has been observed. The working group on long-term prediction of CCPVE concluded that the accumulation of magma charged after the 1983 eruption was almost enough to induce any eruption, and the next eruption is inevitable in a few years. Expected eruption was generated in 2000, though it was followed by unexpected collapse of the summit caldera.

Accumulation of leveling data useful for evaluation of eruption potential was limited for several volcanoes in Japan. Now, GPS network covers about 20 active volcanoes and will provide useful data for evaluation of eruption potential.

However, *we should never be overconfident of deformation data*. Usu volcano did indicate no deformation until the onset of the 2000 eruption. At Izu-Oshima, the summit area did not indicate any inflation just before the 1996 fissure eruption, though other data strongly suggested increase in activity. We need some model on magma supply system to evaluate deformation data accurately.

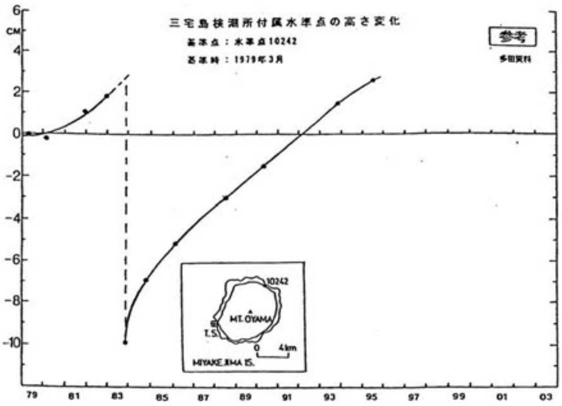

Fig. 4 Vertical displacement at the tidal station south west of Miyakejima referred to BM 10242 (GSI, 1997). The rapid subsidence corresponds to the 1983 eruption.

2.4 Other Information and data

Recently, it has been proved that geothermal, geochemical and geomagnetic observations are useful tools for evaluation of eruption potential. For example, geomagnetic change, electric resistivity change of the ground and increase in geothermal activity has observed a few months to a few years before the 1986 eruption at Izu-oshima (Ishihara, 1997). Geoelectric, geomagnetic, geochemical and geothermal data will become powerful tools for evaluation of eruption potentials by combined with seismic data at volcanoes which repeated phreatic or small magmatic eruptions: Kusatsu-Shiraneyama, Kuchinoerabujima and other volcanoes.

2.5 Condition for evaluation of eruption potential

Geological studies on volcano structure and past eruption are of course indispensable for evaluation of eruption potential as basic knowledge, but mainly used for long-term evaluation of volcanic activity. In contrast, the role of geophysical and geochemical studies and data is more important to evaluate eruption potential. The data onditions necessary for evaluation of eruption potential will be summarized as follows:

[1] Accumulation of geophysical or geochemical data on volcano monitoring over 10 years. This is most important for discrimination of abnormal activity from base-line activity. The volcanoes which satisfy this condition are approximately 30.

[2] Monitoring data which include epochs of significant eruptions or volcano crisis and detected any abnormal sign before eruptions. This is helpful to estimate approximate time and size of eruption empirically. This condition is fairly satisfied at about 15 volcanoes.

[3] There are some models on magma supply system or subsurface structure of the volcano to be useful for evaluation or interpretation of observed data.

It may be possible to evaluate eruption potential at volcanoes which satisfy all the three conditions mentioned. Those are 9 volcanoes: Usu, Iwate, Asama, Izu-Oshima, Miyakejima, Aso, Unzen, Sakurajima and Izu-Tobu volcanoes. At all of these volcanoes, various kinds of data have been accumulated including periods of significant eruptions or volcano crises, and some models on magma supply system or underground structure are proposed.

Evaluation of eruption potential might become possible at approximately other 10 volcanoes, including Mt. Fuji, with additional efforts. At these volcanoes, volcano monitoring data of more than 10 years are accumulated, and the probability of unexpected eruptions will become low, if evaluation of eruption potential is done and volcano monitoring and research are improved

In contrast, the probability of unexpected significant eruptions is much high at other many volcanoes, mainly due to lack in volcano monitoring.

In the next section, evaluation of eruption potential at Sakurajima volcano is shown as a example.

3. Evaluation of Eruption Potential of Sakurajima

Sakurajima has repeated large eruptions in 764-766, 1471-1476, 1779-1982 and 1914. Time interval of large eruptions seems to become short with time. These eruptions ejected 1 to 2 km^3 of lava, pumice and ash from new craters formed on the flank. It was also clarified from geological studies that Sakurajima has repeated large eruptions since the gigantic eruption of 25,000 years ago.

