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IAVCEI Field Trip Guide

B5: Kirishima, Sakurajima volcanoes and their source calderas in southern Kyushu

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1. Introduction

This trip covers two active volcanoes of the southern Kyushu; Kirishima and Sakurajima, where the volcanic deposits and their impacts on residents can be observed. We will also observe some large-scale ignimbrites and their source calderas. Sakurajima is a post-caldera volcano of Aira caldera which produced a vast ignimbrite plateau in southern Kyushu in 29 cal kBP. Kirishima consists of more than 20 vents, which are also post-caldera volcanoes of Kakuto caldera. Shinmoedake, one of the active post-caldera volcanoes erupted sub-plinian pumice in January 2011. We can observe the new tephra deposit at the foot of the volcano.

2. Tectonic setting and general geology of southern Kyushu

The 1000 km long southern Kyushu-Ryukyu volcanic arc includes the active volcanoes of Kirishima, Sakurajima, and Kaimondake on Kyushu, and several volcanic islands to southwest.

The Okinawa trough, located behind this volcanic arc, is a marginal back-arc basin active since the late Miocene (Fig. 1). Conspicuous extensional movement along the axis of the trough was initiated 1.9 Ma (Kimura, 1985). Simultaneous with its opening, tectonic movements associated with intense volcanism occurred and volcanism has predominated over a wide area to the west of southern Kyushu. The Kagoshima graben, trending NNE-SSW, defines the eastern margin of the volcano-tectonic depression. Kagoshima Bay, approximately 20 to 30 km in width, occupies two-thirds of the southern part of Kagoshima graben.

The basement complex of southern Kyushu is composed mainly of the Shimanto supergroup, Miocene silicic plutonic rocks, and Pliocene - early Pleistocene volcanic rocks. The Shimanto supergroup, made up of highly deformed Cretaceous to Paleogene shales, sandstones, conglomerates, and minor pillow lavas, underlies the graben. The Shimanto supergroup is broken by step faulting and overlain by a densely welded ignimbrite that is dated at about 2.9 Ma (Shibata *et al.*, 1978), and marks the beginning of formation of the volcano-tectonic depression.

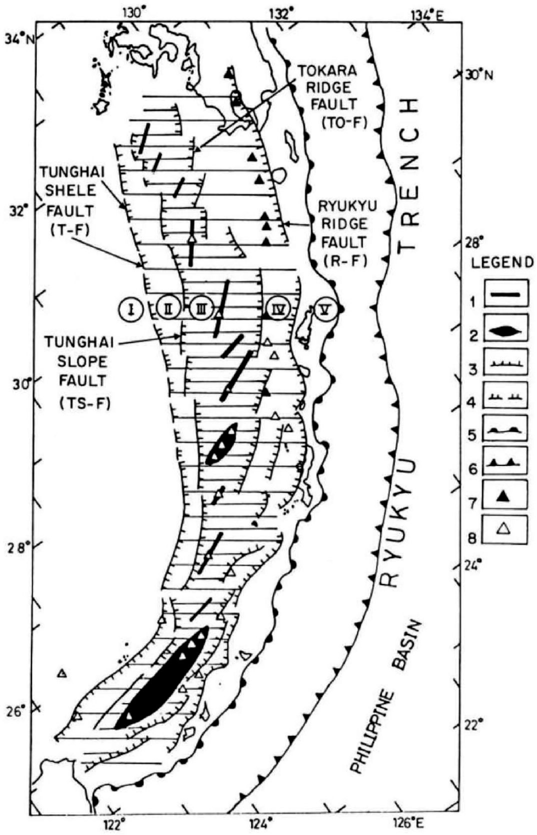

Fig. 1 Geological and structural map of the Ryukyu arc, Okinawa trough, Taiwan, and vicinity (Kimura, 1985). Legend 1, central graben; 2, basin occupied by Pleistocene igneous intrusions; 3, major fault and fault scarp; 4, buried major fault and fault scarp; 5, eastern boundary of the Ryukyu Ridge; 6, trench; 7, active volcanoes; 8, submarine intrusions or volcanoes since Late Pleistocene time.

Kagoshima graben contains the Kakuto, Aira and Ata calderas and other small and unidentified depressions (Fig.2). The Aira, Ata, and Kikai calderas, including the Aso caldera in central Kyushu, were first proposed by Matumoto (1943). The Kikai caldera, one of the youngest Holocene calderas in Japan erupted in 7.3 cal KBP is located about 30 km south of Kagoshima Bay. Large volumes of highly vesiculated silicic magma in the form of pyroclastic falls and flows were repeatedly erupted from these calderas and formed vast pyroclastic plateaus around the area. These calderas are now partly occupied by the active volcanoes.

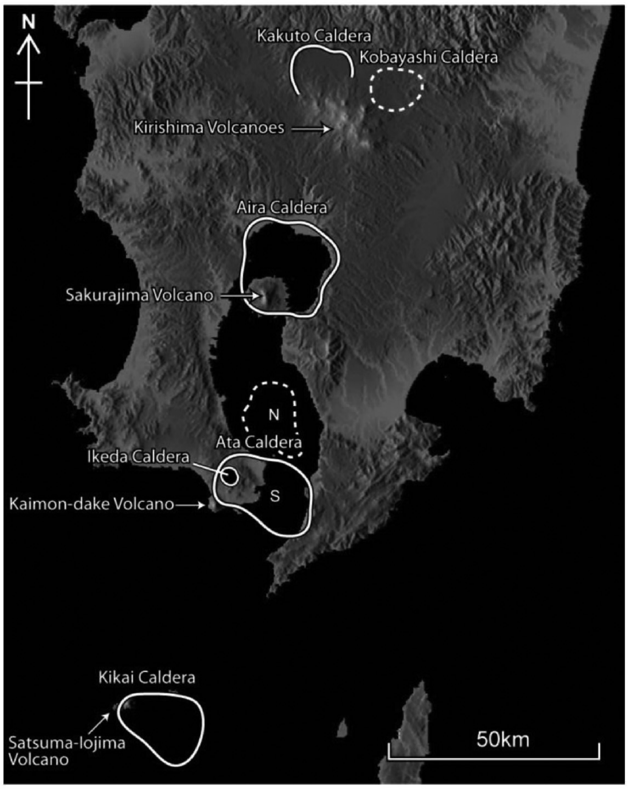

Fig. 2 Index map showing the location of main calderas and the associated active volcanoes in southern Kyushu.

3. Aira caldera

3-1. Outline of activity

Aira caldera occupies the northern end of Kagoshima Bay, and being controlled by regional fault systems, is not circular but rather rectangular in shape. Its north-eastern portion, having a deeper flat bottom at 200 m below sea level, is the so-called Wakamiko caldera (Shimomura, 1960). The south-eastern rim consists of remnants of alternating pyroclastic flow deposits and lava flows, ranging from 2.9 Ma to 0.2 Ma in age (Kaneoka *et al.*, 1984). This sequence suggests that intense volcanism, with large-scale pyroclastic eruptions and minor lava flows, has repeatedly taken place in the caldera region. Moreover, Nagaoka (1988) and Nagaoka *et al.* (2001) observed that at least seven pyroclastic eruptions had taken place during the last 100,000 years. Rough calculation shows that eruptions occurred every 14,000 years (on average) within the Aira caldera, resulting in a complex topography in its eastern portion.

3-2. Climactic eruption (Aira tephra eruption)

At 29 cal kBP, a great pyroclastic eruption occurred within the Aira caldera (Okuno, 2002). Figs. 3 and 4 represent the sequence of this eruption and the distribution of pumice fall and Tarumizu and Tsumaya ignimbrites, respectively.

