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A03: Suwanosejima - Lighthouse of East China Sea: Ongoing strombolian activity and proximal facies of the 1813 eruption

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Introduction

Suwanosejima volcano is one of the most active volcanoes in Japan. This andesitic stratovolcano is situated on the volcanic front along the Ryukyu arc in southwest Japan **(Fig. 1)**. The crater in the central part of the island, Otake crater, has been active for more than fifty years with strombolian and small vulcanian eruptions (JMA, 2013). Despite its intense activity, the oldest eruptive record of Suwanosejima volcano only goes back to the 1813 eruption. There are no adequate records of recent activities either until the 1990s, except for some occasional reports. Geological studies of Suwanosejima were first reported by Omori (1918), followed by Hirayoshi (1983) and Hirasawa and Matsumoto (1983). Moriwaki et al. (1996) applied the stratigraphic approach in examining the volcano. Shimano and Koyaguchi (2001) reconstructed the sequence of the 1813 eruption.

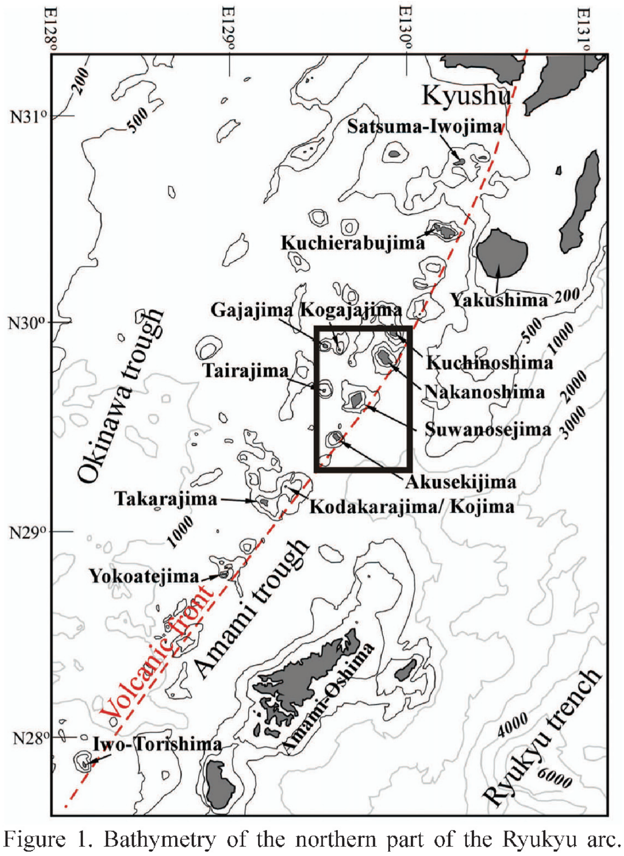

Figure 1. Bathymetry of the northern part of the Ryukyu arc. Part of "Geological Map of Japan 1:200,000, Nakano Shima and Takara Jima" (after Figure 1 of Shimano et al., 2013). Numbers beside the contours indicate depth below sea level (m). The box shows the area in Figure 2.

Although the volcano had been very active, geophysical observation has been carried out only every few years as campaigne observation until 1980's (DPRI, 2000). Continuous observation was first established in the late 1980s, when the Sakurajima Volcano Observatory in Kyoto University started telemetric data transmission (Iguchi, 1991).

On the basis of these previous works, we have accumulated both geological and geophysical data about this volcano. This guidebook summarizes the knowledge from researches in recent years on the history of eruptions and the magma ascent system of Suwanosejima volcano in Part I, as well as on the sequence and mechanism of the most violent eruptions in 1813 and the successive eruptions to date. In Part II, the characteristics of topography and deposits at representative stops of field excursion are described. The geological description in Part I is based on the Geological Map of Suwanosejima Volcano (Shimano et al., 2013).

Part I　Geology of Suwanosejima volcano

1. The geological setting of Suwanosejima

Suwanosejima volcano is situated on the volcanic front along northern part of Ryukyu arc in southwest Japan **(Fig. 1)**, where the Philippine Sea Plate is subducting northwestward under the Eurasian Continental Plate with the Okinawa

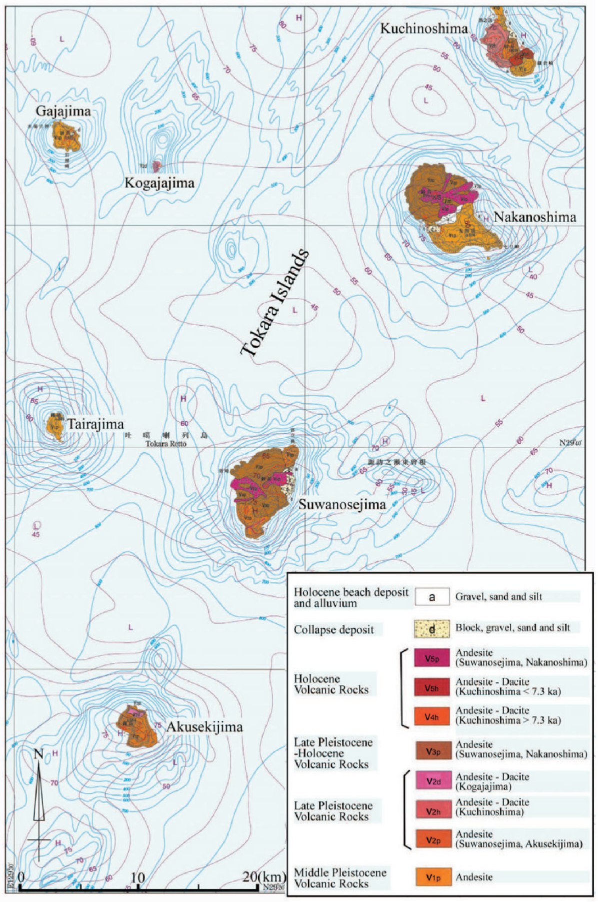

Figure 2. Outline of the topography and geology of Suwanosejima island and the surrounding area (northern part of the Tokara Islands) with bathymetry (m) and gravity anomalies (mgal). Part of "Geological Map of Japan 1:200,000, Nakano Shima and Takara Jima" (after Figure 1 of Shimano et al., 2013).

Trough on the back-arc side. There are some active volcanoes along the volcanic front of the northern part of the Ryukyu arc in order from north to south: Satsuma-Iwojima, Kuchinoerabujima, Kuchinoshima, Nakanoshima, Suwanosejima, and Iwo-Torishima. The Tokara Islands consist of 7 inhabited and several uninhabited islands. Kuchinoshima, Nakanoshima, and Suwanosejima are active volcanic islands. Most of the other islands also consist of volcanic rocks of, in order by age, Quarternary to late Pliocene (Kaminonejima and Yokoatejima), late Pliocene (Kogajajima and Akusekijima), and middle Pliocene (Gajajima and Tairajima) age **(Fig. 2)**. Takarajima, Kodakarajima, and Kojima are composed of hydrothermally altered volcanic rocks of Miocene age fringed by raised coral reef deposits (Nakano et al., 2008). Most of these volcanic islands of Tokara Islands are composed of lava and volcaniclastics of two types: pyroxene andesite and hornblende dacite.

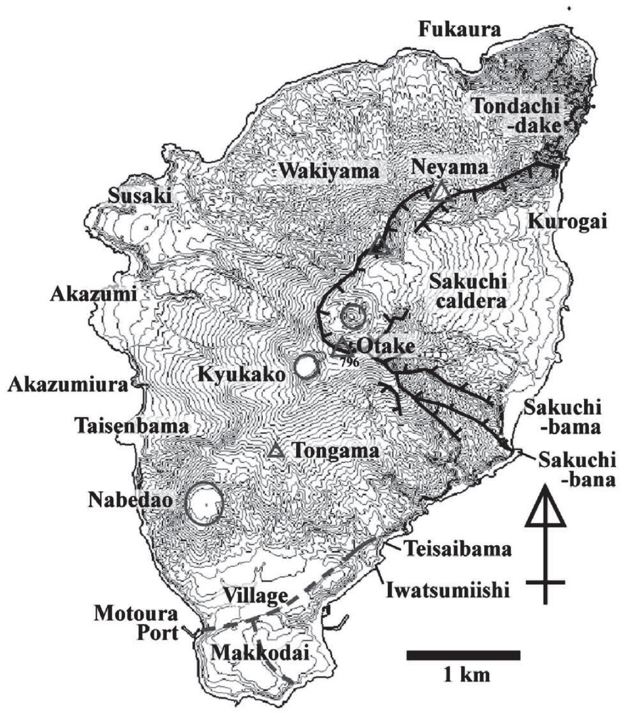

Figure 3. Topography of Suwanosejima island. The interval of contours is 20 m. Broken lines are active faults (The Research Group for Active Faults of Japan, 1991).

2. The topography of Suwanosejima

Suwanosejima is an island with a conical edifice with a long and short axis of ca. 8.7 and 4 km, respectively **(Fig. 3)**, and is the second largest among the Tokara Islands (area ca. 28 km^2). It is situated 796 m above sea level (asl) and has a total height of ca. 1400 m above the seafloor, which is 500-600 m below sea level (bsl). There are two heights in the sea whose peaks are at 100 m and 300 m bsl, ca. 10 km to the east and ca. 10 km to the northwest of the island, respectively **(Fig. 2)**. Suwanosejima island is mostly surrounded by steep cliffs. The east-side cliff of an old edifice, Tondachidake volcano, is up to ca. 500 m high. The west-side cliff of another old edifice, Nabedao volcano, is up to ca. 100 m high. In contrast, the height of the cliff is about 10-20 m near Sakuchi and Akazumi, where younger volcanic edifices have developed on the eastern and western side of the island, respectively. There are also many beaches, of which Sakuchibama is the largest. Some coral reefs have developed near Makkodai and Wakiyama, along the southern and northwestern coast of the island.

Suwanosejima consists of a few volcanoes that have volcanic centers at different locations **(Fig. 4)**. Nabedao volcano in the southern part and Tondachidake volcano in the northern part of the island are edifices of the oldest volcanoes. Otake

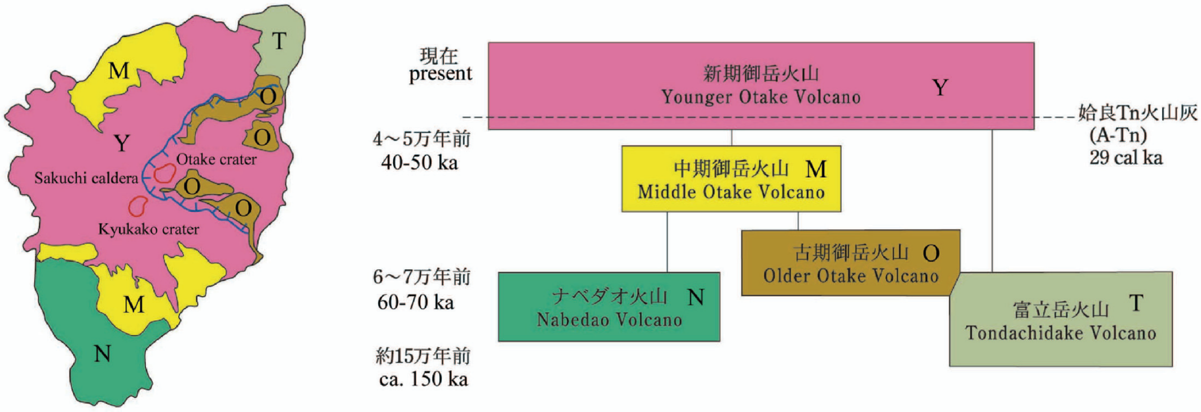

Figure 4. Stratigraphic relation of the volcanic edifice of Suwanosejima island showing the evolution of the volcanic edifices (after Figure 3 of Shimano et al., 2013).

volcano, in the central part of the island, covers a major part of Suwanosejima volcano and was the area of concentration of volcanic activities in the Holocene.