Sakurajima is one of the most well studied volcanoes in the world. Many researchers have been studied the volcano and the Aira caldera, which is located at north of the volcano, and models of magma supply system were proposed. One of them from geophysical studies (Kamo and Ishihara, 1980) is illustrated in Fig. 5.

[1] Two magma chambers are assumed, the one is the main one located approximately 10 km beneath the caldera, and the other is shallow one 4-6 km deep under the volcano.

[2] Magma rises up to the main chamber from deeper portion at a constant rate of $10^7 m^3/y$. and are accumulated there. Then, it migrates under Sakurajima volcano. The other pass way might exist from south of the volcano.

This model has been useful for evaluation of volcanic activity and prediction of volcanic explosions until now, together with other empirical laws, fore example, on relationship among deep volcanic earthquakes, shallow volcanic earthquakes and eruptive activity. Based on this model and other information, we will try to evaluate eruption potential at Sakurajima volcano.

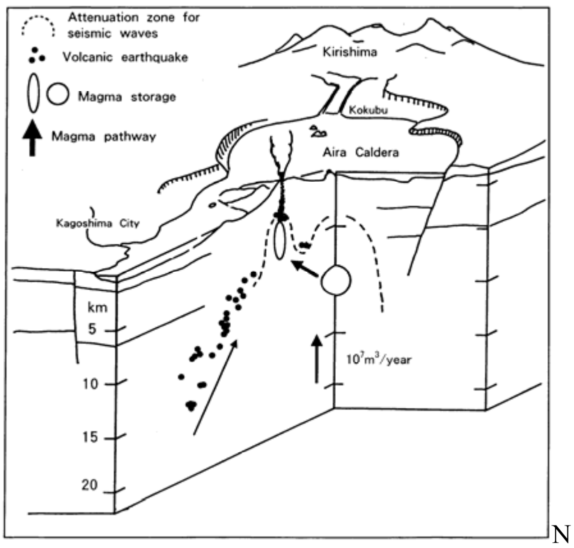

Fig. 5 A model on the magma supply system of Sakurajima volcano.

3.1 Magma storage and urgency of eruption

The ground around the Aira caldera has behaved until present as Sassa (1956) expected, as illustrated in Fig. 6. The ground tentatively stopped inflation during two highly active periods: 1960-1962 and 1974-1993, while a few ten millions tons of volcanic ash was ejected each year. Inflation of the ground resumed since 1993 when the amount of ejected ash decreased to a few million tons per year. We may assume that amount of magma discharged by the 1914 eruption (1.5 km^3) has been already charged again by 80 % under the caldera.

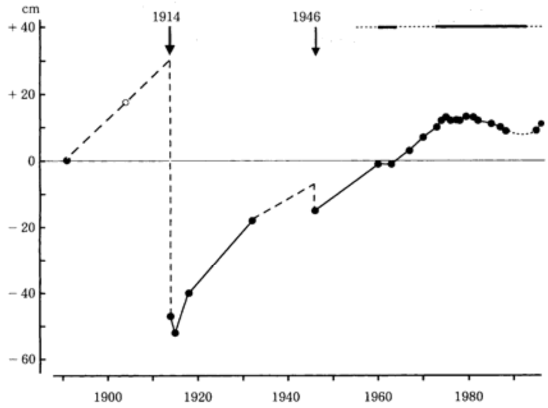

Fig. 6 Vertical ground deformation of the Aira caldera (BM 2474). Arrows indicate large flank eruptions, and horizontal bars do periods of summit eruption

Recent deformation has been traced using GPS network. Iguchi (2006) estimated that approximately 90 million cubic meters of magma was accumulated during 10 years since 1995, as illustrated in Fig.7. If inflation progress in a similar rate for 10 to 20 yeas, accumulation of magma will reach the level just before the 1914 eruption.

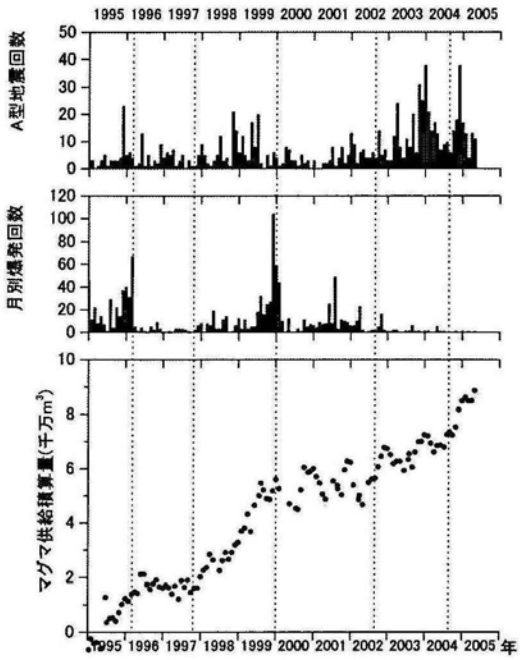

Fig. 7 Recent volcanic activity of Sakurajima (Iguchi, 2006). Monthly numbers of A-type earthquakes (top) and volcanic explosions (middle), and accumulated volume of magma estimated from GPS data (bottom).