Phase 3	Ito ignimbrite + LCZ	*climactic pyroclastic flow*
Phase 2	Tsumaya ig.	*post-plinian flow*
Phase 1	Tarumizu ig.	*intra-plinian flow* + *plinian fall*
	Osumi pumice fall	

Fig. 3 Stratigraphy of the Aira tephra formation (29 cal kBP)

The first phase of the eruption was plinian, forming the Osumi pumice fall (Aramaki and Ui, 1966) with a dispersal axis to the southeast (Fig. 4). The dispersal pattern indicates that the source vent is located near the present Sakurajima volcano on the southern rim of Aira caldera. The Osumi deposit generally lacks stratification and is nearly homogeneous except for an overall reverse grading. The bulk volume is calculated to be about 98 km^3 (Kobayashi *et al.*, 1983).

Although the thickness of the Osumi pumice in Tarumizu area, 20 km southeast of the vent, is supposed to be more than 8 m, the actual thickness is less than 2 m (Fukushima and Kobayashi, 2000). This basal pumice fall deposit is overlain by Tarumizu ignimbrite distributed only in the Tarumizu area, which consists of alternations of many small-scale pyroclastic flow deposits, mostly less than 1 m thick. Field evidence suggests that the stratified flow deposit had been generated almost simultaneously with the plinian column formation. This intra-plinian ignimbrite consists of two different lithofacies; one is thinly stratified and forms low-angle cross-bedding structures, and the other is massive and much thicker and coarser. These two lithofacies are stratigraphically complicated, but the massive unit generally occupies the upper horizon of the deposit.

After the plinian eruption, the Tsumaya pyroclastic flow was erupted, the vent for which might have shifted to the present Wakamiko caldera which occupies the northeast sector of the Aira caldera. Tsumaya ignimbrite tends to be very fine-grained and massive, and often involves large accretionary lapilli especially in the lower unit. The general distribution of the deposit is confined within the pre-Aira basin, in strong contrast with the Ito ignimbrite that extends beyond the basin boundaries.

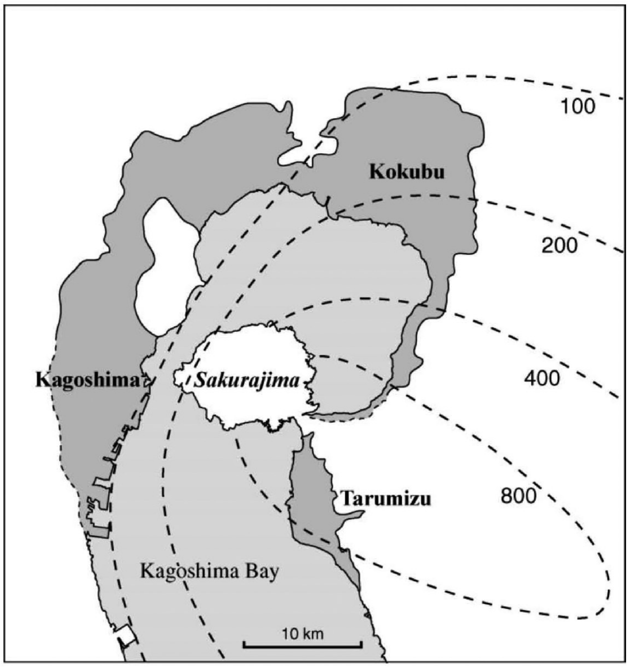

Fig. 4 Isopach map of the Osumi pumice fall deposit (cm) and the distribution of Tarumizu ignimbrite in Tarumizu area and Tsumaya ignimbrite in Kokubu and Kagoshima areas.

After a geologically short pause, the major phase of the Ito eruption occurred, resulting in the formation of a vast pyroclastic plateau over southern Kyushu (Fig. 5). The most distal deposits are found at 90 km to north of the center of the caldera (Yokoyama, 2000). The depositional surface is generally flat, but is affected by the general local relief of the basement rocks (Yokoyama, 1972). Basement rocks are directly exposed along the eastern and western portions of the caldera, where the depositional surface of the ignimbrite shows a gentle outward dip. A thick lag-breccia, called Kamewarizaka breccia (Aramaki, 1969) is confined to the north-eastern caldera rim, but the lithic concentration layer of the ignimbrite is distributed in all directions. The Ito ignimbrite is very homogeneous in color and grain-size distribution, and is mostly non-welded. However, local deposits showing a wide range of welding are found, especially in the north-eastern sector of the distribution.

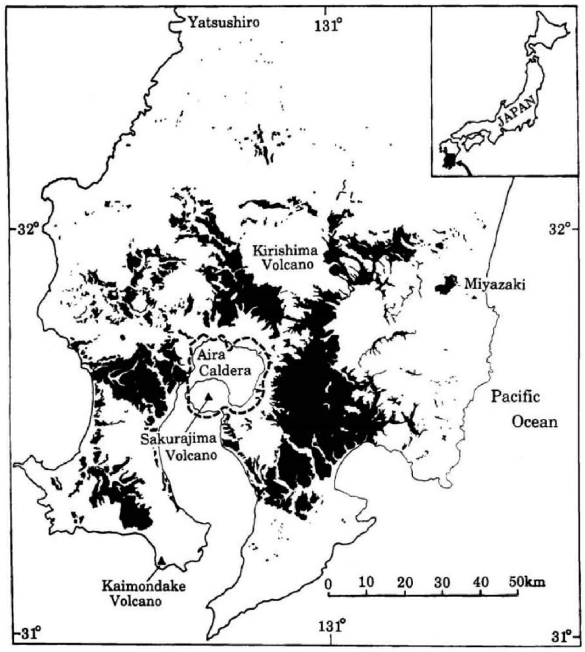

Fig. 5 Distribution of the Ito ignimbrite (Yokoyama, 2000)

Ito co-ignimbrite ash (AT ash), first described by Machida and Arai (1976), is found up to 1,400 km from the vent, and covers almost whole Japan and became a good marker key bed for tephrochronology (Fig. 6). The total volume of magma erupted during the Ito eruption is about 110 km^3 (Aramaki, 1984).

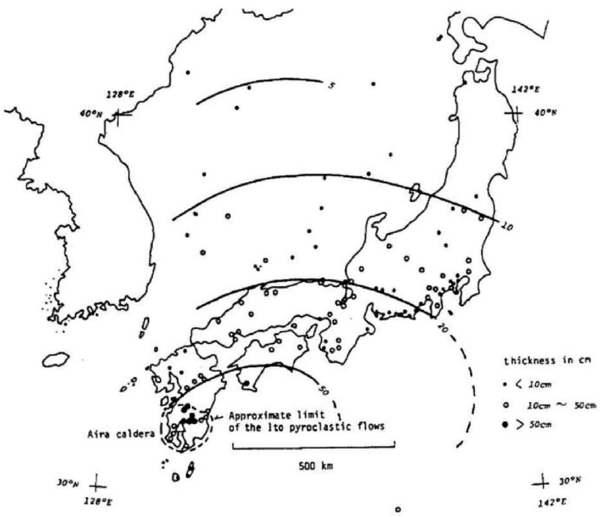

Fig. 6 Isopach map of the Aira-Tn ash (AT) with thickness in cm (Machida and Arai, 1983)

Based on the distribution and grain size of the lithic breccia, the vent position for the Ito ignimbrite is estimated to be at the center of Aira caldera (Aramaki, 1984), or at the Wakamiko caldera (Nagaoka, 1988). However, Fukushima (2001) suggested that the Ito ignimbrite eruption occurred from multiple vents, one at the initial Osumi vent (the present site of Sakurajima volcano), and the other at Wakamiko caldera, and that both vents were active simultaneously.

3-3. Post climactic eruption

Medium or small-volume pyroclastic deposits younger than the Ito ignimbrite are found not only within the Aira caldera but also on its eastern periphery. Shinjima pumice, a submarine pyroclastic flow, was deposited within the caldera ca. 16 ka (Kameyama et al., 2005), whereas Takano base surge was deposited on land ca. 19 cal kBP (Okuno, 2002). These deposits are intercalated within the tephra layers of Sakurajima. Chemical compositions of these deposits are different from the volcanic products from Sakurajima, but are quite similar to the pyroclastic materials from Aira caldera. The pumice deposits also contain orthopyroxene phenocrysts (ferrohypersthene), which are quite different from those of Sakurajima volcano. This means that new pyroclastic eruptions occurred within Aira caldera during the growth of Sakurajima volcano. Their vent positions are estimated to be the Wakamiko for the Shinjima pumice and Okise, one of the submarine peaks aligned along the eastern margin of Aira caldera, for the Takano base surge (Nishimura and Kobayashi, 2012). Vigorous submarine fumarolic activity, called "Tagiri", occurs on the floor of Wakamiko caldera.