Tondachidake volcano is deeply eroded, with an edifice that has many radial gullies and valleys surrounding the summit, and has almost no smooth primary slopes. Nabedao volcano is also deeply eroded but still has a crater-like topographic depression on the summit. Makkodai in the southern end of the island consists of flat lava flows that had been effused from Nabedao volcano (see section 3.2). Otake volcano is a composite volcano with an elongated outline in the NNE-SSW direction. The summit of Mt. Otake is at the center of this volcano, on top of a horseshoe-shaped cliff facing eastwards and surrounding the active Otake crater (Sakuchi caldera). The cliff consists of several smaller segments. In the southern part, these segments show a double- or multi-step topography indicating that collapse has occurred several times.

The Otake pyroclastic cone in Sakuchi caldera is a flat-shaped cone as large as 600 m and 80 m in diameter and height, respectively, with a crater 400 m in diameter. All the eruptions to date after the last stage of the 1813 eruption occurred at this crater (see section 4.2). To the southwest of the summit, there is another crater called “Kyukako” with a diameter of 300 m, where a major eruption occurred in 1813 (see section 4.1).

There are some well-preserved lava flows on the slope of Otake volcano. Two lava flows on the western slope down to the shoreline of Akazumi and Taisenbama were effused during the 1813 eruption (see section 4.1; Fig. 10, Appendix A). The compound lava flows of the 1884 eruption show many lobes of flows on the slope from Otake crater down to the eastern shoreline in Sakuchi caldera (see section 4.2; Appendix A).

A lineament in the ENE-WSW with a 20-m gap (N down) and another in the NW-SE (E down) are perpendicular to each other and have been classified as active faults with degree of accuracy II (Fig. 3; The Research Group for Active Faults of Japan, 1991).

3. Geological history of Suwanosejima volcano

3-1. Overview of the evolution of Suwanosejima

The geological history of Suwanosejima volcano is shown in **Fig. 5**. Tondachidake and Nabedao volcanoes seem to have grown into subaerial volcanoes by 50-60 ka, judging from the results of K-Ar dating of lava distributed around their shoreline (Toshida et al., 2004; Matsumoto et al., 2006). Otake volcano covers most of the central part of the islandand can be subdivided into three volcanoes; Older, Middle and Yougner Otake volcanoes (**Fig. 4**). Otake volcano has grown with the activity around the present Otake crater and now covers both Tondachidake and Nabedao volcanoes. Otake volcano seems to have become a volcanic edifice 400-500 m high by 40-50 ka, judging from the ages of the covering and overlying deposits at some localities in Suwanosejima. Large explosive activities with pumice and scoria fall deposits in the distal part of the island have continued from 40-50 ka until 10 ka **(Fig. 5)**. Then, such explosive eruptions decreased, and successive ash-emitting activities with some repose intervals became dominant until recently.

In the following sections, the details of each volcanic edifice are described.

3-2. Tondachidake and Nabedao volcanoes

Tondachidake and Nabedao volcanoes are the lowermost units in the subaerial part of

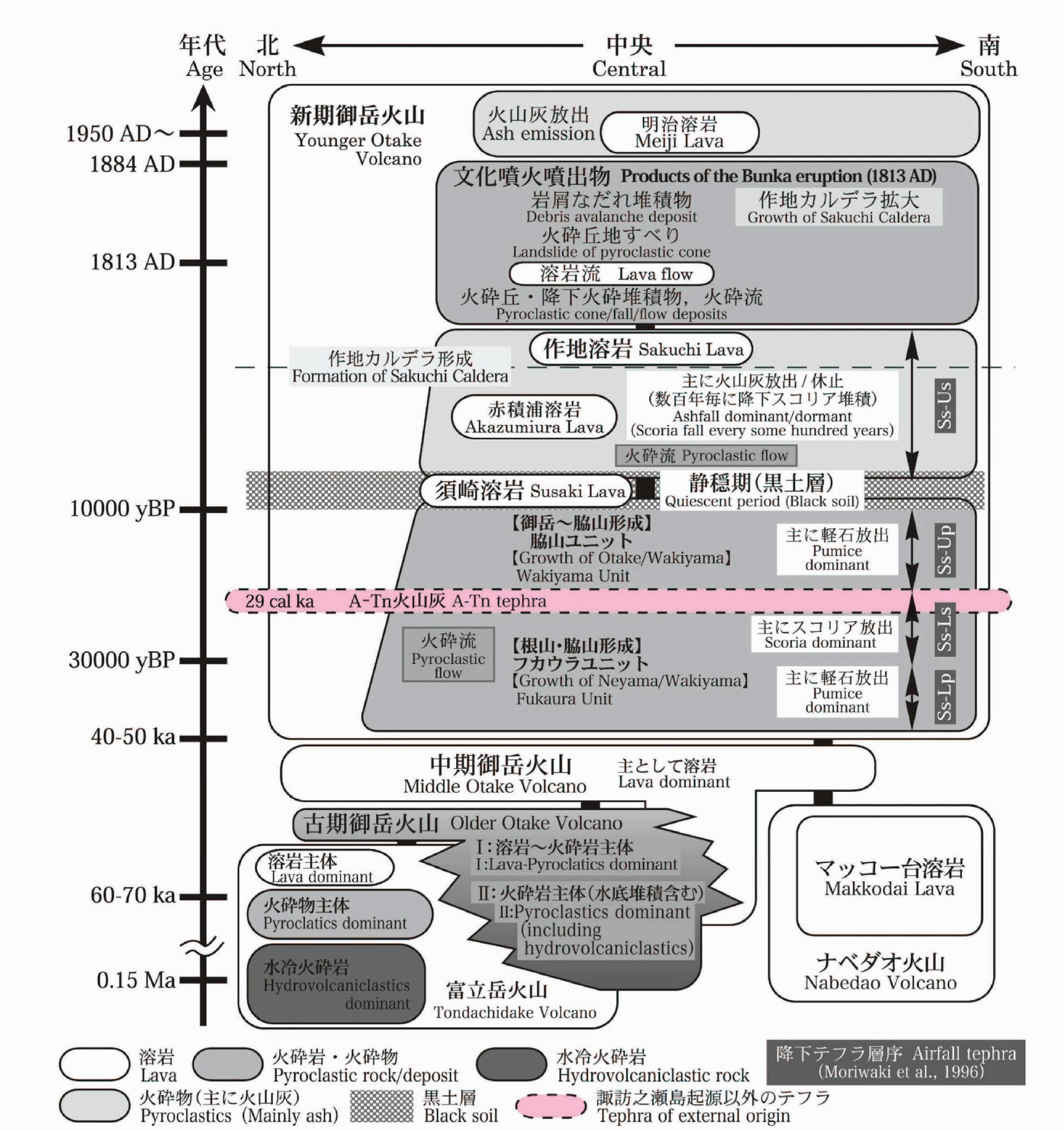

Figure 5. Volcanic stratigraphy of Suwanosejima volcano (after Figure 3 of Shimano et al., 2013).

Suwanosejima volcano **(Fig. 4)**.

Tondachidake volcano is located in the northern part of the island. Tondachidake volcano could be the oldest volcano, judging from its topographic features with more heavily distributed gullies than the other edifices. Its base consists of alternating layers of deposits by phreatomagmatic eruptions that have cauliflower-shaped volcanic bombs with a quenched rim. We call the deposit "hydrovolcanic rocks." The overlying deposit consists of alternating layers of subaerial lava and pyroclastic deposits that form a small composite volcanic edifice. There are several sheets of dikes that show a radial distribution from the summit of Tondachidake. K-Ar dating of the lava in the middle part of Tondachidake volcano indicates an age of 65±15 ka (Matsumoto et al., 2006).

Nabedao volcano is located in the southern part of the island and consists of a stratified main edifice and Makkodai lava at the southernmost portion. Although Nabedao volcano is heavily eroded, it could be younger than Tondachidake volcano,

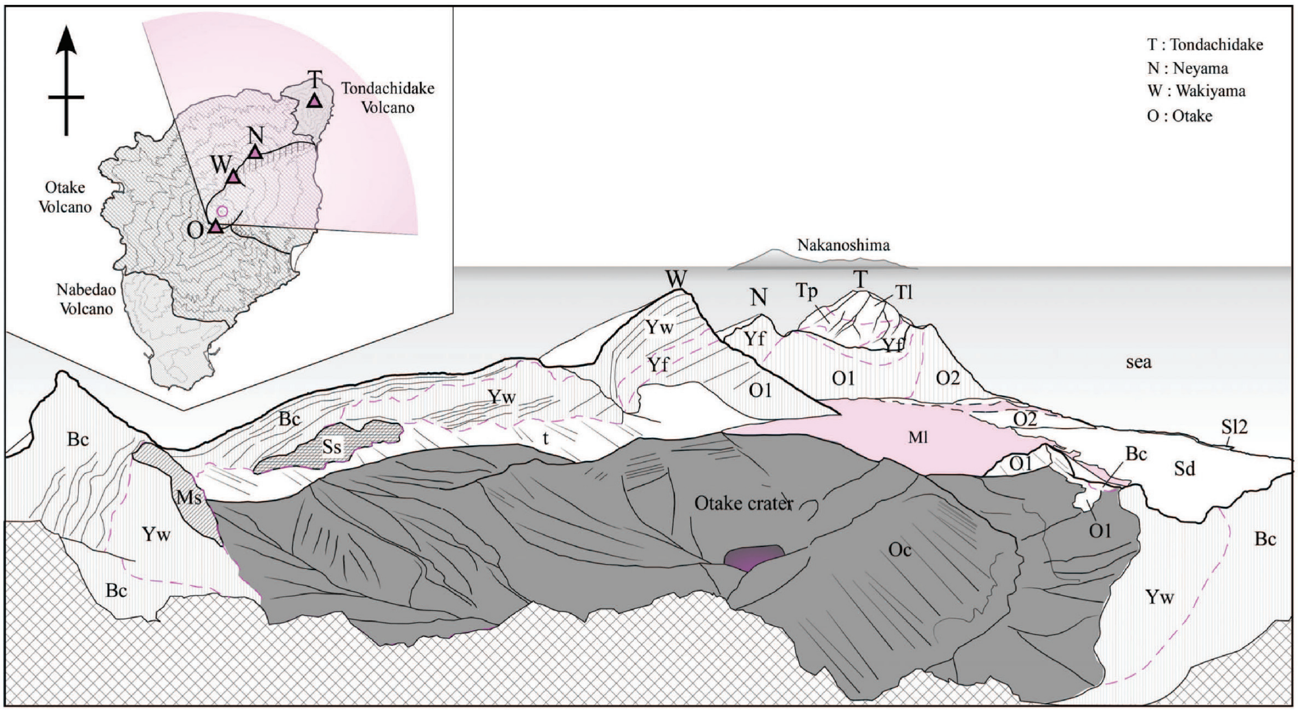

Figure 6. Northeastern view from the summit of Mt. Otake of Suwanosejima volcano (after Figure 4 of Shimano et al., 2013). Tl, Tp Tw: lava dominant part, pyroclastics dominant part, and hydro-volcaniclastic rocks of Tondachidake Volcano, O1, O2: Old Otake volcano I and II, Yw, Yf: Wakiyama Unit and Fukaura Unit (Pyroclastic fall deposit of Younger Otake volcano), Ss: Susaki lava, Sl2: Sakuchi lava II, Bc: Bunka pyroclastic cone deposit (weakly welded), Sd: Bunka debris avalanche deposit, Ml: Meiji lava, Oc: Otake pyroclastic cone deposit, t: talus.

considering that the surface topography of the crater and lava flows has still partly survived erosion **(Fig. 3)**. The results of K-Ar dating of lava at the basal part of the main edifice and of some lobes of Makkodai lava indicate an age of ca. 150 ka and ca. 60-70 ka, respectively (Toshida et al., 2004). A drilling survey by JMA in 2009 showed that the apparent thickness of andesite lava near the summit of Nabedao was ca. 100 m (Group for Drilling Core Analysis, Coordinating Committee for the Prediction of Volcanic Eruption, 2011), whereas a drilling survey near Makkodai showed a lava thickness >80 m (Oshima, 2000).