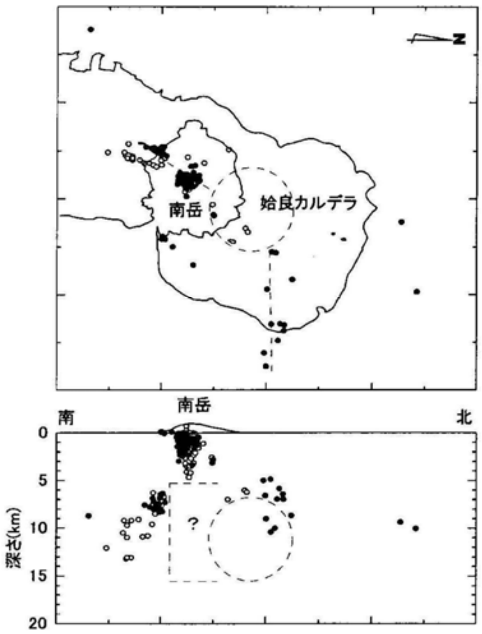

Fig. 8 Distribution of A-type earthquakes (Iguchi, 2006). Open circles indicate those originated before 1988, and closed circles do those during 2001 to 2004.

Note in Fig. 7 that the rate of accumulation of magma seems to increase since 2002 as synchronized with the increase in number of A-type earthquakes. In particular, seismic activity southwest off of Sakurajima and in the caldera increased, as illustrated in Fig.8. This may suggest that pressure in the main magma reservoir is gradually becoming high to make pass ways of magma to go upwards. Seismic activity also seems to issue a sign of forthcoming eruption together with the ground deformation.

We might conclude that *remarkable volcanic crises or eruption will surely originate in 20 years.* However, significant intrusion of magma from the caldera to Sakurajima has not yet observed. It may take a few years or more to activate significantly eruptive activity at Sakurajima.

3.2 Eruption scenarios and volcanic processes

Eruption scenarios should include site, style and size of eruptions. In the following paragraphs, these are discussed.

[Eruption site] During the period from 1955 until around 2000, A-type earthquakes had been often followed by increase of B-type earthquakes and explosive eruptions. However, recently this relationship is not recognized. It is imagined that magma conduit from the shallow magma chamber to the crater becomes narrow due to cooling or magma becomes more viscous due to cooling and poor volatile contents. As the result, magma cannot rise up smoothly, and B-type earthquakes and explosions become rare. If such state continues, the conduit might be closed, and magma may find other pass ways. Though most plausible location of eruption is still the summit crater, we must also take into account of other places, those are, flank and seashore of the volcano, or sea bottom of the caldera like the 764-766 eruption and the 1779-1782 eruption.

[Eruption style] We may draw various scenarios, but here, we show four probable ones. If eruption starts at the summit, typical eruption style will become of vulcanian, and may persist for a few decades (**Scenario 1**). If new craters are formed on the flank, huge amount of volcanic ash and pumice will ejected at the onset of eruption, and pyroclastic and lava flows will occur (**Scenario 2**), as experienced in the 1914 and other large eruptions. There is the possibility of submarine eruption in the Aira caldera **(Scenario 3**), since significant seismic activity is recognized as illustrated in Fig.8, and the 1779-1782 flank eruption was followed by significant submarine eruption: several islands were formed northeast off of Sakurajima and citizens of Kagoshima were suffered by tsunamis. The fourth possibility is collapse of volcanic edifice (**Scenario 4**). During the current activity, the location of active vent in the summit crater has migrated and the crater wall became thin. The partial collapse of the uppermost part of the flank might occur, when viscous magma rises as a lava dome.

[Process before eruption] Sequence of phenomena expected before eruption are described for each scenario, based on experiences at Sakurajima and other volcanoes.

Scenario 1 (activation of summit eruption): Gradual uplift of Sakurajima (a few cm/y) caused by migration of magma from the caldera a few years before → Increase in number and size of A-type earthquakes a few months before→ Increase in number of B-type earthquakes and volcanic tremors

Scenario 2 (large flank eruption): Intermittently significant earthquakes might be occurred around the caldera a few years before →Significant uplift of Sakurajima (more than several cm/month) due to rapid intrusion may start a few months to a few years before → Swarm of significant earthquakes start a few days before

Scenario 3 (submarine eruption): Probably, abnormal seismic activity in the caldera will be observed a few weeks before eruption. If a local GPS network covers and across eruption site, local deformation might be observed.