4. Sakurajima Volcano

4-1. Outline of topography

Sakurajima volcano, which started its eruption at 26 cal kBP on the southern rim of the Aira caldera, is composed of two adjacent stratovolcanoes, the Kitadake (1117 m) and the overlying Minamidake (1040 m), and small parasitic volcanoes (Fig. 7). Nakadake, a small peak between Kitadake and Minamidake is interpreted as a parasitic cone that formed near the summit crater. A small plateau called Hakamagoshi which consists of basement deposits exists in the western slopes of the volcano.

4-2. Tephra sequence

Fig. 8 shows the general stratigraphy of the

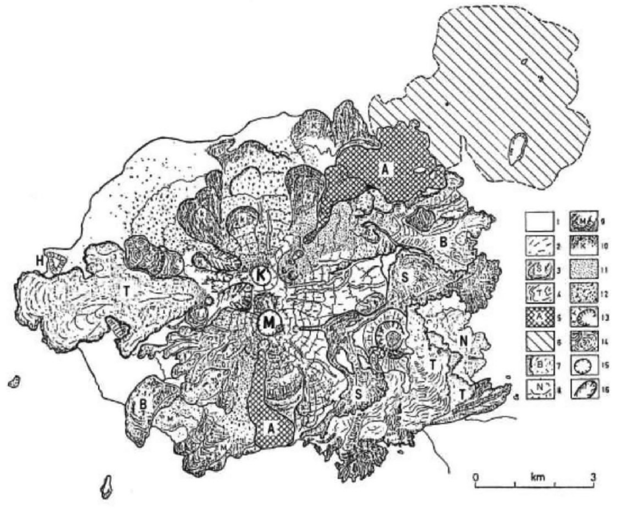

Fig. 7 Geomorphological map of Sakurajima volcano (Aramaki and Kobayashi, 1986). 1, volcanic fan; 2, recent ejecta; 3, Showa lava (S: 1946); 4, Taisho lava (T: 1914-1915); 5, An-ei lava (A: 1779); 6, cryptodome of An-ei lava into the bottom (1779-1781); 7, Bunmei lava (B: 1471-1476); 8, Nagasakibana lava (N: AD 764); 9, Minamidake lava; 10, Kitadake lava; 11, agglutinate; 12, pyroclastic flow deposit; 13, tuff cone; 14, lava dome; 15, crater; 16, cliff, **K**: Kitadake, **M**: Minamidake, H: Hakamagoshi

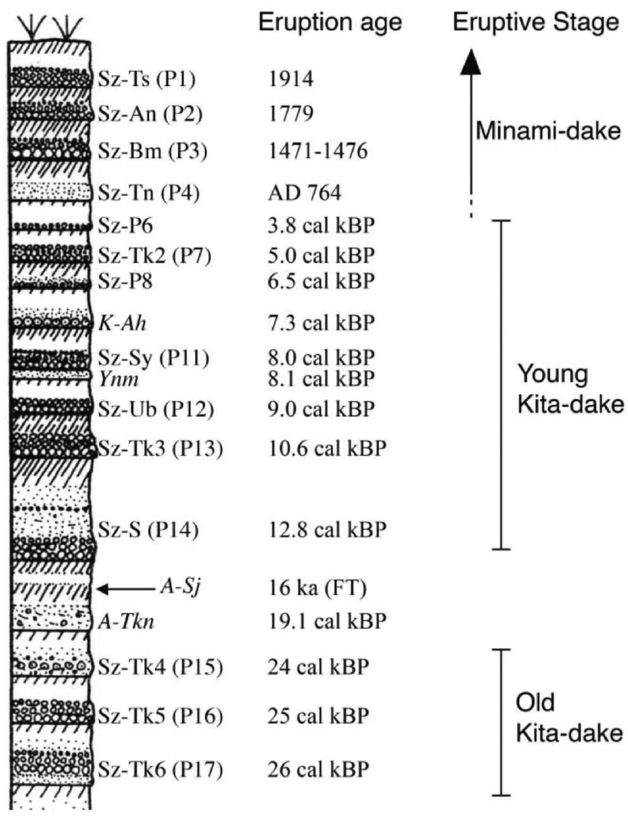

Fig. 8 Summary section of the Sakurajima tephra group on the northern part of Osumi peninsula (modified from Okuno et al., 1997)

Sakurajima tephra group as described by Okuno et al. (1997). The volcanic activities of Sakurajima can be subdivide into three stages: Older Kitadake (26-24 cal kBP), Younger Kitadake (13-4.5 cal kBP) and Minamidake (<4.5 cal kBP).

At least 17 tephras were erupted (P17-P1 in ascending order) from the volcano. The oldest tephras, P17-P15, were erupted from Older Kitadake, P14-P5 from Younger Kitadake, and P4-P1 from Minamidake. The P14 tephra (12.8 cal kBP), representing the beginning of the Younger Kitadake, was the most voluminous (11 km^3: Kobayashi and Tameike, 2002). There was a long dormant period for about 10,000 years between "Older Kitadake" and "Younger Kitadake". During this dormant period, Takano base surge (19 cal kBP) and Shinjima pumice (ca. 16 ka) were erupted within the Aira caldera. Since the P14 eruption, a plinian eruption occurred from Kitadake volcano within the period of 800-2000 years.

4-3. Outline of geology

The upper part of the Kitadake volcano consists mainly of pyroclastic rocks, while the lower slope is predominantly of lava flows. The western part has been thoroughly dissected by deep gorges. In contrast, some areas have a flat surface of thick pumice deposits and cut by deep valleys whose flat and smooth bottoms consist of red-brown welded pumice. This is the Take pyroclastic flow deposit (P5) erupted from the Kitadake summit crater. Parasitic volcanoes of Kitadake volcano are mainly distributed in the eastern and western flank of the main volcano. They are aligned in WNW-ESE direction, probably erupted through the fissure vents. In the western flank of the Kitadake, three major lava domes trend in this direction, e.g. Harutayama, Yunohira and Furihata. The western half of Yunohira lava dome slid down toward the northwest, thus producing Furihata which exhibits as uneven surface. Chemical compositions of these lava domes are all dacitic (67 wt% SiO_2), which were probably erupted from the fissure vents at the same time. The exact age is not known, but those lava domes are overlain by P11 of ca. 8.0 cal kBP.

Minamidake is an active stratovolcano that grew on the southern slope of Kitadake. The upper part of the volcanic edifice is composed mainly of alternations of lavas with minor pyroclastics, suggesting that Minamidake has grown up mainly by the accumulation of lavas, while thick volcanic ash layers have accumulated around the volcano. These tephras consist of many sandy ash layers separated by humic soils (Fig. 9). They represent the deposition by intermittent vulcanian and/or strombolian eruptions, continued for a long period. Based on the distribution, surface texture, and chemical characteristics of lavas of Minamidake, they are divided into older and younger group. Those of the younger group are restricted in historical time. During the Minamidake stage, four plinian eruptions occurred only in historical time, whose deposits are named as P4 (AD 764), P3 (1471-1476), P2 (1779) and P1 (1914) in ascending order.