3-3. Otake volcano

Otake volcano is in the central part of the island and forms a stratified volcanic edifice mostly with andesitic lavas and agglutinates. The volcano has been subdivided into three volcanoes according to major unconformities; these are Older, Middle, and Younger Otake volcano, in ascending order (e.g., Hirasawa and Matsumoto, 1983). Shimano et al. (2013) defined the following new classification of Older, Middle, and Younger Otake volcano based on recent findings and previous reports **(Figs. 4 and 5)**.

3-3-1. Older Otake volcano

The deposits at Older Otake volcano occur at the bottom of Sakuchi caldera **(Fig. 6)**. The deposit can be subdivided into Older Otake deposits I and II, in descending order, based on an unconformity and lithology. Older Otake I consists of altered lava and pyroclastics, and Older Otake II consists of pyroclastics with finely stratified structures indicating deposition under water.

The distribution of the edifice of Older Otake volcano is unknown because it is mostly covered by Middle and Younger Otake volcano. However, the eruptive center seems to have moved westward gradually, judging from the westerly incline and distribution of its upper layers.

Direct data from radioisotopic dating have not been reported for Older Otake volcano. Intercalation between the Older Otake volcanic deposit II and the upper part of the Tondachidake volcanic deposit implies that the formation of Older Otake volcano started at least at the later stage of the activity of Tondachidake volcano.

3-3-2. Middle Otake volcano

The deposits at Middle Otake volcano occur on the northwestern shore from around the south of Fukaura to Susaki, and on the southeastern shore from the south of Sakuchibana to Iwatsumiishi. We subdivided this volcano into northern and southern units, respectively. The stratigraphic relation between these units is unidentified. However, the distribution of the lavas indicates that the eruptive

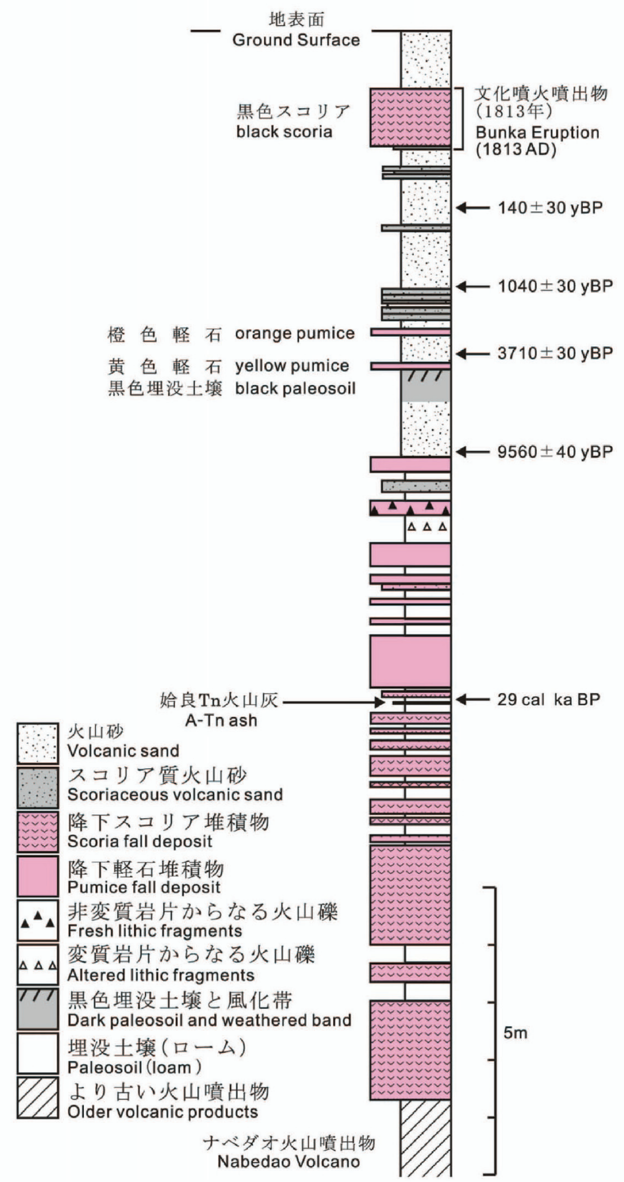

Figure 7. Columnar section of the pyroclastic fall deposit of Younger Otake volcano in the southern part of Suwanosejima (after Figure 5 of Shimano et al., 2013).

center was located near the summit of Otake for both units. The Middle Otake volcanic deposit consists mainly of subaerial lava flows with minor pyroclastics. The edifice of Middle Otake volcano is highly eroded, but some lobes of lava flows remain uneroded. K-Ar dating of lava from Middle Otake volcano at Iwatsumiishi indicates an age of 67±7 ka (Toshida et al., 2004).

3-3-3. Younger Otake volcano

The deposits of Younger Otake volcano can be mainly classified into thick agglutinates and pyroclasts in the proximal part, and pyroclastic fall deposits and some lava flows at the foot of Mt. Otake.

The thick agglutinates at Younger Otake volcano occur near the summits of Wakiyama and Otake and covers the Older and Middle Otake volcanic deposits. The total thickness of the agglutinates reaches a maximum of 150 m. The agglutinates can be subdivided into three units based on the degree of welding or the unconformity **(Fig. 6)**. The lowest unit of alternating agglutinates, the Fukaura unit, occurs around the summit of Mt. Neyama to the north of Mt. Otake. The agglutinate layers of the upper unit, the Wakiyama unit, occurs around Otake crater. The uppermost agglutinate layers are those of the 1813 eruption and occur in the area around Otake and Kyukako craters.

The thick pyroclastic fall deposits of Younger Otake volcano widely cover the foot of Mt. Otake **(Fig. 7)**. The lower half consists of scoria and pumice fall deposits with a maximum total thickness of ca. 20 m (Moriwaki et al., 1996). These deposits could be correlated with the agglutinates in the proximal area, judging from the characteristic facies and alternating patterns of the layers. A key tephra layer, A-Tn, is found in this scoria-pumice deposit, indicating an age of 29 kyBP (Moriwaki et al., 1996). ^{14}C dating of charcoal indicated an age of 30,290±190 cal BP for the Younger Otake volcanic deposit at Fukaura Bay in the northern part of the island (Fukaura unit; Yf in Fig. 6 and Appendix A), which covers Tondachidake and Middle Otake volcanoes. Thus, it is inferred that Younger Otake volcano started its activity at around 40-50 ka.

Volcanic sand layers of several meters in thickness cover the scoria and pumice layers in the southern part of the island. ^{14}C dating of charcoal showed an age of 9,560±40 cal BP in black soil between the pumice fall layer and the volcanic sand layer near Motoura port, indicating that the dominant activity shifted from relatively large explosive eruptions into moderate but successive ash emissions at ca. 10 ka.

There are some remarkable lava flows on Younger Otake volcano. Susaki lava is pyroxene-bearing, thick dacite lava and occurs on the western shore of the island. There are no dating results on the age of this lava, but judging from the stratigraphic relation, the lava could have erupted during the active stage of Younger Otake volcano. There are at least three lobes of lava flows on the eastern coast of the island in Sakuchi caldera. All are pyroxene-bearing andesite lava and, judging from their distribution, are considered to have erupted from Otake crater. A lobe of andesite lava, called Akazumiura lava, occurs on the western coast of the island, which is covered by pyroclastic

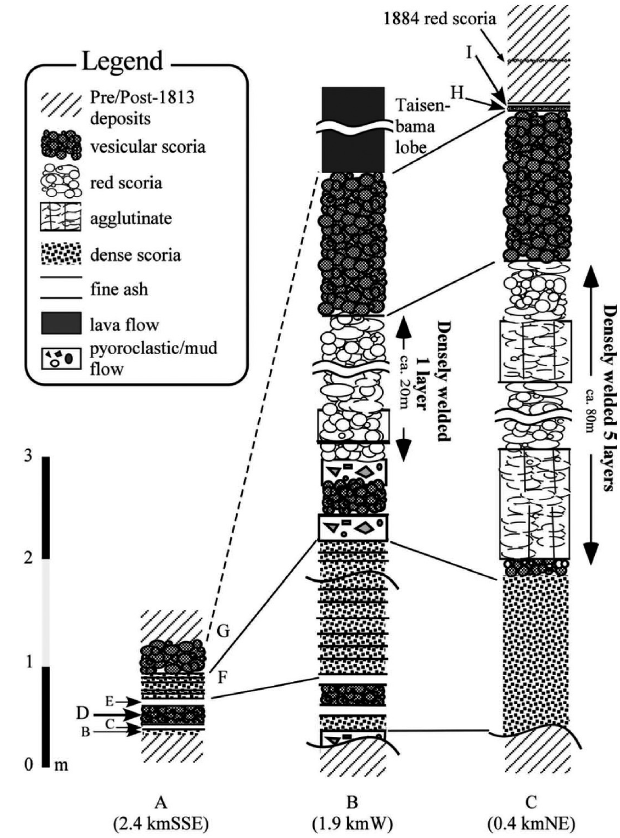

Figure 8. Correlation of the 1813 fall deposit from the proximal to the distal part in Suwanosejima volcano. A: Near Stop 3 in Figure 22, B: Near Stop 13, C: Stop 10 (after Fig. 2 of Shimano and Koyaguchi, 2001).

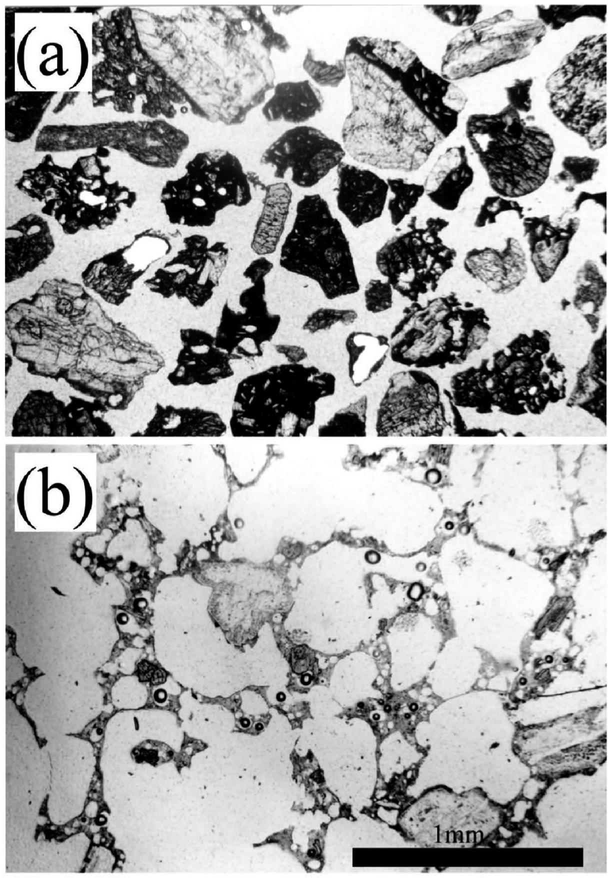

Figure 9. Microscopic photographs of some scoria of the 1813 eruption at Suwanosejima. (a) Less-vesicular scoria sand in Unit F and (b) vesicular scoria in Unit G of the 1813 eruption.

deposits of the 1813 eruption.