Scenario 4 (Collapse of volcanic edifice): Probably, similar to Scenarios 1 and 2, uplift of Sakurajima will be observed → Both significant earthquakes and local but significant deformation of volcanic edifice might continue for several days

3.3 Volcanic hazards and affected area

Kinds of volcanic hazards, affected area and others expected for the four scenario-eruptions are summarized in Table 1.

In case of re-activation of summit eruption, serious damage due to volcanic blocks and ash may appear in Sakurajima, and temporally in the area of downwind direction due to ash-fall.

The other three scenario-eruptions will commonly cause serious damages on life of people out of Sakurajima. Large flank eruption like the 1914 and 1779-1782 eruption will cause severe damage much wider area. The eruption may affect on life of approximately one million people out of Sakurajima: heavy ash-fall, debris flow, tidal wave due to subsidence of the ground, collapse of houses, tsunamis, and land-slide due to strong earthquakes, and so on.

The most serious hazard by submarine eruption and collapse of volcanic edifice may be tsunamis, as houses and dikes of rivers and coast destroyed by repeated tsunamis in the 1779-1782 eruption.

4. Some Problem on Eruption Potential

In each century since 17th century, Japan has experienced several big eruptions, which ejected volcanic materials more than 0.5 km^3. The final one occurred at Hokkaido-Komagatake in 1929. In 21st century, the possibility of big eruptions is statistically very high. Systematic investigation of eruption potential should be initiated urgently for mitigation of volcanic disasters.

In addition, some caldera volcanoes, which caused big eruptions in the past, indicate abnormal seismic activity. For example, shallow earthquakes have been intermittently swarmed at Mashu in Hokkaido and Towada in the Tohoku district. Both the volcanoes are known from geological studies to generate big eruptions about 1000 years ago. However, volcano monitoring is very poor, and we have not enough data to evaluate eruption potential. Volcano monitoring and research should be quickly begun.

5. Conclusions

Table 1 Eruption scenarios of Sakurajima volcano in near future

Eruption Scenarios	Place	Main Hazards	damaged area (km^2)	Duration (years)
Activation of summit eruption	Summit area of Sakurajima	volcanic blocks, ash, gases, and debris flows	10^2 mainly Sakurajima	10^{1-2} a few decades
Large flank eruption	Flank or coast of Sakurajima	Lava flows, pyroclastic flows, debris flows ,volcanic blocks, ash and pumice, tidal waves, strong earthquakes, Tsunamis	10^{3-4} Sakurajima and 50 to 100 km around it	10^0 a few years
Submarine eruption	Aira caldera (Kagoshima bay)	Tsunamis, tidal waves, pumice, strong earthquakes	10^{2-3} Sakurajima and Kagoshima bay	10^0 a few years
Collapse of volcanic edifice	Flank of Sakurajima	Volcanic blocks, rock avalanche, pyroclastic flows, tsunamis, strong earthquakes	10^{2-3} Sakurajima and Kagoshima bay	10^0 a few years

We proposed ‘Eruption potential’ as a concept on middle-term evaluation of volcanic activity and discussed its contents, and data and knowledge necessary for the evaluation. Eruption potential at Sakurajima was evaluated as the first attempt. It was concluded that possibility of remarkable eruption in 20 years is very high and, at present, four possible scenarios should be considered including submarine eruption in the Aira caldera. It may be possible to evaluate eruption potential for about 20 volcanoes in Japan, in a similar way as Sakurajima. However, it is difficult to evaluate it for other volcanoes due to lack of data and knowledge.

Acknowledgements

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火山噴火ポテンシャルの評価について

石原和弘

要　旨

本稿では，火山噴火の予知と火山災害の軽減にとって火山活動の中期的（数10年）な予測評価が重要であるという認識に立って，噴火ポテンシャルという概念を提示し，それに含まれるべき内容と評価に必要なデータ・知識について論じている．桜島を例として噴火ポテンシャル評価を行い，当面の20年に予想される4つの活動シナリオを示し，噴火にいたる過程で発現する現象，予想される災害と影響範囲を見積もった．噴火ポテンシャル評価が可能の知識・データの蓄積のある火山は多く見積もっても全国で20火山程度であり，その他の火山での評価は困難であり予期せぬ顕著な噴火が発生する可能性が高い．

キーワード:噴火ポテンシャル，中期予測，火山災害，桜島