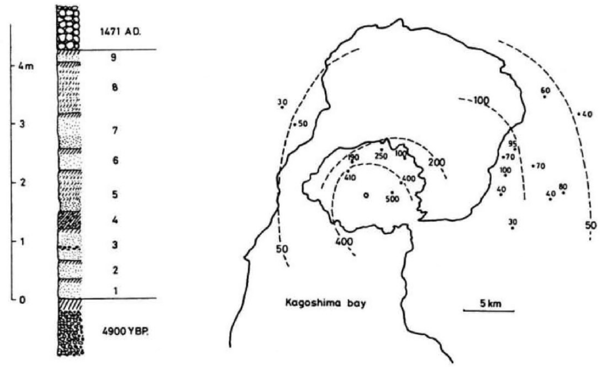

Fig. 9 Columnar section and isopach map of volcanic sand deposit erupted from Minamidake volcano (cm). Diagonal lines of the columnar section indicate tephra containing humus (Kobayashi et al., 1988).

Volcanic fans are also distributed around the volcano. The largest, mainly formed during the growth of Kitadake, is located in the northwestern sector. Recently volcanic fans are progressively developed by lahars, owing to the deposition of new ejecta over the volcano. Representatives of such are observed at Jigokugawara in the eastern side and around the mouth of Nojirigawa River in the southwestern slope of the volcano.

4-4. Historical eruptions and recent activities

1) Pre-Bunmei eruptions

Based on the historical records of eruption, the oldest one took place in AD 708. However, its exact nature and vent position were not known. The first well-documented record of a big eruption was written in AD 764. Although this eruption was long believed to be a submarine eruption, it was a phreatomagmatic eruption occurred at the SE coast of the volcano, and generated the Nabeyama tuff cone whose eastern half was soon after eroded by waves of sea surface, and buried by succeeding lava flow (Kobayashi, 1982; Okuno et al., 1998; Miki, 1999). The Ohira lava flowed down north from the summit crater in ca. AD 950 (Kobayashi et al, 2009), and Nakadake is estimated to be formed in ca. 1200 (Kobayashi, 2010).

Fig. 10 shows the distribution of large-scale tephras in historical time. A series of large-scale fissure eruptions in 1471-1476 (Bummei era), 1779-1782 (An-ei era), and 1914-1915 (Taisho era) started with plinian activity from newly opened fissure vents and ceased with the emission of lava flow. Pyroclastic flows inevitably accompanied these eruptions.

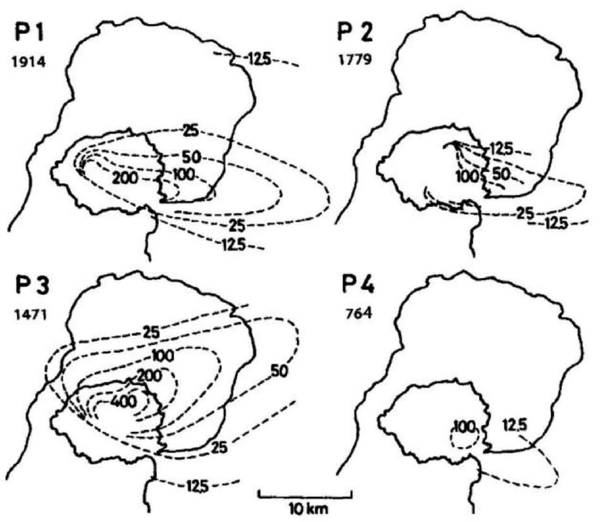

Fig. 10 Isopach maps of pumice fall deposits in historical time with thickness in cm (Kobayashi and Tameike, 2002).

2) Bunmei and An-ei eruptions

Bummei eruption produced voluminous pumice fall from the northeastern fissure vents, and lava emission occurred from the foot of the volcano in the northeast, southwest, and southeast slopes. The next big eruption, An-ei eruption, occurred in 1779 from fissure vents at the northeastern sector of Kitadake and southern sector of Minamidake volcano. Submarine eruptions continuously occurred at the northeastern offshore area for about two years. The intrusion of magma beneath the submarine deposits pushed the sea floor up, producing a submerged 100-m-high cryptodome. On the surface of the cryptodome, four islets are still preserved. One of them is Iojima islet which is composed of massive lava with a summit crater. On the other hand, Shinjima and Nakanoshima islets are composed mainly of submarine deposits with overlying blocks of giant pumice which were settled during the first phase of the An-ei submarine eruption (Kobayashi, 2009).

3) Taisho eruption

The Taisho eruption began on January 12, 1914 from the western and eastern fissure vents. Prior to the Taisho eruption, Sakurajima volcano became active as indicated by swarms of earthquakes that increased in number until the early morning of January 12. The plinian eruption started at 10:05 on the same day at the western flank and, ten minutes later, at the eastern flank. In the evening of the same day, a strong earthquake (M7.1) hit Kagoshima city causing a severe damage to the city. The plinian eruption continued for more than a day, and gradually decreased in intensity during late noon of 13 January. However, another big eruption which lasted for only 15 minutes occurred at around 20:14. This eruption was very violent and spectacular - emitted pyroclastic flow gave the whole volcano a fiery red glow. Lava emission followed just after this event. Small-scale pyroclastic flows were also generated at several times on 14 and 15 of January. Although activity in the western vents ceased within two weeks, lava emission from the eastern vents continued for more than a year. The eastern lava flow filled the Seto Strait by the end of the month and connected the island to the Osumi Peninsula. Lava emission from the eastern vents continued thereafter with small cyclic explosions every two hours, which probably lasted from April to October 1914. From March to May 1915, new lavas poured out from the break in the lava front near the shore and formed a small lava delta.

Figures 11 and 12 show the classification and the origin of surface textures of Taisho lava flow from the western fissure vents. Thick pumiceous deposit, having a general smooth flat surface, is cut by step-faults along the steep slopes around the vent. Pumiceous deposit around the upstream of the lava displays extensional cracks normal to the flow direction, while that in the downstream part is heavily broken and transported by the underlying lava flow. Outpouring of lava continued for some period from the fissure vents aligned along the valley. Consequently, broken pieces of pyroclastic deposit in the area were completely transported for some distance that resulted in block lava presently occupying the valley.

To summarize the general sequence of every big eruption in Sakurajima Volcano in historical time, it can be pointed out that pyroclastic flows were mostly generated as independent phases from violent plinian activity. Moreover, the mode of lava emission changed with time. Although the eruption generally changed from plinian to lava emission during an eruptive cycle, the actual sequence of eruption was not that simple, e.g. pyroclastic flow eruptions occurred several times during the emission of lava flow, and the eruptive sequence was repeated several times. These phenomena might be a result of the change in the physical conditions in the conduit and/or magma chambers during the eruption. This change is probably due to simultaneous ground subsidence caused by magma discharge and new supply of magma to the shallow chambers from deeper plumbing system.

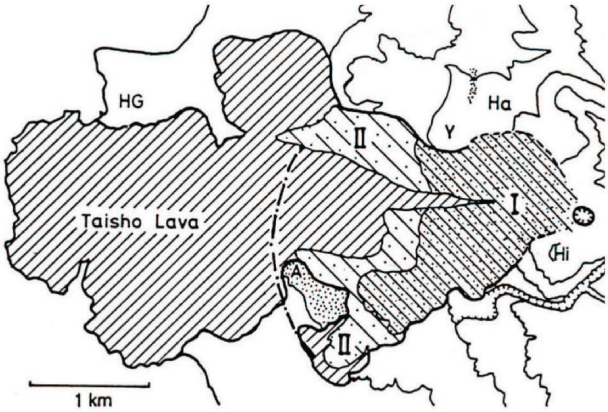

Fig. 11 Classification of the surface textures of Taisho lava flow from the western fissure vents. Dashed line indicates the limit of distribution of pyroclastic flow that occurred on January 15, 1914 (after Yamaguchi, 1967). I: pumiceous deposit field with step-faulted flat surface, II: heavily broken pumiceous field, A: Atagoyama, Ha: Harutayama lava dome, Hi: Hikinohira lava dome, HG: Hakamagoshi plateau, Y: Yunohira lava dome.