4. Historical products of Suwanosejima volcano

There are very few historical records about Suwanosejima island, as well as the others in the Tokara Islands, and the records of eruptions are limited to those around the 1813 eruption and some recent activities. The deposits by these activities belong to Younger Otake volcano.

4-1. Sequence and products of the 1813 eruption

The 1813 eruption (Bunka eruption) was a large explosive eruption that occurred along the crater chain in the NNE-SSW direction **(Figs. 8, 10, and 12)**. The volume of erupted products are estimated to be up to the order of 10^8 m^3 DRE, judging approximately from the distribution of the deposit on land (Shimano and Koyaguchi, 2001). The erupted magma was basaltic andesite in whole rock chemical composition with ca. 56 wt.% of SiO_2.

Shimano and Koyaguchi (2001) classified the sequence of this eruption into Phases I to III based on the characteristics of the deposit. The eruption started with the alternation of phreatomagmatic and strombolian eruptions along fissure vents on the southern flank of Otake volcano (Phase I). Then the fissure propagated toward the summit crater, which resulted in a sub-Plinian eruption at Kyukako crater (Phase II). A large edifice collapse occurred in the last stage of the eruption (Phase III).

The distribution of the deposits of Phase I is concentrated to the southern part of the island due to the eruption at fissures or craters near Tongama (Unit A-F). This activity formed a small pyroclastic cone near Tongama. The products of Phase I are characterized by alternation of many scoria and ash fall layers of different vesicularity **(Fig. 9)**. A part of the cone collapsed at the last stage of Phase I, which resulted in some pyroclastic flows that covered Village area up to the sea.

The climactic phase, Phase II, is characterized by a sub-Plinian eruption accompanied by a fissure fountain from Tongama through Kyukako to Otake crater. Highly welded agglutinate with a maximum thickness of ca 80 m and a wide distribution of tens of km^2 formed a pyroclastic cone, while a vesicular scoria fall deposit covered the entire island (Unit G). Some pyroclastic flows ran down to around Teisaibama on the southeastern shore **(Fig. 3)** and to

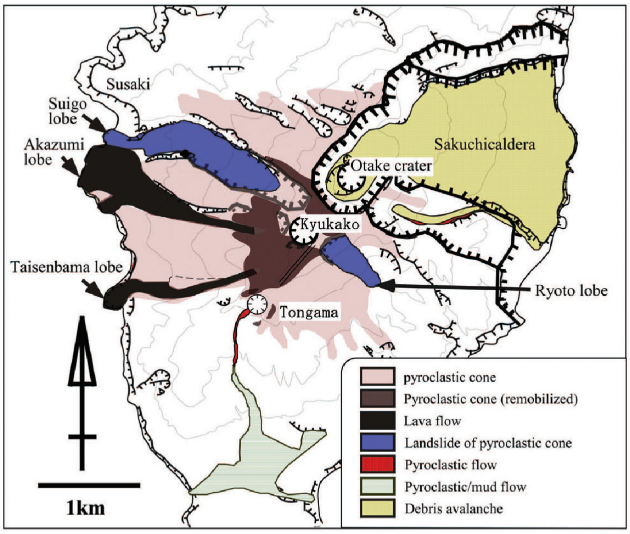

Figure 10. Distribution of the proximal deposit in the 1813 eruption (after Fig. 7 of Shimano and Koyaguchi, 2001).

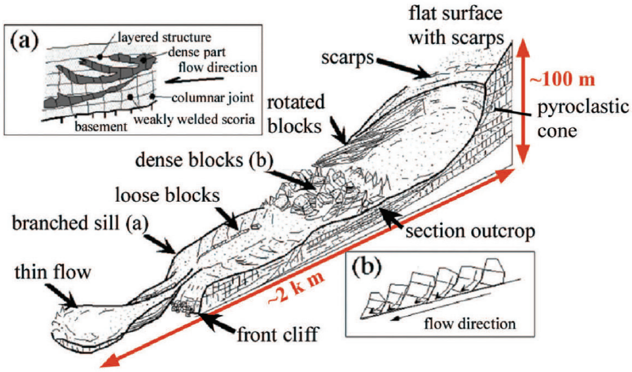

Figure 11. Suigo lobe as a result of remobilization of the pyroclastic cone during Phases II and III of the 1813 eruption (after Fig. 8 of Shimano and Koyaguchi, 2001).

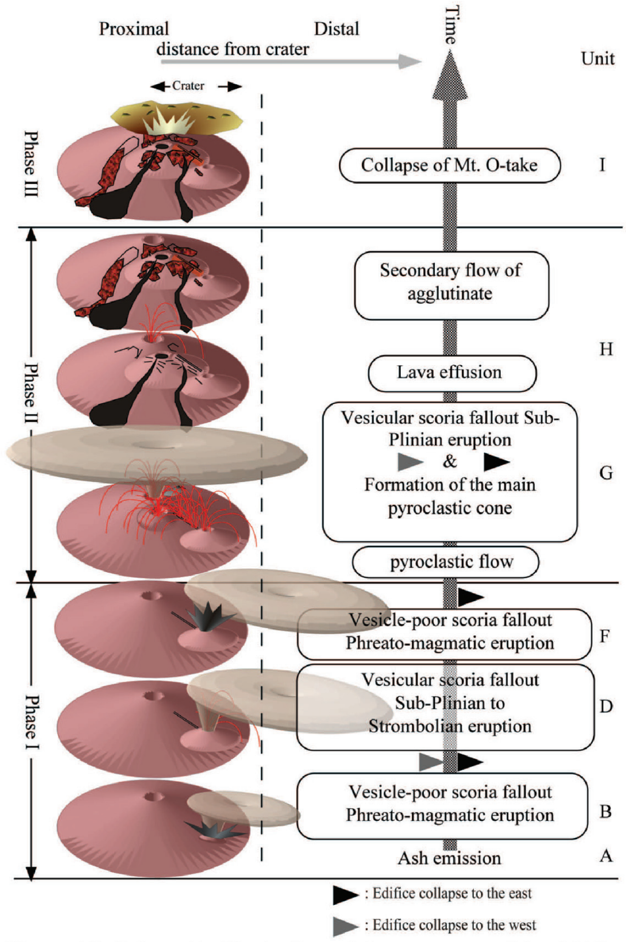

Figure 12. Schematic illustration of the sequence of the 1813 eruption, reconstructed in terms of stratigraphy and distribution (after Fig. 15 of Shimano and Koyaguchi, 2001).

around Sakuchi area in the southern part of Sakuchi caldera **(Fig. 10)**. Lava was also effused from around Kyukako crater and flowed down to Akazumi and Taisenbama coast.

A part of the pyroclastic cone formed on the steep slope of the edifice resulted in remobilization in the form of a landslide during or just after the deposition between Phases II and III **(Fig. 10)**. The landslide deposits formed lobes similar to lava flows, the largest of which flowed down the western slope of Otake crater to Suigo beach **(Fig. 11)**. Many other, smaller-scale surface topographic features formed by remobilization, such as crevasses and cliffs, are found on the surface of the pyroclastic cone.

Phase III is characterized by a large-scale collapse of the volcanic edifice, which occurred in the last stage of the eruption **(Fig. 12)**. Debris avalanche occurred from near Otake crater toward the shore of Sakuchi. The deposit covers a wide area, about 2/3 of Sakuchi caldera floor, and is as thick as ca. 10 m at the shore.

4-2. Sequence and products of the 1884-85 eruption

An explosion occurred in October of 1884, which was followed by pumice and ash fall on the island and then by effusion of lava flows from Otake crater (Meiji eruption). The eruption seems to have lasted until February of 1885. We could not find the pumice fall deposit of this eruption in the village area, but there is a pumice layer near the summit of Otake that could be correlated with this eruption. Small portions of the pyroclastic cone of the present Otake crater (ca. 450 in diameter) seem to have been formed at this time, judging from some records from the Meiji era. The lava flow covers a wide area from Otake crater toward the shoreline of Kurogai in Sakuchi caldera. Many flow lobes have developed on the surface of the lava flow. Some of these lobes exhibit a pahoehoe-like surface structure, such as ropy wrinkles and tumuli, despite their composition of basaltic andesite with abundant crystals.

4-3. Sequence and products after the 1884-85 eruption

The activity after the Meiji eruption is characterized by small-scale vulcanian, strombolian, and ash-emitting eruptions. The vulcanian eruptions of Suwanosejima volcano feature an explosion of a short duration, with ash plumes and a small amount of volcanic bombs that can fall in the area a few kilometers from Otake crater. The bombs are dense blocks or bread-crust bombs. The strombolian eruptions are characterized by intermittent emissions of incandescent magmatic fragments. In an active period, such as in 2010, highly vesicular and low-crystallinity golden scoria and flaky bombs are erupted by strombolian eruptions. Some eruptions with continuous ash emission are called ash eruptions. The products of an ash eruption consist of scoria fragments of various vesicularity, as well as fragments of dense rock and crystals, most of which are fresh and probably essential materials.

The Otake pyroclastic cone, with a diameter and height of ca. 600 m and 80 m, respectively, was formed by the proximal deposits of these activities surrounding Otake crater. The distal ash fall deposit by this activity covers the whole island (Imura, 1991), with a thickness of a few meters and 0.5-1 m near the summit and in the village 4 km south of the crater, respectively.

5. Recent activities of Suwanosejima volcano

5-1. Eruptions

After the Meiji eruption, strombolian, small vulcanian, and ash eruptions occurred at Otake crater. The frequency and intensity of eruption have changed temporally; thus, the history of Suwanosejima volcano can be subdivided into active and quiescent periods. From at least 1976, when continuous observation records began, the active periods have been identified as 1980 to 1984, September 1989 to August 1994, and December 2000 to 2011. In these active periods, fluctuations in the intensity of activity occurred. In Otake crater, incandescent lava has been reported during active periods.

5-2. Earthquakes

The seismic activities in Suwanosejima have been classified into A-type, B-type, explosion-type, and tremor-type earthquakes (Iguchi, 2000). These show fluctuations of various time scales, from a few weeks or months to several years. The waxing of A-type and B-type earthquakes is well correlated with activation of surface phenomena.

5-3. Fumaroles

The amount and composition of volcanic gas and of leachates on the surface of volcanic ash are analyzed during joint observations carried out every several years. Hirabayashi et al. (1993) indicated the emission of high-temperature gas based on the F/Cl ratio of leachate on the vulcanian ash sample from October 1989. Hirabahashi et al. (2005) estimated the total SO_2 gas release rate to be a few hundred to a thousand tons/day. They also reported the amount just before and after the explosion and indicated a larger amount of release in case of a more intense explosion.

5-4. Geothermal activity and hot springs

There are some geothermal spots around Otake crater, but such activity is not observed anywhere else in the island. The temperature in the crater changes largely with time and varies among different points in the crater (Oshima and Tamekuri, 2000). On the basis of remote visual observation, Kagiyama and Masutani (1993) proposed the idea that an aquifer layer exists at a shallow level under the crater and that the activity of fumaroles waxes or wanes with the ascent or descent of a magmatic body into the aquifer.

At a locality 1 km upward along a river from the shore of Sakuchi, there is a hot spring with a temperature reported to range from 43-49.2 degrees C in 1952, 1980, and 1984 (Ohta, 1988). There are also some spots of hot springs around the shore of Sakuchi.