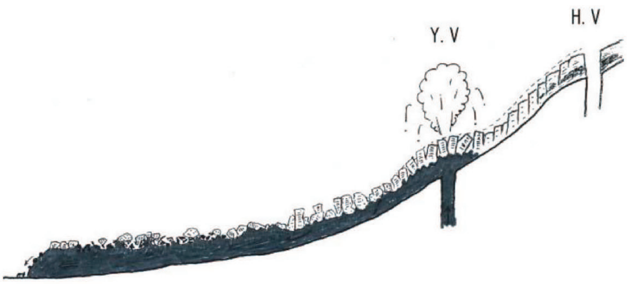

Fig. 12 Origin of the surface textures of Taisho lava flow from the western fissure vents. Pumice cone around the fissure vents, specifically at Yunohira vent (Y.V) which was heaved up by outpouring lava was breached, and pieces of pumice deposit were transported downstream by the moving lava flow. H.V represents the highest fissure vent.

4) Showa eruption

In October 1939, small-scale pyroclastic flow eruptions occurred on the eastern slope near the summit. In 1946 (Showa era), lava emission of 0.18 km^3 (Ishihara *et al.*, 1981) occurred from the same parasitic crater with a very small amount of pyroclastic materials. No pumice ejection occurred at this time.

5) Recent activity

A sudden explosion occurred in the summit crater of Minamidake in 1955. Since then intermittent eruption occurred in the summit. The mode of eruption is mainly vulcanian, however, at times ash-laden cloud was generated continuously without any explosive eruptions for a few days, especially during active periods. Figure 13 represents the annual number of explosions of Minamidake crater since 1955. The most active period of the summit crater was in 1985, and the annual number of explosions was 474. Volcanic activity significantly decreased after 2002, but in 2006 Showa crater resumed activity for the first time in 70 years, and became very active since 2009. The explosions in 2009, 2010, 2011, and 2012 reached a total of 548, 896, 996, and 885, respectively. Two hundred seventy two explosions have already occurred by the end of March in 2013. A new volcanic edifice, Heisei pyroclastic cone, has formed on the eastern slope of the Minamidake.

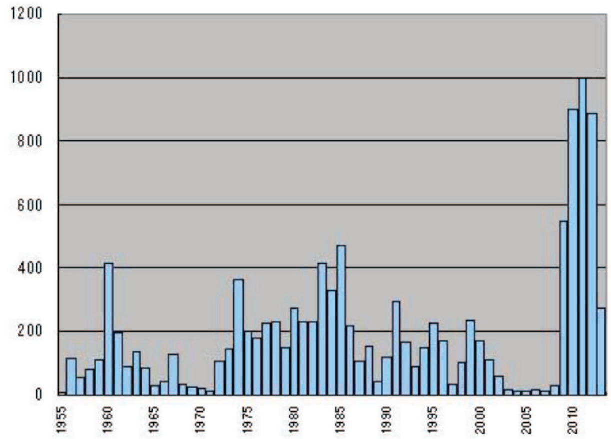

Fig. 13 Annual number of explosions from Minamidake since 1955.

Volcanic rocks of Sakurajima volcano erupted more than 500 years ago are composed of olivine-bearing and/or olivine-free pyroxene andesite and pyroxene dacite, and show a relatively narrow compositional variation, ranging from 67 wt% to 62 wt% $Si0_2$. However, the $Si0_2$ content of lavas and pyroclastic rocks erupted in the period from 1471 to 1939 has regularly decreased from 67 to 57 wt%. In 1946 the $Si0_2$ content of the magma suddenly increased to about 62 wt%, and has remained almost constant with some minor fluctuations up to the present.

Some ejecta in this period have $Si0_2$ content more than 63 wt%, which are thought to be accessary or accidental origin. Some of these ejecta having more than 70 wt% were changed into expanded pumice, which are apparently of silicic tuff origin. Similar ejecta thrown out during the Taisho eruption were described as volcanic scum, ceramicite, thread-lace scoria, and “bread-crust bomb” by Koto (1916) and Yamaguchi (1928). Extremely vesiculated pumiceous materials were thrown out on November, 1987, whose specific gravity is as low as 0.2. They are considered as the lightest rocks in the Sakurajima volcano, resembling “thread-lace scoria”. The existence of extremely expanded tuff (pumice) indicates the walls of conduit were partially, or in some portions completely, molten before eruption due to the latent heat of the andesite magma.

5. Kakuto and Kobayashi calderas

Kakuto caldera is located on the boundary between Kagoshima and Miyazaki prefectures. The caldera occupies the northern end of Kagoshima graben in which the topography is clear in the west, north and eastern rim, but the southern portion is obscured due to the growth of older Kirishima volcano which subsequently buried the southern rim. At ~340 ka, a large amount of magma was erupted as pyroclastic flows, which was deposited in wide area around the Kakuto caldera. The densely welded part is well preserved, and is suitably called Kakuto welded tuff or Kakuto ignimbrite. Kobayashi caldera, adjoining Kakuto caldera to the east, is much older than Kakuto, and its caldera topography is not clear. The existence of the caldera is only estimated from Bouguer anomaly (Tajima and Aramaki, 1980) and distribution of old ignimbrite around this caldera.

Figure 14 represents the landforms of Kakuto caldera. Kakuto caldera was filled with lake water for a long time. The accumulated lacustrine deposits are divided into lower Ikemure Formation and upper Kyomachi Formation (Aramaki, 1968). Figure 15 represents the boundary between the Ikemure formation (lower grey part) and Kyomachi Formation (upper pale part). The Kyomachi Formation, which was quickly formed by the entrance of Ito pyroclastic flow into the lake at 29 cal kBP, consists mainly of sorted pumiceous materials ranging from coarse pumice aggregates through pumiceous sand to fine vitric ash.

At ca. 22 cal kBP, the marginal part of Iimoriyama lava flow at southeastern shore of the caldera lake slid down into the lake, which was probably triggered by severe ground shakings. Due to the quick mass movement, the unconsolidated lake deposits were strongly deformed resulting in the formation of conspicuous alternation of anticline and syncline. Due to this event, lake level quickly reached the highest, but the lake was drained soon after and formed lake terraces, at least three different levels, along the margin of the Kakuto lake.

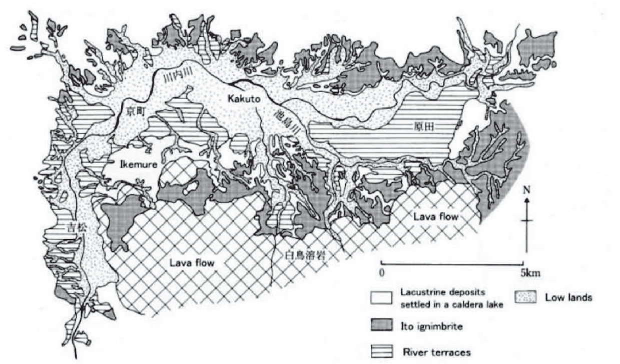

Fig. 14 Landforms of the Kakuto basin (after Machida et al., 2001).

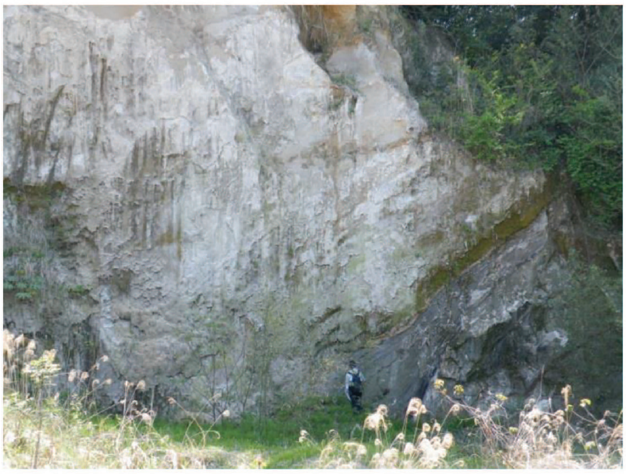

Fig. 15 Large outcrop of lacustrine deposit in the Kakuto basin. Ikemure Formation (right side) is overlain by Kyomachi Formation (left side).

6. Kirishima volcano

The Kirishima volcano is composed of more than 20 eruptive centers which occupy an area of about 600 km^2 trending NW-SE. It is situated on the southern rims of the Kakuto and the Kobayashi calderas, which occupy the northern end of the Kagoshima graben.