6. Petrology of Suwanosejima volcano

The products of Suwanosejima volcano are basaltic andesite to dacite with SiO_2 of 55-67 wt.% **(Fig. 13)**. Three compositional trends in variation are shown in the SiO_2-MgO diagram. The first is a trend in which the mafic end member is Meiji lava, which is the most primitive composition in Suwanosejima volcano and has high MgO content; most of the products of recent activity belong to this trend. The second is a trend in which the mafic end member consists of Bunka products; Sakuchi lava belong to this trend. The third indicates some parallel trends in which the mafic and felsic end members are Tondachidake volcano lava and Susaki lava, respectively; most of the products of Older to Young Otake volcanoes belong to this group.

The amount of phenocrysts in the products of Suwanosejima volcano is 19-43 vol.%. Phenocrysts consist mainly of plagioclase and small amounts of orthopyroxene, clinopyroxene, and magnetite. Some samples have a trace amount of olivine **(Fig. 14)**, and some historical products after the 1813 eruption do not have magnetite phenocrysts.

The products of recent activity are ash particles and some amounts of volcanic bombs. They show similar textures and compositions to the other, older products. However, the crystallinity of groundmass

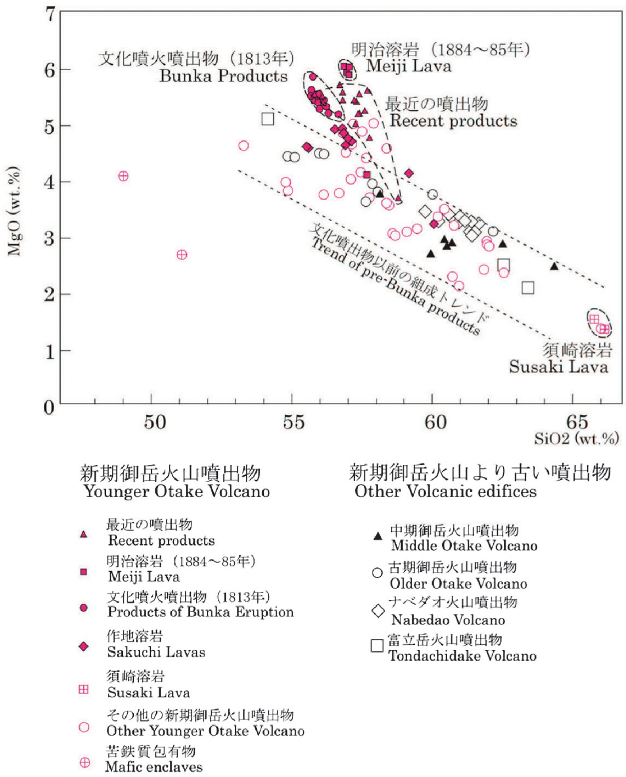

Figure 13. Whole rock chemical compositions of the products of Suwanosejima (after Figure 8 of Shimano et al., 2013).

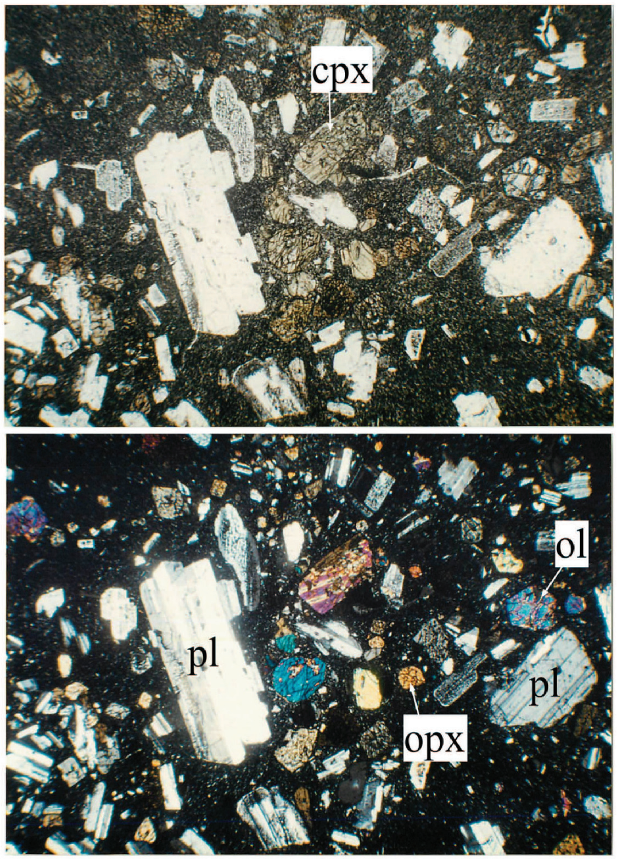

Figure 14. Microscopic photograph of a representative product of Suwanosejima, two pyroxene basaltic andesite with abundant phenocrysts of plagioclase (pl), pyroxenes (cpx, opx), and trace amounts of olivine (pl) (Dense spatter in agglutinate of the 1813 eruption). (a) Paralleled polar and (b) crossed polar. Each photo is about 2.5-mm wide.

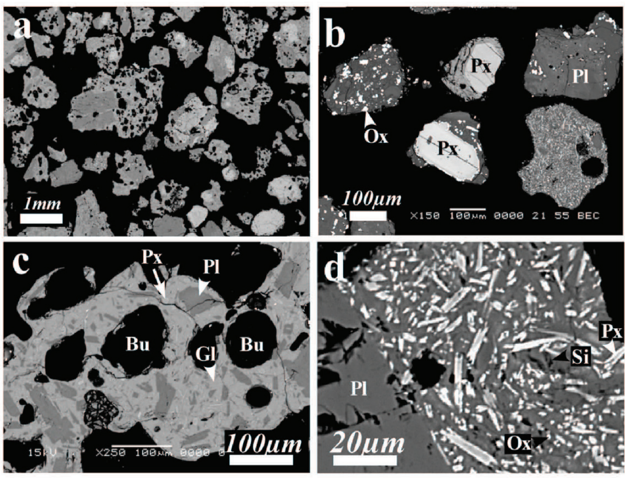

Figure 15. Secondary electron microscope images of ash particles from recent ash falls in Suwanosejima. (a) Representative ash particles from an active period, (b) several particles from a quiescent period, (c) part of a glassy particle with abundant bubbles (C-type), and (d) part of a crystalline particle (D-type). Gl: glass, Bu: bubble, Px: pyroxene, Pl: plagioclase, Ox: oxide mineral, Si: silica mineral.

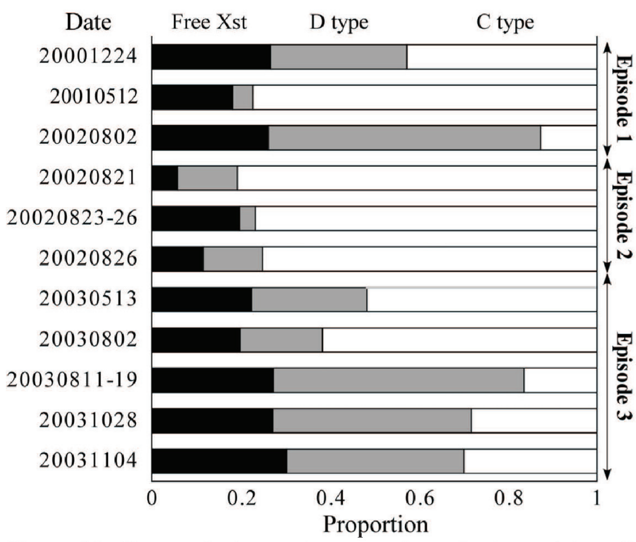

Figure 16. Temporal change in proportion of ash particles of Suwanosejima volcano from Dec. 2000 to Nov. 2003. C-type is dominant during continuously active periods (Episode 2), and D-type is dominant during quiescent and successively active periods (Episodes 1 and 3).

changes temporally with the transition of eruption styles **(Figs. 15 and 16)**. Ash samples are rich in vesicular glassy particles (C-type), having up to 80 % content during continuously active periods, which are sometimes accompanied by strombolian eruptions. In contrast, ash samples dominantly consist of crystalline particles (D-type) in quiescent and successively active periods with vulcanian explosions.

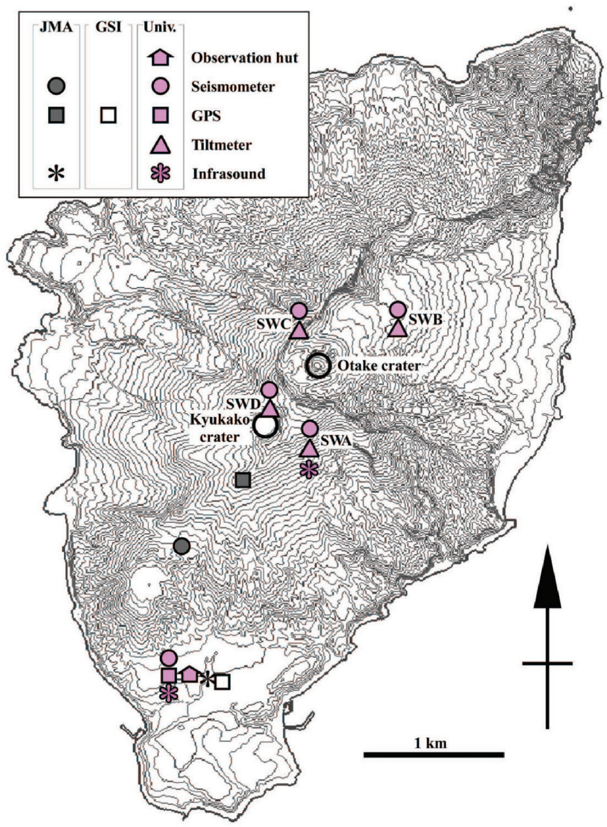

Figure 17. Representative geophysical observation sites at Suwanosejima volcano (Japan Meteorological Agency, 2013).

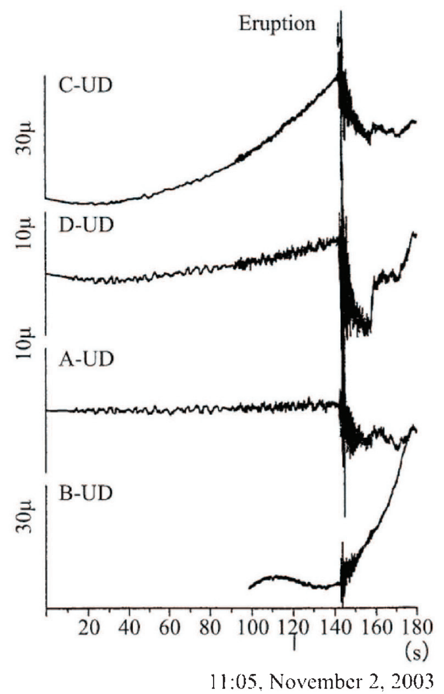

Figure 18. Vertical displacement associated with an explosive eruption at Suwanosejima volcano. The seismograms were recorded by broadband seismometers at four stations around Otake crater (after Figure 4 of Iguchi et al., 2008).