Ranging from Pleistocene to recent in age, a large pile of lavas and ejecta formed several stratovolcanoes which produced the main framework of the present-day Kirishima volcano. This volcano is divided into two groups by the 340 ka Kakuto ignimbrite, i.e., the older and the younger Kirishima volcanoes. The older volcanoes started the eruption ca. 600 ka (Nagaoka et al., 2010), and predominantly underlie the younger volcanoes, and are only exposed in the foot of the Kirishima volcano. The activity of the younger Kirishima began ca. 330 ka. Most of the younger volcanoes are either small stratovolcanoes or monogenetic volcanoes. They are conveniently subdivided into three groups by two wide-spread tephras, i.e., Ito ignimbrite from Aira caldera (29 cal kBP) and Kikai-Akahoya ash (K-Ah) from the Kikai caldera (7.3 cal kBP).

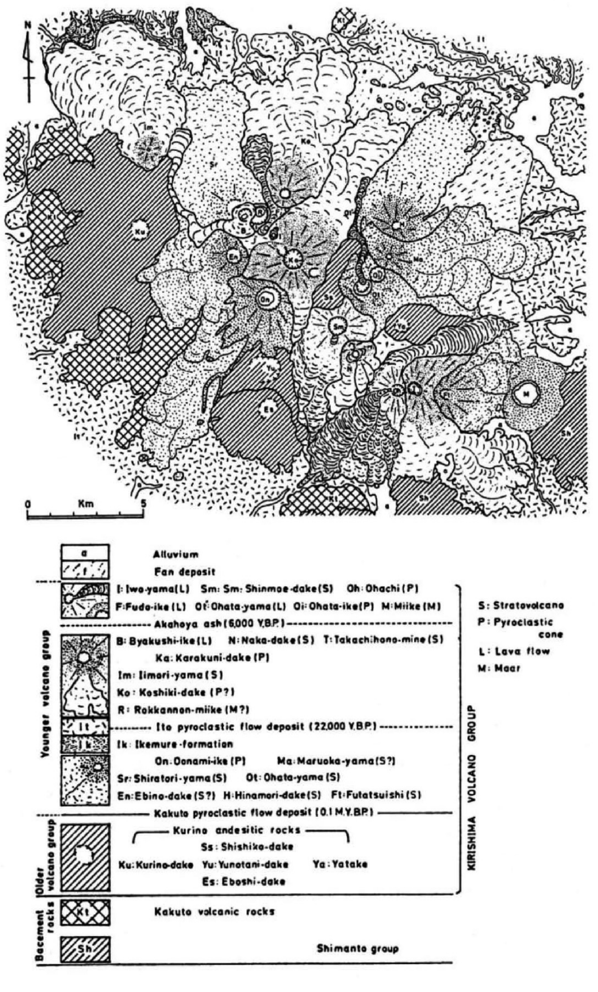

Fig. 16 Geologic sketch map of the Kirishima volcanoes (after Kobayashi et al., 1981)

Fig. 16 shows the geologic sketch map of the Kirishima volcano. The morphology of small stratovolcanoes resembles that of a pyroclastic cone with a large top crater. The representative example is Ohachi volcano, which is usually called Ohachi crater. The volcanic edifice near the vent is composed mainly of alternations of densely and partially welded pyroclastic fall and/or flow deposits, and the lower slope is composed mainly of accumulation of lava flows, pyroclastic flows, and lahar deposits (Fig. 17).

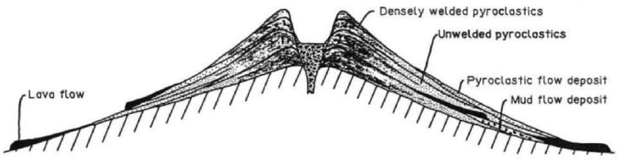

Fig. 17 Schematic cross section of either small stratovolcanoes or monogenetic pumice cones common in Kirishima volcano (Kobayashi and Kagiyama, 1988)

More than 40 eruptions have been documented since AD 742, and they mostly occurred at Ohachi crater and Shinmoedake volcano. Ioyama, a small lava flow, was also formed in historical time at Ebino-kogen, the northwestern foot of the Karakunidake. Its eruption age is generally believed in 1768, but is still not known exactly. Ohachi crater has been the most active in historic time. A large amount of scoria was ejected especially in AD 788 and 1235, and lavas also flowed to the southwest. A small-scale scoria flow was generated in the 1235 eruption. Other than these eruptions, many violent eruptions occurred from this crater, including intermittent eruptions during 1880 and 1923.

In 1716-1717, a series of violent explosions, known as Kyoho eruption occurred at Shinmoedake volcano (Imura and Kobayashi, 1991). Large amount of pumice, scoria, and lithic fragments were ejected forming a thick layer all over the volcano. In 1959, a violent phreatic explosion occurred which ejected mainly clayey ash. This eruption formed fissure vents at the western slope of the volcano. The latest major eruption occurred at the Shinmoedake in January 2011. Precursory activity started with a small phreatic eruption in 2008, which also formed fissure vents along the 1959 fissure vents. Several phreatic eruptions continuously occurred in 2010, and the volcanic activity gradually increased, and culminated to a sub-plinian eruption on January 26 and 27 in 2011. The new lava filled the old summit crater of Shinmoedake by January 31 (Fig. 18), and violent vulcanian eruptions continuously occurred by the end of February. The volcanic activity declined gradually since then, but the gas emission has been continuing until now.

Fig. 18 New lava filled the summit crater of Shinmoedake shows circular wrinkles , taken on January 31, 2011.

The rocks of this volcano are mainly augite-hypersthene andesites which sometime contain a small amount of olivine phenocrysts. However, Ohachi crater issued basaltic scoria and lava, and Miike maar ejected a large amount of pumice of hornblende-bearing pyroxene dacite. There is a tendency for mafic rocks to be restricted to the eastern part of the volcanic area. These rocks show a higher degree of iron-enrichment, suggesting that they belong to the tholeiitic rock series. Other andesites show no iron-enrichment, and are therefore classified in the calc-alkaline rock series.

DESCRIPTION OF FIELD STOPS

DAY 1: Sakurajima volcano (Fig. 19)

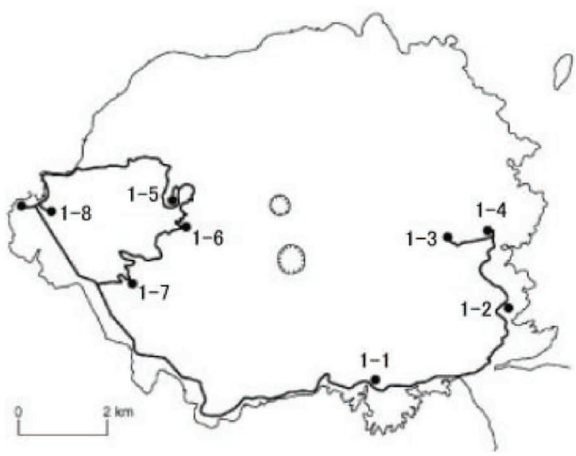

Fig. 19 Field trip route and stop locations in the Sakurajima area (Day 1).

Stop 1-1: Arimura: Historical lava flows

This stop is located on the Taisho lava flow erupted in 1914. In front of us, we can see Minamidake, an active volcano, and the Showa lava flow erupted from a parasitic vent in 1946. Extensive ramp structures are formed in the block lava around the lookout site. A concrete facility at the parking lot is a shelter against projectiles. On clear days, Kaimondake volcano can be seen to the south.

Stop 1-2: Nagasakibana quarry: Cross section of the Tenpyohoji lava (AD 764) and overlying historical tephras

A section of the Tenpyohoji lava erupted in AD 764 can be observed at the quarry along the coast. This lava buried the deep strait more than 100 m thick. Some rocks at this stop contain abundant vapor phase cristobalite. The lava is overlain by three historical pumice fall deposits erupted in 1471-1476, 1779 and 1914 (Fig. 20). The 1471 pumice fall deposit around here is not so thick, which only occurs as a thin layer in the humic soil just above the lava flow.

Fig. 20 A quarry of the AD 764 lava flow which is overlain by three historical pumice fall deposits erupted in 1471, 1779 and 1914.

Stop 1-3: Jigokugawara: Recent volcanic fan overlying the 1946 lava flow

Jigokugawara is a recent volcanic fan formed by frequent lahars onto the 1946 lava flow field. We can see the Nabeyama tuff cone formed in AD 764, and steep lava levees of the 1946 flow along the deep valley between the Nabeyama tuff cone and Gongenyama lava dome. If the weather is fine, we can see the active Showa crater and the Heisei pyroclastic cone, which has grown mainly in recent years (Fig. 21).

Stop 1-4: Kurokami: Buried gate of shrine

The gate of a shrine was almost completely buried by pumice fall of the 1914 Taisho eruption. The thickness of the deposit around here attains 2 m. Recent volcanic ash attains 1 m around this area.

Fig. 21 Explosion from Showa crater of Heisei pyroclastic cone.

Stop 1-5: Yunohira Lookout: Surface structure of the Taisho (1914) lava flow

From this point, we can view the western sector of Sakurajima volcano, especially the western vent of the Taisho eruption in 1914 (Fig. 22). A large pit on the left side of the Hikinohira lava dome is the highest crater of the Taisho fissure vents. One of the lava vents near Yunohira heaved up due to the outpouring of lava, resulting in the formation of a peculiar welded-pumice dome called Yunohira vent. The lava heavily broke the western half of the dome into various sizes of pumiceous blocks, which were then transported downslope. Those on the upper slope are only cut by step faults along steep slopes thus preserving a general smooth flat surface. The brownish wall along the road is the surface of the natural levee of the 1914 lava flow. The lava levee, however consists mainly of pyroclastic flow deposit, which was tilted by the outpouring of lava flow.

Stop 1-6: Pyroclastic deposit and lava flow of Taisho eruption

This stop is located at the western end of the fissure vents, where the floor of a small valley is now occupied by the Taisho (1914) blocky lava flow. Oxidized pyroclastic deposits around the vents were heavily broken and transported downslope by the moving lava flow. Samples of block lava may be collected. We can observe an old bridge which was partially destroyed by lahar. The present site of the bridge is shifted a bit downstream from the original position.

Fig. 22 View from Yunohira lookout. The Kitadake (left, background), the active Minamidake (right, background), and the volcanic products of the Taisho eruption in 1914 (foreground). Yunohira vent was located just behind the brownish natural levee.

Stop 1-7: Large blocks of pumiceous deposits

Large blocks of oxidized pumiceous deposit up to 3 m, which are thought to have been transported from the vent area by the lava flow, are scattered on the surface of the block lava (Fig. 23). Similar pumiceous deposits are widely distributed around the fissure vents which represent various degree of welding.

Fig. 23 Large blocks pumiceous deposit scattered on the surface of the block lava.

Stop 1-8: Sakurajima Volcano Research Center (SVRC)

Sakurajima Volcano Observatory (SVO), which was founded in 1960 to study the mechanisms and prediction of eruptions, was one of the divisions of the Disaster Prevention Research Institute, Kyoto University. The first observatory was built in 1967 on top of the Harutayama lava dome, 2.8 km NW of the active crater. The present observatory is located near the ferry terminal. The Harutayama tunnel was built in 1985. It contains water tube tiltmeters and extensometers which record minor inflation in the summit shortly before explosive eruptions occur.

In 1996, the SVO was incorporated into the Sakurajima Volcano Research Center (SVRC). Geophysical and geochemical monitoring and studies have been carried out at Sakurajima, Satsuma-Iojima, Kuchinoerabujima, Nakanoshima and Suwanosejima volcanoes, in collaboration with other universities and institutions. We will show the two monitoring systems of the volcanoes. The first system consists of a modernized digital system connecting the seismic stations with Ethernet and wireless LAN. The tilt data at Harutayama underground tunnel is automatically processed, which enables fast assessment of the state of the volcano as well as prediction of imminent occurrence of vulcanian eruptions at the summit crater. The second system is a traditional smoked paper drum recorder, which provides quick seismic monitoring. A video of eruptions at Sakurajima and Suwanosejima volcanoes is also displayed.

DAY 2 Kakuto caldera and Kirishima volcano (Fig. 24)

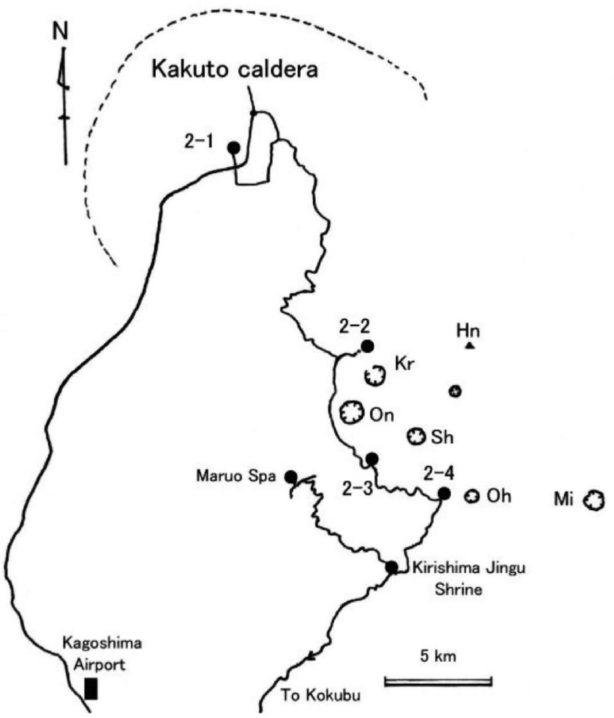

Fig. 24 Field trip route and stop locations in the Kirishima area (Day 2).

Stop 2-1: Deformed tuffaceous deposits in the Kakuto caldera

This place is a large quarry of lacustrine deposits in the Kakuto caldera. We can observe the boundary between the Ikemure Formation (lower grey) and Kyomachi Formation (upper pale). Both formations were tilted, because the lacustrine deposits were soft enough to deform when the broken mass of lava quickly slid into the caldera lake.

The Kyomachi Formation, which was generated by the entrance of Ito pyroclastic flow into the lake at 29 cal KBP, consists mainly of sorted pumiceous materials ranging from coarse pumice aggregates through pumiceous sand to fine vitric ash. The uppermost layer of the Ikemure Formation is intercalated with thin scoria fall deposit, probably derived from the eruption of Hinamoridake.

Stop 2-2: Ebino-kogen highland

Fig. 25 shows the geological sketch map of Ebino-kogen area which is a highland region surrounded by three volcanoes (Ebinodake, Shiratoridake, and Karakunidake). Small crater lakes are scattered around the region. This area was one of the most active geothermal fields in the Kirishima volcano. More than 20 years ago, the most active fumaroles were clustered around the summit crater of Ioyama. This small volcano is thought to be formed in 1768, and is the youngest volcanic edifice in the Kirishima area. Large jointed blocks or bread-crust bombs are scattered around the crater. A short lobe of lava extending north is classified as block lava showing conspicuous wrinkles on the surface.

Behind Ioyama, there is a large volcano, Karakunidake, whose large cliff was formed by sector collapse. This event was triggered by a phreatic eruption ca. 4.3 cal kBP (Tajima et al., 2008). The cliff is composed of layers of welded pumice or agglutinate with rough columnar joints. Between the cliff of Karakunidake and Ioyama, there are many flow mounds which are composed mainly of large blocks of agglutinate. A collapse deposit or debris flow deposit is distributed at Ebino-kogen. Fudoike is a circular crater lake which is now filled with pale greenish water. This vent issued andesitic lava flows both to the north and to the south. The southern lobe of lava is overlain by Kikai-Akahoya ash (K-Ah), indicating that the lava is older than 7.3 cal kBP. This vent was once buried by debris avalanche deposit from Karakunidake, but renewal eruption opened the crater again ca. 1.6 cal kBP (Tajima et al., 2008).