7. Geophysical observation of Suwanosejima

7-1. Observation system

Geophysical observation of Suwanosejima volcano is conducted mainly by the Japan Meteorological Agency (JMA) and the Disaster Prevention Research Institute, Kyoto University (DPRI) **(Fig. 17)**. The JMA established a continuous monitoring system using one seismometer on the southern flank of Otake and one infrasound monitor near the village area. The DPRI and some universities established another continuous monitoring system using 4 pairs of seismometers and tiltmeters around the active Otake crater and a set consisting of a seismometer, an infrasound microphone, and a GPS in the village area. The Geospatial Information Authority of Japan (GSJ) also established a GEONET station in the village area. The JMA and the Japan Coast Guard (JCG) conduct visual aerial surveys of active craters periodically; the JMA also conducts on-site surveys

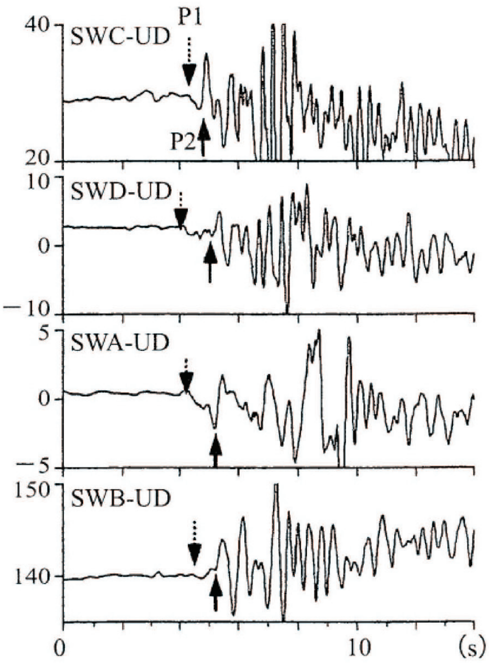

Figure 19. Initial part of displacement waveforms of an explosive earthquake at Suwanosejima volcano. P1 and P2 show the first downward motion (dilatation) and the subsequent upward motion (compression), respectively (after Figure 7-29 of Nishimura and Iguchi, 2011).

occasionally.

Since February of 2005, the JMA has been classifying and announcing the degree of volcanic activity based on 6 levels, from 0 to 5, according to the results of the above-mentioned monitoring. The volcanic activity has been classified as level 2 (moderately active) since December of 2007 to date.

7-2. Sequence of volcanic explosions derived from seismic and infrasonic observations

The broadband seismometers at four stations surrounding Otake crater detected the characteristic vertical displacements before and after explosive eruptions (Iguchi et al., 2008). The upward displacements observed 100 s before the onset of explosion shifted to the downward displacements as the explosion began (**Fig. 18**). Iguchi et al. (2004) estimated that the pressure source causing upward motion was located at a depth of 100 m beneath the crater, with a volume change of 150 m^3.

Figure19 shows the waveforms of ground displacement for an explosion at the crater. The first motion was a slow downward (dilatant) motion, followed by a sharp upward (compressional) motion 0.2-0.3 s later (Nishimura and Iguchi, 2011). Iguchi et al. (2008) located the hypocenters of these dilatations and compressions at depths of 0.3 km and 0.5 km beneath the crater, respectively. Assuming the velocity of sound for the propagation of infrasonic waves from the crater to Station A (SWA), they also estimated that the origin time of the infrasonic waves nearly coincides with the timing of sudden explosion. The infrasonic waves seem to have been generated after the time of sudden expansion. The contraction process at 0.3 km depth prior to the explosion at 0.5 km depth corresponds to cap failure at the uppermost part of the volcanic conduit beneath Otake crater.

Based on geophysical evidence derived from observations not only at Suwanosejima volcano but also at Sakurajima and Semeru volcanoes, Iguchi et al. (2008) proposed a model of the hypothesized sequence of events involved in an explosion (**Fig. 20**). The first stage is inflation beneath the crater due to a gradual increase in pressure generated by the intrusion of magma into the conduit and the accumulation of gas at the top of the conduit. The second stage is minor contraction caused by the leakage of volcanic gas from the accumulation as the gas pressure exceeds the strength of the cap. The third stage is characterized by a transient increase in the volume and pressure of magma as a result of abrupt outgassing of the water-saturated magma due to a decrease in pressure after the previous stage. The fourth stage involves an increase in the volume and pressure of the gas pocket at the top of the conduit, associated with explosive eruptions starting at the bottom of the crater. The fifth stage is deflation of the conduit by a decrease in pressure and volume due to the ejection of volcanic gas and ash. This stage is separated into sudden contraction at the shallow part (5A in **Fig. 20**) and gradual deflation at the deeper portion (5B in Fig.20).

7-3. Three-dimensional P-wave velocity model at the shallow part of the volcano

A seismic experiment using 9 artificial shots in and around Suwanosejima volcano was performed in 2005 to estimate the seismic velocity structure of the volcano. A total of 97 seismic stations successfully recorded the artificial waves. Yakiwara et al. (2010) presented a three-dimensional P-wave velocity model (**Fig. 21**). Because they used only artificial seismic data, the velocity model was well resolved from the surface to about 0.3 km below sea level.

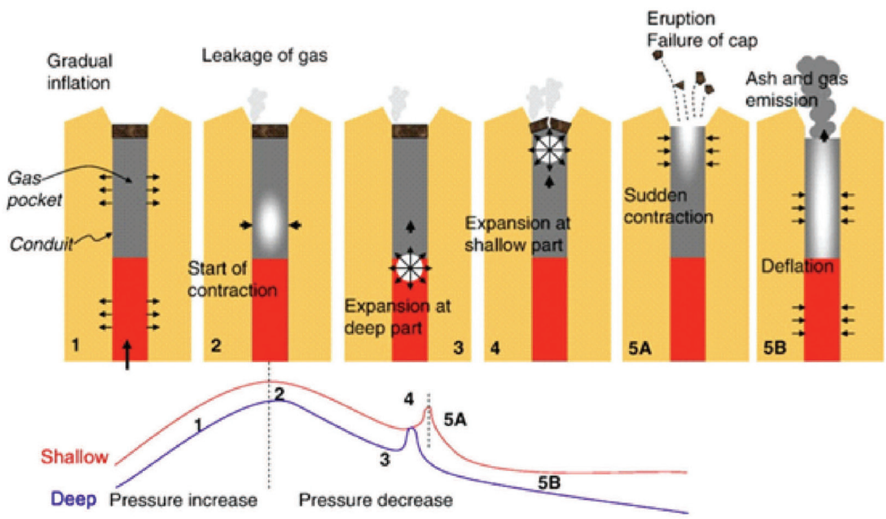

Figure 20. Model of events involved in a volcanic explosion on the bases of geophysical observations at Suwanosejima, Sakurajima, and Semeru volcanoes. Schematic vertical displacement and/or inflation caused by shallow and deep sources are also shown (after Figure 9 of Iguchi et al., 2008).

At 1 km west of Sakuchi caldera, a region with a high P-wave velocity of up to 4.3 km/s exists below sea level, which may represent silicic intrusive rocks. Another mountain-like body with a high P-wave velocity that gradually extends from sea level to the vicinity of Otake crater was estimated. However, the peak of the body offsets southeastward about 0.5 km from the crater. The body is believed to have been formed by the accumulation of dense volcanic blocks and/or agglutinates in the vicinity of past eruptive vents through the growth process of the volcano edifices. On the other hand, pressure sources (shown in the previous section) beneath the crater locate inside the area with a high P-wave velocity of 3.0-3.8 km/s. Therefore, it has been concluded that the explosion field of Suwanosejima volcano is contained in the area of high P-wave velocity.

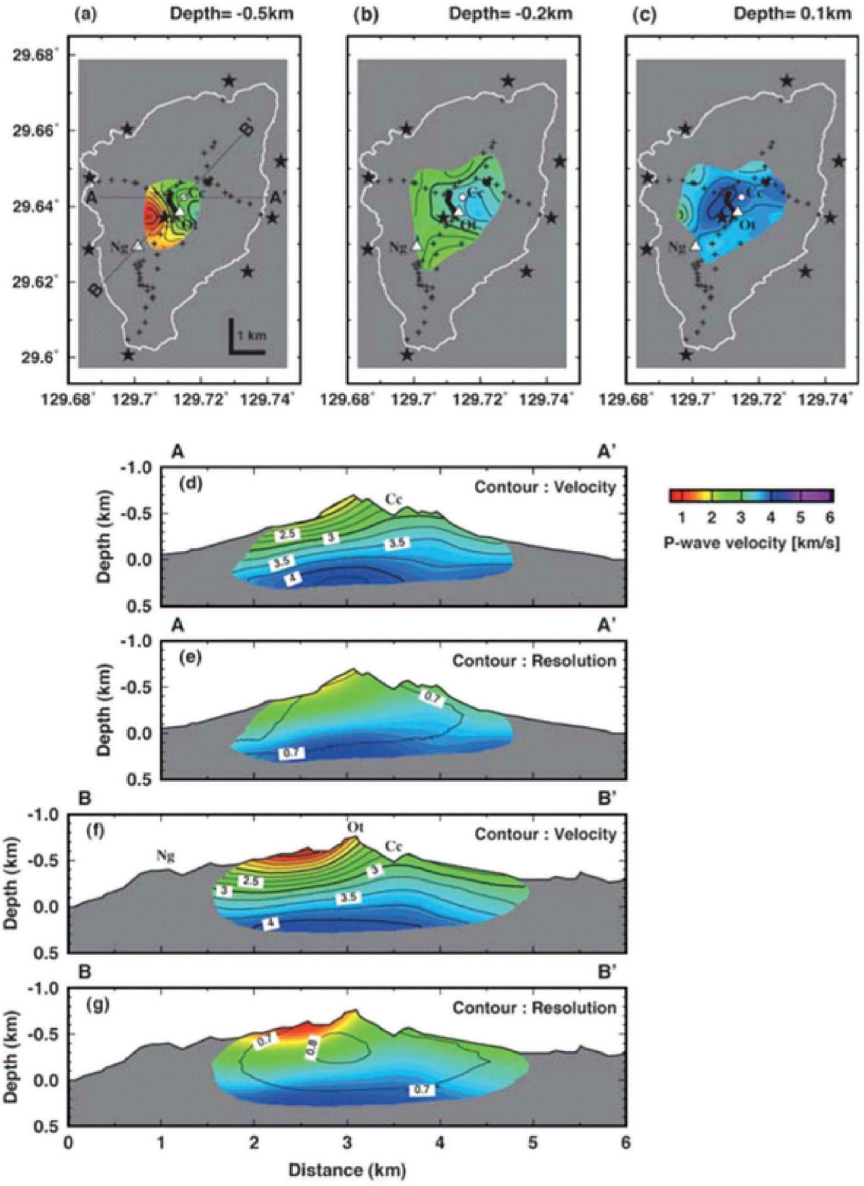

Figure 21. Three-dimensional P-wave velocity model of Suwanosejima volcano. Horizontal and vertical sections are shown with a color index for P velocity. Triangles and a circle denote the summits and an active crater, respectively. Ot: Otake, Ng: Negami-dake, Cc: center of Otake Crater (after Figure 4 of Yakiwara et al., 2010).

8. Recent activity and hazards of Suwanosejima volcano

All the eruptions after the Bunka eruption occurred at Otake crater. Eruptions occur successively due to the continuous ascent of andesitic magma from the depths to the floor of the active vent. Small vulcanian, strombolian, and ash eruptions have been recorded. Some strong explosions carry volcanic bombs down to ca. 1-2 km from Otake crater. Volcanic ash and sand emitted as plumes are brought downwind in all directions, depending on the wind direction during emission.

Large-scale lava effusion has not occurred since the Meiji eruption, during which lava reached the seashore. In cases when Otake crater effused similarly as in the Meiji eruption, lava flows could go down through the valley toward the beach of Sakuchi.

Judging from the geological history, sub-Plinian eruptions, such as the Bunka eruption, or more energetic eruptions may occur every some hundreds of years. Such eruption would cause coarse pyroclastic fragments to fall throughout the island. An eruption may occur at locations other than Otake crater. In cases similar to the 1813 eruption, pyroclastic flows may reach the village area.

It is obvious that Suwanosejima has collapsed several times in its history, and it is highly probable that Otake may collapse again, generating a debris avalanche and consequent tsunami in the sea. The collapse may be triggered by an eruption, such as in 1813, or by other activities, such as distal tectonic earthquakes.