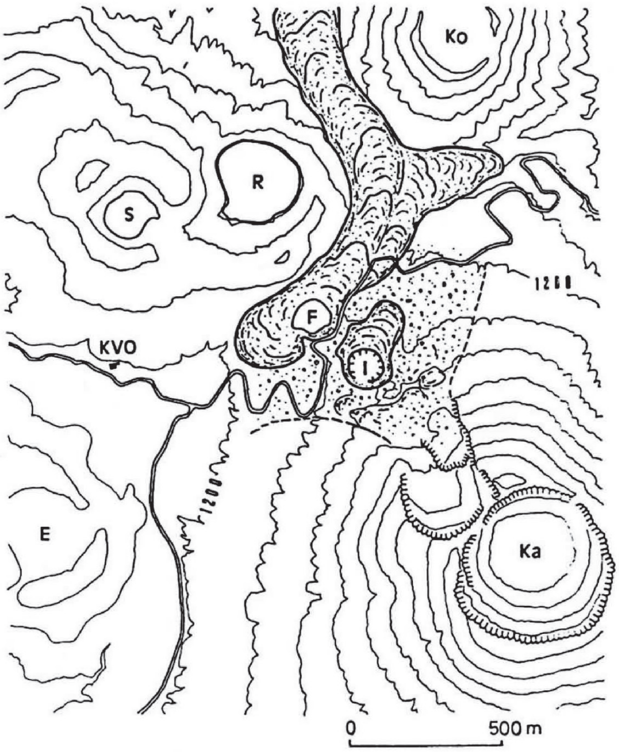

Fig. 25 Geological sketch map of Ebino-kogen area. E: Ebinodake, F: Fudoike, I: Ioyama, K: Karakunidake, Ko: Koshikidake, R: Rokkannon-miike, S: Shiratoriyama, KVV: Kirishima Volcano Observatory of the University of Tokyo.

Stop 2-3: Shin-yu lookout

From left to right, we can see the main volcanic edifices of Kirishima. At the extreme left is Karakunidake which is the highest peak in this region. Shinmoedake volcano is just in front of us, which has fissure vents formed during the 1959 and 2008 phreatic eruptions. We could take wonderful photos from this point (Fig. 26). The sharp peak on the right is Takachihonomine volcano, and Ohachi crater is situated on the flank towards us. Along the road, we can observe a small-scale pyroclastic flow deposit from Onamiike volcano of ca. 40 ka. We may have a short stop around here to observe a sag structure formed at the explosive eruption on Feburary 1, 2011 (Fig. 27).

Stop 2-4: Takachihogawara: the 2011 pumice deposit from Shinmoedake volcano

The Kirishima shrine was once located here, but due to repeated eruptions from Ohachi crater it was destroyed, and had to be relocated to the present site at the lower slope.

The site of Takachihogawara is located near the dispersal axis of the pumice fall deposit of the 2011 Shinmoedake eruption. Hence we can observe the pumice deposits which are well preserved 1 km north of Takachihogawara. We may be able to distinguish three pumice fall units. Small valleys around here are thickly buried by pumiceous lahar deposit (Fig. 28).

Fig. 26 Continuous eruption of Shinmmoedake. Large blocks were repeatedly thrown out from the summit crater. Photo taken from Stop 2-3, at 17:30 on January 27, 2011.

Fig. 27 A small impact crater was formed by a violent vulcanian explosion on February 1, 2011. This sag structure is located about 3.2 km from the summit crater of Shinmmoedake.

Fig. 28 Pumiceous lahar at Takachihogawara.

DAY 3 Aira pyroclastic deposits at Kokubu and Tarumizu areas (Fig. 29)

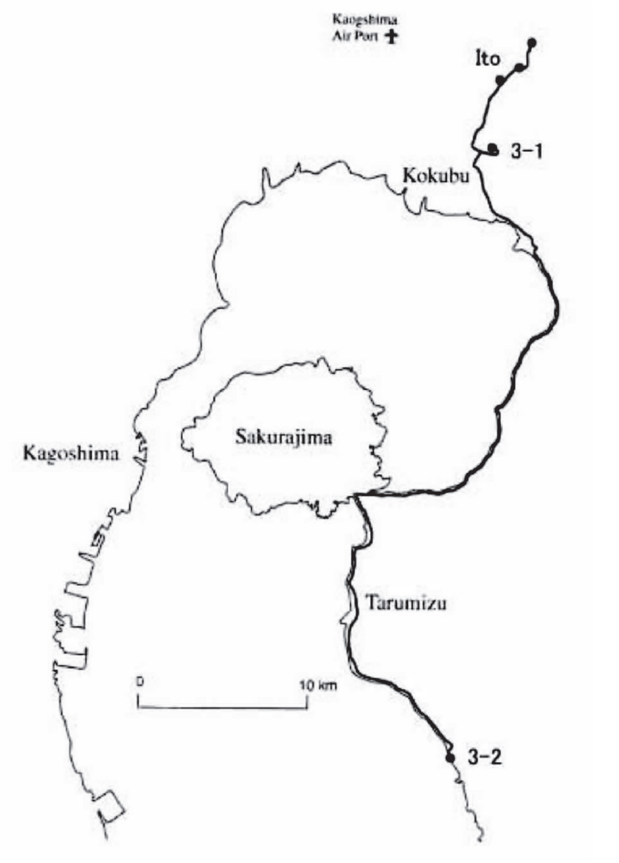

Fig. 29 Field trip route and stop locations (Day 3).

Stop 3-1: Shiroyama Park: Panoramic view of ignimbrite

This park is located on the surface of the pyroclastic plateau of partially welded Iwato ignimbrite, erupted at ca. 60 ka. On a clear day we can have a panoramic view of Ito ignimbrite, which overlies older ignimbrites such as Iwato, Ata, and Kakuto ignimbrites in descending order. We may see Sakurajima volcano to the south, and to the north, Kirishima volcanoes behind the plateau.

Stop 3-2: Fumoto: The whole sequence of the Aira tephra formation

Along the seacoast of Fumoto, we can observe the whole sequence of The Aira tephra formation: from Osumi pumice fall at the bottom, up through the Tarumizu ignimbrite, to the Ito ignimbrite at the top. The Osumi pumice fall is ca. 5 m thick and mantles the underlying topography (Fig. 30).

However, Tarumizu ignimbrite fills the topographic laws, and consists of the lower stratified intra-plinian flows and upper-massive flows (Fig. 31). Many gas-segregation pipes are concentrated in

Fig. 30 Aira tephra formation at Fumoto in Tarumizu area, from bottom to top, Osumi pumice fall deposit, Tarumizu ignimbrite, and Ito ignimbrite.

Fig. 31 Sedimentary structures of the tephra layers. The Osumi pumice fall deposit mantles the basement topography, however, overlying Tarumizu ignimbrite consisting of many stratified thin flow deposits fills the topographic depression.

Fig. 32 Many segregation pipes penetrating lower stratified Tarumizu ignimbrite, which are then truncated by overlying massive upper flow unit.

the middle part of the deposit, and are truncated by the upper-massive ignimbrite (Fig. 32). The Tarumizu ignimbrite is then overlain by non-welded Ito ignimbrite, which contains much large pumice clasts. Lithic fragments are concentrated near the base of the Ito ignimbrite, but do not form a distinct ground layer. Large vertical clastic dikes more than 20 m high penetrate the Ata and overlying Ito ignimbrites (Fig. 33). These dikes are thought to be generated by the severe ground shaking of great earthquakes associated with the 7.3 cal kBP large-scale Kikai caldera eruption (Naruo and Kobayashi, 2002).

Fig. 33 Clastic dikes generating from the crack in the welded Ata ignimbrite, through Osumi pumice fall deposit, to the Ito ignimbrite.

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