Part II Field guide of Suwanosejima volcano

1. General remarks on the field excursion

In this field excursion, we will see some characteristic topographic features and pyroclastic deposits of the 1813 and recent eruptions **(Fig. 22)**. We will also have time to visit some of the observation stations in the island, where university groups in Japan conduct continuous monitoring and telemetric transmission of data. We will see several active volcanoes in the northern Ryukyu arc from a chartered ship on our way back to Kagoshima.

2. Departure

STOP 1: Kagoshima port

You can see Sakurajima volcano to the east of Kagoshima city but you cannot see the active Showa crater because it is on the southeastern flank of Sakurajima. You can go to the island by the Sakurajima ferry, which leaves from another pier in the neighbor. "Ferry Toshima" is the name of the vessel that will take us to Suwanosejima. Our meeting time is 20:45 JST. We will leave Kagoshima port at midnight (23:00 JST). The ferry is in service only twice a week so make sure you come on time! The ship will call at some of the Tokara Islands, namely, Kuchinoshima, Nakanoshima, and Tairajima, before it arrives at Suwanosejima at about 9:00AM. The ship will also call at Akusekijima, Kodakarajima, and Takarajima before arriving at Amami-Oshima in the evening.

3. Day 1 in Suwanosejima

3-1. STOP 2: Arrival at Kiriishi port

We will arrive at Kiriishi port, in the SE part of Suwanosejima, at ca. 9:00AM. Please make sure that you have all your belongings with you before leaving the ship. On the cliff surrounding the port, some units of Makkodai lava (60-70 ka) can be seen. A car service will take you to the village area.

3-2. STOP 3: Otake Inn

There is a nice outcrop of pyroclastic fall deposit in front of Otake Inn. The 1813 scoria fall layers are covered by recent ash fall deposit **(Fig. 8a)**. The 1813 scoria fall layers widely cover the southern part of the island. The deposit can be subdivided into 7 units, from A to G in ascending order. Units A to F consists of alternating layers of scoria sand and ash of various vesicularity. Unit G is a vesicular scoria lapilli layer. The total thicknesses of Units A to F change relatively largely even in the village area, whereas Unit G has a fixed thickness of ca. 20 cm. An ashy loam deposit as thick as ca. 50 cm is found just above the 1813 deposit. It is also worth noting that an ashy loam deposit lies just below the 1813 deposit, indicating similar, successive ash emissions before the 1813 eruption.

In the central part of the village area, a pyroclastic/mudflow deposit with many juvenile blocks covers the 1813 deposit. The pyroclastic/mudflow deposit consists of several flow units, some of which can be traced back to a pyroclastic flow deposit with monolithologic features of red oxidized juvenile scoria and blocks of agglutinates in the proximal area.

4. Day 2 in Suwanosejima

4-1. STOP 4: Nabedao road

There are only a few roads in Suwanosejima, and most of the flat area is densely covered by a bamboo jungle as tall as several meters. Nabedao road leads to the entrance to a trail toward the summit of Mt. Otake. We will see some outcrops along this road. Some debris flow deposits with abundant lava blocks from Nabedao volcano occur in the lower part of the road. Tephra fall layers of Younger Otake volcano cover this deposit of

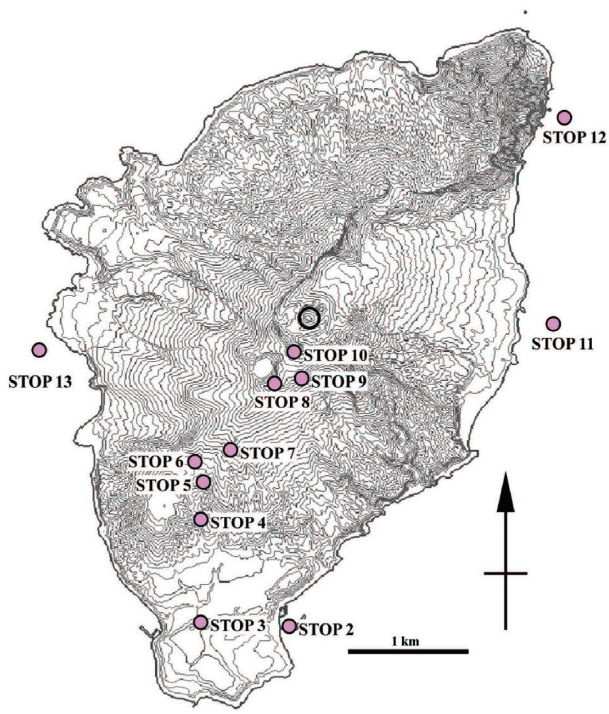

Figure 22. Locality map of the field excursion of Suwanosejima volcano.

Nabedao volcano in the upper part of the road. We will see a ca. 30-ky pyroclastic fall deposit, as summarized in **Fig. 7**.

4-2. STOP 5: Trail entrance

We will see some flow units of the red oxidized pyroclastic flow deposit of the 1813 eruption, with many spatters and agglutinate blocks, at the northern end of Nabedao road. Judging from the stratigraphy, these pyroclastic flows seem to have been generated in the later stage of Phase I. Then, some of them might have turned into the pyroclastic flow or mudflow that reached as far as the village area and into the sea until the latest stage of the 1813 eruption. We will enter a trail and walk from there up to the summit of Mt. Otake.

4-3. STOP 6: Kyoshujo (Training circuit)

There are some clusters of bare land on the surface around here. We will see a weakly welded black scoria deposit from the 1813 eruption. The 1813 deposit is as thick as several meters at this point, including pyroclastic flows. The degree of welding increases on average toward the summit. This area is named after a driving school in Japan due to the view from the summit area.

4-4. STOP 7: Tongama

This area was devastated by the 1813 eruption and has been left bare for 200 years. There are almost no trees taller than a man’s height. But in early summer, you may see beautiful pink azalea (*Rhododendron eriocarpum*) flowers, called *Marubasatsuki*, on the slope of agglutinate. Tongama is the name of a conical peak that sits here, which consists of alternating layers of agglutinates that form a remarkable shape when viewed from the village area. The existence of the strongly welded agglutinate indicates a vent locality that is close to Tongama; thus, Tongama is believed to be the southern end of the fissure or crater chain of the 1813 eruption **(Fig. 10)**. Some parts of the deposit have collapsed down to the valley, where they could have generated some pyroclastic flows that were later deposited at around STOP 5 or further.

4-5. STOP 8: Kyukako crater (permission is necessary to go further)

This was the main active crater in the 1813 eruption, but it has not erupted since then. It has a diameter as large as ca. 300 m and shows no sign of geothermal activity. The lowest point of the crater is at the western rim, where a major lava flow effused down to Akazumi on the west coast **(Fig. 10)**. The lava flow has many blocks of pyroclastic deposit on its surface, indicating that the effusion of lava had already begun when the climactic explosive eruption started (Phase II). Alternation of agglutinate layers of the 1813 eruption occurs on the wall inside the crater. Some lava of the older edifices of Younger and Middle Otake volcanoes occur below the 1813 deposit.

There are many blocks of agglutinates as large as several meters on the surface around this stop. On the steep slope of the edifice, we will see many crevasses and rows of blocks on the surface **(Appendix A)**; these were formed by the remobilization of the pyroclastic cone created during the climactic phase of the 1813 eruption. Especially, the lobe to the west of a characteristic peak on the summit of Otake looks like a landslide deposit but consists of agglutinate layers with some hummock hills on its surface **(Fig. 11)**. We will visit a geophysical observation site, Station D, on the northern rim of the crater.

4-6. STOP 9: Station A (SWA)

Station A is one of the major observation sites surrounding Otake crater **(SWA; Fig. 17)**. A seismometer, a tiltmeter, and an infrasound microphone are continuously in operation, along with telemetric transmission of data to the observation hut in the village by means of a radio set. Electric power is supplied by solar batteries. University groups and some national institutions also recently established other monitoring sites for borehole tiltmeter, GPS, and PS-InSAR observations in the area ca. 1km from Otake crater.

4-7. STOP 10: Otake summit (We cannot go down to Otake crater)

The summit of Mt. Otake is located on the western rim of Sakuchi caldera. On the wall of the caldera, we will see alternating lava and pyroclastic layers of Older Otake volcano, Fukaura Unit, Wakiyama Unit, and the 1813 agglutinate of Younger Otake volcano, from north to south in ascending order **(Fig. 6)**. The active Otake crater will be just in front of us (Watch your step!). Otake crater is now in a quiescent period (as of March 2013), but based on the increasing duration of volcanic tremors since September 27, 2012 (JMA report), it may enter into another active period. Over Otake crater, we will see the lava flow field of the 1884-85 eruption (Meiji eruption) on the caldera floor. There are many flow lobes of a few meters wide on the surface of the lava, some of which reach as far as the shoreline. In the central part of the lava field is a geophysical observation site, Station B, which is accessible only from the eastern coast of Sakuchi.

5. Round cruise

Observation of the shoreline is fundamental to understanding volcanic history and the sequence of the 1813 eruption of Suwanosejima because there are nice outcrops on the sea cliff, and we can grasp the topographic image of the deposits.

We will leave Suwanosejima early in the morning, after a cruise around Suwanosejima on the chartered ship “Nanashima.” We will stop mainly at three spots during the cruise of about an hour: off the eastern, northern, and western coasts of Suwanosejima.

5-1. STOP 11: Off the east of Sakuchi

From east of Sakuchi coast, we will observe a topographic view of Sakuchi caldera and the debris avalanche deposits of the 1813 eruption. There are three flow units, all of which consist of yellowish altered rocks and a minor amount of juvenile rocks but are slightly different in color from each other. We may see fresh lava flow from the 1884-85 eruption that entered the sea, as well as some eroded lava covered by the debris avalanche deposit.

5-2. STOP 12: Off the east of Tondachidake

Tondachidake volcano is the oldest edifice of Suwanosejima. It has been so heavily eroded that one can see a cross-section of this old volcanic edifice with some dikes intruded radially from the summit to the eastern and northern cliffs of the edifice. We will see the Shiramizu waterfall, which flows down stepwise on the cliff from as high as 500 m near the summit of Tondachidake.

5-3. STOP 13: Off the west of Akazumi coast

Red agglutinate formed during Phase II of the 1813 eruption occurs along the western cliff of Akazumi coast **(Fig. 8)**. Most of the deposit is red in color, with slight layering as thick as ca. 30 m, but the uppermost part ca. 1-2 m from the surface is black. This agglutinate is correlated with the thick vesicular scoria fall layer, Unit G, in the village area. The agglutinate deposit covers thin black scoria layers of a few meters in thickness, which may be correlated with the scoria fall layers, Units A to F, in the village area.

6. Return to Kagoshima

We will then go northward through the Tokara Islands. The destination of the ship Nanashima is Miyanoura port in Yakushima **(Fig. 1)**. During the cruise, we will see some active volcanoes, from south to north: Nakanoshima, Kuchinoshima, Kuchinoerabujima, and Satsuma-Iwojima. We will arrive at Miyanoura port in the afternoon. The field excursion ends here. You can choose to stay overnight in Yakushima or take the ferryboat to Kagoshima.

Summary

Suwanosejima volcano is one of the most active volcano in Japan that consists of three volcanic edifices; Otake, Nabedao and Tondachidake volcanoes. The products of the volcano consist of pyroxene basaltic andesite and dacite with whole rock SiO_2 content ranging from 55 to 67 wt.%. Some results of K-Ar dating indicate that the subaerial volcanic activity started at least around 150 ka and this volcano became as large as the present Suwanosejima island at ca. 60-70 ka. The main part of the Younger Otake volcano was formed between ca. 40-50 and 10 ka with some large-scale pyroclastic eruptions.

The oldest and largest historical eruption occurred in 1813. The eruption occurred along the crater chain in the NNE-SSW direction through the summit of Mt. Otake and erupted basaltic andesite magma. The eruption began with phreatomagmatic activities at the end of the crater chain and the fissure propagated to the summit crater, which resulted in sub-Plinian eruption. The eruption built a large pyroclasitc cone that covered as large as a few km^2 with the maximum thickness of ca. 80 m, and emitted some lava flows. In the final stage of the eruption, a sector collapse of summit area of Otake took place and the debris avalanche reached the eastern coast of the island. The second largest historic eruption occurred in 1884-85. This eruption is characterized by the effusion of fluidal andesitic lava flow from Otake crater which covered directly the surface of the debris avalanche deposit of the 1813 eruption. The recent eruptions after 1885 are characterized by continuous activities of strombolian, vulcanian and ash eruptions. The volcanic ash produced by these activities covered all the island with the total thickness 0.5-1.0 m at the Village area.

The geophysical continuous monitoring system has been established in Suwanosejima equipped with seismometers, infrasound microphones,

tiltmeters, and GPS receivers. The analyses of data by four broadband seismometers surrounding summit crater revealed detail sequence of an vulcanian explosion at shallow part of the conduit that consists of five stages; inflation of crater by magma intrusion, minor contraction by leakage of gas accumulated in magma, gradual increase of volume and pressure of magma, increase of volume and pressure of gas pocket at the top of conduit by explosion at the bottom of the crater, and deflation of conduit by ejection of eruptive materials. The artificial seismic experiment in 2005 revealed seismic velocity structure beneath Suwanosejima with 3D model from the surface to about 0.3 km below sea level. The results show heterogeneous distribution of high P-wave velocity zone just below the surface implying complex evolution history of the volcano.

The field excursion guide introduces several outcrops of pyroclastic deposits in Suwanosejima and discusses the evolution history of Suwanosejima volcano as well as the sequence of the 1813 eruption. We will also climb up Mt. Otake to observe active crater and see some geophysical observation sites as well as some proximal deposits of the 1813 eruption.

Acknowledgements

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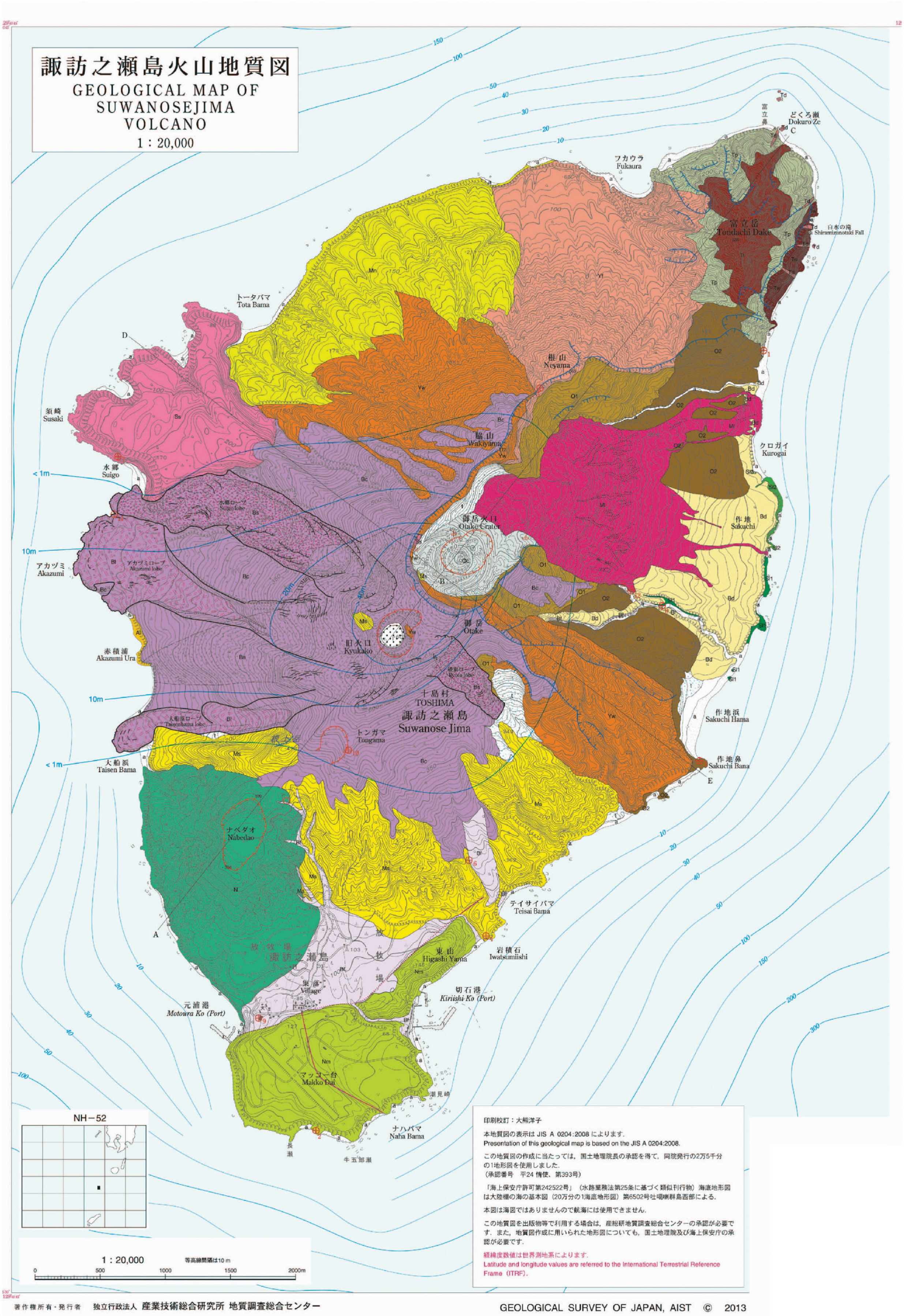
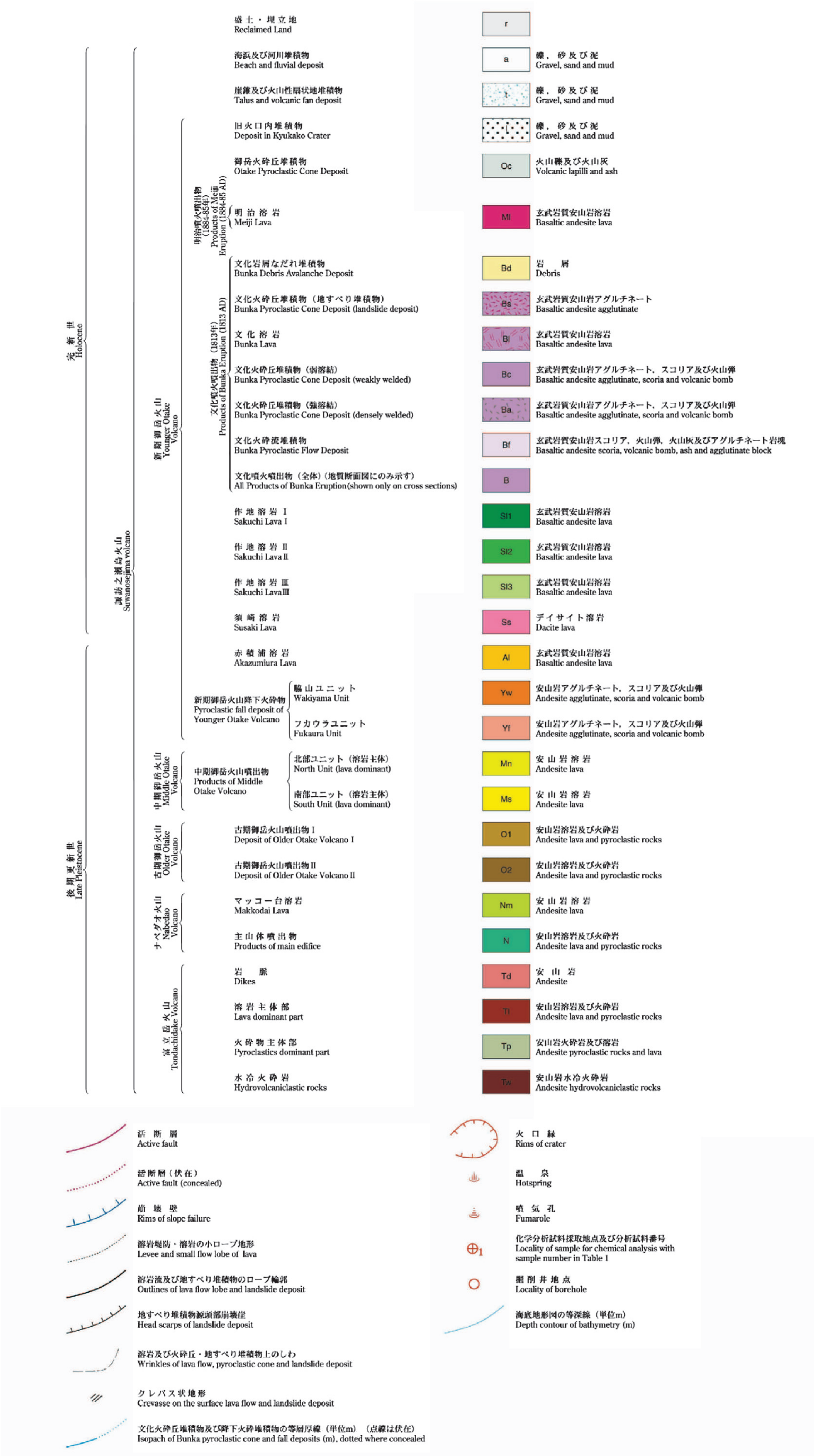
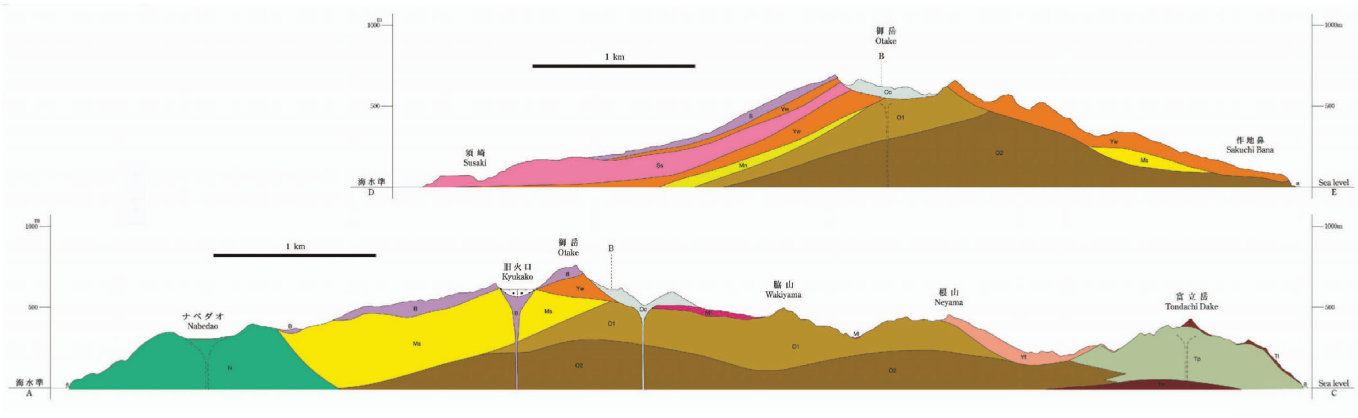


Appendix A: Geological map of Suwanosejima (after Shimano et al., 2013).



Appendix A: (continued).



Appendix B: Geological cross-sections of Suwanosejima along A-B-C and D-B-E of Appendix A (after Shimano et al., 2013).